1. Introduction

When two or more tropical cyclones (TCs) coexist within a certain area, they interact with each other (Brand 1970; Carr and Elsberry 1998; Carr et al. 1997; Chan and Law 1995; Dong and Neumann 1983; Fujiwhara 1921, 1922, 1923, 1931; Haurwitz 1951; Hoover 1961; Lander and Holland 1993; Lander 1995; Liu et al. 2021; Shin et al. 2006). This interaction is known as the Fujiwhara effect as Fujiwhara (1921, 1922, 1923, 1931) discovered the rotational and attractive effect for binary vortices in his laboratory experiment. Binary TCs rotate around the center of “mass” of the two vortices (Brand 1970; Dong and Neumann 1983; Haurwitz 1951). Carr and Elsberry (1998) indicated that binary TCs in the western North Pacific (WNP) tend to have counterclockwise motion in terms of a rotation rate when the two TCs are separated by less than 10°–12°.

Numerical studies with a nondivergent barotropic framework have been intensively conducted to explain observational findings on binary TCs (Chan and Law 1995; DeMaria and Chan 1984; Ritchie and Holland 1993; Shin et al. 2006). It is known that the binary interaction is primarily sensitive to the separation distance. For example, Chan and Law (1995) showed that mutual attraction and repelling motion can occur owing to the vorticity advection in the nondivergent barotropic model simulations depending on the separation distance for TC-like vorticity with a strong positive vorticity region surrounded by a weak negative vorticity region.

Although many studies have been carried out using two-dimensional barotropic models, they lack diabatic heating, which is critical for TC energetics and structure. Recent studies have shown that asymmetric diabatic heating around the TC center can modify the TC track when the vertical wind shear (VWS) of the horizontal wind creates an asymmetric structure (Yamada et al. 2016). Considering that the vortex motion is represented as the wavenumber-1 structure of potential vorticity (PV) tendency (Boos et al. 2015; Wu and Wang 2000), the TC motion can be modified by the preferential asymmetric PV genesis occurring from downshear to downshear-left of the VWS (Corbosiero and Molinari 2003; Ueno and Kunii 2009). This effect cannot be explicitly included in a barotropic model framework.
Recently, Liu et al. (2021) and Lee et al. (2023) conducted a set of idealized three-dimensional simulations of binary TCs on an f plane with diabatic heating. Liu et al. (2021) showed that a pair of upper-tropospheric anticyclonic and lower-tropospheric cyclonic circulations are generated by the system of binary TCs owing to their outflows that have a Rossby’s deformation radius and primary circulation, respectively. These circulations served as the VWS for each TC, causing an asymmetric structure and weakening. Lee et al. (2023) also demonstrated the asymmetric structure of each TC in their idealized simulations. Furthermore, Lee et al. (2023) found that TC tracks could be modified by binary-induced asymmetric diabatic heating. The maximum diabatic heating is directed to the rear left side, looking down at the counterpart TC. Hence, the diabatic heating asymmetry resists counterclockwise and approaching motion due to advection. This effect is particularly evident when the separation distance is greater than 8° latitude. It is because horizontal advection becomes more important when binary TCs are closer. These recent studies have introduced a new three-dimensional perspective on the interaction of binary TCs. However, these results have not been verified in a real atmosphere.

Another unresolved question about the Fujiwhara effect is that the TC track forecast of binary TCs is sensitive to the counterpart TC even when they are separated by more than 1500 km (Peng and Reynolds 2005), despite no major track deviation being detected in previous studies (Carr and Elsberry 1998; Dong and Neumann 1983). Considering that the Rossby deformation radius of the circulation due to a system of binary TCs is approximately 1600 km (Liu et al. 2021), it is possible that the motion following the steering wind is cancelled out by the diabatic heating asymmetry caused by the VWS for each TC. This can explain the sensitivity of the tracks without track deviation. However, the physical background for binary interaction of TCs with a separation distance more than 1500 km has been less explored with real cases.

A deeper understanding of binary interactions is also important in terms of disaster prevention and mitigation because the track forecast error tends to increase when binary TCs exist (Carr and Elsberry 2000; Chan and Lam 1989). In the appendix, we reaffirm that, to date, the track forecast errors for binary TCs remain large in operational track forecasts, including the group with a separation distance of 1500–2000 km.

Therefore, this research aims to analyze binary TCs up to a separation distance of 2000 km during 1979–2020, while focusing on their tracks and the three-dimensional structures with the best track and reanalysis data. We applied the PV budget analysis to decompose the impact of advection and asymmetric diabatic heating on TC tracks for further understanding. We show that the three-dimensional Fujiwhara effects in the WNP are similar to those in idealized simulations. The steering flow provides the tendency of counterclockwise and approaching motion; however, we will show that this tendency can be resisted by asymmetric diabatic heating. Therefore, asymmetric diabatic heating is an indispensable component of the motion of binary TCs.

The remainder of this paper is organized as follows. Section 2 describes the data, methodology, and climatology of binary TCs. Section 3 presents the speed of binary TCs in the reanalysis data and best track. Section 4 shows the VWS and associated asymmetric distribution of rainfall, diabatic heating, and PV budget analysis, focusing on TC tracks. In sections 5 and 6, a discussion and summary are presented.

2. Method
   a. Data source

This study examined binary TCs occurring over the WNP (0°–60°N, 100°E–180°) over a period of 42 years (1979–2020) with tropical storm intensity or greater. Tropical storm intensity is defined as a maximum sustained wind speed of at least 35 kt (1 kt ≈ 0.51 m s⁻¹), as derived from the best track data created by the Regional Specialized Meteorological Center (RSMC) Tokyo–Typhoon Center of the Japan Meteorological Agency (JMA). The best track data are not considered before a TC reaches the threshold of the tropical storm status or after an extratropical cyclone is subjected to transition from the TC.

An individual case is taken from the 6-hourly dataset of the RSMC Tokyo best track, in which two TCs approach within 2000 km. It yields 1876 cases for 366 unique TCs. The mid-point between the centers of binary TCs (hereafter referred to as a binary center point) is frequently observed at 15°–25°N and 115°–140°E, corresponding to the high-density area of TC tracks (Manganello et al. 2012). Binary TC events were more concentrated in the main TC season (June–October). The
occurrence rate of binary TC records was approximately 5% of the total best track records.

To investigate the environmental conditions and structure of binary TCs, we used ERA5 reanalysis with grid spacings of 0.25° longitude–latitude by the European Centre for Medium-Range Weather Forecasts (Hersbach et al. 2020). We used three-dimensional hourly datasets (wind fields, temperature, and PV) in pressure coordinates with a 50-hPa interval, surface wind, sea level pressure, and rainfall amount. As ERA5 cannot properly reproduce binary TCs in some cases, we applied the following criteria to detect a potential TC:

1) We searched for the location of minimum sea level pressure within 2° of latitude and longitude from the TC center position in the RSMC Tokyo best track. This was used as the temporal center location.

2) We defined the potential TC center location that minimizes the total radial variance of sea level pressure within 1° of latitude and longitude from the temporary center location, as in Braun (2002).

3) The potential TC center above (average ring region of 500–800 km) had a sum of temperature deviations at 300, 500, and 700 hPa that exceeds 2 K, as described by Oouchi et al. (2006).

4) The maximum wind speed at 850 hPa within 2° latitude–longitude from the center of the potential TC exceeded 12 m s⁻¹.

5) The minimum sea level pressure of potential binary TCs did not monotonically decrease along the line connecting them. This condition was introduced to ensure the double minima of the minimum sea level pressure.

If the above criteria were satisfied, we regarded them as binary TCs, whose center position is determined by criterion 2. These conditions were met by 1614 cases of 326 unique TCs in ERA5 (approximately 89% of the cases in the best track). It is not clear why some of the binary TCs were not reproduced well. It might be ascribed to the coarse horizontal model grid spacings, model errors such as in parameterized convectons, insufficient number of observations, no bogus TCs used, and deficiencies in a data assimilation system.

For presentation purposes, the TC with the larger circulation is referred to as TC1, whereas the TC with a smaller circulation is referred to as TC2. Here, the circulation $G$ was calculated by integrating the vorticity within 300 km of the TC center. In addition, we divided the results into three categories depending on the separation distance of the TC centers: $d = 0–1000$, 1000–1500, and 1500–2000 km. The number of cases in each category was 114 (58 TCs), 576 (175 TCs), and 924 (297 TCs), respectively. As we regard the 6-hourly data as an individual case, the separation distance of the same binary system can change from one category to another.

To organize our results, we used the two coordinate systems in which the TC center was on the $x$ axis. In an “individual TC”-centered coordinate system (Fig. 1a), the positive $x$ direction corresponds to the direction looking down on the counterpart TC and the positive $y$ direction is to the...
left. For presentation purposes, we divided the coordinates into four quadrants named down-counterpart left (DCL), up-counterpart left (UCL), up-counterpart right (UCR), and down-counterpart right (DCR), as shown in Fig. 1a. The other "binary center point" coordinate system employs the binary center point as the origin of the axis and the center of the two TCs aligned on the x axis. For this coordinate, we placed TC1 and TC2 at the left and right of the origin on the x axis, respectively (Fig. 1b).

The translation speed of the TC was evaluated by the change in the center position in 6 h. To clearly observe the binary interaction, we focused on the relative motion of a TC \( U_r \) with respect to the motion of a binary center point \( U_m \), instead of the original TC motion \( U = U_m + U_r \). We employed the density-weighted average of horizontal wind at 850–300 hPa within 500 km of the TC center as the steering flow. Note that the optimal steering flow may depend on the size and intensity of a TC (Galarneau and Davis 2013; Velden and Leslie 1991), while we employed a single steering layer and region. This is because the methodology on accurate specification of the optimal steering flow has not been established with diabatic heating asymmetry. It is one of the important topics to be investigated in the near future.

b. PV budget equation

The PV equation was used to diagnose the contribution of individual physical processes to TC tracks, as in the previous studies, because the motion of the TC can be regarded as the azimuthal wavenumber-1 component of the PV tendency (Lee et al. 2023; Wu and Wang 2000):

\[
\frac{\partial q}{\partial t} = -\mathbf{v} \cdot \nabla q - w \frac{\partial q}{\partial z} + \frac{1}{\rho} (\mathbf{\eta} \cdot \nabla \theta) + \frac{1}{\rho} (\nabla \times \mathbf{F}) \cdot \nabla \theta, \tag{1}
\]

where \( q \) is PV, \( t \) is time, \( \mathbf{v} \) is the horizontal wind vector, \( w \) is vertical wind, \( z \) is height, \( \rho \) is air density, \( \mathbf{\eta} \) is the absolute vorticity that has three components, \( \theta \) is potential temperature, \( \dot{\theta} \) corresponds to the diabatic heating rate, and \( \mathbf{F} \) is an external force such as friction. This equation indicates that the temporal change in PV can be explained by the sum of several terms. The first term on the RHS represents the horizontal advection of the PV (HADV) whereas the second term represents the vertical advection (VADV). The third term represents the PV sources and sinks according to the gradient of diabatic heating (GDIA). Diabatic heating was evaluated according to the following equation:

\[
\dot{\theta} = \frac{\partial \theta}{\partial t} + \mathbf{v} \cdot \nabla \theta + w \frac{\partial \theta}{\partial z}. \tag{2}
\]

In the inner core of a TC, PV is typically generated by increasing diabatic heating with height at the lower level and is destroyed by decreasing diabatic heating with height at the upper level. If the distribution of diabatic heating associated with a TC has azimuthal wavenumber-1 asymmetry (e.g., due to VWS), GDIA contributes to moving the TC in the direction of maximum diabatic heating. More precisely, in the direction of maximum diabatic heating, PV is generated in the lower troposphere and destroyed in the upper troposphere as a response to diabatic heating maximized in the middle troposphere. However, the contribution to the lower troposphere is more important because TC motion is correlated with
lower- and middle-tropospheric flow (Velden and Leslie 1991). The fourth term in Eq. (1) represents the PV change owing to external forces, such as friction. This term is negligible except for the boundary layer. The vertically averaged contribution of each term is presented in section 4. Note that HADV and VADV not only include large-scale horizontal winds but also small-scale wind. Diabatic heating in the TC inner core region induces a strong upward motion and outward motion.

In this study, we employ the equation below for the PV budget analysis on and above 850 hPa instead of Eq. (2) by neglecting the external force term and considering the relative motion with respect to the motion of the binary center point:

\[
\frac{\partial q_r}{\partial t} = -v_r \cdot \nabla q - \nabla q \cdot \frac{1}{\rho} (\mathbf{d} \cdot \nabla \theta). 
\]  

(3)

Here, \(v_r = v - u_{\text{m}}\) and \(\frac{\partial q_r}{\partial t} = \frac{\partial q}{\partial t} + u_{\text{m}} \nabla q\) represent the relative wind velocity and PV tendency, respectively, by subtracting the advection along with the motion of the binary center point. It simply states that the motion relative to the binary center point is analyzed using the PV tendency equation. The PV tendency on the left-hand side associated with the TC motion in 6 h is diagnosed by the temporal average of hourly meteorological fields on the right-hand side. The PV tendency on the left-hand side is reasonably captured by the sum of the terms on the right-hand side, except for a slight deviation at 300 hPa (Figs. S1 and S2 in the online supplemental material).

Wu and Wang (2000) developed a methodology to convert each PV tendency term to its contribution to TC motion. We apply the same technique in section 4, supposing that the PV within 150 km of the TC center is relevant to TC motion. The technique is useful for evaluating the importance of HADV, VADV, and GDIA in the binary interactions.

3. Track analysis

Figures 2a–c show the frequency distribution and mean speed of relative TC motion, \(U_r = (U_{rx}, U_{ry})\), in the ERA5 which was classified into three groups by the separation distance of the binary TCs. When the separation distance is less than 1000 km, the general tendency of \(U_{rx} > 0\) and \(U_{ry} < 0\) shows the approaching motion toward the counterpart TC and the counterclockwise rotation about the binary center point, respectively.

\[1\] When the surface altitude of a TC center is high, the external force term may not be negligible at 850 hPa. However, only 0.5% of all cases have a surface altitude above 500 m. It has little influence on the conclusions (figure not shown).

\[2\] Because the motion of the binary center point is simply the mean translation speed of TC1 and TC2, this figure is valid both for TC1 and TC2.
The composite-mean $U_{rx}$ and $U_{ry}$ in ERA5 are 1.00 and $-2.61$ m s$^{-1}$, respectively. When the separation distance is 1000–1500 km, the approaching motion is very weak ($U_{rx} = 0.13$ m s$^{-1}$) and the counterclockwise rotation is still obvious ($U_{ry} = -0.98$ m s$^{-1}$) (Fig. 2b). With a separation distance of 1500–2000 km, both the approaching motion and counterclockwise rotation are very weak ($U_{rx} = 0.14$ m s$^{-1}$ and $U_{ry} = -0.14$ m s$^{-1}$), and the direction of relative motion is scattered largely depending on cases (Fig. 2c). The TC motion speed derived from ERA5 is very similar to those in the best track for each category (Figs. 2d–f). In this comparison, the same samples that satisfy the criteria of binary TCs in section 2a are analyzed. It supports the validity of ERA5 to analyze the dynamics of TC tracks.

Figure 3 shows the steering flow relative to the grand center motion based on ERA5. Essentially, the translation speed of binary TCs is similar to the steering flow (Figs. 2a–c and 3a–c). On closer inspection, the speed of actual counterclockwise motion for TCs is weaker than the counterclockwise component of steering wind (Figs. 3d–f). In addition, the actual approaching motion is slower than the corresponding component of the steering wind for binary TCs with $d > 1000$ km, while it is faster for binary TC with $d < 1000$ km. One may think that the deviation of 0.1–0.7 m s$^{-1}$ is negligible. However, multiplying the persistent deviation of 0.4 m s$^{-1}$ by 72 h, we obtain the displacement of 104 km. It is significant in terms of the track forecast.

As such, the actual motion deviates from the steering wind, although it is difficult to properly define the steering wind for binary TCs located very closely. In the following sections, we investigate whether this motion can be explained by shear-induced asymmetry of diabatic heating, as shown in recent studies (Lee et al. 2023).

4. Diabatic heating asymmetry

The idealized simulations by Liu et al. (2021) and Lee et al. (2023) showed that a pair of upper-level anticyclonic and lower-level cyclonic circulations are spontaneously generated by a system of binary TCs owing to their outflow and low-level primary circulation. The pair of circulations consisted of the VWS for each TC, causing asymmetric convection. Figure 4 shows that the composite for binary TCs in ERA5 exhibits a significant VWS to an individual TC, which is consistent with the results from three-dimensional idealized simulations on an $f$ plane with diabatic heating (Lee et al. 2023; Liu et al. 2021). Binary TCs were embedded in the VWS environments directed to the UCL quadrant. The VWS field was circular for binary TCs with $d = 0–1000$ km. The shape becomes more elliptical, with the line connecting the centers of the binary TCs behaving as the major axis when the separation distance increases. Figures 4d–i are the composite means of the upper-level wind and lower-level wind. The outflow of binary TCs is the origin of upper-level anticyclonic circulation (Figs. 4d–f), and the low-level tangential wind of binary TCs serves as low-level cyclonic circulation (Figs. 4g–i). This structure means that binary TCs can contribute to the binary-induced VWS in which each TC is embedded.

Figure 5 shows the frequency distribution of the VWS vectors for TC1 and TC2. Regardless of the separation distance, the VWS vector tends to be directed toward the UCL and not toward the DCR, although there is a spread in individual cases. The average magnitude of VWS is 4–6 m s$^{-1}$, which is slightly weaker in the category $d = 1500–2000$ km. The VWS vector for TC2 was directed slightly toward the counterpart-left compared to TC1. As shown in Fig. 4, the outflow from
TC1 tends to behave as a counterpart-leftward wind in the upper troposphere over TC2.

Note that binary TCs in the WNP are embedded in large-scale features, such as the westerly jet, monsoon, and subtropical high (Prince and Evans 2020). Generally, it is not easy to determine the influence of these features because the extent of the VWS that has a Rossby deformation radius is close to the synoptic scale. Here, we calculated the anomaly with respect to climatology to quantify the influence of binary TCs as a composite mean.

To do so, a daily climatology was created based on an average of 30 years (1980–2009) of ERA5. We then calculated the wind anomaly for each case with respect to the climatology at a given latitude, longitude, and day of the year. The anomaly field for the VWS, upper-level wind, and lower-level wind are shown in Fig. 6. This reveals that the counterclockwise VWS field is robust, even if we remove the climatological mean. The upper- and low-level circulations were evident. However, the magnitude of VWS becomes weaker compared to Fig. 4, particularly in upper-level circulation away from the center of the TCs. This is partly due to the existence of midlatitude westerlies.

Figure 7 shows the frequency distribution and composite mean of the VWS anomaly with respect to climatology. The anomaly vector directs to the UCL in all categories, supporting the existence of binary-induced VWS. The magnitudes of the composite mean of climatological anomalies in the VWS were approximately 30%–70% of the total magnitudes (Table 1). Notably, the VWS anomaly weakens with a larger separation distance.

Figure 8 shows that the composite rainfall in ERA5 is more intense in the UCL quadrant. This is consistent with previous studies that showed that the maximum rainfall tends to appear from the downshear to the downshear-left quadrant (Corbosiero and Molinari 2003; Ueno and Kunii 2009). This rainfall distribution was also consistent with the diabatic heating rate at 700 hPa (Fig. 9). These figures illustrate that the rainfall and diabatic heating of binary TCs are strong in the UCL quadrant and weak in the DCR quadrant, consistent with the VWS.

Considering that the TC motion can be regarded as the wavenumber-1 asymmetry of the PV change, the asymmetric feature of the diabatic heating gradient can be related to the TC motion because the positive vertical gradient of diabatic heating in the presence of positive absolute vorticity is the source of the PV. Figure 10a shows the wavenumber-1 PV tendency at 3

Table 1 shows the absolute value of the composite mean of VWS vectors and their climatological anomalies. The composite mean of the absolute value of VWS vectors is 8.4–10.0 m s⁻¹ in each group, while the composite mean of the absolute value of climatological anomaly vectors is 6.8–7.6 m s⁻¹.
300 hPa for TC1 with \(d = 1000–1500\) km. Figures 10b–d show the wavenumber-1 components of the HADV, VADV, and GDIA at 300 hPa. Figures 10e–l are the same as those in Figs. 10a–d but at 500 and 850 hPa. The dipole pattern of the PV tendency term that is positive in the counterpart-right side and negative in the counterpart-left side corresponds to counterclockwise rotation with respect to the grand center (Figs. 10a,e,i). One major finding is that the PV tendency is not explained by the HADV alone, particularly at 300 and 850 hPa. In the lower troposphere (Figs. 10i–l), the HADV component attempts to rapidly rotate counterclockwise and approach the counterpart TC. However, the GDIA strongly resists this action. In the upper troposphere, the PV budget is largely balanced between the VADV and GDIA. In the middle level, the HADV is relatively strong, whereas VADV and GDIA are not negligible.

The profiles of diabatic heating and PV clarify these characteristics. The composite-mean diabatic heating generally increased from the lower troposphere to the middle troposphere and decreased above the middle troposphere for TC1 with \(d = 1000–1500\) km (Fig. 11a). Owing to the VWS, upward motion and diabatic heating are enhanced in the UCL quadrant compared to the DCR quadrant. It follows that PV is actively generated at 850 hPa by the stronger positive vertical gradient of diabatic heating through the third term on the rhs of Eq. (3), whereas it was destroyed at 300 hPa by a stronger negative vertical gradient. The contribution of the VADV at 300 hPa is explained by the strong negative vertical gradient of the PV with a strong upward motion in the UCL quadrant (Fig. 11b). At 500 hPa, VADV and GDIA played a relatively minor role because diabatic heating and PV were maximized around this level. Notably, the HADV and VADV shown in Fig. 10 include storm-scale transport of PV in addition to large-scale transport. In the UCL quadrant, the low-level inflow and upper-level outflow were stronger relative to DCR, presumably because of the VWS (Black et al. 2002). In addition, the convection also contributes to active negative PV transport through HADV at 500 hPa and positive PV transport through VADV at 300 hPa outside of the radius of maximum wind (RMW) in the UCL quadrant (Fig. 11b). Although it is not easy to separate the impact of the heating-induced asymmetry in the flow field on the TC motion, these results imply that the asymmetry of diabatic heating is involved in the binary TC motion at each level, not only through the GDIA term but also through the HADV and VADV terms.

Figures 12a–c show the composite-mean diagnosed contribution of each term to the TC motion vector for TC1 with \(d = 1000–1500\) km based on the method of Wu and Wang (2000). The diagnosed TC motion from the PV tendency reasonably represents the counterclockwise rotation and very weak approaching motion with respect to the grand centers at all levels. The important contributions come from the GDIA
and VADV at 300 hPa, all terms (HADV, VADV, and GDIA) at 500 hPa, and HADV and GDIA at 850 hPa, which is consistent with the PV budget analysis (Fig. 10). To quantify the overall importance, we calculated a vertically weighted mean of the diagnosed contribution to the motion vector for each term using dataset between 300 and 850 hPa with an interval of 50 hPa:

$$\nabla_d = \int_{300\text{hPa}}^{850\text{hPa}} \rho \psi_d dp,$$

(4)

where $\psi_d$ is the motion vector contributed by each term diagnosed by the method of Wu and Wang (2000) (such as in

Fig. 8. Mean precipitation rate in ERA5 (mm h$^{-1}$).

Fig. 9. Diabatic heating rate (K h$^{-1}$) at 700 hPa.
FIG. 10. Composite mean of PV budget analysis for TC1 with $d = 1000$–$1500$ km at (a)–(d) 300, (e)–(h) 500, and (i)–(l) $850$ hPa. (first column) PV tendency and the terms of (second column) HADV, (third column) VADV, and (fourth column) GDIA. Units are $10^{-5}$ PVU s$^{-1}$.

Figs. 12a–c). The result shows that the vertically mean diagnosed motion is composed of the counterclockwise rotation due to HADV modulated by the GDIA term pulling the UCL direction (Fig. 12d). This supports our findings that diabatic heating asymmetry in the UCL quadrant is important for the motion of binary TCs with $d = 1000$–$1500$ km.

Figures 13 and 14 show the PV budget of each term for TC1 with $d = 0$–$1000$ km and $1500$–$2000$ km, respectively. When the separation distance was smaller ($d = 0$–$1000$ km), the contribution of the HADV became relatively stronger than the other terms in the total PV budget especially at 500 and $850$ hPa (Fig. 13). While the GDIA contribution opposing the rotating

FIG. 11. The composite-mean quadrant mean of (a) diabatic heating rate (K h$^{-1}$) and (b) PV (PVU) for TC1 with $d = 1000$–$1500$ km in a radial pressure coordinate. The left-hand side of each panel is the average over the UCL quadrant, while the right-hand side of each panel is the average over the DCR quadrant. The radius is scaled by the RMW.
motion due to the HADV is not negligible, it indicates that the HADV plays a larger role in the motion of binary TCs. This is consistent with the finding of Lee et al. (2023) that the dynamics of TC motion are dominated by horizontal advection as binary TCs become closer. The wavenumber-1 structure of the GDIA has a maximum to the left of the counterpart TC within 100 km of the TC center. The vertically weighted contribution of the GDIA term directs the DCL quadrant (figures not shown). Therefore, the diabatic heating asymmetry resists counterclockwise motion and assists the approach of binary TCs with \( d = 0–1000 \) km. When the separation distance was larger \( (d = 1500–2000 \) km), GDIA and VADV were nearly balanced in the upper troposphere, whereas GDIA and HADV were nearly balanced in the lower troposphere (Fig. 14). The binary interaction is obvious in terms of VWS and the asymmetries in rainfall and diabatic heating for binary TCs with \( d = 1500–2000 \) km (Figs. 4, 8, and 9). However, the impact of diabatic heating asymmetry on TC motion was cancelled out by horizontal advection. It might explain why the sensitivity appears in the study of Peng and Reynolds (2005) even when the separation distance of binary TCs is beyond a separation distance of 1500 km. These results are consistent with the contribution of each term to the TC motion vector (Figs. S3 and S4).

In summary, the motion of binary TCs, viewed as the wavenumber-1 component of the PV tendency, cannot be solely explained by the HADV. Rather, it should be explained by the balance among HADV, VADV, and GDIA, as in recent studies (Lee et al. 2023). The dynamics of the motion of binary TCs are substantially different from those of the conventional framework that uses a two-dimensional barotropic model. The diabatic heating term serves as the strong source (sink) of the PV in the lower (upper) troposphere, and the

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**FIG. 12.** Composite mean of diagnosed contribution to TC motion at (a) 300, (b) 500, and (c) 850 hPa, and for (d) vertically weighted mean for TC1 with \( d = 1000–1500 \) km.

**FIG. 13.** As in Fig. 10, but for TC1 with \( d = 0–1000 \) km.
wind field is also modified owing to heating. The vertical integration of the contribution of GDIA makes the TC move to the UCL or DCL, resisting clockwise rotation. It is also notable that the deviation in TC motion from the steering wind field in Figs. 3d–f is consistent with the diagnosed contribution of the GDIA to TC motion. This indicates that TC motion is modified by asymmetric diabatic heating. Another notable feature is that heating and rainfall asymmetry is seen in a TC even if the counterpart TC is separated by 1500–2000 km. The weak signal in the deviation of motion for this separation distance (Figs. 2c,f) may be due to the cancellation between advection and diabatic heating asymmetry.

5. Discussion

a. Dependency on the intensity, size, circulation, and duration

Considering that the VWS for each TC is induced by a system of binary TCs, it is expected that the properties such as TC intensity, size, circulation, and duration of binary TCs affects the magnitude of the VWS. Here, we categorized binary TCs with $d = 1000–1500$ km into three groups as shown in Table 2. Each group contains at least 100 samples. Table 3 shows that the composite mean of VWS for TC1 decreases with increasing intensity of the two TCs, but the composite mean of the VWS for TC2 is stronger with a pair of strong TCs. Considering that weak TCs can result from the environmental strong VWS, the VWS anomaly is calculated with respect to the climatology for a given location and day of the year (Table 3). This clearly shows that the VWS in the UCL quadrant is enhanced for both TC1 and TC2 when a pair of TCs are stronger. As for the other parameters, both VWS and its climatological anomaly generally increase with increasing size, circulation, and duration as expected.

![FIG. 14. As in Fig. 10, but for TC1 with $d = 1500–2000$ km.](image)

<table>
<thead>
<tr>
<th>Category</th>
<th>Group 1</th>
<th>Group 2</th>
<th>Group 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity</td>
<td>$V_{\text{max},1}, V_{\text{max},2} \leq 30$ (116)</td>
<td>$V_{\text{max},1} &gt; 30$ and $V_{\text{max},2} \leq 30$ (272)</td>
<td>$V_{\text{max},1}, V_{\text{max},2} &gt; 30$ (140)</td>
</tr>
<tr>
<td>Size</td>
<td>$R_{1}, R_{2} \leq 300$ (102)</td>
<td>$R_{1} &gt; 300$ and $R_{2} \leq 300$ (287)</td>
<td>$R_{1}, R_{2} &gt; 300$ (139)</td>
</tr>
<tr>
<td>Circulation</td>
<td>$\Gamma_{1}, \Gamma_{2} \leq 2.8 \times 10^{7}$ (118)</td>
<td>$\Gamma_{1} &gt; 2.8 \times 10^{7}$ and $\Gamma_{2} \leq 2.8 \times 10^{7}$ (293)</td>
<td>$\Gamma_{1}, \Gamma_{2} &gt; 2.8 \times 10^{7}$ (117)</td>
</tr>
<tr>
<td>Duration</td>
<td>$T \leq 36$ (236)</td>
<td>$36 &lt; T \leq 60$ (137)</td>
<td>$T &gt; 60$ (155)</td>
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</tbody>
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$U_{rx} = 0.24 \text{ m s}^{-1}$ and $U_{ry} = -0.86 \text{ m s}^{-1}$ for two weak TCs (intensity group 1), $U_{rx} = 0.03 \text{ m s}^{-1}$ and $U_{ry} = -0.93 \text{ m s}^{-1}$ for one weak TC and one strong TC (intensity group 2), and $U_{rx} = 0.20 \text{ m s}^{-1}$ and $U_{ry} = -1.10 \text{ m s}^{-1}$ for two strong TCs (intensity group 3). The rotating motion for a pair of strong TCs is barely faster than for a pair of weak TCs, although the steering wind with strong TCs is stronger by about 0.5 m s$^{-1}$ (figures not shown). The diagnosed motion vectors at 850 hPa in Figs. 15a–c reveal that the HADV for strong binary TCs is larger than that for weak binary TCs. However, this is compensated for by the large GDIA term associated with the strong VWS for a pair of strong binary TCs. A similar feature was observed in the vertically density-weighted average (figures not shown). As such, the VWS buffers the rotating motion in strong TCs through diabatic heating asymmetry resisting horizontal advection.

The anomalous approaching and rotating speeds are quite low for two small TCs (size group 1). A counterclockwise rotation was observed for binary TCs comprised of a large and a small TC (size group 2), as well as for two large TCs (size group 3). The diagnosed motion vectors at 850 hPa in Fig. 15d show that the HADV is close to being cancelled by the GDIA for small binary TCs. The HADV is sufficiently larger than GDIA when at least one TC is large (Figs. 15e,f), indicating that the impact of HADV on a TC is considerable to the large counterpart. The results for the groups classified by the circulation are very similar to those classified by the size (Figs. 15g-i). It reflects the notable dependency of circulation on the size.

Figures 15j-l show that the GDIA was relatively weak for a “young” couple in which binary TCs had just been established (duration group 1), while it was strong for an “old” couple (duration group 3). Since the clockwise upper-level circulation is expected to strengthen since the couple has been established, the weaker GDIA for the young couple is reasonable. Note that the HADV is relatively insensitive to the duration. Thus, the stronger GDIA causes the repelling motion against the HADV for duration groups 2 and 3.

### 6. Summary

In this study, we analyze the dynamics of binary TCs in the WNP, motivated by recent idealized simulations that have shown the binary-induced VWS and relevant three-dimensional aspects of the TC structure and motion. First, we confirm the traditional facts that binary TCs rapidly rotate counterclockwise and
approach when $d < 1000$ km, rotate counterclockwise with a very weak approach when $d = 1000–1500$ km, and exhibit almost negligible deviation in motion when $d = 1500–2000$ km. However, upon closer inspection, the TC motion deviated in the clockwise direction from the steering flow.

The composite-mean wind field difference between 200 and 850 hPa consists of anticyclonic circulation, serving as the VWS in the UCL quadrant on each TC. The VWS exerted on a TC partly comes from environmental conditions that did not exist in the idealized simulations. We speculate that the binary-induced VWS is approximately 30%–70% of the total VWS through the comparison with climatology as shown in Table 1. The total VWS causes notable rainfall and diabatic heating in the UCL quadrant.

Furthermore, the PV budget analysis and the diagnosis of the motion of binary TCs with $d = 1000–1500$ km indicate that the motion of binary TCs is largely affected by diabatic heating, based on the fact that TC motion can be viewed as the wavenumber-1 asymmetry of the PV tendency. The wavenumber-1 PV tendency is determined by the balance between the gradient of diabatic heating and horizontal advection in the lower troposphere, whereas it is determined by the balance between the vertical advection and gradient of diabatic heating in the upper troposphere. Even in the middle troposphere, the vertical advection and gradient of diabatic heating play substantial roles in the PV budget. The vertically density-weighted diagnosed motion vector indicates that the diabatic heating asymmetry resists the counterclockwise and approaching motion for TCs with $d = 1000–2000$ km. For binary TCs with $d < 1000$ km, horizontal advection is important, but TC motion is slightly modified by diabatic heating asymmetry. The asymmetry of a TC can be affected by another TC even with a separation distance of 1500–2000 km (Figs. 8 and 9), while there was almost no deviation in TC motion about the midpoint.
In terms of TC track, this is presumably the result of the cancellation among the weak steering flow (that attempts to rotate cyclonically and approach each other), the resisting diabatic heating asymmetry, and vertical advection (Fig. 14).

The VWS was shown to depend on the TC intensity, size, circulation, and duration. The impact on the motion did not increase substantially with increasing intensity because the impact of asymmetric diabatic heating became also strong. For two small TCs, the anomalous TC motion was small. The VWS and relevant asymmetries were not generally dependent on the geographical location of TCs except for slight deviation in TCs located in the SW region. The current results are presumably due to binary-induced VWS rather than specie phenomena such as midlatitude westerlies. Our main findings, relevant to the impact of diabatic heating asymmetry on TC motion, are robust. Indeed, the conventional two-dimensional barotropic perspective is insufficient in fully understanding the structure and motion of binary TCs. We have shed light on some three-dimensional aspects of binary TCs in the real world, which supports the findings from recent idealized simulations by Lee et al. (2023) and Liu et al. (2021).

There should be careful interpretation in some respects. The β-gyre effect was not considered in this study. Chan and Law (1995) showed that the relative motion with respect to the grand center in the β plane is almost identical to that on an f plane. The current study analyzes the motion relative to the grand center so that the β-gyre effect seems to play a minor role. Also, the asymmetry of diabatic heating is also involved in the advection term because it induces storm-scale asymmetry in the flow field. It means that the diabatic heating can impact on the TC track.
not only through GDIA but also HADV and VADV. However, fully understanding the effect of diabatic heating is beyond the scope of this work, and it will be a future topic.

From the view of disaster prevention and mitigation, this study suggests that rainfall tends to be strong in the UCL and UCR quadrants in the WNP. The successful reproduction of diabatic heating asymmetry and induced flow, in addition to the large-scale wind field, is needed to improve the track forecast of binary TCs, including cases with d\(\geq\)1500 km. The predictability of binary TCs is beyond the scope of this study but should be investigated in the near future.

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Data availability statement. RSMC Tokyo best track data and ERA5 data are available at https://www.jma.go.jp/jma/jma-eng/jma-center/rsme-hp-pub-eg/besttrack.html and https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5, respectively.

APPENDIX
Track Forecast Errors for Binary TCs

We analyzed the operational track forecast errors during 2011–20 based on the RSMC Tokyo TC forecast error database (Ito 2016) to check if the track forecast errors of binary TCs have remained large to date. We classified the average track forecast errors into three groups according to the status of a TC at the initial forecast time:

- Group 1: A TC does not have a counterpart TC or is separated from its counterpart TC by more than 2000 km.
- Group 2: A TC has a counterpart TC within 1500 km.
- Group 3: A TC has a counterpart TC separated by 1500–2000 km.

Figure A1a shows that the track forecast errors for Groups 2 and 3 for each forecast time (FT) are larger than those for Group 1. In general, these deviations are statistically significant at the 99% confidence level in FT48, FT72, and FT96 for Group 2 and FT72 and FT120 for Group 3, applying a two-tailed t test, based on the samples in the last 10 years (Fig. A1b). These results indicate that track forecasts remain challenging for binary TCs. In particular, the comparison between Groups 1 and 3 is interesting because large track forecast errors are detected even with a relatively large separation distance of 1500–2000 km, despite no major considerable track deviation being detected in previous studies.

REFERENCES


