# JGR Atmospheres 

RESEARCH ARTICLE<br>10.1029/2020JD034434

## Key Points:

- Himawari8-based tangential winds in Typhoon Trami (2018) showed decreases of vorticity in the eye and inner eyewall in a replacement cycle
- An examination of the potential radius clarified the rapid (slow) slowdown of the rotation in the inner eyewall (near the storm center)
- The rapid (slow) slowdown can be mainly explained by angular momentum transport associated with asymmetric eddies (surface friction)

Correspondence to:
S. Tsujino,
satoki@gfd-dennou.org

## Citation:

Tsujino, S., Horinouchi, T., Tsukada, T., Kuo, H.-C., Yamada, H., \& Tsuboki, K. (2021). Inner-core wind field in a concentric eyewall replacement of Typhoon Trami (2018): A quantitative analysis based on the Himawari-8 satellite. Journal of Geophysical Research: Atmospheres, 126, e2020JD034434. https://doi. org/10.1029/2020JD034434

Received 16 DEC 2020
Accepted 25 MAR 2021

## Author Contributions:

Conceptualization: S. Tsujino Data curation: S. Tsujino, T. Horinouchi, T. Tsukada, H.-C. Kuo, H Yamada, K. Tsuboki
Formal analysis: S. Tsujino, H.-C. Kuo Funding acquisition: T. Horinouchi,
H. Yamada, K. Tsuboki Investigation: S. Tsujino Methodology: S. Tsujino, T. Horinouchi, T. Tsukada, H.-C. Kuo Project Administration: T. Horinouchi
Resources: S. Tsujino, T. Tsukada, H. Yamada, K. Tsuboki Software: S. Tsujino, T. Tsukada Supervision: T. Horinouchi

## © 2021. The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

# Inner-Core Wind Field in a Concentric Eyewall Replacement of Typhoon Trami (2018): A Quantitative Analysis Based on the Himawari-8 Satellite 

S. Tsujino ${ }^{1}$ (D) T. Horinouchi $^{1,2}{ }^{(D)}$, T. Tsukada ${ }^{2}$ (D) H.-C. Kuo ${ }^{3}$ (D) H. Yamada $^{4}{ }^{(D)}$, and K. Tsuboki ${ }^{5}$ (D)<br>${ }^{1}$ Faculty of Environmental Earth Science, Hokkaido University, Sapporo, Japan, ${ }^{2}$ Graduate School of Environmental Science, Hokkaido University, Sapporo, Japan, ${ }^{3}$ Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan, ${ }^{4}$ Faculty of Science, University of the Ryukyus, Nishihara, Japan, ${ }^{5}$ Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan


#### Abstract

Dynamics of rapid changes of intensity and structure in an eyewall replacement cycle of tropical cyclones remain an open question. To clarify the dynamics of the inner eyewall decaying, a quantitative estimation of inner-core wind fields based on highly frequent observation images with 2.5min temporal resolution in the Himawari-8 satellite is applied to Typhoon Trami (2018) which had a clear concentric eyewall structure. A high tangential wind of $50 \mathrm{~m} \mathrm{~s}^{-1}$ is estimated at a radius of 30 km , which is located in the inner edge of the inner eyewall, during an active stage of the inner eyewall. During the decaying stage of the inner eyewall, the estimated tangential wind rapidly decreases to about $20 \mathrm{~m} \mathrm{~s}^{-1}$ at a radius of 24 km . The satellite-based tangential winds are validated with dropsondes around the inner core by an aircraft. Vorticity field retrieved by the satellite-based tangential winds during the decaying stage exhibits a rapid decrease in an outer part of the eye and the inner eyewall, and a slow decrease near the storm center. Examination on an absolute angular momentum coordinate indicates that the rapidly slow-down rotation in the outer edge of the eye and inner eyewall is faster than a slow-down rotation explained by surface friction. It suggests that asymmetric eddies transport angular momentum across the moat in the inner eyewall dissipation. This study is the first examination of dynamical contributions of asymmetric eddies to the inner-eyewall dissipation based on satellite-estimated tangential winds.

Plain Language Summary Intense tropical cyclones often have the concentric secondary eyewall outside the original (primary) eyewall enclosing the eye (i.e., concentric eyewalls; CEs). The primary eyewall tends to decay after the secondary eyewall formation (i.e., eyewall replacement cycle; ERC). Dynamics of rapid changes of intensity and structure in an ERC remain an open question. To clarify the dynamics of the inner eyewall decaying, a quantitative estimation of tangential winds is applied to Typhoon Trami (2018) with CEs. The estimation is based on tracking of cloud motions associated with the tangential winds, using 2.5-min images in the Himawari-8 satellite. A high tangential wind of 50 m $\mathrm{s}^{-1}$ is estimated in the inner edge of the inner eyewall in Trami during an active stage of the inner eyewall. During the decaying stage of the inner eyewall, the estimated tangential wind rapidly decreases to about $20 \mathrm{~m} \mathrm{~s}^{-1}$ at a radius of 24 km . The satellite-based tangential winds are validated with dropsondes by an aircraft. Our results highlight that the tangential winds during the inner-eyewall decaying stage is mainly decelerated due to eddies superposed on annular cyclonic circulations in the inner eyewall. The process can be best illustrated on an absolute momentum coordinate.


## 1. Introduction

Secondary eyewall formation (SEF) and concentric eyewall (CE) structure in tropical cyclones (TCs) lead to an increase in storm size. After the SEF, TCs often experience an eyewall replacement cycle (ERC). In an ERC, the primary inner eyewall gradually dissipates and the secondary outer eyewall contracts (e.g., Black \& Willoughby, 1992; Houze et al., 2007, 2006; Sanabia et al., 2015; Sitkowski et al., 2011; Yang et al., 2013). Coincided with the ERC, the maximum wind speed and radius of maximum wind speed (RMW) in TCs rapidly change (e.g., Black \& Willoughby, 1992). Because the observations of the inner-core wind field in TCs with CEs are limited, the dynamics of the ERC (particularly dissipation of the inner eyewall) remain an open question.

Validation: S. Tsujino, T. Horinouchi, T. Tsukada

Visualization: S. Tsujino
Writing - original draft: S. Tsujino, T. Horinouchi
Writing - review \& editing: S.
Tsujino, T. Horinouchi, T. Tsukada

Previous studies proposed several mechanisms of the inner eyewall dissipation in the ERC. Rozoff et al. (2008) proposed that upper-level warming around the inner eyewall associated with enhancement of the outer eyewall convection can induce suppression of the inner eyewall convection. Houze et al. (2006) and Tsujino et al. (2017) proposed that cutting-off of inward transport of the low-level moisture in the outer eyewall can induce the inner eyewall dissipation. Zhou and Wang (2011) proposed suppression of the inner eyewall updrafts due to the reaching of cold air advection originated from the outer eyewall. Wang et al. (2018) indicated that the developing SEF starts to reduce the moisture transport to the inner eyewall, and the convection in the inner eyewall. These studies mainly focus on the boundary layer and thermodynamic processes in the inner eyewall dissipation.

Based on idealized simulations with a non-divergent barotropic model, Kossin et al. (2000) proposed the collapse of the inner eyewall due to barotropic instability across moat (i.e., vorticity redistribution through asymmetric eddies). They also indicated that the barotropic instability is favorable for the CE structure with a narrow moat based on linear stability analysis for a core vortex (corresponding to the eye and inner eyewall) in a ring vortex (corresponding to the outer eyewall). They assume the pre-existing outer vortex ring (i.e., outer eyewall). Thus, this barotropic concept explains the inner-eyewall decaying after the SEF, in contrast to Wang et al. (2018). Yang et al. (2013) examined the statistical features of typhoons with the CE structure based on microwave satellite images from 1997 to 2011. They indicated that typhoons with shortlived CEs had a narrow moat. The results suggest the inner eyewall dissipation for a short period due to the barotropic instability across the moat. Lai et al. (2019) performed an ERC simulation in Hurricane Wilma (2005) with a full physics model and discussed dynamics with a barotropic model. They indicated that an inner eyewall in the simulated Wilma had an elliptic shape after the SEF, which is a general agreement with aircraft observations of an ERC event in Hurricane Gilbert (1986; Black \& Willoughby, 1992). The elliptic shape in the inner eyewall suggests the type-II instability across the moat in Kossin et al. (2000). Lai et al. (2021) indicated a significant contribution of the asymmetric eddies to the inner-eyewall decaying, based on an angular momentum budget with a full-physics simulation.

To clarify the inner-eyewall dissipation mechanism based on the asymmetric eddies, dynamical verification is required from observation of actual TCs with the CE structure. However, there is relatively few observations of inner-core wind fields in CEs due to having a CE structure over an open ocean. In 2015, the Japan Meteorological Agency (JMA) launched a new-generation geostationary satellite, Himawari-8. The satellite is operated to conduct areal observations following typhoons at a highly frequency of 2.5 min , which is called a target observation (Bessho et al., 2016). The high-frequency imaging provides information on the internal structures of typhoons that was not previously available. For example, Horinouchi et al. (2020) found that the tips of the anvils associated with convective bursts frequently form finite amplitude gravity waves, or internal bores. The $2.5-\mathrm{min}$ images also allow us to track cloud motion which represents wind velocity around the cloud. Tsukada and Horinouchi (2020; TH20) developed a method to estimate tangential wind speed around the inner-core region of typhoons based on space-time spectrum analysis of high-frequency image sequence. The estimation method can provide useful information to elucidate the dynamics of the inner eyewall dissipation during ERCs in a typhoon with the CE structure.

Typhoon Trami formed on September 20, 2018 and moved westward while rapidly developing (Figure 1a). The storm had an approximately annular single eyewall on September 24, 2018 (Figure 2a). Coincided with decreasing of the westward translation speed, Trami had reached the lifetime maximum intensity (minimum central pressure of 915 hPa and $10-\mathrm{min}$ maximum wind speed of $54 \mathrm{~m} \mathrm{~s}^{-1}$ ) as estimated by the Regional Specialized Meteorological Center (RSMC) Tokyo on September 25, 2018 (Figure 1b). After September 25,2018 , the moving direction of the storm turned northward with a slow-moving speed of about 2-3 m $\mathrm{s}^{-1}$, and the storm intensity gradually weakened. The special aircraft campaign of the Tropical cyclones-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARCII) project (Ito et al., 2018; Yamada et al., 2018) conducted dropsonde observations by penetrating into the eye at multiple times during the mature and decaying stages (i.e., September 25-28, 2018).

Based on an objective definition for the CE structure in Yang et al. (2013) with images of microwave satellites, we determined the storm with CEs on September 25, 2018 (Figures 2b and 2c). Associated with the weakening of the storm intensity, the inner eyewall gradually decayed (Figure 2c). On September 26, 2018, the inner eyewall convection became more weakened in the microwave images (Figures 2d and 2e), but the


Figure 1. (a) Track (cross markers) and (b) central pressure (black crosses) and maximum wind speed (red crosses) of Typhoon Trami (2018) based on the RSMC-Tokyo (JMA) best-track data. Circle markers denote track and intensity at 0000 UTC every day. In panel (a), the estimated storm center with the $2.5-\mathrm{min}$ interval from 0000 UTC September 25 to 0600 UTC September 27, 2018 is shown by the red line in the sub-figure. In panel (b), blue arrows indicate the times of flights in the T-PARCII observation, the black solid line in horizon denotes the analysis period in the present study (i.e., from 0000 UTC September 25 to 0600 UTC September 27, 2018), and the blue solid line in horizon indicates a period with maintaining the CE structure, based on microwave images (Yang et al., 2013). JMA, Japan Meteorological Agency; RSMC, Regional Specialized Meteorological Center. AND SPACE SCIENCE


Figure 2. Brightness temperature ( K ) based on the $89-\mathrm{GHz}$ band in microwave satellites around the target ERC period in Trami, provided by the Tropical Cyclone Pages in the Naval Research Laboratory (https://www.nrlmry.navy.mil/ TC.html). The storm had the CE structure in panels (b) and (c), based on an objective classification in Yang et al. (2013). The black arrows denote the wavenumber-2 moat structure. ERC, eyewall replacement cycle.


Figure 3. Vertical shear strength (line) and direction (arrows) of horizontal wind around Trami in the JRA55 data. The vertical shear $\left(\mathrm{VWS}_{200-850}\right)$ is defined as $\left[\left(U_{200}-U_{850}\right)^{2}+\left(V_{200}-V_{850}\right)^{2}\right]^{1 / 2}$, where $U$ and $V$ are the area averages of zonal and meridional wind components from the storm center to about $400-\mathrm{km}$ radius. The subscripts 200 and 850 indicate the 200 and $850-\mathrm{hPa}$ levels in the vertical. The length of the arrows is normalized at each time. JRA55, Japanese 55-year Reanalysis.
estimated intensity was mostly maintained (Figure 1b). Of particular interest is an asymmetric moat with a wavenumber- 2 structure in the inner core as shown by black arrows in Figures 2d and 2e. On September 27, 2018, the inner eyewall mostly dissipated (Figure 2f). The CE structure defined by the microwave images was maintained within 20 h , which is classified by the "ERC" type in Yang et al. (2013). The evolution of the CE structure was in general agreement with the observation of an ERC event in Hurricane Gilbert (Black \& Willoughby, 1992). Vertical shear of horizontal wind around Trami with the CE structure had small values below $5 \mathrm{~m} \mathrm{~s}^{-1}$ (Figure 3). The weak shear suggests that the evolution of the CE structure in Trami can be controlled by internal dynamics rather than the effects of environmental shear (e.g., Kaplan \& DeMaria, 2003; Tang \& Emanuel, 2010) on the storm structure.

The purpose of the present study is to clarify the dynamics of the inner eyewall dissipation in Trami during the ERC event, based on the tangential wind estimation with the $2.5-\mathrm{min}$ target observation of the Himawari-8 satellite (TH20). Trami is the first case of the dropsonde observations in the inner-core region during an eyewall replacement period after 2015. The estimated winds are validated with dropsonde observations conducted in the T-PARCII project. A formulation of the azimuthally averaged vertical vorticity equation on the potential radius coordinate (Schubert \& Alworth, 1987; Schubert \& Hack, 1983) is used to isolate the asymmetric eddies because axisymmetric radial advection of the vorticity is not explicitly included in the equation. Based on the projection of the vorticity retrieved by the satellite-based tangential winds on the potential radius, roles of asymmetric processes in the inner eyewall dissipation are discussed.

## 2. Data and Methods

### 2.1. Tangential Wind Estimation From Satellite Images

Advanced Himawari Imager (AHI) installed in the Himawari-8 satellite covers 16 wavelengths from 0.47 to $13.3 \mu \mathrm{~m}$. Horizontal resolutions of visible and infrared bands are $1 \mathrm{~km}(500 \mathrm{~m}$ for $0.64 \mu \mathrm{~m})$ and 2 km , respectively (Bessho et al., 2016). The target observation of AHI covers an area of about $1,000 \times 1,000 \mathrm{~km}$ that follows a typhoon at a time interval of 2.5 min . We use the method proposed by TH20. The method utilizes space-time spectral analysis to obtain tangential wind speed as a function of TC radius. As in TH20, the Himawari-8 data over 1 h are sampled at a specified radius after applying the parallax correction as described below, and the two-dimensional Fast Fourier Transform is conducted along azimuth and time to obtain the space-time power spectrum. The spectrum is converted to a function of azimuthal phase velocity, and the tangential wind representative of the radius is estimated from it as a weighted average over a range. The method is the same as in TH20, except for applying an additional procedure before spectral computation as described in what follows.

We examine the continuous evolution of inner-core wind fields in Trami for September 25-27, 2018. Thus, images at an infrared wavelength of $10.4 \mu \mathrm{~m}$ (Band 13), which are available even in the night time, were used in the present study, instead of images at the visible wavelength of $0.64 \mu \mathrm{~m}$ (Band 03) in TH20.

In general, well-developed TCs have vertical shear of tangential winds associated with the warm-core structure in the upper troposphere. The fact indicates that cloud motions in lower levels are faster than those in upper levels. There are both lower and upper clouds at a certain radius in the inner core during inner eyewall dissipation in an ERC event. Figure 4 shows the evolution of clouds in the inner-core region during the inner eyewall dissipation of Trami captured by the Himawari-8 satellite. When the inner eyewall was still active on early September 25, 2018, the inner core had a clear eye with high brightness temperature ( $T_{b}$ ), and the upper clouds originated from the inner eyewall convection expanded on the outside of the inner


Figure 4. (a)-(h) Parallax-corrected infrared (Band 13) images around the inner core of Trami in the target observation of the Himawari8 satellite. Colors denote brightness temperature (K). Black circles correspond to radii of $30-80 \mathrm{~km}$ (every 10 km ) from the storm center.
eyewall (Figure 4a). As the inner eyewall was weakening, the upper clouds were partly disappearing in the outside of the eyewall (Figures 4b and 4c). On September 26 and 27, 2018, lower clouds with high $T_{b}$ and their motions were captured in most areas of the inner core including the moat (Figures 4d-4h).

Parallax correction is conducted for the original infrared images. The cloud top height at each pixel with a certain value of $T_{b}$, which is required in the parallax correction, is derived from information on temperature and geopotential height at the storm center provided by the Japanese 55-year Reanalysis (Kobayashi


Figure 5. Azimuth-time cross-sections of the brightness temperature (color; K ) at a radius of 24 km (a) before and (b) after the filtering procedure in Section 2.1.
et al., 2015). After the projection of the parallax-corrected infrared images on the polar coordinate with respect to the TC center (i.e., the step 1 in the TH20 method), time sequences of the $T_{b}$ at each radius are obtained. Determination of the TC center every 2.5 min was documented in Appendix A. The radial and azimuthal resolutions are 2 km and $2 \pi / 512$ radian, respectively. The spectral analysis (i.e., the step 3 in the TH20 method) in the present study is conducted without any radial averages of the power spectra, in contrast to TH20.

We are interested in information on lower cloud motions associated with lower-level circulations. To isolate the information on the lower cloud motions, an additional procedure was introduced in the present study to mask upper cloud motions using $T_{b}$ on the infrared images. In regions with $T_{b}$ values below a threshold value ( 263 K in the present study, corresponding to a height of 8 km ), the $T_{b}$ values are substituted with the threshold. The sensitivity of the threshold to the estimated wind speed was examined in Appendix B. In regions with $T_{b}$ values above the threshold, the $T_{b}$ values are also substituted with the threshold if their azimuthal extent is smaller than a threshold (the azimuthal angle of $60^{\circ}$ in the present study). Since the small regions appear in between upper clouds (i.e., breaks in the upper clouds), their motions are controlled by the upper clouds. An example of the small regions was exhibited in the northeast sector at a radius of 24 km on later of September 26, 2018 (Figure 5a), which is masked by the substituting procedure (Figure 5b). The threshold of $60^{\circ}$ in the present study corresponds to an azimuthal distance of about 10 km at a radius of 10 km , corresponding to a horizontal scale of typical convective clouds. We are interested in the tangential winds represented by cloud motions at small scales. Spectra at high wavenumbers $(\geq 3)$ on the spectral space were covered in the binning procedure (i.e., $k_{\min }=3$ in the step 4 of the TH20 method). The upper cloud motions can be mostly removed by the additional procedure.

The satellite-based estimation was conducted every 30 min during an analysis period from 0000 UTC 25 to 0600 UTC September 27, 2018. Tangential winds at a certain time were estimated using the infrared images for 30 min before and after the time, with permitting to temporally overlap every 30 min .

### 2.2. T-PARCII Observation

Flights of T-PARCII were conducted from September 25 to 28, 2018. The Gulfstream-II aircraft operated by Diamond Air Service was used in the flights. In the T-PARCII observation, two GPS dropsonde receivers were installed in the aircraft as conducted in Typhoon Lan (2017; Ito et al., 2018; Yamada et al., 2018). The flights were operated around 0600 UTC each day. The aircraft succeeded to penetrate into the eye of Trami on multiple times during the active and decaying periods of the inner eyewall. Dropsondes from the aircraft


Figure 6. Paths of dropsondes around the inner core on (a) September 25, (b) September 26, and (c) September 27, 2018 during the T-PARCII campaign. The path of each dropsonde is shown by different colors and types of markers. The background image in each panel shows a snapshot of the Himawari-8 satellite (Band 13) within each flight period in T-PARCII. Black circles denote radii of $25,50,75,100,150$, and 200 km , respectively.
observed horizontal wind, temperature, and moisture fields of the inner core during the ERC event (Figure 6). Temperatures in the dropsondes were used to get information on height corresponding to $T_{b}$ in the Band 13. Tangential winds in the dropsondes were used to validate the tangential winds derived from the Himawari-8 satellite.

## 3. Results

### 3.1. Evolution of Estimated Tangential Wind

Figure 7 shows the evolution of tangential winds estimated by the TH20 method, vertical component of relative vorticity, and absolute angular momentum. The vorticity and angular momentum were derived from the estimated tangential winds. Tangential winds at radii smaller than 10 km are extrapolated by the estimated angular velocity at the radius of 10 km with assuming rigid-body rotation, since they are overestimated as is apparent from a comparison against azimuth-time sections of $T_{b}$. This is presumably because error in the storm-center determination induces positive bias in the estimated tangential wind near the center, as shown by TH20. Tangential winds are shown for smaller radii before 0000 UTC September 26, 2018, but they might be too large at around 5 km .

On early September 25, 2018, the estimated tangential winds increased with radius, and the maximum value was $50 \mathrm{~m} \mathrm{~s}^{-1}$ at a radius of 30 km (Figure 7b). The estimation is scarce outside the $30-\mathrm{km}$ radius by the upper-cloud mask because the active inner eyewall clouds covered far from the $30-\mathrm{km}$ radius (Figure 7a). The continuous estimation with the infrared images indicated the detailed evolution of the tangential winds during the analysis period. The relative vorticity was approximately constant $\left(\sim 4 \times 10^{-3} \mathrm{~s}^{-1}\right)$ within the inner eyewall (Figure 7c). The angular momentum had a large radial gradient within the inner eyewall on early of 25 September, compared with those after 0000 UTC September 26, 2018 (Figure 7d).

As the inner eyewall decayed from September 25 to 27, 2018, the estimated tangential winds within the 30km radius gradually decreased to below $20 \mathrm{~m} \mathrm{~s}^{-1}$ (Figure 7b). The relative vorticity within the inner eyewall also decreased below $2 \times 10^{-3} \mathrm{~s}^{-1}$, which was comparable to the magnitude in the moat between the radii of 30 and 80 km (Figure 7c). The angular momentum decreased in the inner core (Figure 7d). In particular, the decrease in the angular momentum within the inner eyewall suggested cutting off inward transport of the angular momentum associated with low-level inflows. Evolutions of the estimated tangential wind, vorticity, and angular momentum are in general agreement with previous observation and numerical studies (e.g., Abarca \& Montgomery, 2013; Black \& Willoughby, 1992; Wu et al., 2012).

The weakening of the tangential winds can be confirmed with the azimuth-time cross-sections of $T_{b}$ as shown in Figure 8. Cyclonic rotation speed ( $38 \mathrm{~m} \mathrm{~s}^{-1}$ ) of filtered low-level clouds at a radius of 24 km on early of September 25, 2018 (before the inner eyewall dissipation) was much faster than that ( $18 \mathrm{~m} \mathrm{~s}^{-1}$ ) on


Figure 7. Radius-time cross-sections of (a) azimuthal averages of cloud-top height (color; km) and $T_{\mathrm{b}}$ (contours; K ) over pixels used in the estimation, (b) satellite-based tangential winds ( $\mathrm{m} \mathrm{s}^{-1}$ ), (c) vertical component of relative vorticity ( $10^{-3} \mathrm{~s}^{-1}$ ), and (d) absolute angular momentum ( $10^{6} \mathrm{~m}^{2} \mathrm{~s}^{-1}$ ). The values within $r=10 \mathrm{~km}$ were extrapolated, assuming the rigid-body rotation with the estimated angular velocity at the 10-km radius (corresponding to the vertical red-dashed lines) in panels (b), (c), and (d). Based on the microwave images during the CE period shown by the blue line in Figure 1 b , the inner and outer eyewalls were approximately located at around $40-50$ and 90 km as shown in panel (b), respectively.

September 26, 2018. The good correlation between the estimated tangential wind and low-level cloud motions indicates that the upper-cloud mask worked well. Note that azimuthally averaged cloud-top heights (corresponding to azimuthal averages of $T_{b}$ ) temporarily increased within the $30-\mathrm{km}$ radius during the inner eyewall dissipation (Figure 7a). The increase in the cloud top within the $30-\mathrm{km}$ radius can be mainly due to (1) dissipation of a stable layer on the top of the boundary layer in the eye coincided with the weakening of the warm core (described in Section 3.2), and (2) inward advection of remnants in the decaying inner eyewall. The first process can mainly occur near the storm center. The second process can mainly occur



Figure 8. Azimuth-time cross-sections of the brightness temperature (color; K) at a radius of 24 km during (a) maintaining period ( 0600 UTC to 0700 UTC September 25, 2018) and (b) decaying period ( 0600 UTC to 0700 UTC September 26,2018 ) of the inner eyewall. Red dotted lines denote the estimated tangential wind speeds of (a) 38 and (b) $18 \mathrm{~m} \mathrm{~s}^{-1}$.
in the inner edge of the inner eyewall. As shown in the evolution of the cloud-top heights, the estimated tangential winds are not always located at the same altitude during the analysis period. To examine vertical variations of the estimated tangential winds, the estimated tangential winds are validated with dropsondes by the T-PARCII campaign in the next subsection.

### 3.2. Validation With the T-PARCII Dropsondes

Dropsondes from the T-PARCII aircraft directly observed wind and thermodynamic fields around the inner core in Trami during the analysis period. The tangential winds based on the Himawari-8 satellite are verified by wind profiles in the dropsondes. Figure 9 shows the wind and temperature profiles by the dropsondes during the ERC event. Each dropsonde profile was projected on radius-height coordinates with a bilinear interpolation in Figure 9. It is not azimuthal average. However, the projection is useful for seeing the dynamic and thermodynamic structure in the storm inner core. On early September 25, 2018, Trami with the active inner eyewall had the RMW at about 40 km from the center, and the maximum tangential wind was $60 \mathrm{~m} \mathrm{~s}^{-1}$ (Figure 9c). The tangential winds by the dropsondes did not capture the second peak corresponding to the outer eyewall around a radius of 100 km . It might be due to relatively fewer dropsondes around the radius (Figure 9a). Synthetic aperture radar observation retrieved the second maximum of wind speed corresponding to the outer eyewall of Trami (not shown). The temperature field in the dropsondes exhibited a clear warm-core structure within a $30-\mathrm{km}$ radius, which was enclosed by the active inner eyewall (Figure 9b). The tangential wind maximum at a radius of 40 km on September 25, 2018 (Figure 9c) was located in the inner eyewall. Thus, it was unavailable to estimate the tangential wind maximum with the TH20 method because of the mask by upper clouds in the eyewall. We caution that the weak shear of the tangential winds in Figure 9c may be due to the sparse of dropsondes which cannot resolve the structure of the tangential wind near the inner eyewall. Actually, the temperature gradient in Figure $9 b$ is large from 1 to 6 km at around 30 km radius.

On September 26 and 27, 2018 (during the inner eyewall dissipation), the RMW moved to the location of the outer eyewall around a radius of 100 km (Figures 9 f and 9 i ). The warm core within the $30-\mathrm{km}$ radius mostly disappeared (Figures 9 e and 9 h ). Although the equivalent barotropic structure in the tangential wind was still maintained below a height of 5 km on September 26, 2018 (Figure 9f). The inner-core tangential winds had a slight vertical shear (i.e., weak baroclinic structure) in the troposphere on September 27, 2018 (Figure 9i). ADVANCACG SCARTH


Figure 9. (left) Paths of the T-PARCII dropsondes around the inner core, (middle) observed air temperature (K), and (right) storm-relative tangential wind speed $\left(\mathrm{m} \mathrm{s}^{-1}\right)$. Colors and types of the markers in panels $(\mathrm{a})$, (d), and (g) correspond to the colors and types in Figures 6a-6c, respectively.

From the dropsonde temperature field, the threshold of $T_{b}(263 \mathrm{~K})$ used in the filtering procedure of the present study corresponds to a height of about 8 km . It indicates that the estimated tangential winds in the TH20 method can correspond to tangential winds below the $8-\mathrm{km}$ height. The present approach based on cloud motions in a range of the $T_{b}$ is difficult to represent the vertical distribution of the tangential winds. Since the vertical shear observed by dropsondes was weak, we expect that the satellite-estimated tangential winds are close to their vertical average below 8 km . Our comparison suggested that it was not a bad assumption. To directly compare the satellite-based tangential winds, dropsonde tangential winds ( $V_{\mathrm{D}}$. 8 km ) averaged vertically over the altitude where temperature is greater than 263 K are shown in Figure 10. In the comparison, we also calculated dropsonde tangential winds ( $V_{D}$ ) vertically averaged over a layer
(a) 25Sep2018

(b) 26 Sep 2018

(c) 27Sep2018


Figure 10. Comparison of the satellite-based and dropsonde tangential winds. The black lines show the satellite-based tangential winds averaged over (a) 0430 to 0530 UTC September 25, (b) 0530 to 0800 UTC September 26, and (c) 0400 to 0530 UTC September 27, 2018, during which the aircraft observations were conducted. The crosses show the dropsonde tangential winds averaged vertically where temperature is greater than $T_{b}=263 \mathrm{~K}$, corresponding to the vertical average below $\sim 8 \mathrm{~km}\left(V_{\mathrm{D} 8 \mathrm{~km}}\right)$; the stars are the same but for temperature between 293 and 288 K , corresponding to the vertical averages between $\sim 1$ and $\sim 2 \mathrm{~km}\left(V_{\mathrm{D} 2 \mathrm{~km}}\right)$. The bullets show the tangential winds averaged over the bottom and top heights corresponding to the maximum and minimum $T_{b}$ used in the tangential-wind estimation at the radii $\left(V_{D}\right)$. Colors of these markers are set equal to those in the corresponding panels in Figure 9 . As in Figure 7 b , the satellitebased tangential winds within the $10-\mathrm{km}$ radius were extrapolated, assuming the rigid-body rotation with the angular velocity at the 10-km radius, which was denoted by the black-dashed lines.
corresponding to the maximum and minimum $T_{b}$ values used in the satellite estimation. The satellite-based tangential winds at radii in the dropsondes were in agreement with the $V_{\text {D8km }}$ and $V_{D}$ within a range of about $5 \mathrm{~m} \mathrm{~s}^{-1}$. As with the satellite-based tangential winds, $V_{\text {D8km }}$ increased with radius. Note that $V_{\mathrm{D} 8 \mathrm{~km}}$ and $V_{D}$ are in a certain azimuthal section, different from the estimation in the TH20 method. On September 26, 2018, two sondes were dropped near a radius of 15 km (Figure 10b). The difference of the $V_{\mathrm{D} 8 \mathrm{~km}}$ is within $5 \mathrm{~m} \mathrm{~s}^{-1}$, which partly represents the azimuthal anomaly of the tangential wind. It is much smaller than azimuthally averaged tangential winds at the radius.

We are also interested in the relationship of the tangential winds between the satellite estimation and the boundary-layer top. The vertically averaged dropsonde tangential winds ( $V_{\mathrm{D} 2 \mathrm{~km}}$ ) over temperature levels of 293-288 K (corresponding to heights of 1-2 km) are shown in Figure 10. The $V_{\mathrm{D} 2 \mathrm{~km}}$ is quite similar to the $V_{\mathrm{D} 8 \mathrm{~km}}$, except for dropsondes on September 26, 2018 and at a radius of 60 km on September 27, 2018. Corresponding to the increase in the cloud-top height on early September 26, 2018 (Figure 7a), the $V_{\text {D2km }}$ is always higher than the $V_{D}$. However, the difference between the $V_{\mathrm{D} 8 \mathrm{~km}}$ and $V_{\mathrm{D} 2 \mathrm{~km}}$ is within $5 \mathrm{~m} \mathrm{~s}^{-1}$. The radial variation of the $V_{\mathrm{D} 2 k m}$ followed that of the $V_{\mathrm{D} 8 \mathrm{~km}}$. On September 27, 2018, the $V_{\mathrm{D} 8 k m}$ in the inner edge of the outer eyewall is weaker than the $V_{\mathrm{D} 2 \mathrm{~km}}$, which corresponds to the slight increase in the vertical shear of the tangential winds in the storm inner core (Figure 9i). However, the $V_{\mathrm{D} 2 \mathrm{~km}}$ at the $60-\mathrm{km}$ radius on 27 September is weaker than that at a radius of 50 km on September 26, 2018. The above facts indicated that the decrease of the satellite-based tangential winds reasonably followed the decrease in the $V_{\mathrm{D} 2 \mathrm{~km}}$ during the ERC period.

## 4. Discussion

Here, we discuss possible roles of asymmetric processes in the inner eyewall dissipation. Although our analysis does not derive axially asymmetric wind distributions from the infrared images, we can discuss their roles indirectly from the time evolution of the radial distribution of tangential winds. The vorticity is projected onto the potential radius $(R)$ coordinate, where $R$ is defined by the absolute angular momentum $(M)$ and Coriolis parameter $(f)$ as $M=f R^{2} / 2$ (Schubert \& Hack, 1983).

The azimuthal-mean tendency equation of absolute vertical vorticity ( $\bar{\zeta}=\partial(r \bar{v}) / r \partial r+f$ ) on annular coordinates $(r, z)$ is as follows:

$$
\begin{equation*}
\frac{D \bar{\zeta}}{D t}=-\bar{\zeta} \frac{\partial r \bar{u}}{r \partial r}-\frac{\partial \bar{M}}{\partial z} \frac{\partial \bar{w}}{r \partial r}+\frac{\partial \overline{\dot{M}}}{r \partial r}, \tag{1}
\end{equation*}
$$

where the overbar indicates azimuthal average, and the material derivative is $\mathrm{D} / \mathrm{D} t=\partial / \partial t+\bar{u} \partial /$ $\partial r+\bar{w} \partial / \partial z$. Time is defined as $t$ on the coordinates. Radial ( $r$ ), tangential, and vertical ( $z$ ) components of wind velocity are $u, v$, and $w$, respectively. A symbol of $\overline{\dot{M}}$ is azimuthal-mean angular momentum sources:

$$
\begin{equation*}
\overline{\dot{M}} \equiv r \bar{F}-\overline{u^{\prime} \frac{\partial M^{\prime}}{\partial r}}-\overline{w^{\prime} \frac{\partial M^{\prime}}{\partial z}}, \tag{2}
\end{equation*}
$$

where the prime means asymmetric components, and $\bar{F}$ is external forcing in tangential wind including surface friction.

According to Schubert and Alworth (1987), the projection of Equation 1 on the potential radius coordinates $(\bar{R}, Z)$ is

$$
\begin{equation*}
\frac{\partial \bar{\zeta}}{\partial \tau}=\bar{\zeta}^{2}\left[\frac{\partial}{\bar{R} \partial \bar{R}}\left(\frac{\bar{R} \dot{R}}{\bar{\zeta}}\right)+\frac{\partial}{\rho_{0} \partial Z}\left(\frac{\rho_{0} \bar{w}}{\bar{\zeta}}\right)\right], \tag{3}
\end{equation*}
$$



Figure 11. Evolution of the satellite-based relative vorticity (color; $10^{-3}$ $\mathrm{s}^{-1}$ ) around the storm projected on the potential radius ( R ) coordinate. Note that the vorticity profile on the R is a view to zoom the vorticity profile around the storm eye on the physical radius (red and cyan contours; km ). As in Figure 7c, the values within the physical radius of 10 km (corresponding to the red contour) were extrapolated, assuming the rigidbody rotation with the angular velocity at the $10-\mathrm{km}$ radius.
where time and height are defined as $\tau$ and $Z$ on the potential radius coordinates, respectively, $\rho_{0}$ is a reference air density proportional to $e^{-Z / H}$ ( $H$ is a constant scale height of 8 km ). In the first term within the bracket of the right-hand side,

$$
\begin{equation*}
\bar{R} \overline{\dot{R}} \equiv \frac{\overline{\dot{M}}}{f} \tag{4}
\end{equation*}
$$

Vorticity advection associated with $\bar{u}$ is not explicitly included in Equation 3 because a certain $\bar{R}$ is identical to a constant- $\bar{M}$ surface. This feature is an advantage in discussing the roles of asymmetric processes indirectly from the axisymmetric tangential wind information estimated by the TH20 method without having estimation of radial winds. Any asymmetric contribution to the vorticity tendency is included in the first term on the right-hand side of Equation 3. If the vortex is barotropic (i.e., $\bar{\zeta}$ and $\bar{R}$ are constant for given $r$ ), the density-weighted vertical average of Equation 3 between $Z=0$ and $Z_{\mathrm{t}}$ gives

$$
\begin{equation*}
\frac{\partial \bar{\zeta}}{\partial \tau}=\bar{\zeta}^{2}\left[\frac{\partial}{\bar{R} \partial \bar{R}}\left(\frac{\bar{R}\langle\overline{\dot{R}}\rangle}{\bar{\zeta}}\right)+\frac{e^{-\left(Z_{t} / H\right)} \bar{w}\left(Z=Z_{t}\right)}{\bar{\zeta} H\left(1-e^{-\left(Z_{t} / H\right)}\right)}\right] \tag{5}
\end{equation*}
$$

where the bracket represents the vertical average for an arbitrary variable of $q:\langle q\rangle \equiv \int_{0}^{Z_{t}} \rho_{0} q d Z / \int_{0}^{Z_{t}} \rho_{0} d Z$, and $\bar{w}(Z=0)$ is set to zero.

Figure 11 shows the projection of the satellite-derived vertical vorticity in Trami (Figure 7c) on the potential radius coordinate. Note that the projection is radially zooming in Figure 7c (red contours in Figure 11), depending on the strength of tangential wind speed. Around 0000 UTC September 26, 2018, the vorticity in potential radii of $80-130$ km rapidly decreased from 4.0 to $2.0 \times 10^{-3} \mathrm{~s}^{-1}$. The duration of the decrease was about $6-12 \mathrm{~h}$. The rapid decrease in the vorticity is associated with the inner eyewall dissipation during the ERC event.

External forcing $\langle\bar{F}\rangle$ for tangential wind can be parameterized with the surface friction stress $-C_{D} \overline{v_{s}} \bar{v}$, where $C_{D}$ is the surface exchange coefficient for momentum, $\overline{v_{s}}$ is the tangential wind speed at the surface, and $H$ is the depth of the air column. In the present study, $C_{D}=1.0-2.0\left(\times 10^{-3}\right)$ (Powell et al., 2003), $\bar{v}_{s}=0.78 \bar{v}$ (Kuo et al., 2016). Using the first term on the rhs of Equation 5, the contribution of the surface friction to the vorticity tendency is expressed as:

$$
\begin{equation*}
\frac{\partial \bar{\zeta}}{\partial \tau} \sim-\frac{3}{2} \frac{C_{D} \bar{v}_{s}}{H\left(1-e^{-1}\right)} \bar{\zeta} \tag{6}
\end{equation*}
$$

A rigid-body rotation was assumed in the above equation. If $\bar{v}=30 \mathrm{~m} \mathrm{~s}^{-1}$, the $e$-folding time for the surface friction is $20-40 \mathrm{~h}$. The duration is much longer than that ( $6-12 \mathrm{~h}$ ) of the observed decrease in the vorticity at the potential radii of $80-130 \mathrm{~km}$.

According to the dropsonde observation, tangential wind (or vorticity) in Trami can be assumed as equivalent barotropic structure over the column within a height of 8 km during the inner eyewall dissipation (Figure 9). Thus, the contribution of vertical advection to the tendency in Equation 5 is approximated as:

$$
\begin{equation*}
\frac{\partial \bar{\zeta}}{\partial \tau} \sim \frac{1}{e-1} \frac{\bar{w}(Z=H)}{H} \bar{\zeta} \tag{7}
\end{equation*}
$$

The term can contribute to the development of the storm vorticity in updraft regions. Also, the contribution of the term to the decrease in the storm vorticity is given in areas with significant axisymmetric subsidences, which leads to adiabatic warming in the areas. If $\bar{w}=-0.1$ to $-0.2 \mathrm{~m} \mathrm{~s}^{-1}$, for example, the $e$-folding time for the vertical advection is $20-40 \mathrm{~h}$, which is comparable to that for the surface friction. This is a typical value of the eye subsidence in some numerical simulations of mature TCs under idealized situations (e.g., Ohno \& Satoh, 2015; Stern \& Zhang, 2013). The eye subsidence during the inner-eyewall dissipation period in the present study can be much weaker than that in the mature TC cases. According to the dropsondes, the observed warm core within a radius of 30 km decayed during a period of September 25-26, 2018. The dissipation of the warm anomaly suggests that there were fewer areas with $\bar{w}<0$ even in the storm eye around 0000 UTC September 26, 2018. Therefore, it is unlikely that the subsidence provided a major contribution to the vortex slowdown.

According to the above analysis, the axisymmetric processes in the surface friction and vertical advection are minor contributions to the observed decrease in the vorticity at the 80 to $130-\mathrm{km}$ radii. These facts suggest that the decrease was mainly caused by the remaining factor, which is attributed to the second and the third terms of the rhs of Equation 2, that is, $-\overline{u^{\prime}\left(\partial M^{\prime} / \partial r\right)}-\overline{w^{\prime}\left(\partial M^{\prime} / \partial z\right)}$. Since their density-weighted vertical average is equal to $-\left\langle(\bar{\zeta} / f)\left(\overline{\partial r u^{\prime} M^{\prime} / \bar{R} \partial \bar{R}}\right)\right\rangle-\left(\left.\overline{w^{\prime} M^{\prime}}\right|_{Z=H} / H(e-1)\right)$, the first term is the horizontal convergence of the angular momentum flux by asymmetric processes.

Contrary to the fast slowdown over the 80 to $130-\mathrm{km}$ potential radii, the vorticity within a potential radius of 80 km decreased much slowly with an $e$-folding time of $\sim 36 \mathrm{~h}$. As mentioned above, this $e$-folding time can be explained solely by the surface friction. Because of the radial contrast in the vortex slow-down rate, the radial distribution of vorticity is altered from being nearly uniform in early September 25, 2018 over $r<30 \mathrm{~km}$ to be centralized to $r<10 \mathrm{~km}$ after September 26, 2018. This behavior resembles to a time evolution of barotropic vortices mimicking TCs with CEs; when a core vortex is surrounded by a ring of secondary vorticity peak, the vortices can interact with each other by barotropic instability to result in their erosion (see Appendix C). This similarity indicates that the eddy angular momentum flux convergence suggested by our analysis is likely initiated by the interaction between a region with high vorticity inside the inner eyewall and another along the outer eyewall, as suggested by the wavenumber- 2 moat structure in the microwave images (Figure 2). In this case, the slowdown around the inner eyewall occurs through the mixing with the air mass in the moat. The large dilution of vorticity in the outer edge of the core vortex associated with asymmetric eddies has been also pointed out by a hurricane simulation in Lai et al. (2019). As with Lai et al. (2021, 2019), in order to quantitatively assess this interpretation, we would need numerical simulations with three-dimensional models with full-physics with an adequate initialization to reproduce the actual TC structure because the barotropic model in Appendix C does not have processes in surface friction and convection, unlike the observational results. This task is left for future works.

After 0600 UTC 26 September, the entire inner core region is slowed down gradually at an $e$-folding time much longer than 24 h (Figure 11). This process can be explained by surface friction. In other words, vorticity changes in this region/time do not require eddy angular momentum transport. In the stage, there is less supply of the angular momentum to the eye rotation associated with the inner-eyewall updrafts and boundary-layer inflow. Montgomery et al. (2001) examined spin-down processes for the axisymmetric hurricane-like vortices with bottom friction under a dry situation (i.e., no diabatic heating in the eyewall), and indicated that the time scale for the spin down is mostly predicted by Ekman-layer spin-down processes based on Eliassen (1971). The vorticity changes in the present study are similar to axisymmetric spin-down of hurricane-like vortices due to surface friction under idealized situations by Montgomery et al. (2001).

As mentioned in Section 3.2, note that the sparse dropsondes may not precisely resolve vertical shear of tangential winds in the eye ( $r<30 \mathrm{~km}$ ) on September 25, 2018 (Figure 9c). We discuss impacts of the unresolvable vertical shear of the tangential winds to the examination on the potential radius. If the unresolvable vertical shear can largely contribute to deceleration in the tangential winds, the slowdown of the rotation near the center (where the surface friction is dominated) will be faster than the $e$-folding time (20-40 h) for
the surface friction during a period of $\sim 0600$ UTC September 25 to 0600 UTC September 26, 2018. However, the actual slowdown of the rotation near the center can be mostly explained by the surface friction. Thus, we consider that the impact of the unresolvable vertical shear can be minor for the examination on the potential radius in the eye.

## 5. Summary and Conclusions

CEs in TCs increase the storm size and precipitation area associated with TCs. An ERC after the SEF drastically changes the inner-core structure of the storm. Previous studies based on theory, statistic, and full-physics modeling approaches have proposed roles of asymmetric processes, which is associated with barotropic instability across the moat, on the inner eyewall dissipation during the ERC event (e.g., Kossin et al., 2000; Lai et al., 2019; Yang et al., 2013). Based on images captured by the Himawari-8 satellite with $2.5-\mathrm{min}$ interval, a method to quantitatively estimate tangential winds in the inner core of TCs proposed by TH20 was used to examine the contribution of the asymmetric processes to the inner eyewall dissipation in a typhoon with the CE structure.

The target typhoon in the present study is Trami in 2018. Trami exhibited a CE structure after the SEF around 0000 UTC September 25, 2018. Then, Trami experienced an ERC event during a period of later of 25 to early of September 27, 2018. The inner eyewall gradually decayed in the period. To estimate the continuous evolution of tangential winds at lower levels in Trami for about 2 days, the method used in the present study was slightly changed from the original method in TH20. The change includes an additional procedure to mask upper cloud motions using images at an infrared wavelength of $10.4 \mu \mathrm{~m}$ (Band 13).
The estimated tangential winds increased with radius in the inner core. The maximum value was $50 \mathrm{~m} \mathrm{~s}^{-1}$ at a 30-km radius with an active inner eyewall around 0000 UTC September 25, 2018 (Figure 7b). As the inner eyewall was decaying from September 25 to 27, 2018, the estimated tangential wind decreased to $20 \mathrm{~m} \mathrm{~s}^{-1}$ at the radius. Coincided with the decrease in the tangential winds, the satellite-derived vertical vorticity also decreased from $\sim 4 \times 10^{-3} \mathrm{~s}^{-1}$ to $2 \times 10^{-3} \mathrm{~s}^{-1}$ within the inner eyewall during the inner eyewall dissipation (Figure 7c). Moreover, the estimated tangential winds were validated with tangential winds observed by dropsondes during penetration flights into the eye in the Tropical cyclones-Pacific Asian Research Campaign for Improvement of Intensity estimations/forecasts (T-PARCII) project. The satellite-based tangential winds were close to the dropsonde-derived tangential winds at several radii. The evolution of the tangential winds based on the dropsondes was also consistent with the satellite-based tangential winds during the inner eyewall dissipation.

Projection of the satellite-derived vorticity on the potential radius coordinates is used to discuss the roles of asymmetric processes on the inner eyewall dissipation. According to scale analysis and observations, we find that the surface friction provides the dominant contribution among axisymmetric processes to the slow-down rotation in the inner core. However, a slow-down rotation (e-folding time of 6-12 h) at around the potential radii of $80-130 \mathrm{~km}$ (corresponding to the physical radii of $10-30 \mathrm{~km}$ ) is faster than the $e$-folding time ( $20-40 \mathrm{~h}$ ) for the surface friction during the inner eyewall dissipation ( 0600 UTC September 25 to 0600 UTC September 26, 2018). It suggests that the slow-down rotation was mainly explained by asymmetric processes. On the other hand, a slow-down rotation ( $e$-folding time of $\sim 36 \mathrm{~h}$ ) near the storm center within the $80-\mathrm{km}$ potential radius was mostly comparable to the $e$-folding time for the surface friction. It indicates that the slow-down near the center can be explained by the surface friction. After 0600 UTC September 26, the entire inner core is slowed down gradually at an $e$-folding time much longer than 24 h . The inner-core vorticity changes in the period are mostly explained by the axisymmetric spin-down due to the surface friction (Montgomery et al., 2001).
The results lead to the following conclusions for the evolution of the inner-core tangential winds and vorticity during the inner eyewall dissipation of Trami. First, the slow-down rotation in the inner eyewall and an outer part of the eye (at around $10-30 \mathrm{~km}$ radii) can be associated with angular momentum transport due to asymmetric eddies, which is in general agreement with previous studies (e.g., Lai et al., 2019; Yang et al., 2013). Particularly, the slow-down rotation has been also pointed out as a large dilution of vorticity in the outer edge of the eye and inner eyewall in a hurricane simulation (Lai et al., 2019). The asymmetric slowdown lasts for about 1 day after the SEF. The present study is the first
examination on the dynamical roles of the asymmetric processes in the inner-eyewall dissipation using the satellite-based tangential wind estimation. Second, the slow-down rotation near the storm center can be mainly due to surface friction. After the asymmetric slowdown lasting until 0600 UTC September 26,2018 , the rotation in the outer part of the eye and inner eyewall can be decelerated by the axisymmetric surface friction.

Images captured by the target observation with a $2.5-\mathrm{min}$ in the Himawari- 8 satellite and the method to estimate tangential winds by TH20 allow us to examine the detailed evolution of inner-core wind fields in TCs with CE structure. A combination of the tangential wind estimation with several theories can discuss dynamics and potential roles of asymmetric processes on the inner eyewall dissipation. The present approach is helpful for fully understanding mechanisms of the intensity and structural changes in ERCs. The present study focused on one case. On the other hand, the target observation in the Himawari-8 satellite, which has been launched in 2015, captured many more cases with the CE structure in the present. In future works, we will examine more cases using the present approach. Besides, the present approach with the potential radius coordinates will be applied to realistic ERC simulations with full-physics models.

Currently, it is difficult to capture the inner-core tangential winds of typhoons in the western North Pacific since operational reconnaissance by the U.S. ceased in 1987. We consider that our results provide profiles of inner-core tangential winds with high spatiotemporal resolution ( 2 km in radius and 1 h in time). In-ner-core wind observations by aircraft dropsondes and airborne Doppler radars can be largely contributed to improvement of the storm intensity prediction through data assimilation procedures in the Atlantic hurricanes (e.g., Feng \& Wang, 2019; Pu et al., 2016). Thus, the inner-core winds based on the satellite images in the present study may be contributed to improvement of intensity prediction of typhoons through any data assimilation procedures.

## Appendix A: Determination of the storm center

The storm center during 0000-1500 UTC 25 September 2018 was determined by the method of Braun (2002), which calculates the azimuthal variance of $T_{b}$ between 2 and 50 km at each pixel within a radius of 65 km from the best-track position and searches for the point of minimum variance every 2.5 min . Originally, the method was proposed to determine the axisymmetric center from the pressure field in the cloud-resolving simulation data. The method is also effective for the determination of the storm center from satellite infrared images in cases of an annular eyewall. On the other hand, the method is difficult to determine the storm center from the satellite images in cases of highly asymmetric structure. Thus, the storm center after 1500 UTC September 25, 2018 (i.e., the inner eyewall dissipation period) was subjectively determined by the satellite images every 30 min . The storm center every 2.5 min was determined by the cubic spline interpolation with the subjectively determined storm center every 30 min .

## Appendix B: Sensitivity of the threshold in the upper-cloud mask

In the present study, a procedure to remove upper cloud motions in the Himawari-8 images was introduced in the TH20 method. A threshold of $T_{b}(263 \mathrm{~K})$ was used to remove the upper clouds. To examine the sensitivity of choice of the threshold to the estimated tangential winds, we estimated the satellite-based tangential winds with different thresholds of 268 and 273 K corresponding to heights of 7 and 6 km , respectively (Figure B1). There was no large difference over most areas in the eye until 0000 UTC September 26, 2018. After 0000 UTC September 26, 2018, both the estimated tangential winds with 268 and 273 K were slightly faster $\left(\sim 1-5 \mathrm{~m} \mathrm{~s}^{-1}\right)$ than those with 263 K over narrow radii within a radius of 30 km (i.e., the inner edge of the inner eyewall). The faster tangential winds might be induced by strong vertical shear of tangential wind. Although the relative difference of the tangential winds is about $5 \%-20 \%$, the difference can be minor for the discussion in the present study.


Figure B1. Radius-time cross-sections of the difference of the tangential winds estimated by the threshold of 263 K from the tangential winds estimated by thresholds of (a) 268 K and (b) 273 K .

The estimated tangential winds with 263 K had difference $\left(-2.5-2.5 \mathrm{~m} \mathrm{~s}^{-1}\right)$ from the estimated tangential winds with 268 K (and 273 K ) in the outside of the $30-\mathrm{km}$ radius during the inner eyewall dissipation and near the storm center after 1200 UTC September 26, 2018. On the other hand, it seems that there was randomly the difference in contrast to the coherent bias exhibited in the inner edge of the inner eyewall. Moreover, higher values in selecting the threshold decrease areas for the estimation. For example, in the threshold of 273 K , the tangential winds were not estimated over most areas in the inner core after 0000 UTC September 26, 2018. Thus, the choice of the threshold in the additional procedure is appropriate for the discussion.

## Appendix C: An idealized numerical experiment with a barotropic model

On the basis of an idealized numerical experiment, we demonstrated the large dilution of vorticity in the outer edge of the eye and inner eyewall in a TC, as pointed out by Lai et al. (2019). A non-divergent barotropic spectral model used in the present study is based on the formulation and procedures in Kossin et al. (2000). The model domain is a square area of $1,000 \times 1,000 \mathrm{~km}$ with double periodic boundaries. The model grid points of $1024 \times 1024$ are uniformly located on physical space. The model is run with a dealiased calculation of the nonlinear terms in Equation 6 of Kossin et al. (2000), resulting in resolved Fourier modes of $331 \times 331$. The time integration is accomplished with the standard fourth-order Runge-Kutta scheme. The time step is 7.5 s , and viscosity value in the diffusion term with the first order of Laplacian is $100 \mathrm{~m}^{2} \mathrm{~s}^{-1}$ (corresponding to the $e$-folding time of about 40 min for the maximum wavenumber of 331).

Based on a formulation (Equation 11 in Kossin et al., 2000), the initial profile of vorticity in the vortex was given as vortex parameters of vorticities $\left(\zeta_{1}, \zeta_{2}, \zeta_{3}, \zeta_{4}, \zeta_{5}\right)=(3.5,0.01,1.5,0.1,-0.082) \times 10^{-3} \mathrm{~s}^{-1}$, switching at the radii of $\left(r_{1}, r_{2}, r_{3}, r_{4}\right)=(40,60,90,150) \mathrm{km}$ smoothly over the distances $\left(d_{1}, d_{2}, d_{3}, d_{4}\right)=(2.5,2.5,2.5,15)$ km, respectively, as shown in Figures C1a and C2b. The parameters were modeled by the satellite-based tangential winds (Figure 7b), derived vorticity (Figure 7c), dropsonde-based tangential winds (Figure 9c), and a microwave image (Figure 2b). The inner vorticity peak inside 40 km mimics the observed one associated with the inner eyewall. The outer secondary peak over $60-90 \mathrm{~km}$ is not necessarily validated by the sparse dropsonde observation, so we rather supposed it from the presence of the moat and the observed development of the wavenumber-2 feature. The initial vortex had two local peaks of the tangential wind at radii of 40 and 90 km (Figure C1a). Initial perturbations embedded in the vortex ring $\left(\zeta_{3}\right)$ were given by Equation 12 in Kossin et al. (2000). The amplitude was $2.718 \times 10^{-5} \mathrm{~s}^{-1}$.


Figure C1. (a) Radial profiles of axisymmetric vorticity (red) and tangential wind speed (black) and horizontal distributions of the vertical component of relative vorticity (color; $10^{-3} \mathrm{~s}^{-1}$ ) at (b) initial time, and (c) 24 h in a TC-like vortex simulated by a non-divergent barotropic model. The storm had a core vortex (corresponding to the eye and inner eyewall) and a vortex ring (corresponding to the outer eyewall). At the initial time, perturbations of vorticity were embedded in the vortex ring.

The core vortex quickly evolved to have an elliptical shape due to interaction with the vortex ring at 2 h (not shown). The elliptic core vortex and inward permeation of vorticity in the vortex ring indicate asymmetric eddy mixing of vorticity associated with barotropic instability across a low vorticity area between the core and ring vortices (corresponding to the moat), which is identical to the type-II instability in Kossin et al. (2000). The large dilution (and decrease) of vorticity in the outer edge of the eye and inner eyewall ( $\sim$ potential radii of $270-320 \mathrm{~km}$ ) occurred during a period of $2-8 \mathrm{~h}$, and the radial profile of the vorticity had a periodic oscillation after 8 h (not shown), in contrast to the observation. After 24 h , the vortex reached the quasi-steady state maintaining the low vorticity area of the wavenumber- 2 structure in the moat (Figure C1c). The wavenumber-2 moat was similar to the microwave images during the inner eyewall dissipation of Trami (Figures 2d and 2e). The inner peak of the tangential wind in the initial vortex totally disappeared at 24 h (the black dash-dotted line in Figure C1a). Coincided with the dissipation of the inner peak, the high vorticity at radii of $20-40 \mathrm{~km}$ was decreased due to an asymmetric transport with the barotropic instability (the red dash-dotted line in Figure C1a). The decrease in the high vorticity occurs in the radii of the outer edge of the eye and inner eyewall. It corresponds to the large dilution of vorticity in the outer edge of the core vortex in the realistic hurricane simulation of Lai et al. (2019). The present barotropic model does not have a parameterized surface friction. Therefore, unlike the observational results presented in Section 4, the simulated core vortex is not decelerated near its center where the eddy angular momentum transport does not reach (here, $r<20 \mathrm{~km}$ ).

## Data Availability Statement

The Himawari-8 data are downloaded from the NICT Science Cloud (https://sc-nc-web.nict.go.jp/wsdb_osndisk/shareDirDownload/03ZzRnKS). The typhoon best track data by the RSMC-Tokyo is available online (at https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/besttrack.html). The data derived in this study, the satellite-derived tangential winds of Trami, are available online (https://dx.doi.org/10.5281/ zenodo.3958835). The numerical model in the present study is available online (https://dx.doi.org/10.5281/ zenodo.3959297). Details of the T-PARCII are found online (http://www.rain.hyarc.nagoya-u.ac.jp/~tsuboki/kibanS/index_kibanS_eng.html).

## References

Abarca, S. F., \& Montgomery, M. T. (2013). Essential dynamics of secondary eyewall formation. Journal of the Atmospheric Sciences, 70, 3216-3230. https://doi.org/10.1175/JAS-D-12-0318.1
Bessho, K., Hayashi, K. M., Ikeda, A., Imai, T., Inoue, H., Kumagai, Y., et al. (2016). An introduction to Himawari-8/9—Japan's new-generation geostationary meteorological satellites. Journal of the Meteorological Society of Japan, 94, 151-183. https://doi.org/10.2151/ jmsj.2016-009
Black, M. L., \& Willoughby, H. E. (1992). The concentric eyewall cycle of Hurricane Gilbert. Monthly weather review, 120, 947-957. https:// doi.org/10.1175/1520-0493(1992)120<0947:TCECOH>2.0.CO;2
Braun, S. A. (2002). A cloud-resolving simulation of Hurricane Bob (1991): Storm structure and eyewall buoyancy. Monthly Weather Review, 130, 1573-1592. https://doi.org/10.1175/1520-0493(2002)130<1573:ACRSOH>2.0.CO;2
Eliassen, A. (1971). On the Ekman layer in a circular vortex. Journal of the Meteorological Society of Japan, 49A, 784-789. https://doi. org/10.2151/jmsj1965.49A.0_784
Feng, J., \& Wang, X. (2019). Impact of assimilating upper-level dropsonde observations collected during the TCI field campaign on the prediction of intensity and structure of Hurricane Patricia (2015). Monthly Weather Review, 147, 3069-3089. https://doi.org/10.1175/ MWR-D-18-0305.1
Horinouchi, T., Shimada, U., \& Wada, A. (2020). Convective bursts with gravity waves in tropical cyclones: Case study with the Himawari-8 satellite and idealized numerical study. Geophysical Research Letters, 47, e2019GL086295. https://doi.org/10.1029/2019GL086295
Houze, R. A., Jr, Chen, S. S., Smull, B. F., Lee, W.-C., \& Bell, M. M. (2007). Hurricane intensity and eyewall replacement. Science, 315, 1235-1239. https://doi.org/10.1126/science. 1135650
Houze, R. A., Jr, Lee, S. S. W.-C., Rogers, R. F., Moore, J. A., Stossmeister, G. J., Bell, M. M., et al. (2006). The Hurricane Rainband and intensity change experiment: Observations and modeling of Hurricanes Katrina, Ophelia, and Rita. Bulletin of the American Meteorological Society, 87, 1503-1522. https://doi.org/10.1175/BAMS-87-11-1503
Ito, K., Yamaguchi, H. M., Nakazawa, T., Nagahama, N., Shimizu, K., Ohigashi, T., et al. (2018). Analysis and forecast using dropsonde data from the inner-core region of tropical cyclone Lan (2017) obtained during the first aircraft missions of T-PARCII. SOLA, 14, 105-110. https://doi.org/10.2151/sola.2018-018
Kaplan, J., \& DeMaria, M. (2003). Large-scale characteristics of rapidly intensifying tropical cyclones in the north Atlantic basin. Weather and Forecasting, 18, 1093-1108. https://doi.org/10.1175/1520-0434(2003)018<1093:LCORIT>2.0.CO;2
Kobayashi, S., Harada, Y. Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., et al. (2015). The JRA-55 reanalysis: General specifications and basic characteristics. Journal of the Meteorological Society of Japan, 93, 5-48. https://doi.org/10.2151/jmsj.2015-001

Kossin, J. P., Schubert, W. H., \& Montgomery, M. T. (2000). Unstable interactions between a Hurricane's primary eyewall and a secondary ring of enhanced vorticity. Journal of the Atmospheric Sciences, 57, 3893-3917. https://doi.org/10.1175/1520-0469(2001)058<3893:UIB AHS>2.0.CO;2
Kuo, H.-C., Cheng, W.-Y., Yang, Y.-T., Hendricks, E. A., \& Peng, M. S. (2016). Deep convection in elliptical and polygonal eyewalls of tropical cyclones. Journal of Geophysical Research: Atmospheres, 121, 14456-14468. https://doi.org/10.1002/2016JD025317
Lai, T., Hendricks, E. A., Menelaou, K., \& Yau, M. K. (2021), Roles of barotropic instability across the moat in inner eyewall decay and outer eyewall intensification: Three-dimensional numerical experiments. Journal of the Atmospheric Sciences, 78, 473-496. https://doi. org/10.1175/JAS-D-20-0168.1
Lai, T.-K., Menelaou, K., \& Yau, M. K. (2019). Barotropic instability across the moat and inner eyewall dissipation: A numerical study of Hurricane Wilma (2005). Journal of the Atmospheric Sciences, 76, 989-1013. https://doi.org/10.1175/JAS-D-18-0191.1
Montgomery, M. T., Snell, H. D., \& Yang, Z. (2001). Axisymmetric spindown dynamics of hurricane-like vortices. Journal of the Atmospheric Sciences, 58, 421-435. https://doi.org/10.1175/1520-0469(2001)058<0421:ASDOHL>2.0.CO;2
Ohno, T., \& Satoh, M. (2015). On the warm core of a tropical cyclone formed near the tropopause. Journal of the Atmospheric Sciences, 72, 551-571. https://doi.org/10.1175/JAS-D-14-0078.1
Powell, M. D., Vickery, P. J., \& Reinhold, T. A. (2003). Reduced drag coefficient for high wind speeds in tropical cyclones. Nature, 422, 279-283. https://doi.org/10.1038/nature01481
Pu, Z., Zhang, S., Tong, M., \& Tallapragada, V. (2016). Influence of the self-consistent regional ensemble background error covariance on hurricane inner-core data assimilation with the GSI-based hybrid system for HWRF. Journal of the Atmospheric Sciences, 73, 4911-4925. https://doi.org/10.1175/JAS-D-16-0017.1
Rozoff, C. M., Schubert, W. H., \& Kossin, J. P. (2008). Some dynamical aspects of tropical cyclone concentric eyewalls. Quarterly Journal of the Royal Meteorological Society, 134, 583-593. https://doi.org/10.1002/qj. 237
Sanabia, E. R., Barrett, B. S., Celone, N. P., \& Cornelius, Z. D. (2015). Satellite and aircraft observations of the eyewall replacement cycle in Typhoon Sinlaku (2008). Monthly Weather Review, 143, 3406-3420. https://doi.org/10.1175/MWR-D-15-0066.1
Schubert, W. H., \& Alworth, B. T. (1987). Evolution of potential vorticity in tropical cyclones. Quarterly Journal of the Royal Meteorological Society, 113, 147-162. https://doi.org/10.1002/qj. 49711347509
Schubert, W. H., \& Hack, J. J. (1983). Transformed Eliassen balanced vortex model. Journal of the Atmospheric Sciences, 40, 1571-1583. https://doi.org/10.1175/1520-0469(1983)040<1571:TEBVM>2.0.CO;2
Sitkowski, M., Kossin, J. P., \& Rozoff, C. M. (2011). Intensity and structure changes during hurricane eyewall replacement cycles. Monthly Weather Review, 139, 3829-3847. https://doi.org/10.1175/MWR-D-11-00034.1
Stern, D. P., \& Zhang, F. (2013). How does the eye warm? Part I: A potential temperature budget analysis of an idealized tropical cyclone. Journal of the Atmospheric Sciences, 70, 73-90. https://doi.org/10.1175/JAS-D-11-0329.1
Tang, B., \& Emanuel, K. (2010). Midlevel ventilation's constraint on tropical cyclone intensity. Journal of the Atmospheric Sciences, 67, 1817-1830. https://doi.org/10.1175/2010JAS3318.1
Tsujino, S., Tsuboki, K., \& Kuo, H.-C. (2017). Structure and maintenance mechanism of long-lived concentric eyewalls associated with simulated Typhoon Bolaven (2012). Journal of the Atmospheric Sciences, 74, 3609-3634. https://doi.org/10.1175/JAS-D-16-0236.1
Tsukada, T., \& Horinouchi, T. (2020). Estimation of the tangential winds and asymmetric structures in typhoon inner ore region using Himawari-8. Geophysical Research Letters, 47, e2020GL087637. https://doi.org/10.1029/2020GL087637
Wang, X., Li, Q., \& Davidson, N. E. (2018). The coupled dynamic and thermodynamic processes for secondary eyewall formation. Journal of Geophysical Research: Atmospheres, 123, 9192-9219. https://doi.org/10.1029/2018JD028604
Wu, C.-C., Huang, Y.-H., \& Lien, G.-Y. (2012). Concentric eyewall formation in Typhoon Sinlaku (2008). Part I: Assimilation of T-PARC data based on the Ensemble Kalman Filter (EnKF). Monthly Weather Review, 140, 506-527. https://doi.org/10.1175/MWR-D-11-00057.1
Yamada, H., Tsuboki, K., Nagahama, N., Shimizu, K., Ohigashi, T., Shinoda, T., \& Nakazawa, T. (2018). Double warm-core structure of Typhoon Lan (2017) as observed through upper-tropospheric aircraft reconnaissance during T-PARCII. Preprints, 33rd Conference on Hurricanes and Tropical Meteorology, Ponte Vedra Beach: American Meteor Society, Retrieved from https://ams.confex.com/ ams/33HURRICANE/webprogram/Manuscript/Paper339931/201804_HurricaneConf_Yamada_extendAbst.pdf
Yang, Y.-T., Kuo, H.-C., Hendricks, E. A., \& Peng, M. S. (2013). Structural and intensity changes of concentric eyewall typhoons in the western North Pacific basin. Monthly Weather Review, 141, 2632-2648. https://doi.org/10.1175/MWR-D-12-00251.1
Zhou, X., \& Wang, B. (2011). Mechanism of concentric eyewall replacement cycles and associated intensity change. Journal of the Atmospheric Sciences, 68, 972-988. https://doi.org/10.1175/2011JAS3575.1

