^aAn Observational Study on the Rapid Intensification of Typhoon Chanthu (2021) near the Complex Terrain of Taiwan

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ABSTRACT: Intensification of Typhoon Chanthu (2021) along the eastern coast of Taiwan was accompanied by pronounced asymmetry in eyewall convection dominated by wavenumber-1 features, as observed by a dense radar network in Taiwan. The maximum wind speed at 3-km altitude, retrieved from radar observations, exhibited a rapid increase of approximately 18 m s⁻¹ within an 11-h period during the intensification stage, followed by a significant decrease of approximately 19 m s⁻¹ within 8 h during the weakening stage. Namely, Chanthu underwent both rapid intensification (RI) and rapid weakening (RW) within the 24-h analyzed period, posing challenges for intensity forecasts. During the intensifying stages, the region of maximum eyewall convection asymmetry underwent a sudden cyclonic rotation from the eastern to the northern semicircle immediately after the initiation of terrain-induced boundary inflow from the south of the typhoon, as observed by surface station data. This abrupt rotation of eyewall asymmetry exhibited better agreement with radarderived vertical wind shear (VWS) than that derived from global reanalysis data. This finding suggests that the meso- β -scale VWS is more representative for tropical cyclones than meso- α -scale VWS when the terrain-induced forcing predominates in the environmental conditions. Further examination of the radar-derived VWS indicated that the VWS profile pattern provided a more favorable environment for typhoon intensification. In summary, Chanthu's RI was influenced by the three factors: 1) terrain-induced boundary inflow from the south of the typhoon, observed by surface station data; 2) low-level flow pointing toward the upshear-left direction; and 3) weak upper-level VWS.

SIGNIFICANCE STATEMENT: Tropical cyclone intensity change has been an important issue for both real-time operation and research, but the influence of terrain on intensity change has not been fully understood. Typhoon Chanthu (2021) underwent a significant intensity change near the complex terrain of Taiwan that was observed by a dense radar network. This study analyzes 24 h of radar and weather station data to investigate Chanthu's evolution. The analyses indicate that the complex terrain affected the low-level flow near the TC. Such a change in flow pattern provided additional boundary inflow and a relatively favorable vertical wind shear pattern for TC intensification.

KEYWORDS: Hurricanes/typhoons; Intensification; Topographic effects; Shear structure/flows; Radars/Radar observations; Surface observations

1. Introduction

Taiwan is a mountainous island characterized geographically by the Central Mountain Range (CMR), which stretches south-north across most of Taiwan with the highest peak at approximately 4000 m. Consequently, as tropical cyclones (TCs) approach or move across Taiwan, terrain-induced circulation frequently causes many unique features, such as extreme rainfall (Yang et al. 2008, 2011a,b; Yu and Cheng 2013; Wu 2013; Huang et al. 2014), the confluence of TC and secondary low-pressure circulation (Lee et al. 2008), track deflection/loop (Yeh and Elsberry 1993a,b; Jian and Wu 2008; Huang et al. 2011; Yeh et al. 2012; Hsu et al. 2018; Huang et al. 2020; Hsu et al. 2021), change in translation speed (Hsu et al. 2013), eyewall reintensification or reformation (Liou et al. 2016; Yang et al. 2018; Lin et al. 2020), coastal barrier jet (Kao et al. 2019), foehn winds (Chang and Lin 2011), and temporary intensification before making landfall with eyewall contraction (e.g., Jian and Wu 2008; Chang et al. 2009, 2019; Kao et al. 2019).

Typhoon Chanthu (2021) was a very intense typhoon with an eyewall radius of 10-20 km as it moved along the eastern coast of Taiwan at a distance of 100-150 km from the coast. A remarkable intensification of Chanthu near the complex terrain of Taiwan provided a great opportunity to explore how the nearby terrain may have induced the changes in TC intensity. According to the TC intensity issued by the Central Weather Administration (CWA) and Japan Meteorological Agency (JMA), Typhoon Chanthu became a typhoon in the southwestern Pacific Ocean and reached its maximum sustained wind of more than 70 m s⁻¹ when moving to the ocean adjacent to northeastern Luzon Island of the Philippines. Subsequently, it weakened slightly as it passed through the Bashi Strait with a northwestward motion. After it recurved toward the southeastern offshore area of Taiwan (Fig. 1), its intensity further decreased to a maximum sustained wind of $\sim 50 \text{ m s}^{-1}$. It retained its intensity and gradually weakened when moving along and away from the east coast of Taiwan. During this

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FIG. 1. Track of Typhoon Chanthu (2021) determined by the tropical cyclone eye tracking (TCET) algorithm, overlaid with the distribution of ocean heat content (OHC) from the National Centers for Environmental Information (NCEI) on 11 Sep. Track covered by thick green, yellow, red, and blue lines indicate the first intensifying (stage I), second intensifying (stage II), peak (stage III), and weakening stages (stage IV), respectively, as described in section 3b. The numbers beside the tracks are the dates and times in UTC. The radars, for which the abbreviations with the superscript of R or V indicate the reflectivity or velocity, respectively, were used in this study for analysis. The black triangle denotes the location of the Lan-yu station on Orchid Island.

period, Chanthu was sequentially observed by RCKT, RCGI, RCHL, and RCWF radars. The average distance from RCKT to RCGI, RCGI to RCHL, or RCHL to RCWF is ~100 km (Fig. 1), which provides essential data for conducting high spatial-temporal resolution analyses of the evolution of the TC inner core including the intensity change and eyewall asymmetry during its passage.

The mechanisms for TC asymmetric structures are frequently dominated by environmental vertical wind shear (VWS), which is also highly connected to changes in TC intensity (e.g., Frank and Ritchie 2001; Corbosiero and Molinari 2003; Chen et al. 2006; Riemer et al. 2010; Ryglicki et al. 2021). A strong environmental VWS is considered a negative factor for TC intensification due to the vortex tilting and stabilization that it induces (DeMaria 1996). Additionally, the ventilation effect caused by VWS, which includes radial and downdraft pathways (Alland et al. 2021a,b; Alland and Davis 2022), also exerts a negative impact on TC intensification. Meanwhile, TCs can still intensify under low- to medium-VWS environments (Rios-Berrios and Torn 2017), even undergoing RI through persistent convective bursts (CBs) in the inner-core region (Chen and Gopalakrishnan 2015; Heng et al. 2020). The sheared TCs may tilt toward the downshear side and consequently increase the eyewall convection asymmetry (Jones 1995; Frank and Ritchie 1999, 2001; Reasor et al. 2013). Studies conducting model simulations also indicate that the VWS-induced vertical differential advection to the vortex leads to ascent on the downshear side and descent on the upshear side (Jones 1995; Frank and Ritchie 1999, 2001). Therefore, the eyewall convection exhibits high wavenumber-1 asymmetry with a reflectivity maximum on the left-of-shear side.

A sudden change in the orientation of the eyewall wavenumber-1 asymmetry of TCs may be attributed to shifts in the direction of the VWS. Previous studies have extensively discussed the impact of terrain on the surrounding flow of TCs. Huang et al. (2019) indicated that TC tracks can be influenced when they are located within the typical distance range of 100-300 km from terrain. Simulations by Yeh and Elsberry (1993a,b) demonstrated that TC deflections occur when storms are approximately 200 km away from the terrain due to modifications in the mean steering flow induced by topographic barriers. Tang and Chan (2014, 2015) proposed that the presence of terrain can induce the formation of gyre pairs, leading to gyre-associated flow near the TC center that can influence the TC track prior to landfall. Wu et al. (2015) and Huang and Wu (2018) defined asymmetric flow as the mean state within a 50-km radius around the TC center, examining both the deep-layer mean and vertical distribution of asymmetric flows. Their findings revealed that as TCs approached Taiwan at a distance of approximately 200 km, terrain-induced asymmetric flows were primarily initiated below 625 hPa, while changes in the flow above this level were found to be insignificant. This suggests that terrain-induced flow can modulate the direction and magnitude of low-level flow, consequently modifying the VWS as well. Accordingly, estimating VWS that can properly capture the scale of environmental forcing where TCs are embedded is critical (Wong and Chan 2004; Reasor et al. 2009; Reasor and Eastin 2012; Reasor et al. 2013; Boehm and Bell 2021).

Under the shear-relative framework, a TC can be separated into downshear-left (DL), upshear-left (UL), upshear-right (UR), and upshear-left (UL) quadrants to discuss the innercore convective features induced by the VWS. The relative direction between the VWS and low-level flow (LLF) is also one of the essential factors for TC intensification. To investigate this issue during the tropical cyclogenesis stage, Rappin and Nolan (2012) conducted a numerical simulation. They found that if the orientations of the VWS and LLF were counteraligned (i.e., the LLF is upshear-pointing), the superposition of the TC main circulation and LLF induced a positive LLF anomaly and further moistened the boundary layer on the left-of-shear side. The moistened air parcels propagated cyclonically into the upshear region which promoted the axisymmetrization of the convection. This pattern has the potential to mitigate the vortex tilt and contribute to TC intensification. However, studies with opposite arguments have also been proposed. Chen et al. (2019) conducted idealized simulations with fixed sea surface temperatures (SSTs) of 29.5° and

	RCKT	RCGI	RCHL	RCWF	ISHI
Observation range of reflectivity (km)	460	400	460	460	400
Observation range of Doppler velocity (km)	150	200	190	300	250
Elevation (m)	51.0	284.0	62.0	754.0	533.5
Wavelength (cm)	10	5	10	10	5
Polarization	Single	Dual	Single	Dual	Single
Nyquist velocity (m s ⁻¹)	26.41	40.0	21.16	26.58	52.71
Location	21.90°N, 120.85°E	22.65°N, 121.48°E	23.99°N, 121.63°E	25.07°N, 121.77°E	24.43°N, 124.18°E

TABLE 1. Specifications of the radars used in this study.

31.0°C to investigate the effects of the direction of low-level mean flow (LMF) under the same VWS on changes in TC intensity. The experiment with an SST of 31.0°C was consistent with Rappin and Nolan (2012), but the experiment with an SST of 29.5°C revealed a different result: a DL-pointing LMF is favorable for TC intensification. Chen et al. (2021) further used version 5 of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis product (ERA5; Hersbach et al. 2020) to examine the relationship between intensity change and LMF direction based on 720 TCs from multiple basins, and suggested that the DL-pointing LMF favors intensification.

In contrast to Rappin and Nolan (2012) and Chen et al. (2019), who initiated their simulations with relatively weak initial vortexes (less than 20 m s⁻¹), Lee et al. (2021) took a different approach by initiating their simulations with a strong vortex, starting at a strength of 70 kt (1 kt ≈ 0.51 m s⁻¹). In their idealized experiments, they imposed a consistent 7.5 m s^{-1} VWS while manipulating the direction of the LLF. Results showed that the UL-pointing LLF prompted fast intensification by enhancing surface heat fluxes on the downshear side. These enhanced surface heat fluxes recovered the moist static energy of shear-enhanced downdrafts within the boundary layer over the inflow area. This recovery process prevents the TC eyewall from entraining low-energy air parcels. The convection in the UL quadrant can be maintained by reducing the downdraft ventilation (Alland et al. 2021a,b; Alland and Davis 2022; Fischer et al. 2023). Consequently, the enhancement of axisymmetric heating benefits subsequent intensification.

In this study, comprehensive radar observations of Chanthu were used to investigate the physical mechanisms of dramatic changes in intensity and evolution of the inner core during its passage near Taiwan. Single- and multiple-radar wind retrievals were conducted to examine the evolution of the inner-core structure and discuss the relationship between the eyewall asymmetry and radar-retrieved VWS. The data processing and methodology are described in section 2. The radar analysis and discussion are provided in sections 3 and 4. The final section presents the conclusions.

2. Data and methodology

The operational radar network in Taiwan comprises ten radars, including one S-band dual-polarization (RCWF), three S-band single-polarization (RCHL, RCCG, and RCKT), and six C-band dual-polarization (RCCK, RCMK, RCGI, RCLY, RCNT, and RCSL) radars (Fig. 1) operated by the Central Weather Administration and the Air Force Weather Wing in Taiwan (Chang et al. 2021). As Typhoon Chanthu moved semi-parallel to the eastern coast of Taiwan, it was observed not only by the RCKT, RCGI, RCHL, and RCWF radars but also by the ISHI radar of Japan. The specifications of the five radars are summarized in Table 1. The data observed by the above five radars show that Chanthu's eyewall was well organized with a clear eye during its passage near Taiwan (Fig. 2).

The ground-based velocity tracking display algorithm (GBVTD; Lee et al. 1999) is a single-radar wind retrieved technique that can estimate various aspects of the primary circulation of a TC, including the axisymmetric tangential and radial winds, and asymmetric tangential winds. However, the accuracy of the retrieved TC circulation using the GBVTD is highly dependent on the precise determination of the center position, as the calculations are based on a ring with a fixed radius from the center of the TC. Chang et al. (2009) introduced the Tropical Cyclone Eye Tracking (TCET) algorithm, which was developed to objectively detect and track the eye and center of a TC using radar reflectivity data. The results demonstrate that it can enhance the quality of the GBVTDretrieved circulation for TC with well-organized eyewall structures when compared to the utilization of the TC center derived from the GBVTD-simplex algorithm (Lee and Marks 2000). Therefore, the TCET algorithm was utilized to estimate the TC center from five radars, for which the abbreviations have a superscript of R in Fig. 1. The aliased Doppler velocity was recovered by the vortex-based Doppler velocity dealiasing (VDVD) algorithm described in Chang et al. (2019). Then, the GBVTD algorithm was used for single-Doppler radar retrieval with the data from four radars, for which the abbreviations have a superscript of V in Fig. 1. Both radar reflectivity and Doppler velocity data are interpolated to achieve a spatial resolution of 1 km \times 1°, centered on the TCET centers. The temporal resolutions are 6-8 min, as determined based on the volume scan times of multiple radars. Furthermore, the dense radar network provides the opportunity for dual-Doppler synthetic analysis (Ray et al. 1975; Shapiro et al. 2009; Liou and Chang 2009), offering valuable information for the analysis and evaluation of the accuracy of single-Doppler wind retrievals. The composite dual-Doppler synthetic wind (DDW) data result from six sets of dual-Doppler analyses (Chang et al. 2019), incorporating



FIG. 2. The lowest available DDW at (a) 1000 UTC 11 Sep, (b) 1600 UTC 11 Sep, (c) 2200 UTC 11 Sep, and (d) 0400 UTC 12 Sep 2021. The wind barbs, depicted in dark blue, blue, purple, red–pink, and pink, represent wind retrievals from altitudes of 0–2, 2–4, 4–6, 6–8, and >8 km, respectively. The color shading corresponds to the composite reflectivity.

data from RCKT, RCGI, RCHL, and RCWF radars. This dataset features a high spatial resolution of 1 km in both horizontal and vertical dimensions, along with a temporal resolution of 10 min. The azimuthal gaps in the radar data and the gap-filling process may influence both the magnitude and phase of the Fourier decomposition. To primarily extract the characteristics of wavenumber-0 axisymmetric tangential wind, a gap size of 180° is considered acceptable (Lorsolo and Aksoy 2012; Cha and Bell 2021). Consequently, the GBVTD technique is applied to retrieve the mean tangential wind when the azimuthal coverage of the available data exceeds 50%. In cases where there are gaps in the Doppler velocity data, linear interpolation is used to fill the azimuthal gaps, allowing for the utilization of fast Fourier transform (FFT) (Heideman et al. 1985) decomposition in the GBVTD algorithm. For the azimuthal average of reflectivity data, the same 50% azimuthal coverage criterion is applied, but no attempts are made to fill any data gaps. The temporal coverage of the GBVTD retrieval from each radar is limited to a specific portion of the overall analyzed period. To capture a comprehensive temporal evolution of the wind structure within the inner core of the TC (within a 60-km radius from the TCET centers) from these four radars, the GBVTD-retrieved winds from each radar were composited within 10-min intervals using the inverse distance weighting.

In addition to the retrieval of the main circulation of Chanthu, the VWS of the embedded TC is also an essential information corresponding to its convection asymmetry. However, an accurate estimate of the mean flow of a TC is not straightforward to obtain in real time, especially when the terrain is nearby and terrain-induced flow is enhanced. While the DDWs were indeed conducted for the analysis of Typhoon Chanthu, which can provide more accurate wind information compared to the single radar retrieval method, there are certain limitations to be considered. Specifically, the winds near the baseline between two radars cannot be directly retrieved using the DDW. During the major intensification stage of Typhoon Chanthu, which occurred from 1600 to 2100 UTC 11 September, the storm happened to be located near the baseline between the RCGI and RCHL radars. As a result, the DDW data were unavailable for the western to northwestern sides of the typhoon (Fig. 2b). To ensure comprehensive analysis and maintain continuity in the dataset, the GBVTD method was employed for wind retrieval during this specific period. Moreover, the horizontally uneven distribution of the DDW makes the calculation of mean flow difficult. The directions of the mean flow derived from the DDW dataset were found to be unstable over time and did not consistently align with the observed eyewall asymmetry (figure not shown).

To address this limitation and obtain a more reliable estimate of the mean flow, the authors conducted a further application of the GBVTD method. This involved utilizing two adjacent radars capable of simultaneously observing the Doppler velocity within the inner core of the typhoon. The detailed methodology for this approach is documented in the appendix of Murillo et al. (2011). They argued that the unresolved cross-beam mean flow is one of the sources of error when estimating the mean tangential wind using the GBVTD. Building upon this concept, the authors extended and applied this method in the present study for the estimation of the mean flow of a TC. This allowed for a more comprehensive examination of the mean flow, which could be further correlated with the observed TC eyewall asymmetry. Area-average V_M (the magnitude of mean flow) and θ_M (the direction of mean flow) with different radii criteria of rings (0-60, 10-60, 20-60, and 30-60 km) were first evaluated. The

results showed a significant fluctuation of the mean flow time series if the strong wind data near the RMW (radius of maximum wind) were included (e.g., 0-60, 10-60, 20-60 km) for calculation. Therefore, V_M and θ_M averaged within 30-60-km radii (2-4 times the RMW) were utilized for improved data interpretability. Note that the mean tangential winds presented in this study were corrected by the GBVTD-derived mean flow according to the Eq. (20) in Lee et al. (1999). The other mean flow utilized in this study, derived from ERA5 data, was the mean wind within a 500-km radius from the TC center (Reasor and Eastin 2012). The VWS is commonly determined by calculating the vector difference of the mean flow between 200 and 850 hPa. However, due to reduced radar data density at higher elevations, the calculation of radar-derived mean flow is not feasible above 8 km. To facilitate a more comprehensive and comparable analysis between radar data and ERA5 data, the selected layers of the ERA5 dataset are at 800, 700, 600, 550, 450, 400, and 350 hPa, which closely correspond to the altitude of 2, 3, 4, 5, 6, 7, and 8 km, respectively. As a result, the VWS derived from GBVTD was computed by taking the vector difference of the mean flow between 8 and 2 km, corresponding to the pressure levels of 350 and 800 hPa, along with the ERA5-derived VWS.

It is important to note that the mean flows analyzed in section 3 contain the information of typhoon motion speeds and are exclusively used for the calculation of the deep-layer mean (DLM). However, for the subsequent analysis discussed in section 4, the mean flows were adjusted by subtracting the motion speeds to specifically focus on the discussion of the relative direction between the VWS and the LLF. To evaluate the agreement between the TC motion and the DLM derived from these mean flows, we utilize the DLM definition provided by Velden and Leslie (1991) and Hu and Zou (2021). The original formula is as follows:

$$\frac{\text{DLM} = \frac{75\mathbf{V}_{300} + 100\mathbf{V}_{400} + 150\mathbf{V}_{500} + 175\mathbf{V}_{600} + 175\mathbf{V}_{700} + 150\mathbf{V}_{850}}{825},$$
(1)

where \mathbf{V}_{300} , \mathbf{V}_{400} , \mathbf{V}_{500} , \mathbf{V}_{600} , \mathbf{V}_{700} , and \mathbf{V}_{850} indicate the wind vector at 300, 400, 500, 600, 700, and 850 hPa, respectively. As discussed above, we have adjusted the vertical layers in the ERA5 data to 800, 700, 600, 550, 450, 400, and 350 hPa to align more closely with the 2–8-km vertical range, where the radar data provide more comprehensive coverage. Accordingly, the above formula has been modified to

$$\frac{\text{DLM}_{\text{ERA5}}}{\frac{75\mathbf{V}_{350} + 100\mathbf{V}_{400} + 150\mathbf{V}_{550} + 175\mathbf{V}_{600} + 175\mathbf{V}_{700} + 150\mathbf{V}_{800}}{825}}{825}$$

The corresponding formula for radar-derived DLM is

$$\frac{\text{DLM}_{\text{GBVTD}}}{\frac{75\mathbf{V}_{8km} + 100\mathbf{V}_{7km} + 150\mathbf{V}_{5km} + 175\mathbf{V}_{4km} + 175\mathbf{V}_{3km} + 150\mathbf{V}_{2km}}{825}}.$$
(3)

In the following sections, the GBVTD-derived mean flow was compared with the ERA5-derived mean flow and was used to interpret the connection between the movement and convection asymmetry of TY Chanthu.

3. Radar analysis

a. Overall structure

Figure 1 shows the TCET track with a 10-min interval from the radars, for which the abbreviations have an upper index of "R". A northwestward track with a speed of approximately less than 3 m s⁻¹ before 0600 UTC 11 September was found when Typhoon Chanthu moved into the Bashi Strait. Afterward, Chanthu slowed, recurved to a northeastward motion, and started to accelerate to ~6 m s⁻¹. Chanthu moved northward with a similar speed as it moved into the eastern offshore region of Taiwan. Later, it accelerated after 0000 UTC 12 September and exhibited a north-northwestward motion when it was close to the northeastern tip of Taiwan. After 0400 UTC 12 September, the track turned back to northeastward motion and slowed to a speed of approximately 5 m s⁻¹ in the northeastern offshore area of Taiwan as it moved to the East China Sea.

Figure 2 shows the composite dual-Doppler wind retrievals every 6 h from 1000 UTC 11 September to 0400 UTC 12 September. Very intense cyclonic structures were found as the typhoon moved northward from the southeastern to the northeastern offshore area of Taiwan. The significant eyewall circulation had a maximum wind speed of more than 50 m s⁻¹ and an RMW of approximately 15–20 km at altitudes of 3–4 km. The wind speeds were rapidly reduced to 20–25 m s⁻¹ at a radius of 50 km from the circulation center. This strong radial gradient of tangential wind indicates that Chanthu was a compact TC. In the outer rainband regions over the northern part of Chanthu, the winds were characterized by southeasterly winds with wind speeds of approximately 15–20 m s⁻¹ (Fig. 2a).

As the typhoon moved northward, the wind speeds increased, with a maximum wind speed of more than 60 m s^{-1} within the inner core (Fig. 2b). At 2200 UTC 11 September, the wind speeds were further enhanced, with a maximum wind speed of more than 65 m s^{-1} in the eastern quadrant (Fig. 2c). In addition, the presence of echo-free areas was consistently observed in the southeastern offshore region of Taiwan. This phenomenon, which has been observed in numerous typhoon cases, including Haitang (2005), Talim (2005), Matsa (2005), and Krosa (2007), has been hypothesized to be associated with the adiabatic warming of downslope flow induced by the eastward wind component originating from the southern quadrant of the typhoon circulation across the CMR (Chen et al. 2010). At 0400 UTC 12 September, the typhoon intensity gradually weakened with a maximum wind speed of approximately 55 m s⁻¹ as it approached the northeastern tip of Taiwan (Fig. 2d). The echo-free areas exhibited a consistent spatial position, but their size notably expanded.

Figure 3 illustrates the temporal evolution of reflectivity within a 90-km radius from the TCET center of Typhoon

Chanthu. According to the evolution of GBVTD-retrieved maximum tangential wind (v_{max}) and RMW, the analyzed period can be divided into four stages: the first (or minor) intensification, second (or major) intensification, peak, and weakening stages (Fig. 4). During stages I and III, the eyewall convection prominently displayed wavenumber-1 azimuthal asymmetry. In stage I, the maximum asymmetry was observed in the eastern sector (Figs. 3a,b). Toward the end of stage I, the asymmetry diminished, resulting in a more axisymmetric eyewall (Fig. 3c). At 1600 UTC, the wavenumber-0 signal became most pronounced (Fig. 3d). However, this axisymmetric structure persisted for only approximately 2 h before the wavenumber-1 signal regained dominance, albeit with a shift in the maximum from the eastern to northeastern sector (Figs. 3e,f). Subsequently, the area of high reflectivity above 45 dBZ extended beyond the northeast sector, encompassing the downstream sector on the northwestern side (Figs. 3g-i).

The comparison between ERA5-derived and radar-derived VWS revealed discrepancies after 1200 UTC. Prior to 1200 UTC, the eyewall asymmetry correlated well with both VWS datasets (Figs. 3a,b). Between 1400 and 1600 UTC, the eyewall displayed an increased axisymmetric structure, aligning with the weak VWS obtained from radar (Figs. 3c,d). After 1600 UTC, the VWS intensified and shifted from northerly to northwesterly. Simultaneously, the maximum eyewall asymmetry shifted from the eastern sector to the northeastern sector, located on the DL side (Figs. 3b,e). However, it is worth noting that the ERA5-derived VWS consistently maintained a northerly direction throughout stages I to III, which contrasts with the observed eyewall asymmetry.

The previous paragraphs provide a general and qualitative review of the kinetic and convective features of Typhoon Chanthu. Quantitative information on v_{max} and RMW of Chanthu derived from the GBVTD at 3-km altitude is described in the following. During the first intensification stage (denoted by stage I), the $v_{\rm max}$ had a minor increase from ~48 to 52 m s⁻¹ accompanied by a significant RMW contraction from 20 to 12 km (e.g., reduced 40%) from 1000 to 1600 UTC 11 September. At approximately 1600 UTC, the RMW dramatically expanded from 12 to 20 km; however, v_{max} remained at ~50 m s⁻¹. After the stage I, the RMW started to contract again from 20 to 12 km between 1600 and 2100 UTC 11 September which was defined as the major intensification stage (denoted by stage II) in this study. The v_{max} significantly increased from ~50 to ~64 m s⁻¹ in only 5 h during this stage. Later, Chanthu evolved into the most intense stage and remained at a $v_{\rm max}$ of 58–62 m s⁻¹ in the following 5 h (denoted by stage III). Finally, Chanthu weakened quickly after 0200 UTC with an average rate of \sim 2.4 m s⁻¹ h⁻¹ in the last 8 h of the analysis time (denoted by stage IV). The $v_{\rm max}$ and RMW evolution derived from GBVTD is consistent with that of DDW, indicating that GBVTD is a robust algorithm for retrieving TC winds, as documented by Cha and Bell (2021).

Overall, the 3-km-altitude GBVTD-retrieved v_{max} increased by ~18 m s⁻¹ in 11 h (1000–0200 UTC 11 September). The intensification rate can be considered RI, which is commonly defined as the maximum surface wind intensifying by more than 20 kt (10.3 m s⁻¹) in 12 h (Kaplan et al. 2015). Although the



FIG. 3. Reflectivity snapshot at 3-km altitude centered on the TCET centers at (a) 1000, (b) 1200, (c) 1400 (stage I); (d) 1600, (e) 1800, (f) 2000 (stage II); and (g) 2200 11 Sep, (h) 0000, and (i) 0200 12 Sep (stage III). The blue arrows indicate GBVTD-derived VWS, while the black arrows represent ERA5-derived VWS. Solid arrows denote VWS between 2 and 8 km, and dashed arrows correspond to VWS between 2 and 5 km. The interval between the thick circles is 30 km, and between the thin circles it is 10 km. The interval between thin circles also represents 3 m s⁻¹ for VWS.

definition of RI is based on surface wind change, Franklin et al. (2003) found that the ratio of wind speed from the eyewall surface to 700 hPa is approximately 0.9. Therefore, the change in wind speed at 3 km should generally reflect the increasing rate near the surface. In the weakening stage, the 3-km altitude v_{max} decreased significantly by 19 m s⁻¹ in 8 h, which is also considered rapid weakening (RW), defined as the TC intensity decreasing by 20 kt (10.3 m s⁻¹) or more in 24 h (DeMaria et al. 2012). The decrease in intensity of Chanthu reached 10.3 m s⁻¹ only during an ~3-h period from 0200 to 0500 UTC and sequentially weakened to the end of the analysis period. Notably, Chanthu experienced both RI and RW within 24 h. Such a dramatic change in intensity is a serious challenge for

operation centers to issue and forecast the intensity of the TC. The possible factors that caused the intensification and weakening of Typhoon Chanthu will be further discussed in the following section.

b. Evolution of the inner-core structure

The Hovmöller diagram of axisymmetric tangential winds reveals that Chanthu retained its compact wind structure over the whole analysis period (Fig. 5a). Typhoon Chanthu not only had an extremely small eyewall radius compared with the climatology value of 54.7 km in the western Pacific (Knapp et al. 2018), but also had an extremely strong nearcore (RMW to $3 \times RMW$) radial gradient of tangential wind



FIG. 4. Temporal evolutions of the v_{max} (blue line) and RMW (R_{max} , red line) of Typhoon Chanthu at 3-km altitude. The v_{max} and RMW derived from dual-Doppler synthetic winds are indicated in light blue and light red, respectively.

of 0.8–0.9 m s⁻¹ km⁻¹ compared with that of TCs in the same intensity category (Vinour et al. 2021).

Due to the RMW dramatically expanding from 12 to 20 km at approximately 1600 UTC 11 September (Fig. 4), it is suggested that Chanthu was experiencing an eyewall replacement cycle (ERC). However, the tangential wind did not present an apparent secondary eyewall formation (SEF) at 3-km altitude during the first intensifying stage (Fig. 5a), and v_{max} remained at a value of $\sim 50 \text{ m s}^{-1}$. To highlight the presence of the double wind peak associated with the ERC, Hovmöller diagrams of tangential wind were constructed at elevations ranging from 1 to 10 km, with contour intervals of 1 m s⁻¹ (figure not shown). Analysis of the Hovmöller diagrams at 2-4 km revealed that the RMW was predominantly situated between 12 and 15 km. Notably, a significant jump in the RMW occurred at approximately 1600 UTC; however, a clear double wind peak pattern was not found. In contrast, at higher elevations of 5-7 km, a progressive increase in wind speed was observed within the radius range of 20-30 km, starting from 1400 UTC and extending radially until 1430 UTC. Over the subsequent 2.5 h, this secondary wind maximum ceased its radial extension, and the radius of this secondary wind maximum exhibited a slight contraction. The presence of a distinct double wind peak pattern was most pronounced at 1600 UTC. Following this time, the primary eyewall dissipated, and the secondary eyewall underwent a gradual contraction. Based on these findings, it is proposed that Typhoon Chanthu underwent an ERC between 1400 and 1700 UTC. Notably, the primary and secondary eyewalls of Chanthu were separated by a mere 10 km. The observed ERC in this case, characterized by the merging of the secondary eyewall with the primary eyewall rather than complete replacement, shares similarities with the flight-level tangential wind pattern observed during the second ERC

event of Hurricane Irma (2017), as documented by Fischer et al. (2020; see their Fig. 5).

Moreover, the radius-time Hovmöller diagram of azimuthally averaged reflectivity at an altitude of 3 km provides further evidence, showing that the secondary eyewall began to form two hours prior to the completion of the ERC, with a radius of 17 km from the TC center (Fig. 5b). This observation is consistent with the tangential wind field observed at elevations between 5 and 7 km. A contraction of the eyewall, similar to RMW evolution, was found in both the first and second intensification stages. The eyewall radius changed dramatically from ~ 12 to ~ 18 km between the end of the first intensification stage and the beginning of the second intensifying stage. Another noteworthy observation is the displacement of the eyewall, defined by the region of peak reflectivity, relative to the RMW before and after the ERC. Prior to the ERC, the eyewall was situated inward of the RMW. However, after the ERC, the eyewall shifted outward and aligned with the RMW. The eyewall reflectivity reached 40-50 dBZ at approximately 0000 UTC 12 September when the TC was evolving to the end of the peak stage. At the same time, the eyewall width started to increase and became much larger in the following weakening stage. Generally, the eyewall radii varied from 12 to 18 km during the first three stages.

Figure 6 shows four snapshots of axisymmetric tangential winds, taken at approximately 6-h intervals, from the RCKT, RCGI, RCHL, and RCWF radars during the analysis period. At 1010 UTC (Fig. 6a), the axisymmetric tangential wind maximum reached 50 m s⁻¹, and the RMW was approximately 15 km at an altitude of 1 km. Additionally, a double-peak signal between altitudes of 3 and 6 km at radii of 15 and 22 km was found. Approximately six hours later, axisymmetric tangential winds increased for all levels with a maximum



FIG. 5. (a) Radius-time Hovmöller diagram of the GBVTD-derived axisymmetric tangential wind at 3-km altitude for Typhoon Chanthu, observed by the RCWF, RCHL, RCGI, and RCKT radars between 1000 UTC 11 Sep and 1000 UTC 12 Sep 2021. The shading intervals are every 5 m s⁻¹, and the black solid lines indicate the RMW. (b) As in (a), but for the azimuthally averaged reflectivity field. The shading intervals indicate the reflectivity every 5 dBZ. The blue line along the ordinate indicates the time period with mean-flow correction.

wind speed of more than 55 m s^{-1} at 2 km. The double-peak signals were still apparent and could reach an altitude of 8 km (Fig. 6b). The double peak in the tangential wind observed in Typhoon Chanthu resembles that observed in Hurricane Irma (2017) (Fischer et al. 2020; see their Fig. 11). At 2200 UTC (Fig. 6c), the RMW contracted to 13 km, and tangential winds dramatically increased. The maximum wind speed reached more than 65 m s⁻¹ at an altitude of 1 km, whereas the double-peak signal disappeared and reached sharper gradients horizontally and vertically compared with that at the previous analysis time. The tangential winds generally decreased with a maximum wind speed of 55-60 m s⁻¹ occurring at an altitude of 1 km, as the typhoon center was located offshore of northeastern Taiwan, where the distance to the RCWF radar was 59 km at 0400 UTC (Fig. 6d). Generally, the axisymmetric structure of tangential winds changed obviously during the analysis period. The vertical extent of tangential winds greater than 50 m s⁻¹ varied from an altitude of 2 km to more than 10 km during the first three times analyzed. In addition, the horizontal extent for tangential winds greater than 35 m s^{-1} at an altitude of 2 km showed no significant difference from 40 to 45 km during the intensifying stages. At the weakening stage,

the radius for the horizontal extent of 35 m s⁻¹ at an altitude of 2 km decreased to 30 km.

c. Radar-derived mean flow and VWS

Figures 7a and 7b present the GBVTD-derived mean flow from 2- to 8-km altitude and the ERA5-derived mean flow from 800 to 350 hPa, respectively (see section 2 for details). The moving speed and direction of Chanthu calculated from the TCET track from 1000 UTC 11 September to 1000 UTC 12 September are also illustrated in Fig. 7. The moving speeds of Typhoon Chanthu were mainly between 3 and 12 m s^{-1} , with the moving directions distributed from north-northwest to north. The ERA5 DLM flow speeds were mainly between 3 and 7 m s⁻¹, and the directions were mainly from the south to southwest, roughly agreeing with the typhoon motions. The GBVTD-derived DLM flow contained more detailed information because of its high spatial and temporal resolution and showed a better consistency with the TC moving speeds and directions than those from ERA5. In particular, the GBVTD-derived DLM flows accelerated after 2300 UTC 11 September, which is consistent with the apparent increasing speeds of Chanthu's movement. This indicates that the



FIG. 6. Axisymmetric structure of tangential winds at (a) 1010 UTC from RCKT, (b) 1600 UTC from RCGI, (c) 2200 UTC 11 Sep from RCHL, and (d) 0400 UTC 12 Sep from RCWF.

GBVTD-derived mean flow can approximately represent the steering flow when Chanthu is near Taiwan.

However, the VWSs derived from the two datasets were remarkably different. Both VWSs ranged from north-northeasterly to north-northwesterly before 1400 UTC 11 September. After 1600 UTC, the ERA5-derived VWS remained northerly, but the GBVTD-derived VWS apparently turned northwesterly. The magnitudes of the mean flows derived from the two datasets at an altitude of 8 km were similarly small. The major factor influencing the VWS difference between the two datasets was the direction of the LMF. The directions of both the GBVTD-derived and ERA5-derived mean flows were vertically homogeneous (e.g., south-southwesterly) between 1400 and 1600 UTC. Only the GBVTD-derived LMF turned from south-southwesterly to south-southeasterly after 1600 UTC. This change might be caused by the terrain blocking effect as the TC moved to the southeast offshore of Taiwan, which drove the LMF to turn south-southeasterly from the open ocean without being blocked. As the height of the southern part of the Taiwan terrain is lower than 2000 m, the flows above 3 km remained south-southwesterly. The mid- to upper-level mean

flows decreased from ~5 to ~3 m s⁻¹ and turned southwesterly after 1800 UTC. This change in direction resulted in a gradual increase in the GBVTD-derived VWS. It is worth emphasizing that the mean flow obtained from GBVTD characterizes the spatially averaged state within an annulus ranging from 30- to 60-km radii from the TC center, signifying a meso- β -scale mean flow. In contrast, the ERA5-derived mean flow represents the mean wind within a 500-km radius from the TC center, corresponding to a meso- α -scale mean flow. Consequently, the ERA5-derived LMF exhibited only minor changes in direction, which may have resulted from the inability of the ERA5 data to resolve the terrain-induced flow.

Wong and Chan (2004) suggested that the VWS estimated by different area-mean criteria could significantly affect the relationship between the VWS and TC intensity change. They found that the shears within areas close to the TC center (i.e., 200, 200–400, and 400–600 km) are larger than those within areas far from the TC center (i.e., 600–800 and 800–1000 km). The former shear also has larger temporal variations than the latter shear. Reasor et al. (2009) and Reasor and Eastin (2012)



FIG. 7. Temporal evolution of the mean flow in different layers (blue, green, and brown colors), along with the associated DLM (gray color) and VWS (red color) fields for Typhoon Chanthu. The mean flow is derived from (a) GBVTD retrievals and (b) ERA5 data. TC motion derived from TCET centers is depicted in black. The GBVTD and TC motion fields are presented at 20-min intervals, while the ERA5 data are displayed at 60-min intervals. The magnitude and direction of each field are represented by dots and arrows, respectively. A reference arrow length of 5 m s⁻¹ is provided at the bottom-right corner of the figure. The spatial coverage of the region represented by the GBVTD- and ERA5-derived mean flows relative to the geographical extent of Taiwan is illustrated on the right-hand side of (a) and (b).

used airborne Doppler analyses to estimate the local VWS within 60 km from the center of Hurricane Guillermo, and their results showed remarkable agreement with those of the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria and Kaplan 1994; DeMaria et al. 2005). Reasor et al. (2013) utilized 75 TC flights of airborne Doppler radar data through a composite approach to examine the TC asymmetry induced by the VWS. However, they found that the local deep-layer shear from radar is on the clockwise side of large-scale shear by

approximately 40°. This direction bias was also found in Cha et al. (2021), who used ground-based radars and airborne Doppler radar to analyze the ERC process of Hurricane Matthew (2016) influenced by a strong VWS. The above studies showed that estimating the VWS that can reflect what the TC core actually "feels" is important (Reasor and Eastin 2012; Boehm and Bell 2021). Therefore, a new estimation of the local VWS near the inner-core region derived from ground-based radar is proposed in this study. The consistency of the GBVTD-derived (i.e.,



FIG. 8. As in Fig. 5b, but for the reflectivity averaged over radii of RMW \pm 2 km from TCET centers. The shading intervals indicate the reflectivity every 5 dBZ. Dots of black, gray, navy blue, and royal blue color indicate the downshear, upshear, left-of-shear, and right-of-shear sides determined from (a) ERA5 data every 60 min and (b) GBVTD data every 10 min, respectively. The text boxes UR, UL, DR, and DL are abbreviations for upshear-right, upshear-left, downshear-right, and downshear-left, respectively. The cyan arrows indicate the shift direction of UR, UL, DR, and DL.

meso- β -scale) and ERA5-derived (i.e., meso- α -scale) VWSs with eyewall asymmetry were also examined and compared as follows.

Figure 8 illustrates the time-azimuth distribution of reflectivity within the eyewall region, averaged over radii of RMW \pm 2 km from the center of the TC. This analysis follows the methodology employed by Cha et al. (2021) to examine the asymmetric structure of the eyewall. Throughout the entire analysis period, a significant wavenumber-1 asymmetry was consistently observed, also depicted in Fig. 3. Additionally, a counterclockwise orientation of the eyewall wavenumber-1 asymmetry occurred just after the completion of the ERC. For the GBVTD-derived mean flow, the low-level mean flow turned from south-southwesterly to south-southeasterly after 1600 UTC, which caused a change in the VWS direction from northeasterly to northwesterly (Fig. 7). Accordingly, the DL quadrant of the GBVTD-derived VWS was initially observed approximately between east-southeast and south-southwest at 1100 UTC and subsequently rotated to a direction approximately between

north-northeast and east-southeast after 1700 UTC (Fig. 8b). This rotation of the VWS direction aligns well with the continuous presence of the reflectivity maximum on the left side of the shear. In contrast, the DL quadrant of the ERA5-derived VWS only exhibited a slight rotation to a direction approximately between east and south after 1600 UTC (Fig. 8a). The reflectivity maximum was in the UL quadrant, which is inconsistent with previous studies when the eyewall asymmetry is contributed by the VWS. Thus, the direction of the GBVTD-derived VWS was 40°-50° to the left of that of the ERA5-derived VWS when Chanthu was \sim 100 km from the Taiwan coast. This finding indicates that the GBVTD-derived meso-\beta-scale VWS can properly reflect the sudden change in direction caused by the terrain and shows better agreement with the asymmetry of the TC eyewall. The above analyses reveal that a dense radar network can provide additional information, such as VWSs with high temporal resolution, for real-time diagnosis. It also indicates that when the TC was near the Taiwan terrain, the applicability of the ERA5-derived meso- α -scale VWS may have been reduced.

4. Discussion

Typhoon Chanthu underwent RI when it moved roughly parallel to the eastern coast of Taiwan at a distance of approximately 100 km. Because the TC was very close to Taiwan, terrain effects might have played an important role in modulating the TC circulation at low levels that potentially contributed to TC intensification. In addition, this extremely compact (e.g., small RMW and strong near-core radial wind gradient) TC was also embedded in a moderate VWS. Shimada (2022) found that small TCs are less impacted by waters with relatively low ocean heat content (OHC) if the SST is sufficiently high; however, they are more vulnerable to VWS than large TCs. During the RI period in Typhoon Chanthu, the SST and OHC encountered by the storm remained above 30°C (figure not shown) and 100 kJ cm⁻¹ (Fig. 1), respectively. This indicates that Chanthu's intensification was not primarily attributed to a positive change of the heat flux. Consequently, Typhoon Chanthu's intensification relies on the support of additional internal or environmental factors to counteract the adverse effects of VWS. In this section, possible factors or processes, such as terrain effects and VWS profile patterns, will be discussed.

a. Terrain effects

To investigate the effects of flow detouring around the CMR near the surface on TC intensity change, wind observations from two island surface stations on Orchid Island (e.g., Lan-yu station) and Green Island in offshore areas of southeastern Taiwan and one weather buoy station in the north offshore of Orchid Island were analyzed. Figure 9 shows the composite dual-Doppler retrieval winds between 1400 and 1700 UTC 11 September overlaid with surface wind observations. At 1400 UTC, the surface winds were generally consistent with the dual-Doppler retrieval winds aloft but with lower speeds. The surface wind directions near Orchid Island (green and cyan wind barb) were dominated by TC cyclonic circulation (Fig. 9a). However, a change in wind direction was observed at the surface near Orchid Island at 1700 UTC, with winds turning more radially inward toward the TC center compared to earlier analyzed times (Fig. 9d). This change in wind direction was not found at higher altitudes. In contrast, similar changes were not observed near Green Island. Therefore, the radial-inward change in surface wind direction near Orchid Island may have been induced by detouring flow around the terrain and is one possible factor in enhancing eyewall asymmetry convection.

To further investigate the vertical extent of terrain-induced circulation influence, we analyzed the evolution of vertical wind profiles. These profiles were constructed from surface wind data from Lan-yu station and upper-level wind data from DDW, with the TC motion speed subtracted (Fig. 10). As the TC moved northward from the southeastern to north-northeastern side of the Lan-yu station between 1000 and 1800 UTC 11 September (Fig. 1), the wind directions at every elevation roughly turned from northwest, north to northeast, primarily agreeing with the wind direction of the TC main circulation. The inflow angles above Lan-yu station are basically less than 10° because of the lack of the effect from surface friction. In contrast, the magnitude of the inflow angles near the surface wind are significant with a trend initially increasing (i.e.,

became more outward) at 1130 UTC and then decreasing (i.e., became more inward) at 1330 UTC again (Fig. 10). This observed trend aligns with a dropwindsonde-based parametric model proposed by Zhang and Uhlhorn (2012), which performs a sequential change in inflow angles from the left-front, to left, to left-rear quadrant relative to a TC's motion direction. However, the magnitudes of the inflow angles significantly exceeded those estimated by the parametric model, particularly after 1500 UTC, indicating that the influence was not only from friction but also from terrain. While both the friction and terrain have a noticeable impact on altering the inflow angles, their effect is primarily limited to the near-boundary layer region.

To clarify whether the aforementioned inflow angles in the TC boundary layer were mainly driven by friction or terrain, a comparison was made between the inflow angles estimated by the parametric model proposed by Zhang and Uhlhorn (2012) and those obtained in this study. The parametric model indicated that for a TC with similar characteristics to Typhoon Chanthu, with a translational speed of 6 m s^{-1} and a maximum wind speed of 55 m s⁻¹, the storm-relative inflow angles in the left-rear quadrant are less than 20° (see the fourth row and third column of Fig. 14 in Zhang and Uhlhorn 2012). However, after 1400 UTC, when Chanthu moved to the northeast side of the Lan-yu station, the wind direction turned from northerly to west-southwesterly (Fig. 9). The storm-relative inflow angles (Fig. 10) exceeded 30° (indicated by brown shading), surpassing the values estimated by the parametric model. It is thus suggested that the terrain effect can partly contribute to the increase in the inflow angle.

The sudden change in wind direction at Lan-yu station from northerly to west-southwesterly serves as an indicator for identifying the initiation of terrain-induced detouring flow (TDF), which is a unique phenomenon that occurs when TCs approach the east coast of Taiwan. As TCs approach the east coast, the airflow direction on the western side of Taiwan gradually transitions from being dominated by northerly components to westerly components. During this transition, the component of the airflow direction perpendicular to the terrain becomes more prominent, resulting in airflow blockage by the terrain and causing the airflow to shift in a south-southeast direction parallel to the terrain. This blockage persists until the airflow reaches the southern tip of Taiwan, where the blocking effect of the terrain diminishes, enabling the airflow to resume its movement toward the TC center. Finally, this detouring process forces the airflow to approach the TC center with a larger inflow angle. A demonstration of the surface streamlines of TDF can be found in Fig. 1a of Yeh and Elsberry (1993b).

During the study period, the wind direction at Lan-yu station underwent a sudden change from northerly to west-southwesterly within a span of 3 h (1400–1600 UTC, Fig. 10), which clearly indicated the initiation of TDF. The occurrence of TDF depends on the relative positions between the typhoon and Taiwan Island, the size of the typhoon's wind field structure, and the preexisting background flow direction. In cases where a TC approaches Taiwan from the eastern side with a much larger size than that of Chanthu, the initiation of TDF occurs earlier, even when the TC is still far from Taiwan. For instance, during the passage of Typhoon Soudelor (2015)



FIG. 9. The composite dual-Doppler wind retrievals overlaid with surface wind observations at (a) 1400, (b) 1500, (c) 1600, and (b) 1700 UTC 11 Sep. The color bars of the DDW bars are as in Fig. 2. The green, red, and cyan colors indicate the observations from surface stations, automatic surface stations, and buoys, respectively.

with a 15 m s⁻¹ radius extending over 400 km, as it approached Taiwan from the eastern ocean, the initiation of TDF was observed when the TC was over 200 km away from Lan-yu station (figure not shown). Although the impact of the TDF on TC intensification change is not fully understood and well documented, a numerical model simulation study of Typhoon Maria (2018) revealed the possibility that the TDF can cause TC intensification. Huang et al. (2020) claimed that when a TC moved to the northeast offshore of Taiwan, the terrainenhanced low-level southerly flow east of Taiwan transported angular momentum to the eyewall, resulting in TC intensification. Therefore, the authors suggest that the occurrence of TDF is a significant factor influencing the angles of TC inflow and a possible factor prompting TC intensification.

To further examine the vertical extent over which the circulation was influenced by terrain, the evolution of vertical wind profiles that combine the surface wind at the Lan-yu station

and the DDW aloft were analyzed (Fig. 10). The TC motion speed was subtracted from the wind profiles for quantitative comparisons with the theoretical tangential wind direction. It is found that the influence of TDF is related to the distance from the station to the RMW of the typhoon. Since the TDF speed is relatively small ($\sim 10 \text{ m s}^{-1}$) compared to the wind speed near the RMW, its impact on the wind direction becomes more evident as the station is located further away from the RMW. Therefore, when the station is approximately 2 times the RMW away, the observed wind direction deviates from the tangential wind due to the influence of TDF. With the TC moving northward and the distance between the station and the TC center increasing to more than 30 km (2 times the RMW), the TDF started to dominate the local circulation, and the wind direction turned west-southwesterly at approximately 1600 UTC (Fig. 10), containing an inflow component compared with the tangential wind (brown shading in Fig. 10).



FIG. 10. Temporal plot of storm-relative horizontal wind at the Lan-yu station, including data from the surface level (324 m) and altitudes ranging from 1 to 10 km. The background shading indicates positive (e.g., outflow; green color) and negative (e.g., inflow; brown color) degree differences compared with the tangential wind direction. The distance and azimuthal angle shown in parentheses beneath the UTC time indicate the position of Lan-yu station relative to the TC center. Illustrations along the abscissa depict the relative location between the TC center (black typhoon symbol) and Lan-yu station (black solid triangle). The interval between each circle of the illustrations is 60 km.

This process only extended to an altitude of approximately 1 km.

The direction of the GBVTD-derived VWS showed a transition from northeasterly to northwesterly at approximately 1600 UTC (Fig. 8b). According to the conceptual model proposed by Black et al. (2002), the VWS-induced updraft also shifted from the southern to southeastern section of the eyewall. The substantial inflow angle observed at the Lan-yu station after 1600 UTC, as illustrated in Fig. 10, suggests that the TDF and the primary circulation of the TC may converge in the southeastern quadrant of the TC eyewall within the boundary layer (Huang et al. 2016). Consequently, this convergence, resulting from the TDF coinciding with the updraft area induced by VWS, may have coincidentally intensified convection on the downshear side. This enhanced convection can provide more energy transport to the cyclonic downstream to mitigate the radial ventilation effect due to VWS in the UL quadrant. The radius-time Hovmöller diagram of the averaged reflectivity in the eastern, northern, western, and southern quadrants within 100 km from the TC center is shown in Fig. 11. Note that these quadrants also represent the DL, UL, UR, and DR quadrants only for stages II and III, as the VWS direction was approximately toward the southeast during these two stages (Fig. 7). In stage II, the eyewall asymmetry was obvious. The eyewall on the left-of-shear semicircle accompanied by stronger reflectivity and a wider thickness than that on the right-of-shear semicircle was observed. This convection distribution generally agrees with the schematic illustration of the shear-induced eyewall convection asymmetry in Black et al. (2002) and Eastin et al. (2005). However, the

narrower eyewalls with reflectivities above 35 dBZ in the UR and DR quadrants still underwent development. The development over the right-of-shear side indicated axisymmetric heating on the eyewall, benefiting TC intensification. The reflectivity enhancement on the UR side of the eyewall may have been caused by the VWS profile pattern, which will be further discussed in the following subsection.

b. VWS profile patterns

The consistency between the deep-layer (2-8-km) VWS and the evewall asymmetry is discussed in section 3c. This subsection will focus on the possible impacts on TC intensification according to the VWS profile patterns. The deep-layer VWSs were further separated into lower-layer (2-5-km or 800-550-hPa) and upper-layer (5-8-km or 550-350-hPa) VWSs for a more detailed discussion. The features of the lower- and upper-layer VWSs are described as follows. The magnitude of the GBVTD-derived lower-layer VWS decreased at 1100 UTC and became almost zero at 1400 UTC. The small-magnitude VWS remained for approximately 2 h (Fig. 12a; gray dots), during which Typhoon Chanthu experienced the ERC process and the eyewall asymmetry was also reduced (Fig. 8). The GBVTDderived lower-layer VWS started to increase after 1600 UTC at a rate of 2 m s⁻¹ h⁻¹ in the following 6 h, and the shear direction turned from northerly to northwesterly. With variations in both direction and magnitude, the direction of the ERA5 VWS turned from north-northeasterly to northnorthwesterly and only showed a minor change in magnitude $(1.5-5.0 \text{ m s}^{-1})$ in the same period (Fig. 12b; gray dots). The GBVTD-derived lower-layer shear direction also agrees well



FIG. 11. As in Fig. 5b, but showing the azimuthally averaged reflectivity with 1-dBZ-interval shading in the (a) eastern, (b) northern, (c) western, and (d) southern quadrants during stages II and III. Note that these quadrants correspond to (a) DL, (b) UL, (c) UR, and (d) DR, respectively, as the VWS direction was approximately toward the southeast during these two stages. The quadrants filled with a dark blue background in the circles indicate the shear-relative quadrants.

with the reflectivity maximum shift described in section 3c (Fig. 8). The GBVTD-derived upper-layer VWS was very weak during almost the whole analysis period (Fig. 12a; black dots). The magnitude only slightly increased after 0000 UTC 12 September.

Although an increasing VWS has been considered a negative factor for TC intensification, certain patterns of the VWS profile can provide a relatively favorable environment for evewall convection to develop and cause axisymmetric heating (Rappin and Nolan 2012; Chen et al. 2019; Lee et al. 2021; Wadler et al. 2022). Figure 12a shows that the VWS derived from the GBVTD, especially at the lower level, increased during stage II as the TC quickly intensified. During stage II of the study, the VWS direction estimated using the GBVTD analysis exhibited a southeastward orientation, while the LLF exhibited a north-northwestward direction (Fig. 12a). This LLF, which imposed a UL-pointing flow onto the TC's primary flow, has the potential to augment the surface wind speeds and the associated heat fluxes within the downshear quadrant. These increased fluxes, advected by the TC's primary flow, resulted in a higher energy supply to the UL quadrant and enhanced the convection. (Lee et al. 2021; Rappin and Nolan 2012). However, Chen et al. (2019) conducted idealized simulations with a fixed SST of 31.0°C and revealed a different result: a DL-pointing LMF is favorable for TC intensification. A statistical analysis based on ERA5 data also suggested the same argument (Chen et al. 2021). The disagreement between the above studies and this study may result from the relatively high initial intensity at which Chanthu underwent RI, which differs from typical RI cases (Fischer et al. 2020). Statistical analyses or idealized

simulations employing weak initial vortexes may not be suitable for comprehensively elucidating the intensification mechanisms of Chanthu.

In addition to the relative direction between the VWS and LLF, the magnitude of the VWS vertical distribution is also one of the critical factors in determining whether a TC intensifies. The effect of a unidirectional VWS with the same magnitude (10 m s⁻¹) but different profiles on TC intensity change was discussed in Fu et al. (2019). They defined the lower-layer shear as the vector difference of the mean flow between heights of 1.3 and 5.8 km and the upper-layer shear between heights of 5.8 and 12.6 km. Two shear profiles were imposed on a TC with an intensity of $\sim 60 \text{ m s}^{-1}$. The experiment imposing the upper-layer shear led to upper-level warm core weakening and vortex tilt, which consequently caused topdown weakening of the vortex. The GBVTD-derived VWS shows that the speed of the upper-layer VWS was less than 1.5 m s^{-1} during stage II, which was much smaller than that of the lower-level VWS (Fig. 12a). This VWS profile pattern was less detrimental for TC intensification because the upper-level warm core of the vortex was under a weaker radial ventilation. The findings in this subsection indicate that the VWS profile pattern provides a relatively favorable environment for the intensification of Chanthu.

However, an opposite argument was proposed by Finocchio et al. (2016). They argued that a shallower and lower VWS that tilts the simulated vortex to the downshear side is more destructive to the simulated vortexes. They also found that those tilted vortexes are unable to vertically realign and have a negative impact on intensification. Thermodynamic environments between low-level and upper-level VWSs have been



FIG. 12. As in Fig. 7, but for the storm-relative mean flows. Arrows and dots represent the direction and magnitude of VWS at different altitude ranges. Ranges from 2 to 8 km (800 to 350 hPa), 5 to 8 km (550 to 350 hPa), and 2 to 5 km (800 to 550 hPa) are presented in red, black, and gray colors.

compared. It is suggested that the middle-level dry-air entrainment is a possible factor that induces a low equivalent potential temperature flux into the boundary layer for low-level VWS experiments. In contrast, the low equivalent potential temperature downdraft flux in the upper-level VWS experiments is less active. Nevertheless, we suggest that the impact of VWS on the intensity change of TCs varies depending on their intensity or size levels (Finocchio and Rios-Berrios 2021). The intensity of Typhoon Chanthu over the analyzed period in this study ranges from ~50 to ~65 m s⁻¹. The initial vortex used for the simulation in Finocchio et al. (2016) is relatively weak (30 m s⁻¹) compared to that of Chanthu. The relationship between the depth of the steering layer and vortex intensity, as shown in Velden and Leslie (1991), implies that the vortex depth of intense TCs is higher than that of weak TCs. As a result, the shear layers focused on the upper level have less impact on weak TCs due to their shallow vortex depth. In contrast, the shear layers focused on the lower level can cause the tilt of weak TCs and be more destructive to their intensity (Finocchio et al. 2016). For intense TCs, such as the model setting in Fu et al. (2019) with an initial vortex of 60 m s⁻¹, the resistance from low-level shear is higher due to their high inertial stability at the lower level. However, shear at the upper level can be harmful to the warm core of intense TCs and lead to significant weakening.

As mentioned above, the VWS profile pattern appears to have provided a favorable environment for Typhoon Chanthu to quickly intensify with less harm to its mid- to upper-layer warm core. Moreover, the terrain-induced boundary inflow led to convergence enhancement in the DL quadrant of the eyewall and could have also prompted convection development and further intensification. Although the main goal of this study was to discuss the mechanisms of RI, Chanthu also notably underwent RW during the last 8 h of the analysis period. Such a rapid change in intensity is also an important issue for research on TC intensity and forecasting. Previous studies indicate that the main factors resulting in RW include a sharp SST gradient, low OHC, increasing VWS, dry-air intrusion and interaction with the monsoon gyre (DeMaria et al. 2012; Wood and Ritchie 2015; Liang et al. 2016, 2018; Wada 2021). During the period of RW in Typhoon Chanthu, the SST encountered by the storm remained above 29°C (figure not shown). However, a notable decline in the OHC was observed along Chanthu's track in the northeastern offshore region of Taiwan, decreasing from 80 to 40 kJ cm⁻¹ (Fig. 1). This suggests that the reduced OHC in the vicinity may have contributed to the occurrence of RW in Chanthu. Nonetheless, importantly, the intricacy of the mechanisms responsible for the RW of Chanthu exceeds the limitations of the data utilized in this study. Therefore, future research aimed at delving into the underlying mechanisms of RW in TCs is important to enhance our understanding of this phenomenon.

5. Conclusions

The dense radar network captured the notable intensification of Typhoon Chanthu as it tracked along the eastern coast of Taiwan, characterized by a dominance of wavenumber-1 asymmetry in the eyewall convection. By analyzing radar reflectivity and Doppler velocity data from multiple radars, along with weather station measurements, the study investigated the temporal evolution of the TC's inner-core structure and its connection to the mean flow characteristics. The GBVTD method was employed to derive the TC's circulation and investigate its kinematic features with a high temporal resolution of 10 min. The application of the GBVTD algorithm was utilized to estimate the meso-\beta-scale mean flow of the TC with a higher temporal resolution compared to that derived from the ERA5 data. During the intensification stage, the horizontal wind speed at an altitude of 3 km exhibited a rapid increase of approximately 18 m s⁻¹ within an 11-h period, indicative of RI. At the peak of the intensification stage, the maximum wind speed exceeded 65 m s⁻¹, with a RMW of only 12 km. In contrast, the typhoon experienced a period of RW, with the maximum wind speed at 3-km altitude decreasing by approximately 19 m s^{-1} within an 8-h period during the weakening stage. Remarkably, Typhoon Chanthu underwent both RI and RW within a short 24-h period, presenting significant challenges for accurate intensity forecasting and timely warning issuance.

During the intensifying stages, a significant rotation of the eyewall convection maximum in Typhoon Chanthu occurred, transitioning cyclonically from the eastern to the northern semicircle at 1600 UTC 11 September, coinciding with the completion of an apparent ERC. Simultaneously, the terraininduced west-southwesterly boundary inflow from the south of the TC was initiated. Additionally, it was observed that the LMF rotated from southwesterly to southeasterly. Both modifications in the flows are suggested to be influenced by the terrain. The analysis of mean flow reveals that the meso-\beta-scale VWS derived from the GBVTD can effectively capture the abrupt changes induced by the terrain and is consistent with the observed eyewall convection asymmetry. In contrast, the meso- α -scale VWS derived from the ERA5 shows only minor directional changes throughout the analyzed period, resulting in the maximum reflectivity being located on the upshear side. This discrepancy is inconsistent with the documented location of shear-induced convection asymmetry in TC eyewalls in previous studies. These findings suggest that radar-derived meso-ß mean flow can provide accurate VWS information that reflects the actual conditions experienced by the TC when it is in close proximity to the Taiwan terrain, while the applicability of ERA5-derived meso- α -scale VWS may be limited in such cases.

Based on the analyses conducted in this study, the factors that possibly contributed to the intensification of Typhoon Chanthu are summarized in Fig. 13 and itemized as follows:

1) Terrain-induced boundary inflow south of the TC:

The significant change in wind direction observed at the Lan-yu station suggests that the flow was influenced by terrain. The terrain-induced boundary inflow and the primary circulation of the TC may potentially converge in the southeastern quadrant of the TC's eyewall within the boundary layer, subsequently enhancing the convection on the downshear side of the TC.

2) UL-pointing low-level flow:

The vertical profile of the meso- β -scale mean flow indicates that the low-level flow was directed UL during stages II and III. Previous studies by Rappin and Nolan (2012) and Lee et al. (2021) suggested that when the directions of VWS and low-level flow were counter-aligned, surface heat fluxes can be enhanced on the downshear side. These enhanced surface heat fluxes were hypothesized to play an important role in recovering the moist static energy of shear-enhanced downdrafts within the boundary layer over the inflow area, preventing the TC eyewall from entraining low-energy air parcels. The maintenance of the convection in the UL quadrant can consequently enhance the axisymmetric heating that benefits subsequent intensification.

3) Weak upper-level VWS:

The vertical profile of the mean flow also indicates that the magnitude of the upper-level VWS was close to zero during stages II and III. Fu et al. (2019) noted that stronger upper-level VWS hampers TC intensification by weakening the warm core through the radial ventilation pathway in the middle-upper troposphere. Therefore, the



FIG. 13. Schematic illustration of the speculated factors prompting the RI of Typhoon Chanthu under the moderateshear environment. The black curved arrow indicates the main flow of the TC. The black straight arrows indicate the TDF in the boundary layer. The blue, green, and gold horizontal arrows indicate the mean flow at 3, 5, and 8 km, respectively. The gray, cyan, and orange vertical arrows indicate the deep-, lower-, and upper-layer meso- β VWS, respectively. The circle indicates the TC inner-core region, which is separated into DL, UL, UR, and DR quadrants under the shear-relative framework.

low magnitude of the upper-level VWS provided a favorable environment for the intensification of Typhoon Chanthu.

An intriguing point worth highlighting is that Chanthu underwent an ERC concurrently during the RI process between stages I and II. Following the completion of the ERC, more favorable internal and external conditions for subsequent intensification became evident. In the minor intensification stage (e.g., stage I), as Typhoon Chanthu underwent ERC, the meso-β-scale VWS between 2 and 5 km decreased to values under 2 m s⁻¹ (Fig. 12). Simultaneously, eyewall asymmetry also reduced during this stage (Fig. 8). It was found that the VWS magnitude approached zero (Fig. 12), and axisymmetry significantly increased right after the ERC, establishing enhanced internal and external conditions for subsequent intensification. Furthermore, favorable external conditions, such as boundary layer inflow triggered by the proposed TDF (Fig. 10) and a VWS pattern promoting TC intensification, emerged after 1600 UTC. These combined internal and external factors provided an opportunity for Chanthu to intensify by approximately 12 m s^{-1} within only 5 h during stage II (e.g., the major intensification stage).

The distinctive nature of the ERC event, as elaborated in section 3b, is a collective characteristic observed in both Typhoon Chanthu (2021) and Hurricane Irma (2017) during their respective RI processes. Chanthu's ERC, characterized by the merging of the secondary eyewall with the primary eyewall rather than complete replacement, shares similarities with the second ERC event of Irma, as documented by Fischer et al. (2020). However, Torgerson et al. (2023b) termed this phenomenon a "short-term intensity fluctuation" rather than a complete ERC (see their Fig. 14 for the proposed schematic diagram). The inner-core convection evolution of this intensity fluctuation exhibited a period of less than 6 h, having a lesser impact on the primary eyewall and allowing for immediate subsequent intensification. Torgerson et al. (2023a,b) provided an alternative perspective to examine the significance of the ERC (or intensity fluctuation) toward the RI in Chanthu.

This study identifies several possible factors that may have contributed to the intensification of Typhoon Chanthu. However, the traditional dual-Doppler wind synthesis method and GBVTD method employed in this study were still limited in providing a comprehensive three-dimensional circulation of Chanthu to offer direct evidence for the aforementioned possible factors. To achieve a more detailed understanding, variational-based multiple-Doppler-radar synthesis techniques (Gao et al. 1999; Chong and Bousquet 2001; Liou and Chang 2009; Potvin et al. 2012) could be employed for retrieving a more comprehensive three-dimensional circulation in the future research. Additionally, a quantitative assessment of the major physical mechanism of Chanthu's intensification lies beyond the scope of this study. The detailed physical processes through which terrain influences the surrounding flow of the typhoon were not fully resolved at the data resolution used in this study. Future investigations could involve sensitivity tests using model simulations that vary the height of the Taiwan terrain to verify the effects on TDF (Fig. 10) and the pattern of VWS (Fig. 7). The timing and intensity of TDF initiation may also play a crucial role in influencing TC intensification. Therefore, it is recommended to conduct numerical simulations with data assimilation of dense radar and surface observations in the future to further investigate and clarify the impacts of 1) terrain effects on changes in storm-scale vertical wind shear and eyewall asymmetry; 2) how the ERC (or intensity fluctuation) influenced the meso-β-scale VWS and eyewall convection axisymmetry, which contribute to the RI of Typhoon Chanthu as discussed in this study.

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Data availability statement. The radar raw data and weather station data used in this study are from the Central Weather Administration. Due to its proprietary nature, supporting data cannot be made openly available. The contact information of data and conditions for access can be found at https://www.cwa.gov.tw/V8/E/S/service_guide.html.

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