

Intensity change of binary Tropical Cyclones (TCs) in idealized numerical simulations: two initially identical mature TCs

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1 **Intensity Change of Binary Tropical Cyclones (TCs) in Idealized Numerical**
2 **Simulations: Two Initially Identical Mature TCs**

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Abstract

This study investigates the intensity change of binary tropical cyclones (TCs) in idealized cloud-resolving simulations. Four simulations of binary interaction between two initially identical mature TCs of about 70 ms^{-1} with initial separation distance varying from 480 to 840 km are conducted in a quiescent f -plane environment. Results show that two identical TCs finally merge if their initial separation distance is within 600 km. The binary TCs presents two weakening stages (stages 1 and 3) with a quasi-steady evolution (stage 2) in between. Such intensity change of one TC is correlated with the upper-layer vertical wind shear (VWS) associated with the upper-level anticyclone (ULA) of the other TC. The potential temperature budget shows that eddy radial advection of potential temperature induced by large upper-layer VWS contributes to the weakening of the upper-level warm core and thereby the weakening of binary TCs in stage 1. In stage 2, the upper-layer VWS first weakens and then re-strengthens with relatively weak magnitude, leading to a quasi-steady intensity evolution. In stage 3, due to the increasing upper-layer VWS, the non-merging binary TCs weaken again until their separation distance exceeds the local Rossby radius of deformation of the ULA (about 1600 km), which can serve as a dynamical critical distance within which direct interaction can occur between two TCs. In the merging cases, the binary TCs weaken prior to merging because highly asymmetric structure develops as a result of strong horizontal deformation of the inner core. However, the merged system intensifies shortly after merging.

43 **1. Introduction**

44 When two tropical cyclones (TCs) interact with each other, errors in both track and intensity
45 forecasts are often larger than those for a single TC (Brand 1970; Jarrell et al. 1978; Liu and Tan
46 2016). Fujiwhara (1921, 1923, and 1931) first demonstrated the interaction of two vortices in
47 proximity in the tank experiments and found that the two cyclonic vortices rotated
48 counterclockwise, moved toward each other, and finally merged (i.e., *Fujiwhara effect*). In the real
49 atmosphere, binary TCs are detected by using various statistical parameters such as their intensities,
50 relative locations, coexistence time and separation distance. The critical separation distance
51 determining whether two TCs belong to binary TCs ranges from 1300 to 1800 km (Brand 1970;
52 Dong and Neumann 1983; Wu et al. 2011; Jang and Chun 2015a; Ren et al. 2020). Within the
53 critical separation distance, the motion of binary TCs presents mutual approaching, mutual cyclonic
54 orbiting, or mutual escaping (Brand 1970; Dong and Neumann 1983; Lander and Holland 1993,
55 hereafter LH93). Sometimes mutual anticyclonic rotation of binary TCs happens under the
56 influence of the large-scale environmental flow such as the subtropical high (Dong and Neumann
57 1983; LH93). Real case studies show that the weaker and smaller TC is susceptible to the stronger
58 and larger TC in a binary system, where the former looks like moving around the latter (Wu et al.
59 2003; Yang et al. 2008). Moreover, during the binary interaction, filamentation and deformation
60 occurred in the weaker and smaller TC Typhoon Alex (1998), which finally became a spiral band
61 of the stronger and larger Typhoon Zeb (1998) on satellite images (Kuo et al. 2000).

62 More details relating to the motion and structure change of binary TCs have been investigated

63 in idealized frameworks (Chang 1983; DeMaria and Chan 1984; Wang and Zhu 1989a,b; Waugh
64 1992; Dritschel and Waugh 1992; Ritchie and Holland 1993; Wang and Holland 1995, hereafter
65 WH95; Falkovich et al. 1995; Khain et al. 2000; Prieto et al. 2003; Shin et al. 2006; Jang and Chun
66 2015b, hereafter JC15b). Several barotropic dynamical processes have been discussed in the
67 literature. For example, the horizontal vorticity advection is key to whether the binary TCs may
68 approach each other in nondivergent barotropic model (DeMaria and Chan 1984; Wang and Zhu
69 1989a,b; Shin et al. 2006), while competition between the deformation and filamentation from the
70 opposite vortex and the restoring force of the vortex itself determines whether the two interacting
71 vortices merge or not (Dritschel and Waugh 1992; Waugh 1992; Ritchie and Holland 1993; Prieto
72 et al. 2003).

73 The binary interaction in three-dimensional models is more complicated by resolving the
74 baroclinic TC structure, surface friction, and diabatic heating (Chang 1983; Falkovich et al. 1995;
75 WH95). Compared with dry simulations, diabatic heating can modulate the vortex structure in
76 moist simulations, in which the vortices show relatively axisymmetric structure during the merging
77 (WH95; Khain et al. 2000). WH95 found that two identical TC vortices with the initial separation
78 distance less than 640 km on an f -plane experienced rapid mutual approaching and weakening
79 before merging. They also indicated that the merger of binary TCs was a bottom-up process where
80 the low-level vortices merged first, followed by the merging of the middle-level vortices with much
81 stronger filamentation. The simulation of WH95 also demonstrated a mutual orbiting process,
82 followed by release and escape, or merging, which was consistent with the conceptual model of

83 binary interaction proposed by LH93. More recently, JC15b demonstrated that greater
84 environmental convective available potential energy and higher maximum potential intensity could
85 lead to stronger binary interaction, while the beta-effect could weaken the mutual approaching of
86 binary TCs by generating asymmetric structure.

87 Although previous studies have revealed many features of binary-TCs interaction, most of
88 them focused on the track characteristics of two interacting vortices. Limited studies have
89 investigated the intensity changes of binary TCs. In addition, the coarse model resolution and the
90 use of cumulus parameterization in previous studies are not adequate for understanding the
91 intensity change of binary TCs (e.g., WH95; Khain et al. 2000; JC15b). In this study, we will
92 examine the intensity change of two interacting TCs and understand the involved dynamical
93 processes using an idealized three-dimensional full-physics model. The rest of the paper is
94 organized as follows. The numerical model and experimental design are described in section 2.
95 Section 3 discusses the main results with the focus on the storm structure and intensity changes of
96 the simulated binary TCs. Summary and conclusions are given in the last section.

97 **2. Numerical model and experimental design**

98 *a. Model setup*

99 In this study, the advanced Weather Research and Forecasting (WRF) model version 3.4
100 (Skamarock et al. 2008) was used to investigate the interaction between two TCs. The WRF model
101 is a three-dimensional nonhydrostatic, full-physics, atmospheric model. The model domain was
102 configured with two nested interactive meshes of 901×901 (D01) and 901×901 (D02) grid points,

103 with their horizontal grid spacings of 9 and 3 km, respectively. The open lateral boundary condition
104 was utilized for D01. The model atmosphere had 50 vertical levels topped at the 25-km height
105 (about 28 hPa) with 18 vertical levels below the 3-km height. The model physics included the WRF
106 5-class microphysics scheme (WSM5; Hong et al. 2004) and the Yonsei University planetary
107 boundary layer (PBL) scheme (YSU; Hong et al. 2006). The Kain–Fritsch cumulus
108 parameterization scheme (Kain and Fritsch 1990) was applied only in D01. The scheme for drag
109 and enthalpy coefficients was *Donelan Cd + Constant Ck* (Donelan et al. 2004). The radiations
110 were not activated in this study. All experiments were performed on an *f*-plane at 20°N over ocean
111 with a uniform sea surface temperature (SST) of 28°C.

112 *b. Initial vortex*

113 The initial axisymmetric vortex for all experiments of binary TCs was spun up from a single
114 TC integration (ORIG). In ORIG, the Jordan sounding (Jordan 1958) was used as the unperturbed
115 environment. The initial vortex in ORIG had the radial profile of tangential wind following that in
116 Fiorino and Elsberry (1989). The maximum tangential wind speed was 30 m s⁻¹ at the radius of 120
117 km (RMW) with the exponential decaying factor of 1.0. The maximum wind decreased with height
118 to zero at about 100 hPa following Wang (2007). The vortex in ORIG was initially located at the
119 center of the two meshes and spun up for 96 hours when the storm reached its mature stage. We
120 separated the axisymmetric vortex of the TC after the 96-h simulation as the initial vortex and used
121 the mean fields after removing the axisymmetric vortex as the environmental fields in all binary-
122 TCs experiments. The vortex separation followed that in Liu and Tan (2016), which was an

123 extension of the method introduced by Cha and Wang (2013) and included the following four steps.
124 First, a local three-point spatial filter was conducted, respectively, in the meridional and zonal
125 directions to separate the basic field and the disturbance field. Second, a cylindrical filter was
126 applied to further extract the vortex component from the disturbance field. Third, the axisymmetric
127 TC vortex was calculated as the azimuthally averaged vortex component. Finally, the
128 environmental field was obtained by spatially averaging the total field excluding the axisymmetric
129 vortex. More details can be found in Cha and Wang (2013) and Liu and Tan (2016), and references
130 therein. Figure 1a shows the obtained axisymmetric tangential and radial wind fields of the TC
131 vortex after the 96-h spinup in ORIG. The RMW at the top of the boundary layer was about 60 km
132 and tilted radially outward with height. The inflow was below 2 km, and the outflow occurred
133 mainly in the upper troposphere. The anticyclonic circulation in the upper troposphere (above the
134 14-km height) was outside of a radius of about 500 km from the TC surface center. The
135 environmental sounding was very close to the Jordan sounding (not shown).

136 To ensure the validity of the initial conditions composited by the axisymmetric TC vortex and
137 the mean environmental field in our binary-TCs experiments, we first ran a simulation using a
138 single TC initial condition as a reference (CTRL). Figure 1b compares the intensity evolutions of
139 the simulated TCs in ORIG and CTRL. In ORIG, the TC intensified and reached its mature stage
140 after about 90-h simulation. In CTRL, the vortex experienced some quick adjustment and then
141 reached a steady-stage evolution as in ORIG. Although the intensity evolutions in terms of the
142 maximum 10-m height wind speed (V_{max}) and the minimum sea level pressure (MSLP) differ in

143 details in CTRL and ORIG, the difference can be considered relatively small. This indicates that
144 the axisymmetric vortex obtained from the 96-h spinup in ORIG reached its mature phase. Thus,
145 any significant change in intensity in the binary-TCs simulations can be considered as a result of
146 the binary interaction when two TCs vortices were simultaneously introduced.

147 *c. Experimental design*

148 To investigate the interaction of binary TCs, we conducted four experiments with different
149 initial separation distances, which were 480 (D480), 600 (D600), 720 (D720), and 840 km (D840),
150 respectively. In each experiment, the two initial TCs, which were the same as that in CTRL above,
151 were placed in the east-west direction. The centroid of the binary TCs was located at the center of
152 D01 and D02. For the convenience of discussion, we named the WTC for the TC initially located
153 to the west and the ETC for the TC initially located to the east.

154 Some parameters in the following analysis/discussions are defined here. The TC surface
155 center was simply defined as the location of the MSLP. We will discuss the TC intensity change in
156 terms of the change in MSLP rather than V_{max} (e.g., WH95; Falkovich et al. 1995; Khain et al.
157 2000; JC15b) because the MSLP of one TC can be detected even when binary TCs are undergoing
158 merging process. The eye region was roughly defined as the area from the TC surface center to a
159 radius of 60 km, which was the same as the initial RMW at the low levels in the binary-TCs
160 experiments. The inner core was referred to the area from the TC surface center to a radius of 180
161 km, which was about three time of the initial RMW at the low levels (Wang 2008).

162 **3. Results**

163 *a. An overview*

164 Figure 2 shows the track and intensity evolutions of the binary TCs, together with the change
165 of the separation distance between the centers of two TCs. For a comparison, the intensity evolution
166 of a single TC in CTRL is also shown in Fig. 2. Both TCs mutually rotated cyclonically in all
167 experiments. The two TCs merged as a new TC after 22 h and 67 h in D480 and D600, respectively.
168 In D720 and D840, the binary TCs did not merge with their separation distance increasing with
169 time. As the separation distances increased, the cyclonic rotation also slowed down and the two
170 TCs eventually departed from each other without significant rotation, such as the case in D840 (Fig.
171 2g). These results are roughly consistent with previous studies (WH95; JC15b) and the conceptual
172 model of binary-TCs interaction in LH93.

173 We divided the intensity evolution into three stages (right panels in Fig. 2) depending on their
174 interaction modes. Stage 1 is the first 10 h of the simulations during which the binary TCs
175 experienced the weakening in all experiments. Stage 2 is from 10 h to 55 h of the simulations when
176 the intensity of the binary TCs showed little change or experienced a quasi-steady evolution in
177 D600, D720 and D840. In stage 3, the binary TCs weakened again after 55 h in D600 (55–67 h),
178 D720 (55 h to the end) and D840 (55–78 h), and prior to merging from 10 h to 22 h of the simulation
179 in D480. Although the binary TCs in D480 weakened during the first 22 h of the simulation, the
180 physical processes that led to the two weakening periods were different. Note that an intensification
181 of the merged system occurred in both D480 and D600, which was also found in WH95. It is
182 interesting that the two TCs in D840 after stage 3 intensified again when the separation distance

183 between the two TCs became larger than 1600 km (Fig. 2h). Since the temporal evolutions of the
184 two TCs in the binary experiments are similar and almost symmetric with respect to their centroid
185 due to their identical initial conditions, we take the WTC to discuss the intensity and structure
186 changes in the following discussion.

187 Figure 3 shows the mean potential temperature anomaly in the eye region of the WTC in the
188 four binary experiments. The potential temperature anomaly was calculated as the perturbation
189 relative to the environment, which was the mean potential temperature from the TC surface center
190 to 600-km radius, the same as that in Fu et al. (2019). Following Zhang and Chen (2012), we also
191 calculated the central sea level pressure rises induced by the upper-level (between the 9- and 16-
192 km heights, ΔP_u), lower-level (between the 2- and 6-km heights, ΔP_l) and total-level warm core
193 (ΔP) using the hydrostatic equation with the results shown in Fig. 3. The bias of the central sea
194 level pressure integrated from the hydrostatic equation and the MSLP from the model simulations
195 was less than 5 hPa. The TC presented a warm-core structure at the initial time with two maximum
196 positive potential temperature anomalies centered at the 10- and 15-km heights, respectively, in all
197 four experiments. Influenced by the ETC, the upper-level warm core of the WTC weakened during
198 stages 1 and 3 in all binary experiments and in the meantime both ΔP and ΔP_u rose. In D600,
199 D720 and D840 (Figs. 3b–d), the upper-level warm core weakened and the lower-level warm core
200 strengthened in stage 2, but the potential temperature change in both upper- and lower-levels were
201 quite small. This can be proven by the increasing of ΔP_u and decreasing of ΔP_l , and both were
202 largely offset. As a result, ΔP did not change much in stage 2. The warm core strengthened again

203 as the merged TC intensified in D480 and D600 (Figs. 3a,b). After stage 3 in D840 (Fig. 3d) the
204 warm core re-strengthened with both ΔP and ΔP_u slowly decreased until the end of the
205 simulation.

206 The above results demonstrate that the intensity change of the binary TCs is consistent with
207 the evolution of the warm-core strength. Therefore, the key to understand the intensity change is
208 to understand what caused the change in the warm-core strength under the binary interaction.
209 Previous studies have demonstrated that the weakening of the TC warm core and eyewall entropy
210 is related to the asymmetric structures in the inner-core region and associated ventilation (Simpson
211 and Riehl 1958; Gray 1968; Frank and Ritchie 2001; Tang and Emanuel 2010; Gu et al. 2015).
212 Figure 4 shows the evolution of the inner-core mean relative wavenumber-1 kinetic energy (RKE,
213 defined as the percentage of the wavenumber-1 kinetic energy in the total kinetic energy) of the
214 WTC. The percentages of higher-wavenumbers were quite smaller than the RKE (not shown). In
215 all experiments, the RKE was the largest at the 16-km height and smallest below the 9-km height,
216 indicating that the upper-level (between the 9- and 16-km heights or equivalent 300–100 hPa) RKE
217 was dominant. In stage 1, the RKE increased rapidly above the 14-km height, which was consistent
218 with the weakening of the TC in all experiments. In D600, D720 and D840, the upper-level RKE
219 shrank in stage 2 from 10 h to about 30 h of the simulations. Then the upper-level RKE re-
220 strengthened and expanded downward. The development of upper-level RKE was prior to the
221 increase of the MSLP, suggesting that the development of asymmetric structure in the upper
222 troposphere was most likely responsible for the weakening of the binary TCs. In stage 3, the upper-

223 level RKE and the MSLP increased again in all experiments. After stage 3, the RKE of the whole
224 TC vortex decreased sharply after the two TCs merged and re-intensified in D480 and D600 (Figs.
225 4a,b). Similar features were found after stage 3 in D840 (Fig. 4d) probably because the two TCs
226 were far away from each other.

227 The dominance of wavenumber-1 asymmetry indicates that vertical wind shear (VWS) was
228 playing an essential role in the structure change (Jones 1995; Wang and Holland 1996; Frank and
229 Ritchie 2001; Corbosiero and Molinari 2003; Reasor et al. 2004; Chen et al. 2006; Xu and Wang
230 2013; Zhang et al. 2013; DeHart et al. 2014; Gu et al. 2016). Therefore, it is necessary to examine
231 whether the intensity change of binary TCs is related to the asymmetric structure and the VWS.
232 The VWS over one TC must from the baroclinic circulation of the other TC in the binary system
233 (Fig. 1), since there was no large scale environmental VWS in the simulations. Figure. 5 shows the
234 evolution of the upper-layer VWS (between 100 and 300 hPa) and the commonly used deep-layer
235 VWS (between 200 and 850 hPa) averaged radially from the surface center to 600-km radius,
236 together with the 3-h MSLP change of the WTC in the four experiments. In stage 1, the WTC
237 weakened with the positive 3-h MSLP change when the upper-layer VWS increased and kept a
238 large magnitude in all experiments while the deep-layer VWS presented a decreasing trend in D480
239 and D600. In stage 2, the 3-h MSLP change was small and even a little bit negative, meaning that
240 the WTC did not further weaken but experienced a quasi-steady intensity evolution. Meanwhile,
241 the upper-layer VWS decreased first and then increased again while the deep-layer VWS continued
242 to increase and remained large. In stage 3, the 3-h MSLP change was mostly positive, and the

243 upper-layer VWS increased and was larger than that in stage 2 except for D480 and D600 in which
244 the upper-layer VWS decreased during the merging with a decrease in the deep-layer VWS.
245 Nevertheless, in comparison with the deep-layer VWS, the evolution of the upper-layer VWS is
246 more consistent with the 3-h MSLP change. Namely, the large or increasing upper-layer VWS
247 corresponds to the large and positive 3-h MSLP change, and the small or decreasing upper-layer
248 VWS corresponds to the small or even negative 3-h MSLP change. The correlation coefficients
249 between the upper-layer VWS and the 3-h MSLP change varied from 0.6 to 0.7 at 99% confidence
250 level in all four experiments based on the Student's t-test. This strongly suggests that the upper-
251 layer VWS is a good indicator of the intensity change of the two interacting strong TCs. Note that
252 the more detrimental effect of the upper-layer VWS on the intensity of a single mature TC has been
253 also found in previous studies (e.g., Xu and Wang 2013; Fu et al. 2019).

254 The above results show a strong relationship between the upper-layer VWS and the intensity
255 change of the simulated binary TCs. We hypothesize that the upper-layer VWS of one TC came
256 mainly from the upper-layer anticyclonic circulation of the other TC in the binary system. Previous
257 studies also mentioned the potential role of the VWS originated from the baroclinic structure of
258 one TC imposed on the other TC in the binary system (WH95; Khain et al. 2000; JC15b). However,
259 the physical processes that lead to the structure and intensity change of binary TCs have not been
260 investigated to any extent and will be analyzed in detail in the following subsections.

261 *b. Stage 1: The early weakening of the binary TCs*

262 In stage 1, one TC of the binary system was subject to the imposed vertical shear of tangential

263 wind from the other TC, leading to the initial ventilation of the warm core of each TC. To illustrate
264 the impact of the ETC on the WTC, we interpolated the fields into a new coordinate system for the
265 binary TCs with the origin following the surface center of the WTC as shown in Fig. 6. Thus, the
266 ETC was always to the east of the WTC and the cyclonic (anticyclonic) tangential wind of the ETC
267 across the WTC center was northerly (southerly) wind in this new coordinate system.

268 Figure 7 shows the potential temperature averaged from the 9- to 16-km heights over the WTC
269 in D720 together with the asymmetric wind vectors at the 9- and 16-km heights, respectively. Here,
270 the asymmetric wind of the WTC was calculated as the difference between the storm-relative flow
271 (total horizontal winds relative to the moving vortex) and the azimuthal mean wind as in Fu et al.
272 (2019). Also plotted in Fig. 7 are the vortex center at the 16-km height and the mean upper-layer
273 VWS between the 16- and 9-km heights (very close to the VWS between 100 and 300 hPa). The
274 vortex centers at the 9- and 16-km heights were defined as the centroid of PV for each TC in the
275 innermost domain. Other three experiments (not shown) have similar features to D720 in stage 1.

276 As shown in Fig. 7, the asymmetric winds at the 16-km height ventilated the warm anomalies
277 in the TC core, leading to the weakening of the upper-level warm core in stage 1. The mean
278 asymmetric winds at the 16-km height were roughly perpendicular to the orientation between the
279 surface centers of the binary TCs. Note that the upper-level anticyclone (ULA) of the ETC was the
280 strongest at a height of about 16 km (Fig. 1a) and had southerly winds to the west of the ETC. This
281 is consistent with the asymmetric winds across the inner core of the WTC at the 16-km height in
282 the early stage of the simulations, indicating the important role of the ETC's ULA on the WTC.

283 Moreover, the ULA of the ETC induced the upper-layer VWS over the WTC, which was also
284 mentioned in previous studies (WH95; Khain et al. 2000; JC15b). The upper-level the WTC tilted
285 toward the downshear-left side of the upper-layer VWS. As a result, the differential advection of
286 the upper-level circulation of the WTC by the VWS further enhanced the asymmetric flow crossing
287 the warm core of the WTC. Note that the upper-layer VWS between the 16- and 9-km heights was
288 almost equal to the mean asymmetric wind at the 16-km height because the asymmetric winds at
289 the 9-km height were quite weak (Figs. 4 and 7) during stage 1.

290 To further confirm the ventilation of the upper-level warm core by the asymmetric flow, we
291 performed the potential temperature budget as given below following Stern and Zhang (2013)

$$292 \quad \Delta\theta = (\dot{\theta}_{ADV} + \dot{\theta}_{HEAT} + \dot{\theta}_{PBL} + \dot{\theta}_{DIF})\Delta t, \quad (1)$$

293 where $\Delta\theta$ is the actual change in the potential temperature (θ) during the time period Δt ; $\dot{\theta}_{ADV}$
294 is the total tendency due to horizontal and vertical advections of θ ; $\dot{\theta}_{HEAT}$ is the tendency from
295 diabatic heating; $\dot{\theta}_{PBL}$ is the tendency from the boundary layer parameterization scheme; and
296 $\dot{\theta}_{DIF}$ is the tendency due to subgrid-scale horizontal diffusion. The model potential temperature
297 tendencies are from the model output at every 6 min, and the budget was conducted from 6 to 9 h.
298 The results are consistent across all simulations and thus we choose D720 as an example in the
299 following discussion.

300 The patterns in 3-h actual θ change (Fig. 8a) and the results from the right-hand side (*RHS*)
301 of Eq. (1) (Fig. 8b) are very similar, implying that the budget is reliable. The residual term
302 (difference between 3-h θ change and *RHS* of Eq. 1, Fig. 8c) shows some errors mostly near the

303 TC center above the 15-km height, probably due to the interpolation and/or the tilting of the vortex
 304 at the upper levels. However, these errors do not have impact on our interpretation. Among all four
 305 terms on the *RHS* of Eq. (1) (Figs. 8d–f), only the total advection term ($\dot{\theta}_{ADV}$) induced significant
 306 cooling in the upper-layer eye region and the whole eyewall (Fig. 8d). The cooling in the eyewall
 307 by total advection was largely offset by diabatic heating (Fig. 8e). The boundary layer process
 308 ($\dot{\theta}_{PBL}$) and horizontal diffusion ($\dot{\theta}_{DIF}$) caused warming in the inflow layer and cooling at the top of
 309 the boundary layer (mainly contributed by $\dot{\theta}_{PBL}$ term) but their tendencies were quite small
 310 compared to $\dot{\theta}_{ADV}$ and $\dot{\theta}_{HEAT}$ (Fig. 8f). The total advection ($\dot{\theta}_{ADV}$) can be further decomposed
 311 into the azimuthal mean radial advection ($\dot{\theta}_{RADVM} = -\bar{u}(\partial/\partial r)\bar{\theta}$), the eddy radial advection
 312 ($\dot{\theta}_{RADVE} = -(\partial/\partial r)(\overline{u'\theta'}) - \overline{u'\theta'}/r$) and the total vertical advection ($\dot{\theta}_{VADV}$); where \bar{u} and u'
 313 are azimuthal mean and asymmetric radial wind, $\bar{\theta}$ and θ' are azimuthal mean and asymmetric
 314 potential temperature, and r is the radius from the surface TC center. $\dot{\theta}_{RADVM}$ was much smaller
 315 than other two terms (Fig. 8g) because the azimuthal mean radial wind could neither pass through
 316 the TC eye region nor ventilate the warm core. Only $\dot{\theta}_{RADVE}$ contributed negatively to the
 317 tendency of the upper-level warm core (Fig. 8h) because the asymmetric flow at the 16-km height
 318 brought the cold air in and took the warm air out of the eye region (Fig. 7). $\dot{\theta}_{VADV}$ had an opposite
 319 distribution to $\dot{\theta}_{RADVE}$, but its magnitude was smaller than that of $\dot{\theta}_{RADVE}$, giving rise a net
 320 negative advection tendency in the upper-level eye region and the whole eyewall. Therefore, based
 321 on the potential temperature budget, we can conclude that the eddy radial advection of potential
 322 temperature ($\dot{\theta}_{RADVE}$) due to the upper-level asymmetries (Figs. 4 and 7) is the major process that

323 caused the weakening of the upper-level warm core and thus the intensity of binary TCs in stage 1.
324 The asymmetries of one TC resulted from the upper-layer VWS (Fig. 5), which in turn was
325 originated from the baroclinic circulation of the other TC in the binary system (Fig. 7).

326 *c. Stage 2: The quasi-steady intensity evolution of the binary TCs*

327 During 10 to 55 h of the simulations, the binary TCs in D600, D720, and D840 experienced a
328 quasi-steady intensity evolution. We still take D720 as an example since the results are similar for
329 D600 and D840. The upper-level warm core of the WTC changed very slowly during this period
330 (Figs. 3c and 9). The asymmetric flow at the 9-km height strengthened during this period, which
331 can also be found in Fig. 4c. The VWS between the 16- and 9-km heights decreased first and then
332 increased, with the shear direction changing with time from southwesterly to northerly. As a result,
333 the vortex centers at the 16- and 9-km heights gradually aligned and then departed again. This
334 implies that the vortex tilting did not continue to increase in stage 2. The relatively weak upper-
335 layer VWS could still lead to the slow weakening of the upper-level warm core and the intensity
336 of the TCs (Figs. 3c and 9), but its effect was largely counteracted by the faintly strengthening of
337 the lower-level warm core. Potential temperature budget (not shown) indicates that the
338 strengthening of the lower-level warm core was contributed by $\dot{\theta}_{VADV}$, which was caused by the
339 relatively weak downward motion in the eye region. This downdraft was a consequence of the
340 reconstructed secondary circulation under the weakening of upper-level VWS. Therefore, the
341 intensity of binary TCs showed a quasi-steady intensity evolution in stage 2.

342 Changes in the upper-layer VWS over the WTC in stage 2 can be largely inferred from the

343 evolution of asymmetric flow at the height of 9 km because the asymmetric flow over the WTC at
344 the 16-km height did not change much. At the beginning of stage 2 (Fig. 9a), the mean asymmetric
345 wind across the center of the WTC was weaker than that at the 16-km height and hence the upper-
346 layer VWS was southwesterly. However, the asymmetric flow over the WTC at the 9-km height
347 strengthened and became southerly (Figs. 9b–e), which corresponded to the ULA of the ETC. This
348 led to a decrease in the difference of the mean winds between the 16- and 9-km heights over the
349 WTC, which means that the upper-layer VWS over the WTC decreased because the asymmetric
350 flow at the 9-km height strengthened. As the asymmetric wind at the 9-km height continued
351 strengthening as the ULA of the ETC expanded downward (see discussion below) and became
352 stronger than that at the 16-km height, the upper-layer VWS over the WTC changed to northerly
353 with the shear magnitude increasing again (Figs. 9f–i).

354 Since the upper-layer VWS over the WTC results from the ULA of the ETC in the binary
355 system, it is necessary to examine how the ULA of the ETC evolved to lead to the variation of the
356 upper-layer VWS over the WTC in stage 2. Figure 10 shows the radius-height cross sections of the
357 azimuthal mean tangential and radial winds of the ETC on the near and opposite sides to the WTC
358 center. The near side of the ETC was defined as the quadrant close to the WTC and the opposite
359 side was the rest part of the ETC away from the WTC, as shown in light and dark gray zones in
360 Fig. 6, respectively. The interaction of binary TCs should have much stronger impact on the near
361 side, but relatively weaker impact on the opposite side of each TC. In stage 2, the opposite-side
362 ULA of the ETC strengthened and expanded outward in D600, D720 and D840, similar to that for

363 a single TC simulated in CTRL (not shown), but weaker because the TC in the binary system
364 weakened due to binary interaction. The azimuthal mean anticyclonic tangential wind on the
365 opposite side of the ETC at the 9-km height also increased but was still weaker than that at the 16-
366 km height, which is different from the asymmetric flow at the 9- and 16-km heights over the WTC.
367 This implies that the tangential wind of the ETC could not fully explain changes in the upper-layer
368 VWS over the WTC. Therefore, the binary interaction must play some role in changing the upper-
369 layer VWS over the WTC. The azimuthal mean tangential wind on the near side of the ETC was
370 quite different from that on the opposite side. On the near side, the ULA of the ETC expanded
371 downward and the azimuthal mean anticyclonic tangential wind at the 9-km height became stronger
372 over the WTC surface center in D600, D720 and D840 (Figs. 10a,d,g), leading to a decrease in the
373 upper-layer vertical shear of the azimuthal mean tangential wind of the ETC between the 16- and
374 9-km heights over the WTC. As the azimuthal mean anticyclonic tangential wind of the ETC at the
375 9-km height continued to strengthen and became stronger than that at the 16-km height (Figs.
376 10e,f,h,i), the upper-layer vertical shear of the azimuthal mean tangential wind of the ETC over the
377 WTC turned to the opposite direction and increased again in D720 and D840. This is consistent
378 with changes in the asymmetric flows at the 9- and 16-km heights (Fig. 9) and the upper-layer
379 VWS over the WTC (Figs. 5c,d) in D720 and D840. Different from that in D720 and D840, as the
380 two TCs in D600 approached each other, the WTC entered the area of the upper-level outflow of
381 the ETC by the end of stage 2 (Fig. 10c). The outflow of the ETC at the 16-km height was stronger
382 than that at the 9-km height over the WTC, resulting in a re-strengthening of the upper-layer VWS

383 over the WTC in D600.

384 Note that at the beginning of the simulations, the difference in the azimuthal mean tangential
385 wind of the ETC between the near and opposite sides is primarily due to the superposition of winds
386 of the two TCs, that is, the near-side ULA of the ETC was strengthened by the superposition of the
387 cyclonic circulation on the near side of the WTC. However, this cannot explain why the ULA
388 expanded downward. We hypothesize that the weakening of the secondary circulation in each TC,
389 which caused downdraft anomaly in the near side of each TC and induced the downward advection
390 of the ULA. Figure 11 shows the distributions of the vertical motion vertically averaged between
391 the 16- and 9-km heights over the WTC in D600, D720, and D840 at 20-h interval from 10 h to 50
392 h of the simulations. In stage 2, the updraft on the near side in the WTC eyewall became weaker
393 than that on the opposite side. Downward motion anomalies occurred on the near side of the WTC,
394 especially in the southeast quadrant because of the confluence of the upper-level outflows of the
395 WTC and the ETC. This resulted in the weakening of the secondary circulation of both TCs, and
396 thereby the weakening of updraft on the near side of the WTC. The downward motion anomaly
397 favored the downward penetration of the ULA (and southerly) of the ETC from the top down. This
398 thus led to changes in the upper-layer VWS over the WTC as mentioned above.

399 The above process can be confirmed by the meridional wind (V) budget in the binary
400 coordinate system as defined earlier. The budget equation can be given as:

$$401 \quad \Delta V = (\dot{V}_{HADV} + \dot{V}_{VADV} + \dot{V}_{PRES} + \dot{V}_{CORI} + \dot{V}_{PBL} + \dot{V}_{DIF})\Delta t, \quad (2)$$

402 where ΔV is the actual change in V over a given period Δt ; \dot{V}_{HADV} and \dot{V}_{VADV} are the

403 tendencies due to horizontal and vertical advectons, respectively; \dot{V}_{PRES} and \dot{V}_{CORI} are the
404 tendencies due to pressure gradient and Coriolis forces, respectively; \dot{V}_{PBL} is the tendency from
405 the boundary layer parameterization scheme; and \dot{V}_{DIF} is the tendency due to subgrid-scale
406 horizontal diffusion. All terms of the *RHS* of Eq. (2) are based on the model output at every 6 min
407 as in the potential temperature budget. Figure 12 shows the V budget of the WTC at the 9- and
408 16-km heights in D600, D720 and D840 in stage 2 (42–48 h). The difference between the model
409 V change and the sum on the *RHS* of Eq. (2) integrated from 42- to 48-h simulations was quite
410 small. At the 9-km height, all three experiments show the increasing in V (southerly or
411 anticyclonic tangential wind relative to the ETC). \dot{V}_{ADV} was positive during the budget period
412 and was the primary cause for the increase in V (namely southerly strengthened). Other terms on
413 the *RHS* of Eq. (2) contributed little or even negative tendency to the southerly wind. At the 16-
414 km height, V changed little in D720 (Fig. 12d) and decreased in both D600 and D840 (Figs. 12b,f).
415 The tendencies contributed by \dot{V}_{PRES} and \dot{V}_{HADV} were largely offset in both D720 and D840.
416 Therefore, the momentum budget of meridional wind demonstrates that the enhancement of
417 asymmetric southerly at the 9-km height over the WTC mainly resulted from the downward
418 advection of the near-side ULA of the ETC in stage 2. Namely, the binary interaction weakened
419 the near-side vertical secondary circulation of each TC in stage 2, causing the downward expansion
420 of the near-side ULA. As a result, the upper-layer VWS over each TC weakened first and then re-
421 strengthened, leading to marginally changes in the upper-level warm core and the intensity of the
422 binary TCs.

423 *d. Stage 3a: The second weakening of the non-merging binary TCs*

424 The TCs in the two non-merging binary experiments (D720 and D840) experienced the second
425 weakening (stage 3). This stage can be considered as a continuation of stage 2 because the upper-
426 layer VWS continued strengthening and remained large by the end of stage 2 (Figs. 5c,d). The
427 binary TCs in both D720 and D840 experienced a weakening in stage 3 as in stage 1. The large
428 upper-layer VWS led to the strengthening of the RKE above the 9-km height (Figs. 4c,d). The
429 potential temperature budget shown in Fig. 13 indicates that $\dot{\theta}_{RADVE}$ weakened the warm core at
430 the 15- and 9-km heights of the WTC. Compared with stage 1, the weakening of the warm core at
431 the 9-km height caused by $\dot{\theta}_{RADVE}$ in stage 3 further confirms that the binary interaction resulted
432 in downward expansion of the near-side ULA as discussed for stage 2 in section 3c.

433 After stage 3 in D840, the upper-layer VWS decreased and the binary TCs deepened (Fig. 5d)
434 until the end of the simulation when the separation distance between the two TCs increased over
435 1600 km (Fig. 2h). We also examined additional experiments with the same initial vortices but
436 different initial separation distances and found that the overall behavior of the binary TCs are quite
437 similar (not shown) with the weakening terminated once their separation distance exceeding about
438 1600 km. This seems to be a critical separation distance in our experiments and is consistent with
439 some relevant statistical analyses of binary-TCs interaction based on observations (Brand 1970;
440 Dong and Neumann 1983; Wu et al. 2011; Jang and Chun 2015a; Ren et al. 2020). Since the ULA
441 of one TC affects the intensity of the other TC in the binary system, we further introduce the local
442 Rossby radius of deformation L_R ($= NH/I$, where N is the Brunt-Väisälä frequency; H is the

443 scale height; and I is the inertial stability) of the azimuthal mean ULA for understanding the
444 dynamics. NH is 60 m s^{-1} the same as that in Bell et al. (2012), and $I (= \sqrt{(f + \zeta)(f + \frac{2\bar{v}}{r})})$,
445 where ζ is the relative vorticity and \bar{v} is the azimuthal mean tangential wind) is calculated from
446 the model output. We did not use the near-side azimuthal mean ULA because once the two TCs
447 were far enough away from each other, the difference of the azimuthal mean ULA on the near and
448 opposite sides was negligible. We can estimate L_R to be 1500–1700 km, comparable to 1600 km in
449 our experiments. Note that L_R is much smaller in the middle–lower troposphere than in the outflow
450 layer because of the much larger inertial stability. Therefore, it is expected that once the separation
451 distance between the two TCs becomes larger than the horizontal scale L_R determined by the ULA,
452 the binary interaction and the associated intensity change would become very weak and can be
453 ignored.

454 *e. Stage 3b: The weakening of the binary TCs during merging*

455 From 10 h to 22 h of the simulation in D480 and from 55 h to 67 h of the simulation in D600,
456 the binary TCs experienced a weakening period prior to their merger. During this stage, the two
457 TCs presented increasingly asymmetric structure as they approached each other with their
458 separation distance decreasing rapidly, consistent with the weakening of the two TCs. Since the
459 structure and intensity evolutions are similar in D480 and D600, we take D480 as an example to
460 describe the merging process. Figure 14 shows the simulated maximum radar reflectivity in D480
461 prior to merging. The binary TCs showed an “8” shaped rainband structure. The eyewall on the
462 near side of each TC was weaker than that on the opposite side and gradually weakened but

463 suddenly disappeared before merging. The partial eyewalls of the two TCs finally formed a new
464 closed eyewall of the merged TC system. Figure 15 shows the PV distributions in D480 at four
465 different heights. In the boundary layer (at the 1-km height) in D480 (Fig. 15a), the two vortices
466 presented weak deformation at 18 h of the simulation but then accelerated the rotation with more
467 and more deformation and filamentation until they merged (Figs. 15b–c). The similar deformation
468 and filamentation also occurred in the lower- (at the 2-km height, Figs. 15d–f) and middle-
469 troposphere (at the 5-km height, Figs. 15g–i), but both were weaker and the merging of the two
470 vortices lagged that in the boundary layer. Going to higher levels, the PV structure (Figs. 15j–l) was
471 more asymmetric as the circulation in the upper troposphere (at the 9-km height) was much weaker.
472 The two vortices at the upper level rotated more slowly than that at the lower- and middle-levels,
473 implying a large vertical tilt of the TC vortices. Different from those in the middle–lower
474 troposphere, the PV field at the 9-km height shows no merging but strong deformation and
475 filamentation, leading to banded structure as the low-level vortices merged. The results thus
476 demonstrate a bottom-up merging process of the binary TCs in the simulations, which is consistent
477 with the findings in WH95.

478 Figure 16 shows the vertical cross sections of the total wind speed through the surface vortex
479 centers of the two TCs in D480. The eyewalls as inferred by large wind speed on the near side of
480 the binary TCs weakened from the top down partly due to the vertical tilt of the TC vortices.
481 Meanwhile, both TC vortices became more asymmetric. This highly asymmetric TC structure
482 resulted primarily from the strong shearing deformation of the TC vortices, a process well studied

483 with both barotropic and baroclinic models in the literature (Holland and Dietachmayer 1993;
484 WH95; Falkovich et al. 1995; Khain et al. 2000; Prieto et al. 2003; Shin et al. 2006). After the two
485 TCs merged, the new eye was larger than the eye of either TC prior to merging. The merger
486 occurred very rapidly and the new TC became more and more axisymmetric and also experienced
487 intensification after merger. These are consistent with those documented in previous studies
488 (WH95; Khain et al. 2000) and can also be seen from Figs. 2a–d. Therefore, the weakening and
489 structure change of the binary TCs prior to merging, including the highly asymmetric rainbands,
490 the near-side eyewall weakening and breakdown from the top down, and the large tilt, were due to
491 the combined effect of large VWS and strong horizontal shearing deformation of the drastic binary
492 interaction when the two TCs approached rapidly toward merging.

493 **4. Conclusions and Discussion**

494 In this study, the intensity change of binary TCs has been investigated using a three-
495 dimensional numerical model with a finest grid spacing of 3 km under idealized conditions on an
496 f -plane with a constant sea surface temperature and in a quiescent environment. To allow more
497 realistic binary interaction, we first simulated a single TC for 96 h until it reached its mature stage
498 with the fully-developed secondary circulation and used its axisymmetric vortex as the initial TCs
499 in the binary experiments. Four experiments were performed with the initial separation distances
500 between the two identical TCs being 480 (D480), 600 (D600), 720 (D720), and 840 km (D840),
501 respectively. Results show that the two TCs approached each other and merged only in D480 and
502 D600. In D720, the two TCs rotated cyclonically but with their separation distance increasing with

503 time. In D840, the two TCs rotated cyclonically in the early stage but then anticyclonically and
504 moved away (escaped) from each other. These three interaction modes are very similar to the
505 conceptual model of binary TC interaction proposed by LH93.

506 The intensity of the binary TCs experienced three stages and the intensity change was well
507 correlated with the VWS in the upper troposphere between 100 and 300 hPa over the inner core of
508 each TC. The first stage was the weakening of the binary TCs during the first 10 h of the simulations.
509 In this stage, the vertical shear of the tangential wind from one TC imposed a large upper-layer
510 VWS on the other TC, leading to the ventilation and weakening of the warm core through both
511 horizontal advection and eddy flux of the potential temperature. Such a mutual interaction led to
512 the weakening of the two TCs. The second stage was the quasi-steady intensity evolution in the
513 three binary experiments (D600, D720 and D840) from 10 h to 55 h, when the two TCs did not yet
514 or never merge. During this stage, the upper-layer VWS decreased first due to the enhanced
515 asymmetric flow at the 9-km height. The increasing asymmetric flow resulted mainly from the
516 outward and downward expansion of the ULA due to the superposition of the two TCs' circulations
517 and the binary interaction. As a result, the vertical tilt of the TC vortex largely decreased, the warm
518 core remained its strength, and the TCs experienced little intensity change. In the merging cases of
519 D480 and D600, the two TCs continued weakening until the two TCs merged. The weakening was
520 mainly due to both the VWS and shearing deformation of the cyclonic circulation as previously
521 studied. After merging in D480 and D600, the new TC system experienced intensification due to
522 the continuous axisymmetrization. The non-merging binary TCs in D720 and D840 weakened

523 again after the quasi-steady intensity evolution as the asymmetric flow at the 9-km height induced
524 by the ULA of the opposite TC continued increasing. This led to the increase in the upper-layer
525 VWS over each TC and thus the weakening of the warm core and the TCs. The intensity of the
526 binary TCs in D840 did not decrease further after 78 h of the simulation because the interaction of
527 the binary TCs became very weak after their separation distance increased to 1600 km, which is
528 comparable and even larger than the local Rossby radius of deformation (L_R) of the upper-level
529 anticyclonic circulation of the TCs. Therefore, L_R determines the horizontal scale of the ULA and
530 can be used as a measure to determine whether the two TCs could experience direct binary
531 interaction.

532 Note that the intensity change of binary TCs is investigated under idealized conditions in this
533 study. It is unclear whether the importance of upper-layer VWS in the binary interaction is a model
534 result or also true in real binary TCs. The initial vortex in our experiments was as intense as 895
535 hPa in its MSLP (about 70 m s^{-1} in the maximum near-surface wind speed), which seems to be
536 “unrealistically strong” in the real atmosphere. We used such a strong TC because it is in its mature
537 stage of a simulated TC with well-developed primary and secondary circulations. This can ensure
538 a strong binary interaction and overcome the initial model spinup of a weak TC and also the
539 intensity change of the binary TCs can be attributed to the binary interaction because the single TC
540 would experience a quasi-steady intensity evolution. Note that we also conducted a series
541 experiments of relatively weak binary TCs (initial maximum near-surface wind speed of 35 m s^{-1} ,
542 not shown), the two TCs showed similar intensity evolutions as those shown in this study. In

543 addition, the detailed merging processes have not been analyzed in this study as they seem to be
544 similar to what revealed in previous studies (e.g., WH95; Khain et al. 2000; JC15b). Previous
545 studies (Yang et al. 2008; Jang and Chun 2013; Liu and Tan 2016) also suggested that the structure
546 and intensity changes of binary TCs could be sensitive to the initial TC structure and intensity in
547 real atmosphere. Therefore, how sensitive the binary TC interaction is to the structure of the TCs
548 and the relative intensity and size of the two TC vortices needs to be addressed in future studies.
549 In addition, the binary interaction is often affected by the environmental flow and latitudinal
550 dependence of the Coriolis parameter (e.g., WH95; Khain et al. 2000; JC15b). In those cases, the
551 initial orientation and relative intensity of the two TCs may become also important (WH95). In
552 addition, it is also worth noting that the role of the L_R of the ULA in distinguishing the direct binary
553 interactions is found in fully-physics moist simulations, in case of binary interaction of dry TC-like
554 vortices the ULA may be very weak or even not exist at all. It is unclear what scaling parameters
555 can be used to distinguish the direct interaction for dry vortices. These will be examined in our
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715 **Figure Captions**

716 **Figure 1.** (a) Radial-height distribution of the azimuthal mean radial (m s^{-1} , interval of 5 m s^{-1} ,
717 shading) and tangential (m s^{-1} , contours) winds of the TC at the initial time in CTRL (after a
718 96-h spinup of the model TC vortex). Positive values (solid) with contour intervals of 5 m s^{-1}
719 are for cyclonic circulation and negative values (dashed) with contour intervals of 2 m s^{-1} are
720 for anticyclonic circulation. (b) The temporal evolutions of the V_{max} (m s^{-1}) at the 10-m height
721 and the MSLP (hPa) in ORIG (gray) and CTRL (black). The ORIG simulation started from $-$
722 96 h and the CTRL simulation started from 0 h (see more details in the text).

723 **Figure 2.** The left panels show tracks of binary TCs in (a) D480, (c) D600, (e) D720, and (g) D840,
724 respectively. The blue curves are for the WTC and the red curves are for the ETC. The right
725 panels show the intensity evolutions of the WTC (blue) and the ETC (red) in (b) D480, (d)
726 D600, (f) D720, and (h) D840, together with the intensity evolution of the TC in CTRL (black).
727 The gray curves in (b) and (d) represent the intensity of the merged TC. The green curves denote
728 the separation distance between the two TCs. The dashed vertical lines separate the three stages
729 of the intensity evolution discussed in section 3.

730 **Figure 3.** Time-height cross sections of the potential temperature perturbation (K, shading)
731 averaged within the eye region ($r \leq 60 \text{ km}$) of the WTC in (a) D480, (b) D600, (c) D720, and
732 (d) D840, along with the time evolution of the central sea level pressure changes (solid line)
733 and stage separation lines (dashed vertical lines). The central sea level pressure changes are
734 relative to the initial time and caused by the total-level (ΔP , black line), upper-level (ΔP_u , red
735 line), and lower-level (ΔP_l , blue line), respectively.

736 **Figure 4.** Time-height cross sections of the RKE (% , shading) averaged within the inner core ($r \leq$
737 180 km), together with the evolution of the MSLP (solid line) and stage separation lines
738 (dashed vertical lines).

739 **Figure 5.** Time evolution of VWS between 200 and 850 hPa (black dashed line) and that between
740 100 and 300 hPa (black solid line) over the WTC and the 3-h MSLP change (gray curves with
741 red and blue dots) in (a) D480, (b) D600, (c) D720, and (d) D840. The red and blue dots signify

742 intensification (negative 3-h MSLP change) and weakening (positive 3-h MSLP change),
743 respectively.

744 **Figure 6.** Schematic diagram of the horizontal coordinate system in the analysis for binary TCs.
745 The origin is located at the surface center of the WTC. The x-axis is from the WTC to the ETC.
746 The y-axis is perpendicularly toward the left of the direction from the WTC to the ETC. The
747 near side (light gray zone) is the nearest quadrant of the two TCs and the opposite side (dark
748 gray zone) is the remaining part. We define the zonal wind being along the x-direction and
749 meridional wind being along the y-direction.

750 **Figure 7.** Potential temperature (K, shading) of the WTC vertically averaged between the 9- and
751 16-km heights at (a) 4 and (b) 8 h of the simulation in D720. The center of each panel is the
752 vortex center at the 9-km height. The red and blue arrows represent the asymmetric flow at the
753 16- and 9-km heights, respectively. The black hollow circle denotes vortex center at the 16-km
754 height. The black arrow in the lower left corner of each panel is the VWS (twice longer)
755 between the 16- and 9-km heights averaged within a radius of 600 km from the surface center.

756 **Figure 8.** Radial-height distribution of potential temperature budget terms (K, shading). Upper row:
757 Azimuthal mean of (a) the actual 3-h potential temperature change, (b) the sum of the *RHS* of
758 Eq. (1), and (c) budget errors. Middle row: Azimuthal mean potential temperature tendencies
759 due to (d) total advection ($\dot{\theta}_{ADV}$), (e) diabatic heating ($\dot{\theta}_{HEAT}$), and (f) the sum of the boundary
760 layer process and horizontal diffusion ($\dot{\theta}_{PBL} + \dot{\theta}_{DIF}$). Lower row: Azimuthal mean tendencies
761 due to (g) the azimuthal mean radial advection ($\dot{\theta}_{RADVM}$), (h) eddy radial advection ($\dot{\theta}_{RADVE}$),
762 and (i) total vertical advection ($\dot{\theta}_{VADV}$). All terms are budgeted for the WTC and integrated for
763 3-h period from 6 to 9 h of the simulation in D720.

764 **Figure 9.** Same as Fig. 7, but from 10 to 50 h of the simulation at 5-h interval.

765 **Figure 10.** Same as Fig. 1a, but for the ETC from 10 to 50 h of the simulations at 20-h interval in
766 (a-c) D600, (d-f) D720, and (g-i) D840. The left half in each panel is the azimuthal mean on
767 the near side and the right half is that on the opposite side. The green line denotes the location
768 of the WTC surface center. The result is from the outermost domain as the ULA covers a large

769 area.

770 **Figure 11.** Vertical motion (m s^{-1}) distribution relative to the surface center of the WTC vertically
771 averaged between the 9- and 16-km heights from 10 to 50 h of the simulations at 20-h interval
772 in (a-c) D600, (d-f) D720, and (g-i) D840.

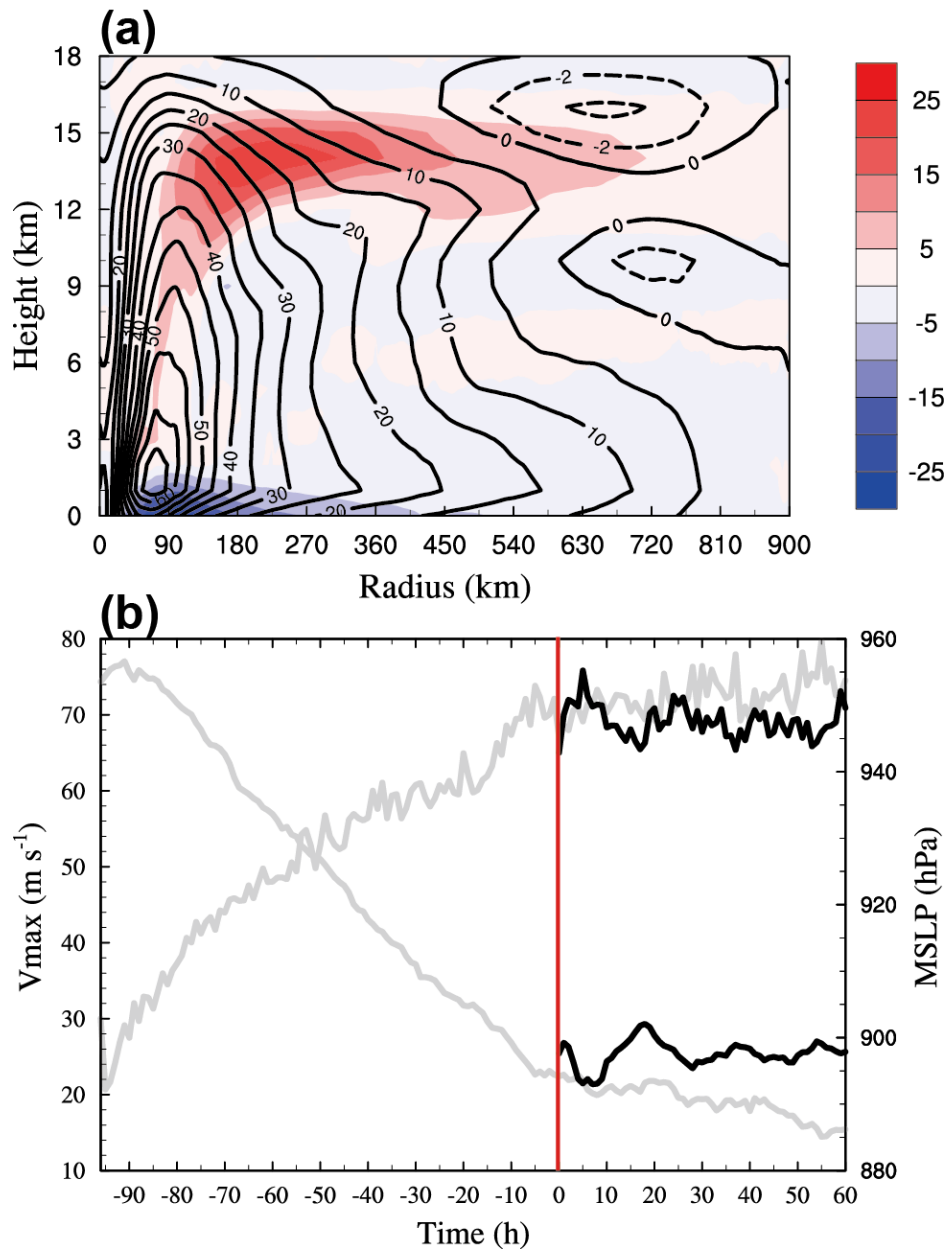
773 **Figure 12.** Time evolutions of the actual inner-core mean meridional wind (V) change (MODE,
774 dashed gray line) relative to 42 h of the simulation of the WTC, the sum of the azimuthal
775 mean RHS of Eq. (2) (black solid line), \dot{V}_{HADV} (blue solid line), \dot{V}_{VADV} (red solid line),
776 \dot{V}_{PRES} (yellow solid line), \dot{V}_{CORI} (pink solid line), \dot{V}_{PBL} (purple solid line), and \dot{V}_{DIF} (green
777 solid line) in Eq. (2) in (a, b) D600, (c, d) D720, and (e, f) D840 at the 9- (left) and 16-km (right)
778 heights. See text for detail.

779 **Figure 13.** Same as Fig. 8, but all tendencies are integrated from 66 to 69 h of the simulation in
780 D720.

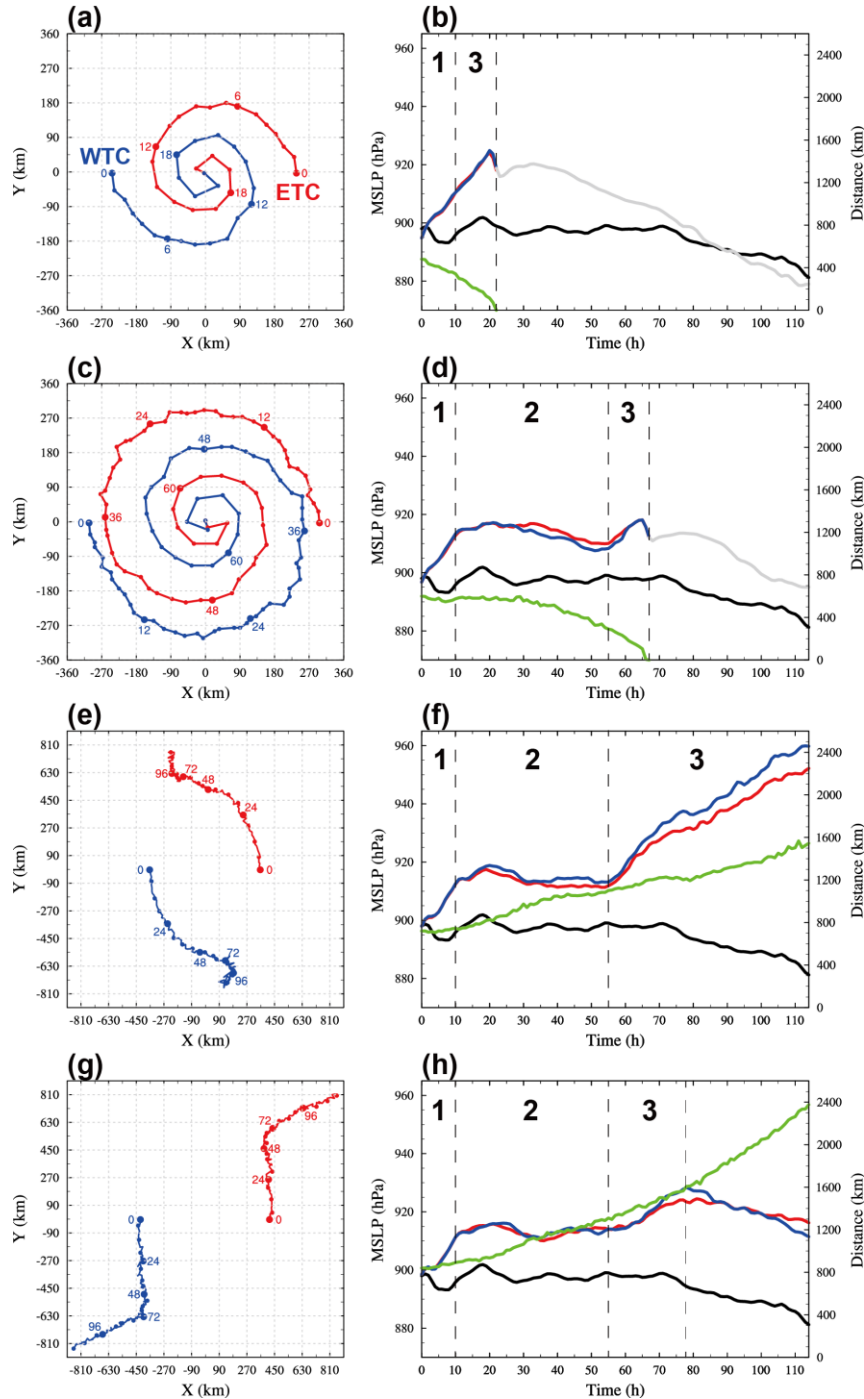
781 **Figure 14.** Horizontal distributions of simulated maximum radar reflectivity (dBZ) every hour
782 from 19 to 22 h in D480.

783 **Figure 15.** Horizontal distributions of PV (PVU) at the (a-c) 1-, (d-f) 2-, (g-i) 5-, and (j-l) 9-km
784 heights in D480. The left, middle, and right columns are at 18, 20, and 22 h of the simulation,
785 respectively.

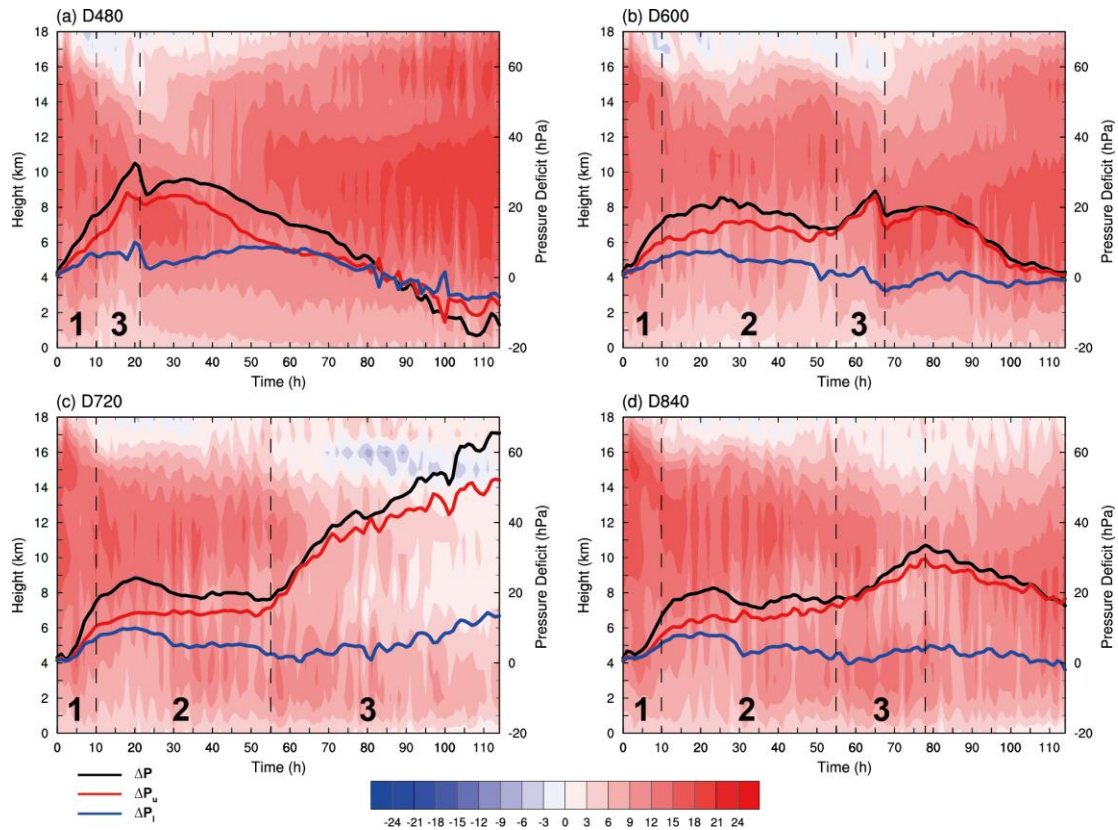
786 **Figure 16.** Vertical cross sections of total wind speed (m s^{-1}) along the x-axis from the WTC (left)
787 to the ETC (right) from 12 to 22 h of the simulation at 2-h interval in D480.



788
 789 **Figure 1.** (a) Radial-height distribution of the azimuthal mean radial (m s^{-1} , interval of 5 m s^{-1} ,
 790 shading) and tangential (m s^{-1} , contours) winds of the TC at the initial time in CTRL (after a
 791 96-h spinup of the model TC vortex). Positive values (solid) with contour intervals of 5 m s^{-1}
 792 are for cyclonic circulation and negative values (dashed) with contour intervals of 2 m s^{-1} are
 793 for anticyclonic circulation. (b) The temporal evolutions of the Vmax (m s^{-1}) at the 10-m height
 794 and the MSLP (hPa) in ORIG (gray) and CTRL (black). The ORIG simulation started from $-$
 795 96 h and the CTRL simulation started from 0 h (see more details in the text).

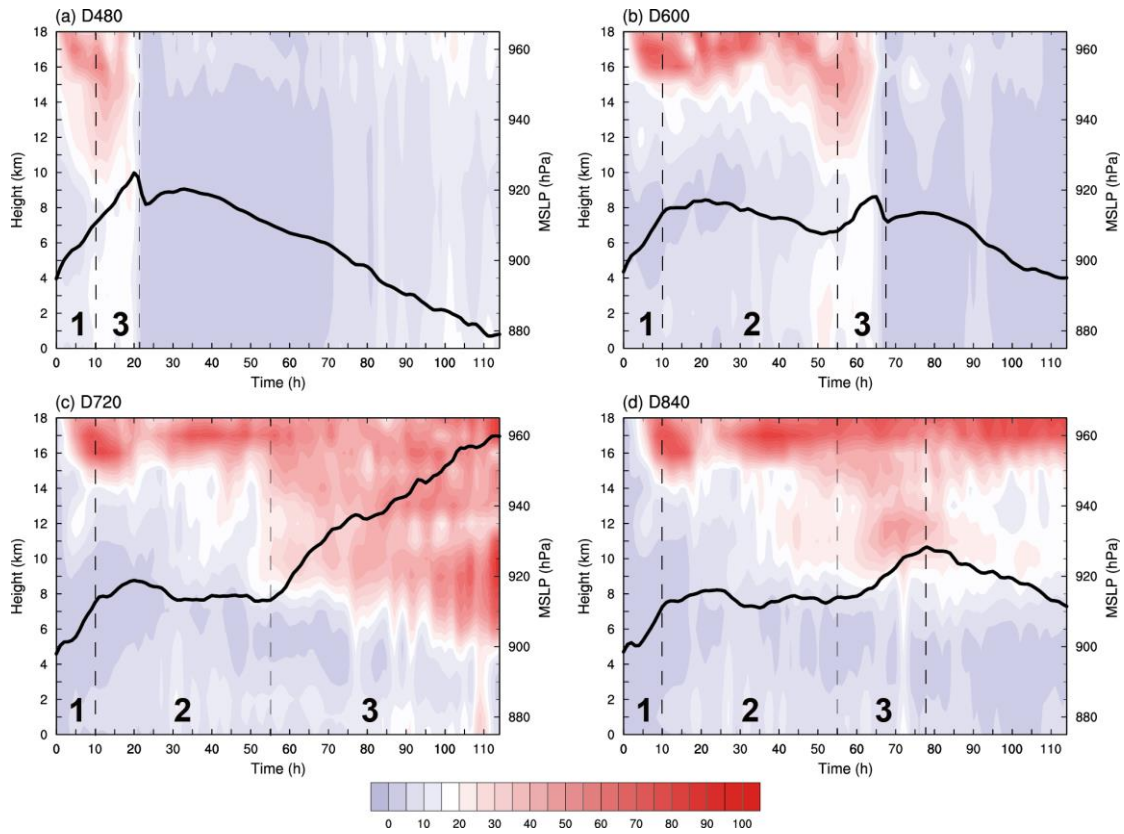


796
 797 **Figure 2.** The left panels show tracks of the binary TCs in (a) D480, (c) D600, (e) D720, and (g)
 798 D840, respectively. The blue curves are for the WTC and the red curves are for the ETC. The
 799 right panels show the intensity evolutions of the WTC (blue) and the ETC (red) in (b) D480,
 800 (d) D600, (f) D720, and (h) D840, together with the intensity evolution of the TC in CTRL
 801 (black). The gray curves in (b) and (d) represent the intensity of the merged TC. The green
 802 curves denote the separation distance between the two TCs. The dashed vertical lines separate
 803 the three stages of the intensity evolution discussed in section 3.



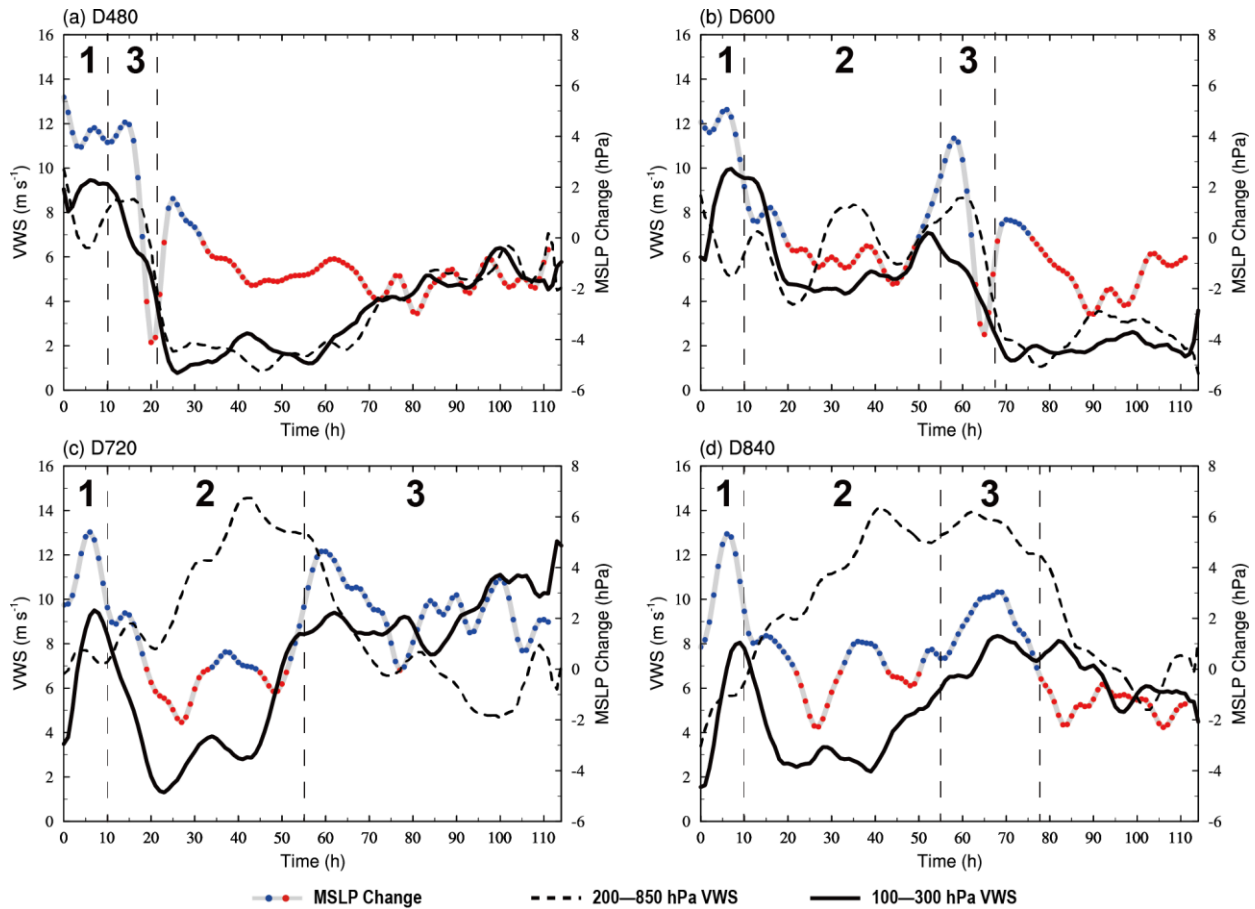
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806 **Figure 3.** Time-height cross sections of the potential temperature perturbation (K, shading)
 807 averaged within the eye region ($r \leq 60$ km) of the WTC in (a) D480, (b) D600, (c) D720, and
 808 (d) D840, along with the time evolution of the central sea level pressure changes (solid line)
 809 and stage separation lines (dashed vertical lines). The central sea level pressure changes are
 810 relative to the initial time and caused by the total-level (ΔP , black line), upper-level (ΔP_u , red
 811 line), and lower-level (ΔP_l , blue line), respectively.

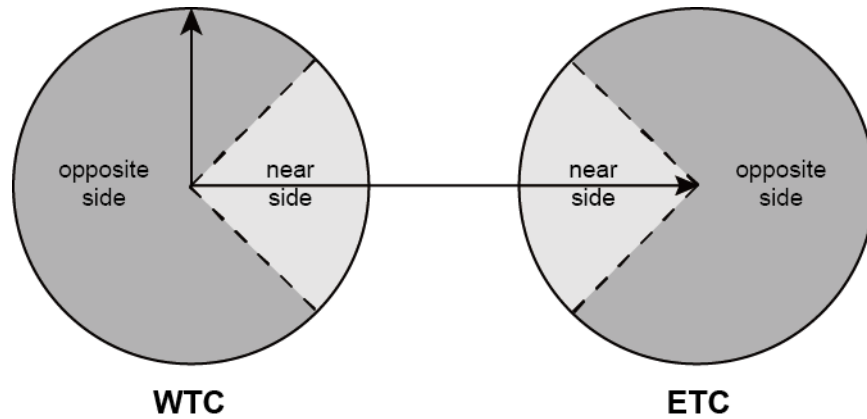


812

813 **Figure 4.** Time-height cross sections of the RKE (% , shading) averaged within the inner core ($r \leq$
 814 180 km), together with the evolution of the MSLP (solid line) and stage separation lines
 815 (dashed vertical lines).



816
 817 **Figure 5.** Time evolution of VWS between 200 and 850 hPa (black dashed line) and that between
 818 100 and 300 hPa (black solid line) over the WTC and the 3-h MSLP change (gray curves with
 819 red and blue dots) in (a) D480, (b) D600, (c) D720, and (d) D840. The red and blue dots signify
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 821 respectively.



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823 **Figure 6.** Schematic diagram of the horizontal coordinate system in the analysis for binary TCs.

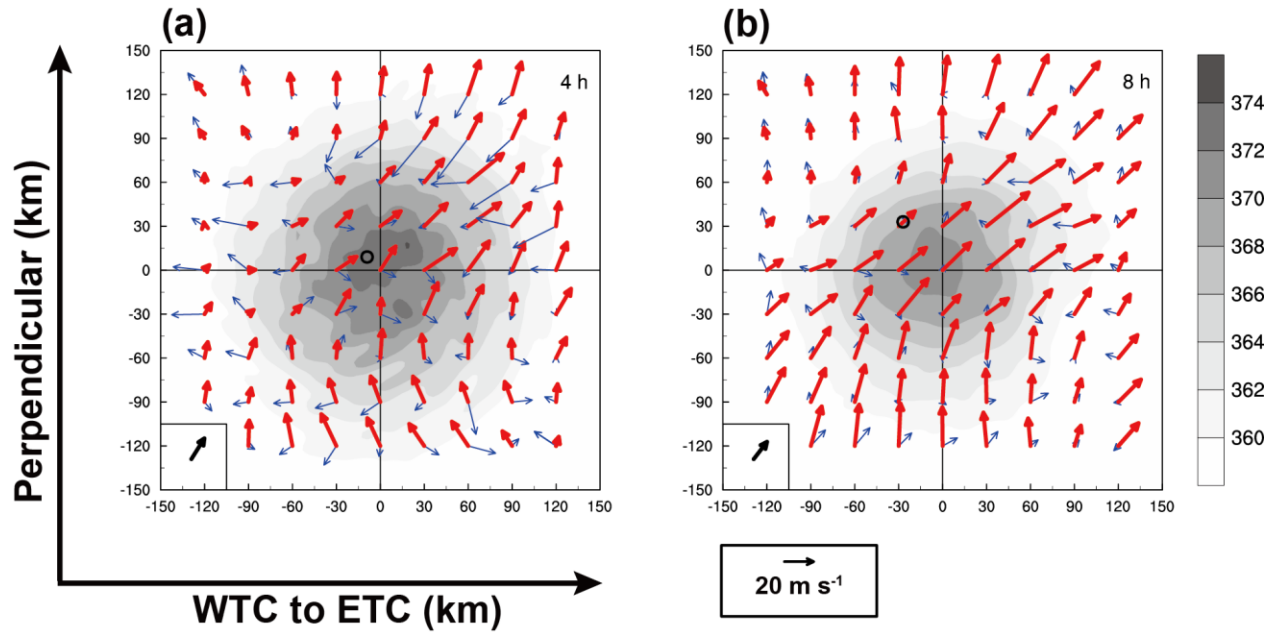
824 The origin is located at the surface center of the WTC. The x-axis is from the WTC to the ETC.

825 The y-axis is perpendicularly toward the left of the direction from the WTC to the ETC. The

826 near side (light gray zone) is the nearest quadrant of the two TCs and the opposite side (dark

827 gray zone) is the remaining part. We define the zonal wind being along the x-direction and

828 meridional wind being along the y-direction.



829

830 **Figure 7.** Potential temperature (K, shading) of the WTC vertically averaged between the 9- and

831 16-km heights at (a) 4 and (b) 8 h of the simulation in D720. The center of each panel is the

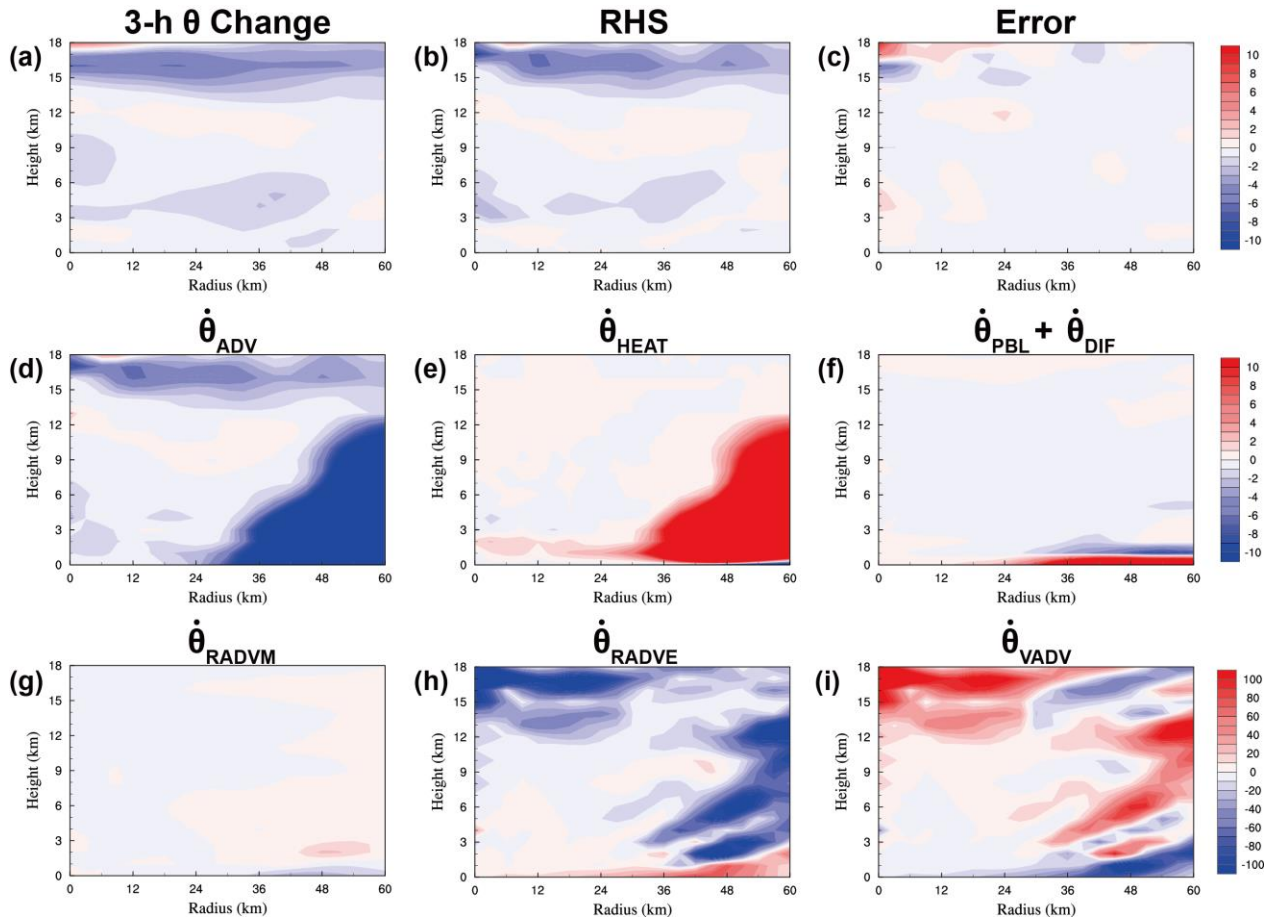
832 vortex center at the 9-km height. The red and blue arrows represent the asymmetric flow at the

833 16- and 9-km heights, respectively. The black hollow circle denotes vortex center at the 16-

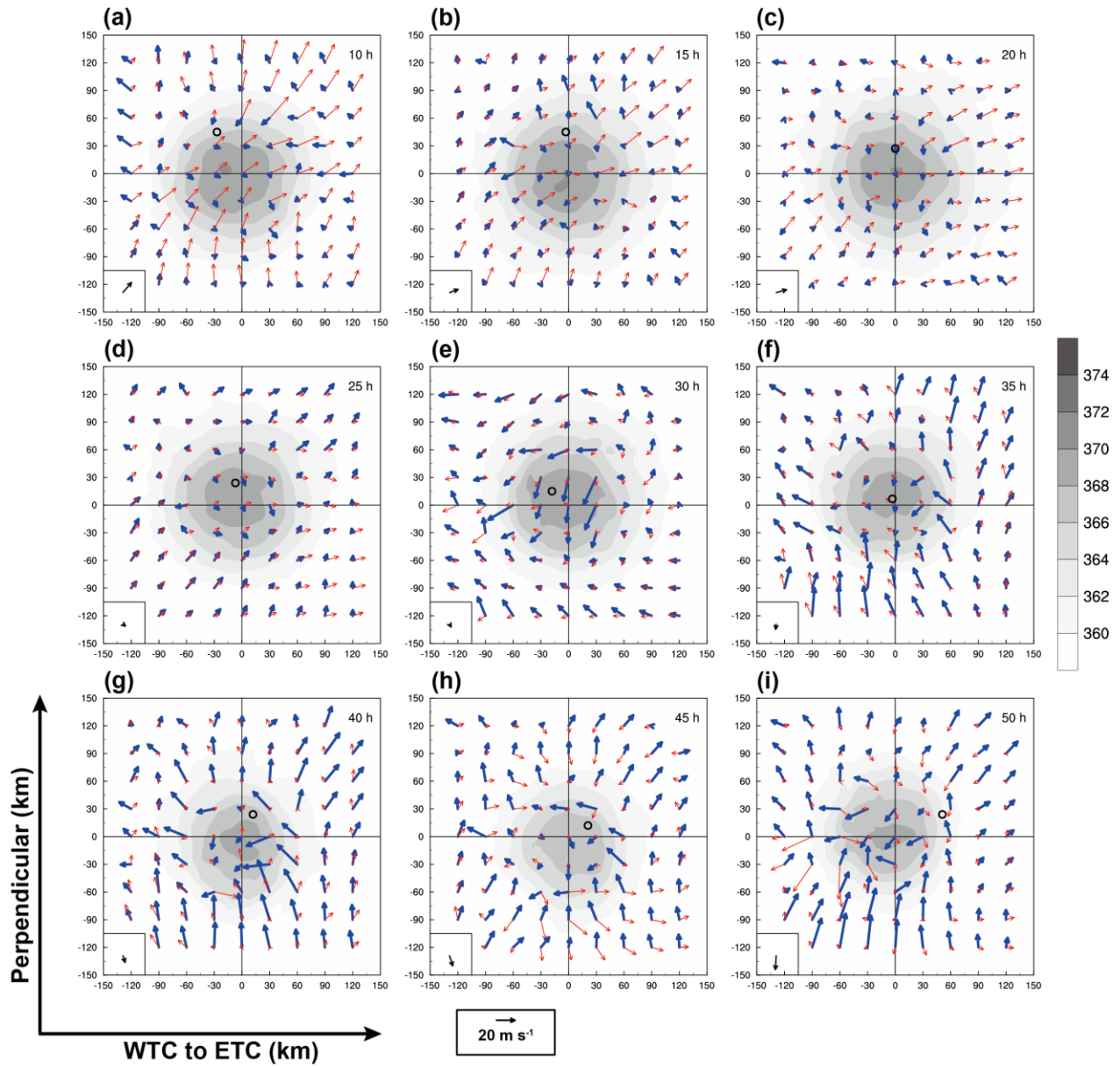
834 km height. The black arrow in the lower left corner of each panel is the VWS (twice longer)

835 between the 16- and 9-km heights averaged within a radius of 600 km from the surface center.

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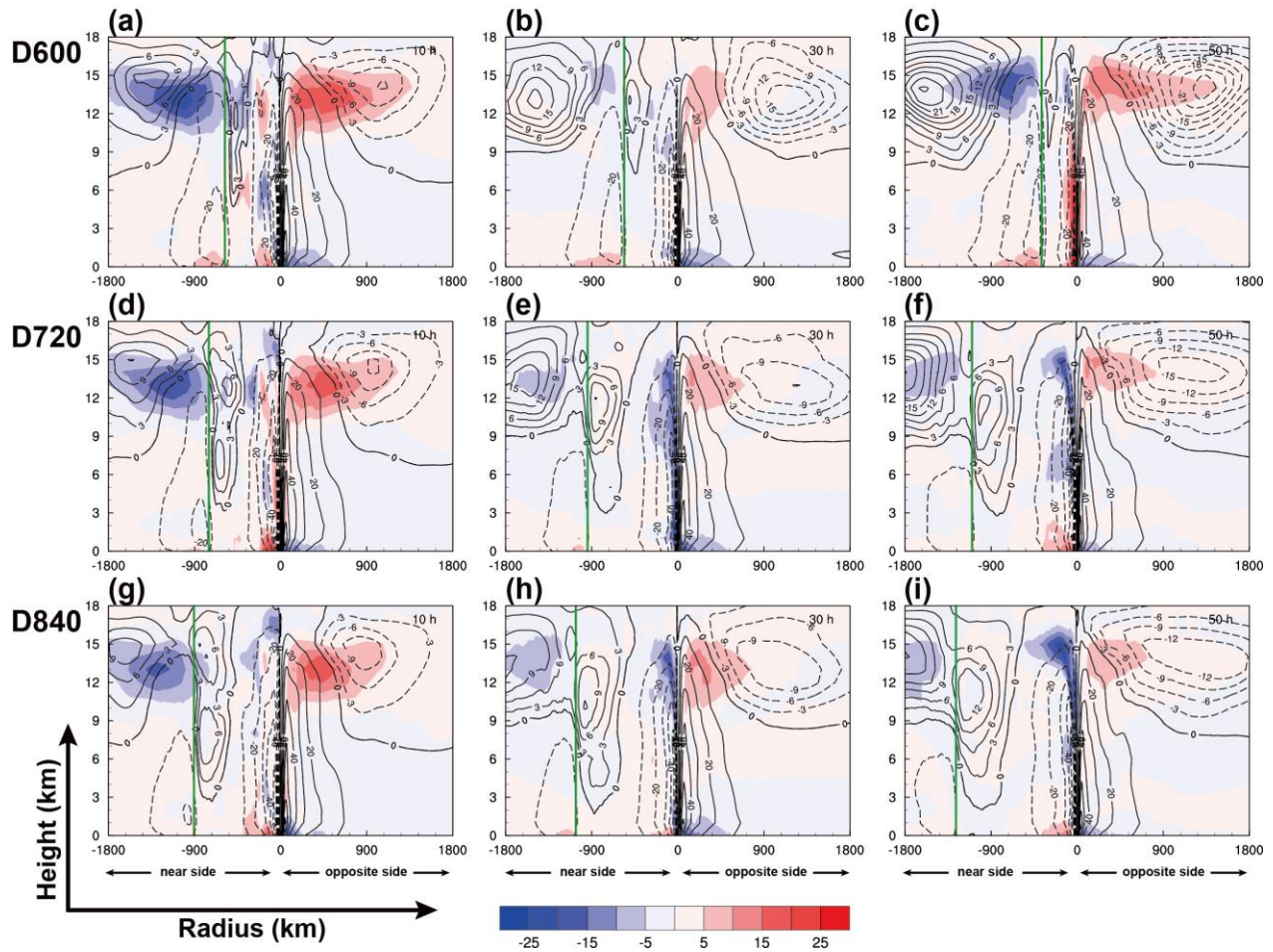


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 838 **Figure 8.** Radial-height distribution of potential temperature budget terms (K, shading). Upper row:
 839 Azimuthal mean of (a) the actual 3-h potential temperature change, (b) the sum of the *RHS* of
 840 Eq. (1), and (c) budget errors. Middle row: Azimuthal mean potential temperature tendencies
 841 due to (d) total advection ($\dot{\theta}_{ADV}$), (e) diabatic heating ($\dot{\theta}_{HEAT}$), and (f) the sum of the boundary
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 844 and (i) total vertical advection ($\dot{\theta}_{VADV}$). All terms are budgeted for the WTC and integrated for
 845 3-h period from 6 to 9 h of the simulation in D720.

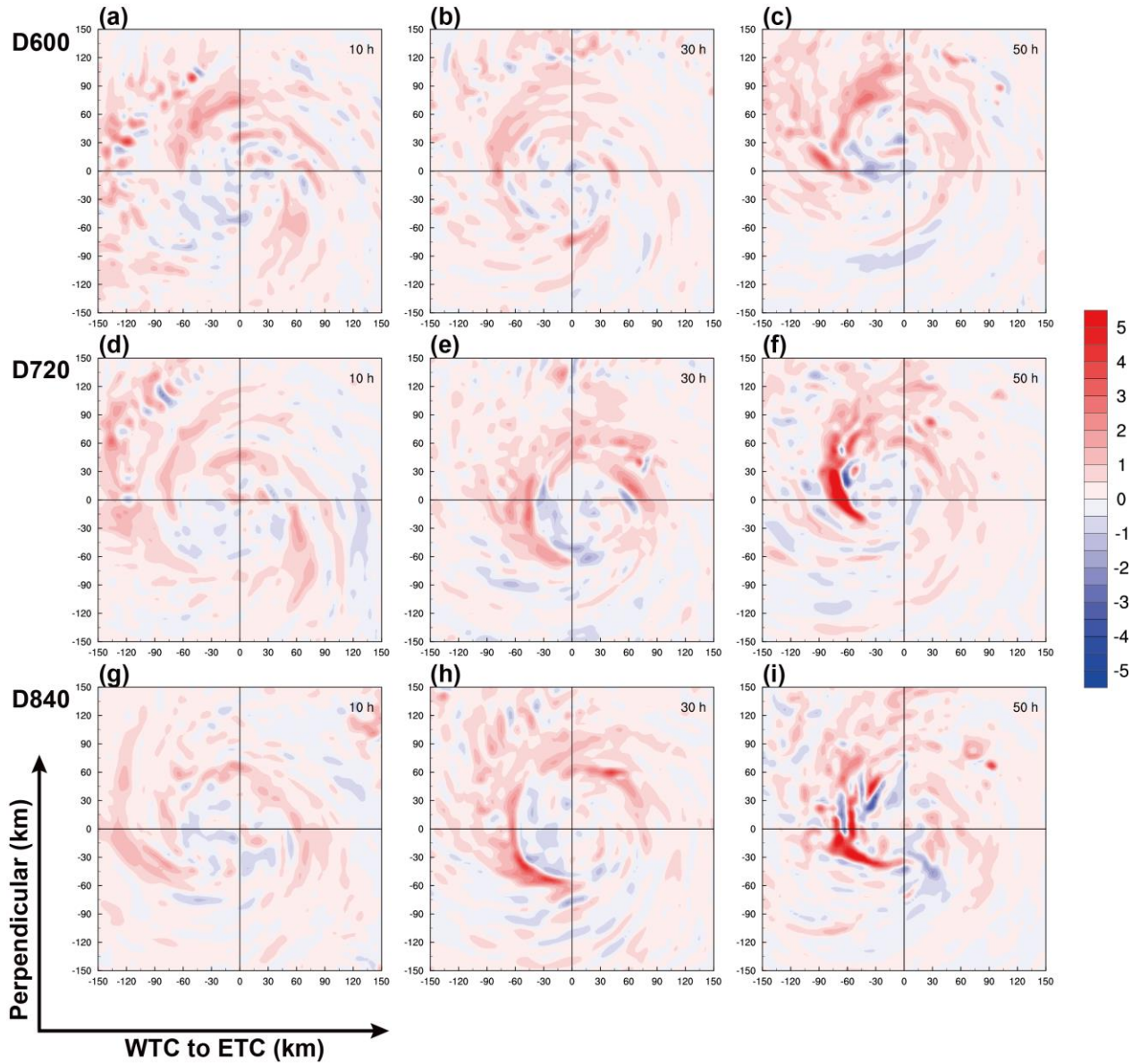


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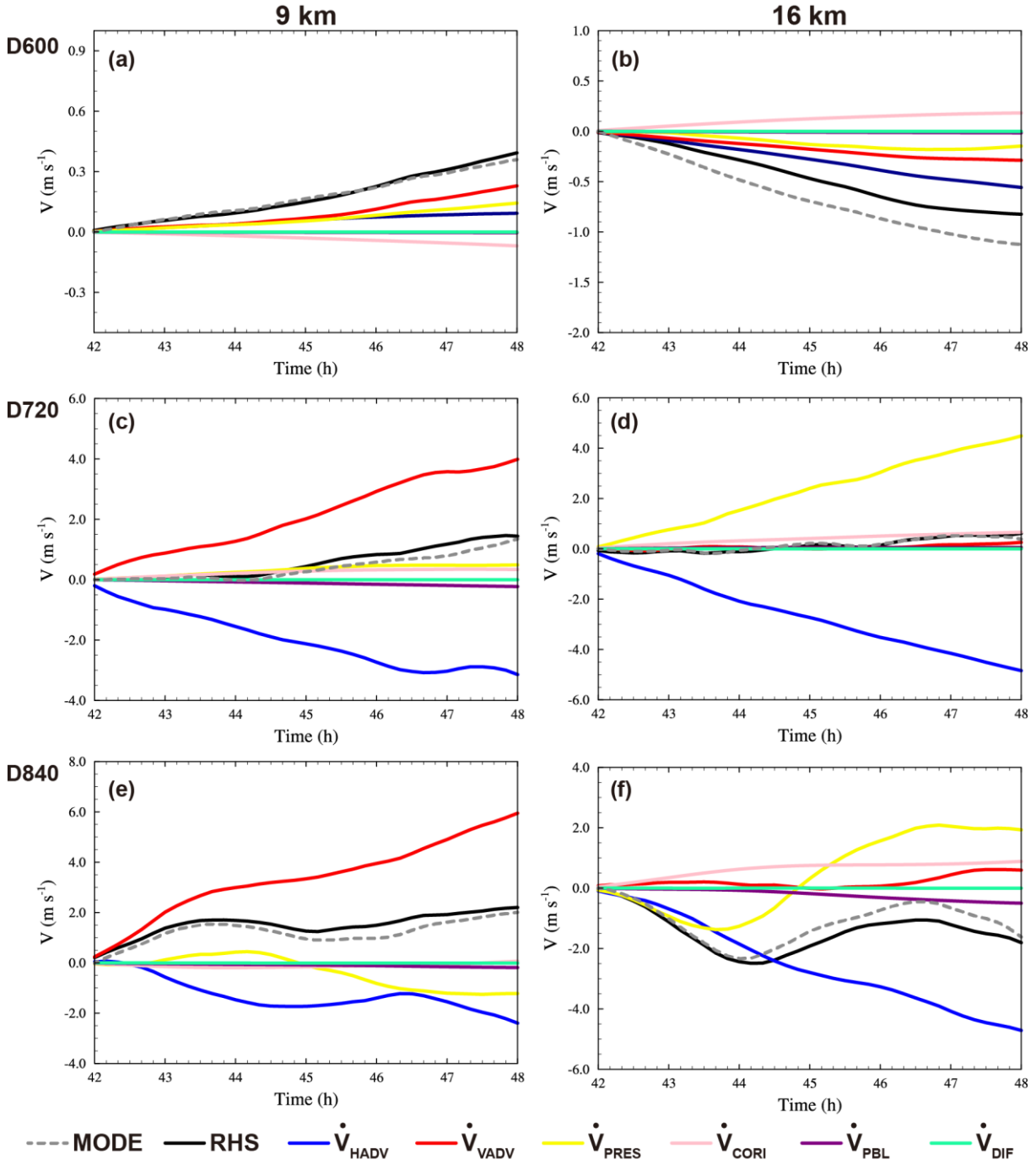
847 **Figure 9.** Same as Fig. 7, but from 10 to 50 h of the simulation at 5-h interval.



848
 849 **Figure 10.** Same as Fig. 1a, but for the ETC from 10 to 50 h of the simulations at 20-h interval in
 850 (a-c) D600, (d-f) D720, and (g-i) D840. The left half in each panel is the azimuthal mean on
 851 the near side and the right half is that on the opposite side. The green line denotes the location
 852 of the WTC surface center. The result is from the outermost domain as the ULA covers a large
 853 area.

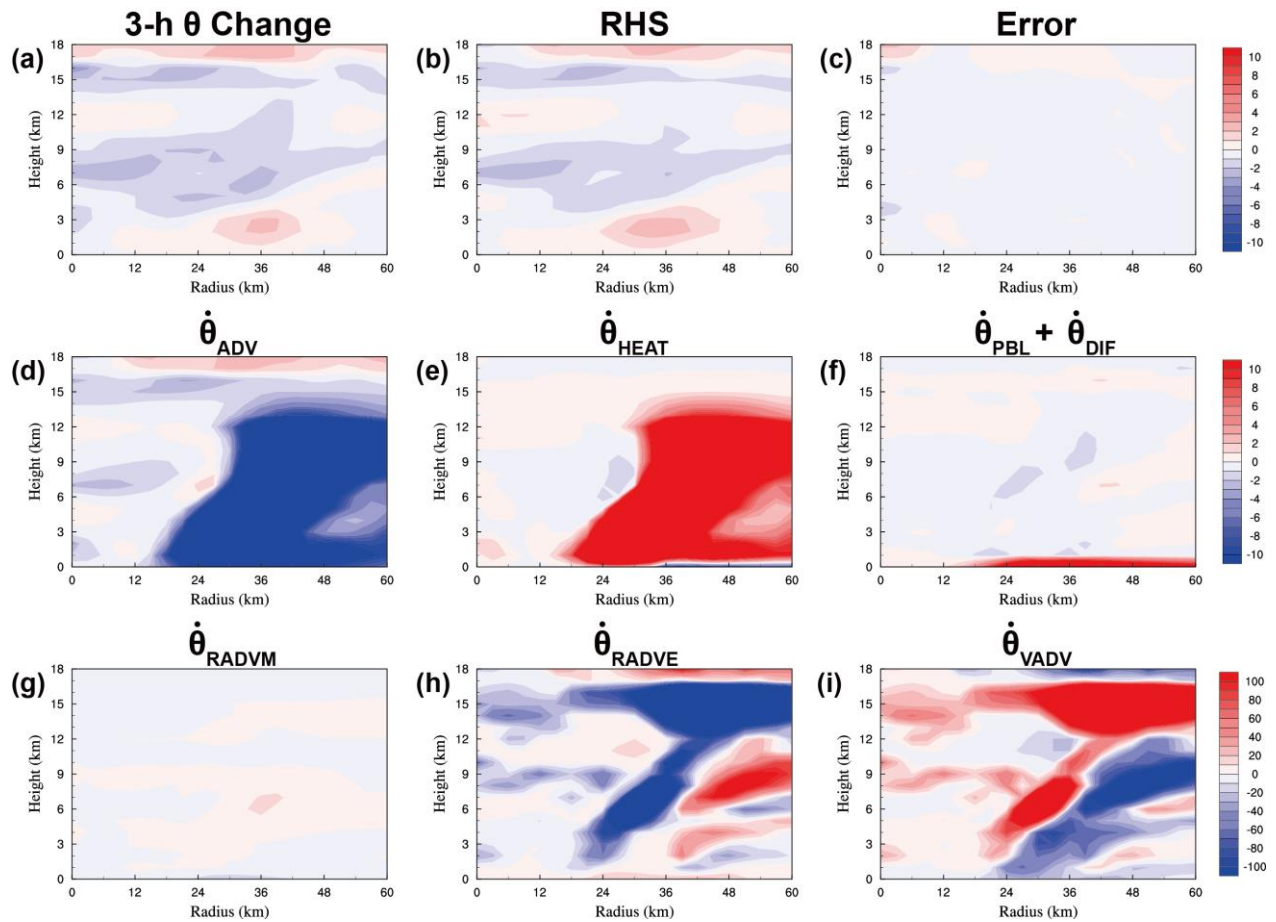


854
 855 **Figure 11.** Vertical motion (m s^{-1}) distribution relative to the surface center of the WTC vertically
 856 averaged between the 9- and 16-km heights from 10 to 50 h of the simulations at 20-h interval
 857 in (a-c) D600, (d-f) D720, and (g-i) D840.

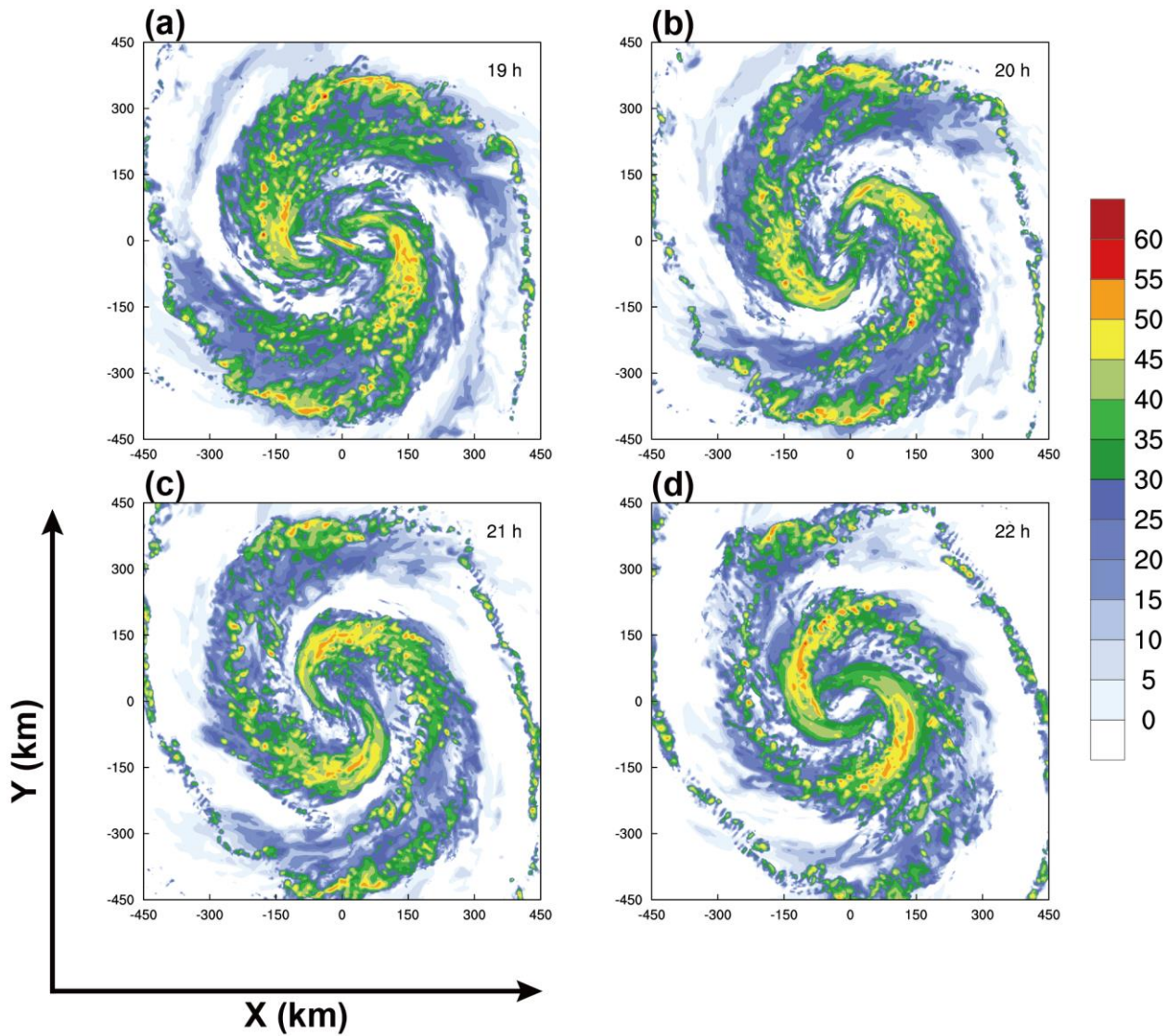


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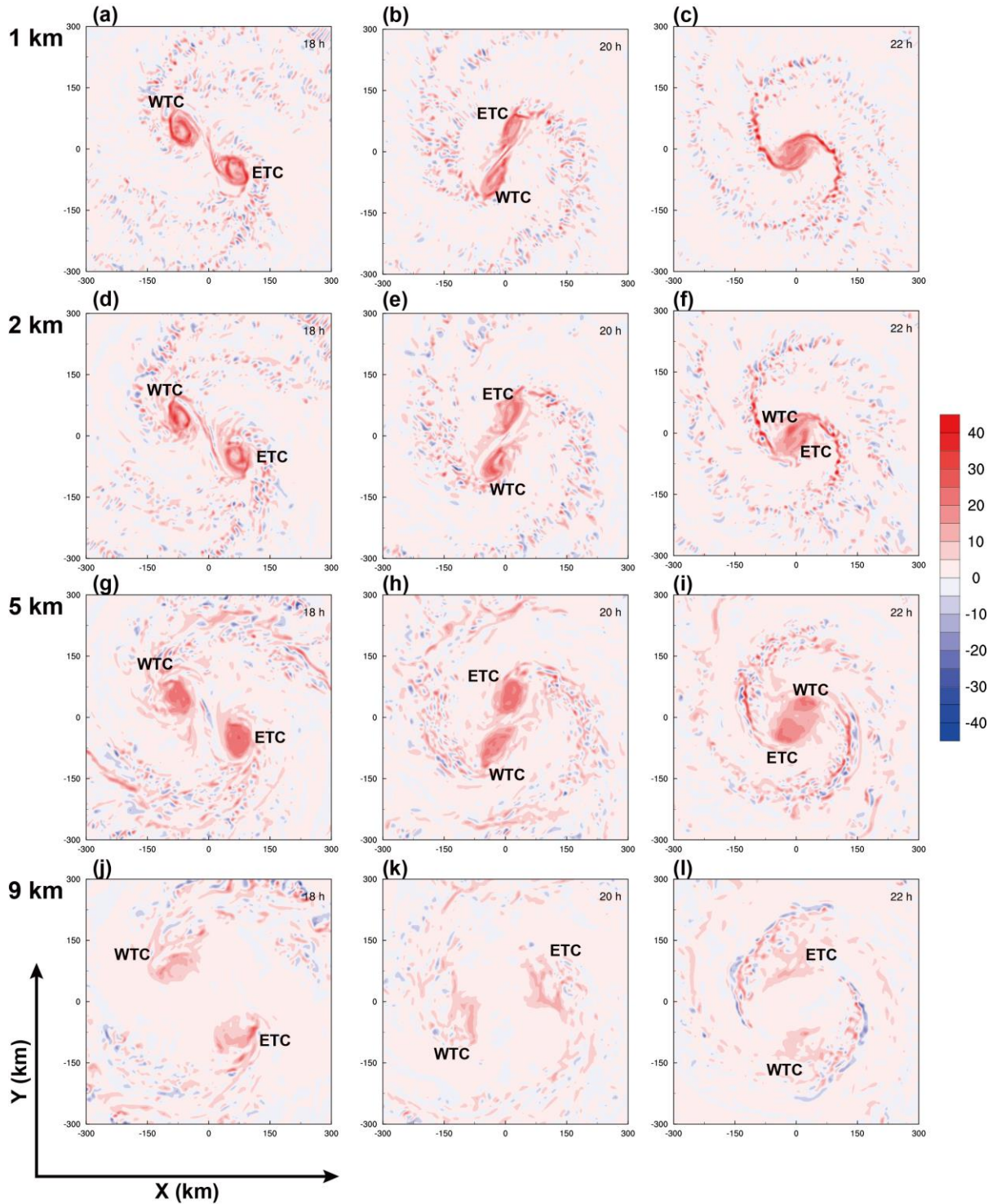
859 **Figure 12.** Time evolutions of the actual inner-core mean meridional wind (V) change (MODE,
 860 dashed gray line) relative to 42 h of the simulation of the WTC, the sum of the azimuthal
 861 mean RHS of Eq. (2) (black solid line), \dot{V}_{HADV} (blue solid line), \dot{V}_{VADV} (red solid line),
 862 \dot{V}_{PRES} (yellow solid line), \dot{V}_{CORI} (pink solid line), \dot{V}_{PBL} (purple solid line), and \dot{V}_{DIF} (green
 863 solid line) in Eq. (2) in (a, b) D600, (c, d) D720, and (e, f) D840 at the 9- (left) and 16-km
 864 (right) heights. See text for details.



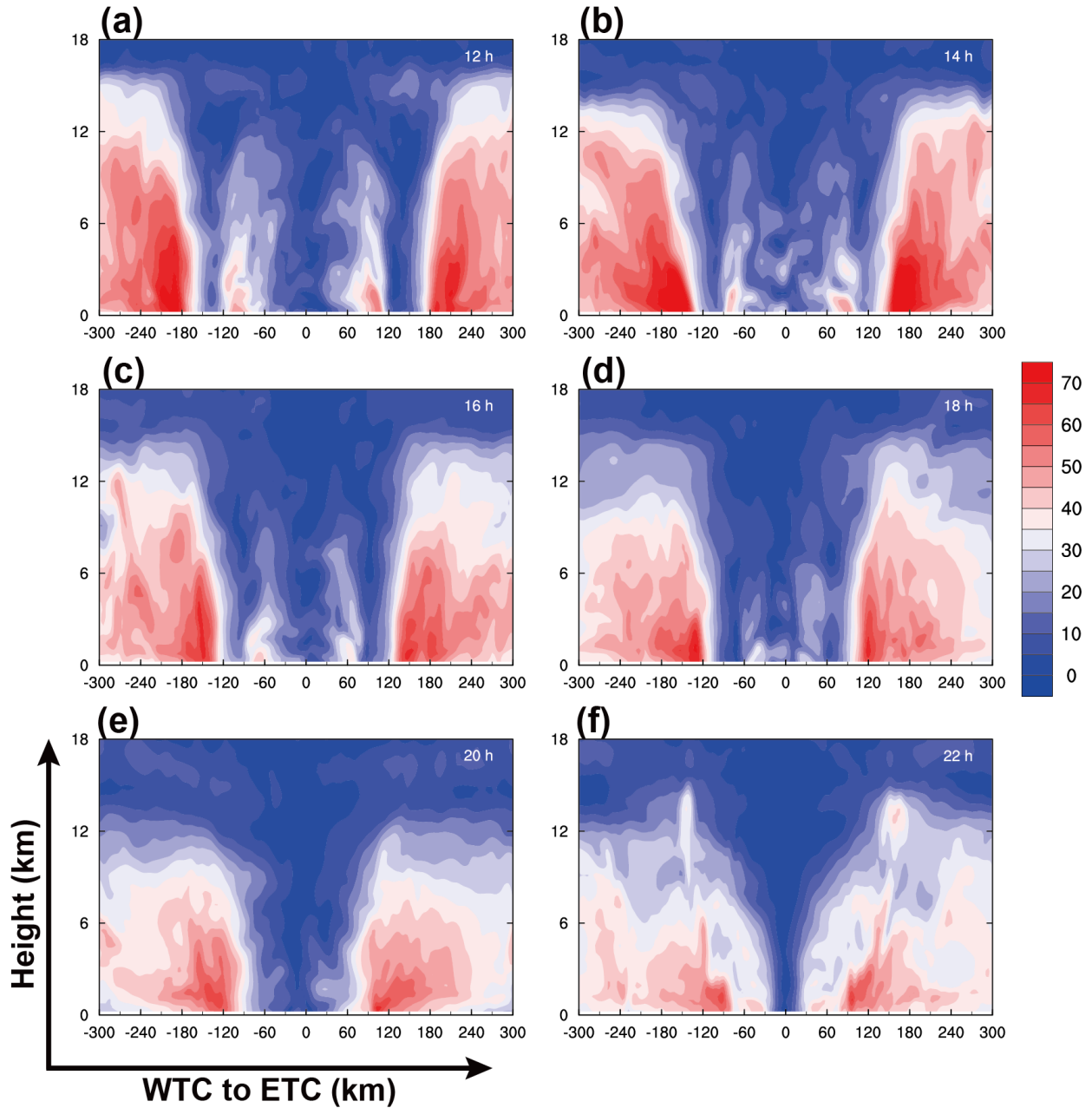
865
 866 **Figure 13.** Same as Fig. 8, but all tendencies are integrated from 66 to 69 h of the simulation in
 867 D720.
 868



869
 870 **Figure 14.** Horizontal distributions of simulated maximum radar reflectivity (dBZ) every hour
 871 from 19 to 22 h in D480.



872
 873 **Figure 15.** Horizontal distributions of PV (PVU) at the (a-c) 1-, (d-f) 2-, (g-i) 5-, and (j-l) 9-km
 874 heights in D480. The left, middle, and right columns are at 18, 20, and 22 h of the simulation,
 875 respectively.



876

877 **Figure 16.** Vertical cross sections of total wind speed (m s^{-1}) along the x-axis from the WTC (left)

878 to the ETC (right) from 12 to 22 h of the simulation at 2-h interval in D480.