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A study to estimate wind distribution in the inner-core region of
tropical cyclones using geostationary meteorological satellites

(静止気象衛星を用いた台風内部コア領域の風速分布の推定に関する研究)

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Abstract

Geostationary meteorological satellites (GMSs) are the only means to continuously observe tropical cyclones (TCs) throughout their lifecycle. Monitoring wind distribution in the inner-core region of TCs is crucial for understanding their dynamics and estimating/forecasting their intensity, which is typically measured as the maximum sustained wind speed. To observe the inner-core region of TCs, in addition to GMSs, aircraft, microwave radiometers/scatterometers and synthetic aperture radars (SAR) on low-earth-orbit satellites, and land-based radar observations are also utilized. However, it has been difficult to continuously estimate the wind distribution in the inner core region due to limitations in spatiotemporal resolution and observational coverage.

Recently, the third-generation GMSs, led by Himawari-8 which began operation in 2015, have dramatically improved spatiotemporal and wavelength resolution compared to their predecessors. They are capable of the “rapid-scan” observations of TCs at a high frequency within a few minutes.

Generally, intensity estimation of TCs in the open ocean mainly relies on subjective and empirical methods based on cloud pattern recognition using GMSs, which are known to occasionally produce significant errors. Since intensity estimation errors are reflected in the accuracy of subsequent forecasts, improving the accuracy of intensity estimation is an important task. One potential approach for improving intensity estimation using GMSs is to physically estimate the intensity from wind distribution obtained by cloud tracking in the inner-core region. Since the clouds in TCs’ eyes are mostly confined in the boundary layer where the tangential winds are maximized at its top, wind derivation from the clouds there should be useful to study and monitor TCs. However, reliable cloud tracking has not been achieved in the rapidly rotating inner-core region using conventional cloud tracking methods. This study aims to develop methods to estimate wind distribution using rapid-scan observations by GMSs and to understand TC dynamics through the obtained results.

Firstly, a method is proposed to derive the axisymmetric component of tangential winds in the eye as a function of radius using spectral analysis for azimuth-time cross-section of rapid-scan imagery. The method is applied to the visible images of boundary layer clouds in the eye of Typhoon Lan (2017) over an 8.5-hr period. The low-level tangential winds over the central two-thirds of the eye in radius were found to be close to a rigid body rotation and increased with time. On its outside was a region with striating clouds rotating at much higher angular velocities, which might have been super gradient. Asymmetric motions are visualized

as the deviation from the inner rotation, and the vorticities of some mesovortices are quantified. These mesovortices are suggested to transport angular momentum to accelerate the inner rotation.

Secondly, a TC-specific cloud tracking method is proposed using template matching with cross-correlation. First, counter-rotating image sequences are created by using preset multiple angular velocities. These sequences are rotated in the opposite direction of the TC's lower winds. Cloud tracking is then performed within a narrow search range in each image sequence. The cloud tracking results that pass a quality control are used as candidate estimates. The estimates with the highest cross-correlation coefficient at each spatiotemporal grid are used as tentative estimates. The candidates that have large differences from the surrounding tentative estimates are iteratively rejected, and the tentative estimates are also updated. The final estimates are determined at the point where the update process stops. By employing this method, wind vectors were obtained at a high spatiotemporal resolution for Typhoon Haishen (2020), Typhoon Nanmadol (2022), and Typhoon Lan (2017). The accuracies of the obtained AMVs was verified to have errors of a few meters per second. The winds in the eye of these typhoons consistently exhibited a transient wavenumber-1 pattern, which is indicative of algebraically growing wavenumber-1 disturbances. The investigation of Typhoon Lan (2017) involves examining the angular momentum transport by mesovortices and the resulting rapid increase in the angular velocity near the TC center using the obtained AMVs.

Finally, a method is proposed to estimate the radius of maximum wind (RMW) from GMSs imagery. RMW is usually located under optically thick eyewall clouds and cannot be observed directly from GMSs. Kossin et al. showed that when TCs have clear eyes, the eye radii estimated from infrared (IR) images have a high correlation with the RMW estimated from aircraft flight-level data. The regression of the former onto the latter was shown to have a mean absolute error (MAE) of 4.7 km. The IR-based RMW estimation is revisited by using C-band SAR sea surface wind estimates. The criteria for selecting clear-eye scenes are simplified. The MAE of the Kossin et al. method is found to be smaller than previously suggested: 3.1 km when the proposed relation is used and 2.7 km when the regression is revised with the SAR-measured RMWs. An improvement of the IR-based method to estimate the eye radii is further proposed. The resultant MAE is shown to be 1.7 km, which indicates that the IR-based RMW estimation can be more accurate than has been suggested. A strong correlation between eyewall slope and eye size is confirmed. Cloud features in the eye that may be closely related to the RMW and wind structure around the RMW are also investigated. Potential applications of highly accurate RMW estimation are discussed.

The proposed methods provide previously unavailable wind distribution, contributing to a deeper understanding of TC dynamics. By extending these methods, it may be possible to estimate TC intensity in a physical and objective manner. Furthermore, the assimilation of the data into TC simulation could be a significant step towards improving the TC intensity estimation and forecasting, which are global challenges.

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Chapter 1

Background

1.1 Tropical Cyclone

Tropical cyclone (TC; commonly called hurricane, typhoon, or cyclone) is one of the most devastating weather phenomena that can affect human activity. A mature TC is characterized by a well-defined eye surrounded by a ring of intense thunderstorms, known as the eyewall. The eyewall is where the strongest winds and heaviest rainfall occur, and it is also where the most intense convection takes place. The convection in the eyewall is fueled by the release of latent heat from the condensation of water vapor, which provides the energy that drives the TC's circulation. During the mature stage, TCs can cause significant damage to coastal areas and islands that are affected by heavy rain, flooding, and storm surges. Overall, the mature stage of TC is a critical time for forecasting and disaster prevention, as it is when the storm is likely to cause the most damage and pose the greatest threat to life and property.

Estimating the intensity of TCs is challenging due to their genesis and intensification over the open ocean. Generally, the intensity of a TC is defined as the maximum sustained wind speed (VMAX) at 10-m elevation or the sea level pressure. Since the VMAX is more directly linked to social impacts than the central pressure, this study defines TC intensity as the VMAX. The intensity of a TC is often categorized into five categories based on the VMAX, known as the Saffir-Simpson Hurricane Wind Scale. Meteorological agencies have different definitions for VMAX due to variations in the averaging period used. In general, the maximum value of the 1-min or 10-min mean wind speed is used. Additionally, there are different spatial definitions of VMAX, such as using the local maximum wind speed within the area affected by TC, or applying some kind of spatial averaging before determining the maximum wind speed. Furthermore, there are storm-relative and ground-relative perspectives for defining VMAX, depending on whether the translation speed of a TC is included or not. In Chapter 5, VMAX is defined as the ground-relative wind speed, averaged over 1 minute and azimuthally. The radius where the TC has its VMAX is called the radius of

maximum wind (RMW). The region within approximately twice the RMW from the TC center is called the inner-core region, where the eye and eyewall clouds and spiral bands are formed. In relation to this, the region outside the inner core is called the outer-core region. The next section presents observations conducted in the inner-core region of TCs over the open ocean. Moreover, the studies on the wind distribution and evolution in the inner-core region of TCs are reviewed in Chapter 2 along with observational findings.

There is a societal demand for accurate prediction of the track and intensity of TCs. Globally, the accuracy of TC track forecasting has been improving year by year. However, the accuracy of TC intensity forecasting is relatively slow. For example, according to the annual reports of the National Hurricane Center (Fig. 1.1), the 24-hour track forecast for Atlantic TCs has improved by about 111 km (from 185 to 74 km) over the past 30 years, while the intensity forecast has improved by ~ 1.5 m/s (from 5 to 3.5 m/s). In the Northeastern Pacific basin, the 24-hour track forecast has improved by about ~ 93 km (from 148 to 55 km), while the intensity forecast has improved by ~ 1 m/s (from 5.5 to 4.5 m/s). According to the annual report of the Japan Meteorological Agency (JMA; Fig. 1.2), the 24-hour track forecast error for TCs in the Northwestern Pacific basin has been reduced by over 100 km (from 200 to 90 km) over the past 40 years. On the other hand, the 24-hour intensity forecast error has remained almost unchanged for more than 20 years (from 5 to 5 m/s). Note that the forecast error is influenced by the quality changes in the best track analysis (Shimada et al., 2020).

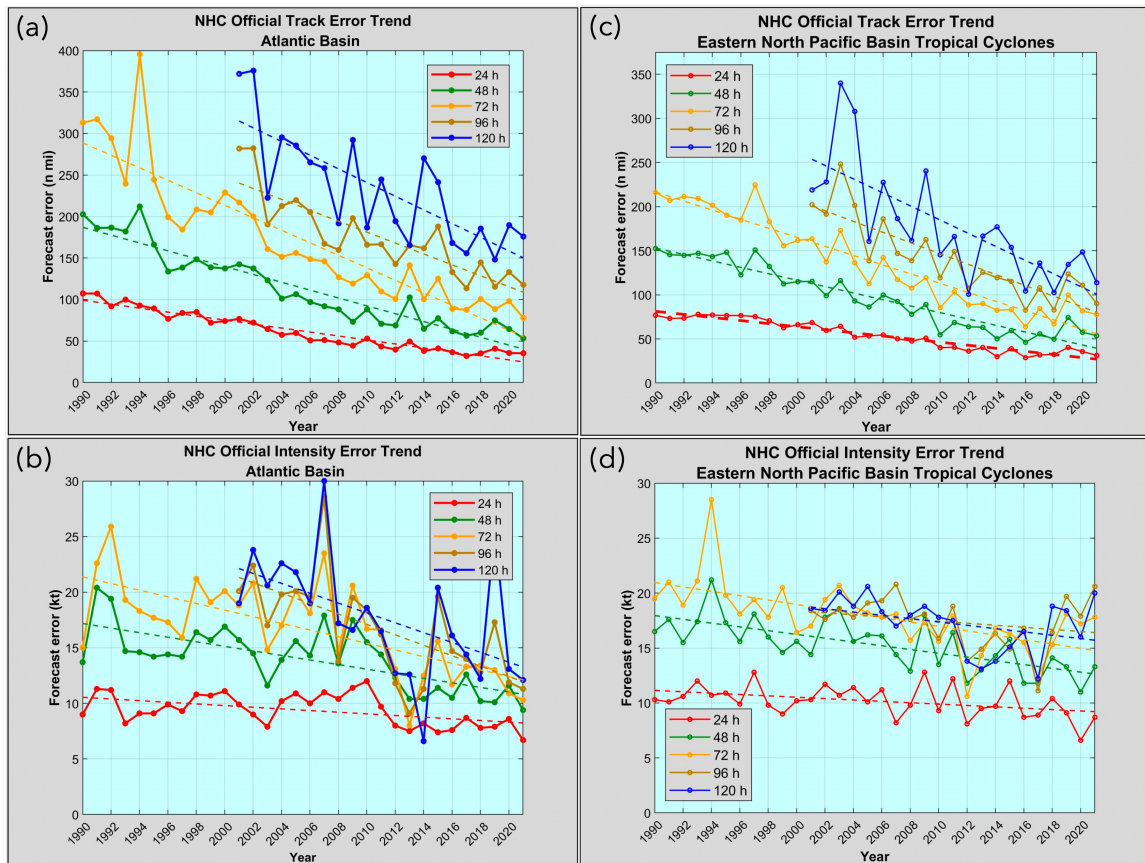


Figure 1.1: Time series of operational TC forecast errors in (left) the Atlantic and (right) the Northeastern Pacific basins. Annual mean position errors in the 24-, 48-, 72-, 96- and 120-hour operational (top) track forecasts, and (bottom) maximum sustained wind speed forecasts are shown. The dashed line indicates the linear fitting. Adapted from National Hurricane Center (2022).

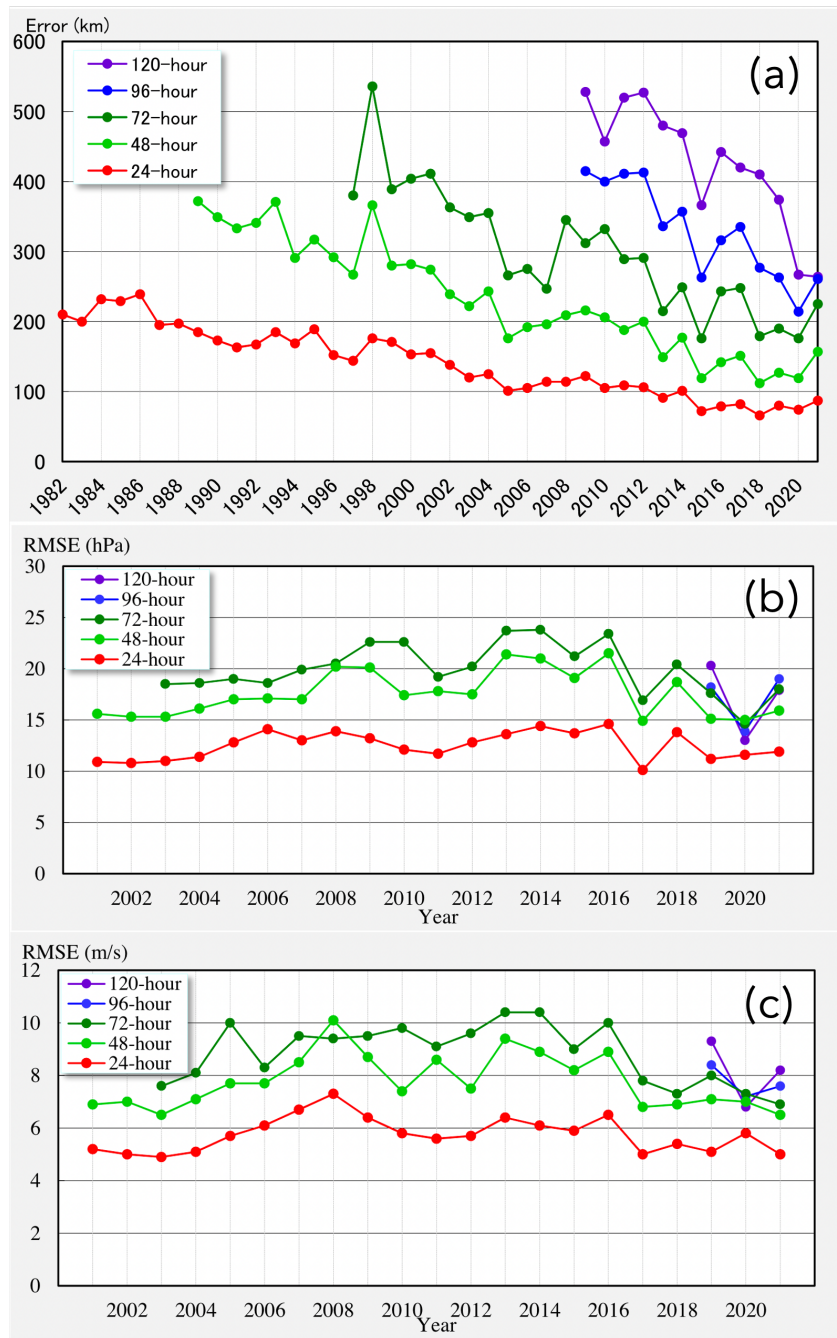


Figure 1.2: Time series of operational TC forecast errors in the Northwestern Pacific basin. Annual mean position errors in the 24-, 48-, 72-, 96- and 120-hour operational (top) track forecasts, and annual Root-mean-square-errors (RMSEs) in the 24-, 48, 72-, 96- and 120-hour operational (middle) central pressure and (bottom) maximum sustained wind speed forecasts are shown. Adapted from Japan Meteorological Agency (2022).

1.2 Monitoring the winds in the inner-core region of TCs

Monitoring the wind distribution in the inner-core region of TCs is important for understanding TC dynamics and for estimating and predicting TC intensity. To observe the inner core region of TCs, commonly used tools include aircraft, land-based radar, low-Earth orbit (LEO) satellites, and geostationary meteorological satellites (GMSs).

1.2.1 Aircraft observations

Aircraft-based TC observations provide the most accurate direct measurements of physical parameters such as wind, pressure, geopotential, temperature, and relative humidity. During aircraft observations, flight-level measurements are obtained using onboard instruments (e.g., Hawkins and Rubsam, 1968). These measurements are also utilized to estimate sea surface winds through various extrapolation algorithms (Powell et al., 1996; Powell, 1980). In addition, the radar-reflectivity is observed by aircraft-mounted radar (e.g., Jorgensen 1984a,b), and pseudo-Doppler wind analysis is performed by a single aircraft assuming stationarity of the wind speed during the observation (e.g., Marks and Houze, 1984; Martinez et al., 2019), and Doppler wind analysis is performed by multiple aircraft (Fig. 1.3) covering the inner-core region (e.g., Marks and Houze, 1987, Marks et al., 1992; Rogers et al., 2013). Direct observation by dropping a GPS dropsonde (e.g., Hock and Franklin, 1999; Franklin et al., 2003; Powell et al., 2003; Martinez et al., 2019) from aircraft and microwave observation by aircraft-mounted microwave radiometer, such as Stepped Frequency Microwave Radiometer (SFMR; Jones et al., 1981; Uhlhorn and Black, 2003; Uhlhorn et al., 2007; Klotz and Uhlhorn, 2014; Sapp et al., 2019), are also powerful tools.

Aircraft observations have led to many new findings, but currently, steady aircraft observations of the inner-core region of TCs are only conducted in the Northeastern Pacific and the North Atlantic since 1943. In Japan, research-based aircraft observations have been conducted about once a year in the T-PARCII (Tropical cyclones-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts) project (Ito et al., 2018; Yamada et al., 2021; Hirano et al., 2022) since 2017. In Taiwan, the DOTSTAR (Dropsonde Observations for Typhoon Surveillance near the Taiwan Region) project (Wu et al., 2005) allows the team to observe the outer-core region of TCs approaching Taiwan by aircraft a few times a year since 2003. This relatively limited use of aircraft observation is largely due to

the risk and cost issues. Due to these factors, achieving sustained and homogeneous observations over long periods of time using aircraft is challenging.

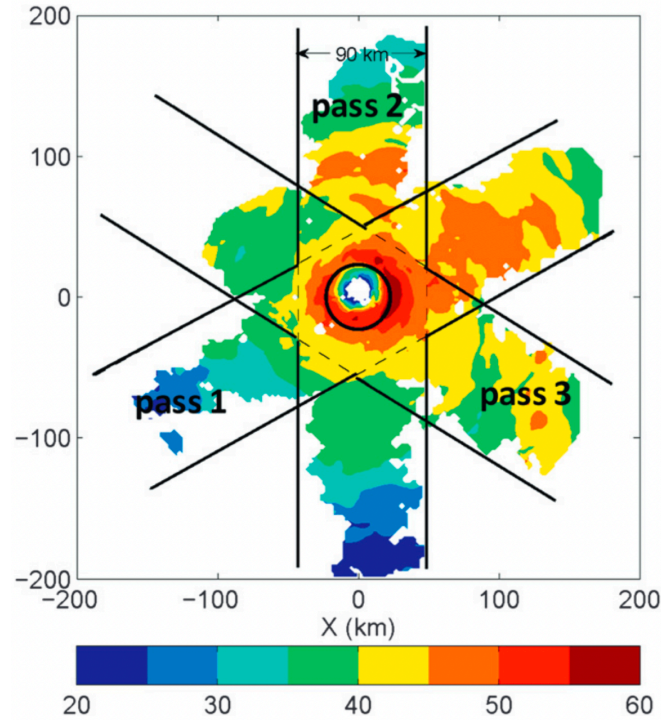


Figure 1.3: Example of wind speed (color shading, m/s) at 2-km altitude during an intense observation period of Hurricane Earl, centered at 0000 UTC 30 August 2010. The period shown here consists of a merger of three individual radial passes separated by 60°. Adapted from Rogers et al. (2013).

1.2.2 Land-based Radar observations

The primary approach for conducting wind observations using land-based radar is through the use of Doppler weather radar. In areas where dual Doppler observation is possible, three-dimensional wind fields can be estimated by utilizing multiple Doppler radars. The Ground-Based Velocity Track Display (GBVTD) technique (Lee et al., 1999) can be utilized with Doppler velocity data, even in areas where only one Doppler radar is available (Fig. 1.4). This approach enables high spatiotemporal resolution of less than 1 km horizontally at a frequency of approximately 5 minutes. This technique has continued to be improved since then (Jou et al., 2008; Tsujino et al., 2023), which is providing insights on the TC dynamics and evolution (Lee and Bell, 2007; Shimada et al., 2018; Shimada and Horinouchi, 2018; Cha et al., 2020).

Land-based radar is a powerful tool for observing winds within the eyewall of a TC, but its applica-

tion is limited to areas within a few hundred kilometers from radar site, and areas without precipitation particles appear as blank (Fig. 1.4). Therefore, there are limitations to continuously monitoring the inner-core wind distribution using land-based radar.

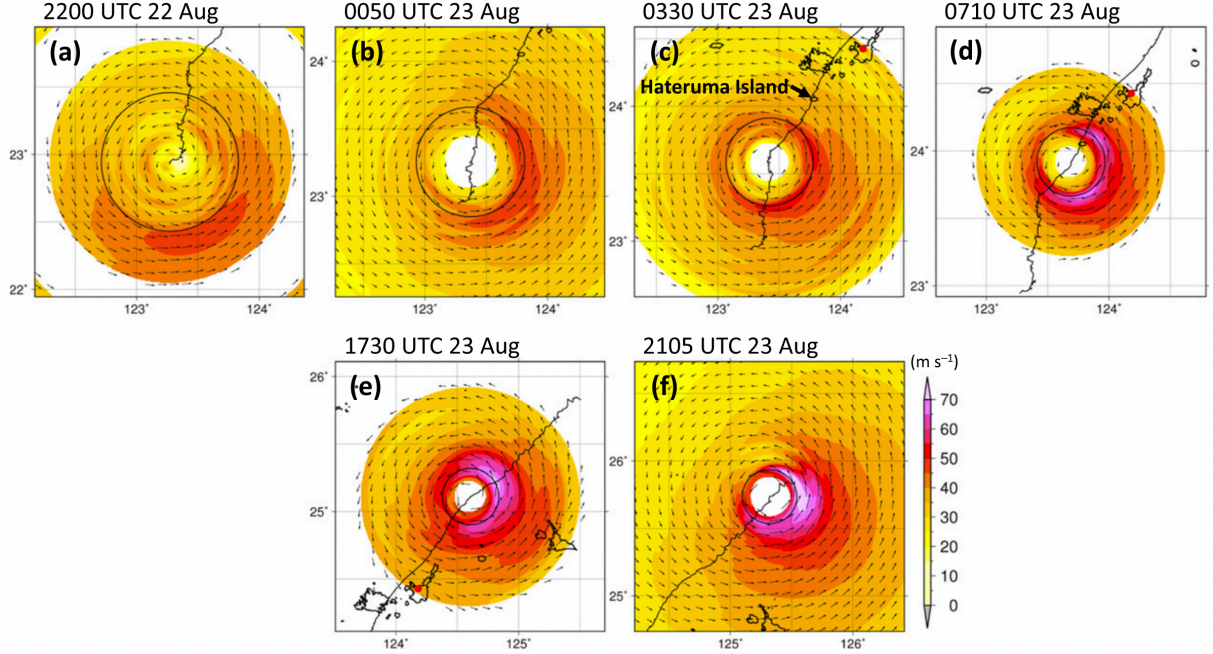


Figure 1.4: The wind speed retrieved at 2-km altitude using the GBVTD technique. The black line indicates track of Typhoon Goni (2015). The red dot indicates the radar site. The black circle denotes the RMW. Panels (a) to (f) show the wind speed at different times, ranging from 2200 UTC 22 August to 2105 UTC 23 August 2015. Adapted from Shimada et al. (2018).

1.2.3 LEO satellite-based observations

Microwave instruments onboard LEO satellites can be either passive, receiving microwave radiations, or active, transmitting microwave signals and receiving the reflected signals. Microwave radiation has high transmissivity through Earth's atmosphere, and longer C-band (4–8 GHz, 3.75–7.5 cm) and L-band (1–2 GHz, 15–30 cm) microwaves have a relationship with wind speed and ocean surface emissivity. This allows us to estimate the extreme surface wind speeds associated with TCs over the open ocean using microwave sensor observations.

L-band radiometers, with a frequency of 1–2 GHz (30–15 cm), are mostly unaffected by liquid or solid precipitation, unlike higher-frequency radiometers (Wentz, 2005; Reul et al., 2012). However, their performance is typically poor relative to other sensors for wind speeds below 15 m/s due to larger radiometer noise and lower sensitivity. Despite this, L-band radiometers can measure extreme surface wind speeds over

the ocean up to 75 m/s (Reul et al., 2016, 2017; Meissner et al., 2017). However, the current 40-60 km resolution of L-band radiometers prevents the observation of small-scale features such as eyewalls and likely underestimates extreme wind speeds in these regions.

Microwave scatterometers, such as the European Remote Sensing (ERS-1 and ERS-2) C-band scatterometers (Attema, 1991) launched in 1991, have been a key tool for monitoring and forecasting TCs (Brennan et al., 2009). Since then, several scatterometers have been launched at various wavelength bands. These instruments are most useful for estimating the radius of 34-knot (17.5 m/s) winds, with reliable wind speed measurements up to around 33 m/s. However, wind speed detection sensitivity decreases starting at 26 m/s, with complete signal saturation at around 36 m/s (Wentz and Smith, 1999; Ricciardulli and Wentz, 2015). Additionally, the horizontal resolution is typically on the order of a few tens of kilometers. There are limitations in observing inner-core wind distribution of mature TCs.

In recent years, some LEO C-band synthetic aperture radar (SAR) satellites have been able to retrieve sea surface winds with a high horizontal resolution of about 1 km (Fig. 1.5), without microwave saturation even under extreme phenomena such as TC by combining single polarization and cross polarization (Mouche et al., 2017, 2019; Zhao et al., 2018). Its wind products of TCs were validated and analyzed (Combot et al., 2020; Vinour et al., 2021). SAR winds are known to be affected by the rainfall attenuation (Mouche et al., 2019; Combot et al., 2020). In addition, the C-band SAR observations, being from LEO satellites, are limited to specific local times of acquisitions, typically at dusk and dawn.

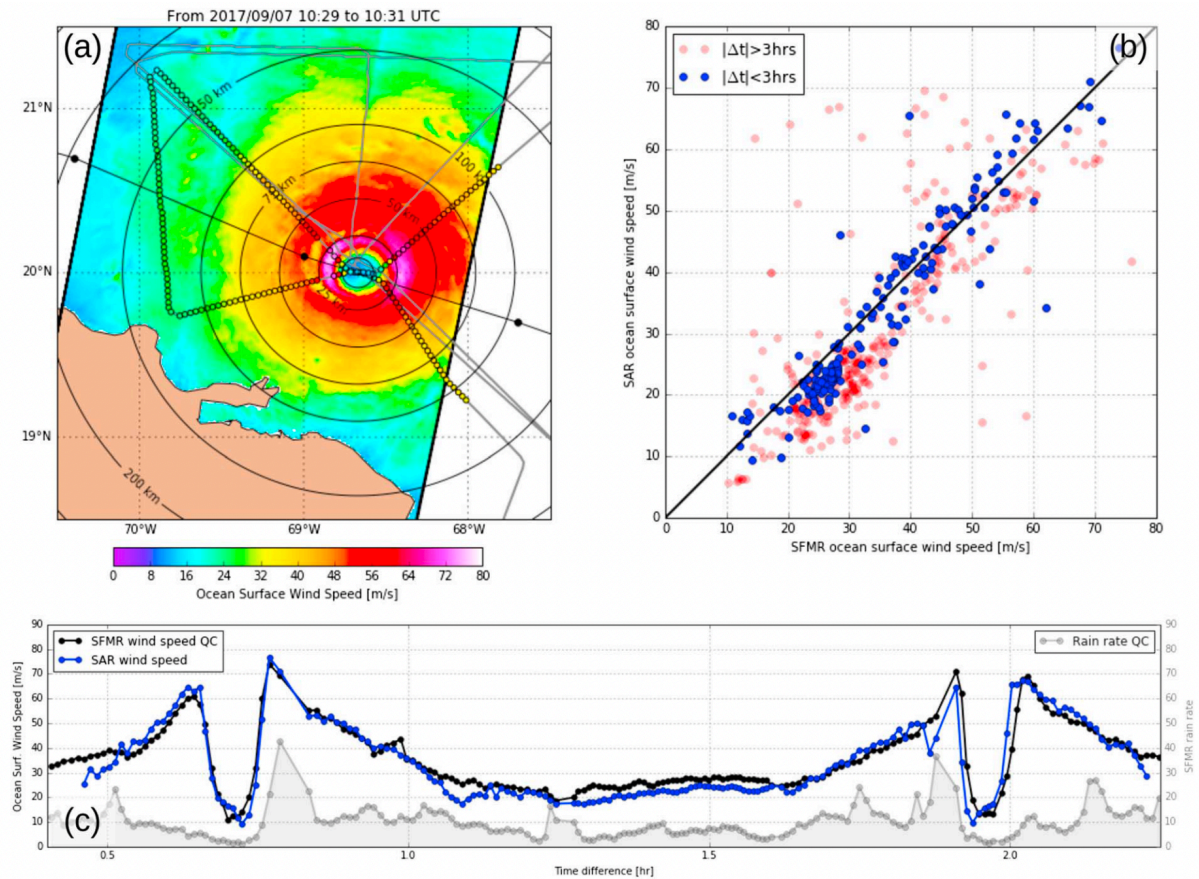


Figure 1.5: Sea surface wind speed for Hurricane Irma (2017), a category 5 hurricane on 7 September 2017. (a) Map of SAR-derived wind speed with a gray solid line indicating the collocated SFMR track. The colored circles along this track indicate SFMR measurements with time difference lower than 2 hr and 30 min. The color code is the same for SAR and SFMR wind speeds. The concentric circles on the map represent radius from the TC center, and dotted black line indicates the best-track positions, black circle being TC position every 6 hr. (b) Scatter plot between SAR-derived and SFMR-derived sea surface wind speed. (c) Transect of collocated SFMR and SAR measurements at 3-km resolution. Quality-controlled SFMR sea surface wind speed (black line) and rain rate (gray line) are shown. The blue line indicates the SAR-derived wind speed. Adapted from Mouche et al. (2019).

1.2.4 GMS-based observations

GMSs observe TCs seamlessly throughout their life cycle without time interruption. This feature enables us to monitor and investigate the TCs' long-time and continuous behavior (e.g., Steranka et al., 1986; Zehr et al., 1992; Dunion et al., 2014). Recent studies have demonstrated that GMSs-based data can enhance the accuracy of estimation and prediction of several TC property. These techniques include determining the wind structure at the surface using infrared brightness temperature data with multiple linear regression technique (Muellor et al., 2006), identifying the formation of annular hurricanes (Knaff et al., 2003; Knaff et al., 2008), estimating the probability of secondary eyewall formation (Kossin and Sitkowski, 2008), diagnosing rapid intensification events (Kaplan et al., 2010), predicting intensity changes (DeMaria et al., 2005), and characterizing major hurricanes (Zehr and Knaff, 2007), estimating the TC intensity utilizing convolutional neural networks (Chen et al., 2019).

Although the techniques have developed in this way, in the operational TC intensity estimation, there is a series of techniques that have been continuously utilized for a very long time. In the following subsections, the Dvorak technique, a method used for estimating the TC intensity, as well as atmospheric motion vectors (AMVs) are introduced. AMVs derived by tracking clouds or water vapor structures in consecutive satellite images are directly related to the estimation of wind distribution.

1.2.4.1 Dvorak technique

For nearly the past 50 years, a technique called the Dvorak technique (Dvorak, 1975; 1984) has been utilized for monitoring the TC intensity. The Dvorak technique is a subjective and empirical method for estimating TC intensity from satellite image pattern recognition by linking the patterns in the satellite images with actual measurements from aircraft in-situ observations. Specifically, the Dvorak technique analyst assigns "T-numbers" to TCs based on cloud patterns, which range from 1 to 8 in increments of 0.5. One T-number unit represents a typical one-day intensity change based on climatological data (Velden et al., 2006; Courtney and Knaff, 2009; Harper, 2002; Harper et al., 2008). The T-numbers are then used to determine the "Current Intensity" (CI) number, which is a measure of the maximum sustained wind speed of the TCs. The CI number is determined by considering various factors such as the size and organization of the storm, its central dense overcast, and its banding features. The Dvorak technique has the advantage of being applicable to satellite images, which makes it a valuable tool for analyzing TCs in remote areas where

other methods may not be available. Nevertheless, this technique has its limitations, such as the subjective nature of the analysis and the possibility of errors arising from factors like cloud cover and image resolution. Indeed, it is known that the estimation of Dvorak parameters by different agencies does not always agree and that each agency has its own characteristics (Nakazawa and Hoshino, 2009; Mei and Xie, 2016).

Knaff et al. (2010) analyzed the error distribution of the Dvorak technique based on best-track intensities with aircraft reconnaissance within 6 hours in the Atlantic basin. They demonstrated that the Dvorak technique has a mean absolute error (MAE) of ~9 kt (4.6 m/s) and root mean square error (RMSE) of 12 kt (6.2 m/s) for intense TCs (Fig. 1.6). They also showed that the biases and errors of the Dvorak technique can be partly explained by the intensity (Sheets and McAdie, 1988), latitude of TC location (Kossin and Velden, 2004), intensity change trends (Koba et al., 1990), radius of the outer closed isobar, and storm translation speed.

The Automated Dvorak Technique (ADT; Olander and Velden, 2007, 2019) is a method used to automatically estimate the intensity of TCs from satellite imagery. Unlike the Objective Dvorak Technique (Velden et al., 1998) and the Advanced Objective Dvorak Technique (Olander et al., 2004), which attempt to mimic the subjective approach, the ADT focuses on revising digital infrared thresholds and rules, and expanding the method beyond its original application and limitations. The ADT uses a combination of IR brightness temperature patterns, cloud top temperature trends, and environmental information to estimate the TC intensity. Recently, Olander et al. (2021) reported that they achieved further improvement in TC intensity estimation using the “artificial intelligence” enhanced advanced Dvorak technique (AiDT) model, which applies a fully connected neural network that takes the output of ADT as input. When using the Dvorak technique to estimate TC intensity from satellite data, it is important to consider the possibility of misapplication, as this empirical method cannot eliminate random errors.

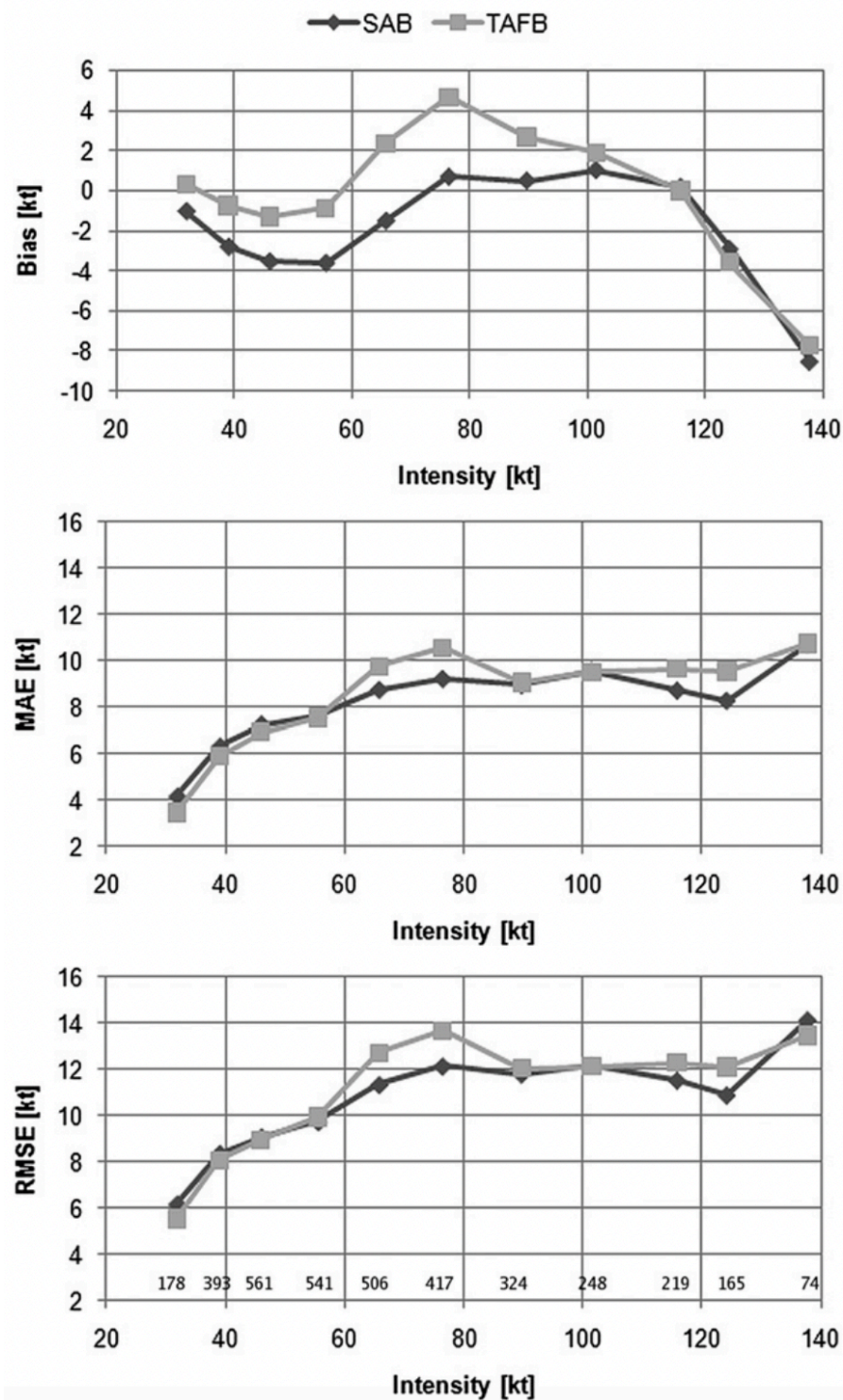


Figure 1.6: (top) Biases, (middle) MAEs, and (bottom) RMSEs associated with the TC intensity estimates (1 kt $\approx$ 0.51 m/s) obtained by the subjective Dvorak technique estimated in the Satellite Analysis Branch (SAB) and the Tropical Analysis and Forecast Branch (TAFB) of the National Oceanic and Atmospheric Administration's (NOAA), that were made with ± 2 hr of an aircraft reconnaissance fix. The verification is based on the best-track intensities at those times, and the analysis was conducted in the Atlantic basin. The total number of cases is displayed in the bottom panel. Adapted from Knaff et al. (2010).

1.2.4.2 Atmospheric Motion Vectors

One potential approach for improving intensity estimation using GMSs is to physically estimate the intensity from AMVs obtained from tracking clouds or water vapor structures in the inner-core region. AMVs derived from GMSs have been available since around 1970 (Fujita, 1969; Leese et al., 1971; Hubert and Whitney, 1971). Operational global numerical weather prediction systems routinely assimilate AMVs, which have been proven to significantly improve the forecasts for TC track (e.g., Goerss, 2009; Langland et al. 2009; Berger et al. 2011). The assimilation of AMVs in regional models has been documented to improve the forecasts of TC track, intensity, central pressure, and storm structure (Soden et al., 2001; Yamashita, 2012, 2017; Wu et al., 2014; Velden et al., 2017; Sawada et al., 2019; Lim et al., 2019; Zhao et al., 2021).

In the data assimilation of AMVs, accurately assigning the height of the AMVs is important. Height assignments of AMVs are performed using various methods. For the height assignment of AMVs over cloudy scenes, one of the oldest methods is the equivalent blackbody temperature (EBBT) method by an infrared window brightness temperature (Fritz and Winston, 1962). In this method, the EBBTs of infrared window channels are compared to the vertical temperature profile in the specific region of interest. The EBBT method assumes that the cloud is opaque and completely fills the spatial scale resolved by the satellite. As a result, it is effective for dense stratiform clouds. However, it is not accurate for semitransparent cirrus clouds and small-element cumulus clouds. To address such situations, various methods have been proposed, including the use of visible reflectance data (Mosher, 1976; Reynolds and Vonder Haar, 1997), stereographic observations of clouds from two simultaneously scanning GMSs (Hasler, 1981), utilizing the CO₂ absorption channel (Smith et al., 1970; Smith and Platt, 1978; Menzel et al., 1983), and utilizing the water vapor absorption channel (Szejwach, 1982; Shmetz and Holmlund, 1992; Nieman et al., 1993).

AMVs have been used to study the winds surrounding TCs (e.g., Molinari and Vollaro, 1989; Velden et al., 1998a; Dunion and Velden, 2002; Dunion et al., 2002; Sears and Velden, 2012; Velden and Sears, 2014; Oyama et al., 2016; Oyama, 2017; Dai et al., 2019; Fukuda et al., 2020; Ryglicki et al., 2021; Elsberry et al., 2023). Since the clouds in TCs' eyes are mostly confined in the boundary layer where the tangential winds are maximized at its top, deriving wind information from these clouds can be valuable for studying and monitoring TCs, as well as for data assimilation purposes. However, obtaining reliable and dense low-level AMVs within the rapidly rotating inner-core region is a challenging task using conventional cloud tracking

methods (Leese et al., 1971; Schmetz et al., 1993; Nieman et al., 1997; Hasler et al., 1998; Velden et al., 2005), presumably because the methods do not treat rotation. As a result, the application of AMVs has been limited to slowly rotating region such as upper-level outflow layer or the outer-core region.

1.3 Third-generation GMSs and winds in the eye

Recently, third-generation GMSs have dramatically improved their capabilities from their predecessors (Bessho et al., 2016; Schmit et al., 2017). For example, Himawari-8/9 and GOES-16/17/18 have twice the spatial resolution of their predecessors, 2 km for infrared channels and 0.5 km for visible channels at nadir. Especially in TCs monitoring, “rapid-scan” observations are made every 2.5 min in the target area for Himawari-8/9 with $1000 \text{ km} \times 1000 \text{ km}$ extents and every 1 min in the meso sector for GOES-16/17/18 with $1000 \text{ km} \times 1000 \text{ km}$ extents. These improvements allow us to reveal the various properties of TCs that were previously unobservable (e.g., Horinouchi et al., 2020; Tsujino et al., 2021a; Duran et al., 2021).

Horinouchi et al. (2023) obtained AMVs widely in a clear TC eye from research-based special observations with Himawari-8 conducted every 30 sec. It has been demonstrated that cloud tracking using template matching with cross-correlation method can be used to derive the lower-level winds in the eye at high frequency of 30 sec (Fig. 1.7a). They also showed that the obtained AMVs significantly decrease when the same method is applied to image sequences with a larger time interval of 2 min (Fig. 1.7). This suggests that even with the frequency of third-generation GMSs, it is not possible to obtain wind distribution within the eye of TC without some elaborate methods. It is desirable to investigate the wind distribution in the inner-core region of numerous TCs and accumulate observational facts by obtaining AMVs not only from 30-sec observations but also from normal 1-min or 2.5-min rapid-scan observations.

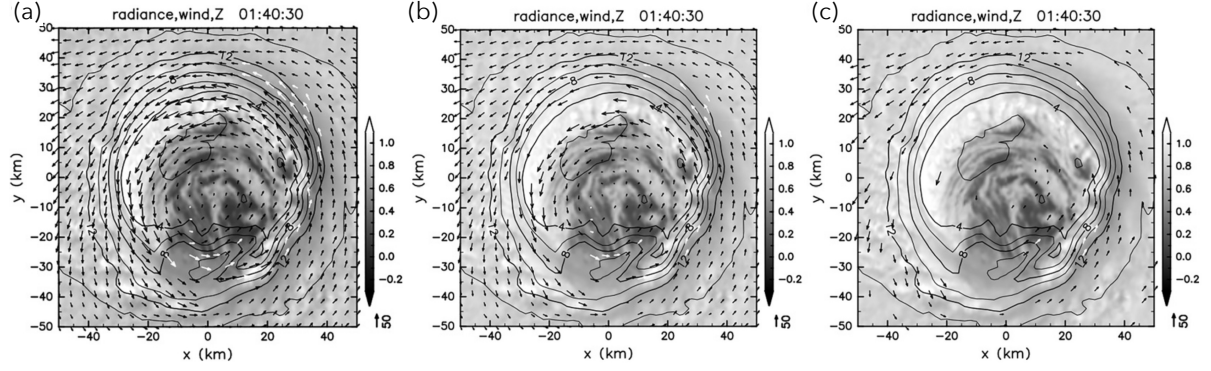


Figure 1.7: The obtained AMVs (vectors) overlaid on the reflectivity (shading) for Typhoon Haishen on 0140 UTC 9 September 2020, with different time sampling intervals: (a) 30 sec, (b) 1 min, and (c) 2 min. The length corresponding to 50 m/s is indicated by the arrow on the lower-right corner of each panel. The white arrows indicate the AMVs that were rejected by a postprocessing. Contours shows the estimated cloud-top height (km). AMVs for (a) 30-sec interval images were obtained by using Lagrangian tracking with updated templates for four steps in both forward and backward time (see section 4.2 for details). AMVs for (b) 1-min and (c) 2-min interval images were obtained by using the initial template subimages at the reference time throughout the Lagrangian tracking. For the (b) 1-min interval, Lagrangian tracking was conducted over 1 min with two steps in both the forward and backward time. For the (c) 2-min interval, Lagrangian tracking was conducted over 2 min with four steps. Adapted from Horinouchi et al. (2023).

1.4 Research objectives and structure of this study

As previously mentioned, all techniques for observing TCs have their own strengths and limitations, and monitoring the wind distribution within the inner-core region over a long time has been challenging. This study aims to develop methods for estimating wind distribution using rapid-scan observations by GMSs and to gain insights into TC dynamics through the obtained results. Specifically, methods for estimating the inner-core winds and RMW of TC from GMSs are developed.

The rest of this paper is organized as follows. Chapter 2 provides a review of the wind distribution and evolution in the inner-core region of TCs. In Chapter 3, a method is developed to estimate tangential winds in the inner-core region as a function of radius using a spectral analysis, which qualitatively differs from the template matching using cross-correlation employed by Horinouchi et al. (2023). The results obtained by applying the method to a historical case are presented. In Chapter 4, a cloud tracking method specifically designed for the inner-core region of TCs is developed. The method utilizes template matching with cross-correlation and incorporates rotation, building upon the method developed by Horinouchi et al. (2023). The results obtained by applying the method to several cases are presented. In Chapter 5, a method is developed to estimate the RMW of TCs when they have a clear eye. This study is summarized in Chapter 6.

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Chapter 2

A review on the wind distribution and evolution in the inner-core region of tropical cyclones

In this chapter, several studies on wind distribution and evolution in the inner-core region of tropical cyclones (TCs) are reviewed along with observational findings.

2.1 Overview of the inner-core region

The use of aircraft is the most useful tool for direct observation of TCs. The first flight was conducted by the US army in July 1943 (Sumson, 1943). Since the early 1950s, TC research using aircraft reconnaissance data has been conducted (e.g., Simpson, 1952). In the mid-1970s, National Oceanic and Atmospheric Administration's (NOAA) customized WP-3D aircraft reconnaissance began, providing more detailed descriptions of TCs. Jorgensen (1984a,b) used the airborne radar reflectivity data to show that the axisymmetric eyewall slopes radially outward with height, the associated maximum wind speed, and the relative position of clouds and precipitation, as well as the location and strength of updrafts, downdrafts, inflow, and outflow (Fig. 2.1). While the schematic did not depict any asymmetries, Marks and Houze (1987) later demonstrated that the maximum tangential wind was not located inside the reflectivity maximum at all levels. Nevertheless, the diagram remains a representative illustration of the average mature axisymmetric TC structure.

Willoughby (1998) focused on the thermodynamics of TC eyes, and showed that the warm and dry air aloft in the eye is separated by an inversion from more moist, usually cloudy air near the surface. Subsidence is the source of the eye's warmth and dryness, and convection in the eyewall causes compensating subsidence and adiabatic warming concentrated in the eye. It was observed that the air above the inversion in the eye remains relatively stable for long periods, only subsides a few kilometers, and has minimal mixing with the moist air from the eyewall. Conversely, the air below the inversion originates

from the low-level inflow and mixes readily with the eyewall (Fig. 2.2).

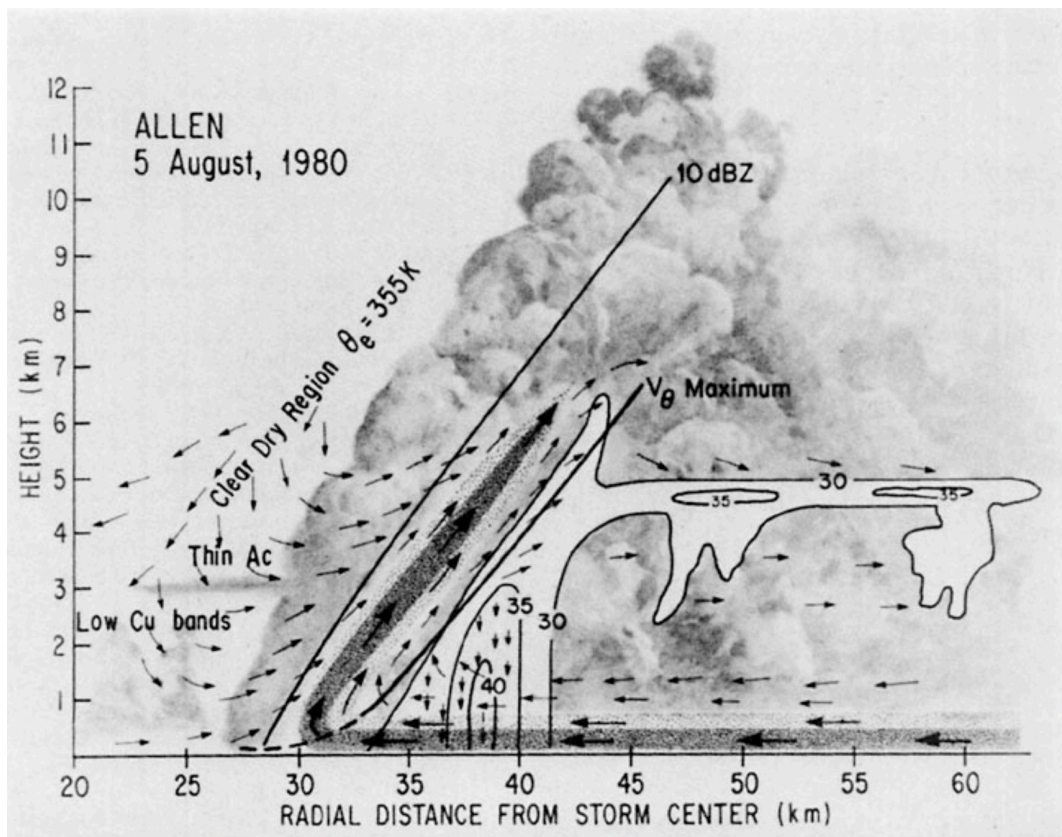


Figure 2.1: Schematic radial-vertical cross section depicting the locations of the clouds and precipitation, winds through the eyewall of Hurricane Allen (1980) on 5 August 1980. The estimate of the downward motion within the eye was determined by calculating the radial divergence, while the downdrafts within the high rainfall area were deduced from the vertical velocity time series obtained from individual flight passes. Reflectivity contours (dBZ) were generated using a composite of 15 passes, although there was significant variability between each pass. The slope of the clouds on the inner edge of the eyewall was determined through analysis of the radar's minimum detectable signal, aircraft altimeter readings, photography, and observer notes. The dark shaded area indicates the location with the highest radial and vertical velocities. Adapted from Jorgensen (1984b).

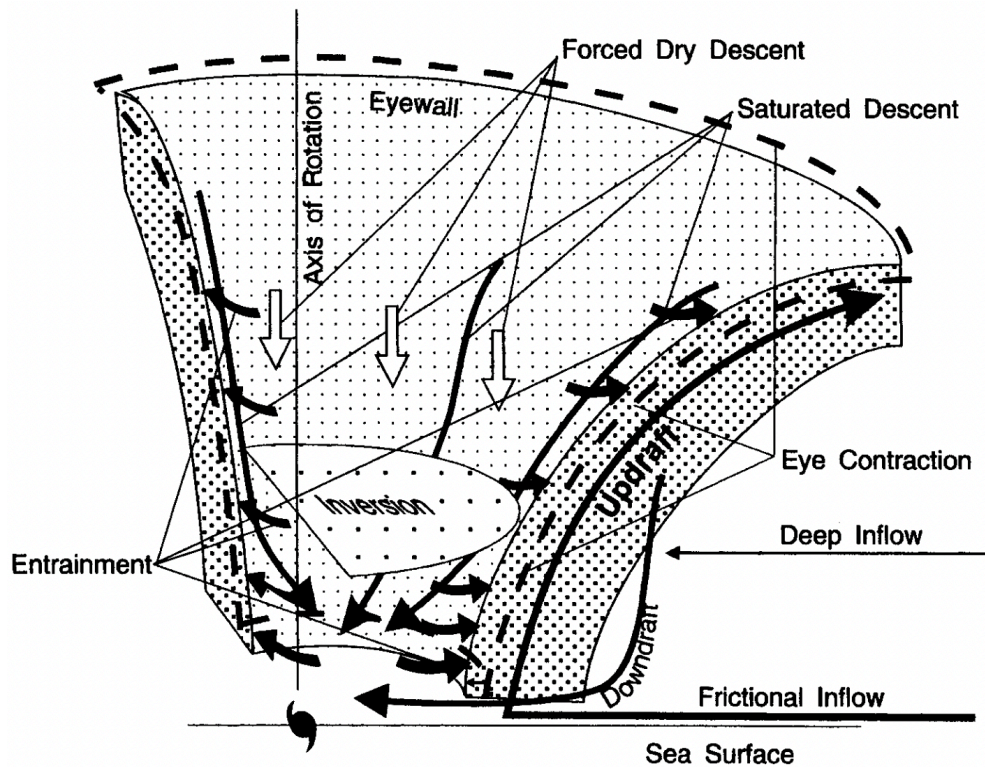


Figure 2.2: Schematic illustration of the secondary flow in the eye and eyewall of a TC. The frictional indraft provides the primary updraft and outflow in the eyewall cloud, which is driven by buoyancy. The inflow beneath the eyewall comes from convective downdrafts, while evaporatively driven descent along the inner edge of the eyewall feed moist air into the volume below the inversion. Gradual descent of dry air inside the eye, either thermodynamically or dynamically driven, causes the air column to warm adiabatically. This descent is a result of convection drawing mass from the bottom of the eye into the eyewall. The rate of rise or fall of the inversion is determined by the balance between the production of moist air and its loss to the eyewall. Adapted from Willoughby (1998).

Montgomery et al. (2006) documented an unprecedented observational analysis of Hurricane Isabel (2003), a category-5 on 13 September 2006 (Aberson et al., 2006; Bell and Montgomery, 2008). They showed the detailed structure of the inner-core region of Hurricane Isabel (2003) using two aircraft and GPS dropsondes (Fig. 2.3). They demonstrated that Hurricane Isabel was in a state known as superintensity (Persing and Montgomery, 2003), exceeding the Maximum Potential Intensity (Emanuel, 1986; Rotunno and Emanuel, 1987; Emanuel, 1988, 1995, 1997; Bister and Emanuel 1998; Emanuel et al., 2004; Emanuel and Rotunno, 2011) estimated theoretically from environmental parameters. They speculated that the high-entropy air inside the low-level eye was transported into the eyewall by small-scale horizontal vortices called mesovortices through horizontal mixing, which was the cause of the superintensity. While the presence of mixing with the eye is important, later studies (Bryan and Rotunno, 2009a; Wang and Xu, 2010)

revealed that the transport of high moist entropy from the eye to the eyewall is small compared to the contribution from the outer region due to the small cross-sectional area. This suggests that there may be other processes to explain the superintensity.

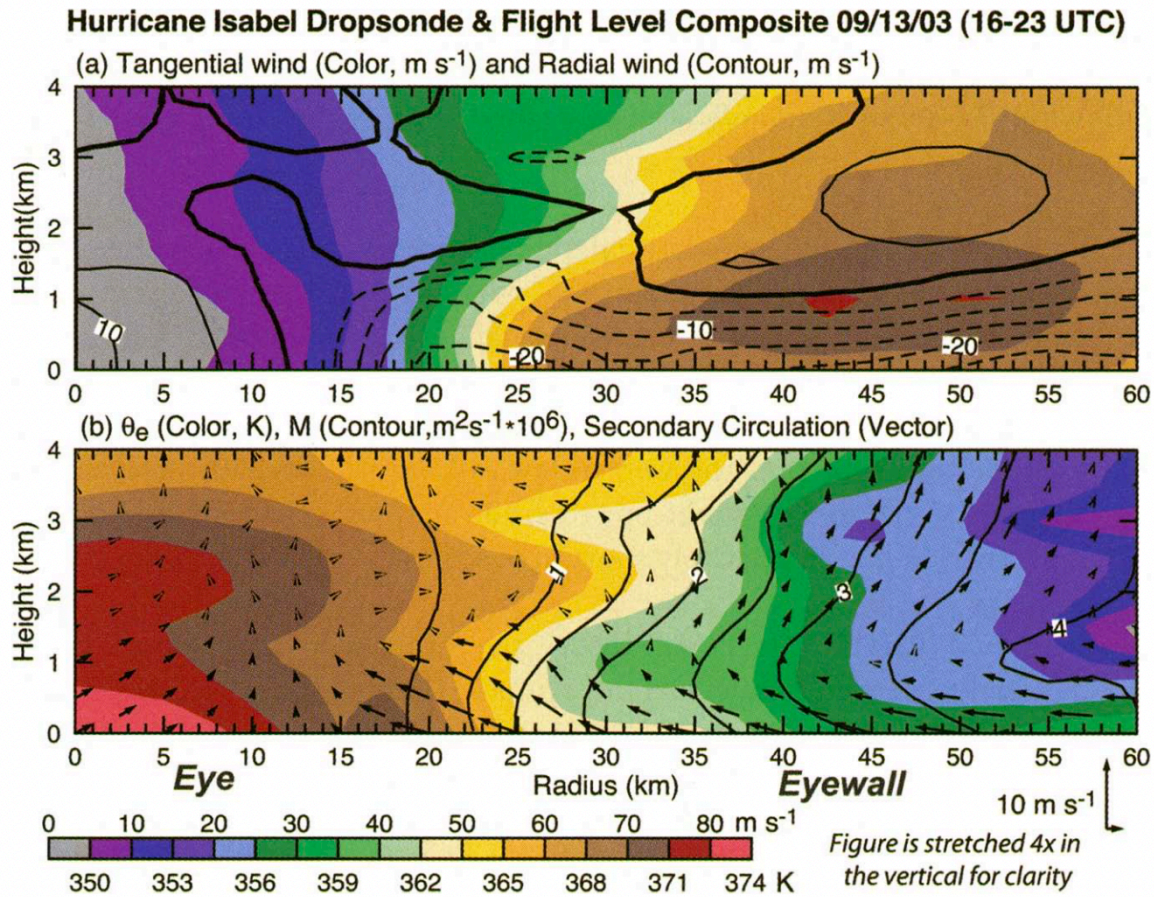


Figure 2.3: Radius-height azimuthal mean structure derived from GPS dropsondes and flight-level data from 1600–2300 UTC 13 September. (a) Tangential wind speed (shading) and radial wind speed (contour) and (b) equivalent potential temperature (shading), absolute angular momentum (contour), and secondary circulation (arrows) of Hurricane Isabel (2003). Adapted from Montgomery et al. (2006).

2.2 Polygonal eyewalls and mesovortices

While the TC eye is typically circular, but occasionally a polygonal structure is observed (e.g., Lewis and Hawkins, 1982; Muramatsu 1986; Kuo et al., 1999, 2016; Hendricks et al., 2012; Cha et al., 2020). Lewis and Hawkins (1982) analyzed radar images from ground-based and airborne radars, revealing the existence of hexagonal, pentagonal, quadrilateral, and triangular eyewalls in several intense hurricanes (Fig. 2.4). The formation of polygonal eyewalls in TCs is believed to be a result of asymmetric vorticity dynamics that can affect the storm's structure and intensity through the propagation of counter-propagating vortex Rossby waves (VRWs; MacDonald, 1968; Guinn and Schubert, 1993; Chen and Yau, 2001; Montgomery and Kallenbach, 1997; Möller and Montgomery, 1999; 2000). In the intense TCs, the Rayleigh condition for barotropic instability can be satisfied by a sign reversal of the mean radial vorticity gradient, which can lead to the breakdown of the potential vorticity (PV) ring and the PV redistribution (e.g., Schubert et al., 1999; Kossin and Eastin, 2001; Bell and Montgomery, 2008; Hendricks et al., 2009).

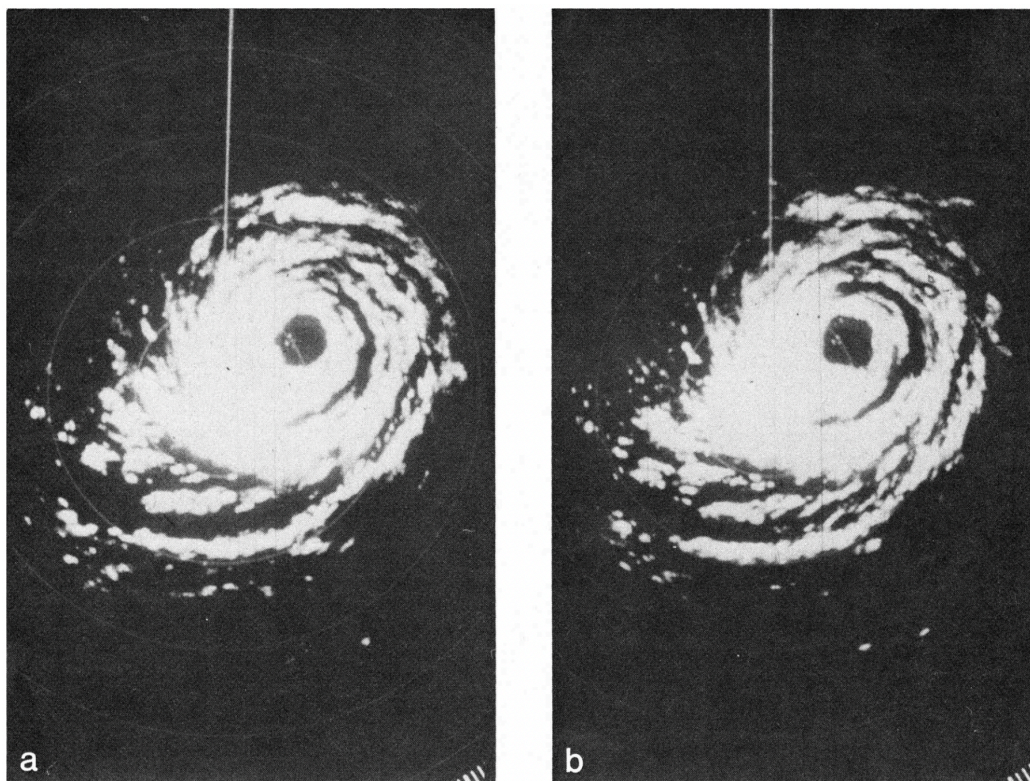


Figure 2.4: Radar images of Hurricane Betsy (1965) on 8 September 1965, showing a polygonal eye. (left) A hexagonal eye at 0748 UTC and (right) a tetragonal eye at 0803 UTC are shown. Adapted from Lewis and Hawkins (1982).

Kossin and Eastin (2001), who analyzed flight-level data from a number of hurricanes, analyzed the kinematic and thermodynamic fields across the eye and eyewall of TCs. They identified two distinct regimes in kinematic and thermodynamic fields, each with following characteristics (Figs. 2.5 and 2.6):

- Regime 1: Angular velocity is greatest within the eyewall and relatively depressed within the eye. The eye is typically very warm and dry, and the equivalent potential temperature is often elevated within the eyewall and relatively depressed within the eye.
- Regime 2: Radial profiles of angular velocity are nearly monotonic, with maxima found at the eye center. The eye temperatures may be lower, higher, or unchanged; dewpoints are higher; and equivalent potential temperature profiles are often nearly monotonic with maxima at the eye center.

The transition from regime 1 to regime 2 was marked by a relaxation of flow across the eye and eyewall toward rigid body rotation, which caused an increase in local tangential flow and angular momentum in the eye. They observed that the transition between the two regimes often occurred in less than one hour, as evidenced by sequential profiles within individual TCs. They mainly demonstrated regime transitions in mature stage TCs, but during intensification, a robust signal in kinematic regime transition was not found, while regime transitions in the thermodynamic field were observed in several TCs.

They used an unforced idealized barotropic simulation to propose that the regime transition is due to horizontal mixing induced by mesovortices associated with the barotropic instability around eyewall, which is theoretically predicted in Schubert et al. (1999). The breakdown of the eyewall vorticity ring caused by barotropic instability may create small horizontal-scale mesovortices (Fig. 2.7). These mesovortices could promote horizontal mixing between the eye and eyewall, leading to the inward transport of angular momentum and resulting in a regime transition. The instability of the eyewall, its breakdown, and the resulting vorticity mixing between the eye and eyewall have been extensively investigated in unforced idealized numerical modeling frameworks (Schubert et al., 1999; Kossin and Schubert, 2001; Nolan and Montgomery, 2002; Tervey and Montgomery, 2002; Rozoff et al., 2006; Kwon and Frank, 2005; Hendricks et al., 2009; Hendricks and Schubert, 2010; Menelaou et al., 2013a), shallow water modeling (Rozoff et al., 2009; Hendricks et al., 2012, 2014), full physics modeling frameworks (Chen and Yau, 2001; Yau et al., 2004; Kwon and Frank, 2008; Yang et al., 2007; Wu et al., 2009; Nguyen et al., 2011; Menelaou et al., 2013b; Naylor and Schechter, 2014; Wu et al., 2016; Hardy et al., 2021; Deng and Ritchie, 2022), and observational or experimental studies (Reasor et al., 2000; Montgomery et al., 2002; Kossin et al., 2002; Kossin and

Schubert, 2004; Corbosiero et al., 2005; 2006; Reasor et al., 2009; Hendricks et al., 2012; Rogers et al., 2013; Wurman and Kosiba, 2021; Mashiko and Shimada, 2021).

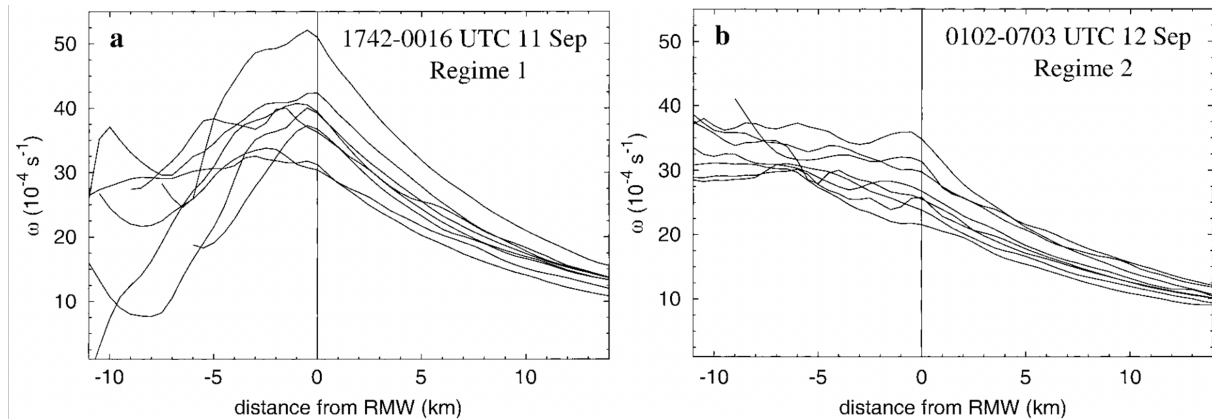


Figure 2.5: Observed flight-level angular velocity at 850 hPa in Hurricane Diana (1984). Each angular velocity profile is positioned relative to the distance from the radius of maximum wind, with negative distance indicating inward distance (into the eye). Panel (a) shows eight radial legs flown prior to maximum intensity during 1742–0016 UTC 11–12 September (regime 1). Panel (b) shows eight radial legs flown subsequent to maximum intensity during 0102–0703 UTC 12 September (regime 2) and represent nearly rigid body rotation across the eye and eyewall. It is notable that there is a general decrease in angular velocity at the RMW (in the eyewall) concurrent with a general increase in the eye. Adapted from Kossin and Eastin (2001) with modified panel arrangement.

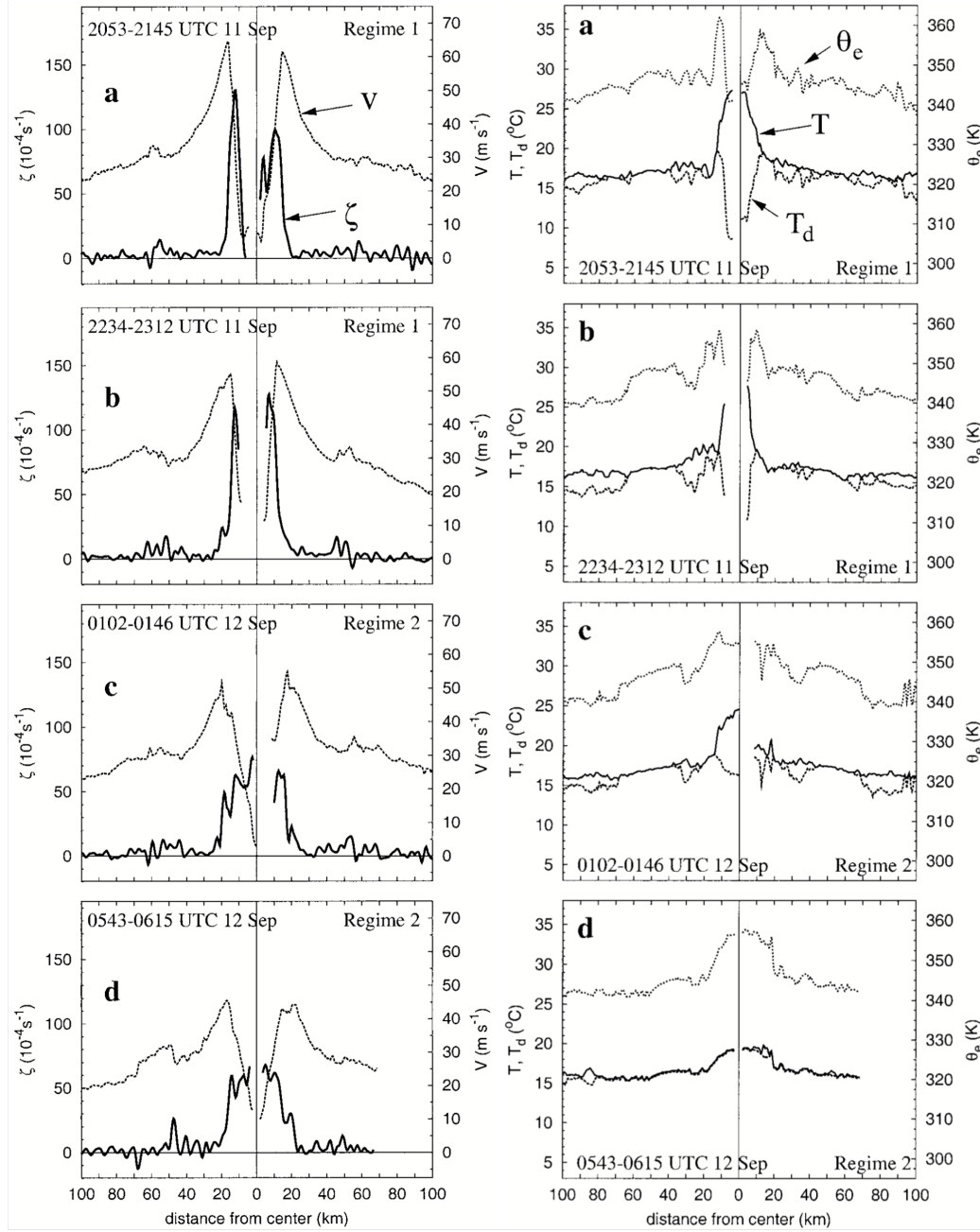


Figure 2.6: (left) Observed flight-level tangential wind (dashed) and estimated relative vorticity (solid) at 850 hPa in Hurricane Diana (1984). (right) As in the left panel, but for temperature (solid), dewpoint (long dash), and equivalent potential temperature (short dash). Each panel displays two radial legs, one inbound and one outbound. The aircraft direction of flight is from left to right. The time period of each radial leg pair is at lower left. Adapted from Kossin and Eastin (2001) with two figures combined.

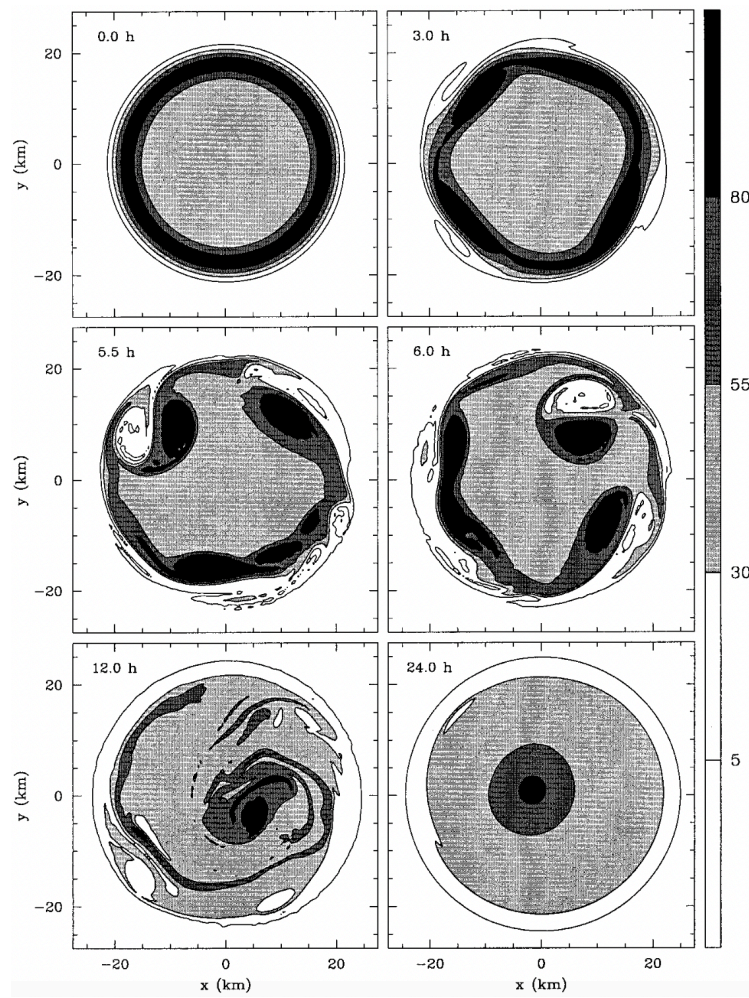


Figure 2.7: Vorticity contour plots for the numerical experiment. The displayed area is $55 \text{ km} \times 55 \text{ km}$, which is a part of the overall model domain of $200 \text{ km} \times 200 \text{ km}$. The contour lines on the plot start at $5 \times 10^{-4} \text{ s}^{-1}$ and increase in increments of $25 \times 10^{-4} \text{ s}^{-1}$. The values on the color bar represent units of 10^{-4} s^{-1} . The shade of the color indicates the magnitude of the vorticity, with darker shades indicating higher values. Model run time in hours is shown on each panel. Adapted from Kossin and Eastin (2001).

2.3 Algebraically growing wavenumber-1 disturbances

The baroclinic instability associated with mesovortices, as introduced in Section 2.2, is explained as an exponentially growing instability with azimuthal wavenumbers greater than or equal to 2. Inviscid symmetric barotropic vortices do not exhibit exponentially growing unstable modes with azimuthal wavenumber-1. Nevertheless, they can still have unstable disturbances where the amplitudes grow proportionally to the square root of time, in terms of long-time behavior, when the rotational angular speed reaches its maximum at a finite nonzero radius. This “algebraically growing” wavenumber-1 disturbance, originally found by Smith and Rosenbluth (1990), was further studied in the context of TCs by Nolan and Montgomery (2000).

Marks et al. (2008) analyzed aircraft observational data in Hurricane Hugo (1989) and reported that the location of the flight-level minimum pressure, which was carefully deduced, rotated counterclockwise at a period of around 19 min, approximately the same as the rotational period at the radius of maximum angular velocity (Fig. 2.8). The characteristics of this phenomenon are suggested to be attributed to an algebraically growing wavenumber-1 disturbance.

Recently, Horinouchi et al. (2023) analyzed low-level AMVs obtained in the eye of Typhoon Haishen (2020) from research-based special observations with Himawari-8 conducted every 30 sec. They documented the stationary and transient asymmetric features in the eye related to the wavenumber-1 disturbance (Fig. 2.9). Their analysis revealed that the wavenumber-1 disturbance plays an important role in the inward angular momentum transport, resulting in the acceleration of eye rotation (Fig. 2.10). They also demonstrated that the process was also reproduced in unforced non-dimensional barotropic simulation.

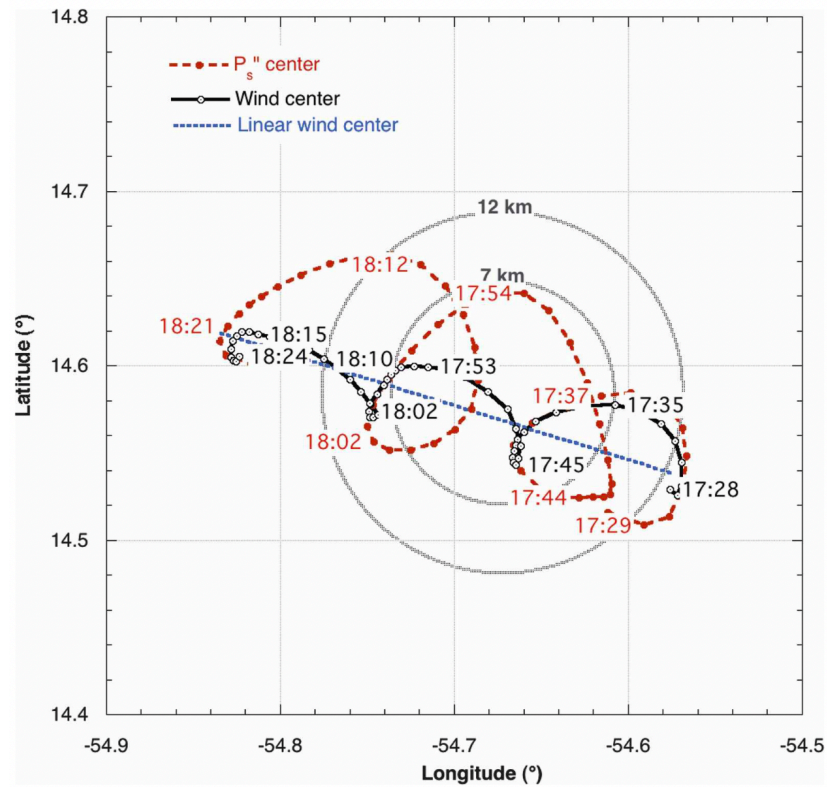


Figure 2.8: Track of wind circulation center (black curve) and flight-level minimum pressure (P_s'' ; red curve) from 1728–1824 UTC of Hurricane Hugo (1989) on 15 September 1989. The blue dotted line includes linear least squares fit to the wind centers over the same period. Additionally, two circles with radii of 7- and 12-km are plotted to indicate the eye radius and radar reflectivity maximum, respectively. Adapted from Marks et al. (2008).

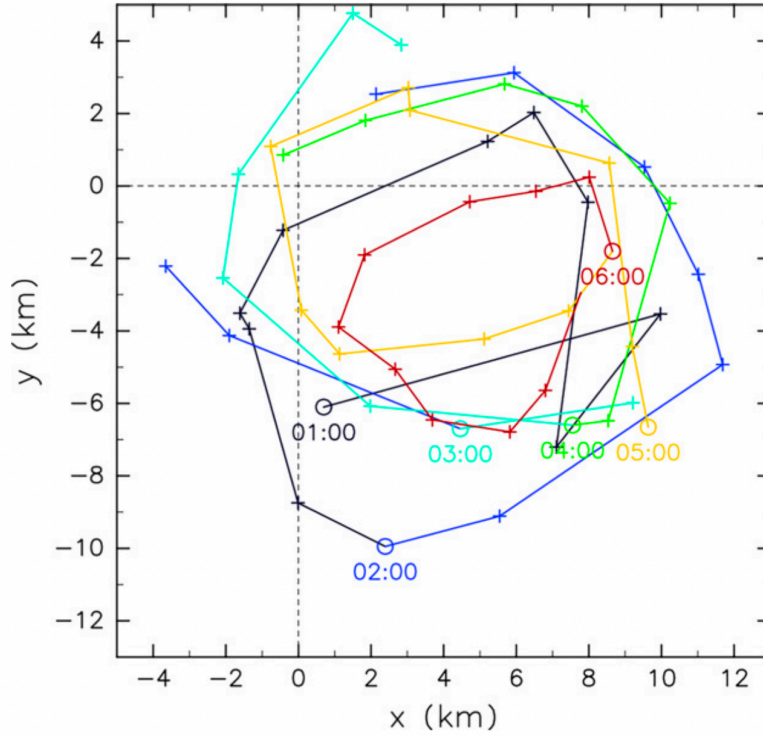


Figure 2.9: The time evolution of the location at which the 6-min-mean horizontal wind speeds, obtained in Typhoon Haishen (2020) on 4 September 2020, are minimized. The wind speeds were smoothed using a 5×5 km horizontal running mean. The results are shown from 0100 UTC, with the colors changing every hour. The coordinate origin is relative to the eyewall. The line is broken where the observation was paused. Adapted from Horinouchi et al. (2023).

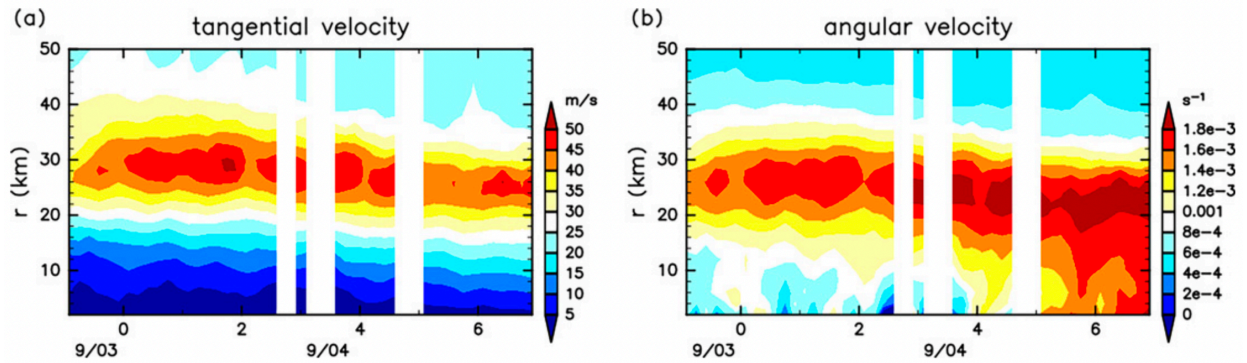


Figure 2.10: Azimuthal-mean and 10-min running-mean (a) tangential velocity and (b) angular velocity of Typhoon Haishen (2020) with respect to the circulation relative origin, which is indicated in Fig. 2.8. The horizontal axis is date and time in UTC. Note that the TC center is defined as the circulation relative center, which is determined based on the low-level circulation obtained from AMVs. Adapted from Horinouchi et al. (2023).

2.4 Summary

In this chapter, several studies on wind distribution and evolution in the inner-core region of TCs have been reviewed along with observational findings. Axisymmetric and asymmetric features are extensively revealed by many observational studies. There are some asymmetric processes, such as mesovortices and algebraically growing wavenumber-1 disturbances associated with barotropic instabilities. Mesovortices are thought to induce a horizontal mixing that transports angular momentum from the eyewall to the eye, resulting in increased vorticity in the eye. Algebraically growing wavenumber-1 disturbances are also thought to contribute to vorticity increase, but their processes require more time compared to the horizontal mixing process by mesovortices. To study the evolution of vorticity in the eye from an observational perspective, it is necessary to employ observational techniques that can capture the velocity field in the eye over a long period of time.

Unfortunately, there are very limited instruments available that can continuously observe the wind field across a wide spatial range in the eye of a TC, especially in areas where there are no precipitation particles. One possible way to achieve this is by estimating the wind distribution through tracking clouds in the eye using geostationary meteorological satellites. However, the imaging frequency was not sufficient until the introduction of third-generation satellites like Himawari-8, which started in July 2015. While the introduction of third-generation satellites like Himawari-8 opened up the possibility for unprecedented diagnosis of TCs, the development of such a method is still limited. In this study, Chapter 3 presents a method for estimating axisymmetric wind structures in the eye of a tropical cyclone using spectral analysis. This method allows for the diagnosis of the time evolution of the axisymmetric view. In Chapter 4, a TC-specific cloud tracking method is developed to obtain atmospheric motion vectors in the eye, including the asymmetric components. This enables the diagnosis of both axisymmetric and asymmetric wind structures in the eye, with a focus on investigating the time evolution of vorticity distribution related to mesovortices. In Chapter 5, an estimation method for the radius of maximum wind is developed, leading to frequent and accurate diagnosis of the radius of maximum wind.

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Chapter 3

Tangential wind estimation using spectral analysis

3.1 Introduction

Geostationary meteorological satellites (GMSs) observe tropical cyclones (TCs) throughout their life cycle without interruption. Their observations are used in the Dvorak technique to estimate the intensity of TCs (Dvorak, 1975, 1984). These are also used to derive atmospheric motion vectors (AMVs; see Menzel, 2001, and the references therein). AMVs are assimilated not only in global forecasts but also in TC forecasts (Velden et al., 1998b). AMVs are normally derived using the cross-correlation method (Leese et al., 1971). Even the state-of-the-art AMV products do not cover the inner-core region of TCs (Oyama et al., 2018), presumably because the operational methods do not treat rotation, which is discussed in more detail in Chapter 4. Monitoring winds in the inner-core region of TCs is important for understanding their dynamics and intensity estimation. However, conventional wind observations do not cover TCs seamlessly as described in Chapter 1.

In this study, a method is proposed to derive tangential winds from high-frequency imaging as done by third generation GMSs such as Himawari-8. This method utilizes space-time spectral analysis to obtain tangential winds as a function of the distance from the TC center (radius) at a time resolution of ~ 1 hr. It is markedly different from the conventional AMV derivation method including the method, which typically relies on template matching with cross correlations; the method of Horinouchi et al. (2023) and the method developed in Chapter 4 also employ the template matching. The method is especially useful to estimate winds in the lower inner-core regions of TCs. The results of the method can be used to visualize and quantify the asymmetric wind components as the deviations from the axisymmetric components. It has been suggested numerically that the asymmetric components such as mesovortices play the important roles to transport angular momentum into the eye (e.g., Schubert et al., 1999). Observational studies have documented the presence of mesovortices in the inner-core region (e.g., Kossin et al., 2002; Kossin & Schubert,

2004). Some observational studies further quantified the vorticity of mesovortices in the eyewall region (Marks et al., 2008; Wingo & Knupp, 2016), but this study is the first to report a quantification of mesovortices within the eyes. Note that the quantification of the mesovortices is subjectively achieved.

3.2 Data and Projection

In this study, the primary data used for analysis was the visible (VIS) reflectivity at $0.64\ \mu\text{m}$ from the target observations of Typhoon Lan (2017) as captured by Himawari-8 in the Northwest Pacific basin (as shown in Figs. 3.1a and 3.1b). The target observation captures a TC over an $\sim 1000 \times 1000\ \text{km}$ region every 2.5 min. Its resolution is 0.5 km at nadir. To estimate cloud top heights (CTH), this study utilized the infrared (IR) brightness temperature at $10.4\ \mu\text{m}$ (resolution at nadir: 2 km) as well as the isobaric temperature and geopotential height of the Japanese 55 years Reanalysis data set (JRA55; Kobayashi et al., 2015). The JRA55 data has a resolution of $1.25^\circ \times 1.25^\circ$ and is available at 6-hour intervals. Reference vertical profiles of temperature and geopotential height at each observation time were defined by linearly interpolating the JRA55 reanalysis data with space and time onto the TC center positions. Here (only for this purpose), the TC centers were derived from the 6-hourly best-track data compiled by Regional Specialized Meteorological Center Tokyo (RSMC-Tokyo) by using the cubic spline interpolation with time.

When analyzing objects observed by GMS, it is important to account for the phenomenon known as parallax shift and apply the necessary corrections (Roebeling and Holleman, 2009; Henken et al., 2011). The parallax shift refers to the apparent shift that occurs when an object observed by a GMS is mapped to a point on the Earth ellipsoid where the line passing through it intersects. The parallax shift has a greater impact when the cloud-top height is high or when the cloud is located far from the sub-satellite point. There are several attempts to correct parallax shift incorporating an ellipsoid model of Earth (Vincent et al. 2002; Bieliński, 2020). Different methods employ different approximations in calculating the parallax shift, but the resulting differences in approximations typically amount to only a few tens of meters. This difference is considered negligible, especially when considering the resolution of modern GMSs. All of these methods require determining the cloud top height of observed clouds to calculate the parallax. In this study, the cloud top height is estimated by comparing the IR brightness temperature with temperature profiles obtained from reanalysis data. Subsequently, parallax correction is applied to the entire satellite images using the estimated cloud top heights. The same correction is performed in Chapters 4 and 5.

The satellite images were projected onto the azimuthal equidistant projection with respect to the TC center (Fig. 3.2a). Here, the TC centers were derived every 30 min by subjectively examining the corrected IR images, as the best-track position was not accurate enough for this purpose. The derived TC center positions (Table 3.1) were then interpolated with time (t) using cubic spline interpolation (Fig. 3.1c). The

projected images were resampled on the polar coordinate with the resolutions $\Delta r = 0.5$ km along radius (r) and $\Delta\theta = 2\pi/440$ radian along the counterclockwise azimuth (θ) from the east (Fig. 3.2b). The inner-core region of Typhoon Lan was observed from 21–22 October 2017 by GPS dropsonde during the first aircraft missions of the T-PARCI project (Ito et al., 2018; Yamada et al., 2021). For verification, a dropsonde profile obtained at $r \sim 20$ km around 0650 UTC 21 October were used.

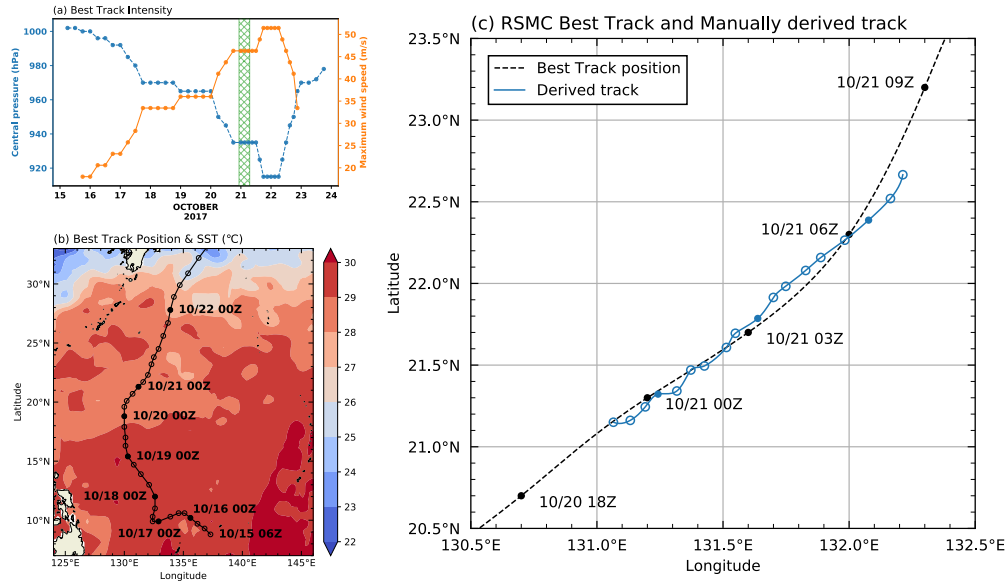


Figure 3.1: (a) Maximum 10-min surface wind (orange) and central pressure (blue) based on the best track data by RSMC-Tokyo. The analysis period is shown by green hatches. The abscissa is date and time in UTC. (b) The best-track positions and the mean sea surface temperature on 21 October from the daily Optimum Interpolation Sea Surface Temperature (OISST; Banzon et al., 2016). (c) The best-track positions (black) and the track derived manually in this study (blue).

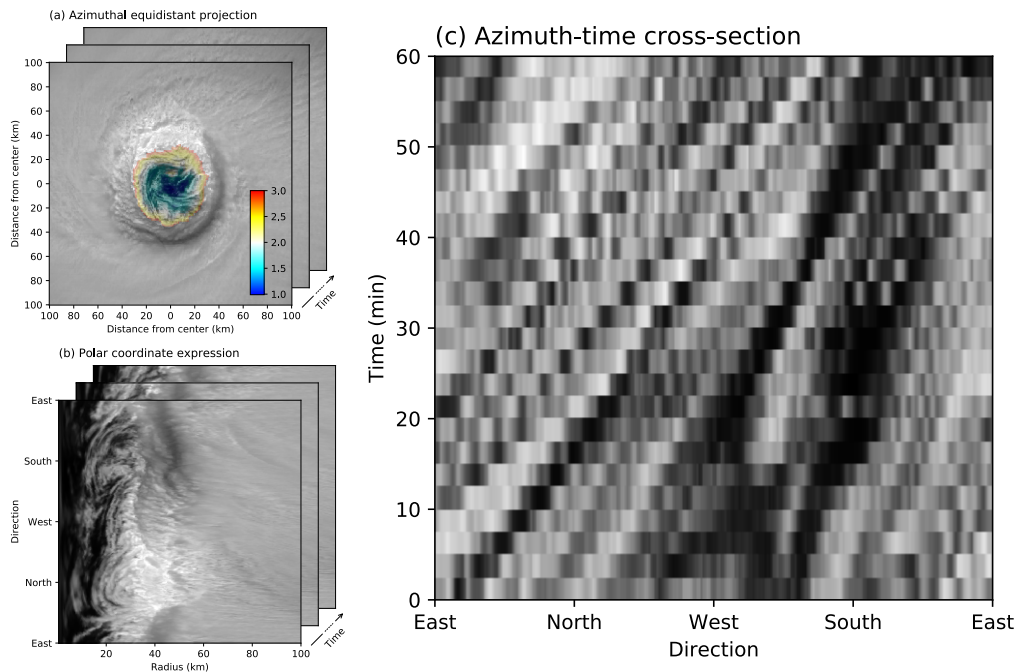


Figure 3.2: Examples of image preprocessing. (a) Parallax-corrected and projected VIS reflectivity (gray scale) and estimated CTH (km; color shading) in the eye. The CTH of 0, 1, and 2 km correspond to the temperatures of 301.15, 294.15, and 290.65 K, respectively. (b) VIS reflectivity resampled on the polar coordinates. (c) Azimuth-time cross section for 1 hr at 20 km radius.

Time (UTC)	Latitude (°N)	Longitude (°E)
2200 on 20 Oct	21.1026	131.0390
2230	21.1502	131.0654
2300	21.1617	131.1323
2330	21.2444	131.1917
0000 on 21 Oct	21.3222	131.2423
0030	21.3415	131.3169
0100	21.4700	131.3724
0130	21.4947	131.4261
0200	21.6081	131.5134
0230	21.6949	131.5489
0300	21.7856	131.6378
0330	21.9142	131.6996
0400	21.9824	131.7489
0430	22.0794	131.8278
0500	22.1587	131.8876
0530	22.2650	131.9828
0600	22.3875	132.0772
0630	22.5197	132.1638
0700	22.6655	132.2129
0730	22.7940	132.2343

Table 3.1: The center positions of Typhoon Lan (2017) derived subjectively from IR images.

3.3 Method

The following five steps yield a tangential velocity profile $v_E(r)$ as a function of r . If the TC is nearly axisymmetric, v_E is expected to be close to the azimuthal-mean tangential wind around the cloud top. Therefore, v_E is referred as “representative tangential wind” in this chapter. For simplicity, the counter-clockwise rotation in the Northern Hemisphere is assumed in the following description.

Step1: Project image data obtained at a short time interval, Δt , onto the polar coordinate with respect to the TC center (e.g., Figs 3.2a and 3.2b).

Step2: Take a time sequence over a duration of T (e.g., Fig. 3.2c), and apply the standard preprocess for spectral analyses including detrending and cosine tapering with t , and conduct the Fast Fourier Transform along θ and t to obtain two-dimensional power spectra with angular frequency, ω , and azimuthal wavenumber, k (e.g., Fig. 3.3a).

Step3: Stabilize the power spectra by averaging over $r_j - \frac{d_r}{2} \leq r \leq r_j + \frac{d_r}{2}$ at each of the radius $r_j \equiv d_r j$, where j is an integer and d_r is a constant increment.

Step4: Bin the power spectrum as a function of azimuthal phase velocity, $c = \omega/k$, by integrating over the area enclosed by $c = b_i, c = b_i + \Delta b, k = k_{\min}, k = k_{\max}$, after applying the interpolation and extrapolation along ω as described below (e.g., Fig. 3.3b). Here, $b_i = b_{\min} + i\Delta b$ ($i = 0, 1, \dots, n$) is the bin boundary, $\omega_N \equiv \pi/\Delta t$ is the Nyquist frequency, and the other undefined symbols are constants defined in what follows. The resultant phase velocity spectrum is normalized by the maximum value and referred to as f_i , so $\max(f_i) = 1$ (e.g., Figs. 3.3f–h). Note that c corresponds to the rotational angular velocity, since k is integer.

Step5: Compute the representative tangential wind as

$$v_E \equiv r_j \frac{\sum_{i=1}^n c_i w_i}{\sum_{i=1}^n w_i}, \quad (3.1)$$

where w_i is the weight defined by using f_i and a threshold f_{thresh} as

$$w_i = \begin{cases} f_i & (f_i \geq f_{\text{thresh}}) \\ 0 & (f_i < f_{\text{thresh}}) \end{cases}. \quad (3.2)$$

Symbols	Definitions
Δt	Time interval of satellite image sequence.
Δr	Radial resolution in polar coordinates.
$\Delta \theta$	Azimuthal resolution in polar coordinates.
T	Time width of azimuth-time cross section.
d_r	Radial width to average the spectrum.
r_i	Radius for deriving representative tangential velocity.
$\Delta \omega$	Angular frequency resolution of the spectrum.
ω_N	Nyquist angular frequency of the spectrum.
$k_{\min}$	Minimum azimuthal wavenumber of the spectrum used in binning process.
$k_{\max}$	Maximum azimuthal wavenumber of the spectrum used in binning process.
$L_{\min}$	Minimum wavelength corresponding to $k_{\max}$.
c_0	First estimate of angular velocity.
c	Angular velocity corresponding to a bin.
$b_{\min}$	Minimum angular velocity of bins.
$b_{\max}$	Maximum angular velocity of bins.
Δb	Interval angular velocity of bins.
b_i	Angular velocity at i -th bin boundary.
n	Number of bins.
a_0	A measure of angular velocity bin accuracy.
J	Spectral interpolation factor.
A	Spectral expansion factor.
f_i	Normalized spectrum at i -th bin.
f_{thresh}	Threshold to limit the lowest normalized spectrum when obtaining weighted average.
w_i	Weight at i -th bin used in the weighted average.
v_E	Representative tangential wind speed at a radius.

Table 3.2: A list of symbols for the developed method along with brief definitions.

The symbolized variables are listed in Table 3.2. The azimuth resolution $\Delta \theta$ must be smaller than $\pi/k_{\max}$. In order to accurately derive tangential winds, the TC center positions used should be less than a few kilometers from the center of gravity of the lower layer in the eye. The effect of its error, as measured by its distance E_r , is investigated in section 3.5.1, which demonstrates that it is likely small if E_r/r is much smaller than 1; when this ratio is high, it tends to erroneously increase v_E if the motion is close to rigid-body rotation.

The duration T should be comparable to the time scale of the variation of rotation to be quantified. However, it should also be long enough to secure a desired spectral resolution. The following guideline on parameter setting requires a first guess of the TC's angular velocity, c_0 ; if it is not available, one can start with an ad hoc value to improve it iteratively. Since the frequency resolution $\Delta \omega$ corresponds to the phase velocity resolution $\frac{\Delta \omega}{k} = \frac{2\pi}{Tk}, \frac{2\pi}{Tk_{\min}}$ should be smaller than c_0 , which constrains the relation between T and $k_{\min}$. TC eyes can have vortex Rossby waves (e.g., Montgomery and Kallenbach, 1997). Their prop-

agation could erroneously decrease v_E . Therefore, $k_{\min}$ should be set to avoid it, if vortex Rossby waves are observed, for example, as a polygonal eyewall. It is suggested that $k_{\min}$ should always be greater than 1.

In principle, $k_{\max}$ can be arbitrarily large, since the original image resolution provides a natural spectral cutoff. However, it was found in the trial that setting

$$k_{\max} = \text{round} \left(\frac{2\pi r}{L_{\min}} \right) \quad (3.3)$$

yields better results, where $\text{round}()$ is a function that rounds a number to the nearest integer, and $L_{\min}$ is an empirical minimum wavelength to be treated in section 3.4. It makes $k_{\max}$ as a function of r .

Now the interpolation and extrapolation in Step 3 are defined. To conduct the binning adequately, the phase velocity resolution should be comparable or smaller than Δb . This can be achieved by subdividing the ω grid points by J times as many and interpolating the spectra linearly with ω , where J satisfies $\frac{\Delta\omega}{Jk_{\min}} < \Delta b$, so it can be set by

$$J = \text{ceil} \left(\frac{\Delta\omega}{k_{\min} \Delta b} \right), \quad (3.4)$$

where $\text{ceil}()$ is a function that rounds a number up to the nearest integer. The extrapolation along ω is introduced to compensate for the aliasing arising from insufficient Δt ; the clockwise spectral peak at $k \sim -20$ and $\omega \lesssim \omega_N$ in Figure 3.3a is actually due to counterclockwise signals at $k \sim 20$ and $\omega \gtrsim \omega_N$. When cloud motions are dominated by a single angular velocity, the spectrum at $\omega > \omega_N$ can be reproduced to some extent by repeating the spectra as in Figure 3.3b. Here an integer parameter A is introduced, which sets the maximum ω as $A\omega_N$. Because of the dominance of counterclockwise motions in the eye, it is safe to set $A = 2$. Even a number greater than 2 can be used, if it is validated from the actual spectra.

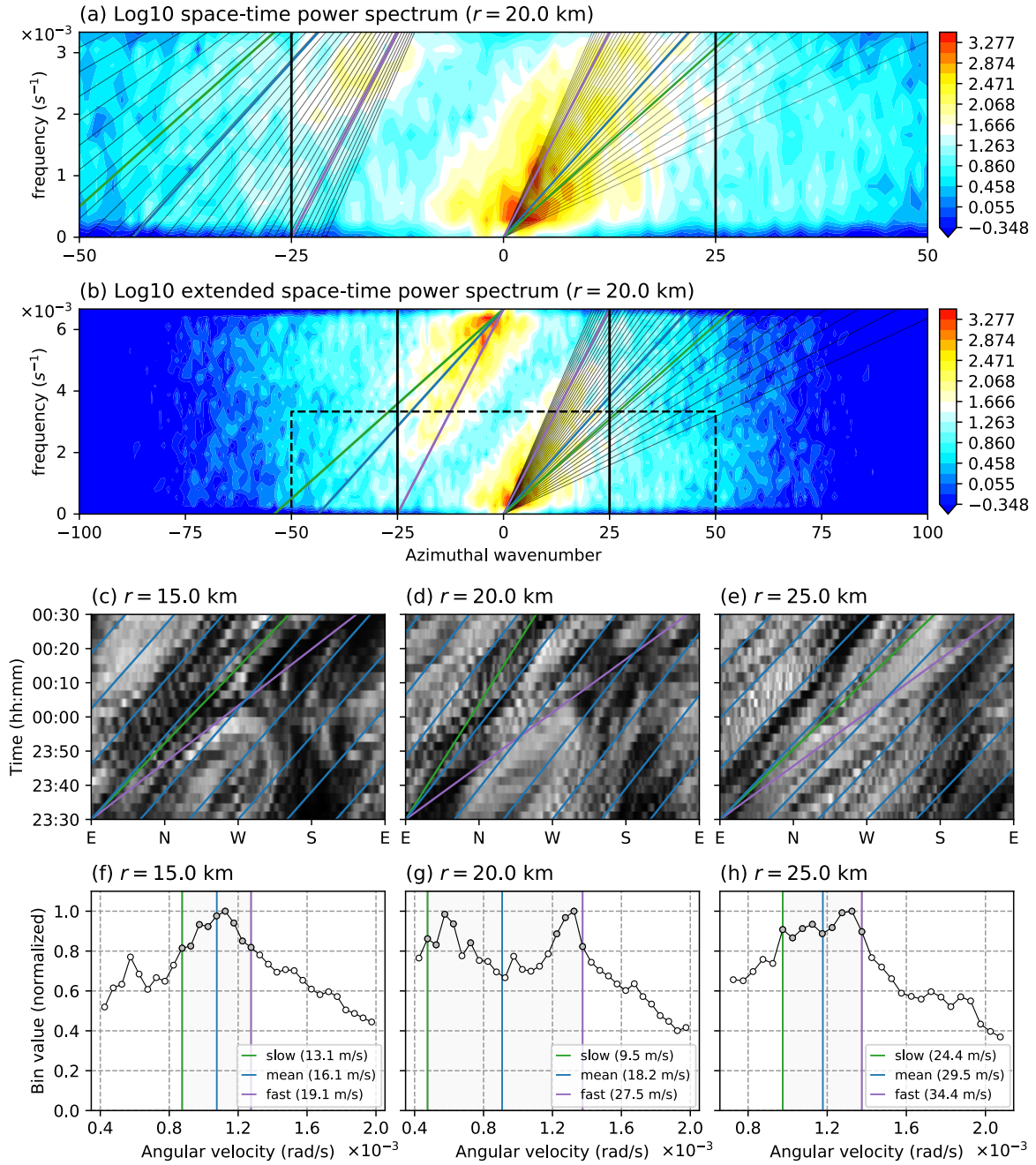


Figure 3.3: Examples of power spectra, azimuth-time cross sections, and velocity binning results. (a) The log10 of the power spectrum at $r = 20$ km. Black lines are drawn at $|k| = k_{\max}$. Gray lines indicate bin boundaries. (b) Extended spectrum up to $\omega = 2\omega_N$. The black dashed rectangle demarks the area shown in (a). (c–e) Azimuth-time cross sections at radii of 15, 20, and 25 km for 1 hr from 2330 UTC 20 October. The blue lines indicate motions at v_E , while green and purple lines indicate those at the slowest and the fastest velocities of the top 80% bins, respectively. (f–h) Binning results corresponding to (c)–(e). The top 80% bins are indicated by filled gray circles.

The bin boundaries $b_i = b_{\min} + i(b_{\max} - b_{\min})/n$ ($i = 0, 1, \dots, n$) and the bin velocities $c_i = b_{\min} + (2i - 1)(b_{\max} - b_{\min})/2n$ ($i = 1, \dots, n$) are determined by setting the range $(b_{\min}, b_{\max})$ and the number of bins n . It is convenient to set n as

$$n = \text{ceil} \left(\frac{b_{\max} - b_{\min}}{\Delta b} \right) = \text{ceil} \left(\frac{b_{\max} - b_{\min}}{a_0 c_0} \right) \quad (3.5)$$

where $a_0 \equiv \Delta b/c_0$ is the fractional increment at c_0 ; a_0 can be set to 0.05–0.1.

As shown in Figures 3.4a and 3.4b, signals at $\omega > 2\omega_N$ are aliased onto $\omega < \omega_N$ in the same rotational direction. This could bias v_E , which should be avoided by examining the $\omega - k$ spectra and thereby choosing sufficiently high $b_{\min}$ or low $k_{\max}$ (Fig. 3.4b), and low $b_{\max}$ (Fig. 3.4c). If $A \geq 3$, double counting occurs in the binning when $k_c < k_{\max}$ and $\omega_c < A\omega_N$, where (k_c, ω_c) is the intersection of $\omega = b_{\min}k + 2\omega_N$ and $\omega = b_{\max}k$ (Fig. 3.4c). This should be avoided by ensuring $k_c \geq k_{\max}$ or $\omega_c \geq A\omega_N$, namely,

$$b_{\max} \leq \max \left(b_{\min} + \frac{2\omega_N}{k_{\max}}, \frac{A}{A-2} b_{\min} \right) \quad (3.6)$$

A sensitivity test is performed for f_{thresh} (section 3.5.2), which suggests that the values around 0.7–0.8 are appropriate. It is recommended to conduct a similar test.

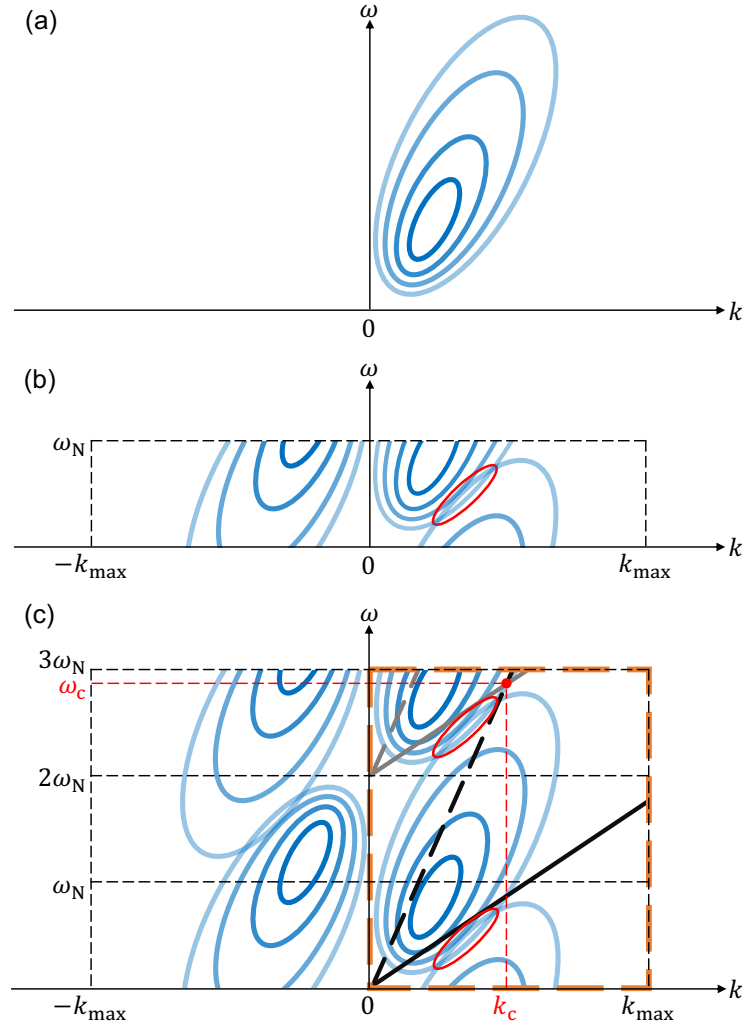


Figure 3.4: Schematic illustration of aliasing related issues. (a) A hypothetical true ω - k spectra, where there is no aliasing. (b) The power spectra from discretely sampled data. Signals at $\omega > \omega_N$ are aliased onto $\omega < \omega_N$. This figure demonstrates that counterclockwise ($k > 0$) signals at $\omega_N < \omega < 2\omega_N$ are aliased as clockwise ($k < 0$) signals. Counterclockwise signals at $2\omega_N < \omega < 3\omega_N$ are aliased as counter-clockwise signals to contaminate the actual $\omega < \omega_N$ signals. The red ellipse indicates where this contamination occurs. It is recommended to check this contamination before conducting step 4 to avoid bias by setting $b_{\min}$ or $k_{\max}$ appropriately. (c) The extended spectrum up to $\omega = 3\omega_N$ (i.e., $A = 3$). The bold solid black line shows where $\omega = b_{\min} k$, and the bold dashed black line shows where $\omega = b_{\max} k$. The bold gray lines indicate the bold black lines shifted positively by $2\omega_N$. The red dot (k_c, ω_c) indicates the intersection of $\omega = b_{\min} k + 2\omega_N$ and $\omega = b_{\max} k$. The double counting occurs if the point (k_c, ω_c) is included in the region to compute the phase-velocity spectra (the rectangle with the bold dashed orange lines), as is the case in the present figure. Equation (3.6) gives the condition to exclude it, which can be realized either by changing $b_{\min}$, $b_{\max}$, or $k_{\max}$. This panel also indicates that the aliasing contamination demonstrated with the panel (b) can also occur at high phase velocities when $A \geq 3$, so $b_{\max}$ should also be set to avoid it.

3.4 Application to Typhoon Lan (2017)

3.4.1 Parameter setting

The proposed method was applied to Typhoon Lan (2017) using the VIS imagery over 8.5 hr since 2230 UTC 20 October. By the time, Typhoon Lan has developed a clear eye with a radius of ~ 35 km. In each estimation, $T = 1$ hr was utilized, resulting in the use of 24 images. After visual inspection, c_0 was subjectively set to 1.0×10^{-3} rad/s. The other parameter values used are as follows: $d_r = 5$ km; $k_{\min} = 2$; $L_{\min} = 5$ km; $a_0 = 0.05$; $J = 18$. For radii of 10, 15, 20 km, $A = 2$, $b_{\min} = 0.4 \times 10^{-3}$ rad/s, and $b_{\max} = 2.0 \times 10^{-3}$ rad/s (which provides $n = 32$) were used. For radii of 25 and 30 km, $A = 3$, $b_{\min} = 0.7 \times 10^{-3}$ rad/s, $b_{\max} = 2.1 \times 10^{-3}$ rad/s (which provides $n = 28$) were used. These values meet the requirements presented in section 3.3. Multiple values of f_{thresh} were tested and subsequently set to a fixed value of 0.8. Figures 3.2 and 3.3 shown in section 3.3 are based on this setting.

3.4.2 Tangential winds of Typhoon Lan (2017)

Figure 3.5 shows the time series of the tangential winds v_E and the rotational angular velocities v_E/r derived every 30 min for radii from 10 to 30 km (dots). The angular velocities fluctuate relatively greatly at radius of 10 km, which is presumably due to the frequent presence of clear air regions (e.g., Fig. 3.2a) and asymmetric velocity components as explored in section 3.6. The five-point temporal running mean angular velocities (curves) at $r \leq 25$ km are nearly uniform (except at radius of 25 km at 5–6 UTC). The angular velocities are increased gradually through the 8.5 hr from $\sim 1.1 \times 10^{-3}$ to $\sim 1.2 \times 10^{-3}$ rad/s. The rotation at radius of 30 km is faster throughout the analysis period. This region with $r \sim 30$ km is characterized by striating clouds rotating at much higher angular velocities, which is investigated in section 3.6.2 and discussed in section 3.7.

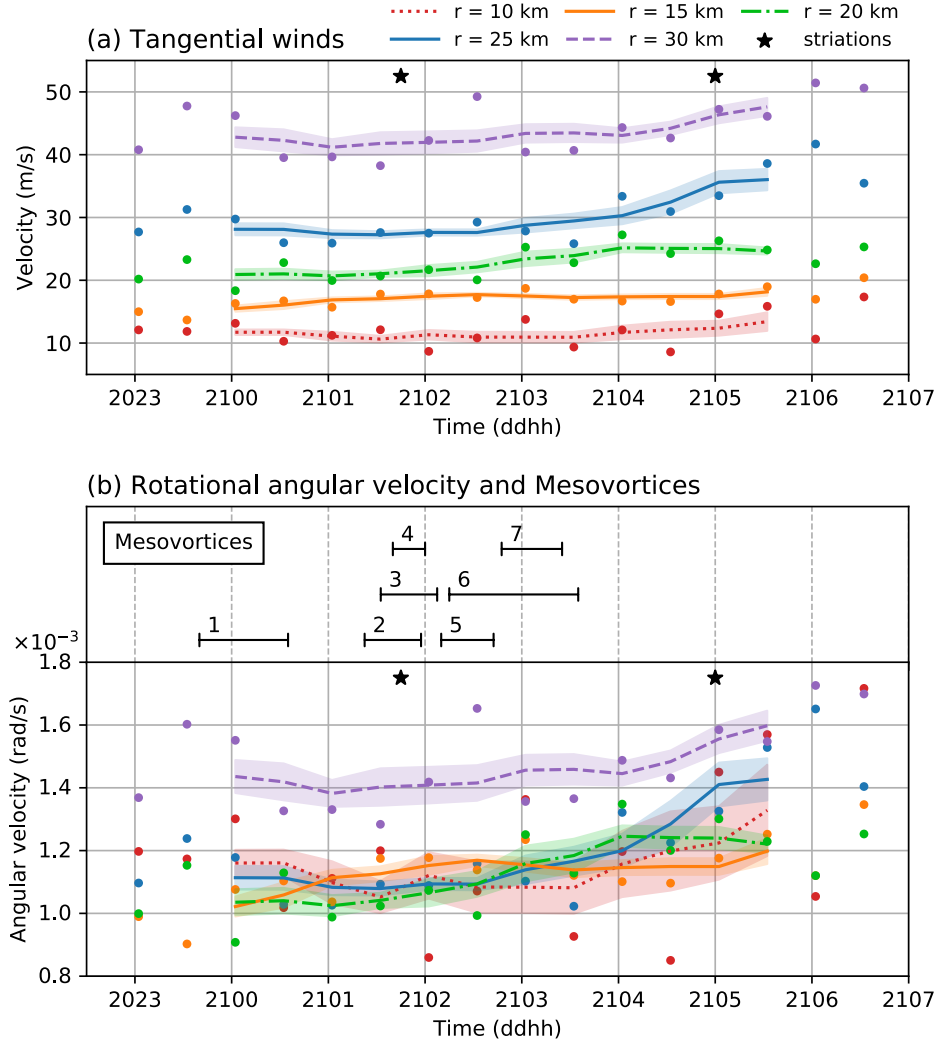


Figure 3.5: Time variation of (a) tangential winds and (b) rotational angular velocities at the radii of 10 (red), 15 (orange), 20 (green), 25 (blue), and 30 km (purple), respectively. Dots indicate the v_E every 30 min, while the solid curves show the running means with time over the five samples of v_E . The shading indicates $\pm$ the standard error computed from the variance among the five samples of v_E . Stars indicate the manually derived (angular) velocities of the striating clouds alongside the eyewall (section 3.6). The black lines at the top of (b) show the durations when the seven mesovortices were observed by visual inspection (section 3.6).

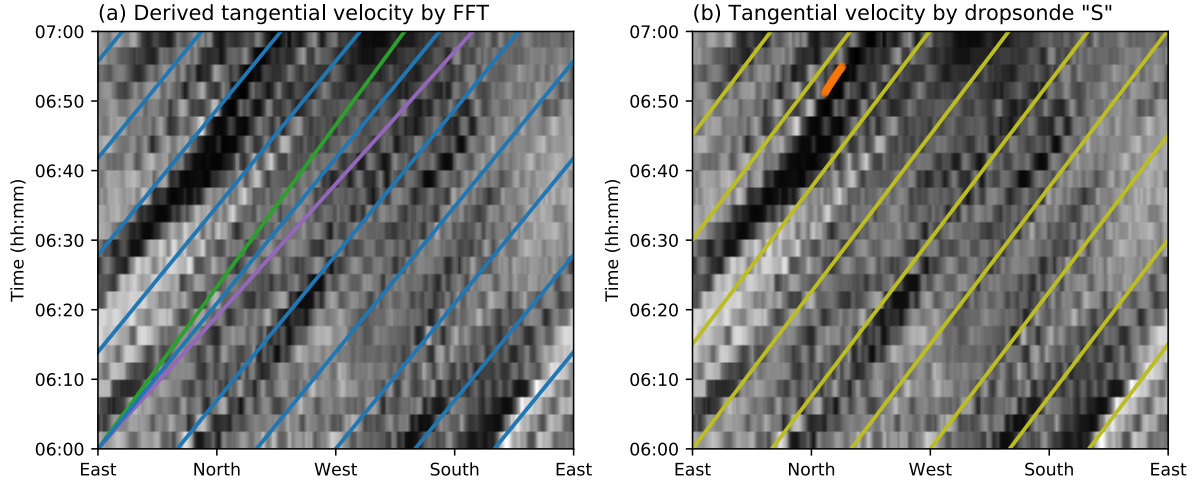


Figure 3.6: (a) As in Figure 3.3c–e but for 1 hr from 0600 UTC 21 October at a radius of 20 km and (b) a direct observation result by a dropsonde around 0650 UTC 21 October. Lines representing tangential wind speed superimposed on a time-azimuth cross section at 06–07 UTC. The yellow line in panel (b) corresponds to the average tangential wind speed recorded by a dropsonde at altitudes from ~ 3 to ~ 1 km. The orange line represents the trajectory of the dropsonde at altitudes below 3 km.

To verify the results, extensive comparisons were made with cloud motions in the azimuth-time cross sections, as shown in Figures 3.3c–e. Additionally, a movie was used where the VIS images were rotated clockwise to compensate for the five-point temporal running-mean angular velocity at a radius of 15 km. All these comparisons indicated the validity of the results.

The results in $r \leq 25$ km are consistent with the GPS dropsonde observations obtained through the T-PARCII project (Ito et al., 2018; Yamada et al., 2021; Hirano et al., 2022). For example, the dropsonde wind data obtained at radius of 20 km around 0650 UTC had the angular velocities around 1.16×10^{-3} rad/s, which corresponds to 23.2 m/s over the altitudes from ~ 3 to ~ 1 km (Fig. 3.6b). While the estimated angular velocity using the proposed method at radius of 20 km, 0630 UTC was 1.25×10^{-3} rad/s, which corresponds to 25.0 m/s (Fig. 3.6a). The estimation error of tangential wind was 1.8 m/s, corresponding to an error rate of 7.8%.

3.5 Sensitivity tests

In this section, the sensitivity of v_E to TC center positioning error and f_{thresh} is documented.

3.5.1 Sensitivity to TC center positioning error

If the TC center position is not specified correctly, it may cause error in the derived tangential wind v_E . An idealized experiment is conducted to investigate this sensitivity. A time series of an azimuthally sinusoidal wavy pattern with a wavenumber of 10 (Fig. 3.7a,b) is used, which undergoes a rigid-body rotation at an angular velocity of 1.0×10^{-3} rad/s. The time interval, Δt , of the time series is set to 2.5 min. In the estimation, $T = 6300$ sec was utilized, resulting in the use of 42 images (Fig. 3.7c). The other parameter values used are as follows: $k_{\min} = 1$; $L_{\min} = 0$ km; $A = 1$; $a_0 = 0.05$; $b_{\min} = 0.0$ rad/s; $b_{\max} = 3.0 \times 10^{-3}$ rad/s; $J = 20$; $f_{\text{thresh}} = 0.1$ or 0.8 . Here $f_{\text{thresh}} = 0.1$ is mainly used to demonstrate the nature of the problem; this low value is permissible because there is no motion other than the rotation.

From Stokes' theorem, the azimuthally averaged tangential wind speed is not affected by the center positioning error for the rigid body rotation as assumed here. However, since the proposed method estimates velocity as the phase velocity of an azimuthally propagating wave, a phase velocity measured along a direction different from the true wave propagation direction will be faster than the actual phase velocity. As a result, the resulting v_E will be larger than the ground-truth of tangential velocity if there is a center positioning error.

Figures 3.7a-d visualizes the case in which the distance between the true center (wavy pattern's center) and the assumed center (red plus), E_r , is 0.2 times the radius r at which v_E is derived (i.e., $\varepsilon \equiv E_r/r = 0.2$). The wavy feature on the right-hand-side (left-hand-side) along the red circle in Figure 3.7a moves at a faster (slower) speed than the true speed at r . Therefore, the TC center positioning error makes the phase-velocity spectrum bimodal as shown in Figure 3.7d. The resultant v_E is faster than the true one by 2% when $f_{\text{thresh}} = 0.1$ (Fig. 3.7d,e); the error is small because the weighted average in step 5 makes the result in between the bimodal peaks. In other words, the error induced by small non-zero ε is canceled to its first order. To set f_{thresh} to 0.8 does not change the error drastically.

Figure 3.7e shows the error ratio as a function of ε . It actually indicates that the error is the second order of ε . It also shows that a center positioning error provides a positive bias to v_E . This relation holds as long as the tangential wind increases with r , so it is likely a robust feature within the eye. Thus, the sensitivity of

the error of v_E to ε should be more-or-less similar to Figure 3.7e. It suggests that the bias is likely small when $\varepsilon \ll 1$.

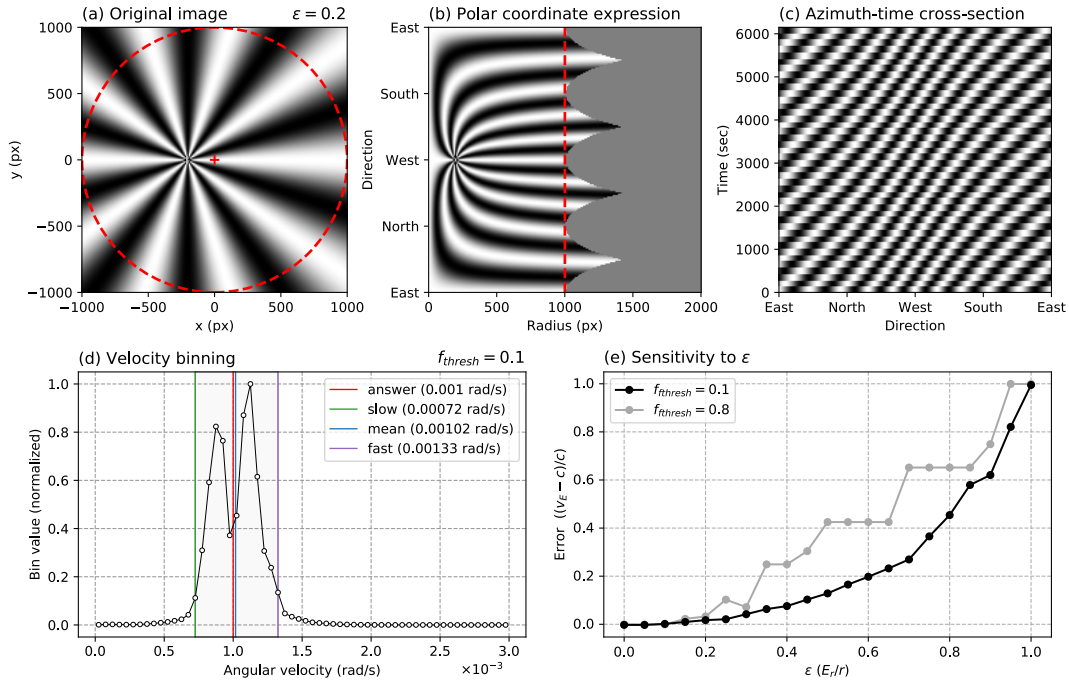


Figure 3.7: (a) An example of the idealized image with azimuthal wavenumber of 10. The red dashed circle indicates where $r = 1000$ px for the assumed center (red plus) which has an error of $E_r = 200$ px, so $\varepsilon \equiv E_r/r = 0.2$. (b) The idealized image projected onto the polar coordinate. (c) Azimuth-time cross-section over 6300 seconds at $r = 1000$ px. The rotational angular velocity c was set to 1.0×10^{-3} rad/s. (d) Binning results. The red line indicates the correct angular velocity, and the blue line indicates v_E . (e) Normalized derivation error $(v_E - c)/c$ as a function of ε when $f_{\text{thresh}} = 0.1$ (black) and $f_{\text{thresh}} = 0.8$ (gray).

3.5.2 Sensitivity to f_{thresh}

Notes on the setting of f_{thresh} can be described as follows. The brightness of clouds changes by many factors other than the rotation, and all of them are reflected in the phase velocity spectra. Therefore, the lower the value of f_{thresh} is, the greater the non-rotational signals affect v_E . In this respect, a high value is desirable. However, if f_{thresh} is too high, v_E would depend on the detailed shape of the phase-velocity spectrum. Note that $f_{\text{thresh}} = 1$ simply means to use the greatest peak.

The sensitivity of v_E to f_{thresh} is investigated here using the parameter values in section 4.1 and varied f_{thresh} from 0.0 to 0.9 every 0.1. Figure 3.8 shows the results for $f_{\text{thresh}} = 0.3, 0.7, 0.8$, and 0.9. The five-point standard error (shading) is the smallest at $f_{\text{thresh}} = 0.3$ among the four, so one may think that it

may be the best (Fig. 3.8a). However, the derived v_E is heavily dependent on $b_{\min}$ and $b_{\max}$, which are set differently for $r \leq 20$ km and $r \geq 25$ km. This is a consequence that v_E depends on non-rotational signals too much. At moderately high settings of $f_{\text{thresh}} = 0.7$ and 0.8 , there is no significant difference in the running means with time over the five samples of v_E (solid curves), which indicates robustness (Fig. 3.8b,c). At $f_{\text{thresh}} = 0.9$, not only the standard error is large compared to the other settings, but also the running means differ from the results of $f_{\text{thresh}} = 0.7$ and 0.8 (Fig. 3.8d). This suggests that $f_{\text{thresh}} = 0.9$ is not appropriate for the case in this study. Therefore, $f_{\text{thresh}} = 0.8$ were chosen in section 3.4.

The appropriate value for f_{thresh} may depend on the cases (e.g., the TC to be analyzed and whether the images are visible or IR). Therefore, it is recommended to conduct a similar test before fixing it. The appropriate value may depend on $a_0 \equiv \Delta b/c$. If a_0 is lowered, the phase-velocity spectra may become spikier, so it may be appropriate to lower f_{thresh} . However, considering the reason mentioned earlier, it is preferable to avoid setting a_0 to a very small value in order to ensure that a higher value of f_{thresh} (such as 0.7-0.8) is appropriate.

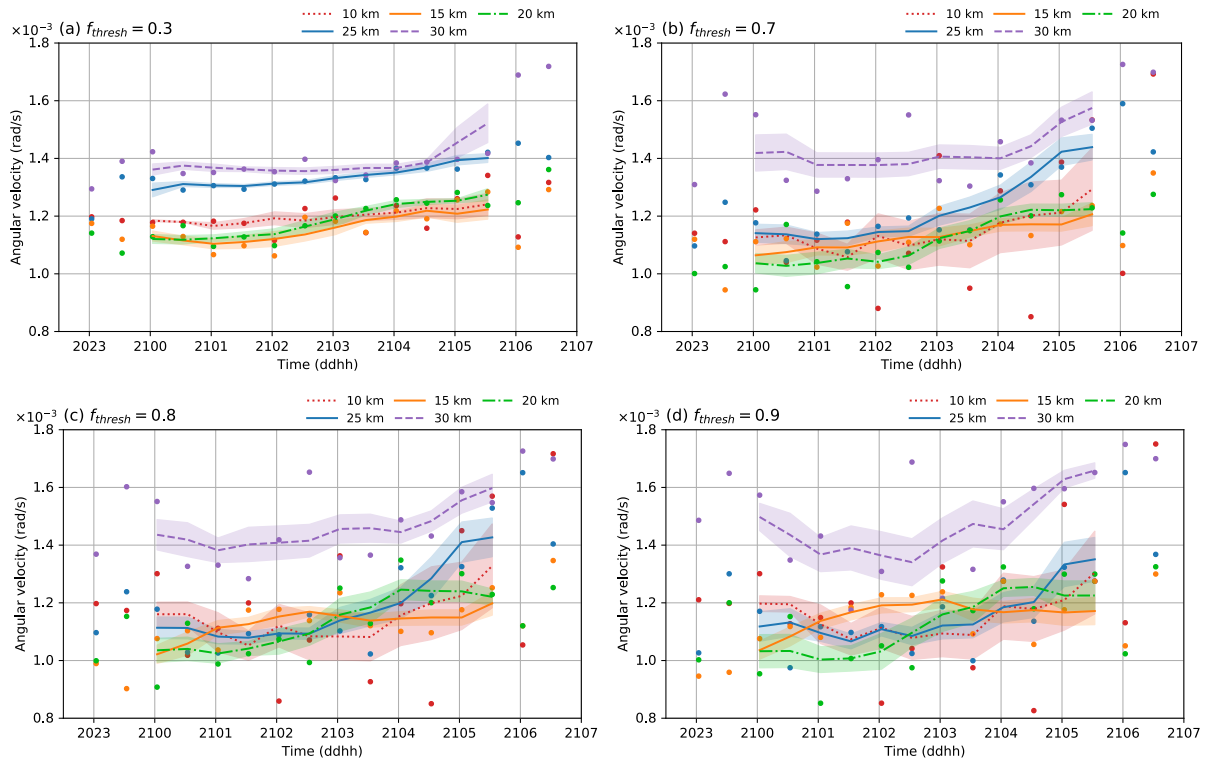


Figure 3.8: As in Figure 3.5b, but f_{thresh} values are (a) 0.3, (b) 0.7, (c) 0.8, (d) 0.9, respectively. Dots indicate the v_E every 30 min, while the solid curves show the running means with time over the five samples of v_E . The shading indicates $\pm$ the standard error computed from the variance among the five samples of v_E .

3.6 Quantification of asymmetric structure

In this study, a method was developed to estimate axisymmetric tangential velocities as a function of the radius. TCs are known to exhibit asymmetric motions. Therefore, this study attempts to visualize and subjectively quantify these asymmetric motions. In section 3.4, it was observed that within a radius of 25 km, the motion was close to the rigid-body rotation. Hence, any deviations from this rigid-body rotation within that range can be visualized as asymmetric motion.

3.6.1 Mesovortices in the eye

To visualize the asymmetric motions in the eye, a movie was created where the VIS images are rotated clockwise to compensate for the five-point temporal running-mean angular velocity at a radius of 15 km derived in section 3.4. It was confirmed that the eye of Typhoon Lan was full of asymmetric motion by visual inspection of the movie. Seven mesovortices (MV-1, ..., MV-7) were subjectively identified at the times and locations shown in Figures 3.5b and 3.9a–d. Cloud tracking was performed manually by using traceable cloud features with horizontal scales of 1–5 km, and their vorticities relative to the background rotation was estimated from three features around mesovortices; the example features for MV-1 and MV-6 are shown in Figure 3.10. Let their positions be (x_i^t, y_i^t) , where $i = 0, 1, 2$. From temporally intermediate positions

$$(x'_i, y'_i) = \left(\frac{x_i^{t_0} + x_i^{t_0+\Delta t}}{2}, \frac{y_i^{t_0} + y_i^{t_0+\Delta t}}{2} \right) \quad (3.7)$$

and velocities

$$(u'_i, v'_i) = \left(\frac{x_i^{t_0+\Delta t} - x_i^{t_0}}{\Delta t}, \frac{y_i^{t_0+\Delta t} - y_i^{t_0}}{\Delta t} \right), \quad (3.8)$$

the mean vorticity in the triangle is approximated by

$$\zeta = \frac{\Delta u_1 \Delta x_2 - \Delta u_2 \Delta x_1 + \Delta v_1 \Delta y_2 - \Delta v_2 \Delta y_1}{\Delta x_1 \Delta y_2 - \Delta x_2 \Delta y_1}, \quad (3.9)$$

where $(\Delta x_i, \Delta y_i) = (x'_i - x'_0, y'_i - y'_0)$ and $(\Delta u_i, \Delta v_i) = (u'_i - u'_0, v'_i - v'_0)$. This relation, which is exact when Δt , Δx_i , and Δy_i are infinitesimal, can be derived from Stokes's theorem. The mean relative vorticities of several estimates of MV-1, MV-4, and MV-6 were obtained as $\zeta_1 = 2.0 \times 10^{-3} \text{ s}^{-1}$, $\zeta_4 = 3.2 \times 10^{-3} \text{ s}^{-1}$, and $\zeta_6 = -2.2 \times 10^{-3} \text{ s}^{-1}$, respectively. Their magnitude is comparable to the background vorticity of the rotation of $2.2 \times 10^{-3} \text{ s}^{-1}$ to $2.4 \times 10^{-3} \text{ s}^{-1}$. The vorticities of MV-2, MV-3, MV-5,

and MV-7 were not estimated due to the lack of sufficient number of concurrent traceable features.

The result is consistent with earlier studies since the vorticity inside the eye was increased after the mesovortices were observed. The observed asymmetric motions might have transported the high angular momentum into the eye.

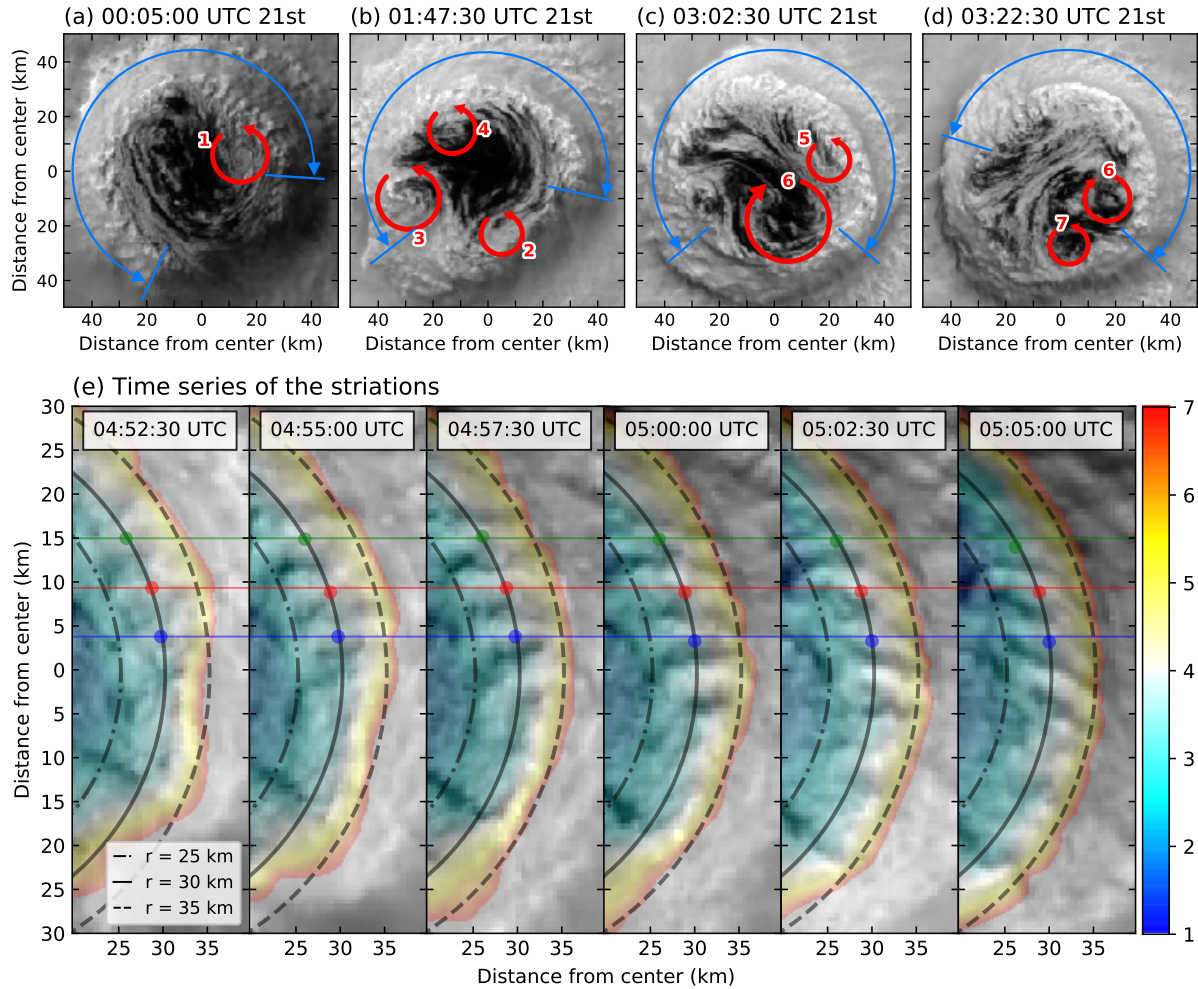


Figure 3.9: Mesovortices and striations in the eye of Typhoon Lan (2017) on 21 October. (a–d) VIS images (directed north on top) at 0005:00, 0147:30, 0302:30, and 0322:30 UTC, respectively. Red arrows with numbers indicate the seven mesovortices, and blue arcs indicate the range of striations. (e) Time series of the striations; the VIS images were rotated clockwise at an angular velocity of 1.75×10^{-3} rad/s and shown every 2.5 min from 0452:30 UTC 21 October. Color shading indicates the estimated CTH (km). Black arcs show where radii of 25, 30, and 35 km, respectively. Colored bullets show the manually identified positions of striating clouds. The colored horizontal lines are shown to indicate their positions at the same radius if they are rotated at 1.75×10^{-3} rad/s.

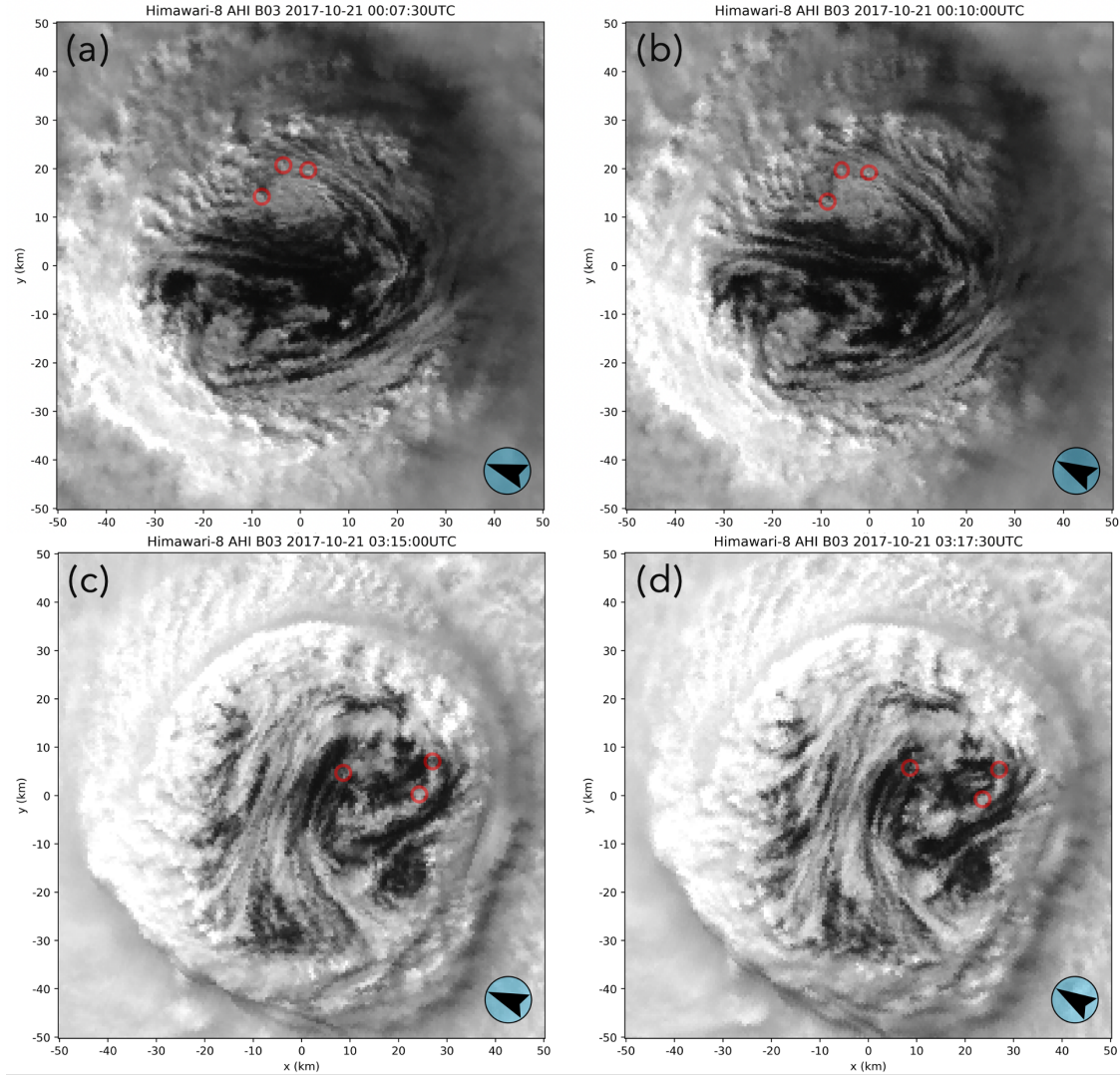


Figure 3.10: The three features around the (a–b) MV-1 and (c–d) MV-6 used to derive their vorticity (red circles) shown on visible images which is rotated clockwise to compensate for the eye's rotation at a radius of 15 km on 21 October. Black arrowhead near the lower right corner indicates the north direction.

The traceable feature positions of (a) are $(x_1^{t_0}, y_1^{t_0}) = (1.57, 19.24)$, $(x_2^{t_0}, y_2^{t_0}) = (-3.6, 20.29)$, $(x_3^{t_0}, y_3^{t_0}) = (-8.18, 13.74)$ at $t_0 = 0007:30$ UTC in local coordinates (units: km). The feature position of (b) are $(x_1^{t_0+\Delta t}, y_1^{t_0+\Delta t}) = (-0.26, 18.85)$, $(x_2^{t_0+\Delta t}, y_2^{t_0+\Delta t}) = (-5.89, 19.37)$, $(x_3^{t_0+\Delta t}, y_3^{t_0+\Delta t}) = (-8.77, 12.96)$ at $t_0 + \Delta t = 0010:00$ UTC. The feature positions of (c) are: $(x_1^{t_0}, y_1^{t_0}) = (8.44, 4.58)$, $(x_2^{t_0}, y_2^{t_0}) = (24.21, 0.39)$, $(x_3^{t_0}, y_3^{t_0}) = (26.83, 7.07)$ at $t_0 = 0315:00$ UTC. The feature positions of (d) are $(x_1^{t_0+\Delta t}, y_1^{t_0+\Delta t}) = (8.57, 5.63)$, $(x_2^{t_0+\Delta t}, y_2^{t_0+\Delta t}) = (23.56, -0.85)$, $(x_3^{t_0+\Delta t}, y_3^{t_0+\Delta t}) = (27.16, 5.30)$ at $t_0 + \Delta t = 0317:30$ UTC.

3.6.2 Striations at the inner edge of the eyewall

The angular velocity at $r \sim 30$ km had remarkably high (Fig. 3.5). The clouds at $r \sim 30$ km are characterized by striating clouds (Figs. 3.9a–d and 3.11). It has a structure similar to the “striations” or “finger-like features,” which have been reported several times in previous aircraft observational studies (e.g., Aberson et al., 2006; Bluestein and Marks, 1987; Marks et al., 2008). The angular velocity of the striations were derived by visual inspection. The result was $\sim 1.75 \times 10^{-3}$ rad/s throughout the analysis period (Figs. 3.5 and 3.9e). The striations were situated over 26–33 km from the TC center, and their CTH increase with radius from 3 to 6 km. They tend to appear with radial orientation and are gradually tilted over time (Fig. 3.9e), which is consistent with the decrease of tangential winds with altitude.

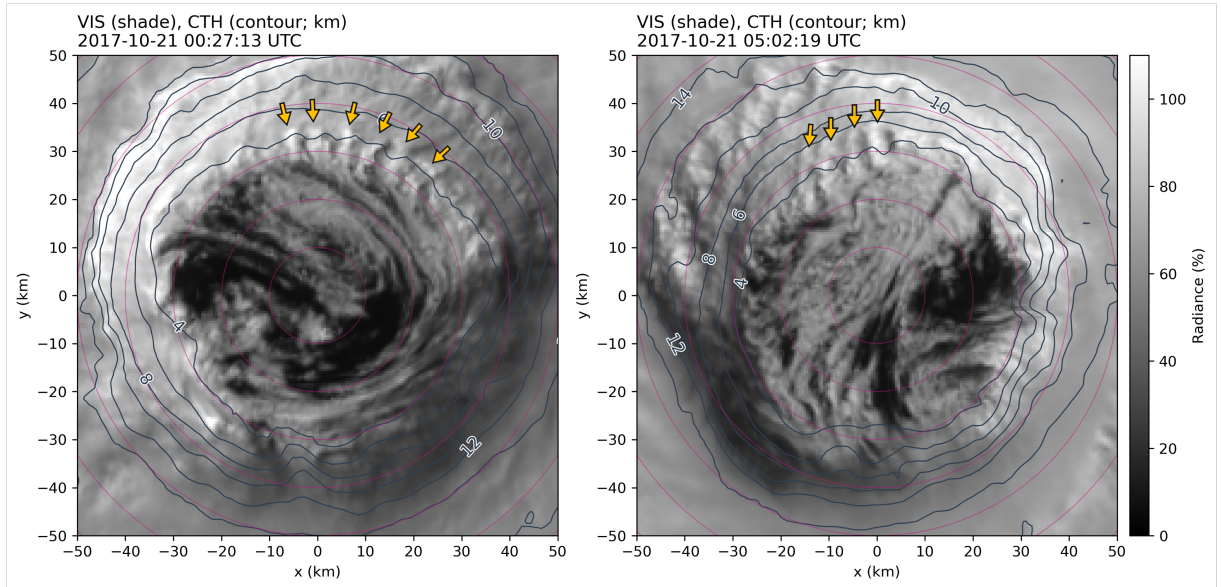


Figure 3.11: Example of striations in the eye of Typhoon Lan (2017) at (a) 0027:13 UTC and (b) 0502:19 UTC 21 October 2017. The cloud top height (km) is represented by navy-blue contours on the VIS reflectivity (gray shading). The positions of distinct striating clouds are indicated by yellow arrows. Magenta circles are plotted at a radial interval of 10 km. Striated structures are more visible and distinct when the solar zenith angle is smaller, as it creates shadows along the striations, making them easier to see.

3.7 Discussions

The derived rotational angular speed increases with radius abruptly at the inner edge of the striations. This fact suggests that the striations reside in the secondary circulation associated with the eyewall. If this is the case, the fact that the striations bulge out toward the TC center suggests the inertial overshoot (Bryan and Rotunno, 2009b). Thus, the regularity of the striations might be due to the shear instability between the outgoing return flow, which is fast and supergradient, and the slower flow aloft. If this is true, it follows that the tangential winds below the striations can be even faster since the Kelvin-Helmholtz billows move at an intermediate velocity in the shear. The diabatic heating in the striations may contribute to TC intensification, since they are likely inside the radius of the maximum wind (Pendergrass and Willoughby, 2009).

The space-time spectral analysis can separate multiple velocities, so even when the upper clouds and the lower clouds overlap, the upper and lower velocities are separable, if upper clouds have gaps or are optically thin. Therefore, the method may be applicable outside the eye, after some modification. Moreover, the method can be applied to not only VIS but also IR imagery with some modification if the conditions are favorable (Tsujino et al., 2021a).

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Chapter 4

Wind distribution in the eye revealed by a novel atmospheric motion vectors derivation

4.1 Introduction

As described in Chapter 1, geostationary meteorological satellites (GMSs) observe tropical cyclones (TCs) throughout their life cycles without interruption. In recent years, third-generation GMSs such as Himawari-8, which began operating in 2015, have significantly improved the spatiotemporal and wavelength resolution compared to their predecessors (Bessho et al., 2016; Schmit et al., 2017). For instance, Himawari-8/9 and GOES-16/17/18 have twice the spatial resolution of their predecessors, with 2 km for infrared (IR) channels and 0.5 km for visible (VIS) channels at nadir. In particular, the “rapid-scan” observations for TCs are made every 2.5 min in the target area of Himawari-8/9 and every 1 min in the meso sector of GOES-16/17/18, both covering an area of $\sim 1000 \text{ km} \times 1000 \text{ km}$. These advancements have enabled us to reveal various properties of TCs that were previously unobservable (e.g., Horinouchi et al. 2020).

In a recent study, Horinouchi et al. (2023; hereinafter, H23) investigated low-level atmospheric motion vectors (AMVs) captured in the eye of Typhoon Haishen (2020) using research-based special observations with Himawari-8, which were conducted every 30 sec. They identified both stationary and transient asymmetric features in the eye that were associated with the algebraically growing wavenumber-1 disturbance. These features were found to be important in the transport of angular momentum towards the center, which results in an acceleration in the rotation of the eye (Figs. 2.9 and 2.10). They used template matching method with cross-correlation to derive AMVs. There was no special processing specifically designed for TCs, but with the short interval of 30 sec, they were able to obtain sufficient AMVs. To investigate the impact of 30-sec observations, H23 reproduced the AMVs in situations where the observation frequency was relatively low (see Fig. 1.7). They showed that as the observation frequency decreases, the number of obtained AMVs significantly decreases, and discussed the need for more elaborated methods to

estimate wind distribution in such situations.

There are following three major obstacles to obtaining AMVs in the inner-core region from a relatively long-time (e.g., 2.5-min) interval image sequence.

- (1) Large rotational component. The TC inner-core region has a large rotational angular velocity, making it difficult for many cloud tracking algorithms that assume parallel or smooth motion of clouds. Moreover, a high wind speed at a large radius requires a wide search range, increasing the risk of obtaining inaccurate AMVs.
- (2) Cloud deformation. Due to the spatial shear of the flow in the eye and eyewall, clouds are deformed, resulting in a loss of shape identity of the tracking target between consecutive images.
- (3) Cloud generation and dissipation. Cloud generation/dissipation and cloud motion can be indistinguishable, leading to incorrect estimates.

These characteristics can occur individually or simultaneously. One of the most challenging aspects of cloud tracking in the eye of an intense TC is the presence of “striations,” which were described in Chapter 3 as having the following characteristics (see Figs. 3.9e and 3.11):

- They exist at inner edge of the eyewall clouds from the lower to middle levels.
- Their cloud top heights have a wavy pattern that regularly rises and falls in the azimuthal direction.
- They become inclined due to the vertical shear of the tangential wind.
- The radial shear of tangential wind is greater inside the striations due to its higher angular velocity compared to the region inside it.

Around the inner edge of the eyewall cloud, where the cloud top height varies greatly along the radial direction, there is little continuity with the surrounding AMVs. The wavy pattern can easily lead to incorrect tracking, and the cloud deformation caused by vertical shear leads to loss of cloud similarity between consecutive images. Therefore, tracking the clouds of the striations is a very challenging task.

The method developed in Chapter 3 derives the sustained tangential winds in the eye as a function of radius using spectral analysis for azimuth-time cross section of rapid-scan imagery taken by GMSs. Using this method, the wind distribution in an image sequence with a 2.5-min interval was successfully estimated. However, the method only provides the representative tangential wind speed in an azimuth-time cross section around a certain radius, and does not provide the asymmetric motions. Here, the term “representative tangent wind speed” refers to a value that is closer to the average of azimuth and time. Time averaging is a

low-pass filter that eliminates variations on short time scales, while azimuthal averaging eliminates asymmetric motions including the algebraically growing wavenumber-1 disturbances (Nolan and Montgomery, 2000; Nolan et al., 2001; Marks et al., 2008; Horinouchi et al., 2023), barotropic instability and mesovortices (Schubert et al., 1999; Kossin and Eastin, 2001; Kossin and Schubert, 2001), and striations or finger-like features (Bluestein and Marks, 1987; Aberson et al., 2006; Marks et al., 2008; Yamada et al., 2021). Therefore, there are limitations to discuss such inner-core asymmetric dynamics using the method.

It is desirable to investigate the wind distribution in the inner-core region of numerous TCs and accumulate observational facts by obtaining AMVs not only from 30-sec observations but also from normal 1-min or 2.5-min rapid-scan observations. Therefore, this study aims to develop a cloud tracking method specialized for TCs by extending the method of H23 with considering the unique characteristics of TCs. The objective is to obtain AMVs in the TC inner-core region from an image sequence even for a few minutes time interval. Furthermore, the purpose of this study includes to investigate the TC dynamics based on the AMVs obtained from the method.

In this study, the proposed method is applied to Typhoon Haishen (2020), Typhoon Nanmadol (2022), and Typhoon Lan (2017). As in H23, Typhoon Haishen and Typhoon Nanmadol were observed by a research-based special observation of Himawari-8 conducted every 30 sec. For these cases, the AMVs from 2.5-min and 30-sec interval image sequences are compared. As in Chapter 3, Typhoon Nanmadol and Typhoon Lan were directly observed using dropsondes released from aircraft by the Tropical cyclones-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARCII; Ito et al., 2018; Yamada et al., 2021; Hirano et al., 2022) project. For these cases, AMVs obtained from 2.5-min interval image sequence are evaluated by comparing them with wind observations obtained from dropsondes.

The obtained AMVs are utilized to study the dynamics in the eye of the three TCs. As in H23, wavenumber-1 features are also observed in their eyes. Furthermore, the contribution of mesovortices to the angular momentum transport in the eye of Typhoon Lan are investigated. The results are consistent with the observational and numerical study of Kossin and Eastin (2001), who used aircraft flight-level data to demonstrate a rapid increase in angular velocity in the eyes of multiple TCs within a time span of one hour. This rapid increase in angular velocity was explained by the transport of angular momentum by mesovortices associated with the barotropic instability around the eyewall. This explanation was derived from an

idealized barotropic simulation.

Section 4.2 provides a review of the H23 method. In section 4.3, the data used in this study and the proposed method are described. In section 4.4, the results of applying the method to several intense TC cases and evaluation of its accuracy are shown. In section 4.5, the asymmetric motions in the eye are investigated. In section 4.6, the findings of this study are discussed.

4.2 A review of the Horinouchi et al. (2023) method

H23 investigated low-level AMVs obtained in the eye of Typhoon Haishen (2020) using research-based special observations with Himawari-8, which were conducted every 30 sec. In this section, a review of the cloud-tracking method used in H23 are provided. The variable parameters are symbolized as listed in Table 4.1.

The images were first resampled onto a Cartesian coordinate grid on the azimuthal equidistant projection with respect to the TC center after parallax correction. The AMVs derived in H23 represent storm-relative velocities. This is because the images were sampled with respect to the moving TC center.

High-frequency imaging has the advantage of allowing for easy tracking of small morphological changes in cloud features. However, decreasing the time interval between images (Δt) for a given horizontal resolution (Δh) results in an increase in the nominal discretization error of velocity ($\Delta h / \Delta t$). To overcome this issue and take advantage of high-frequency imaging while minimizing discretization errors, a novel method was introduced in which tracking is performed over multiple steps. H23 used four steps by using five consecutive images taken over 2 min. Additionally, subgrid estimation was employed to further reduce discretization errors. To prevent artifacts from cirrostratus clouds, a screening process was conducted during post-processing.

4.2.1 Cloud tracking

H23 employed a cloud tracking that relies on the cross-correlation method, similar to the conventional particle image velocimetry (PIV). However, it differs in that it utilizes five consecutive images taken over a period of 2 min.

- AMVs were derived at time intervals of T_g on two different types of grids:
 - 1) Cartesian grid has a resolution of H_g along both x (eastward) and y (northward) axes.
 - 2) Polar-coordinate grid samples the radius and azimuth counterclockwise from the east at resolutions of R_g (km) and θ_g (rad), respectively.

H23 set $T_g = 1$ min, $H_g = 2$ km, $R_g = 2$ km, and $\theta_g = 2\pi/60$ rad, respectively. These grids are used to specify the initial positions of the centers of template subimages, which are used to define AMVs. The tracking of template subimages is always conducted on Cartesian-coordinate images. AMVs derived on the polar-coordinate grid were used when analyzing data on the polar co-

ordinate, such as to show azimuthal means or wavenumber decomposition.

- At every reference time, a template subimage with a size of $W \times H$ pixels in x and y directions is subsampled at each grid point (either in Cartesian or polar-coordinate grids), and it was tracked in a Lagrangian manner for N_t steps forward and backward under the following conditions. The tracking process is carried out only when the subimage has a contrast greater than the threshold C_{th} . H23 set $W = H = 11$, which corresponds to a size of $5 \text{ km} \times 5 \text{ km}$, $N_t = 2$, which corresponds to a duration of 1 min, and $C_{th} = 0.05$ in reflectivity.
 - 1) The search area for finding the displacement of template subimages across temporally adjacent images is set to cover a velocity range of $-V_s$ to V_s (m/s) in both the x and y directions. Corresponding maximum displacement in pixels (h_s) is calculated as $h_s = \text{ceil}(V_s \cdot \Delta t / \Delta h)$ for both x and y directions, where $\text{ceil}()$ is a function that rounds a number up to the nearest integer. To ensure that the correlation maximum is a local peak, an additional 1-pixel displacement is tested, resulting in a computation range $\pm(h_s + 1)$ pixels. If the correlation maximum is found on the edge of the search area, i.e., at additional 1 pixel, the result is rejected.
 - 2) The cloud tracking process is terminated and the result is rejected if the maximum cross-correlation coefficient is below the threshold S_{th} . H23 used a value of $S_{th} = 0.8$ for their analysis.
 - 3) The 5-point parabolic fitting around the peak cross-correlation pixel is performed to determine the subpixel destination of the template subimage. The subsequent-step tracking is then carried out using a resampled template subimage centered at this subgrid destination, which is obtained using bilinear interpolation.
 - 4) The tracking result is discarded if either of the two horizontal velocity components changes by more than V_c (m/s) between consecutive tracking steps. Additionally, if the mean velocities obtained from forward and backward tracking differ by more than V_d (m/s) as vectors, the result is also rejected. H23 set $V_c = 20 \text{ m/s}$ and $V_d = 20 \text{ m/s}$ for their analysis.
- AMV is defined as the average of all $2N_t$ velocity vectors. For the H23 setting, a total of four vectors are used, with $N_t = 2$ for each forward and backward tracking.

4.2.2 Postprocessing

Height assignments of AMVs were performed using the equivalent blackbody temperature (EBBT) method by an infrared window brightness temperature (Fritz and Winston, 1962). The altitude at which the EBBTs of the infrared window channel matched the temperature profile from the reanalysis data was assigned as the height of the AMV.

In TCs with eyes, the upper troposphere sometimes contains stratiform (cirrostratus) clouds, which can obscure the eyes. The movements of some opaque clouds reflect the flow in the upper troposphere. AMVs derived where nearly transparent clouds mostly reflect the movements of clouds in the boundary layer of the eye. However, these AMVs may have significant parallax errors due to the presence of optically thin cirrus clouds, which can lower the brightness temperature. Therefore, it is preferable to exclude these AMVs. To address this issue, H23 used a “split window” technique (e.g., Inoue, 1987) that masks AMVs where the differences in brightness temperature between $10.4\ \mu\text{m}$ and $11.2\ \mu\text{m}$ are greater than T_{sp} , which was set to 2 K. This technique effectively filters out optically thin upper clouds, and the results were not significantly affected when the threshold was lowered to 1.5 or 1 K. They also applied a masking process based solely on the brightness temperature at $10.4\ \mu\text{m}$, as needed.

Symbol	Definition	H23 setting
Δt	Time interval between consecutive images.	30 sec
Δh	Horizontal resolution of images.	500 m
T_g	Temporal grid spacing of AMVs derivation.	1 min
H_g	Horizontal grid spacing of AMVs derivation.	2 km
R_g	Radial grid spacing of AMVs derivation.	2 km
θ_g	Azimuthal grid spacing of AMVs derivation.	$2\pi/60$ rad
W, H	Template subimage width (W) and height (H), respectively.	11×11 pixels
N_t	Tracking time steps for both forward and backward.	2 steps
C_{th}	Minimum contrast of template subimage.	0.05 (reflectivity)
V_s	Search range for cloud tracking in velocity dimension.	80 m/s
h_s	Search range for cloud tracking in pixel count.	5 pixels
S_{th}	Threshold to limit the lowest value of the peak cross-correlation coefficient.	0.8
V_c	Threshold to limit the maximum velocity change between consecutive images.	20 m/s
V_d	Threshold to limit the maximum velocity difference between velocities obtained from forward and backward tracking as vectors.	20 m/s
T_{sp}	Threshold to limit the maximum brightness temperature difference between $10.4 \mu\text{m}$ and $11.2 \mu\text{m}$.	2 K
θ_d	Threshold to limit the maximum angle difference between velocities obtained from forward and backward tracking as vectors.	60°
v_{th}	Threshold wind speed for screening by θ_d .	5 m/s

Table 4.1: A list of symbols for the H23 method along with brief definitions and values used in H23. The parameters θ_d and v_{th} are not included in the original H23 method, but it is added in this study. The description about it is provided in section 4.3.3.

4.3 Data and method

4.3.1 Data

The data mainly used in this study are visible (VIS) and infrared (IR) images from Himawari-8 (Bessho et al. 2016) obtained by a 2.5-min rapid scan observation and research-based special observation conducted every ~ 30 sec (mostly between 25 and 35 sec). Cloud tracking was performed using the VIS reflectivity at $0.64 \mu\text{m}$, with a resolution of 0.5 km at nadir. The radiance was adjusted to simulate albedo (nondimensional; values up to ~ 1.2). For parallax correction and thin-cloud masking, the IR brightness temperature at $10.4 \mu\text{m}$ and $11.2 \mu\text{m}$ were used, which have resolutions of 2 km at nadir. To correct parallax, the ERA5 (Hersbach et al. 2020), a global reanalysis dataset produced by the European Centre for Medium Range Weather Forecasts, was used to obtain temperature, geopotential, and relative vorticity around TCs. The use of ERA5 in these computations was justified by Slocum et al. (2022). The tracks and intensities of TCs analyzed by Japan Meteorological Agency (JMA) and Joint Typhoon Warning Center (JTWC) were obtained from the IBTrACS best-track dataset (Knapp et al. 2010, 2018). For verification, the 30-sec image data for Typhoons Haishen and Nanmadol are used. The dropsonde (DS) profiles obtained in the eye of Typhoon Lan on 21 October 2017 and Typhoon Nanmadol on 17 September 2022 are also used. The analysis period and other properties for these cases are summarized in Table 4.2.

Name (year)	Analysis period	Eye radius	2.5 min	30 sec	DS
Haishen (2020)	9 hr from 2300 UTC 3 Sep.	~ 35 km	○	○	×
Nanmadol (2022)	8 hr from 2300 UTC 16 Sep.	~ 20 km	○	○	○
Lan (2017)	9 hr from 2230 UTC 20 Oct.	~ 40 km	○	×	○

Table 4.2: Analysis information on the TCs used in this study. First column indicates the name and year to identify the TC. Second column indicates the analysis period. Third column indicates the approximate radius of the eye. The remaining columns indicate the availability of data, with a circle symbol indicating availability and a cross symbol indicating unavailability, for 2.5-min interval images, 30-sec interval images, and dropsonde (DS) data, respectively.

4.3.2 TC center determination & image resampling

The parallax are corrected from the entire Himawari-8 data with cloud top height (CTH) estimates obtained by equating the IR brightness temperature to the temperature in the reference profiles as in Chapter 3. The best-track TC center lacks the necessary precision for the intended purposes, so the TC centers were manually determined every 30 min by subjectively analyzing the corrected VIS and IR images. The TC center is determined with the intention of corresponding to the center of circulation at the inner edge of the eyewall clouds at altitudes of 4–5 km. The results were then interpolated with time (t) using cubic spline interpolation. The image data were projected onto the azimuthal equidistant projection for the TC center, with a resolution of 0.5 km along the eastward (x) and northward (y) coordinates.

4.3.3 Method: a TC-specific cloud tracking

A TC-specific cloud tracking method is developed. The H23 method is employed in the core part of the cloud tracking, specifically in step 2 of the following description. In this study, an optional quality control step is added to the H23 method, where AMVs are rejected if the directions of the velocities obtained from forward and backward tracking differ by more than θ_d , given that either the forward or backward wind speed is greater than or equal to v_{th} . While H23 obtained the final AMVs by averaging the results of N_t steps of forward and backward tracking separately and then averaging the two means, for comparison purposes, the final AMVs are obtained by calculating the vectors connecting the start and end points of each forward and backward tracking, and then averaging the two velocity vectors.

The following nine steps yield low-level AMVs using projected image sequence.

- Step 1: Create image sequences that are rotated in the direction opposite to the rotation of the TC to compensate for the rotation with respect to time. This is done using constant angular velocities of $\Omega = \Omega_i$ ($i = 1, 2, \dots, N$).
- Step 2: For each sequence, conduct the cloud tracking as in H23 (section 4.2) with a narrow search range (i.e., small V_s and h_s). The quality-controlled AMVs are converted to velocities in the non-rotating coordinate system (i.e., $\Omega = 0$) by adding the corresponding $\Omega_i \Delta t$ to the tangential component of each AMV. These converted AMVs are treated as candidate estimates, $\mathbf{v}_{cand}(x, y, t, \Omega)$, which consist of two horizontal velocity components at each grid point.
- Step 3: Keep only the AMVs with CTH between Z_{min} and Z_{max} , and mask out the rest.
- Step 4: Assign the peak cross-correlation coefficient as a “score” for each AMV.

- Step 5: Select the AMVs from $\mathbf{v}_{\text{cand}}(x, y, t, \Omega)$ with the highest score along the Ω axis as the tentative estimates, $\mathbf{v}_{\text{tmp}}(x, y, t)$.
- Step 6: Compute the spatiotemporal median wind field, denoted as $\mathbf{v}_{\text{med}}(x, y, t)$, using a median filter that calculates the median for each horizontal velocity component of $\mathbf{v}_{\text{tmp}}(x, y, t)$. The filter window has a three-dimensional shape along the (x, y, t) dimensions with preset window sizes as described below.
- Step 7: Compute $d_2(x, y, t, \Omega) \equiv \|\mathbf{v}_{\text{cand}} - \mathbf{v}_{\text{med}}\|_2$, which is the L2 norm of the difference vector between $\mathbf{v}_{\text{med}}$ and $\mathbf{v}_{\text{cand}}$ for each grid point.
- Step 8: Reject $\mathbf{v}_{\text{cand}}$ where $d_2 \geq d_{\text{th}}$ or $d_2 \geq d_c \times \|\mathbf{v}_{\text{med}}\|_2$, where $\|\mathbf{v}_{\text{med}}\|_2$ is the L2 norm (wind speed) of $\mathbf{v}_{\text{med}}$ for each grid point. Then update the $\mathbf{v}_{\text{tmp}}$ with the remaining $\mathbf{v}_{\text{cand}}$.
- Step 9: Repeat steps 6–8 until there are no further updates to the tentative estimates. Use the resulting estimates as the final value ($\mathbf{v}_{\text{final}}$).

The symbolized variables are listed in Tables 4.1 and 4.3. In this study, Ω_i are set as $\Omega_i = \Omega_{\min} + (i - 1)(\Omega_{\max} - \Omega_{\min})/(N - 1) = \Omega_{\min} + (i - 1)\Delta\Omega$ ($i = 1, 2, \dots, N$). While the $\Omega_{\max}$ should be set sufficiently large, it is advisable to keep it within realistic limits to avoid erroneously generated AMVs. The interval $\Delta\Omega$ should be set sufficiently small, and empirically, a value of approximately 1.0×10^{-3} rad/s is sufficient for small eye with a radius of ~ 20 km or less, while a value of 0.5×10^{-3} rad/s is sufficient for larger eye. Since the striations rapidly deform with time (section 4.1), the threshold of cross-correlation coefficient (i.e., S_{th}) should be set relatively low (e.g., 0.7).

From step 6, candidate estimates that are not smooth with the surrounding flow are rejected based on comparison with the median. The spatiotemporal window shape for median filter is dependent on the grid type of AMVs derivation as described in section 4.2.1 (i.e., the Cartesian grid and the polar-coordinate grid). For the Cartesian grid type, the window shape and size is determined by setting H_w in x and y axes and T_w in time axis. For the polar-coordinate grid type, the window shape and size is determined by setting R_w in r axis, θ_w in θ axis, and T_w in time axis. If the window size is too large, the median wind may not be effective as a local reference wind. Since appropriate parameter values may vary depending on the TC case, it is recommended to try several values. The approach of rejecting erroneous AMVs is similar to the relaxation labeling, also known as the relaxation method, which is used for assigning labels to objects or scenes (Rosenfeld et al., 1976). The relaxation method has been utilized to correct erroneous template matching for optical flow detection and particle tracking velocimetry (Wu, 1995; Baek and Lee, 1996; Ohmi and Li, 2000; Evans, 2000; Ogohara et al., 2012; Kouyama et al., 2012; Horinouchi et al., 2017). In the relaxation method, the “labels” are assumed to be independent, meaning that the candidate AMVs at a grid point

should have distinct or well-separated destinations. However, the candidate AMVs in this study are not independent as they involve the same destination. In such cases, utilizing a rejection process based on comparison with the median wind field, as done in this study, is considered an effective approach.

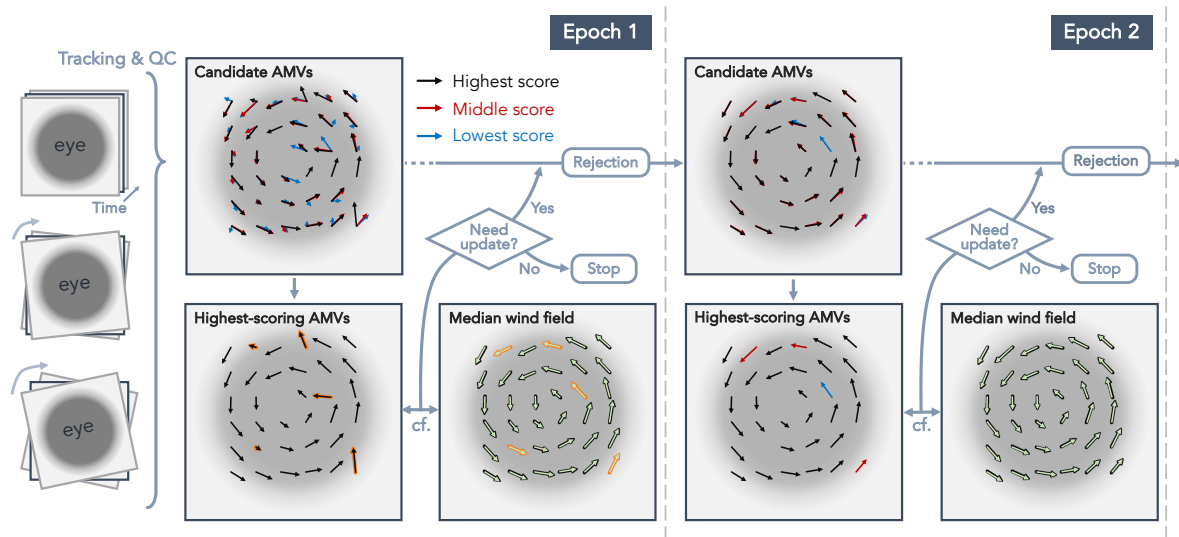


Figure 4.1: A schematic diagram illustrating the procedure of the TC-specific cloud tracking method. The gray shading represents a VIS image around the eye of a TC, with the eye depicted as a dark area and the top of the eyewall cloud displayed as a white area. The thin vectors are AMVs, referred to as candidate AMVs, obtained from three image sequences (one original, two counter-rotated at different angular velocities). The vectors are colored black, red, and blue based on their score, which is determined by the cross-correlation coefficient. The thick green vector represents the median wind. It is calculated by applying a spatiotemporal median filter to the AMVs with the highest scores. The orange-bordered vectors indicate pairs that exhibit a large difference between the highest-scoring AMVs and the median wind at the same grid point. If such vectors are present, it indicates the need to proceed with a rejection process. The rejection process involves discarding all candidate AMVs that have a large difference from the median wind at the same grid point. After the rejection process, if the difference between the highest-scoring AMVs and the median wind is not large at all grid points, the highest-scoring AMVs are considered the final AMVs. If the difference is large, the process continues to the next rejection process.

While the above procedure allows for obtaining low-level AMVs in the eye, but on striations, often incorrect AMVs are obtained in a few-minute interval image sequence due to the following reasons. That error occurs when cloud-tracking points that were on a certain striation switch to a different following striation. Each individual striation is generated sequentially at a certain position and deformed by the vertical shear of the tangential wind with time elapsed from its generation (Fig. 3.9e). Therefore, a template sub-image on a striation at a certain time has a decrease in the cross-correlation coefficient due to the deformation with time. In contrast, a subsequent younger striation has not yet been deformed, resulting in a switching of the striation. This feature has been taken into consideration, and an optional additional process is presented that establishes a lower limit on $\Omega_{\min}$ for grids where striations are present. The grids on the striations are identified based on the cloud tracking results described above. These processes are summarized in the following two steps:

Step A1: The grids that satisfy both of the following conditions in the obtained wind field are considered as *striations grid*:

- The velocity contrast, which is the difference between the maximum and minimum velocities within a time width τ for $\|\mathbf{v}_{\text{final}}\|_2$, where $\|\mathbf{v}_{\text{final}}\|_2$ is the L2 norm (wind speed) of $\mathbf{v}_{\text{final}}$ for each grid point, is greater than or equal to v_{stri} .
- The cloud top height is below Z_{stri} .

Step A2: At the striations grid, reject the results obtained at $\Omega_i < \Omega_{\text{stri}}$ and restart the above procedure from Step 5.

The setting for v_{stri} and Ω_{stri} should be tested with several values as they depend on the velocity of striations, the radius of striations, the azimuthal spacing of each striation, and the search range for cloud tracking. In the following section, an example of configuration values for these parameters are shown.

Symbol	Definition
Ω_i	Preset angular velocities to create counter-rotating image sequences ($i = 1, 2, \dots, N$).
$\Omega_{\min}$	The minimum value of Ω_i .
$\Omega_{\max}$	The maximum value of Ω_i .
$\Delta\Omega$	The equally spaced intervals of Ω_i .
$\mathbf{v}_{\text{cand}}$	Candidate AMVs passed the quality control of H23 method for each image sequence.
$Z_{\min}$	Threshold to limit the minimum cloud top height for masking of $\mathbf{v}_{\text{cand}}$.
$Z_{\max}$	Threshold to limit the maximum cloud top height for masking of $\mathbf{v}_{\text{cand}}$.
$\mathbf{v}_{\text{tmp}}$	Tentative AMV estimates obtained from $\mathbf{v}_{\text{cand}}$.
$\mathbf{v}_{\text{med}}$	Median filtered AMVs obtained from $\mathbf{v}_{\text{tmp}}$.
d_2	L2 norm of the difference vector between $\mathbf{v}_{\text{med}}$ and $\mathbf{v}_{\text{cand}}$ for each grid point.
d_{th}	Threshold to limit the maximum d_2 for rejection of $\mathbf{v}_{\text{cand}}$.
d_c	Coefficient to be multiplied by the L2 norm of $\mathbf{v}_{\text{med}}$ for rejection of $\mathbf{v}_{\text{cand}}$.
$\mathbf{v}_{\text{final}}$	Final AMVs after the quality control.
T_w	Temporal window size for median filter.
H_w	Horizontal window size for median filter.
R_w	Radial window size for median filter.
θ_w	Azimuthal window size for median filter.
τ	Temporal window size to compute the velocity contrast of $\mathbf{v}_{\text{final}}$ for detection of striations.
v_{stri}	Threshold to limit the maximum velocity contrast for detection of striations.
Z_{stri}	Threshold to limit the maximum cloud top height for detection of striations.
Ω_{stri}	Threshold to limit the minimum Ω_i for the striations grid.

Table 4.3: A list of symbols for the developed method along with brief definitions.

4.4 Results and evaluations

The proposed method is applied to three Typhoons Haishen (2020), Nanmadol (2022) and Lan (2017) with the parameters listed in Table 4.4. Since cloud tracking is relatively straightforward with 30-sec interval images, a more stringent parameter is set to them.

Symbol	30-sec observations		2.5-min observations		
	Haishen	Nanmadol	Haishen	Nanmadol	Lan
Δt	30 sec		2.5 min		
Δh	500 m		500 m		
T_g	30 sec		2.5 min		
H_g	1 km		1 km		
R_g	1 km		1 km		
θ_g	$2\pi/180$ rad	$2\pi/90$ rad	$2\pi/180$ rad	$2\pi/90$ rad	
W, H	7×7 pixel		7×7 pixel		
N_t	5 steps		1 step		
C_{th}	0.03		0.03		
V_s	80 m/s		10 m/s		
h_s	5 pixels		3 pixels		
S_{th}	0.8		0.7		
V_c	20 m/s		N/A		
V_d	20 m/s		20 m/s		
T_{sp}	2 K		2 K		
θ_d	N/A	N/A	60°		
v_{th}	N/A	N/A	5 m/s		
Ω_{min}	0.0×10^{-3} rad/s		0.0×10^{-3} rad/s		
Ω_{max}	3.0×10^{-3} rad/s	6.0×10^{-3} rad/s	3.0×10^{-3} rad/s	6.0×10^{-3} rad/s	2.5×10^{-3} rad/s
$\Delta\Omega$	0.5×10^{-3} rad/s	1.0×10^{-3} rad/s	0.5×10^{-3} rad/s	1.0×10^{-3} rad/s	
Z_{min}	0 km		0 km		
Z_{max}	6 km		6 km		
d_{th}	20 m/s		20 m/s		
d_c	0.5		0.5		
T_w	10 min		20 min		
H_w	6 km		6 km		
R_w	6 km		6 km		
θ_w	15°		15°		
τ	N/A	N/A	1 hr		
v_{stri}	N/A	N/A	20 m/s		
Z_{stri}	N/A	N/A	6 km		
Ω_{stri}	N/A	N/A	1.5×10^{-3} rad/s	3.0×10^{-3} rad/s	

Table 4.4: A list of setting parameters for Typhoons Haishen, Nanmadol, and Lan with 30-sec or 2.5-min interval observations. Text “N/A” indicates an unused parameter. Only values that differ from the column 2 are shown in column 3, and only values that differ from the column 4 are shown in columns 5–6.

4.4.1 AMVs for Typhoon Haishen (2020)

In this section, the obtained AMVs in Typhoon Haishen (2020) and evaluation of them are provided. The track and intensity of Typhoon Haishen obtained from best-track data are shown in Figure 4.2. The environmental vertical wind shear around Typhoon Haishen and the TC translation are shown in Figure 4.3.

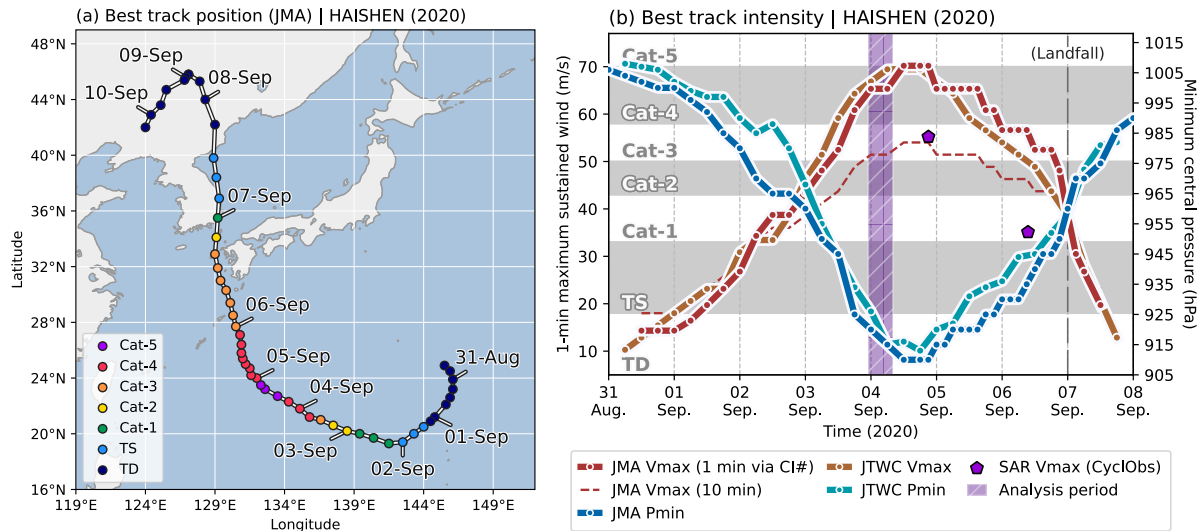


Figure 4.2: (a) The track and (b) the estimated intensity of Typhoon Haishen (2020). The track in (a) is based on the JMA best track data, and the intensity in (b) is taken from the JMA (JTWC) best track data; blue (cyan) solid curve shows the central pressure, and red (brown) solid curve shows the 1-min maximum sustained wind speed. The 10-min maximum sustained wind speed taken from JMA best track (red broken curve) were converted to 1-min maximum sustained wind (red solid curve) using “CI-number method” proposed by Mei and Xie (2016); the 10-min wind data are first converted back to Dvorak CI intensity number using the Koba table (Koba et al., 1990), which is then used to calculate 1-min maximum sustained wind using the Dvorak table (Dvorak, 1984). The color of dot in (a) indicates the Saffir-Simpson category based on the 1-min maximum sustained wind speed converted from JMA best-track intensity. The broken black line in (b) indicates the landfall time. Purple pentagon in (b) indicates the maximum instantaneous wind speed retrieved from C-band Synthetic Aperture Radar observation (Mouche et al., 2017; 2019). A detailed description of this product is provided in Chapter 5. The purple shading in (b) indicates the analysis period.

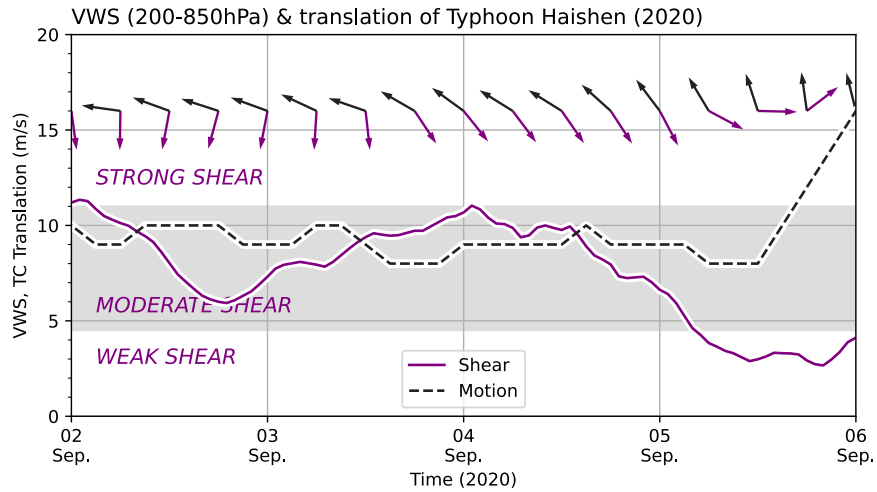


Figure 4.3: Time series of the vector and magnitude of both the environmental vertical wind shear (VWS; m/s) between 200 hPa and 850 hPa (purple) and the TC translation (black; m/s). The range of moderate shear strength defined by Rios-Berrios and Torn (2017) is shaded. The vertical wind shear is defined as the difference between the 200- and 850-hPa mean winds calculated for a circular area of 200–800 km in radius from the maximum 850-hPa relative vorticity position near the center of the real TC using the ERA5 isobaric data. The TC translation speed and direction were obtained from IBTrACS best track data.

Figure 4.4 shows an example of AMVs obtained from 2.5-min and 30-sec interval image sequences using the proposed method. The AMVs obtained from 30-sec interval images (Fig. 4.4b) are similar to the AMVs obtained in H23. The AMVs derived from the 2.5-min interval images (Fig. 4.4a) are relatively fewer in number compared to those obtained from the 30-sec interval images. Nonetheless, they still offer a wide range of valid AMVs. Figure 4.5 shows the azimuthal-mean and 10-min running-mean tangential velocity, angular velocity, and radial velocity. Within a radius of 25 km, the tangential and angular velocities obtained from both intervals are relatively similar. Outside the radius, the velocities obtained from 2.5-min interval sequence are generally underestimated compared to those obtained from the 30-sec interval. This underestimation is believed to be due to errors in deriving AMVs for striations, although a special treatment for this issue (section 4.3.3) is applied. The radial velocity obtained from 2.5-min interval are generally overestimated, but the differences are typically only a few meters per second. The angular velocity obtained from both 2.5-min and 30-sec intervals are characterized by the oscillating signals in time, which is believed to be the signal of an algebraically growing wavenumber-1 disturbance as reported in H23. If this wavenumber-1 feature is centered to the TC center, the signal is not apparent in the azimuthally averaged field. However, according to H23, time mean low-level circulation center was shifted rearward of translation in

Typhoon Haishen. Therefore, the signal was not cancelled out by azimuthal averaging. If the TC center are modified to fit the low-level wind minima, the signal is cancelled out by azimuthal averaging as shown in Figure 2.10. This signal is evident in terms of angular velocity, but it is also present in the radial velocity, as well as the tangent velocity. The overall speed up of the low-level rotation in the eye, which can be explained by the angular momentum transport by the wavenumber-1 disturbance, are confirmed by the AMVs obtained from both interval image sequences. The wavenumber-1 features in the eye of Typhoon Haishen is investigated more in section 4.5.1.

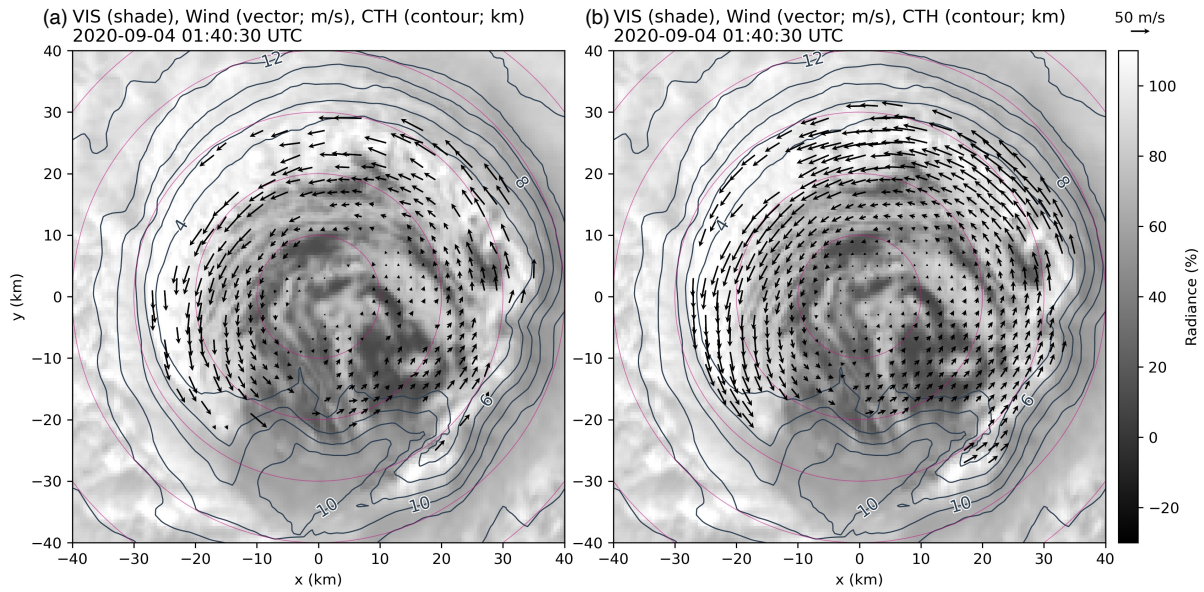


Figure 4.4: Example of AMVs in Typhoon Haishen (2020) obtained from the (a) 2.5-min and (b) 30-sec interval image sequences using the Cartesian grid (vectors) overlaid on the reflectivity (gray shading) at the central time of tracking at 0140:30 UTC 4 September 2020. The AMVs were derived at $H_g = 1$ km intervals, but they are plotted at 2 km intervals for visualization. The length of the arrow on the upper-right corner corresponds to 50 m/s. The contours represent the cloud-top height (km) obtained from 10.4- μm IR brightness temperature and the ERA5 reanalysis. The purple circles are drawn at intervals of 10 km radius.

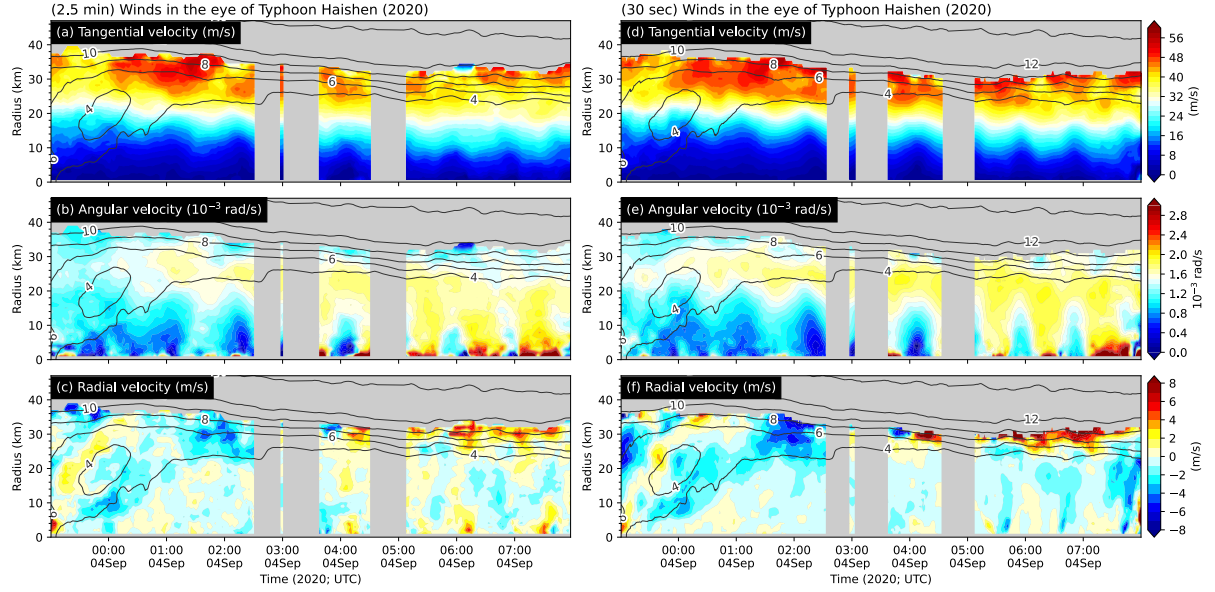


Figure 4.5: Azimuthal-mean and 10-min running-mean (a,d) tangential velocity, (b,e) angular velocity and (c,f) radial velocity obtained from (left) 2.5-min and (right) 30-sec interval image sequences. The contours represent the azimuthal-mean cloud-top height (km).

Assuming that cloud tracking in 30-sec interval images is accurate in AMV derivation, AMVs obtained from 2.5-min interval images are evaluated by comparing them to AMVs obtained from 30-sec interval images. Figure 4.6 shows the normalized histogram of absolute wind speed errors for each grid point, 10-min running-mean winds, azimuthal-mean winds, and azimuthal-mean and 10-min running-mean winds in Typhoon Haishen. In the evaluation for each grid point (Fig. 4.6a), 60% of the AMVs are found to have absolute wind speed errors within 2 m/s, while over 80% of the AMVs have errors within 5 m/s, and over 90% of the AMVs have errors within 8 m/s. About 5% of the AMVs have errors of 10 m/s or more, which is believed to be due to estimation errors in 2.5-min interval images caused by striations or results near the inner edge of the eyewall cloud where the cloud top height changes significantly within the template sub-image. Although there are some erroneous AMVs, the overall error is reduced by spatial and temporal averaging processing. In the evaluation with the 10-min running-mean winds (Fig. 4.6b), the errors were slightly improved. With the azimuthal-mean winds (Fig. 4.6c), the errors were further improved; 80% of the winds have errors within 2 m/s, and 95% have errors within 4 m/s. Moreover, with the azimuthal-mean and 10-min running-mean winds (Fig. 4.6d), the errors were further slightly improved. Table 4.5 summarizes the metrics for evaluating tangential and radial wind components from these perspectives. The bias of the error is almost zero regardless of whether or not averaging processing is applied. In addition, azimuthal averaging

reduces the root-mean-square errors (RMSE) and mean-absolute errors (MAE) for both tangential and radial velocities more than time averaging.

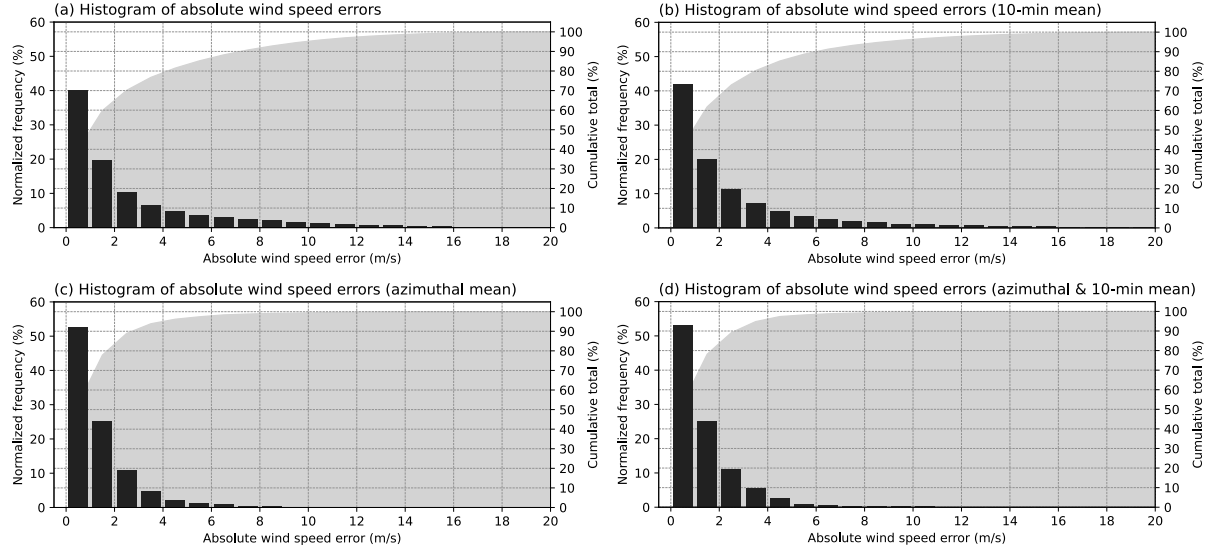


Figure 4.6: Normalized histogram of absolute wind speed errors for (a) each grid point, (b) 10-min running-mean winds, (c) azimuthal-mean winds, and (d) azimuthal-mean and 10-min running-mean winds in Typhoon Haishen (2020). The bar indicates the normalized frequency (%) for a corresponding error at intervals of 1 m/s. The gray shading indicates the cumulative total percentage.

	Tangential velocity				Radial velocity			
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
cc	0.954	0.966	0.989	0.993	0.891	0.919	0.863	0.849
Bias (m/s)	0.1	-0.1	-0.2	-0.4	0.2	0.2	0.2	0.1
RMSE (m/s)	4.6	4.3	2.3	2.1	3.4	2.8	1.4	1.0
MAE (m/s)	2.9	2.6	1.4	1.3	2.2	1.8	0.8	0.6

Table 4.5: Error evaluations of the tangential and radial velocity obtained from 2.5-min interval images by comparing them to those from 30-sec interval images for (a) each grid point, (b) 10-min running-mean winds, (c) azimuthal-mean winds, and (d) azimuthal-mean and 10-min running-mean winds in Typhoon Haishen (2020). Row 1 (“cc”) indicates the correlation coefficient. Rows between 2–4 indicate the bias (m/s), root-mean-square errors (m/s), and mean-absolute errors (m/s), respectively. A positive bias indicates an overestimate (i.e., 2.5-min interval AMVs > 30-sec interval AMVs), and vice versa.

4.4.2 AMVs for Typhoon Nanmadol (2022)

In this section, the obtained AMVs in Typhoon Nanmadol (2022) and evaluation of them are provided like the previous section. The track and intensity of Typhoon Nanmadol obtained from best track data are shown in Figure 4.7. The environmental vertical wind shear around Typhoon Nanmadol and the TC translation are shown in Figure 4.8. According to the JTWC best-track intensity estimation, Typhoon Nanmadol had a comparable maximum wind speed as Typhoon Haishen and an eye with about half the radius. The angular velocity within the eye was very high, making it a challenging case for cloud tracking.

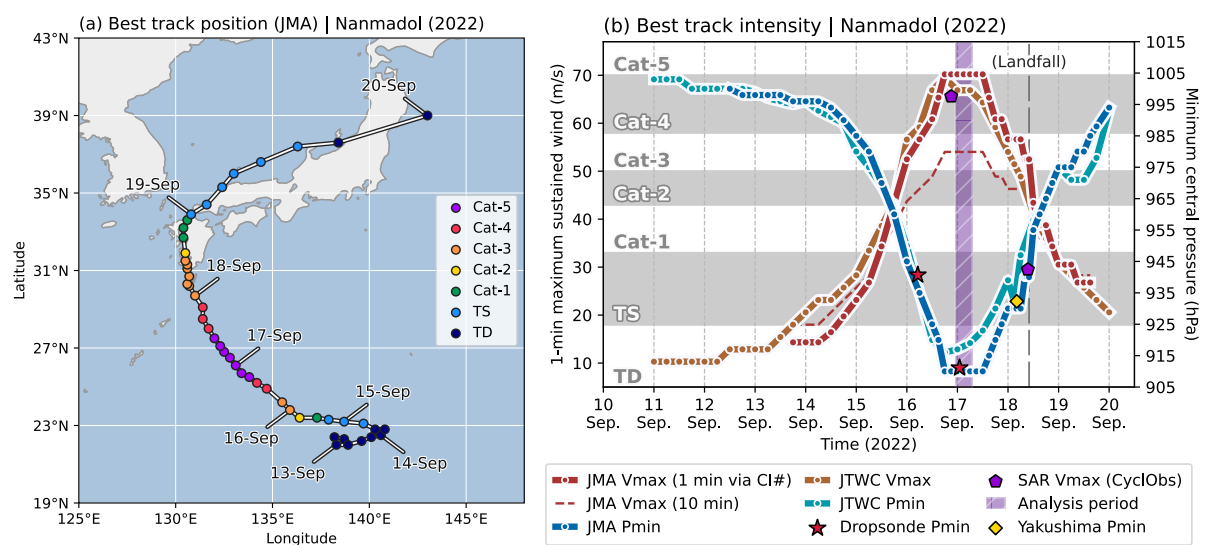


Figure 4.7: As in Fig. 4.2, but for Typhoon Nanmadol (2022). The red star indicate the minimum central pressure obtained from T-PARCII dropsonde observation. The yellow diamond indicates the minimum central pressure obtained from Yakushima weather station (located 36 m above mean sea level) at 0410 UTC 18 September 2022.

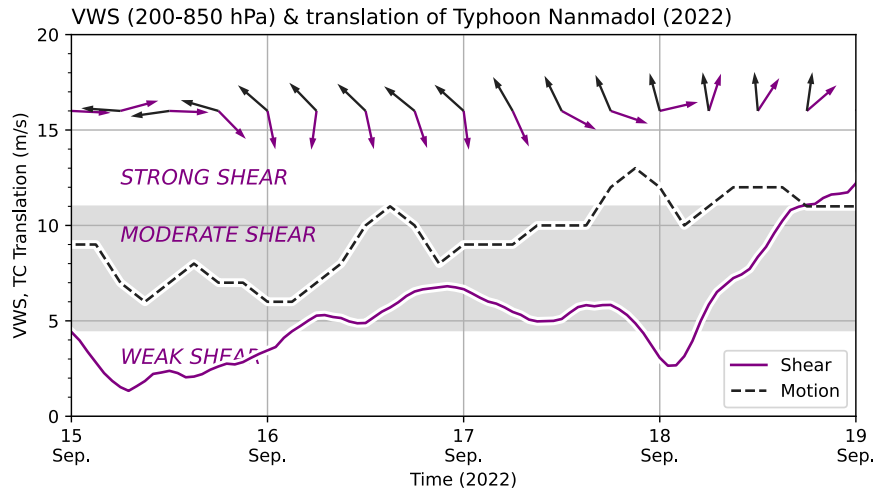


Figure 4.8: As in Fig. 4.3, but for Typhoon Nanmadol (2022).

Figure 4.9 shows an example of AMVs obtained from 2.5-min and 30-sec interval image sequences using the proposed method. As in the results in Typhoon Haishen, the AMVs obtained from the 2.5-min interval images (Fig. 4.9a) are relatively fewer compared to those obtained from the 30-sec interval images. Figure 4.10 shows the azimuthal-mean and 10-min running-mean tangential velocity, angular velocity, and radial velocity. Tangential and angular velocities obtained from the 2.5-min interval are overestimated at some times within a radius of 10 km, while underestimated outside of that radius. As in Haishen, this underestimation is believed to be due to errors in deriving AMVs for striations. The angular velocity (Fig. 4.10b) within a radius of 8 km obtained from 30-sec interval are intensified from ~0330 UTC, while that obtained from 2.5-min interval are intensified from ~0200 UTC. This is believed to be due to the frequent generation and dissipation of clouds within the eye of Nanmadol from around 0200 UTC, which resulted in a positive bias in the tangential winds of the AMVs obtained from 2.5-min interval images. Although the timing is different, the process of gradual intensification of the rotation in the eye, similar to Typhoon Haishen, are confirmed in the AMVs obtained from both image sequences.

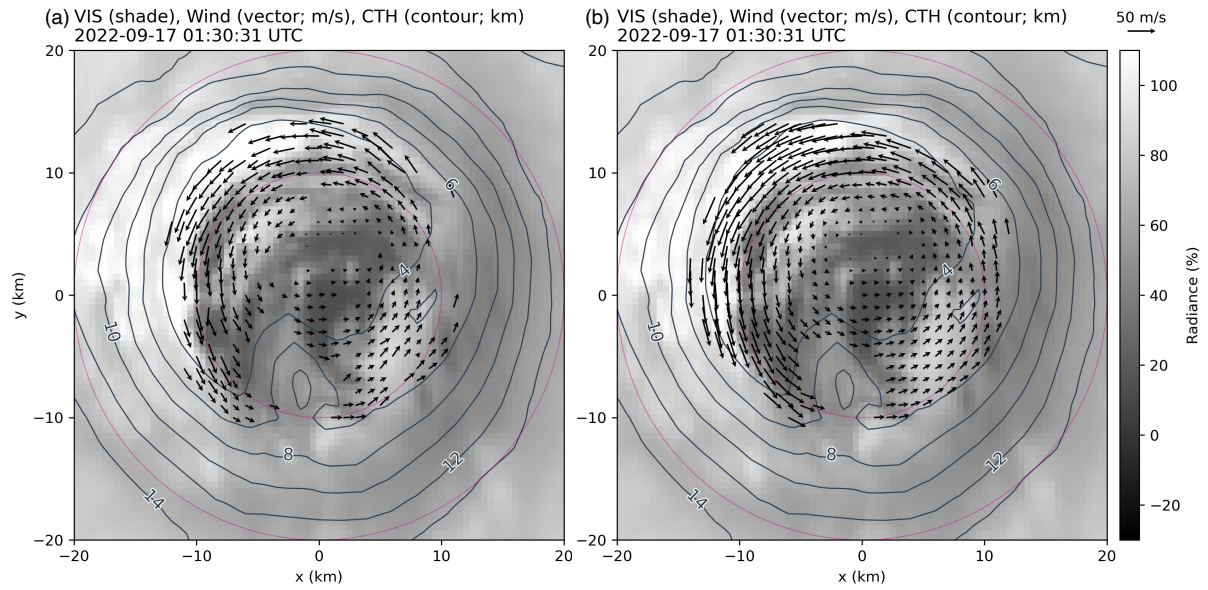


Figure 4.9: As in Fig. 4.4, but for Typhoon Nanmadol (2022) at 0130:31 UTC 17 September 2022. The AMVs are plotted at $H_g = 1$ km intervals.

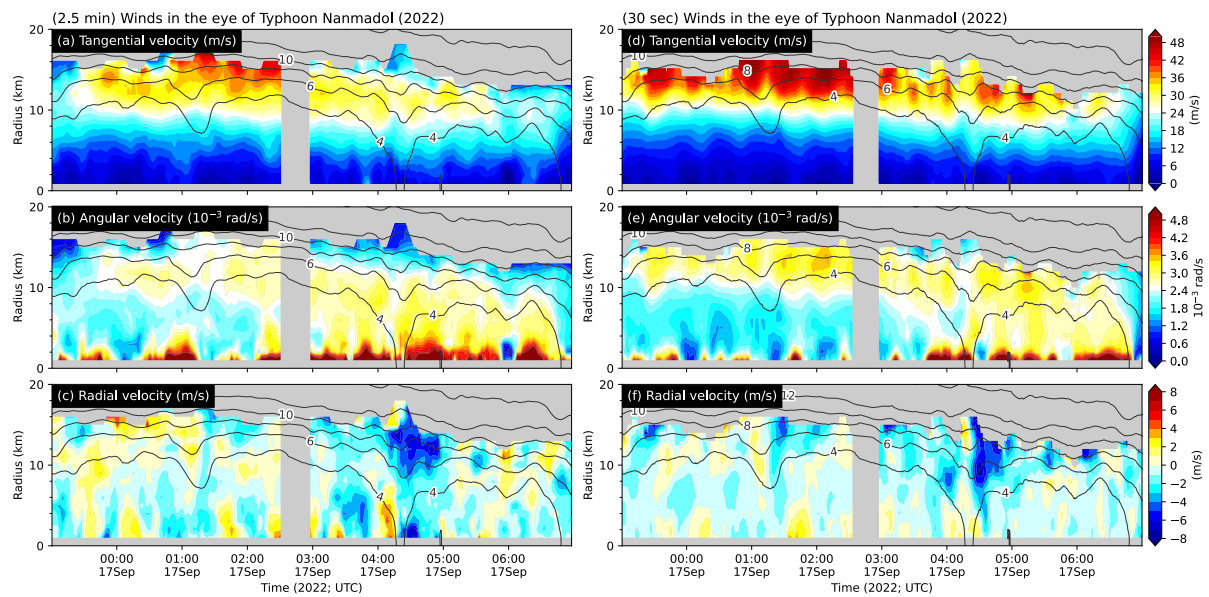


Figure 4.10: As in Fig. 4.5, but for Typhoon Nanmadol (2022).

Assuming that cloud tracking in 30-sec interval images is accurate in AMV derivation, AMVs obtained from 2.5-min interval images are evaluated by comparing them to AMVs obtained from 30-sec interval images. Figure 4.11 shows the normalized histogram of absolute wind speed errors in Typhoon Nanmadol. Although the accuracy is inferior compared to Haishen, the averaging process also greatly reduces the errors. In the evaluation for each grid point (Fig. 4.11a), over 60% of the AMVs are found to have absolute wind speed errors within 3 m/s. With the azimuthal-mean and 10-min running-mean winds (Fig. 4.11d), over 70% of the winds have errors within 3 m/s. Table 4.6 summarizes the metrics for evaluating tangential and radial wind components from these perspectives. The tendency of error improvement is similar to that of Typhoon Haishen, but the tangential velocity errors are almost twice as large. This highlights the difficulty in cloud tracking for cases with small eyes and high angular velocities, such as Typhoon Nanmadol, and suggests the need for shorter imaging intervals.

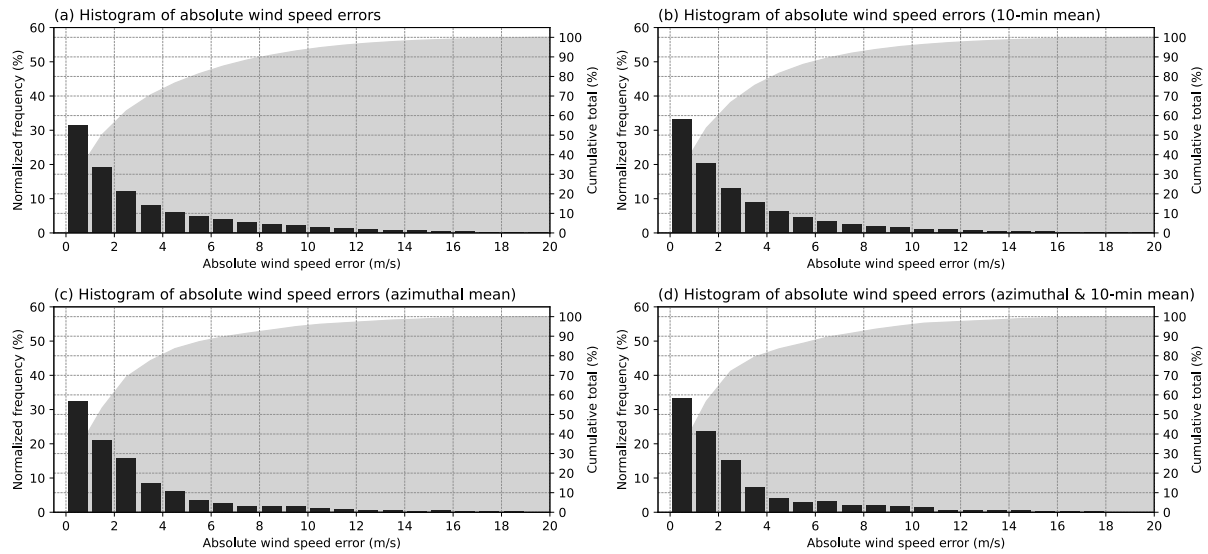


Figure 4.11: As in Fig. 4.6, but for Typhoon Nanmadol (2022).

	Tangential velocity				Radial velocity			
	(a)	(b)	(c)	(d)	(a)	(b)	(c)	(d)
cc	0.869	0.900	0.934	0.946	0.794	0.839	0.815	0.82
Bias (m/s)	0.5	0.4	-0.8	-1.1	0.1	0.1	0.2	0.2
RMSE (m/s)	5.4	4.7	4.7	4.4	3.5	2.8	1.7	1.1
MAE (m/s)	3.6	3.1	3.0	2.8	2.3	1.9	1.1	0.8

Table 4.6: As in Table 4.5, but for Typhoon Nanmadol (2022).

As described in section 4.1, direct observations of Typhoon Nanmadol were conducted using GPS dropsondes released from aircraft as a part of the T-PARCII project. These observations provide the most reliable measurements, which allow us to evaluate the accuracy of the obtained AMVs.

Based on the typical thermodynamic structure of the eyes of intense TCs (e.g., Willoughby 1998), it is expected that AMVs represent the motion of brightness features near the top of the atmospheric boundary layer (Horinouchi et al., 2023). In the observed vertical profile in the eye, the boundary layer is distinguished by a nearly constant lower-level relative humidity that is higher than the humidity above it (e.g., Yamada et al., 2021). Figure 4.12 shows the vertical profiles of relative humidity and wind speed for three dropsondes that were able to be compared with valid AMVs below a cloud-top height of 4 km. All of these profiles show a sharp increase in relative humidity at pressure levels below 700 hPa, followed by a relatively constant value below that, indicating the upper boundary of the boundary layer. For comparison with AMVs, the reference position, time, and wind speed of a falling dropsonde are defined as the 1-min average after the relative humidity exceeded 80% (or 60% if the former is not reached); the altitude range during this 1-min period (gray shading in Fig. 4.12) is approximately 740–780 m. In the boundary layer, the vertical wind shear is relatively weak, so the computation period has little effect on the computation of the reference wind speed. Before the comparison, the AMVs obtained on the Cartesian grid were first smoothed spatially using a $3 \text{ km} \times 3 \text{ km}$ Gaussian kernel with a standard deviation of 0.5 km. The AMV at the nearest grid point to the reference time and position of the dropsonde is used for the comparison. Figure 4.13 shows the comparison of tangential and radial velocities from dropsondes and AMVs obtained from 2.5-min and 30-sec interval image sequences, respectively. The AMVs obtained from 2.5-min interval images had an RMSE of 1.2 m/s for the tangential velocity and 2.5 m/s for the radial velocity, while the AMVs obtained from 30-sec interval images had an RMSE of 1.4 m/s for the tangential velocity and 2.0 m/s for the radial velocity. It is believed that the main factor contributing to the errors in the AMVs obtained from 30-sec interval images, which are less affected by cloud deformation, is cloud generation or dissipation. Although both sets of AMVs had larger errors in the radial velocity compared to the tangential velocity, this relationship is opposite to that observed for Typhoon Lan (2020), as shown in the next section. The above comparisons showed that relatively accurate AMVs can be obtained even with a 2.5-min interval image sequence.

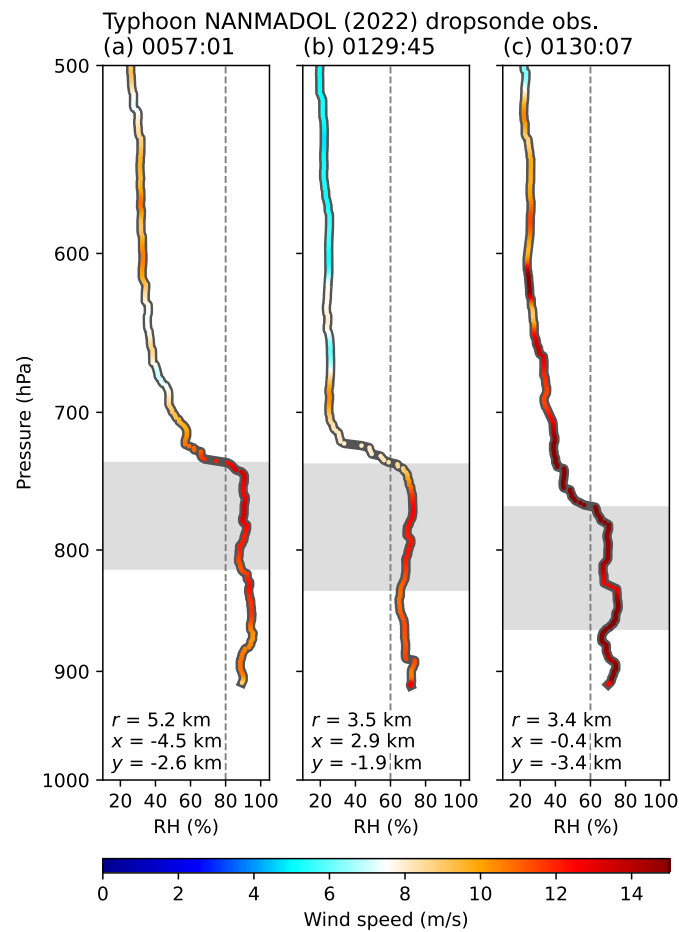


Figure 4.12: Vertical profiles of relative humidity and wind speed observed by GPS dropsondes in the eye of Typhoon Nanmadol (2022) at (a) 0057:01, (b) 0129:45 and (c) 0130:07 UTC 17 September 2022. The vertical axis represents pressure (hPa), while the horizontal axis represents relative humidity (%). The color of the curve represents wind speed (m/s), while the gray areas indicate where only relative humidity is linearly interpolated. The gray shading indicates the pressure range corresponding to 1-min period after the relative humidity exceeds 80% (or 60% if the former is not reached); the threshold relative humidity is indicated by the vertical broken line. The average position radius, x , and y for that 1-min period are written in the lower-left corner in each panel. The time written in the panel title is also the average time (UTC) for that 1-min period.

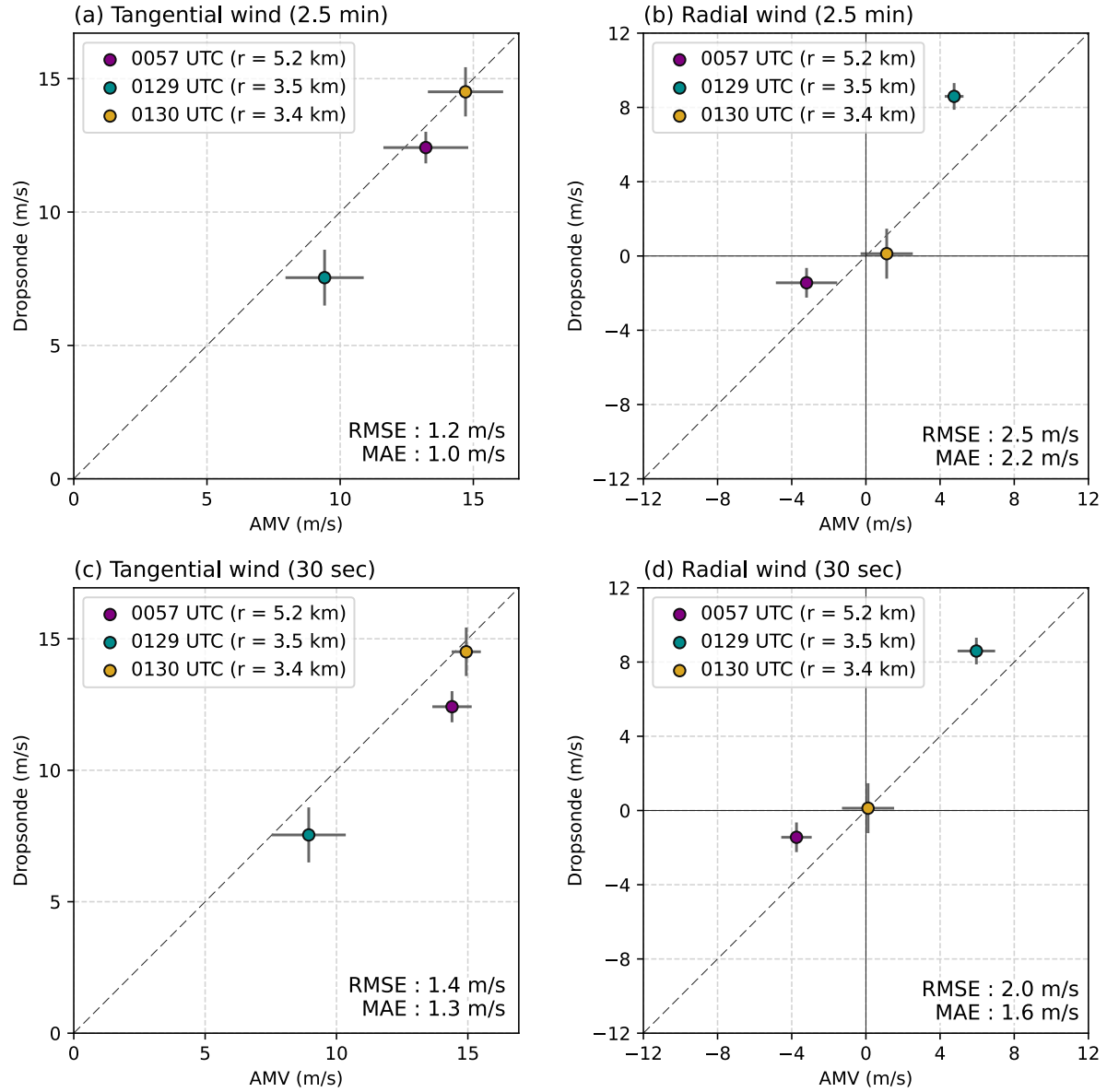


Figure 4.13: Comparison of (left) tangential and (right) radial winds from dropsondes and AMVs in Typhoon Nanmadol (2022) obtained from (upper) 2.5-min and (lower) 30-sec interval image sequences. The wind speed of the dropsonde is the average value within the gray shaded range shown in Fig. 4.12. The error bar for the dropsonde represents the standard deviation of the wind speeds within that range. The reference position and time of the dropsonde observation is also taken as the average value within that range, which is written in Figure 4.12 as a text. The AMVs obtained on the Cartesian grid were first subjected to a spatial running mean using a 3×3 km Gaussian kernel (standard deviation of 0.5 km). The AMV at the nearest grid point to the reference time and position of the dropsonde is used for the comparison. The error bar for the AMV represents the standard deviation of wind speeds of AMVs at eight points on the time-space grid that encloses the reference time and position of a dropsonde. The RMSE and MAE are written in the lower-right corner in each panel.

4.4.3 AMVs for Typhoon Lan (2017)

This section provides the AMVs obtained from only 2.5-min interval images in Typhoon Lan (2017) and evaluates them by comparing them to dropsonde data. The track and intensity of Typhoon Lan obtained from best track data are shown in Figure 4.14. The environmental wind shear around Typhoon Lan and the TC translation are shown in Figure 4.15. According to the JTWC best-track intensity estimation, Typhoon Lan had a comparable maximum wind speed as Typhoon Haishen, but its radius was about 5 km larger than that of Haishen.

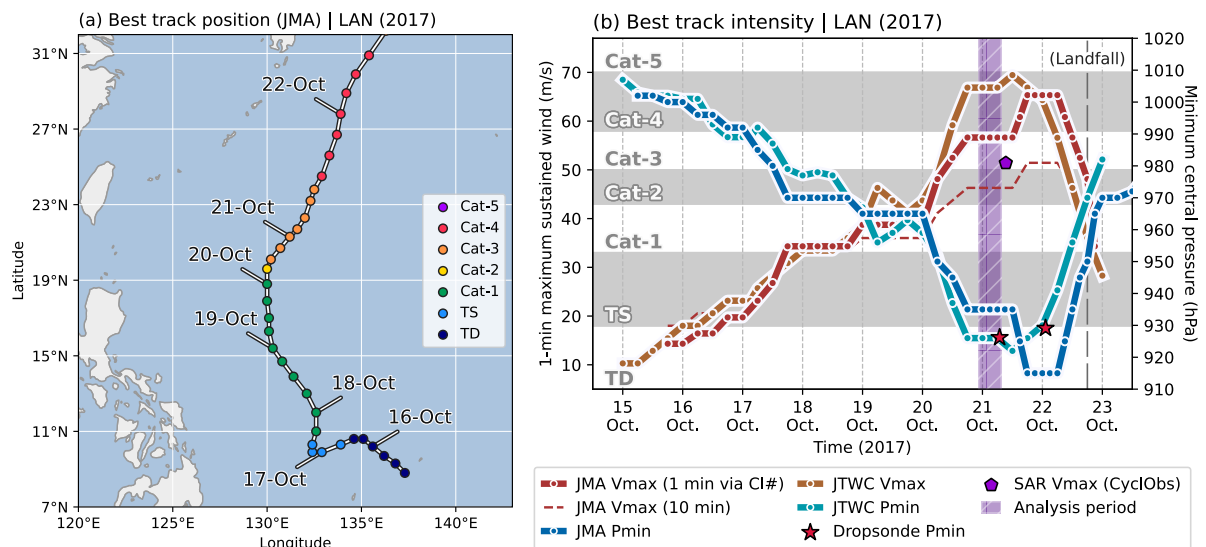


Figure 4.14: As in Fig. 4.2, but for Typhoon Lan (2017). The red star indicate the minimum central pressure obtained from T-PARCII dropsonde observation.

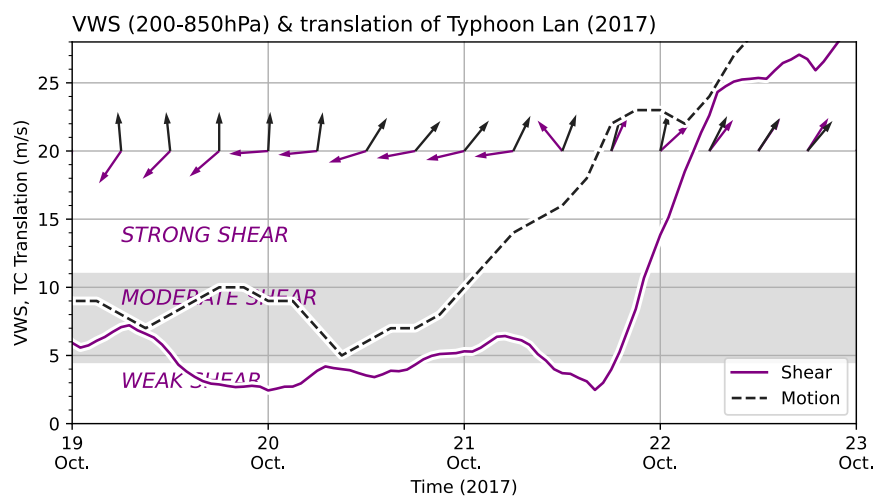


Figure 4.15: As in Fig. 4.3, but for Typhoon Lan (2017).

Figure 4.16 shows an example of AMVs and corresponding angular velocities obtained from 2.5-min interval image sequence at 0032 UTC 21 October 2021. At that time, distinct striations near a radius of 30 km in the northeast quadrant are shown in the visible image. The angular velocities obtained on the striations are about 1.75×10^{-3} rad/s, which is consistent with the subjective analysis presented in Chapter 3. The angular velocity of the striations is greater than that of the inner region and also higher when compared to other azimuths at the same radius.

Figure 4.17 shows the azimuthal-mean and 10-min running-mean tangential velocity, angular velocity, and radial velocity of Typhoon Lan. In the beginning of the analysis period, the angular velocity within a radius of 20 km was about half the magnitude of the angular velocity inside the inner edge of the eyewall. After experiencing an increase in angular velocity from 0000-0100 UTC, it returned to its original value. Around 0300 UTC, the angular velocity rapidly increased again and maintained the angular velocity of about 1.5 times the previous value thereafter. In section 4.5.2, it is shown that the transport of angular momentum by the mesovortices may have played an important role in the rapid increase of angular velocity.

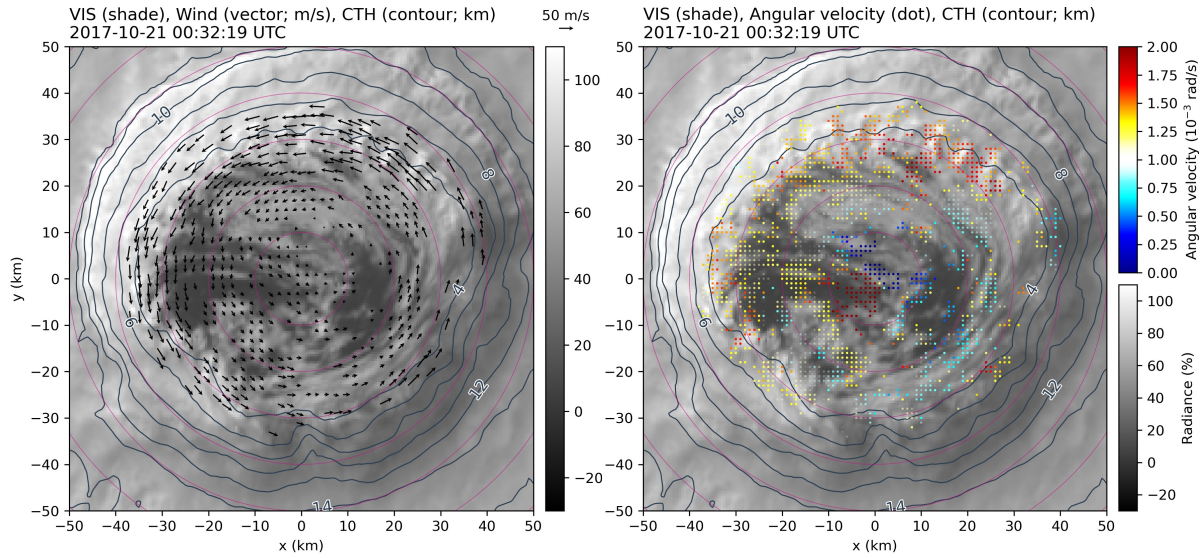


Figure 4.16: (a) As in Fig. 4.4a, but for Typhoon Lan (2017) at 0032:19 UTC 21 October 2017. The AMVs were derived at $H_g = 1$ km intervals, but they are plotted at 2 km intervals for visualization. (b) Angular velocities (colored dots) of AMVs shown in (a) but visualized at 1 km intervals.

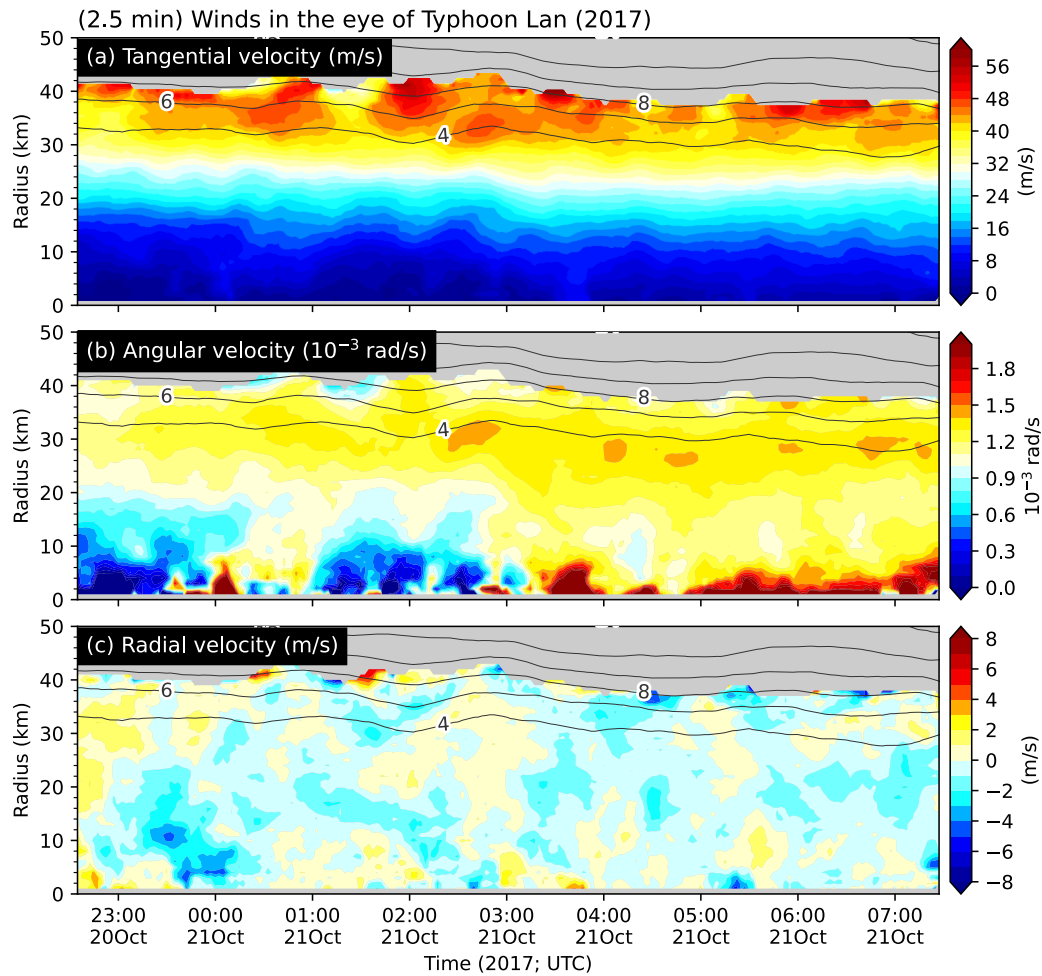


Figure 4.17: As in Fig. 4.5a–c, but for Typhoon Lan (2017).

As in the case of Typhoon Nanmadol, Typhoon Lan was also observed directly using GPS dropsondes as a part of the T-PARCI project. The obtained AMVs are evaluated using the dropsonde observations as in the previous section.

Figure 4.18 shows the vertical profiles of relative humidity and wind speed for three dropsondes that were able to be compared with valid AMVs below a cloud-top height of 4 km. Similarly to Nanmadol, the vertical wind shear in the boundary layer was relatively small. Figure 4.19 shows the comparison of tangential and radial winds from dropsondes and AMVs obtained from 2.5-min interval image sequence. The AMVs had an RMSE of 2.2 m/s for the tangential velocity and 1.5 m/s for the radial velocity. The comparison showed that relatively accurate AMVs can be obtained with a 2.5-min interval image sequence.

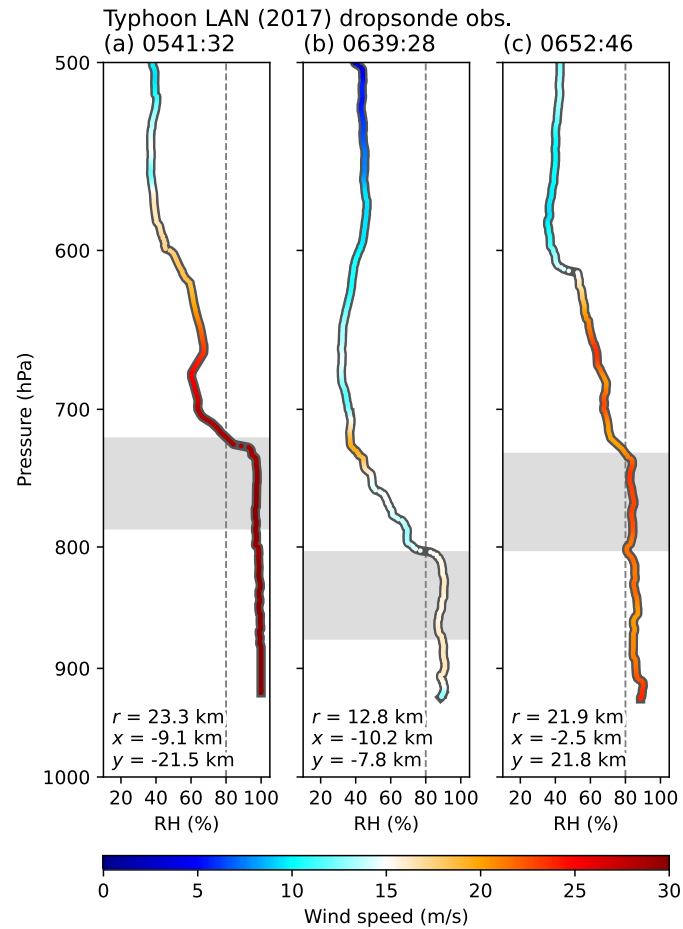


Figure 4.18: As in Fig. 4.12, but for Typhoon Lan (2017) at (a) 0541:32, (b) 0639:28 and (c) 0652:46 UTC 21 October 2017.

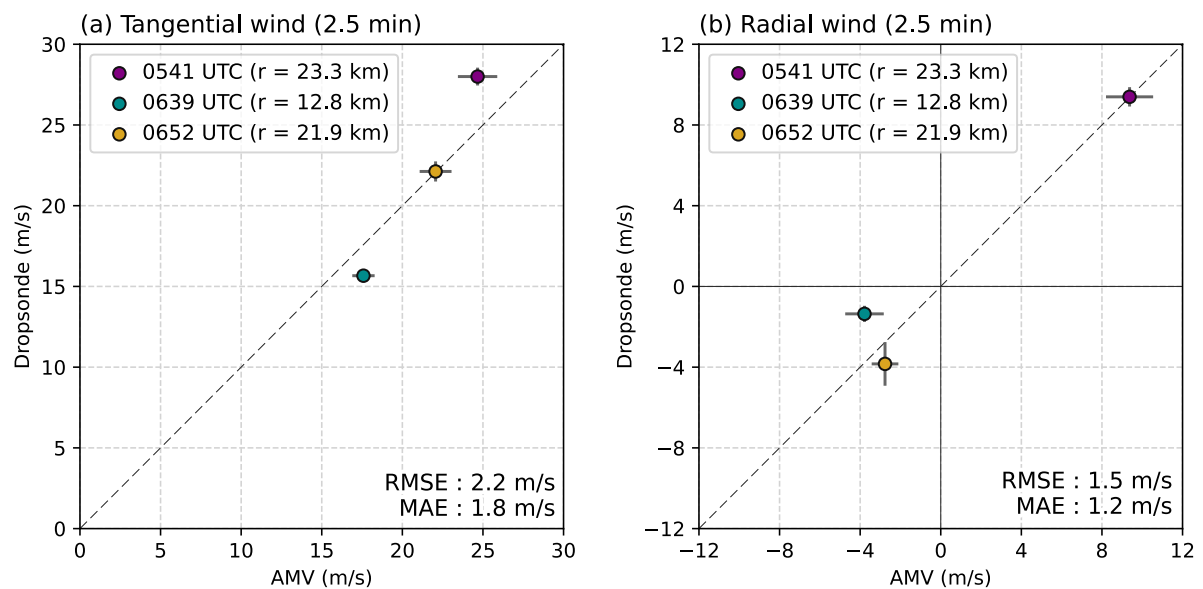


Figure 4.19: As in Fig. 4.13a–b, but for Typhoon Lan (2017). The reference time, position, and wind speed of the dropsondes are based on the gray shading in Fig. 4.18.

4.5 Asymmetric features in the eye of tropical cyclones

In this section, the asymmetric features of AMVs in the eye of the three TCs are documented. The primary emphasis is placed on the algebraically growing wavenumber-1 disturbances and the angular momentum transport by mesovortices associated with the higher wavenumber barotropic instability.

4.5.1 Algebraically growing wavenumber-1 disturbances

As described in Chapter 2 and section 4.1, the algebraically growing wavenumber-1 disturbance in Typhoon Haishen was found by H23 using the AMVs obtained from 30-sec interval image sequence. It has been theoretically demonstrated that this disturbance exists only inside the radius of maximum angular velocity ($RM\Omega$), and its azimuthal phase velocity coincides with the maximum angular velocity (Smith and Rosenbluth, 1990). In H23, the disturbance was investigated using AMVs through the motion of the instantaneous minimum of wind speed or vorticity orbiting around the low-level circulation center. The features of the disturbance were found to be consistent with the results of previous theoretical and numerical studies (Nolan and Montgomery, 2000; Nolan et al., 2001). It should be noted that the positions of the vorticity minimum and the wind speed minimum are opposite to each other with respect to the mean low-level circulation center. This is because the wind-speed minimum is related to a cyclonic anomaly, while the vorticity minimum is an anticyclonic anomaly.

To confirm that the same features of the disturbance are also evident in the AMVs obtained in this study, Figure 4.20 shows the time series of azimuthally averaged angular velocities in each quadrant for both the AMVs obtained from 2.5-min and 30-sec interval images in Typhoon Haishen. From the time series of the angular velocities in each quadrant obtained from 30-sec interval images (Fig. 4.20f-j), it is confirmed that the angular velocities oscillated with a period around 1 hour. The corresponding angular velocity to the oscillation period is around 1.75×10^{-3} rad/s, which is close to the maximum azimuthally-averaged angular velocity inside the inner edge of the eyewall; this agreement is consistent with the theoretical predictions. The phase of the oscillations is in opposite phase between the inside and outside of the ~ 20 km radius, with the outside being faster (slower) when the inside is slower (faster). This oscillation is caused by the wind speed or vorticity minima orbiting around the mean low-level circulation center. When there is a wind speed minimum associated with the wavenumber-1 disturbance in a certain quadrant, the wind speed near the center is small compared to other quadrants. On the other hand, since the disturbance exists only inside the

$RM\Omega$, the streamlines become closer together within $RM\Omega$, causing the wind speed to increase there. This is due to the opposite phase inside and outside of the ~ 20 km radius. The fact that the average angular velocity is stronger in the northwest quadrant and weaker in the southeast quadrant is explained to be due to friction caused by the TC translation (Kepert, 2010; Horinouchi et al., 2023). This friction causes the low-level circulation center to shift rearward (i.e., southeastward) relative to the northwestward TC translation (Figs. 4.2a and 4.3), resulting in the stronger (weaker) angular velocity in the northwest (southeast) quadrant. Although somewhat noisy, similar features are confirmed in the AMVs obtained from the 2.5-min interval images (Fig. 4.20a–e).

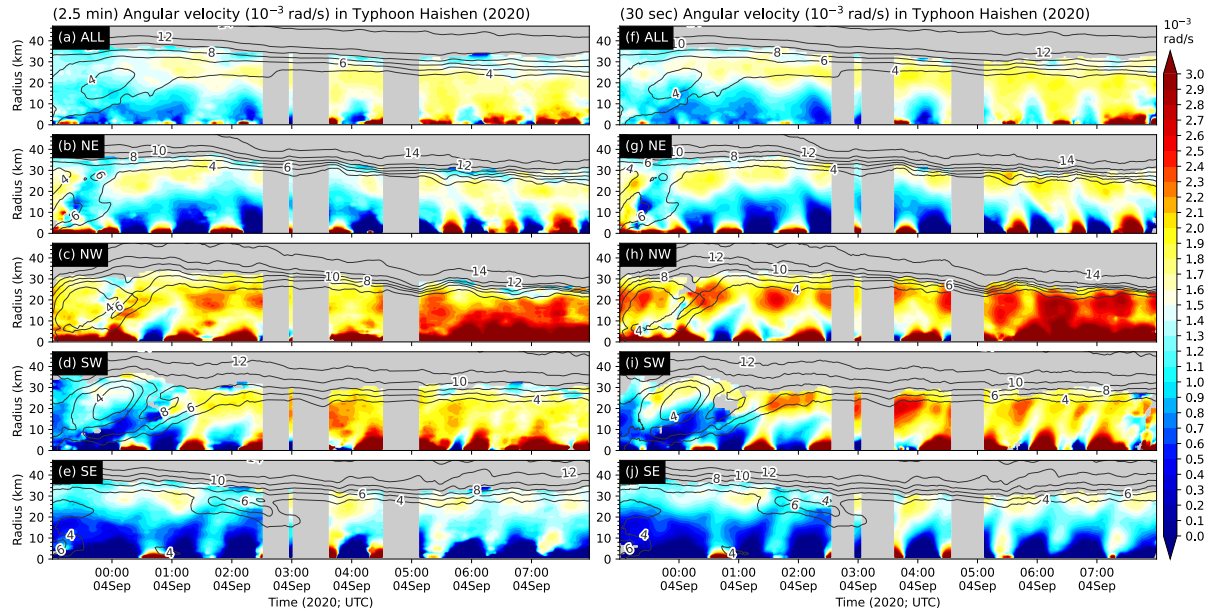


Figure 4.20: Azimuthal-mean and 10-min running-mean angular velocity obtained from (left) 2.5-min and (right) 30-sec interval image sequences computed in (a,f) all azimuths, (b,g) northeast quadrant, (c,h) northwest quadrant, (d,i) southwest quadrant, and (e,j) southeast quadrant, respectively. The contours represent the cloud-top height (km) with corresponding azimuthal averaging.

The wavenumber-1 disturbance is also confirmed in the eye of Typhoon Nanmadol (Fig. 4.21). In the eye of Typhoon Nanmadol, the angular velocities in each quadrant oscillated with a period around 30 min; the corresponding angular velocity is around 3.49×10^{-3} rad/s, which is close to the maximum azimuthally-averaged angular velocity inside the inner edge of the eyewall. Typhoon Nanmadol also showed agreement with the theoretical predictions. Over a long time period, the increase in the azimuthal-mean angular velocity in the eye (Fig. 4.21a,f) suggests angular momentum transport due to the wavenumber-1 disturbance. The slower rotation in the southeast quadrant and faster rotation in the northwest quadrant inside the inner edge of the eyewall can be explained by the northwestward TC translation (Figs. 4.7a and 4.8) as in the case of Typhoon Haishen. However, there might be a different reason for the faster rotation in the southwest quadrant. One possible explanation is the frictional effect of the moderate southward environmental vertical wind shear (Fig. 4.8). To draw a conclusion, a statistical investigation with more samples is required. Similar signals were observed in the AMVs obtained from the 2.5-min interval images, as well. As shown in section 4.4.2, it was a challenging case for cloud tracking, and therefore, it is relatively difficult to distinguish the features accurately.

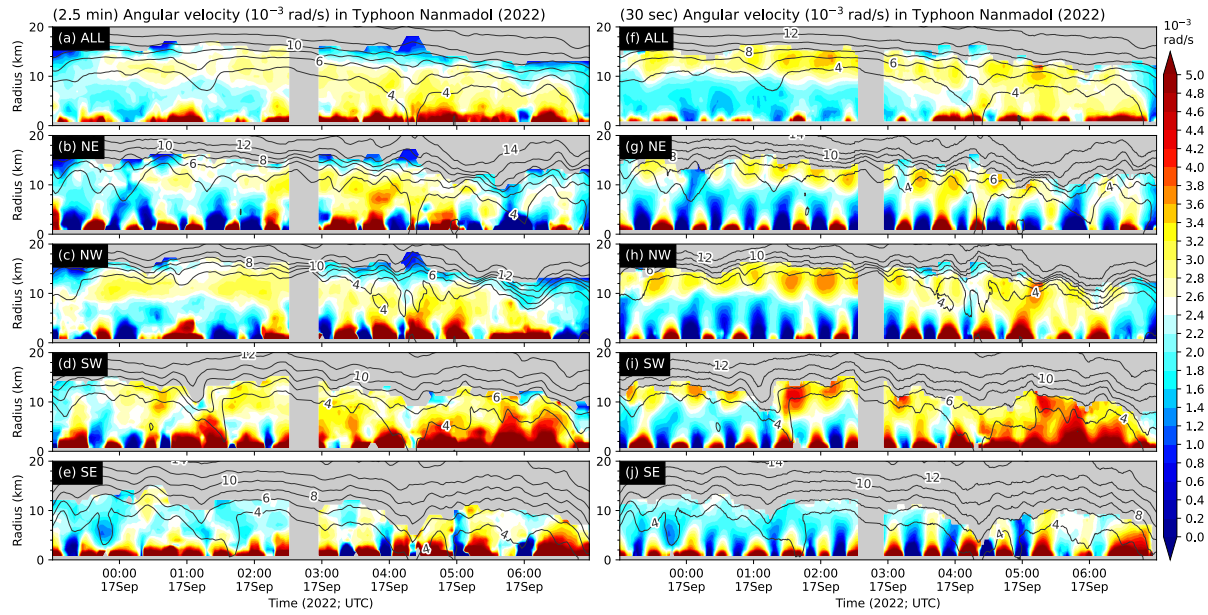


Figure 4.21: As in Fig. 4.20, but for Typhoon Nanmadol (2022).

The wavenumber-1 disturbance are also confirmed in the eye of Typhoon Lan (Fig. 4.22). In the eye of Typhoon Lan, the angular velocities in each quadrant oscillated with a period around 1.5 hour; the corresponding angular velocity is around 1.16×10^{-3} rad/s, which is close to the maximum azimuthally-averaged angular velocity inside the inner edge of the eyewall. Despite the northeastward TC translation (Figs. 4.14a and 4.15), the slower rotation inside the inner edge of the eyewall appeared in the southeast quadrant, while the faster rotation appeared in the northern quadrants. Although the northeastward TC translation, the fact that its circulation center shifted towards the southeast suggests that factors other than its translation, such as moderate westward environmental vertical wind shear (Fig. 4.15), may have some role to the shift. The increase in the azimuthal-mean angular velocity in the eye (Fig. 4.22a) was achieved in a relatively short period of time, within 1 hour (0230–0330 UTC), rather than over a long time period as in the cases of Haishen and Nanmadol. The next section explores the role of mesovortices in the rapid speed up in the eye of Typhoon Lan.

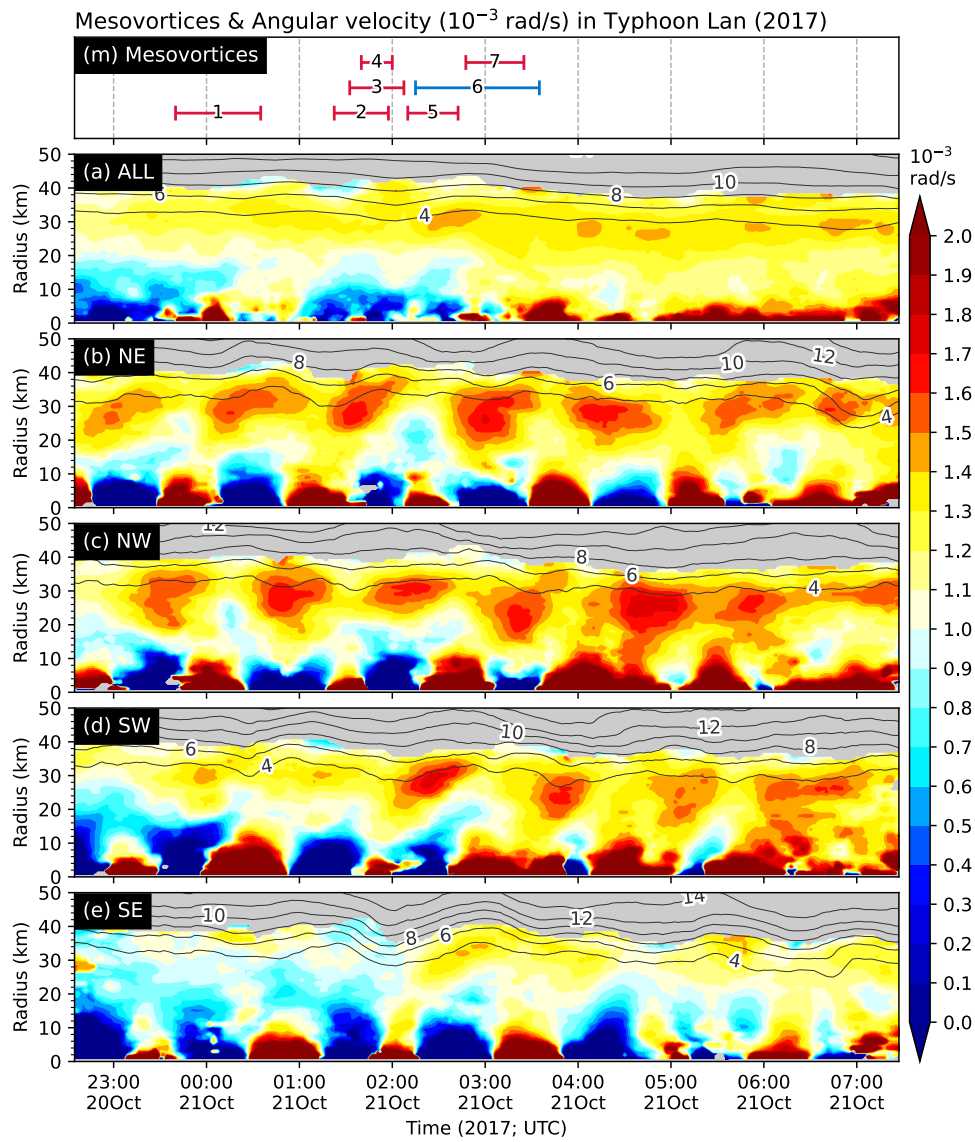


Figure 4.22: (a–e) As in Fig. 4.20a–e, but for Typhoon Lan (2017). (m) The red and blue lines in the top panel show the durations when the seven mesovortices, labeled with their respective IDs, were observed in Chapter 3. The color of the lines indicates the sign of vorticity anomaly, with red (blue) representing positive (negative) anomaly.

4.5.2 Angular momentum transport by mesovortices

In the beginning of the analysis period of Typhoon Lan, the azimuthal-mean angular velocity within a radius of 20 km was approximately half the magnitude of the angular velocity inside the inner edge of the eyewall (Fig. 4.22a). After experiencing a temporary increase in angular velocity from 0000–0100 UTC and returning to its original value, the angular velocity rapidly increased again within 1 hour around 0300 UTC and maintained an angular velocity of nearly 1.5 times its original value. The reason why the rapid changes in angular velocity were not detected by the method in Chapter 3 is due to the characteristic of the method, which computes the representative tangential wind speed over a relatively long period of time.

As described in Chapter 2, Kossin and Eastin (2001) reported the short-term (within 1 hour) increases in angular velocity within the eyes of a number of TCs, using aircraft flight-level data (Figs. 2.5 and 2.6). They referred to the regime before the increase in angular velocity, where a peak in angular velocity is observed near the eyewall, as “regime 1,” and the phase after the increase, where the maximum angular velocity is observed near the TC center, as “regime 2”. The transition from regime 1 to regime 2 was marked by a relaxation of flow across the eye and eyewall toward rigid body rotation, which caused an increase in local tangential flow and angular momentum in the eye. In an unforced idealized barotropic simulation, due to the barotropic instability around the eyewall, the eyewall vorticity ring breaks down and forms mesovortices. They explained the regime transition as the mesovortices transporting angular momentum inward and pushing out the relatively weaker vorticity in the eye, resulting in a regime transition when the vorticity near the TC center is replaced.

When comparing the duration of the visually confirmed mesovortices in the counter-rotating animation in Chapter 3 (Figs. 3.9a–d and 4.22m), it is suggested that mesovortex-1 was involved before the increase in angular velocity around 0000–0100 UTC, and mesovortices 2–7 were involved in the increase in angular velocity around 0230–0330 UTC. The vorticities of the mesovortices which visualized in the counter-rotating animation is the vorticity anomaly from the vorticity corresponding to the angular velocity used in counter-rotation.

From Stokes’ theorem, an increase in azimuthal-mean tangential velocity (or angular velocity) at a certain radius corresponds to an increase in average vorticity in the region inside that radius. Therefore, examining the time evolution of the vorticity field in the eye is one useful way to speculate the cause of the rapid increase in angular velocity. In situations where the eyes of TCs are filled with positive vorticity,

visualizing the vorticity anomaly field from a reference vorticity allows us to conduct a clearer analysis.

The focus is on the distribution of vorticity anomalies with a relatively larger horizontal scale using the AMVs derived at 1-km intervals. The image sequence are rotated clockwise at a constant angular velocity of 1.0×10^{-3} rad/s. Similarly, the same rotational component was subtracted from the AMVs. Subsequently, the resulting AMVs were smoothed using a Gaussian kernel of $10 \text{ km} \times 10 \text{ km}$ (with the standard deviation of 1.7 km) and their vorticities were computed as the anomalies from the corresponding background vorticity of $2.0 \times 10^{-3} \text{ s}^{-1}$. Figure 4.23 shows the time evolution of the vorticity anomaly in the eye of Typhoon Lan, displayed every 1 hour between 2302:19–0702:19 UTC 20–21 October 2017. Within a radius of 20 km, during the first half of the analysis period (Fig. 4.23a–e), there was a concentration of negative vorticity anomalies that occupied about half of the circular area. In contrast, in the latter half (Fig. 4.23e–i), the area occupied by these negative anomalies decreased, and positive vorticity anomalies became dominant. This corresponds to the fact that the azimuth-averaged angular velocities (or tangential velocities) around the radius of 20 km (Fig. 4.22a) were faster in the latter half of the analysis period than in the first half.

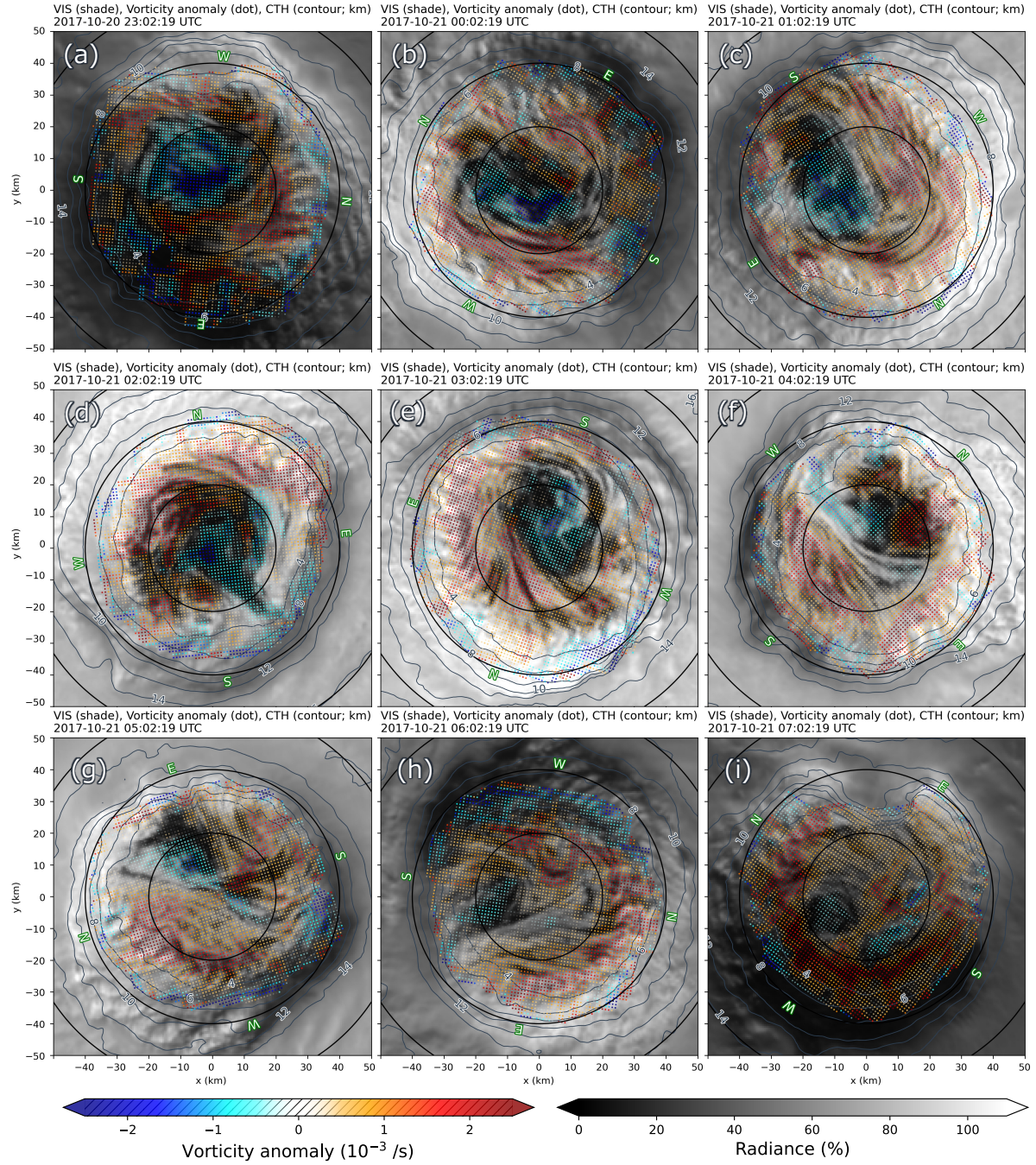


Figure 4.23: Vorticity anomaly (color dots) overlaid on the reflectivity (gray shading) in Typhoon Lan (2017) with the constant clockwise rotation at the angular velocity of $1.0 \times 10^{-3} \text{ rad/s}$ shown every 1 hour during 8 hours from 2302:19–0702:19 UTC 20–21 October 2017. After subtracting the same rotational component from the AMVs, they were smoothed using a Gaussian kernel ($10 \text{ km} \times 10 \text{ km}$, standard deviation of 1.7 km) and computed the vorticity anomaly from the corresponding background vorticity of $2.0 \times 10^{-3} \text{ s}^{-1}$. The colors of the vorticity are translucent, and they become completely transparent near zero; the hatch on the color bar is drawn to indicate the transparency. The contours represent the cloud-top height (km). The black circles are drawn at intervals of 20 km radius. The green texts indicate the azimuths for north (“N”), east (“E”), west (“W”), and south (“S”), respectively.

Here, the focus is on the distribution of vorticity anomalies during the temporary increase in angular velocity at 0000–0100 UTC (Fig. 4.22a). Figure 4.24 shows the time evolution of the vorticity anomaly displayed every 12.5 min between 2344:45–0124:45 UTC 20–21 October 2017. At 2344 UTC (Fig. 4.24a), negative anomalies dominated within a radius of 20 km. At 2357 UTC (Fig. 4.24b), the mesovortex-1 appears from the east (upper-right quadrant in the panel). The surrounding positive vorticity anomaly gradually moved inward, occupying half of the 20 km radius circle by 0059 UTC (Fig. 4.24c–g). After that, the positive vorticity anomaly moved outward, and the TC center again became dominated by negative vorticity anomaly (Fig. 4.24f–i). Therefore, it is considered that the changes in the vorticity distribution associated with mesovortex-1 were involved in the temporary increase in angular velocity within the 20 km radius during 0000–0100 UTC. After that, as the negative vorticity anomaly returned to the TC center, the angular velocities within the 20 km radius returned to its original value.

Next, the focus is on the vorticity anomaly distribution during the rapid increase in angular velocity, around 0230–0330 UTC. Figure 4.25 shows the time evolution of the vorticity anomaly displayed every 10 min between 0222:19–0342:19 UTC 21 October 2017. At 0222 UTC (Fig. 4.25a), negative anomalies associated with mesovortex-6 were located inside the 20 km radius, while the positive anomalies associated with mesovortex-5 were located southwest side (upper-left quadrant in the panel) around the 20 km radius. After that, the positive anomalies moved inward and the negative vorticity moved outward (Fig. 4.25b–d), and by 0312 UTC (Fig. 4.25e–f), a portion of it had protruded outside the 20 km radius. After 0322 UTC (Fig. 4.25g–i), the negative anomaly weakened slightly and the area decreased in size. By that time, positive anomaly had become dominant within the radius of 20 km. It was revealed that the mesovortices were involved in the increase in angular velocity within the radius of 20 km around 0230–0330 UTC. In addition, the mesovortex-6, which was observed as having negative vorticity anomaly in Chapter 3, is suggested to be a relatively weak vorticity inside the ring-shaped vorticity around the eyewall.

The series of processes demonstrated in this study are consistent with the numerical studies on the angular momentum transport by mesovortices generated through barotropic instability with the initial ring-like vorticity field (e.g., Schubert et al., 1999; Kossin and Eastin, 2001). This study is the first observational study to depict such processes as time evolution in two-dimensional vorticity fields in the eye. It should be noted that the analysis only focused on the increase in angular velocity within the eye and the corresponding distribution of vorticity anomalies. The observation did not include the wind distribution in the eyewall, so it

remains unclear whether a transition from a ring-shaped to a monopole-shaped angular velocity profile occurred or not. In fact, the profiles obtained from GPS dropsondes around 0600 UTC, as shown in Yamada et al. (2021), indicate that both the radial profile of equivalent potential temperature and angular velocity had peaks in the eyewall, and the profile were not monopole-shaped. However, with only 8 dropsonde profiles obtained within a radius of 60 km, it is insufficient to diagnose the horizontal distribution of the inner core of Typhoon Lan, which exhibits significant asymmetric motion. Therefore, the possibility remains that it was actually a monopole-shaped thermodynamic field. Other considerations include the process of alternating transitions between regime 1 and regime 2, which is referred to as the inner-core vacillation cycle, and has been studied in numerical simulations (Nguyen et al., 2008; Hankinson et al., 2014; Reif et al., 2014; Hardy et al., 2021). However, no significant changes in the shape of the angular velocity profile in the eye were observed after the rapid increase in angular velocity in the case of Typhoon Lan.

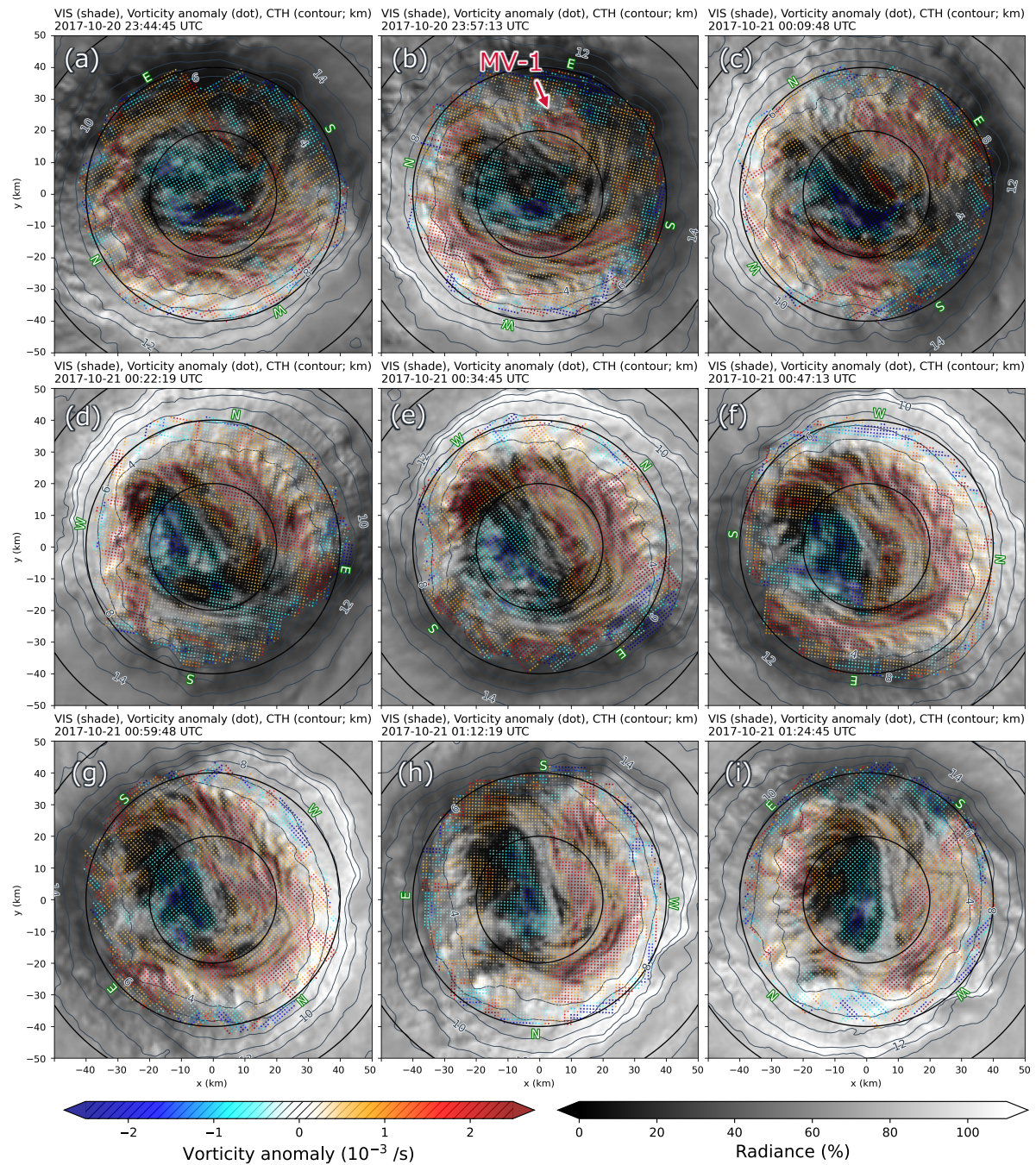


Figure 4.24: As in Fig. 4.23, but shown every 12.5 min during 100 min from 2344:45–0124:45 UTC 20–21 October 2017. The red text and arrow in (b) indicate the mesovortex and its ID, which is identified in Chapter 3.

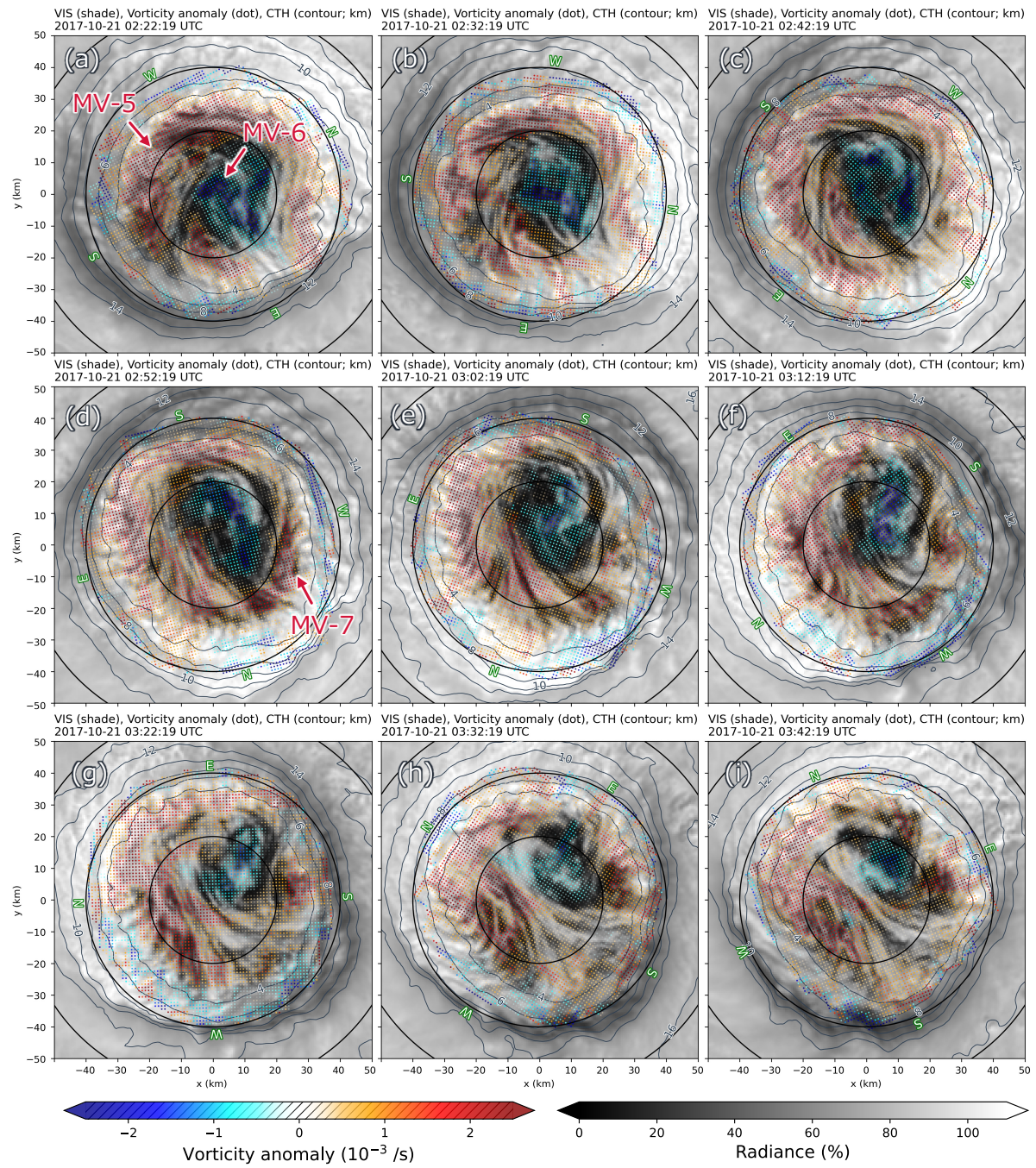


Figure 4.25: As in Fig. 4.23, but shown every 10 min during 80 min from 0222:19–0342:19 UTC () 21 October 2017. The red text and arrow in (a,d) indicate the mesovortex and its ID, which is identified in Chapter 3.

4.6 Discussions

4.6.1 Cloud distribution

The convoluted cloud patterns observed in the eyes of TCs have been reported in earlier studies (Fletcher 1961; Kossin et al., 2002; Montgomery et al., 2002). In Figures 4.23–4.25, the overlay of vorticity anomaly field and visible imagery generally shows a correspondence between the regions of negative vorticity anomaly and the areas with fewer clouds (although not necessarily cloud-free). Could it be related to horizontal mixing processes?

Kossin and Eastin (2001) observed a kinematic and thermodynamic regime transition in the eyes of several TCs, characterized by an increase in equivalent potential temperatures (θ_e) and a shift from a ring-like structure to a monotonic structure with maximum θ_e near the TC center. After the transition, the air in the eye became almost saturated. They presented the results of Hurricane Diana (1984) and Hurricane Olivia (1994) after the hurricanes had reached their maximum intensity. In the eye of Hurricane Diana (1984), despite the fact that the temperature at 850 hPa decreased during the transition, θ_e increased due to the increase in relative humidity. In Hurricane Olivia (1994), the temperature at 600 hPa remained nearly constant during the transition, while an increase in θ_e were achieved due to a corresponding increase in relative humidity. Such increases in θ_e near the eye center due to increases in relative humidity can be interpreted as a result of horizontal mixing from the eyewall where large values of θ_e were found before the transition.

When moist air from the eyewall is entrained into the dry air in the eye, the clouds evaporate in the mixed part with the dry air in the eye. As a result of the evaporation, the area with the cloud (without the cloud) and the air originated from the eyewall (eye) are thought to correspond spatially. If there is a mesovortex present, clouds can show the filamentary structure that formed during the vorticity mixing. In fact, in Chapter 3, mesovortices recognized from the motion of clouds in the eye of Typhoon Lan had swirling patterns even when viewed as still images. In particular, MV-1 in Figure 4.24b and MV-5 in Figure 4.25a are visualized by clouds with relatively clear filaments-like structures. This is consistent with the study by Kossin et al. (2002), who noted that the appearance of clouds in visible imagery of multiple TCs visually resembled the distribution of passive tracer particles that were initially placed in the eyewall region and were transported into the eye along with the mesovortices associated with the barotropic instability in an idealized barotropic

simulation. Therefore, the fact that the area with fewer clouds roughly corresponded to the area with a negative vorticity anomaly, while the area with more clouds moving inward roughly corresponded to the area with a positive vorticity anomaly, may be explained as a result of the entrainment of clouds from the eyewall into the eye of Typhoon Lan.

Hendricks and Schubert (2010) showed the potential vorticity (PV) mixing processes using an idealized simulation with a 3D primitive equation model in an unforced adiabatic framework. They conducted two simulations using the vorticity field as the initial condition with thick and thin PV hollow towers, respectively, and demonstrated the time evolution from a ring-shaped to a monopole PV distribution. In their simulation, both thick and thin hollow towers showed warming from approximately 950 hPa to 700 hPa after PV mixing. The thick tower showed a maximum warming of ~ 3 K at 850 hPa, while the thin tower showed a maximum warming of ~ 6 K at 850 hPa. Their simulation does not include the moist process, so their results suggest that the PV mixing causes the adiabatic warming in the eye. However, Kossin and Eastin (2001) showed cases where eye temperature either decreased or remained nearly constant during the regime transition using the flight-level data. This fact suggests that upon evaporation during the entrainment from eyewall into the eye, there was a diabatic cooling effect that either counteracted or exceeded the adiabatic heating. Since the quantitative magnitude of adiabatic heating and diabatic cooling varies depending on the situation, the temperature changes before and after regime transitions are likely to vary from case to case, as indicated by the observations of Kossin and Eastin (2001).

4.6.2 Middle troposphere entrainment

Yamada et al. (2021) showed the presence of a double warm-core structure (Hawkins and Imbembo 1976; Schwartz et al. 1996; Kieu et al. 2016; Rogers et al. 2017) with a higher perturbation temperature in the middle and upper troposphere in Typhoon Lan (2017) using GPS dropsonde observations conducted by the T-PARCII project around 0500–0700 UTC 21 October 2017. They employed the saturation-point analysis (Betts, 1982) and suggested that air parcels originating in the eye boundary layer move outward and upward in the eyewall through a moist adiabatic process. The eyewall sounding in the upper troposphere indicates an inward flow, suggesting that high- θ_e air is being entrained into the upper warm core from the eyewall. Regarding the formation of the warm anomaly in the lower warm core, they also discussed the possibility of an entrainment from the eyewall into the eye in the middle troposphere (around 4–6 km altitude), but concluded that the warm anomaly was formed through dry adiabatic subsidence at a

depth of 2.5 km, as the horizontal distribution of dropsonde data was insufficient to diagnose the entrainment.

As described in the previous section, Kossin and Eastin (2001) confirmed the occurrence of a thermodynamic regime transition not only at 850 hPa, but also at 600 hPa. If a similar mixing occurred in Typhoon Lan around 0300 UTC, which may not necessarily indicate a regime transition, it is possible that there was an entrainment of air from the eyewall into the eye in the middle troposphere during that time. It could not have been diagnosed by Yamada et al. (2021). If this is the case, it is consistent with the result of potential temperature budget analysis in Typhoon Lan using numerical simulation with a cloud-resolving model conducted by Tsujino et al. (2021b), which showed that the presence of an asymmetric potential temperature inflow from the eyewall into the eye in the middle troposphere during the mature stage.

Here, dropsonde observations are presented to suggest the entrainment in the middle troposphere in Typhoon Lan. Figure 4.26 shows the trajectory and vertical profile of a dropsonde (corresponding to DS-S determined by Yamada et al., 2021) obtained near a radius of 22 km (Fig. 4.26a–d). During its descent, it observed a discontinuous increase of ~ 5 K in θ_e (Fig. 4.26f) at slightly lower than 600 hPa (approximately 4 km altitude), where the relative humidity increased from $\sim 40\%$ to $\sim 50\%$ (Fig. 4.26e). Below 600 hPa, the tangential wind also rapidly intensified (Fig. 4.26g), and an increase of greater than 10 m/s was observed between 600–670 hPa (approximately 4–3 km altitude), with the descending above a cloudy region. The descent into the eye boundary layer corresponds to a relative humidity increase and a slight increase in equivalent potential temperature near 730 hPa (approximately 2 km altitude). Figure 4.27 shows the trajectory and vertical profile of another dropsonde, DS-E in Yamada et al. (2021), which was released around the same radius but on the opposite azimuth to DS-S, approximately one hour before. Although the magnitude of the increase was smaller compared to DS-S, a discontinuous increase of about 3 K in θ_e was observed at 600 hPa (Fig. 4.27f). An outflow of approximately 7–8 m/s was observed around that altitude. An increase of 10 m/s in tangential wind was observed between 600–700 hPa (Fig. 4.27g; approximately 2.5 km), followed by an increase in relative humidity at cloud top (Fig. 4.27e). Unlike DS-S, after θ_e enhancement at 600 hPa, a temporary dry region was observed between 670–700 hPa, where θ_e decreased by about 5 K, before the subsequent θ_e enhancement with entering the eye boundary layer.

The discontinuous increase of θ_e near 600 hPa recorded by these dropsondes may have been caused by the dropsondes vertically crossing the horizontal boundary between pre-existing air and eyewall-originated

air. It suggests that the air from the eyewall was entrained not only into the lower troposphere, but also into the middle troposphere.

Yamada et al. (2021) suggested the possibility that mid-tropospheric entrainment may play a role in the formation of the lower warm core, but did not conclude so because of the small in-flow from dropsonde observations. However, if the asymmetric motions of the mesovortices caused the mid-tropospheric entrainment, it would be difficult to diagnose the presence or absence of the entrainment solely from the presence or absence of inflow at a few observation points. On the contrary, the recording of 7–8 m/s outflow around 600 hPa by DS-E, while DS-S recorded the 2–3 m/s inflow around 600 hPa in the opposite azimuth, suggests an asymmetric field rather than an axisymmetric one.

It should be noted that discontinuous θ_e enhancement in the middle troposphere (around 600 hPa) was not observed in the other two dropsondes released closer to the TC center (at the radii of ~ 13 km and ~ 8 km). Since Typhoon Lan had a large eye with a radius of ~ 40 km, those profiles were obtained far from the eyewall, suggesting that the layers above the boundary layer near the TC center were still dry.

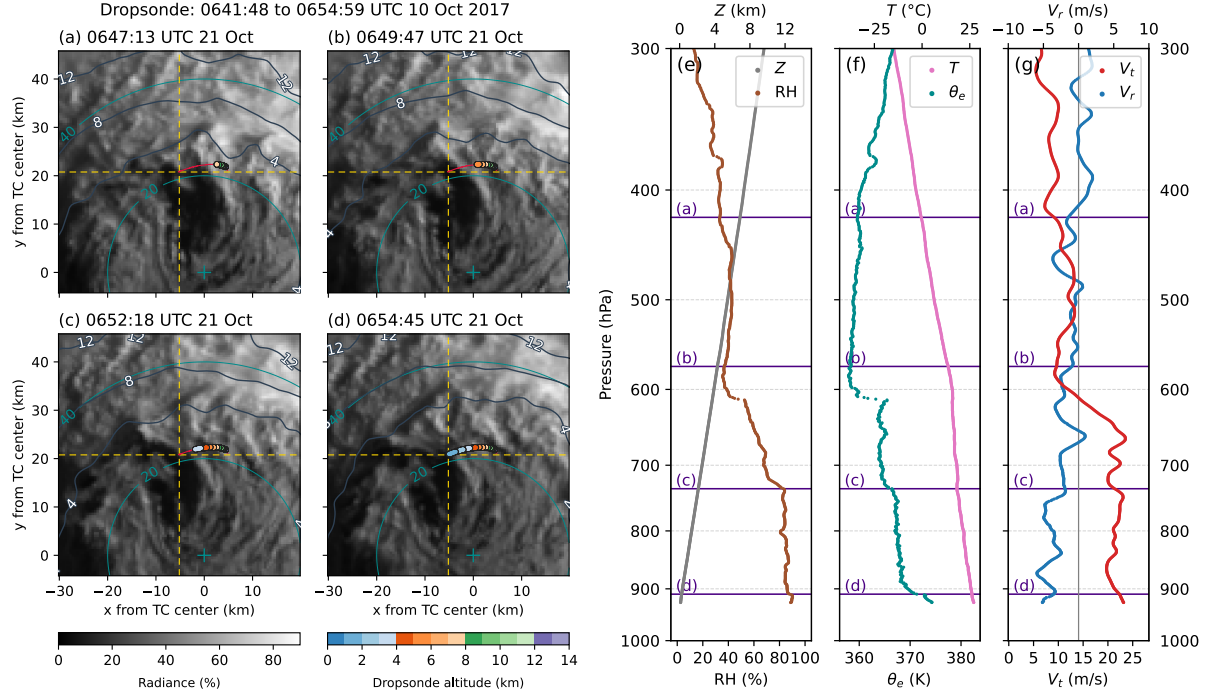


Figure 4.26: (a–d) Dropsonde trajectory (color) relative to the TC center overlaid on the visible images (shading) shown every 2.5 min between 0647:13–0654:45 UTC on 21 October 2017, and observed vertical profiles of (e) relative humidity (brown) and altitude (gray), (f) equivalent potential temperature (green) and temperature (pink), and (g) tangential (red) and radial (blue) velocities. The altitude of descending dropsonde is indicated by color up to the time of visible image acquisition. The navy contours on visible imagery indicate cloud-top heights (km). The green plus sign indicates the TC center, and the green circles indicate the radius from it every 20 km. The red curve represents the complete trajectory of the dropsonde, while the yellow dashed lines indicate the final point of the trajectory. The purple line on the right panels indicates the pressure corresponding to the time of visible image acquisition for each panel, which is indicated by a letter. This dropsonde corresponds to DS-S as determined by Yamada et al. (2021).

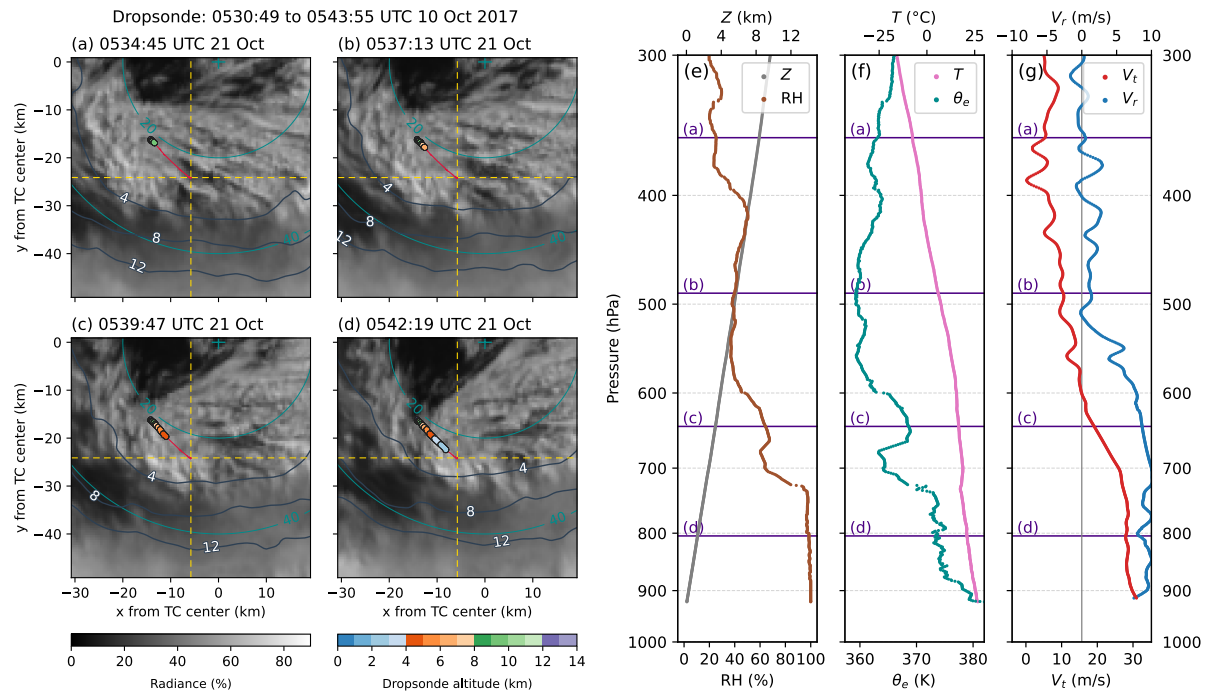


Figure 4.27: As in Fig. 4.26, but for another dropsonde. The visible images are shown every 2.5 min between 0534:45–0542:19 UTC on 21 October 2017. This dropsonde corresponds to DS-E as determined by Yamada et al. (2021).

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Chapter 5

Strong relationship between eye radius and radius of maximum wind of tropical cyclones

5.1 Introduction

The radius of maximum wind (RMW; also see Table 5.1 for this and all other acronyms) of a tropical cyclone (TC) is a significant parameter for a number of applications. For instance, it principally determines the location and areal extent of storm hazards, including extreme wind and rainfall (Lonfat et al. 2007; Lu et al. 2018; Xi et al. 2020) and storm surge (Irish et al. 2008; Irish and Resio 2010; Needham and Keim, 2014). RMW is also an essential scaling factor for wind model parameterization (Holland 1980; Willoughby and Rahn 2004; Wood et al. 2013; Chavas et al. 2015), operational forecasting (Knaff et al. 2007, 2016), and post-storm ocean heat content capacity response (Knaff et al. 2013). RMW estimates are often required at TC forecast centers to generate numerical model input files in order to create best tracks. The maximum wind (VMAX) is one of the key parameters that characterize TCs, as well as RMW. Since a physical relationship has been suggested between VMAX, RMW and outer radius such as the radius of 34-kt ($1 \text{ kt} \approx 0.514 \text{ m/s}$) wind (Chavas et al., 2015; Chavas and Lin, 2016; Chavas and Knaff, 2022), RMW is also important parameter in the TC intensity estimation. Therefore, obtaining highly accurate RMW estimates is required in many situations.

Highly accurate RMW estimates are obtained from wind observations in TCs inner-core region. These observations are mainly obtained by aircraft or microwave radiometers or scatterometers onboard low-earth-orbit satellites. While reliable in-situ observations are possible using aircraft, operational aircraft observations are conducted only in the North Atlantic and eastern Northeast Pacific basins. The sea surface winds retrieved from the microwave radiometers and scatterometers onboard low-earth-orbit satellites are used to obtain VMAX, RMW, and radii associated with maximum radial extent of wind speed thresholds, like 64-, 50-, 34-kt (see Knaff et al., 2021 and the references therein). However, most

of them have a coarse resolution (several tens of kilometers) to study the inner-core structure of TCs, and scatterometers start to saturate at about 50–70 kt. In recent years, some low earth orbit C-band synthetic aperture radar (SAR) satellites have been able to retrieve sea surface winds with a high horizontal resolution of about 1 km, without microwave saturation even under extreme phenomena such as TC by combining single-polarization and cross-polarization (Mouche et al., 2017; 2019; Zhao et al., 2018). Its TC wind products were analyzed and compared with other observations (Combot et al., 2020; Vinour et al., 2021). Although the aircraft observations are highly reliable, they do not provide complete coverage of sea surface wind. On the other hand, SAR winds can cover the entire TC area without spatial gaps. SAR winds are known to be affected by the rainfall attenuation (Mouche et al., 2019; Combot et al., 2020). Combot et al. (2020) showed that rainfall attenuation leads to an underestimation of VMAX but does not have a significant impact on the measurement of RMW. According to a personal communication, the RMW is not affected by attenuation in many cases, but in a few scans the RMW is affected by 1–2 km. Therefore, RMW can be identified with sufficient accuracy using SAR winds even without aircraft observation. However, C-band SAR observations are only available at dusk and dawn and are not operationally available.

Geostationary meteorological satellites (GMSs) observe TCs seamlessly throughout their life cycle without time interruption. To take advantage of the time continuity and wide observation range of GMSs, several methods have been proposed to estimate RMW indirectly using IR imagery. The following are studies that have investigated the relationship between IR image features captured by GMSs and the RMW obtained from in-situ observations. Hsu and Babin (2005) reported from buoy, aircraft, and GMS observations that the IR-measured radius of the coldest cloud-top temperature of the eyewall (R_{CCT}) from the warmest temperature location in the eye were consistent with the RMW at the upper level in Hurricane Lili (2002). Kossin et al. (2007; hereinafter, K07) investigated the relationships between surface RMW estimated from aircraft flight-level tangential wind profiles and IR-measured eye radius (R_{eye}) for “clear-eye” TC cases. They showed that the regression of RMW by R_{eye} can be performed with a mean absolute error (MAE) of 4.7 km (the spatial resolution of the satellite at that time was 4 km at nadir). The RMW is known to be intensity- and latitude-dependent from observations and numerical simulations (Shea and Gray, 1973; Weatherford and Gray, 1988; Kimball and Mulekar, 2004; Mueller et al., 2006; Kossin et al., 2007; Knaff et al., 2015; Ohno et al., 2016). However, K07 showed that R_{eye} is

more dominant factor than intensity or latitude in the RMW regression. Lajoie and Walsh (2008) examined the relationship between IR-measured R_{eye} at surface and R_{CCT} , and aircraft-measured RMW in “well-defined eye” cases, and assumed that they can be approximated as being in the relationship $R_{CCT} - RMW : RMW - R_{eye} = 6.0 : 4.0$. Using this relationship, they proposed a method to estimate RMW from R_{CCT} and R_{eye} , with an MAE of 2.8 km.

Recently, third-generation GMSs have dramatically improved their capabilities from their predecessors (Bessho et al., 2016; Schmit et al., 2017). For example, Himawari-8/9 and GOES-16/17 have twice the spatial resolution of their predecessors, 2 km for infrared (IR) channels and 0.5 km for visible (VIS) channels at nadir. Especially in TCs monitoring, rapid scan observations are made every 2.5 min in the target area with $1000 \text{ km} \times 1000 \text{ km}$ extent for Himawari-8/9 and every 1 min in the meso sector for GOES-16/17/18 with $1000 \text{ km} \times 1000 \text{ km}$ extent. These improvements allow us to reveal the various properties of TCs that were previously unobservable (e.g., Horinouchi et al. 2020). Atmospheric motion vectors (AMVs) derived from GMSs have been available since around 1970 (Fujita 1969; Leese et al. 1971; Hubert and Whitney 1971). These winds have been used specifically to study the winds surrounding TCs (e.g., Molinari and Vollaro, 1989; Velden and Sears, 2014; Oyama et al., 2016; Oyama, 2017; Dai et al., 2019; Fukuda et al., 2020; Ryglicki et al., 2021). In many cases, the RMW is considered to be under the thick eyewall cloud cover, in which case AMVs are not available there. However, as shown in this study, in some cases a portion of the RMW is located near the inner edge of the eyewall cloud. Operational AMVs provide few winds in the TC eye, but Chapter 3 showed that radial profile of tangential winds can be obtained using rapid scan observations when the TC eye is clear. Furthermore, Horinouchi et al. (2022) obtained AMVs widely in a clear TC eye from research-based special observations with Himawari-8 conducted every 30 sec. Chapter 4 showed that the AMVs in the TC eye can be obtained through the TC-specific cloud tracking method even for the 2.5-min interval image sequence. These recent studies indicate that high-frequency satellite imaging is useful to estimate low-level winds near RMWs. Therefore, establishing satellite-based RMW estimation could potentially enable high-frequency availability of intensity estimation for TCs with clear eyes in the future.

In this study, the relationships in TCs between IR satellite estimates of eye radius and the RMW based on SAR winds are reexamined. Furthermore, an IR-based method is proposed to estimate RMW. In order to compare this study with previous studies, it is necessary to separate the eye scenes in IR imagery

into clear-eye and unclear-eye ones. There are many cases where it is difficult to subjectively determine whether a TC's eye is clear or not in homogeneous quality, for example, when thin upper-level clouds exist in the eye, or when a part of the eyewall overhangs inward. Therefore, objective criteria for determining whether a case has a "clear eye", or "well-defined eye" is required. K07 employed a scene classification of the Advanced Dvorak Technique (Velden et al. 1998; Olander and Velden 2007, 2019) for the determination of the clear-eye scene. The Advanced Dvorak Technique, which is an automatic and objective Dvorak technique (Dvorak, 1975, 1984) including the scene classification, has undergone many revisions. In the latest Advanced Dvorak Technique, the scene classification requires a T number introduced by Dvorak, and a Fast Fourier Transform analysis of the center ($0 \leq r \leq 24$ km) and surrounding ($24 \leq r \leq 136$ km) cloud-top regions in IR images, where r is a radius from TC center. Once a scene is classified as an eye type, it is subdivided into "EYE", "PINHOLE" (eye radius less than 5 km), and "LARGE" types (eye radius greater than 38 km) based on its eye radius. According to Olander and Velden (2007), the "EYE" type used to be further subdivided into "clear", "ragged", and "obscured" types, but this subdivision has been eliminated in a revision. Therefore, to reproduce K07's classification would require independent massive computations if possible. However, to the best of the authors' knowledge, there is no published document that specifies how Advanced Dvorak Technique subdivided "EYE" type into "clear", "ragged", and "obscured" before the upgrade. Hence, since an alternative approach is required, a simpler objective clear-eye determination is also proposed.

Section 5.2 provides a review of K07's method for estimating RMW with eye radius. In section 5.3, the used data and the methods for some measurements and clear-eye determination are described. In section 5.4, RMW regressions and related errors are examined. In section 5.5, the results of this study are discussed, including an example application of the proposed RMW estimation to a historical case, the examination of eyewall slope and RMW-related cloud features, and possible application of RMW estimates.

Acronym/Symbol	Definition
AMSU	Advanced Microwave Sounding Unit
AMV	Atmospheric Motion Vector
ANAL	Analysis (in ATCF)
ARCHER	Automated Rotational Center Hurricane Eye Retrieval
ATCF	Automated Tropical Cyclone Forecasting System
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIRA	Cooperative Institute for Research in the Atmosphere
CTH	Cloud Top Height
GMS	Geostationary Meteorological Satellite
IBTrACS	International Best Track Archive for Climate Stewardship
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
IR	Infrared (digital imagery)
K07	Kossin et al. (2007)
kt	nautical miles per hour, 1 kt = 0.514 m/s
MAE	Mean Absolute Error
NOAA	National Oceanic and Atmospheric Administration
r	Radius (distance) from a TC center
r_{L45}, r_{U45}	Critical radii corresponding to the radii of the inner edge of the eyewall at lower and upper levels defined in Sanabia et al. (2014).
R_{eye}, R_{eye}^{K07}	Radius of a TC eye
$R_{max}(-\nabla\sigma)$	Radius at which the radial gradient of $\sigma(r)$ is negatively maximized
RMSE	Root Mean Square Error
RMW, RMW	Radius of Maximum Wind; in this study, it is obtained from SAR winds
RMW_{err}	Difference between RMW retrieved from SAR winds and the RMW_{est}
$RMW_{est}, RMW_{est}^{K07}$	Estimated RMW using R_{eye} (R_{eye}^{K07}) for the TC cases used in this study (in K07)
RMW_{est}^*	Estimated RMW using R_{eye}^{K07} for the TC cases used in this study
R_{CCT}	Radius of Coldest Cloud Top
R_w	Approximate radius of the inner edge of eyewall at upper level
SAR	Synthetic Aperture Radar
$\sigma(r)$	Standard deviation of brightness temperatures in annulus from r to $r + 30$ km
$T_b, \overline{T_b}(r)$	Brightness temperature (barred one is azimuthally averaged)
TC	Tropical Cyclone
T_{th}, T_{th}^{K07}	Threshold temperature to determine TC's eye area
T_{max}, T_{max}^{K07}	Maximum brightness temperature in a TC's eye
T_{top}, T_{top}^{K07}	Representative cloud top brightness temperature above the eyewall
VIS	Visible (digital imagery)
VMAX, $VMAX$	Maximum wind or tropical cyclone's intensity; in this study, it is obtained from SAR winds.
$VMAX_{err}$	Difference between the maximum sea surface wind ($VMAX$) retrieved from SAR and the $VMAX_{est}$
$VMAX_{est}$	Sea surface wind retrieved from C-band SAR at RMW_{est}

Table 5.1: A list of acronyms and symbols used in this paper along with brief definitions. The superscript “K07” on some symbols indicates that the method of Kossin et al. (2007) was used.

5.2 A review of the Kossin et al. (2007) method

In this section, a review of the method proposed by Kossin et al. (2007) for estimating the RMW from IR images are provided. The eye size ($R_{\text{eye}}^{\text{K07}}$) is measured from IR images for well-defined clear and symmetric eyes. The aircraft-measured surface (10 m height) RMW is calculated from flight-level wind profiles from the NOAA WP-3D database assuming a 45° outward inclination with height from 1 km above the surface to flight level. They measured $R_{\text{eye}}^{\text{K07}}$ as follows:

- 1) Identify the IR image nearest in time to the aircraft reconnaissance fix.
- 2) Measure the representative cloud top brightness temperature (T_b) above the eyewall (denoted $T_{\text{top}}^{\text{K07}}$). The average is calculated in the annulus $40 \leq r \leq 70$ km. They stated that this annulus was a good compromise for capturing more eyewall cloud-top brightness temperature with minimal contribution from the warmer brightness temperature in the eye and outside the eyewall in the moat.
- 3) If $T_{\text{top}}^{\text{K07}} \leq -50^\circ\text{C}$, measure the distance from the TC center to the $T_{\text{th}}^{\text{K07}} = -45^\circ\text{C}$ isotherm along the four cardinal directions (N, E, S, and W). Here, they stated that the radius of the -45°C isotherm serves as a good proxy for the circular region of the steep brightness temperature gradient separating the warm eye and the cold eyewall cloud tops and it is more stable than calculating the gradient directly.
- 4) For the rare case of $T_{\text{top}}^{\text{K07}} > -50^\circ\text{C}$, measure the distance from the TC center to the $T_{\text{th}}^{\text{K07}} = (T_{\text{max}}^{\text{K07}} + 2T_{\text{top}}^{\text{K07}})/3$ isotherm along the four cardinal directions (N, E, S, and W), where $T_{\text{max}}^{\text{K07}}$ is the maximum brightness temperature within a radius of 30 km from the TC center.
- 5) The four distances are averaged to define $R_{\text{eye}}^{\text{K07}}$.

The result of their regression of the aircraft-measured RMW using $R_{\text{eye}}^{\text{K07}}$ measured from IR image (horizontal resolution of 4 km at nadir) was

$$RMW_{\text{est}}^{\text{K07}} = 2.8068 + 0.8361R_{\text{eye}}^{\text{K07}}, \quad (5.1)$$

where $RMW_{\text{est}}^{\text{K07}}$ is the estimated RMW in K07. In their dependent test, the MAE was 4.7 km (sample size $N = 164$). They noted that eyewall replacement cycles and asymmetries could be a source of large errors.

5.3 Data and methods

5.3.1 Data

For R_{eye} measurements, the IR brightness temperature data at $\sim 10.4 \mu\text{m}$ (2 km horizontal resolution at nadir) from the Himawari-8 Advanced Himawari Imager's target observations (2.5-min interval; Okuyama et al., 2018) and the GOES-16/17 Advanced Baseline Imager's meso-sector observations (60-sec interval) were used. For RMW measurements, the sea surface (10 m height) wind products (1km horizontal resolution) provided by IFREMER/CyclObs, retrieved from the C-band SAR satellites Sentinel-1A or Sentinel-1B or RadarSat-2, were used.

A total of 153 cases were examined, encompassing instances where SAR observations and rapid scan observations of Himawari-8 or GOES-16 or GOES-17 were conducted simultaneously. These cases were limited to TCs with an intensity of Saffir-Simpson Category 2 or higher (1-min maximum sustained wind speed greater than or equal to 83 kt), and the observations were made between July 2015 and December 2021. These cases were classified as 52 (34%) eye cases and 101 (66%) no-eye cases by visual inspection of IR images (at this point, the distinction of whether the eyes were clear or unclear was not considered). As will be shown later in section 5.4.1, these 52 eye cases were objectively classified as 21 (40%) clear-eye cases and as 31 (60%) unclear-eye cases. Since IR observations are made once every 60 sec (GOES-16 and GOES-17) or 150 sec (Himawari-8), the time difference between IR and SAR observations is shorter than 75 sec. Since TCs typically move less than 1 km in 75 sec at their typical translation speed ($< 10 \text{ m/s}$; Kossin, 2018), the movement over the time was neglected. The ERA5 (Hersbach et al., 2020), a global reanalysis dataset produced by the European Centre for Medium-range Weather Forecasts was used to obtain temperature, geopotential, zonal and meridional winds, and relative vorticity around TCs. These data were used to correct parallax and compute vertical wind shear, justification for the use of ERA5 in such computations was provided by Slocum et al. (2022). The TC translation speed was obtained from the IBTrACS best track data set (Knapp et al., 2010; 2018). The Automated Tropical Cyclone Forecasting System (ATCF; Miller et al. 1990; Sampson and Schrader, 2000) databases and the Automated Rotational Center Hurricane Eye Retrieval (ARCHER; Wimmers and Velden, 2010; 2016) outputs are used to show other RMW estimates of a historical case.

5.3.2 Methods for measuring R_{eye}

The parallax is corrected from the IR brightness temperature data by equating a temperature of the reference profile with a brightness temperature while preserving the original coordinates. The eye radius R_{eye} is defined as the radius of the minimum enclosing circle of the eye region, which is defined as the largest connected region with $T_b \geq T_{\text{th}}$ near the center.

As in K07, $T_{\text{th}} = -45^\circ\text{C}$ was used in most cases. As K07 pointed out, it is better to use higher T_{th} values when brightness temperature of clouds surrounding the eye is high. The K07's correction of T_{th} are modified because of the following drawbacks. When the upper-level clouds of the eyewall have an inner overhang, K07's method (see section 5.2) will cause the calculation results to vary depending on the position of the overhang. In addition, although K07 used the fixed annulus to calculate the average cloud-top brightness temperature above the eyewall, it sometimes causes large errors. Moreover, the K07's T_{th} calculation has a discontinuity point at $T_{\text{top}} = -50^\circ\text{C}$, where T_{th} suddenly changes significantly, making the calculation unstable for cases where T_{top} is near -50°C . Therefore, the modification of K07 was implemented as follows. Figure 5.1 provides a supplementary overview of the method.

- 1) Determine the first estimated TC center. In this study, the location of the TC center recorded in the IBTrACS, interpolated with time by cubic spline interpolation were used.
- 2) Project the IR brightness temperature data onto the azimuthal equidistant projection for the first estimated TC center.
- 3) Measure the representative cloud top brightness temperature above the eyewall (denoted T_{top}) by averaging the brightness temperatures of the annulus with $R_w \leq r \leq R_w + 30$ km, where R_w is defined as an approximate radius of the inner edge of eyewall at upper level. K07 fixed $R_w = 40$ km because their analysis included cases with eye radii from 5 km to 38 km, but such a restriction are not made in the method proposed here, so R_w must be varied according to the case. Thus, to establish the optimal T_{top} calculation annulus for each individual case, R_w was determined using the following procedure.
 - 3-1) Compute the standard deviation of brightness temperatures in the annulus from r to $r + 30$ km at $0 < r \leq 150$ km, which is denoted as $\sigma(r)$. If the calculation annulus includes a region warmer than -10°C , the standard deviation is taken as the missing

value, i.e., it is not used in the following process. In this study, -10°C corresponded to a height of 7.7 ± 0.5 km (mean $\pm$ standard deviation)

- 3-2) Measure the radius at which the radial gradient of $\sigma(r)$ is negatively maximized

(denoted as $R_{\max(-\nabla\sigma)}$). In the next step, R_w is searched for the radial range

$$R_{\max(-\nabla\sigma)} \leq r \leq R_{\max(-\nabla\sigma)} + 30 \text{ km.}$$

- 3-3) Measure R_w defined as the innermost radius at which the azimuthally averaged brightness temperature over $R_{\max(-\nabla\sigma)} \leq r \leq R_{\max(-\nabla\sigma)} + 30$ km, $\overline{T_b}(r)$, coincides with the average of the $\overline{T_b}(r)$ itself. To construct the azimuthally averaged radial profile, the projected data were resampled onto the polar coordinate with the resolutions of 1 km along radius, and 0.5 degrees along azimuth using bilinear interpolation.

- 4) Determine T_{th} by the following equation,

$$T_{th} = \begin{cases} -45^\circ\text{C}, & T_{top} \leq -50^\circ\text{C} \\ (1-c)T_{top} + cT_{max}, & T_{top} > -50^\circ\text{C} \end{cases}$$

$$c = \frac{a}{T_{max} + b}$$

where T_{max} is the maximum brightness temperature in the region of $0 \leq r \leq R_w$, $a = 5^\circ\text{C}$ and $b = 50^\circ\text{C}$. The units for T_{top} and T_{max} are in $^\circ\text{C}$. Figure 5.2a show the T_{th} as a function of T_{top} and T_{max} . It is readily shown that the T_{th} is continuous, since $(1-c)T_{top} + cT_{max} = -45^\circ\text{C}$ when $T_{top} = -50^\circ\text{C}$. When $T_{top} > -50^\circ\text{C}$, T_{th} increases with T_{top} for given T_{max} (Fig. 5.2b). Practically, T_{th} is lower than T_{max} , since $c \geq 1$ only when $T_{max} \leq -45^\circ\text{C}$, which is unlikely for TCs with eyes. In case where the eye was judged to be clear, as described below, $T_{top} \leq -50^\circ\text{C}$ was always satisfied, so $T_{th} = -45^\circ\text{C}$ was used.

- 5) The eye region is defined as the largest connected region with $T_b \geq T_{th}$ near the center. The eye radius R_{eye} is defined as the radius of the minimum enclosing circle of the eye region, and its center is defined as the TC center.

Figure 5.2 provides a comparison of the proposed T_{th} and that of K07 as a function of T_{top} and T_{max} . In both formulations, for $T_{top} \geq -50^\circ\text{C}$, T_{th} increases as T_{top} and T_{max} increase, but the sensitivity is higher for T_{top} (Figs. 5.2a and 5.2c). The major difference is in continuity. The proposed T_{th} is continuous (Fig. 5.2a and 5.2b), whereas that of K07 is discontinuous with respect to T_{top} (Fig. 5.2d). The discontinuity is larger when T_{max} is larger (Fig. 5.2c).

In this study, $T_{th} = -45^\circ\text{C}$ corresponds to a height of 12.4 ± 0.3 km (mean $\pm$ standard deviation), so the minimum enclosing circle of the T_{th} isotherm is computed at the relatively upper level.

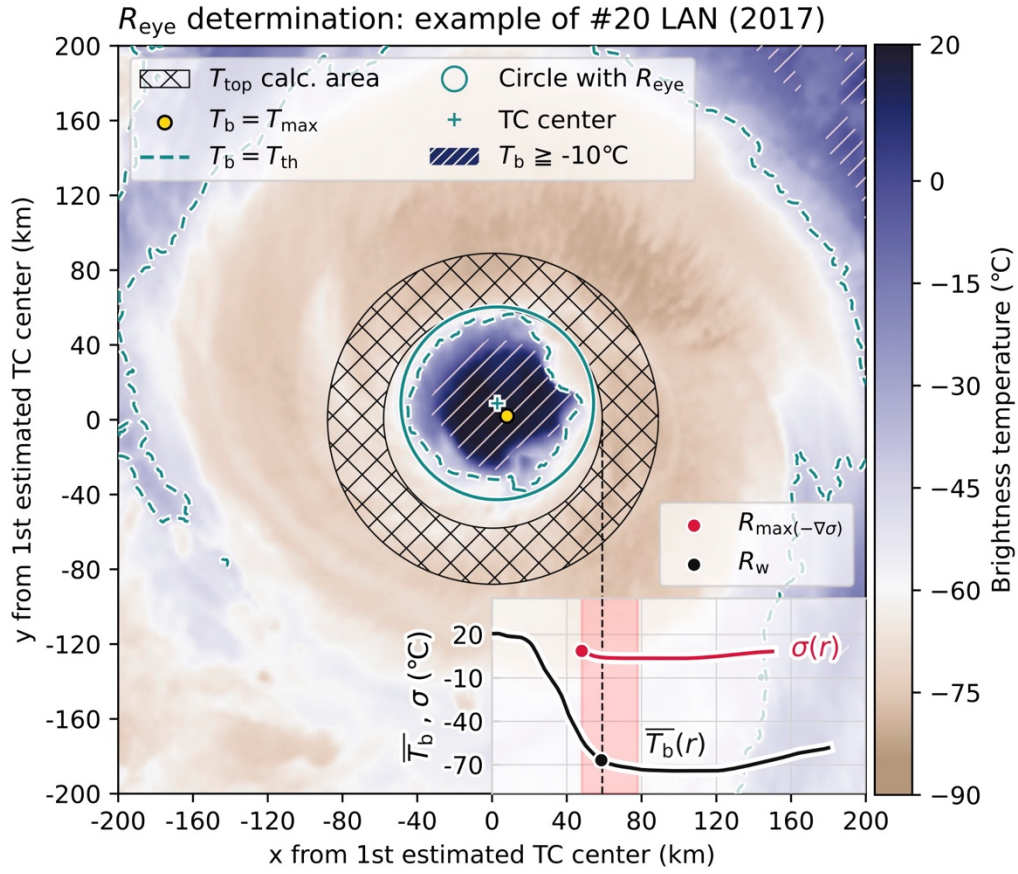


Figure 5.1: Overview of R_{eye} measurement. The color shade represents brightness temperature projected onto the azimuthal equidistant projection for the first estimated TC center. In the panel embedded in the lower-right corner, the red curve shows $\sigma(r)$, and the black curve shows $\bar{T}_b(r)$. The red dot indicates $R_{\max(-\nabla\sigma)}$, and the red shade shows the range of $R_{\max(-\nabla\sigma)} \leq r \leq R_{\max(-\nabla\sigma)} + 30$ km. The black dot indicates R_w . The black hatch shows the $R_w \leq r \leq R_w + 30$ km annulus, which is the calculation area of T_{top} . The yellow dot shows the location of the warmest spot. The white hatch shows the area of $T_b \geq -10^\circ\text{C}$. The green dashed contour shows the T_{th} isotherm, the green circle shows minimum enclosing circle of the T_{th} isotherm near the center, and its radius is defined as R_{eye} . The plus sign indicates the center of the minimum enclosing circle, which is defined as the TC center.

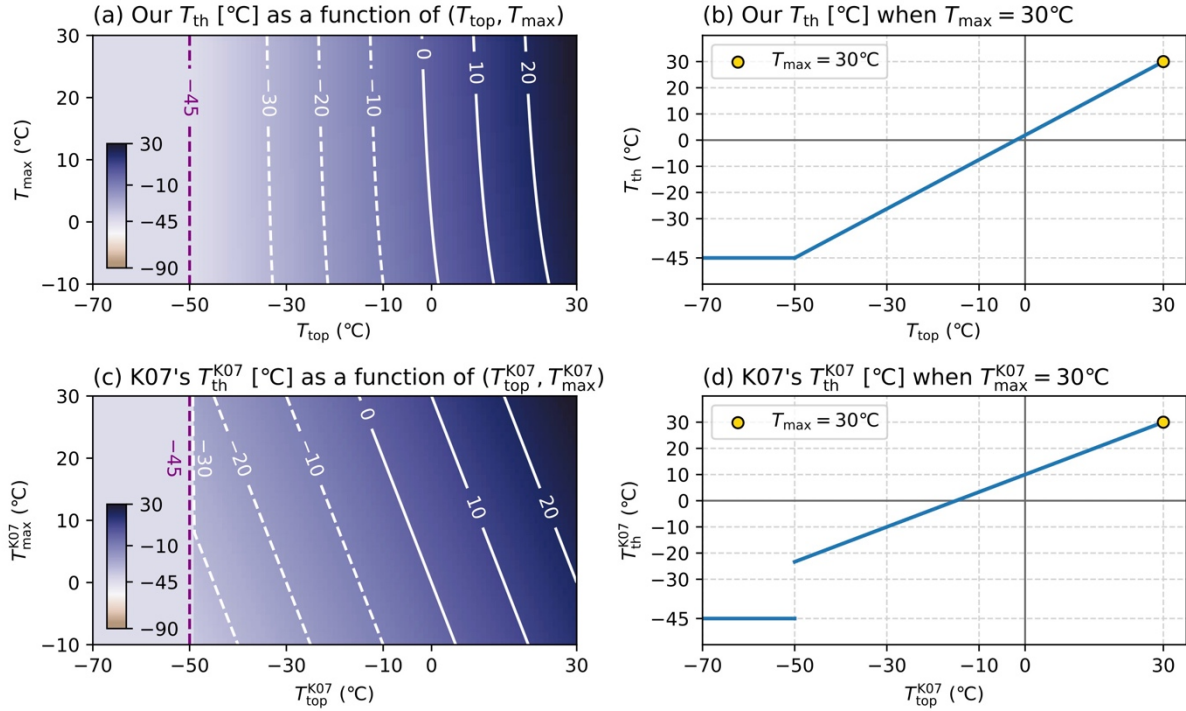


Figure 5.2: A comparison of the proposed T_{th} (the brightness temperature to determine the eye area) and that of K07 as a function of T_{top} (the average brightness temperature above the eyewall cloud) and T_{max} (the maximum brightness temperature near the TC center). The color shade and white contours indicate the T_{th} with respect to T_{top} and T_{max} . Panels (b) and (d) show the T_{th} as a function of T_{top} when $T_{max} = 30^\circ\text{C}$. The K07's function of T_{th}^{K07} is discontinuous along with T_{top}^{K07} but the proposed one is continuous.

5.3.3 Methods for measuring RMW

The RMW was determined from the sea surface wind product retrieved by C-band SAR observation. The heterogeneity mask included in the product was used to remove features not related to wind. To determine the center of circulation at surface, the method of Vinour et al. (2021) were used with minor modifications. Their method is designed based on several wind speed thresholds to gradually approach the TC center. The following is a brief description of their procedure to locate TC center (see Vinour et al., 2021 for details). First, the method locate the centroid (magenta dot in Fig. 5.3) of the high-wind area (red contours in Fig. 5.3) around the first estimated TC center. Second, the method locate the centroid of the low-wind area around the high-wind centroid. The low-wind centroid is then iteratively recomputed, around the last estimated low-wind centroid until finding a stable low-wind centroid (cyan dot in Fig. 5.3). Finally, the method locate the centroid of the eye shape (yellow dot in Fig. 5.3), defined as the

maximal radial wind gradient for each azimuth around the low-wind centroid.

In this study, the high-wind centroid in their method were replaced with the IR-measured TC center position obtained in section 5.3.2 and searched low-wind centroid using search radius of $1.2R_{eye}$. The azimuthally averaged sea surface wind from the center of circulation was calculated and its maximum value was defined as the VMAX and its radius as the RMW. Note that the VMAX is the maximum instantaneous wind speed of SAR winds at a specific time, not the 1-min or 10-min average sustained wind.

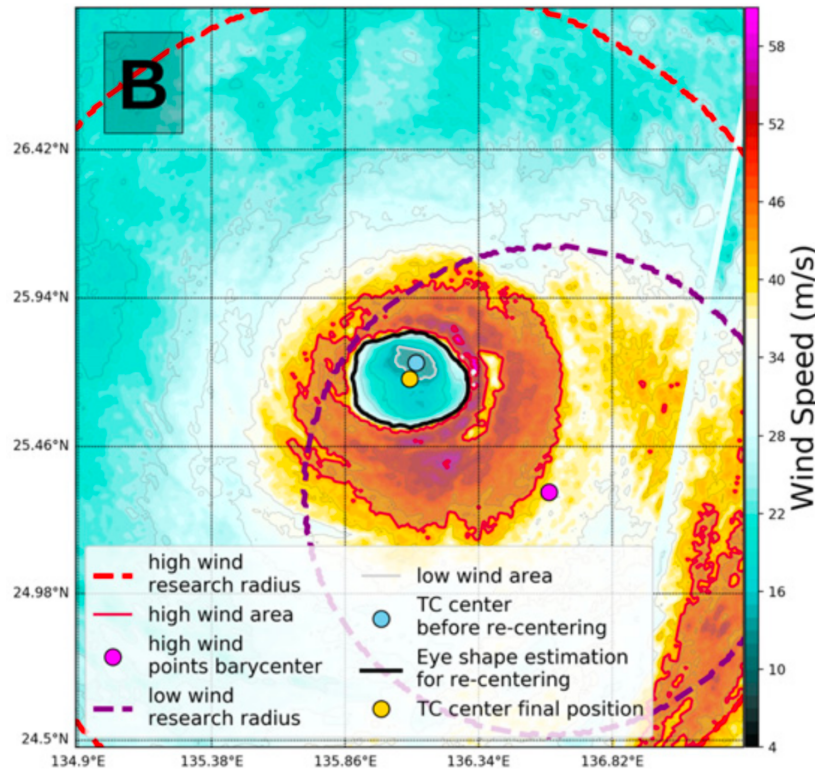


Figure 5.3: Illustration of the TC-center finding algorithm applied to Typhoon Lionrock (2016) observed with Sentinel-1 SAR on 27 August 2016. The color shading represents the retrieved sea surface wind speed. The first search area for the TC center is denoted by a red-dashed circle. The high-wind points are contoured in red, with their centroid indicated by a magenta dot. The second search area is represented by a purple-dashed circle. The low-wind points are contoured in light gray, with their centroid marked by a cyan dot. The raw eye-shape signal is depicted by a black contour, and the final TC center is located using a yellow dot. Adapted from Vinour et al. (2021).

5.3.4 Clear eye criteria

As mentioned in section 5.1, K07 demonstrated regression in clear-eye cases, but the specific method

for determining clear-eye is not published. Therefore, a simple method for determining clear-eye scene is proposed here. As a simple method for detecting the TC's eye from an IR image, the method of Chen and Wu (2022) is instructive. They defined an "eye scene" as a scene that satisfies following two criteria: (1) the warmest brightness temperature within a 40 km radius around the best track TC center warmer than or equal to -30°C ; and (2) the cold area of brightness temperature lower than or equal to -54°C radially expands more than 44 km in all azimuths and tangentially continuous within a 300 km radius from warmest spot found in criterion 1.

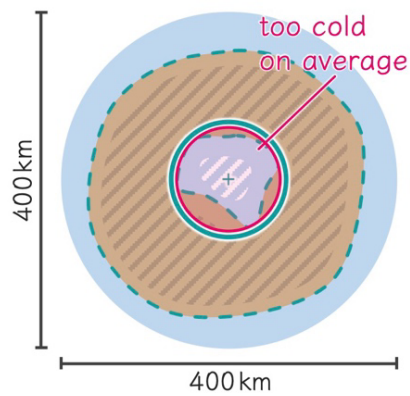
Referring to the eye scene definition of Chen and Wu (2022), a "clear eye" scene was defined as a scene that meets the following criteria:

- a) The average brightness temperature within R_{eye} must be greater than or equal to -13°C . This condition requires that the eye is warm enough and the distortion of the eyewall is small. In this study, -13°C corresponded to a height of 8.2 ± 0.4 km (mean $\pm$ standard deviation)
- b) The cold area with brightness temperatures colder than -50°C surrounding the center is continuous and uninterrupted in the azimuthal direction. This condition requires an unbroken eyewall. In this study, -50°C corresponded to a height of 12.9 ± 0.3 km (mean $\pm$ standard deviation)
- c) The area in the condition (b) has a radial width of at least 44 km in all azimuths within a 200 km radius. This condition requires the eyewall to maintain a strong updraft.

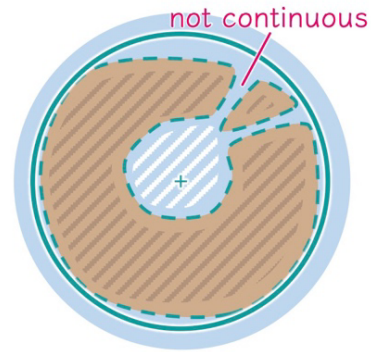
Figures 5.4a–5.4c show schematic diagrams as examples in which these criteria are not met. If the eye area is not sufficiently warm or the eyewall is distorted, criterion (a) is not met (Fig. 5.4a), and if the eyewall is broken or not well developed, criteria (b) or (c) are not met (Figs. 5.4b and 5.4c). As a practical example, four clear-eye cases and unclear-cases are shown in Figures 5.5 and 5.6. Figures 5.6a and 5.6b show the unclear-eye cases where the average brightness temperature within the R_{eye} is not warm. Figures 5.6c and 5.6d show the unclear-eye cases where the eyewall is unable to maintain strong convection in all azimuths (Fig. 5.6c) or is broken (Fig. 5.6d).

Clear eye determination

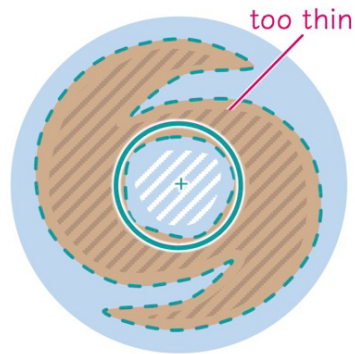
(a) Unclear eye



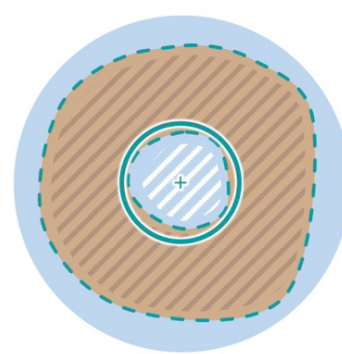
(b) Unclear eye



(c) Unclear eye



(d) Clear eye



 Minimum enclosing circle

 $T_b \geq -13^\circ\text{C}$

 $T_b \leq T_{th}$

 $T_b \leq -50^\circ\text{C}$

Figure 5.4: Schematic diagram of clear eye criteria. Brown area represents upper-level clouds where $T_b \leq T_{th}$, and white hatch represents the area where $T_b \geq -13^\circ\text{C}$. The green dashed contour represents the $T_b = T_{th}$ isotherm, the green circle represents the minimum enclosing circle, and the plus sign represents its center. Panels (a–c) represent unclear-eye cases for different reasons, and panel (d) represents a clear-eye case.

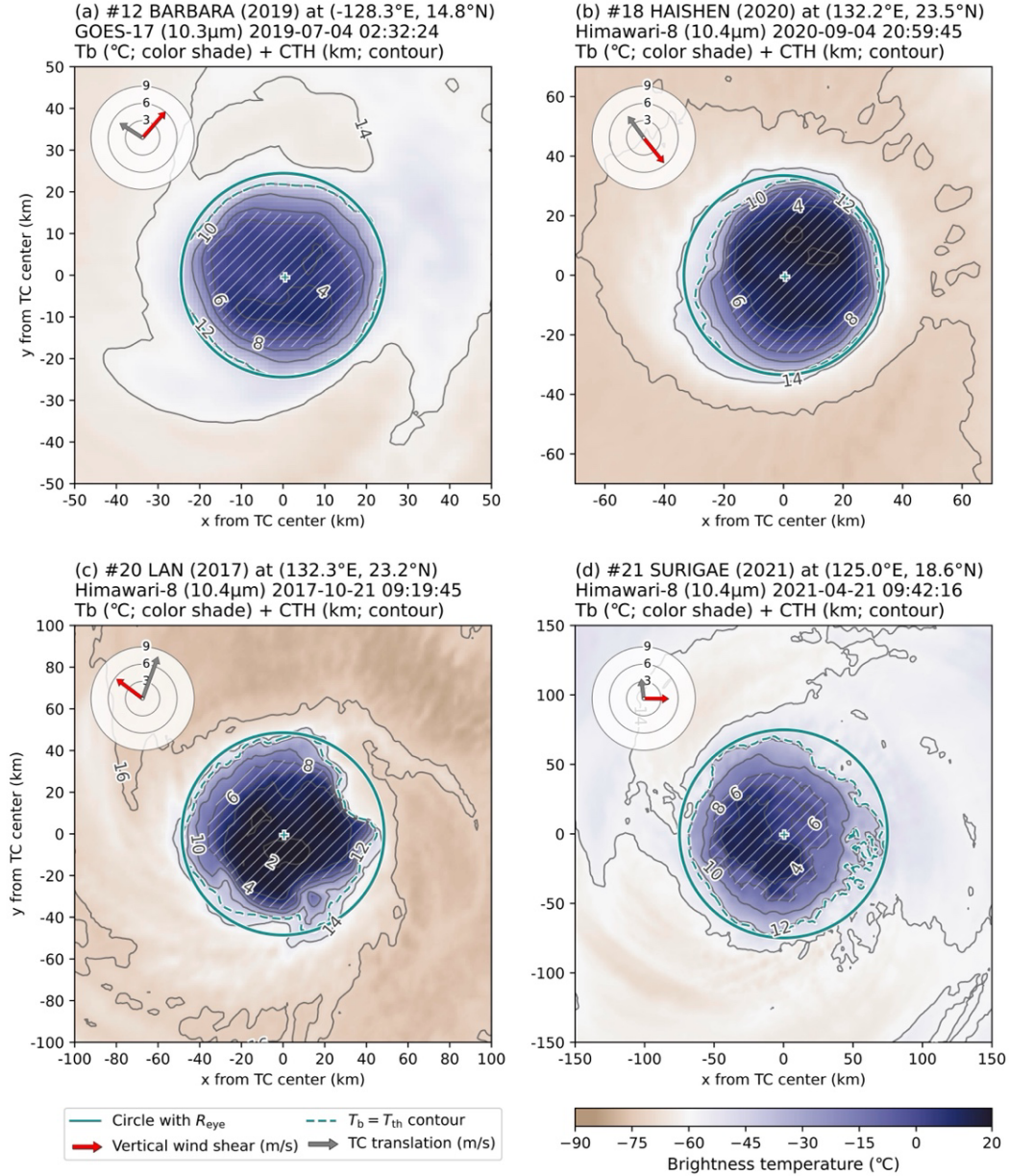


Figure 5.5: Four examples of clear-eye cases. The color shade indicate the brightness temperature (°C). The contour indicates the cloud-top height (CTH; km) estimated from brightness temperature. The green-plus sign is the TC center obtained from the IR image. The green-dashed contour shows the $T_b = T_{th}$ isotherm. The green circle represents the minimum enclosing circle with R_{eye} . The white hatch indicates the warm area with a temperature greater than -13°C . The red and gray arrows in the upper-left corner indicate the vertical wind shear (m/s) and the TC translation speed (m/s), respectively. The vertical wind shear is defined as the difference between the 200-hPa and 850-hPa mean winds calculated for a circular area of 200–800 km in radius from the maximum 850-hPa relative vorticity position near the center of the real TC using the ERA5 isobaric data. Note that the horizontal domain is different for each panel. In this figure, the circle with R_{eye} does not need to enclose strictly to the T_{th} isotherm, because it has been re-mapped for visualization in the azimuthal equidistant projection for the TC center determined by the IR image.

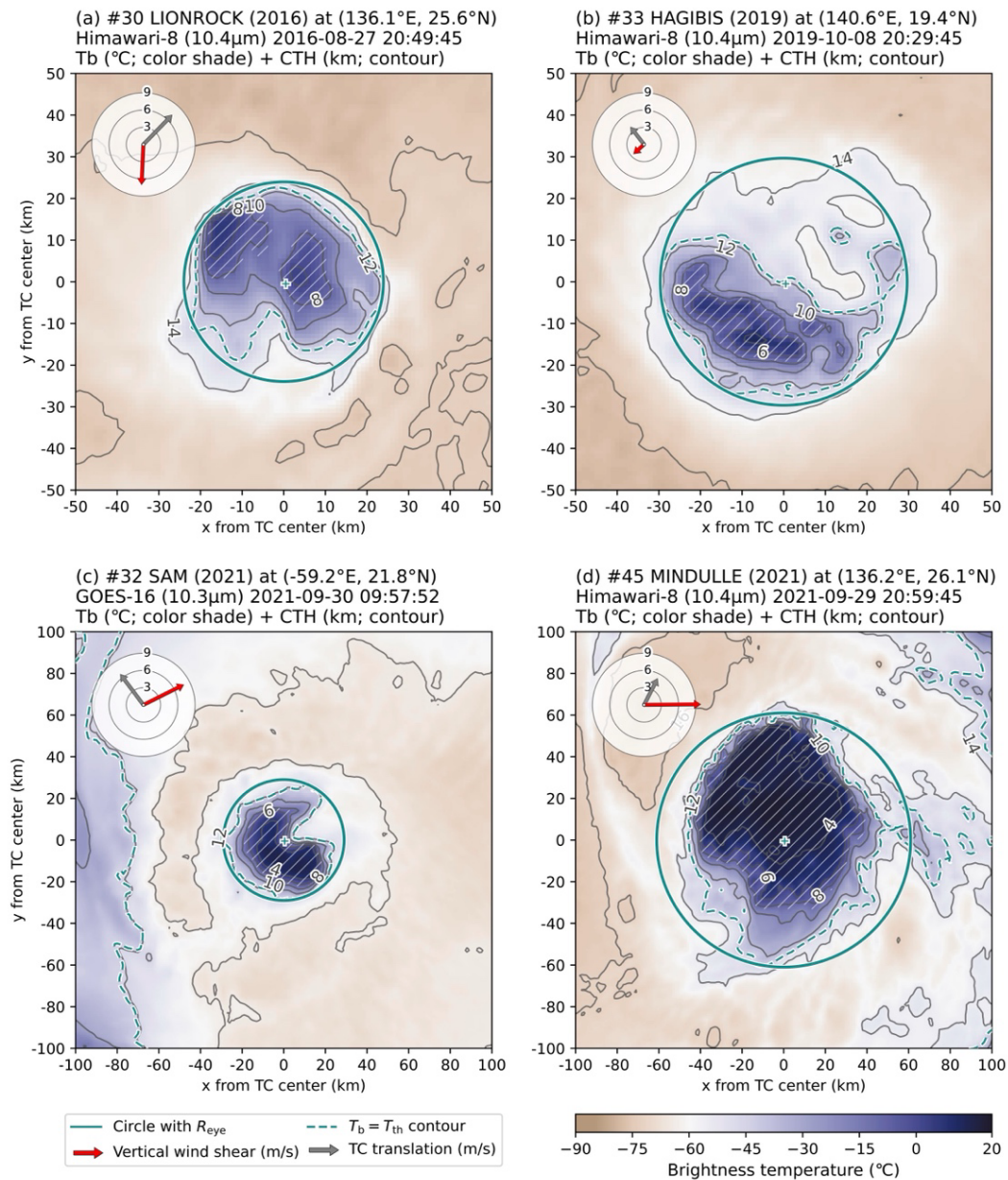


Figure 5.6: Same as Figure 5.5, but for unclear-eye cases.

5.4 Results

5.4.1 Classification of eye scenes

By applying the criteria in section 5.3.4 for 52 eye scenes are classified to 21 (40%) clear-eye cases and 31 (60%) unclear-eye cases as listed in Tables 5.2 and 5.3. All clear-eye cases are shown in Figure 5.7 with small domain and Figure 5.8 with large domain. Table 5.4 shows by which criteria the unclear-eye cases were rejected. Eighty percent of the unclear-eye cases were so judged by criterion (a) only.

5.4.2 Linear regressions using the clear-eye cases

First, the regression of the R_{eye}^{K07} measured by K07's method on the SAR-measured RMW for the clear-eye cases are shown. Among the clear-eye cases, R_{eye}^{K07} and RMW are highly correlated (correlation coefficient of 0.95; as shown in Fig. 5.9a), yielding the regression:

$$RMW_{est}^* = 1.92 + 0.77 R_{eye}^{K07}, \quad (5.2)$$

where RMW_{est}^* is regressed RMW using R_{eye}^{K07} (the green line shown in Fig. 5.9a); the units of all terms are kilometers. When the R_{eye} measured by the proposed method are used (other conditions are the same), the regression equation is

$$RMW_{est} = 3.01 + 0.60 R_{eye}, \quad (5.3)$$

where RMW_{est} is regressed RMW using R_{eye} , with correlation coefficient of 0.97 (Fig. 5.9b). The regression relationship between R_{eye}^{K07} or R_{eye} and RMW does not show a large dependence on the VMAX (color dots shown in Fig. 5.9). This is consistent with the report by K07.

ID	Name	Date	Time (SAR)	Lon (°E)	Lat (°N)	R_{eye} (km)	RMW (km)	VMAX (m/s)	r_{L45} (km)	r_{U45} (km)	Slope (ratio, °)
1	Chanthu	08 Sep 2021	0915	130.84	15.56	4.5	5.0	69.5	2.0	11.0	1.16 (49°)
2	Goni	30 Oct 2020	2115	129.28	15.54	7.0	7.0	68.9	3.0	11.0	0.84 (40°)
3	Goni	30 Oct 2020	0924	131.18	16.12	9.1	7.0	58.2	4.0	14.0	0.83 (40°)
4	Sam	26 Sep 2021	0908	-49.77	13.79	11.6	10.0	54.6	4.0	15.0	1.14 (49°)
5	Felicia	18 Jul 2021	1420	-127.92	15.70	11.8	8.0	49.7	4.0	15.0	1.32 (53°)
6	Meranti	12 Sep 2016	2125	126.00	19.44	14.2	11.0	58.7	7.0	19.0	1.23 (51°)
7	Halong	05 Nov 2019	1956	150.56	20.42	16.1	13.0	64.2	9.0	22.0	1.12 (48°)
8	Dorian	30 Aug 2019	2245	-70.80	25.29	16.6	12.0	53.3	6.0	19.0	1.33 (53°)
9	Dorian	01 Sep 2019	1101	-76.25	26.44	18.3	10.0	64.9	10.0	23.0	1.31 (53°)
10	Wutip	23 Feb 2019	2022	142.25	12.44	20.1	15.0	51.9	9.0	25.0	1.86 (62°)
11	Soudelor	03 Aug 2015	2027	140.24	17.97	21.7	16.0	61.8	13.0	27.0	1.17 (49°)
12	Barbara	04 Jul 2019	0231	-128.33	14.83	24.5	25.0	55.7	13.0	30.0	1.90 (62°)
13	Jebi	31 Aug 2018	2036	139.78	19.26	27.4	21.0	74.0	13.0	33.0	2.13 (65°)
14	Noru	30 Jul 2017	2021	140.71	22.70	27.6	23.0	43.9	12.0	13.0	3.31 (73°)
15	Mangkhut	11 Sep 2018	2046	136.73	13.91	27.8	20.0	74.7	16.0	33.0	1.62 (58°)
16	Mangkhut	12 Sep 2018	0909	134.57	14.19	30.8	19.0	63.1	15.0	38.0	2.04 (64°)
17	Marie	03 Oct 2020	0224	-125.74	17.32	33.1	23.0	56.9	16.0	36.0	2.34 (67°)
18	Haishen	04 Sep 2020	2100	132.20	23.47	33.4	23.0	49.3	19.0	37.0	1.77 (61°)
19	Mangkhut	14 Sep 2018	0949	124.65	17.21	39.3	28.0	56.9	23.0	47.0	2.20 (66°)
20	Lan	21 Oct 2017	0920	132.34	23.23	48.5	33.0	45.5	25.0	55.0	2.56 (69°)
21	Surigae	21 Apr 2021	0943	125.00	18.59	74.9	45.0	55.5	28.0	73.0	5.47 (80°)

Table 5.2: List of the clear-eye cases sorted by R_{eye} . Columns 1 and 2 are IDs and names. Columns 3 and 4 are the date and time of SAR observation in UTC, respectively. Columns 5 and 6 show the longitude (°E) and latitude (°N) of the IR-derived TC center. Column 7 shows the IR-measured R_{eye} (km). Columns 8 and 9 show the SAR-measured RMW (km) and VMAX (m/s), respectively. Columns 10 and 11 show the r_{L45} and r_{U45} (km). Column 12 shows the slope of the eyewall (ratio, °).

ID	Name	Date	Time (SAR)	Lon (°E)	Lat (°N)	R_{eye} (km)	RMW (km)	VMAX (m/s)	r_{L45} (km)	r_{U45} (km)	Slope (ratio, °)
22	Marie	02 Oct 2020	0222	-122.0	15.53	11.1	20.0	33.6	2.0	16.0	1.91 (62°)
23	Goni	21 Aug 2015	2145	122.54	19.91	11.3	45.0	33.5	2.0	12.0	2.67 (69°)
24	Michael	10 Oct 2018	1147	-86.30	29.00	15.8	25.0	59.9	-	-	-
25	Kong-Rey	02 Oct 2018	2110	130.07	19.85	17.5	14.0	51.2	10.0	21.0	2.19 (65°)
26	Veronica	23 Mar 2019	2137	117.79	-19.98	17.9	46.0	41.6	-	-	-
27	Mindulle	25 Sep 2021	2045	136.91	18.63	18.5	23.0	60.6	6.0	29.0	5.18 (79°)
28	Mindulle	25 Sep 2021	2047	136.90	18.62	18.7	23.0	63.3	5.0	28.0	4.71 (78°)
29	Marie	03 Oct 2020	1418	-126.82	18.37	22.8	23.0	43.7	4.0	10.0	1.83 (61°)
30	Lionrock	27 Aug 2016	2050	136.11	25.63	24.0	24.0	49.3	5.0	8.0	4.53 (78°)
31	Yutu	26 Oct 2018	0900	138.35	17.04	27.4	45.0	43.8	15.0	32.0	3.18 (73°)
32	Sam	30 Sep 2021	0957	-59.23	21.75	29.0	24.0	73.1	15.0	31.0	2.30 (66°)
33	Hagibis	08 Oct 2019	2029	140.60	19.43	29.7	26.0	60.5	18.0	45.0	5.40 (80°)
34	Soulik	18 Aug 2018	0801	140.06	24.77	30.5	33.0	36.8	18.0	34.0	2.20 (66°)
35	Kilo	06 Sep 2015	1856	166.39	24.46	32.1	83.0	35.8	18.0	35.0	5.39 (79°)
36	Soulik	18 Aug 2018	0835	140.06	24.75	32.2	33.0	39.9	3.0	11.0	3.46 (74°)
37	Koppu	17 Oct 2015	0956	123.35	15.90	32.9	35.0	37.4	11.0	43.0	4.94 (79°)
38	Maysak	31 Aug 2020	0939	127.40	24.52	32.9	30.0	32.6	16.0	40.0	4.09 (76°)
39	Surigae	18 Apr 2021	2121	126.53	14.13	33.0	36.0	55.7	4.0	12.0	6.65 (81°)
40	Larry	07 Sep 2021	2144	-56.03	25.21	43.0	57.0	39.8	10.0	35.0	3.33 (73°)
41	Surigae	19 Apr 2021	2128	126.20	15.43	46.2	50.0	56.9	3.0	4.0	7.73 (83°)
42	Megi	26 Sep 2016	2142	123.65	22.80	51.5	47.0	52.2	25.0	28.0	7.48 (82°)
43	Surigae	20 Apr 2021	0940	125.92	16.31	60.4	49.0	58.5	17.0	40.0	3.93 (76°)
44	Veronica	23 Mar 2019	1044	117.42	-19.25	60.7	45.0	37.4	3.0	8.0	6.41 (81°)
45	Mindulle	29 Sep 2021	2059	136.16	26.09	61.0	54.0	37.4	29.0	62.0	3.64 (75°)
46	Noru	04 Aug 2017	2117	130.56	29.43	64.8	72.0	32.0	11.0	18.0	4.13 (76°)
47	Soulik	18 Aug 2018	2042	139.46	25.32	69.3	38.0	35.1	32.0	40.0	10.66 (85°)
48	Mindulle	28 Sep 2021	2059	135.45	22.88	70.9	51.0	45.4	13.0	14.0	7.79 (83°)
49	Larry	06 Sep 2021	0922	-52.26	21.50	72.5	57.0	48.2	23.0	24.0	20.30 (87°)
50	Maysak	01 Sep 2020	2124	126.82	30.11	82.1	104.0	32.0	9.0	17.0	12.25 (85°)
51	Trami	28 Sep 2018	0934	127.26	23.27	138.2	97.0	36.7	49.0	53.0	7.94 (83°)
52	Trami	29 Sep 2018	0926	128.40	27.34	162.9	99.0	39.4	29.0	42.0	10.40 (85°)

Table 5.3: Same as Table 5.2, but for the unclear-eye cases sorted by R_{eye} .

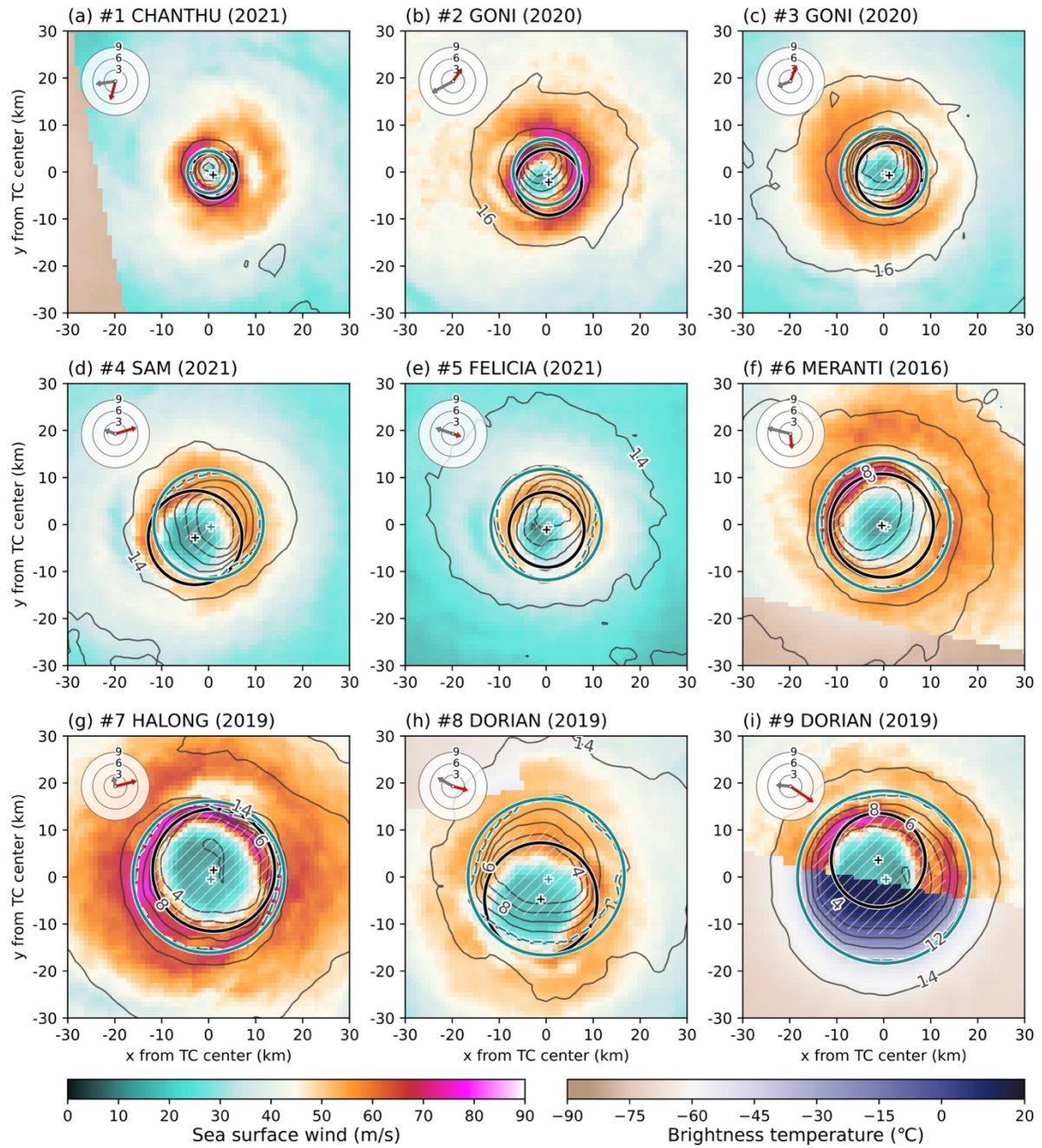


Figure 5.7: Collocated sea surface winds (color shading) and cloud-top height (km; black contour) for all clear-eye cases (first half). The color shade show the sea surface wind (m/s) superimposed on the brightness temperature (°C), and the brightness temperature is shown only where the surface wind is missing. The black-plus sign is the TC center obtained from the surface winds. The black circle represents the circle with RMW. Other components are the same as in Figure 5.5. All panels show the horizontal domain of 30 km $\times$ 30 km.

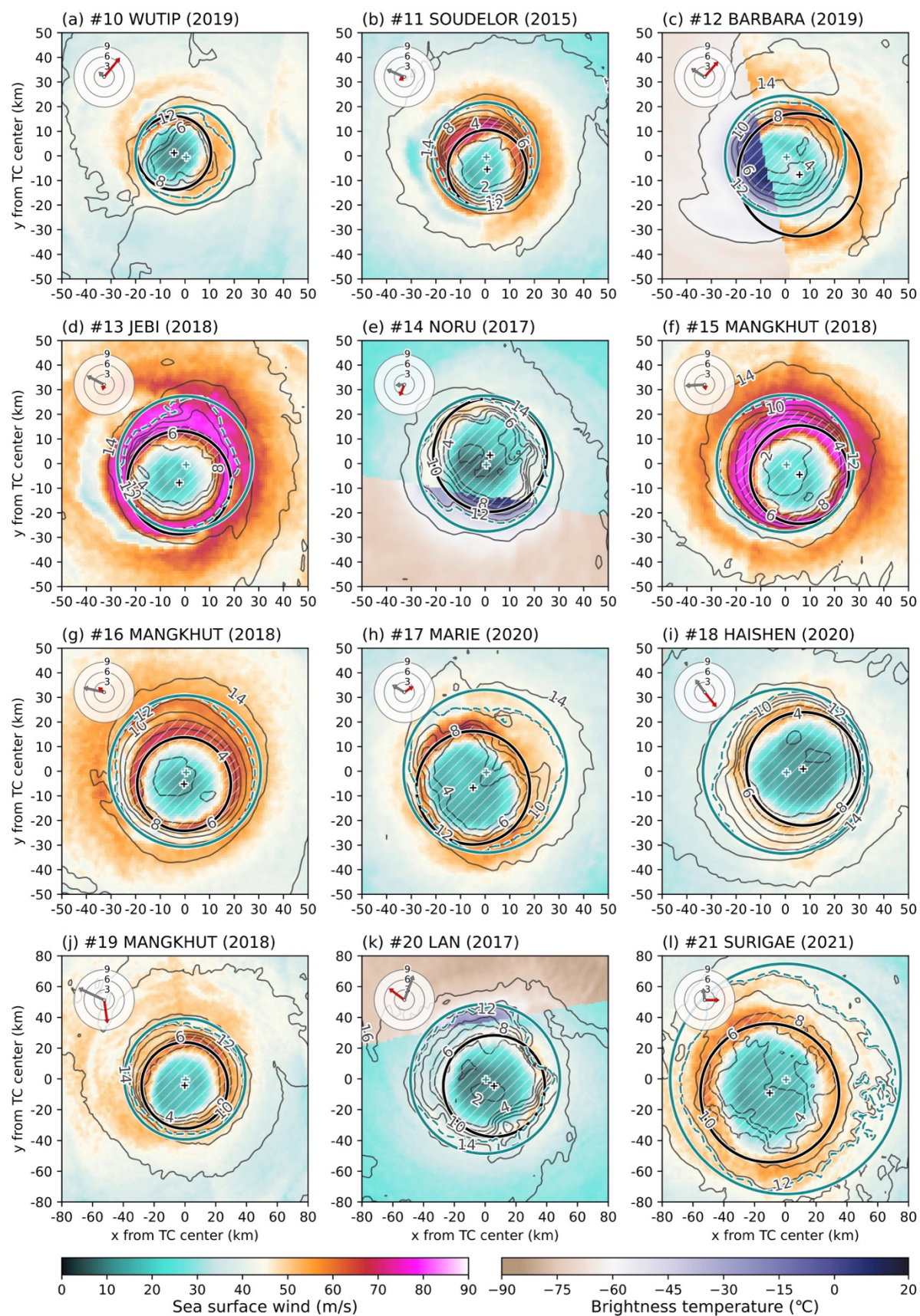


Figure 5.8: Same as Figure 5.7 (second half). All panels except the bottom row are shown in 50 km $\times$ 50 km domains. The panels in the bottom row are shown in 80 km $\times$ 80 km domains.

Criteria	No. of cases	ID
(a) only	25	22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 33, 34, 36, 37, 38, 39, 40, 41, 42, 43, 44, 46, 47, 48, 50
(b) only	0	N/A
(c) only	1	45
(a) $\cap$ (b)	0	N/A
(b) $\cap$ (c)	0	N/A
(c) $\cap$ (a)	5	32, 35, 49, 51, 52
(a) $\cap$ (b) $\cap$ (c)	0	N/A

Table 5.4: Details of the 31 unclear-eye decisions. Column 1 shows the combination of criteria in section 5.3.2, i.e., (a) maximum $T_b \geq -13^\circ\text{C}$, (b) continuous surrounding $T_b \leq -50^\circ\text{C}$, (c) surrounding $T_b \leq -50^\circ\text{C}$ have a width ≥ 44 km. The symbol “ $\cap$ ” indicates the intersection of some sets. Column 2 shows the number of cases rejected for each set of criteria. Column 3 indicates the IDs of the unclear-eye cases listed in Table 5.3 (from #22 to #52). Note that “(b) only” and “(a) $\cap$ (b)” must be zero because when a case is rejected in the criterion (b), it is always rejected in the criterion (c) as well.

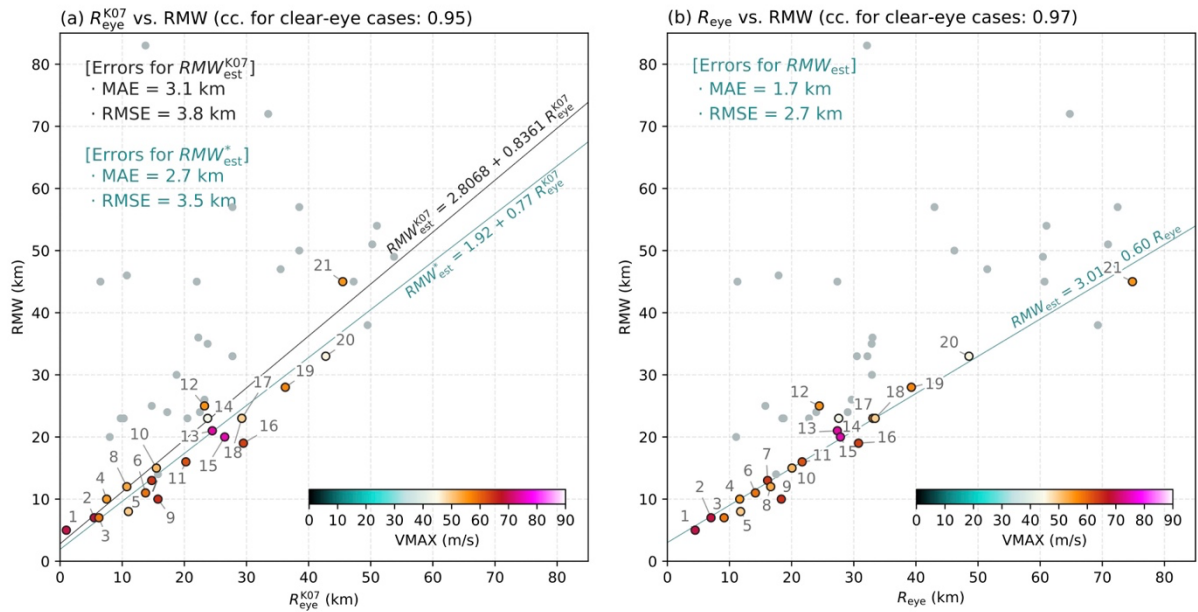


Figure 5.9: RMW with respect to (a) R_{eye}^{K07} and (b) R_{eye} . The number and color of each dot indicate the ID listed in Table 5.2 and the VMAX (m/s) of the clear-eye case, respectively. Gray dots indicate the unclear-eye cases. (a) The black line shows the RMW regression line of K07 (eq. (5.1)) and the green line shows the RMW regression line for the used data using R_{eye}^{K07} (eq. (5.2)). (b) The green line shows the RMW regression line using R_{eye} (eq. (5.3)).

5.4.3 Evaluation of the linear regression models

To evaluate the errors of the linear regression models, the MAE and the root-mean-square error (RMSE) were calculated for all cases (clear-eye and unclear-eye cases combined), clear-eye cases, and unclear-eye cases, respectively. Since the regression equations (eqs. (5.2) and (5.3)) were constructed using the clear-eye cases, a leave-one-out cross-validation were performed, i.e., each case was individually removed from the full sample and linear regression was performed on the subsample of remaining cases, in order to better reflect the independently derived error in the evaluation of those equations for the clear-eye cases. The MAE and the RMSE of the regressions (eqs. (5.1)–(5.3)) are summarized in Table 5.5.

Among all cases, the equation (5.3) constructed in this study has the best accuracy in both metrics. Equations (5.1) and (5.2) have larger errors than that. The fact that the error in equation (5.1) is smaller than in equation (5.2) suggests that the data used for training in K07 contained more unclear-eye cases.

Among the clear-eye cases (color dots in Fig. 5.9), the MAE of K07's equation (5.1) is 3.1 km for SAR data (Fig. 5.9a), and the MAE of the revised regression equation (5.2) with $R_{\text{eye}}^{\text{K07}}$ is 2.7 km (Fig. 5.9a). The former result indicates that the K07's equation is more accurate than previously thought. The MAE of the equation (5.3) is 1.7 km (Fig. 5.9b), which is the smallest among the other regressions, which suggest that the proposed method further tighten the regression.

The RMW estimation error is defined as $RMW_{\text{err}} \equiv RMW_{\text{est}} - RMW$. Among the clear-eye cases, Hurricane Barbara (#12 in Table 5.2; Fig. 5.8c) had the largest absolute RMW_{err} of -7.3 km. It had a circular eye in the IR image (contours), but its sea surface winds had a pronounced elliptical structure (color shading). Thus, it appears natural that the correspondence between R_{eye} and RMW is poor. For elliptical winds, the procedure for determining the RMW from the azimuthally averaged wind may not be appropriate. Therefore, instead of using the all-azimuthal mean winds, the error was also examined when the RMW was defined as the average of the radius of maximum wind of the azimuthal mean winds in each of the eight azimuthal regions. The RMW_{err} for Hurricane Barbara in this case was -6.4 km, which is smaller than the above error of -7.3 km. However, the error is still large, and fundamentally in such cases (circular eyes, elliptical winds), regression from the eye radius would be quite challenging. Upon rerunning all the regressions using the aforementioned RMW definition, the average errors exhibited an increase for all the regressions (not shown). This is likely due to the fact that the split

azimuths were affected by subregions with unstable wind structures.

Among the unclear-eye cases (gray dots in Fig. 5.9), the equation (5.3) also has the best accuracy, but the errors are much larger than that of the clear-eye cases. Among most of the unclear-eye cases, actual RMWs are greater than regressed lines. In other words, all regressions give the lower bounds of RMW regardless of eye shape. Therefore, it would be possible to use these regressions for the purpose of obtaining a lower bound of the RMW even for unclear-eye cases.

Regressed RMW (Eq. No.)	Method	Wind data	All cases		Clear eye cases		Unclear eye cases	
			MAE	RMSE	MAE	RMSE	MAE	RMSE
$RMW_{\text{est}}^{\text{K07}}$ (5.1)	K07	K07	—	—	4.7	—	—	—
$RMW_{\text{est}}^{\text{K07}}$ (5.1)	K07	This study	13.0	21.6	3.1	3.8	19.6	27.8
RMW_{est}^* (5.2)	K07	This study	14.0	23.1	2.7	3.5	22.0	29.8
RMW_{est} (5.3)	This study	This study	9.8	16.1	1.7	2.7	15.5	20.8

Table 5.5: Evaluations for the RMW regressions. Column 1 shows the regressed RMW and its equation number. Column 2 indicates the method used to measure the eye radius from an IR image, where “K07” means that the eye radius ($R_{\text{eye}}^{\text{K07}}$) was measured by the K07 method, and “Ours” means that the eye radius (R_{eye}) was measured by the method proposed in this study. Column 3 indicates the wind data used to obtain the RMW, where “K07” refers to the aircraft-measured RMW used in K07, and “This study” refers to the SAR-measured RMW used in this study. Columns 4–5 show the MAE (km) and the RMSE (km) in each regression for all cases. Columns 6–7 and 8–9 are that for clear-eye cases and unclear-eye cases. Note that the errors in equations (5.2) and (5.3) for clear-eye cases are calculated using leave-one-out cross validation. The error reported by K07 (MAE = 4.7 km) is the result of their dependent test.

5.5 Discussion

5.5.1 RMW Dependencies

During the investigation of the RMW regression results, no evident dependence on ocean basin, day/night, latitude, vertical wind shear, or TC translation speed was observed (not shown). However, a larger number of data would be needed to draw that conclusion. Furthermore, a clear dependence on intensity was not identified. This is consistent with the results of K07 and maybe because the variance of RMW explained by VMAX is sufficiently small compared to that of R_{eye} .

5.5.2 Application example: Hurricane Marie (2020)

An example application of the proposed RMW estimation to a historical TC is demonstrated in Figure 5.10 for the Hurricane Marie (2020), which formed at 1200 UTC on 27 September 2020 in the Northeast Pacific and moved northwestward, intensified to a Category 4 at 06:00 UTC on 2 October, and dissipated at 0000 UTC on 10 October (Figs. 5.10a and 5.10b). The results presented are for periods when the intensity exceeded Category 2. Marie was observed by SAR three times during the analysis period (clear-eye: #17 in Table 5.2, unclear-eye: #22 and #29 in Table 5.3). In Fig. 5.10c, the RMW estimates are compared against the RMWs measured by SAR, as well as the RMWs obtained from the final ATCF b-decks (best track) and f-decks (fix), and the ARCHER method. The storm had an eye from approximately 18:00 UTC on 1 October to 21:00 UTC on 3 October. It was determined to have clear eyes from about 00:00 UTC on 3 October, when RMW_{est} was ~ 24 km; it contracted to ~ 20 km from 03:00 UTC to 04:00 UTC and remained the same size until about 15:00 UTC when it was last determined to be a clear eye. During this period, the RMWs were analyzed to be ~ 28 km on the ATCF best track, which is outside of the estimates. On the other hand, our estimates are in good agreement with passive microwave derived RMWs from the ARCHER method. One SAR observation was made during the clear-eye period at 02:25 UTC on 3 October (#17 in Table 5.2). The RMW obtained from the SAR winds agree well with the RMW_{est} . Note that these SAR data were used to obtain the regression equation (5.3), so it is not an independent comparison.

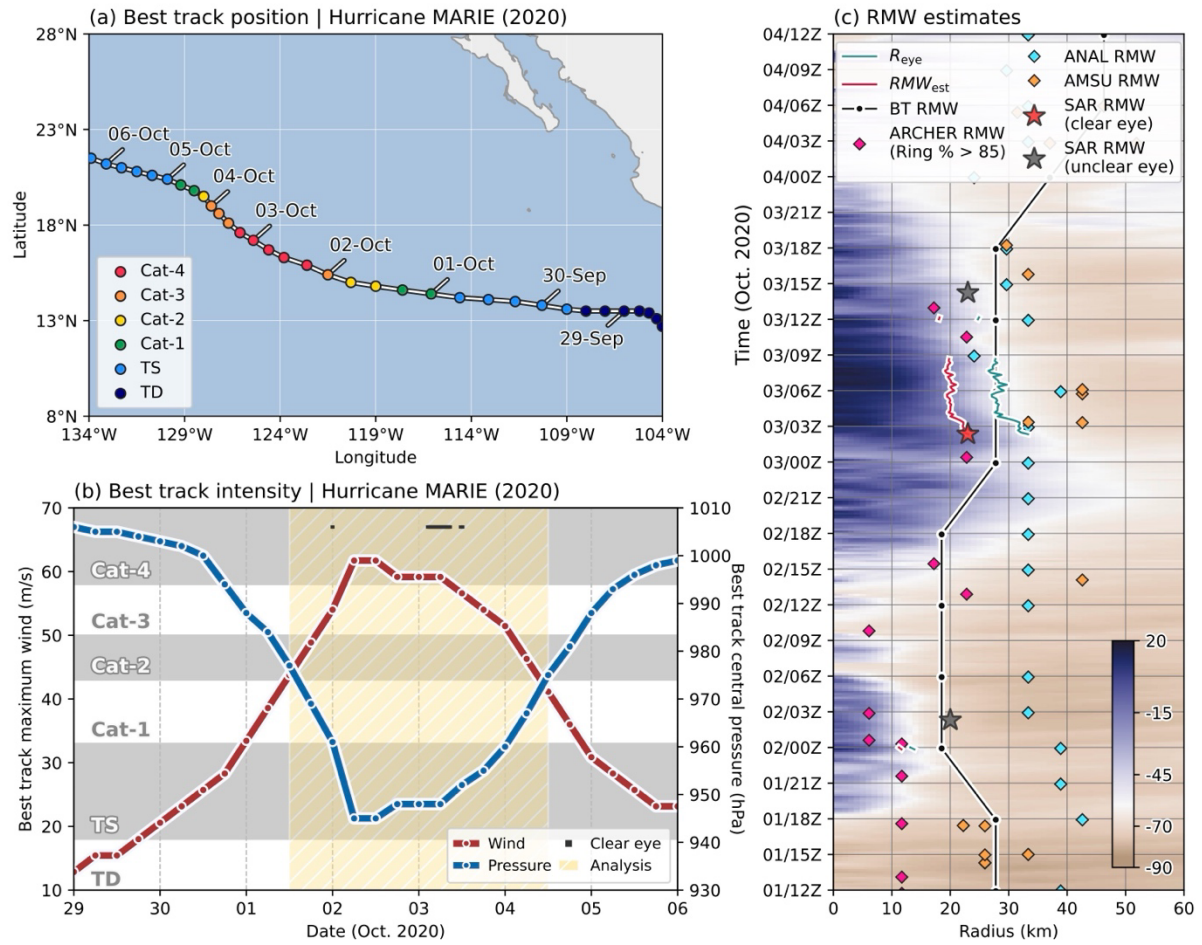


Figure 5.10: Example application of the proposed RMW estimation to Hurricane Marie (2020). (a) Map of storm track (color dots) and (b) time series of best track maximum sustained wind (red) and minimum central pressure (blue). The yellow hatch and black squares in (b) shows the analysis period and clear eye period, respectively. (c) Radius-time cross section of azimuthally averaged brightness temperature with IR-measured R_{eye} (green solid line) and RMW_{est} (red solid line) when clear-eye period using 10-min frequency full-disk scan imagery. The magenta diamond indicates the RMW from the ARCHER method when “Ring %” is greater than 85. The ARCHER method estimates the surface RMW using a 45-degree assumption for the eye radius in the mid to upper troposphere retrieved from passive microwave observations, and the outputs are provided by Cooperative Institute for Meteorological Satellite Studies (CIMSS). The red and black stars indicate the RMWs calculated using SAR winds on clear-eye scene and unclear-eye scene, respectively. The best track RMW on ATCF b-decks (black solid line), the RMWs of the “AMSU” (orange diamonds) and “ANAL” (cyan diamonds) on ATCF f-decks are also shown. The “AMSU” RMWs are estimated using Advanced Microwave Sounding Unit (AMSU; Demuth et al., 2006). According to the comments in ATCF, “ANAL” RMWs for this period indicate the RMWs retrieved from Multiplatform Tropical Cyclone Surface Wind Analysis (Knaff et al. 2011) provided by Cooperative Institute for Research in the Atmosphere (CIRA).

5.5.3 Slope of eyewall and eye size

The strong linear relationship between the R_{eye} and the RMW with regression coefficient between 0 and 1 suggests that the slope of the eyewall increases as the eye size increases (as noted in section 5.3.4, IR-measured R_{eye} corresponds to the eye radius at upper level). It is known that the eyewall slope increase with increasing size of the RMW (Stern and Nolan, 2009; Hazelton and Hart, 2013; Stern et al., 2014). Stern et al. (2014) found that the slope of the absolute angular momentum surface that originates at the RMW at 2-km height increased with increasing size of the RMW at low levels using three-dimensional Doppler wind fields data. From their 39 cases analysis, they found a strong linear relationship between them with a correlation coefficient of 0.724.

To confirm the relationship in this study, the slope of the eyewall is measured from IR imagery and its relationship to eye size is investigated. The eyewall slope was estimated using the method of Sanabia et al. (2014), which involved a statistical analysis of the eyewall slope and its comparison to TC intensity or intensity change using 14 TC cases. Two critical radii (r_{L45} and r_{U45} as described in their paper) were initially measured, representing the radii of the inner edge of the eyewall at the lower and upper levels. Those radii are found from a radial profile of azimuthally averaged brightness temperature that are non-dimensionalized based on R_{CCT} and radius of maximum temperature in the eye. Sanabia et al. (2014) defined r_{L45} as the radial location closest to the TC center where the gradient of the non-dimensionalized radial profile exceed 45° and r_{U45} as the first point outer r_{L45} where the gradient falls below 45° . Subsequently, the eyewall slope was measured between those critical radii by calculating the ratio of the radial difference to the difference in cloud top height (CTH). By definition, a nearly vertical eyewall has a slope of zero, and if the slope is greater than 1, it is greater than 45° in angle. Figure 5.11 demonstrates a linear relationship between the eyewall slope and both the RMW (Fig. 5.11a) and the R_{eye} (Fig. 5.11b) in this study. The correlation coefficient with eyewall slope is 0.88 for RMW and 0.90 for R_{eye} , which is a higher correlation than reported by Stern et al. (2014). When unclear-eye cases are included, the correlation coefficients fall from 0.88 to 0.67 for RMW and from 0.90 to 0.67 for R_{eye} , respectively, but these correlation falls are inconclusive because the measurement method used may not be appropriate for the unclear-eye scenes.

5.5.4 RMW in the eye?

In the clear-eye cases, the azimuthally averaged CTH and brightness temperature at the RMW were 8.3 ± 2.5 km and 254.6 K (-18.5°C) ± 16.9 K, respectively. This indicates that most of the surface RMWs were located below the sloping inner edge of the eyewall. In some azimuths, the RMWs were located at radii with even lower CTHs. For example, as shown in Figure 5.8i, in the northwest quadrant of Typhoon Haishen (#18 in Table 5.2), the location of the RMW coincided with the CTH contours from 4 to 6 km (corresponding to the temperatures from 10 to -1°C in this case). In fact, a structure known as “striations” was present in the same quadrant and heights in 2.5-hours later VIS image (Fig. 5.12b; SAR acquisition time was before sunrise and no VIS image was available at that time, so the 2.5-hour later image is shown). Developed TCs often have “striations” (or “finger-like features”), quasi-regularly aligned stripy cloud features whose intervals are typically a few kilometers, at the lower levels of the inner edge of the eyewall (Aberson et al., 2006; Bluestein and Marks, 1987; Marks et al., 2008), and the presence of winds much stronger than those around them has been reported (Yamada et al., 2021). Figure 5.12a shows the IR image at the SAR acquisition time, but the 2 km resolution of the IR imager was not sufficient to resolve the striations. Since striations tend to persist over more than several hours, the RMW in that quadrant may have been located below the striations in the eye. If true, the velocity of striations (Daniels et al., 2004; Yamada et al., 2021) would correlate with VMAX, and RMW could be estimated directly from GMSs.

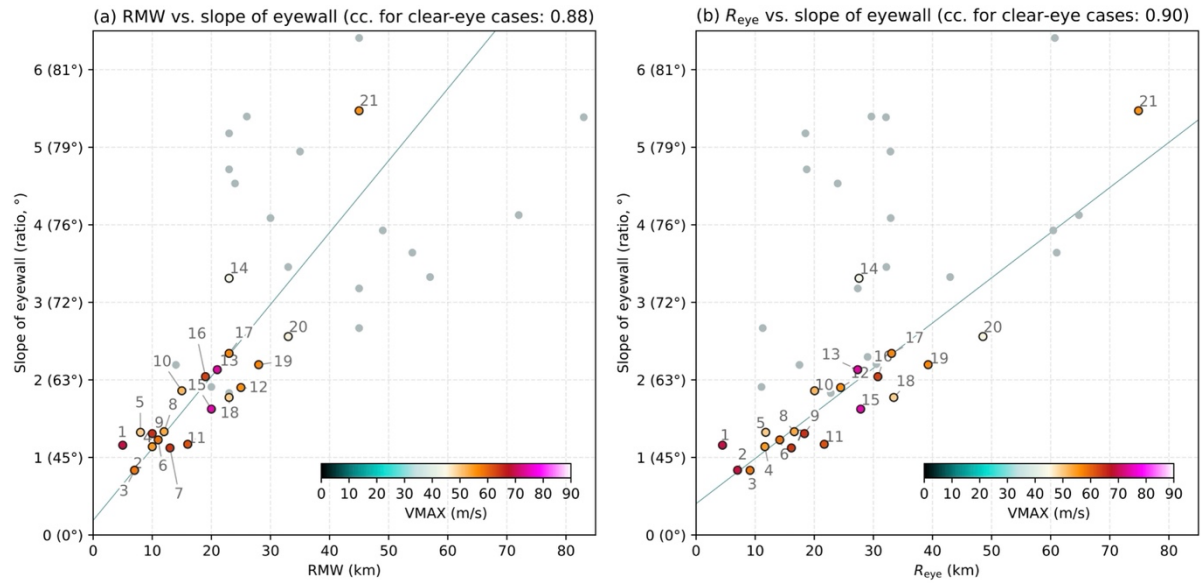


Figure 5.11. Slope of the eyewall with respect to (a) RMW and (b) R_{eye} . The color dots indicate the clear-eye cases, and the gray dots indicate the unclear-eye cases. The green solid lines indicate the best fit to the clear-eye cases. The slope of nearly vertical eyewall is zero. If the slope ratio is greater than 1, the slope is greater than 45° in angle.

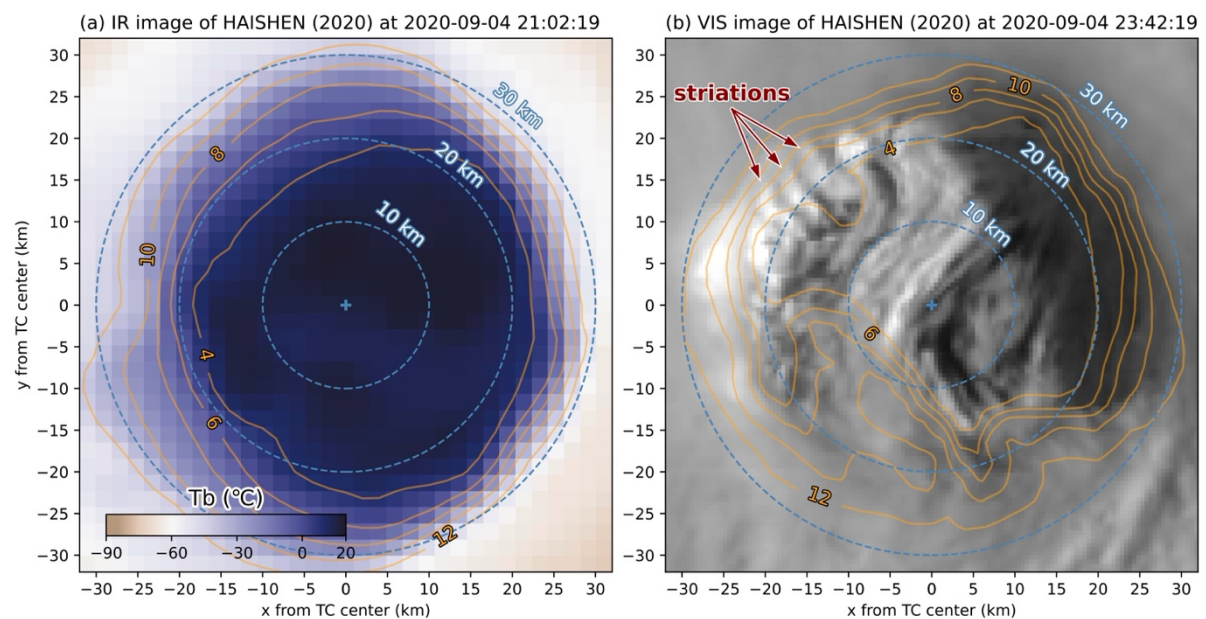


Figure 5.12: Himawari-8 AHI (a) IR brightness temperature image at 21:02:19 UTC (SAR acquisition time) and (b) VIS image at 23:42:19 UTC of Typhoon Haishen (2020) on 4 September 2020, showing the presence of the striations. Orange contours are the CTH (in km) estimated from brightness temperature. In (b), striations exist in the northwest quadrant. Note that the images in this figure are not parallax-corrected, because the parallax correction hides half of the striations under the upper clouds.

5.5.5 Possible applications

The increased accuracy of RMW estimation would progress operations and climatological research and understanding, especially in ocean basins where aircraft observations do not exist. In operations, it could improve the initial conditions for numerical models as well as being used for disaster prevention and mitigation. It would also contribute to improved forecasting. Studies related to climatological RMW (e.g., Kimbal and Mulekar, 2004) could be revisited with more samples using more accurate RMW estimates, even in ocean basins without aircraft observations.

RMW estimates could also be applied to GMS-based TC intensity estimation. As discussed in section 5.5.4, in the clear-eye cases, most of the surface RMWs were located below the sloping inner edge of the eyewall. This means that the RMW is located slightly outside the area in the eye where the lower clouds are observed from GMSs. In Chapter 3, a method was developed to derive the sustained tangential winds in the eye as a function of radius using spectral analysis for azimuth-time cross section of rapid scan imagery taken by latest GMSs. In Chapter 4, a TC-specific cloud tracking method was developed to derive the AMVs in the TC inner-core region. If near-surface winds in the eye could be estimated as a function of radius in such a way, TC intensity might be estimated by extrapolation to estimated RMW. In this study, the wind speed difference between VMAX and the wind speed at RMW_{est} was examined using SAR winds. Note that this study only shows wind speed differences in SAR winds and not actual errors in intensity estimation based on the approach described above. The wind speed difference is defined as $VMAX_{err} \equiv VMAX - VMAX_{est}$, where $VMAX_{est}$ is the azimuthally averaged SAR wind at RMW_{est} only using SAR winds. Figure 5.13 shows the distribution of $VMAX_{err}$ with respect to RMW_{err} for clear-eye cases. In many cases, $VMAX_{err}$ has a small value of less than 2 m/s. Based on these results, it is suggested that the estimation of wind speed at RMW_{est} from GMSs could potentially enable accurate estimation of VMAX with high frequency and small errors. In a few cases with elliptical or radially sharp wind structures, $VMAX_{err}$ is large. Since Hurricane Barbara (#12 in Table 5.2; Fig. 5.8c) had a circular eye and an elliptical wind structure as described in section 5.4.3, the $VMAX_{err}$ was especially large.

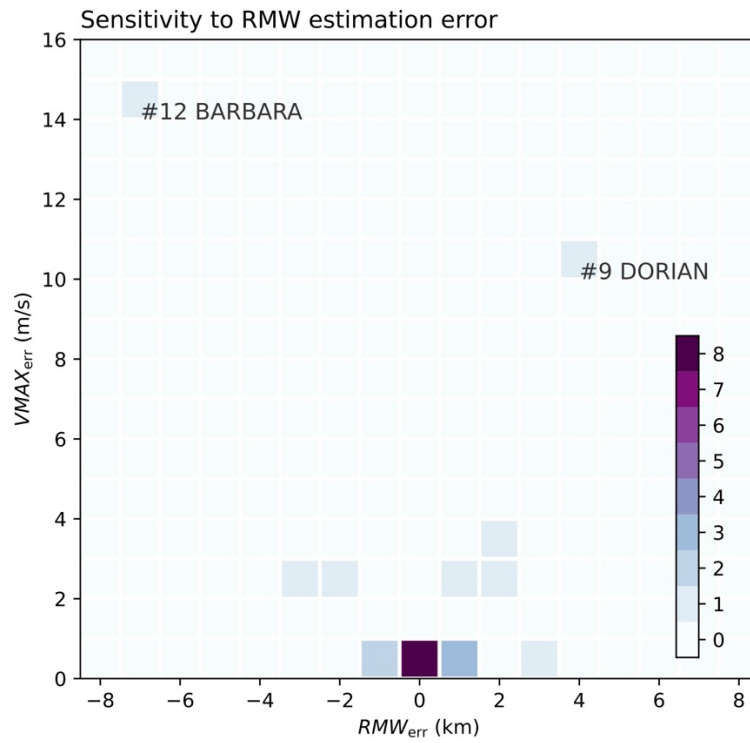


Figure 5.13: 2D-histogram of $VMAX_{err}$ with respect to RMW_{err} . RMW_{err} is defined as $RMW - RMW_{est}$, where a negative (positive) value indicates an under- (over-) estimation of RMW. Cases where $VMAX_{err}$ is greater than 5 m/s are numbered and named.

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Chapter 6

Concluding remarks

Tropical cyclone (TC) is identified by its fast rotation, low-pressure center, closed low-level atmospheric circulation, powerful winds, and a spiral pattern of thunderstorms that generate intense rainfall and gusts of wind. While monitoring wind distribution in the inner-core region of TCs is crucial for understanding their dynamics and estimating/forecasting their intensity, it has been a challenge due to limitations in spatiotemporal resolution and observational coverage. However, the third-generation geostationary meteorological satellites (GMSs), such as Himawari-8, have significantly improved spatiotemporal and wavelength resolution compared to their predecessors, making it possible to observe the inner-core region of TCs with higher horizontal resolution and frequency. This study has focused on developing methods to estimate wind distribution using rapid-scan observations of TCs by GMSs and to understand TC dynamics through the obtained results.

In Chapter 3, a new method has been developed for estimating the tangential winds of TCs based on the space-time Fourier analysis of high-frequency geostationary satellite images. The method was applied to the 2.5 min VIS images from Himawari-8 to quantify the rotation at the top of the atmospheric boundary layer of the eye of Typhoon Lan (2017). The rotational angular speed was nearly uniform and increased gradually with time for $r \lesssim 25$ km. At the inner edge of the eyewall ($r \approx 30$ km), there were the striations that rotated faster than the near center rotation. It was suggested that the striations may be associated with the secondary circulation. The validity of the wind derivation is supported by direct observations using dropsondes. Asymmetric motions were visualized as the deviations from axisymmetric rotation. The flow in the eye was full of asymmetric motions, among which some mesovortices had vorticity whose magnitude is comparable to the vorticity associated with the rotation of the eye. It was suggested that the asymmetric motions may have transported angular momentum inward to intensify the near center rotation.

In Chapter 4, a TC-specific cloud tracking method are proposed and applied to typhoons observed by Himawari-8. By considering the rotational motion of TCs, it became possible to obtain AMVs widely even

from a 2.5-minute interval image sequence. This method was applied to three Typhoons, Haishen (2020), Nanmadol (2022), and Lan (2017), and the uncertainty of the resulting AMVs were evaluated. The characteristics of the obtained AMVs were specifically investigated with a focus on the asymmetric motions. According to the intensity estimation conducted by JTWC, all three typhoons had a similar 1-min maximum sustained wind speed during the analysis period.

In the case of Typhoons Haishen and Nanmadol, the AMVs obtained from 2.5-min interval images were compared with those obtained from 30-sec interval images from research-based special observations conducted by Himawari-8. In the eye of Typhoon Haishen, which had a relatively large eye, 60% of the AMVs were found to have absolute wind speed errors within 2 m/s, while over 80% of the AMVs had errors within 5 m/s. With the azimuthal-mean and 10-min running-mean winds, 80% of the winds had errors within 2 m/s, and 95% had errors within 4 m/s. In the eye of Typhoon Nanmadol, which had a radius about half that of Typhoon Haishen, over 60% of the AMVs had absolute wind speed errors within 3 m/s. With the azimuthal-mean and 10-min running-mean winds, over 70% of the winds have errors within 3 m/s. In both cases, the tangential wind error is thought to be largely due to the difficulty in tracking the rapidly rotating and deformable striations. Additionally, it is thought that the larger angular velocity and greater radial shear of tangential wind in Typhoon Nanmadol compared to Typhoon Haishen made cloud tracking more difficult. Typhoons Nanmadol and Lan were directly observed using GPS dropsondes as part of the T-PARCII project. The AMVs obtained from 2.5-min interval images were compared with wind observations obtained by the dropsondes. In the eye of Nanmadol, the RMSE was 1.2 m/s for tangential wind and 2.5 m/s for radial wind, while in the eye of Lan, the RMSE was 2.2 m/s for tangential wind and 1.5 m/s for radial wind. However, it should be noted that the small number of samples used for comparison may include sampling errors.

The wind distributions in the eyes of analyzed TCs were full of asymmetric motions. The presence of transient wavenumber-1 features in both the tangential and radial velocities were confirmed for all three typhoons throughout the analysis period. These features were consistent with algebraically growing wavenumber-1 disturbances reported theoretically and numerically (Smith and Rosenbluth, 1990; Nolan and Montgomery, 2000; Nolan et al., 2001) or observationally (Marks et al., 2008; Horinouchi et al., 2023). The azimuthal mean angular velocities of all three typhoons were initially characterized by a hollow-like distribution at the start of the analysis period, but became more monotonic with time. In the eyes of Ty-

phoons Haishen and Nanmadol, the angular velocity homogenization gradually occurred from the inner-edge of the eyewall over several hours, while in the eye of Typhoon Lan, the angular velocity in the eye are homogenized in less than 1 hour. The findings align with the observational and numerical analysis conducted by Kossin and Eastin (2001), who utilized aircraft flight-level data to demonstrate a quick enhancement in angular velocity in the eyes of several TCs within 1 hour. They attributed this rise to the angular momentum transport by mesovortices associated with the barotropic instability vicinity of the eyewall, using an idealized barotropic simulation.

To investigate the two-dimensional distribution of vorticity evolution in the eye, aircraft flight-level observations need to be taken a long time to fill the spatial gaps, and radar observations cannot observe the winds in the eye because the lack of precipitation particles. Low-orbit satellites, especially C-band Synthetic Aperture Radar, can estimate the sea surface winds (Mouche et al., 2017; 2019; Zhao et al. 2018) with high spatial resolution. While the high-resolution sea surface wind product can provide an instantaneous vorticity distribution, but it is impossible to sustainably observe the same target for several hours. The TC-specific cloud tracking method developed in this study using third-generation meteorological satellites allows us to fill the spatiotemporal gaps of other observational instruments. In this study, the two-dimensional distribution of vorticity anomalies were first visualized from the AMVs obtained in the eye of Typhoon Lan. The investigation revealed that the rapid changes in the angular velocity field of Typhoon Lan were attributed to horizontal mixing caused by mesovortices. In particular, the positional relationship between the relatively weak vorticity (negative anomaly) near the TC center and the relatively high vorticity (positive anomaly) near the eyewall changed rapidly in a short period of time, indicating its relation to the quick enhancement in angular velocity in the eye. Combining the wind analysis within the eyewall using Doppler radar observations and the lower-level AMVs within the eye may lead to new findings in analyzing the long-term behavior, and is expected to be a future work.

The findings by Kossin and Eastin (2001), which showed that the relative humidity increase associated with the increased equivalent potential temperature near the TC center during the regime transition, suggesting the entrainment from the eyewall into the eye. It was observed that, in the eye of Typhoon Lan, there was generally more cloud cover in the positive anomaly region of vorticity and less cloud cover in the negative anomaly region. This is consistent with the study by Kossin et al. (2002), who showed that the appearance of clouds in visible imagery of multiple TCs visually resembled the distribution of passive tracer

particles that were initially placed in the eyewall and were transported into the eye along with the mesovortices associated with the barotropic instability in an idealized barotropic simulation. Furthermore, the possibility was discussed that entrainment in the middle troposphere is associated with horizontal mixing by mesovortices using dropsonde observations in Typhoon Lan. The advection of equivalent potential temperature from the eyewall into the eye due to the asymmetric motion is consistent with the potential temperature budget analysis from numerical simulations with cloud-resolving model conducted by Tsujino et al. (2021b). The results shown in this study indicate the great potential in investigating the TC dynamics using operational rapid-scan observations of TCs by third-generation meteorological satellites. Statistical studies applying the proposed method to more cases are expected as a future work.

In Chapter 5, the relationships between IR-measured eye radius (R_{eye}) and SAR-measured radius of maximum wind (RMW) were reexamined. The RMW estimation method has been improved and objective criteria has been proposed to classify an eye scene as a clear-eye scene or not. In the 21 clear-eye cases, a very strong relationship between R_{eye} and RMW was shown, although it should be noted that the sample size is small. Regression of RMW by R_{eye} (eq. (5.3)) was accurate to the MAE of 1.7 km. It is more accurate than the regressions shown in previous studies. In most of the unclear-eye cases, the estimated RMW gave the lower bound of RMW regardless of eye shape. In some unclear-eye cases, optically thin clouds covering the eye made the R_{eye} too small. In such cases, masking the optically thin clouds using differential images with other wavelengths might provide a better estimation.

The relationships between the slope of the eyewall and eye sizes were investigated. Consistent with previous studies, a strong linear relationship was confirmed between the eyewall slope and the RMW with high correlation of 0.88. The eyewall slope also showed a strong linear relationship with the R_{eye} (correlation coefficient of 0.90). The cloud features existing near the RMW were discussed. Most of the RMWs were located below the sloping inner edge of the eyewall. In some azimuths, the RMWs were located at radii with even lower CTHs. It was demonstrated that these areas may have been characterized by the presence of characteristic cloud known as striations. These features suggest the possibility of directly estimating RMWs and VMAXs from GMSs. The wind structure around the RMW was also examined, and no clear relationship was found between the RMW estimation error and the wind structure. The difference between VMAX and wind at estimated RMW was shown to be small, and its application to VMAX estimates in combination with RMW estimation is expected.

It is expected that the use of highly accurate RMW estimation will improve the operations through the improvement of the initial conditions for numerical models. Improving the accuracy of RMW estimation in unclear-eye cases, detailed analysis of striations and their statistical investigation, VMAX estimates from GMSs as an application of RMW estimation, and revisiting this study with a larger sample are possible future work.

The developed methods provide wind distribution that was previously unavailable, and are expected to deepen the understanding of TC dynamics. It is expected that the method developed in this study, which estimates the lower-level wind distribution in the eye, can be combined with wind distribution in the eye-wall obtained from radar observations, to reveal previously unknown dynamic processes of mature TCs. TCs form over the ocean and many of them reach their mature stage while still over the ocean. Advances in monitoring techniques for mature TCs would enable us to capture their behavior in detail and contribute to predicting their intensity and the onset of weakening. Estimating the wind distribution of numerous past typhoons using our method and accumulating observational facts can provide insights into the climatological characteristics of wind distributions and yield statistical perspectives. There is a possibility to realize the estimation of the TC intensity in a physical and objective manner by extending the developed methods. Furthermore, the assimilation of the wind-related estimates into TC simulation could be a significant step towards improving the TC intensity estimation and forecasting, which are global challenges.

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