Estimation of the Tangential Winds and Asymmetric Structures in Typhoon Inner Core Region Using Himawari-8

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Abstract Observations of the winds in tropical cyclones (TCs) are still limited. We propose a new method for deriving the tangential winds in tropical cyclones, which employs a spectral analysis of high-frequency cloud imaging by latest-generation geostationary meteorological satellites such as Himawari-8. The method was applied to the visible images of boundary layer clouds in the eye of Typhoon Lan (2017) over an 8.5-hr period. The low-level tangential winds over the central two thirds of the eye in radius were close to a rigid body rotation and increased with time. On its outside was a region with striating clouds rotating at much higher angular velocities, which may have been supergradient. Asymmetric motions were visualized as the deviation from the inner rotation, and the vorticity of some mesovortices were quantified. These asymmetric motions are suggested to transport angular momentum to accelerate the inner rotation.

1. Introduction

Geostationary meteorological satellites seamlessly observe tropical cyclones (TCs) throughout their life cycle without interruption. Their observations are used in the Dvorak technique to estimate the intensity of TCs (Dvorak, 1975, 1984). These are also used to derive Atmospheric Motion Vectors (AMVs; see Menzel, 2001, and the references therein). AMVs are assimilated not only in global forecasts but also in TC forecasts (Velden et al., 1998). AMVs are normally derived using the cross-correlation method (Leese et al., 1971; Schmetz et al., 1993). Even the state-of-the-art AMV products do not cover TC’s inner core region (Oyama et al., 2018), presumably because the operational methods do not treat rotation.

Monitoring winds in TCs’ inner core regions is important for understanding their dynamics and intensity estimation. However, conventional wind observations do not cover TCs seamlessly. Aircraft observations provide high-quality data, but their availability is limited. Ground-based Doppler radar observations are extensive (Bluestein & Hazen, 1989; Ishihara et al., 1986; Lee et al., 1999) but limited to near their sites. Microwave scatterometers onboard low-orbit satellites and aircrafts provide sea surface wind speeds, but saturation tends to occur under high-wind conditions (Yang et al., 2011). Surface winds estimated from satellite-borne C-band SARs may be more tolerant to saturation, but the number of the satellites suitable for this observation is limited (Mouche et al., 2017; Yu et al., 2019).

The latest-generation geostationary satellite “Himawari-8” has been operating since July 2015. Its spatiotemporal resolutions were greatly improved from its predecessor (Bessho et al., 2016). The satellite observes TCs...
ever 2.5 min, which is called the target observation. The high temporal resolution is suitable to capture the rapid motions in TCs, but it has not been attempted. Since the clouds in TCs' eyes are mostly confined in the boundary layer where the tangential winds are maximized at its top, wind derivation from the clouds there should be useful to study and monitor TCs.

In this study, we propose a method to derive tangential winds from high-frequency imaging as done by Himawari-8. This method utilizes space-time spectral analysis to obtain tangential winds as a function of the distance from the TC center (radius) at a time resolution of ~1 hr. It is markedly different from the conventional method using cross correlations. Our method is especially useful to estimate winds in the lower inner core regions of TCs, as shown in section 4.

The results of the method can be used to visualize and quantify the asymmetric wind components as the deviations from the axisymmetric components, as shown in section 5. It has been suggested numerically that the asymmetric components such as mesovortices play the important roles to intensify TCs (e.g., Hendricks et al., 2009; Kossin & Schubert, 2001; Naylor & Schecter, 2014; Schubert et al., 1999). Observational studies have documented the presence of mesovortices in the TCs inner core region (e.g., Fletcher et al., 1961; Kossin et al., 2002; Kossin & Schubert, 2004; Muramatsu, 1986; Shimada & Horinouchi, 2018). Some observational studies further quantified the vorticity of mesovortices in the eyewall region (Marks et al., 2008; Wingo & Knupp, 2016), but this study is the first to report a quantification of mesovortices within the eyes (section 5.1).

2. Data and Projection

We used visible (VIS) reflectivity at 0.64 μm (Band 03) from the target observations of Typhoon Lan (2017) with Himawari-8. Lan is a super typhoon that passed the Pacific Northwest region in 2017 (Figures 1a and 1b). The target observation captures a TC over an ~1,000-km × 1,000-km region every 2.5 min. Its resolution is 0.5 km at the subsatellite point. To estimate cloud top heights, we also used the infrared (IR) brightness temperature at 10.4 μm (Band 13; subsatellite point resolution: 2 km) and the isobaric temperature and geopotential height of the Japanese 55 years Reanalysis data set (Kobayashi et al., 2015; resolution: 1.25°). We defined reference vertical profiles of temperature and geopotential height at each observation time by linearly interpolating the Japanese 55 years Reanalysis data with space and time onto the TC centers. Here (only for this purpose), the TC centers were derived from the 6-hourly best track data compiled by Regional Specialized Meteorological Center Tokyo (RSMC-Tokyo) by using the cubic spline interpolation with time. We corrected the parallax from the entire Himawari-8 data used by equating the IR brightness temperature to the temperature in the reference profiles. The Himawari-8 data were projected onto the azimuthal equidistant projection with respect to the TC center (Figure 2a). Here, since the best track is not accurate enough for this purpose, we derived the TC centers every 30 min by subjectively examining the corrected IR images (Table S1 in the supporting information), and the results were interpolated with time, t, by the cubic spline interpolation (Figure 1c). The projected images were sampled on the polar coordinate with the resolutions every 2.5 min, which is called the target observation. The high temporal resolution is suitable to capture the rapid motions in TCs, but it has not been attempted. Since the clouds in TCs' eyes are mostly confined in the boundary layer where the tangential winds are maximized at its top, wind derivation from the clouds there should be useful to study and monitor TCs.

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Δr = 0.5 km along radius, r, and Δθ = 2π/440 radian along the counterclockwise azimuth from the east, θ (Figure 2b).

The inner core of Typhoon Lan was observed from 21 to 22 October by GPS dropsondes during the first aircraft missions of the Tropical Cyclones-Pacific Asian Research Campaign for the Improvement of Intensity Estimations/Forecasts (Ito et al., 2018). For verification, we used a dropsonde profile obtained at r~20 km at around 6:50 UTC, 21 October.

3. Proposed Method

The following five steps yield a tangential velocity profile \( v_E \) as a function of \( r \). It is expected that \( v_E \) is close to the azimuthal-mean tangential wind at around the cloud top, if the TC is nearly axisymmetric, so we shall call it the representative tangential wind. For simplicity, we assume that the rotation is counterclockwise as in the Northern Hemisphere.

Step 1: Project image data obtained at a short time interval, \( \Delta t \), onto the polar coordinate with respect to the TC center (e.g., Figures 2a and 2b).

Step 2: Take a time sequence over a duration of \( T \) (e.g., Figure 2c), apply the standard preprocess for spectral analyses to detrend and cosine-taper with \( t \), and conduct the Fast Fourier Transform along \( \theta \) and \( t \) to obtain two-dimensional power spectra with angular frequency, \( \omega \), and azimuthal wavenumber, \( k \) (e.g., Figure 3a).

Step 3: Stabilize the power spectra by averaging over \( r_j - \frac{dr}{2} \leq r \leq r_j + \frac{dr}{2} \) at each of the radius \( r_j \equiv dr_j \), where \( j \) is an integer and \( dr \) is a constant increment.

Step 4: Bin the power spectrum as a function of azimuthal phase velocity, \( c = \omega/k \), by integrating over the area enclosed by \( c = b_i \), \( c = b_i + \Delta b \), \( k = k_{\min} \), \( k = k_{\max} \), after applying the interpolation and extrapolation along \( \omega \) as described below (e.g., Figure 3b). Here, \( b_i = b_{\min} + i\Delta b \) (\( i = 0, 1, ..., n \)) is the bin boundary, \( \omega_N \equiv \pi/\Delta t \) is the Nyquist frequency, and the other undefined symbols are constants defined in what follows. The resultant phase velocity spectrum is normalized by the maximum value and referred to as \( f_i \), so \( \max(f_i) = 1 \) (e.g., Figures 3f–3h). Note that \( c \) corresponds to the angular velocity of rotation, since \( k \) is integer.

Step 5: Compute the representative tangential wind as \( v_E \equiv \frac{\sum_{i=1}^{n} c_i w_i f_i}{\sum_{i=1}^{n} w_i} \),

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

\[
    w_i = \begin{cases} 
        f_i & (f_i \geq f_{\text{thresh}}) \\
        0 & (f_i < f_{\text{thresh}})
    \end{cases}.
\]

In order to accurately derive tangential winds, the TC centers used should be less than a few kilometers from the center of gravity of the lower layer in the eye. The effect of its error, as measured by its distance \( E_r \), is investigated in Text S1, which demonstrates that it is likely small if \( E_r/r \) is much smaller than 1; when this ratio is high, it tends to erroneously increase \( v_E \) if the motion is close to rigid-body rotation. The azimuth resolution \( \Delta \theta \) must be smaller than \( \pi/k_{\max} \). The projection described in section 2 satisfies these conditions.

Figure 2. Examples of image preprocessing. (a) Parallax-corrected and projected VIS reflectivity (gray-scale) and estimated altitude in the eye (km; color shading). The altitudes of 0, 1, and 2 km correspond to the temperatures of 301.15, 294.15, and 290.65 K, respectively. (b) Brightness data on the polar coordinates. (c) Azimuth-time cross section for 1 hr at a radius of 20 km.
Figure 1. Examples of power spectra, azimuth-time cross sections, and velocity binning results. (a) The log10 of the power spectrum at \( r = 20 \) km. Black lines are drawn at \(|k| = k_{\text{max}}\). Gray lines indicate bin boundaries. (b) Extended spectrum up to \( \omega = 2 \omega_N \). The black dashed rectangle demarks the area shown in (a). (c–e) Azimuth-time cross sections at \( r = 15, 20, \) and \( 25 \) km for 1 hr from 23:30 UTC, 20 October. The blue lines indicate motions at \( v_E \), while green and purple lines indicate those at the slowest and the fastest velocities of the top 80% bins, respectively. (f–h) Binning results corresponding to (c)–(e). The top 80% bins are indicated by filled gray circles.

10.1029/2020GL087637

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The duration $T$ should be comparable to the time scale of the variation of rotation to be quantified. However, it should also be long enough to secure a desired spectral resolution. The following guideline on parameter setting requires a first guess of the TC’s angular velocity, $\omega_0$; if it is not available, one can start with an ad hoc value to improve it iteratively. Since the frequency resolution $\Delta \omega$ corresponds to the phase velocity resolution $\Delta v = \frac{2\pi}{Tk}$, $\Delta v$ should be smaller than $c_0$, which constrains the relation between $T$ and $k_{min}$. TC eyes can have vortex Rossby waves (e.g., Montgomery & Kallenbach, 1997). Their propagation could erroneously decrease $v_{E}$; Therefore, $k_{min}$ should be set to avoid it, if vortex Rossby waves are observed, for example, as a polygonal eyewall. We suggest that $k_{min}$ should always be greater than 1.

In principle, $k_{max}$ can be arbitrarily large, since the original image resolution provides a natural spectral cutoff. However, we found in our trial that to set

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

(1)

provides better results, where $L_{min}$ is an empirical minimum wavelength to be treated (section 4). It makes $k_{max}$ as a function of $r$.

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

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

(2)

The extrapolation along $\omega$ is introduced to compensate for the aliasing arising from insufficient $\Delta t$; the clockwise spectral peak at $k_{c} = 20$ and $\omega \leq \omega_N$ in Figure 3a is actually due to counterclockwise signals at $k_{c} = 20$ and $\omega \geq \omega_N$. When cloud motions are dominated by a single angular velocity, the spectrum at $\omega > \omega_N$ can be reproduced to some extent by repeating the spectra as in Figure 3b. Here we introduce an integer parameter $A$, which sets the maximum $\omega$ as $A \omega_N$. Because of the dominance of counterclockwise motions in the eye, it is safe to set $A = 2$. Even a number greater than 2 can be used, if it is validated from the actual spectra.

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

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

(3)

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

As demonstrated in Figures S2a and S2b, signals at $\omega > 2\omega_N$ are aliased onto $\omega < \omega_N$ in the same rotational direction. This could bias $v_{E}$, which should be avoided by examining the $\omega$-$k$ spectra and thereby choosing sufficiently high $b_{min}$ or low $k_{max}$ (see Figure S2b), and low $b_{max}$ (Figure S2c). If $A \geq 3$, double counting occurs in the binning when $k_{c} < k_{max}$ and $\omega_c < A \omega_N$, where $(k_{c}, \omega_c)$ is the intersection of $\omega = b_{min} + 2\omega_N$ and $\omega = b_{max}k$ (Figure S2c). This should be avoided by ensuring $k_{c} \geq k_{max}$ or $\omega_c \geq A \omega_N$, namely,

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

(4)

We performed a sensitivity test for $f_{th}$(Text S2), which suggests that values around 0.7–0.8 are appropriate. It is recommended to conduct a similar test.
4. Application to Typhoon Lan (2017)

4.1. Parameter Setting

We applied the proposed method to Typhoon Lan using the VIS data over 8.5 hr since 22:30 UTC, 20 October. By the time, Lan has developed a clear eye with a radius of 35 km. We set \( T = 1 \) hr, so 24 images were used for each estimation. From visual inspection, \( c_0 \) was set to \( 1.0 \times 10^{-3} \) rad/s. The other parameter values used are as follows: \( d_r = 5 \) km; \( k_{\text{min}} = 2 \); \( L_{\text{min}} = 5 \) km; \( \omega_0 = 0.05 \); \( J = 18 \). For \( r = 10,15,20 \) km, we used \( A = 2, b_{\text{min}} = 0.4 \times 10^{-3} \) rad/s, and \( b_{\text{max}} = 2.0 \times 10^{-3} \) rad/s (which provides \( n = 32 \)). For \( r = 25,30 \) km, we used \( A = 3, b_{\text{min}} = 0.7 \times 10^{-3} \) rad/s, \( b_{\text{max}} = 2.1 \times 10^{-3} \) rad/s (which provides \( n = 28 \)). These values meet the requirements presented in section 3. We tested several values of \( f_{\text{thresh}} \) and fixed it to 0.8. Figures 2 and 3 shown in section 3 are based on this setting.

4.2. Tangential Winds of Typhoon Lan (2017)

Figure 4 shows the time series of the tangential winds \( v_E \) and the rotational angular velocities \( v_E/r \) derived every 30 min for \( r = 10 \) to 30 km (dots). The angular velocities fluctuate relatively greatly at \( r = 10 \) km, which is presumably due to the frequent presence of clear air regions (e.g., Figure 2a) and asymmetric velocity.
components as explored in section 5.2. The five-point temporal running-mean angular velocities (curves) at $r \leq 25$ km are nearly uniform (except at $r = 25$ km at 5–6 UTC), suggesting a high degree of horizontal mixing. The angular velocities are increased gradually through the 8.5 hr from $1.2 \times 10^{-3}$ to $1.2 \times 10^{-3}$ rad/s, suggesting an intensification. The rotation at $r = 30$ km is faster throughout the analysis period. This region with $r=30$ km is characterized by striating clouds rotating at much higher angular velocities, which is investigated in sections 5.2 and 6.

To verify the results, we compared them extensively with cloud motions in the azimuth-time cross sections like Figures 3c–3e. We also used movies like Movie S1, in which the VIS images are rotated clockwise to compensate for the five-point temporal running-mean rotation at $r = 15$ km. All these comparisons indicated the validity of our results.

Our results for $r \leq 25$ km are consistent with the Tropical Cyclones-Pacific Asian Research Campaign for the Improvement of Intensity Estimations/Forecasts dropsonde data (Yamada et al., 2018). For example, the dropsonde winds obtained at $r = 20$ km around 06:50 UTC correspond to the angular velocities around $1.2 \times 10^{-3}$ rad/s over the altitudes between ~3 and ~1 km, while our result at $r = 20$ km, 06:30:00 UTC is $1.25 \times 10^{-3}$ rad/s.

5. Quantification of Asymmetric Structure of TC Inner Core Region

5.1. Mesovortices in the Eye

Movie S1 visualizes that the eye of Lan was full of asymmetric motions. We subjectively identified seven mesovortices (MV-1, ..., MV-7) at the times and locations shown in Figures 4b and 5a–5d. Visual cloud tracking was performed by using traceable features with horizontal scales 1–5 km, and their vorticities relative to the background rotation was estimated from three features around mesovortices; the features are shown in supplemental figures (Figures S4–S11). Let their positions be $(x_i^0, y_i^0)$ at $t$, where $i = 0, 1, 2$. From temporally intermediate positions

$$\left( x_i, y_i \right) = \left( \frac{x_i^0 + x_i^{0+\Delta t}}{2}, \frac{y_i^0 + y_i^{0+\Delta t}}{2} \right)$$  \hspace{1cm} (5)$$

and velocities

$$\left( \bar{u}_i, \bar{v}_i \right) = \left( \frac{x_i^{0+\Delta t} - x_i^0}{\Delta t}, \frac{y_i^{0+\Delta t} - y_i^0}{\Delta t} \right),$$  \hspace{1cm} (6)$$

the mean vorticity in the triangle is approximated by

$$\zeta = \frac{\Delta u_1 \Delta x_2 - \Delta u_2 \Delta x_1 + \Delta v_1 \Delta y_2 - \Delta v_2 \Delta y_1}{\Delta x_1 \Delta y_2 - \Delta x_2 \Delta y_1}.$$  \hspace{1cm} (7)$$

where $(\Delta x_1, \Delta y_1) = (x_1 - x_0, y_1 - y_0)$ and $(\Delta u_i, \Delta v_i) = (u_i - u_0, v_i - v_0)$. This relation, which is exact when $\Delta t, \Delta x_i$, and $\Delta y_i$ are infinitesimal, can be derived from Stokes’s theorem. The mean relative vorticities of several estimates of MV-1, MV-4, and MV-6 were obtained as $\zeta_1 = 2.0 \times 10^{-3}$ s$^{-1}$, $\zeta_4 = 3.2 \times 10^{-3}$ s$^{-1}$, and $\zeta_6 = -2.2 \times 10^{-3}$ s$^{-1}$, respectively. Their magnitude is comparable to the background vorticity of the rotation of $2.2 \times 10^{-3}$ to $2.4 \times 10^{-3}$ s$^{-1}$. The vorticities of MV-2, MV-3, MV-5, and MV-7 were not estimated due to the lack of sufficient number of concurrent traceable features.

Our result is consistent with earlier studies, since the vorticity inside the eye was increased when the mesovortices were observed. The observed asymmetric motions might have transported the high angular momentum associated with the secondary circulation into the eye.

5.2. Striations of the Inner Edge of the Eyewall

The striating clouds at $r=30$ km had remarkably high angular velocities (section 4.2). They existed over a half of the inner edge of the eyewall (Figures 5a–5d). It has a structure similar to the “striations” or “finger-like features,” which have been reported several times in previous aircraft observation studies (e.g., Aberson et al., 2006; Bluestein & Marks, 1987; Marks et al., 2008). We derived the angular velocity of the striations.
by visual inspection. The result was $1.75 \times 10^{-3}$ rad/s throughout the analysis period (Figures 4 and 5e). The striations were situated over 26–33 km from the center, and their cloud top heights increase with $r$ from 3 to 6 km. They tend to appear with radial orientation and are gradually tilted over time (Figure 5e), which is consistent with the decrease of tangential winds with altitude.

6. Discussion

The derived rotation speed increases with $r$ abruptly at the inner edge of the striations. This fact suggests that the striations reside in the secondary circulation associated with the eyewall. If so, the fact that the striations bulge out toward the TC center suggests the inertial overshoot (Bryan & Rotunno, 2009). Thus, the regularity of the striations might be due to the shear instability between the outgoing return flow, which is fast and supergradient, and the slower flow aloft. If this is true, it follows that the tangential winds below the striations can be even faster, since the Kelvin-Helmholtz billows move at an intermediate velocity in the shear.

Figure 5. Mesovortices and striations in the eye. VIS images at 00:05:00 (a), 01:47:30 (b), 03:02:30 (c), and 03:22:30 UTC (d), 21 October (directed north on top). Red arrows with numbers indicate the seven mesovortices, and blue arcs indicate the range of striations. (e) Time series of the striations. The VIS images were rotated clockwise at an angular velocity of $1.75 \times 10^{-3}$ rad/s and shown every 2.5 min from 04:52:30 UTC, 21 October. Color shading indicates the estimated cloud top heights. Black arcs show where $r = 25, 30, \text{and} 35$ km. Colored bullets show the manually identified positions of striating clouds. The colored horizontal lines are shown to indicate their positions at the same $r$ if they are rotated at $1.75 \times 10^{-3}$ rad/s.
The diabatic heating in the straits may contribute to TC intensification, since they are likely inside the radius of maximum wind (Pendergrass & Willoughby, 2009).

The space-time spectral analysis can separate multiple velocities, so even when the upper clouds and the lower clouds overlap, the upper and lower velocities are separable, if upper clouds have gaps or are optically thin. Therefore, our method may be applicable outside the eye, after some modification. Also, it can be applied not only VIS but also to IR data.

7. Conclusions

We have developed a new method for estimating the tangential winds of TCs based on the space-time Fourier analysis of high-frequency geostationary satellite images. The method was applied to the 2.5-min VIS images from Himawari-8 to quantify the rotation at the top of the atmospheric boundary layer of the eye of Typhoon Lan (2017). The rotational angular speed was nearly uniform and increased gradually with time for $r \lesssim 25$ km. At the inner edge of the eyewall, there were striations that rotated faster than the near center rotation. It was suggested that the striations may be associated with the secondary circulation. The flow in the eye was full of asymmetric motions, among which some mesovortices had vorticity whose magnitude is comparable to the vorticity associated with the rotation of the eye. It was suggested that the asymmetric motions may have transported angular momentum inward to intensify the near center rotation. Our results demonstrate the usefulness of geostationary satellite observations to diagnose and study TCs.

Acknowledgments

The Himawari-8 data we used are downloaded from the NICT Science Cloud. The data are publicly available upon registration through the contact address shown (https://sc-web.nict.go.jp/sc_staff.html). The typhoon best track data by the RSMS-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 time series of rotational angular velocities of Typhoon Lan (2017), are available online (https://doi.org/10.5281/zenodo.3761911). We thank Hiroyuki Yamada and Kazuhiro Tsuboki for discussion and information on the T-PARCII dropsonde observation. Details of the T-PARCII are found online (http://www.rain.hyrac.nagoya-u.ac.jp/~tsuboki/kibanS/index_kibanS_eng.html). We thank Uda Shimada and Satoki Tagino for helpful discussion on this study. We also thank the two anonymous reviewers for valuable comments. The authors declare no competing interests. This work was supported partially by the JSPS Grant-in-aid 19H050705.

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