Hindawi
Advances in Meteorology
Volume 2019, Article ID 8072914, 14 pages
https://doi.org/10.1155/2019/8072914

Research Article

Observational Study on the Characteristics of the Boundary Layer during Changes in the Intensity of Tropical Cyclones Landing in Guangdong, China

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Received 2 June 2019; Accepted 26 August 2019; Published 29 September 2019

Academic Editor: Haydee Salmun

Eleven tropical cyclones that landed in Guangdong Province since 2012 and experienced strengthening or weakening over the offshore area were studied. Since the structure of the tropical cyclone boundary layer significantly influences the variation of the intensity of the cyclone, continuous observations of the wind profile radar at a coastal radar station in Guangdong Province were combined with aircraft observation data of the No. 1604 "Nida" cyclone to analyse the variations in the distributions of the radial wind, tangential wind, and angular momentum in the typhoon boundary layer and the similarities and differences between the boundary layers of the 11 tropical cyclones during the strengthening or weakening of their intensities. The analysis results show that the presence of the supergradient wind and the enhancement effect of the radial inflow play important roles in enhancing the intensity of a tropical cyclone. The observations indicate that when the tangential wind velocity in the maximum wind velocity radius reaches the velocity of the supergradient wind and when the radial inflow either gradually increases towards the centre of the tropical cyclone or gradually covers the entire boundary layer, the angular momentum tends to be shifted towards the centre. At this time, the maximum radial inflow, maximum tangential wind, and maximum angular momentum are in the same height range in the vertical direction. When a strong radial outflow occurs in the boundary layer of a tropical cyclone or the area with maximum wind velocity is located in the air outflow, the angular momentum cannot easily be transported towards the centre of the typhoon. Therefore, the spatial configuration of the three physical quantities will determine future changes in the intensity of tropical cyclones. The scope of the results presented here is limited to the 11 selected cases and suggests extending the analysis to more data.

1. Introduction

A tropical cyclone is an organized large-scale vortex system, and it is predicted by two main methods: the first method predicts the path and the second predicts the strength. Because the path of a tropical cyclone mainly depends on large-scale environmental airflows, as the global forecasting ability is continuously improved, the prediction capability for tropical cyclone paths is also significantly improved [1]. Tropical cyclones experience dramatic exchanges of momentum, heat, and water vapor during their birth, strengthening, maturation, and decay, resulting in many unresolved scientific questions about the evolution of the tropical cyclone intensity and the delay of enhancements in the forecasting techniques for the tropical cyclone strength [2].

The change in the intensity of tropical cyclones has always been an important scientific problem. Early research on this topic lacked observational data and mainly used numerical simulation; the results of these simulations indicate that the dynamic processes of the boundary layer are more important for strengthening tropical cyclones than thermodynamic processes are [3, 4]. However, due to the lack of observations of the boundary layers of tropical cyclones, the further examination of these results has been very limited. Over the last 30 years, observational experiments have been conducted [5] to determine how the boundary layer influences the intensity of a tropical cyclone.

The presence of supergradient winds in the middle and lower layers of tropical cyclones has been confirmed by data from aircraft observations [6]. The presence of supergradient winds indicates the presence of an imbalanced pressure-gradient force, which could cause convergence in the lower layer [7]. The development of supergradient wind is very important to the formation and development of a typhoon [8]. With the advent of the supergradient wind, a radial air inflow often appears inside the typhoon, and the resulting convergence of the airflow was previously considered to be the main reason for typhoon intensification [9]. After the lower-layer convergence-induced circulation develops and strengthens, it can offset the effect of ground friction on the decline of the system, thus promoting typhoon development [10]. Therefore, the distribution of the radial wind significantly influences the wind field structure and intensity of a typhoon [11]. In addition, the distributions of the tangential wind velocity and angular momentum are also very important. Studies have shown that the maximum tangential wind velocity [3] and the radial convergence of the angular momentum [12] in the typhoon boundary layer are indispensable physical processes in the strengthening of a typhoon, and observations have also confirmed that the radial convergence of the angular momentum causes typhoon intensification [6].

These studies indicate that the boundary layer of a tropical cyclone plays an important role in controlling the change in intensity of a typhoon [15]. However, these studies are mostly based on aircraft observations over the open ocean surface, while observational studies on the boundary layer of tropical cyclones from the coast of China experiencing changes in intensity are still relatively few. Guangdong is the region with the most frequent tropical cyclone activities in China and is influenced by tropical cyclones for the longest period of time. Each year, there are approximately two enhanced tropical cyclones over the offshore area of Guangdong. Investigations of the variation characteristics of the supergradient wind, radial wind, and angular momentum in the boundary layer during the changes in the tropical cyclone intensity using observations of the wind profile radar network at coastal radar stations in Guangdong would be beneficial to understanding the characteristics of physical processes in the boundary layer during tropical cyclone intensification over the offshore area of Guangdong.

2. Overview of Typhoon Cases

The intensity of a tropical cyclone determines the magnitude of its impact, and therefore accurate predictions of the intensity of landfalling tropical cyclones are very important (Elsberry, 2005). To study the characteristics of the boundary layer, which has an important influence on the change in intensity of a landfalling tropical cyclone, we select a total of eleven tropical cyclones with offshore changes in intensity that occurred in 2012–2017 and landed in Guangdong (Table 1). Eight of these tropical cyclones strengthened and three weakened offshore from Guangdong. The tropical cyclones can be divided into the following categories by their intensity: tropical depression, tropical storm, severe tropical storm, typhoon, intense typhoon, and superintense typhoon. According to the offshore variation in the intensity, tropical cyclones can be divided into two types: the strengthening type and the weakening type. Among the cases of the strengthening type over the offshore area, cases of tropical cyclones that intensified from typhoon to intense typhoon (three cases) were the most frequent, followed by cases that intensified from tropical storm into severe tropical storm (two cases). Among the cases of the weakening type over the offshore area, the cases of an intense typhoon weakening to a typhoon (two cases) were the most frequent. In these cases, some experienced intensity changes twice over the offshore area. For example, Vicente intensified from severe tropical storm to typhoon and from typhoon to intense typhoon; Mujigae intensified from typhoon to intense typhoon and from intense typhoon to superintense typhoon; and Usagi weakened from superintense typhoon to intense typhoon and from intense typhoon to typhoon. However, no matter how many times the intensity changes, as long as a tropical cyclone keeps strengthening or weakening during the observation period, it is classified as the strengthening type or the weakening type, respectively.

3. Data and Methods

Since 2008, the Guangdong Meteorological Service has gradually constructed a network for wind profiles, and a total of 17 radars have been constructed to date. In particular, there are 15 boundary layer wind profilers (that of the Shenzhen station was produced by Vaisala of Finland, and the type is LAP3000; those of the other stations are from the Beijing Metstar Radar Co., Ltd., and the type is TWP3) and two radars that measure the wind profile of the troposphere (Zhanjiang and Guangzhou Huadu stations, both of which were produced by the Beijing Institute of Radio Measurement, and the type is CFL-08). The time interval for the real-time sampling of the wind profile is 6 min. According to the data from 13 tropical cyclones landing in Guangdong Province selected in Table 1, Figure 1 shows the distribution of the paths; according to the landing position, we select the nearest coastal radar station for the wind profile in the analysis (for example, for the No. 1306 tropical cyclone, we select the Zhanjiang radar). The frequency of observation of the wind profile radar is 1 time/6 min, and the vertical resolution values are 60 m (for the boundary layer wind profiler) and 120 m (for the tropospheric wind profiler). The observation data have a high spatiotemporal resolution and provide valuable information for analysing the characteristics of the boundary layer for landfalling tropical cyclones.

A study showed that the radial inflow causes convergence in the lower layer, especially when the inflow is in the lower layer outside the maximum wind velocity radius

Table 1: Typhoons with a change in intensity over an offshore area of Guangdong Province during the period 2012 to 2017.

Type	Number	Name	Tropical depression ⟶ tropical storm	Tropical storm ⟶ severe tropical storm	Severe tropical storm ⟶ typhoon	Typhoon ⟶ intense typhoon	Intense typhoon ⟶ superintense typhoon	Landing site
Strengthening type	1608(a)	Dianmu	√					Zhanjiang
	1306(b)	Rumbia		√				Zhanjiang
	1702(c)	Merbok		√				Hong Kong
	1604(d)	Nida			√			Huidong
	1714(e)	Pakhar			√			Macao
	1208(f)	Vicente			√	√		Taishan
	1713(g)	Hato				√		Macao
	1522(h)	Mujigae				√	√	Zhanjiang
Type	Number	Name	Tropical storm ⟶ tropical depression	Severe tropical storm ⟶ tropical storm	Typhoon ⟶ severe tropical storm	Intense typhoon ⟶ typhoon	Superintense typhoon ⟶ intense typhoon	
Weakening type	1716(i)	Mawar		√				Shanwei
	1622(j)	Haima				√		Shanwei
	1319(k)	Usagi				√	√	Shanwei

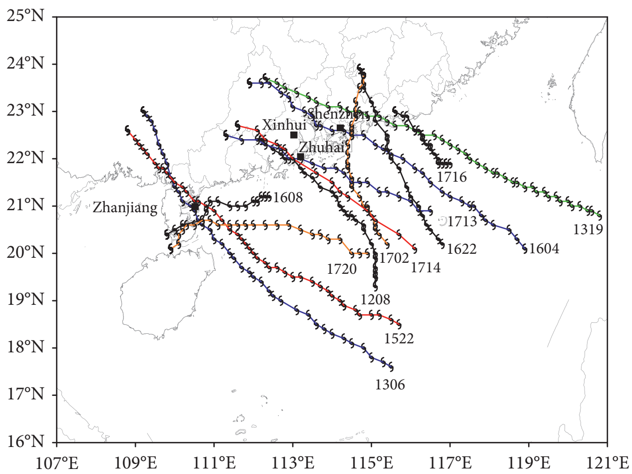


Figure 1: Path diagram of 13 typhoons with landfalls (the black squares represent the locations of the wind profiler stations).

[15], which will offset the impact of the decline of the tropical cyclone caused by ground friction and further promote the development of the cyclone [10]. Therefore, the method of Liao et al. [16] was adopted first to control the quality of the wind profile radar data. On this basis, the horizontal wind velocity observed by the wind profile radar was decomposed to obtain the distribution of the tangential wind and radial air inflow of the tropical cyclone, from which the corresponding changes in the radial and tangential winds during the intensity changes are analysed. In addition, since the radial convergence of the angular momentum in the boundary layer can enhance the strengthening of the circulation in tropical cyclones, the vortex development is also very important for the maintenance of the cyclone [17]. Therefore, following Montgomery et al. [6], we calculate the absolute angular momentum by $M = rv + (1/2)fr^2$, where r is the distance from the centre of the cyclone, v is the tangential wind velocity, and f is the Coriolis force parameter.

For No. 1604, "Nida," we conducted continuous vertical and horizontal aircraft observations near the centre of the cyclone. Based on the wind velocity, pressure, and temperature observations and according to the equilibrium relationship $(1/\rho(\partial p/\partial r) = (v_g^2/r) + fv_g)$ among the pressure-gradient force, centrifugal force, and Coriolis force, we calculate the theoretical corresponding gradient wind V_g, which aids in determining whether a supergradient wind is present in the tropical cyclone. The presence of the supergradient wind suggests an imbalanced pressure-gradient force, which may result in convergence in the lower layer [7].

4. Boundary Layer of a Typhoon

4.1. Aircraft Observation Results. During the No. 1604 "Nida" cyclone (which strengthened offshore), the Hong Kong Observatory conducted aircraft observations through the clouds along the coast of Guangdong Province. These observations were conducted from 07:00 UTC to 09:41 UTC (Coordinated Universal Time) on August 1, 2016. During the aircraft observations, the longitude, latitude, and elevation above sea level were recorded every 1 s, as were the pressure, temperature, wind direction, wind velocity, and vertical velocity. Due to a malfunction of the humidity detector, the relative humidity data were lost.

Using the flight path of the airplane (Figure 2), we can divide the data into 6 different stages: (1) vertical climbing stage (part 1: 0–1650 m), (2) vertical descending stage (part 2: 1650–650 m), (3) horizontal observation through cloud (part 3: 650 m height), (4) vertical climbing stage (part 4: 650–2700 m), (5) horizontal flight stage (part 5: 2700 m), and (6) vertical descending stage (part 6: 2700–0 m). Over the period of the aircraft observation, "Nida" was a typhoon at 07:00–09:40 (part 1–part 6) and intensified to an intense typhoon at 10:00. Using the centre of the cyclone as the origin, Figures 3(a)–3(c) show the vertical distributions of the radial wind, tangential wind, and absolute angular momentum calculated for the four vertical observation stages (parts 1, 2, 4, and 6). In part 5, the airplane was mainly used for horizontal detection. Based on the aforementioned calculation method for the gradient wind, we can obtain the distribution of the gradient wind from theoretical calculations, and the tangential wind can be calculated from observations with respect to the radius (Figure 3(d)).

4.1.1. Characteristics of Tangential Wind and Inflow. According to the distance between the airplane and the centre of the typhoon, in the three stages part 1, part 2, and part 6, the airplane was far from the centre of the typhoon, at a distance of 340–400 km, and was located in the peripheral spiral cloud zone; in part 4, the airplane was approximately 260 km from the centre of the typhoon. In part 1 and part 2, the tangential wind velocity was smaller than 5 m/s below 500 m but increased by 5 m/s as the height increased by approximately 500 m; above 1.5 km, the tangential wind velocity was 10 m/s. The entire layer below 1.5 km is dominated by radial inflow, but the characteristics of the distribution of the radial inflow through a height gradient are essentially similar. As the height increases, the radial inflow velocity gradually increases, and above 1.5 km, the radial inflow velocity was approximately 14 m/s. The two vertical profiles for part 1 and part 2 reflect the tangential wind and inflowing air, which exhibit the essentially the same characteristics.

As the typhoon continuously approaches, the plane in part 4 and part 6 stages is close to the centre of the typhoon. The tangential wind obviously increases, and, especially in part 4, the tangential wind continuously intensifies as the height increases. At a 3 km height, the tangential wind velocity is approximately 25 m/s, while in part 6, the tangential wind increases as the height increases and reaches its maximum value at 1200 m, approximately 17 m/s. When the height further increases, the tangential wind velocity generally exhibits a downward trend. Similar to the obvious difference exhibited by the distribution of the tangential wind, the radial inflowing air is also obviously different. In part 4, which is close to the centre of the typhoon, the velocity of the inflowing air in the entire detection range

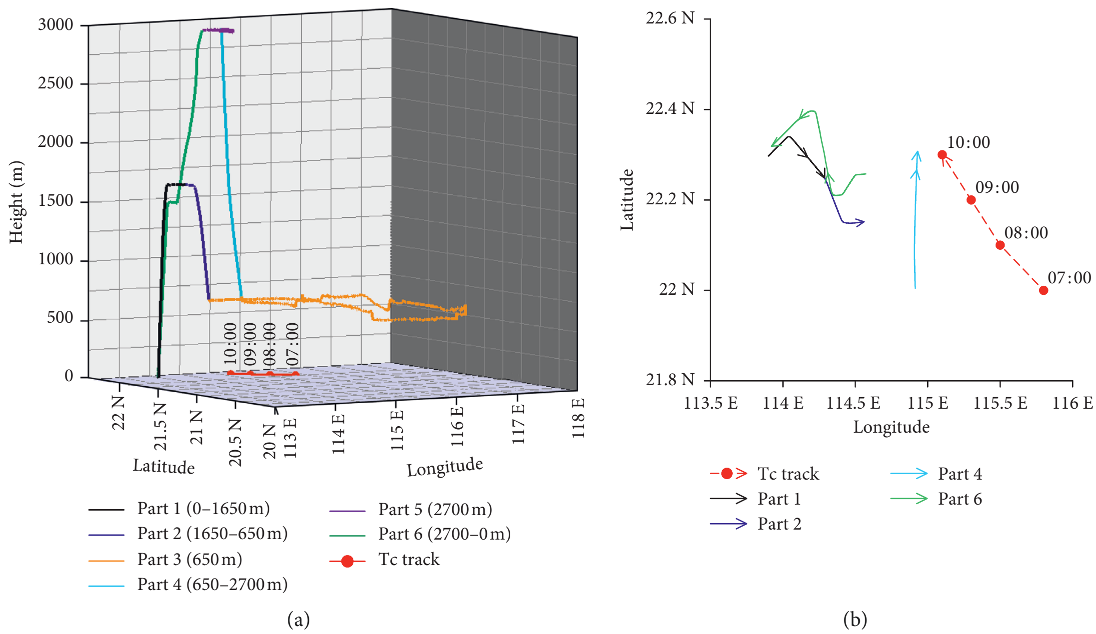


FIGURE 2: Aircraft observation map for the No. 1604 "Nida" cyclone. (a) Three-dimensional stereogram, where the red dots are the positions of the typhoon centre at different times. (b) Planar projections of airplane and typhoon paths.

(700–3000 m) is approximately 18 m/s, and the inflow below 1700 m is stronger than that at higher altitudes. This outcome indicates that closer to the centre of a typhoon, the more obvious the middle- and lower-level inflows. In part 6, when the distance from the centre of the typhoon is farther than in part 4, the vertical distribution of the inflowing air is similar to that of part 1 and part 2; it gradually intensifies from the ground surface as the height increases and reaches its maximum value at 1700 m, approximately 20 m/s. Above 1700 m, the inflow obviously weakens and stays at approximately 12 m/s.

According to the analysis above, in different locations of a typhoon, the vertical distributions of its tangential wind and radial inflow are different. (1) In the region relatively close to the centre (such as in part 4), the tangential wind velocity continuously monotonically increases with the height, and the whole layer (especially the middle and lower layers) maintains the same relatively large inflow airflow. (2) For the region relatively far from the centre (such as in part 1, part 2, and part 6), the tangential wind monotonically increases with the height but then reaches a maximum and then gradually decreases. The farther from the centre of the typhoon, the smaller the tangential wind velocity. The radial air inflow has similar features. At the maximum height of the tangential wind, the radial inflow has also reached a maximum. Above this height, the tangential wind gradually decreases as the height increases, but the high-level inflow is stronger than the low-level inflow.

4.1.2. Characteristics of Absolute Angular Momentum. The absolute angular momentum is related to the tangential wind velocity and the distance from the centre of the typhoon. In part 1 to part 2 (Figure 3(c)), the airplane turned and then declined after rising. During this period, the airplane gradually approached the centre of the typhoon, and the corresponding absolute angular momentum gradually declined. The increase in the absolute angular momentum as the radius increases indicates that the typhoon is inertially stable [18]. However, in part 6, the airplane gradually flew away from the centre of the typhoon as the typhoon also gradually moved in a northwest direction. Therefore, the distance from the airplane to the centre of the typhoon was smaller than that in part 1, but the absolute angular momentum in this stage was larger than that in part 1 in the 0–1700 m height range. Moreover, the higher the height, the larger the absolute angular momentum, and the absolute angular momentum increases in an upward-inward direction. This outcome indicates that the absolute angular momentum is transported towards the centre of the typhoon, and the boundary-layer inflow is strengthened. Therefore, in comparison with part 1, the tangential wind is obviously enhanced, and the air inflow also increases relatively quickly. "Nida" intensified to an intense typhoon at 10 : 00.

4.1.3. Supergradient Wind. Figure 3(d) shows the distributions of the theoretical value of the gradient wind and the calculated tangential wind velocity relative to the radius of the typhoon during the horizontal flight stage in part 4. The gradient wind slowly increases as the radius increases. The gradient wind velocity at 50 km is approximately 8 m/s and that at 250 km is approximately 17 m/s. In comparison, the tangential wind is larger, and the maximum wind velocity (over 40 m/s, which is nearly five times the gradient wind velocity) occurs at 70 km. The tangential wind velocity is essentially steady at approximately 30–40 m/s, which generally

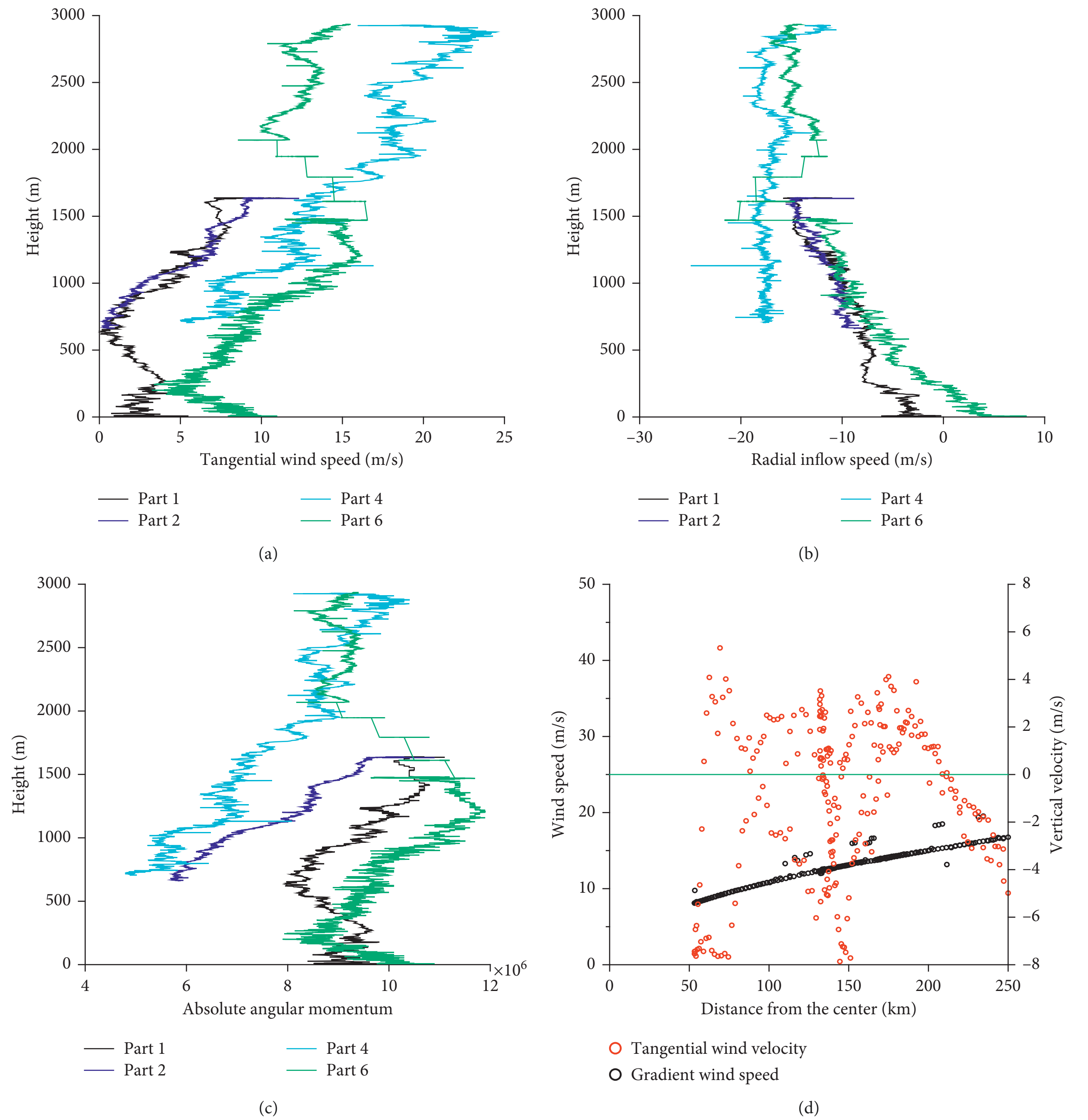


Figure 3: Aircraft observation results at different observation stages for the No. 1604 "Nida" cyclone. (a) Vertical distribution of the tangential wind. (b) Vertical distribution of the radial wind. (c) Vertical distribution of the angular momentum. (d) Distributions of the theoretically calculated gradient wind and radial wind as the radius changes.

exceeds 200% of the corresponding gradient wind velocity. However, it begins to decrease at 200 km. At 250 km, the tangential wind velocity decreased to close to the gradient wind velocity.

Figure 2(a) shows that in the horizontal flight stage, the airplane first approached the centre of the typhoon, flew far away, and then approached again. Figure 3(d) shows that the supergradient wind phenomenon always exists, and the characteristics of this large-scale supergradient wind are very obvious within a radius of 200 km. Within 3-4 times the radius of the maximum wind velocity, the lower layer of the typhoon has same characteristics as that of the radial inflow, which also indicates that the typhoon can maintain or increase its strength [19].

4.2. Results of Observation for Wind Profilers. Due to the limitations of observations, there are still not many aircraft observations on tropical cyclones landing in Guangdong that can be used to further understand the characteristics of the boundary layer for tropical cyclones with different characteristics (strengthened and weakened offshore). Using the radar observation data of the wind profile along the coast of Guangdong Province, after the quality control of the data, we analyse the characteristics of the supergradient wind, radial inflow, and absolute angular momentum for the boundary layer of a landfalling tropical cyclone. The position information of the centre of the tropical cyclone was updated once every hour. The wind profiler radar acquired observation data every 6 minutes, i.e., the wind profile radar had 10 observations within one hour. The distance between the initial position of the tropical cyclone centre and its position one hour later was equally divided into six parts to calculate the distance between the wind profiler radar and the centre of the tropical cyclone every 6 minutes. Using the distance as the coordinates, the radial distributions of the calculated physical quantities were obtained.

4.2.1. Characteristics of Radial Outflow and Inflow. Since a tropical cyclone is a large vortex system, the distribution of its radial airflow has an important influence on its evolution, and the airflow convergence caused by the radial inflow is initially considered to be the main cause of typhoon intensification [9]. Moreover, when the low-level circulation gradually develops and the convergence trend strengthens, it can counteract the dissipation of the vortex system caused by ground friction. Therefore, the distribution of the radial wind above the boundary layer is very important for the structure of the typhoon wind field and influences the typhoon intensity [11]. For strengthened or weakened tropical cyclones along the coast of Guangdong, we use continuous radar observation data of wind profiles near the landing point to determine the characteristics of the radial airflow for eight strengthened (Figures 4(a)–4(h)) and three weakened (Figures 4(i)–4(k)) tropical cyclones.

Due to the different life cycles and paths of tropical cyclones, the data from selected radar stations cover different lengths of time, and this coverage is reflected by the different scales of the abscissas in the graphs with the radius as the x-coordinate (Figure 4).

Figures 4(b) and 4(c) both show strengthened cyclones (from a tropical storm to severe tropical storm). During the strengthening process, the whole-layer inflow is dominant in both cases. However, during a severe tropical storm, "Rumbia," the whole-layer inflow is maintained roughly constant, while the outflow appears at a 0–2 km height and at a distance of 50–100 km from the centre of the typhoon for "Merbok." A similar lower-level outflow also occurs in other tropical cyclones (Figures 4(d)–4(h)). However, when the tropical cyclone intensifies, the inflow layer sometimes extends downward (such as at 100 km in Figure 4(d) and 50 km in Figure 4(e)) or the air inflow is obviously intensified (50 km in Figure 4(e), 80 km in Figure 4(f), and 50–100 km in Figure 4(g)). In addition, the radial inflow of "Nida" observed in Figure 3(b) (approximately 260–400 km) is consistent with that of the corresponding region in Figure 4(d), and the radar observation results of the wind profile are thus reliable.

In contrast, for weakened tropical cyclones, although a thick inflow layer is present in the lower level (1-2 km), its outflow layer occupies the greatest range of the typhoon (such as within 200 km in Figure 4(i), within 350 km in Figure 4(j), and outside 160 km in Figure 4(k)), and the air inflow above the outflow layer is also relatively small in comparison with the strengthened cyclones. Even for typhoon "Usagi" (Figure 4(k)), the maximum inflow velocity, approximately 20 m/s, occurs at 0–1.5 km within the 160 km range. The speed is small, but it is also restricted to a relatively low height.

The distribution of the air inflow characterizes the intensity of a tropical cyclone. If the outflow layer occupies the entire tropical cyclone level near the ground surface and the air inflow above the outflow layer is also relatively small, the intensity of the tropical cyclone weakens. In contrast, although persistent outflow occurs at heights below 1-2 km, the outflow layer gradually becomes obvious only when it appears in the vicinity of the eye area. Moreover, the upper-level inflow layer is intensified and extends downward or the intensification of the air inflow occurs, both indicating the intensification of the tropical cyclone strength.

4.2.2. Distribution of Tangential Wind. The location and wind velocity of the maximum tangential wind can determine the maximum wind velocity radius and maximum wind velocity of a tropical cyclone and further describe the intensity. We can see from Figure 5 that there is usually a certain maximum wind velocity range at a height above 1 km and a radius of approximately 100 km. For a tropical cyclone below the level of a severe tropical storm, the maximum tangential wind velocity range is often in the region above 1 km and at a radius of 50–100 km, and the maximum wind velocity range is relatively small. When the strength gradually intensifies to typhoon or the grades above, the maximum wind velocity appears in a region farther from the centre of the typhoon, and the location of appearance also expands to 100–200 km and 300 km in a superintense typhoon (Figure 5(h)). Therefore, according to the horizontal and vertical ranges of the maximum tangential wind velocity, we can evaluate the intensity level for the current tropical cyclone. In addition, in combination with part 6 of "Nida" in Figure 3(a) and corresponding to the radius of 260 km in Figure 5(d), the maximum wind velocity range for both is located at the 1–1.5 km height, and the observation results are consistent. Because the tangential wind at 250 km is essentially consistent with the gradient wind (Figure 3(d)), the maximum tangential wind range is considered a supergradient wind.

In a strengthened tropical cyclone, when the centre of the maximum tangential wind velocity is more concentrated at the lower level and the radial inflow is dominant, the intensity is easily maintained or intensified. For example, both "Nida" (Figure 5(d)) and "Vicente" (Figure 5(f)) exhibit an obvious maximum wind velocity range at a radius of approximately 150 km. The radial inflow range is distributed above 1.5 m, and the maximum wind velocity range of "Nida" falls within 1–2.5 km (partly in the inflow area). Thus, the last stage in the

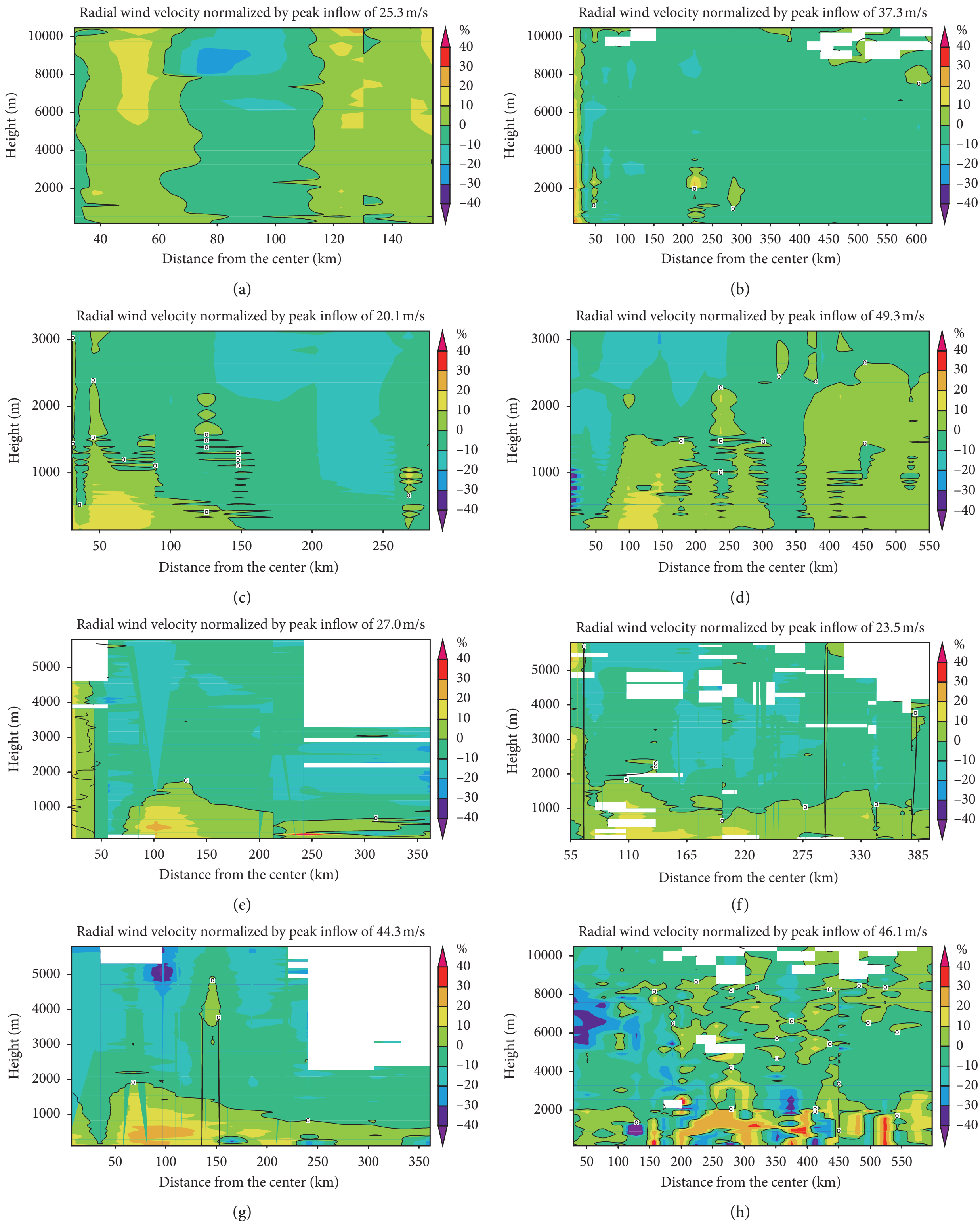


Figure 4: Continued.

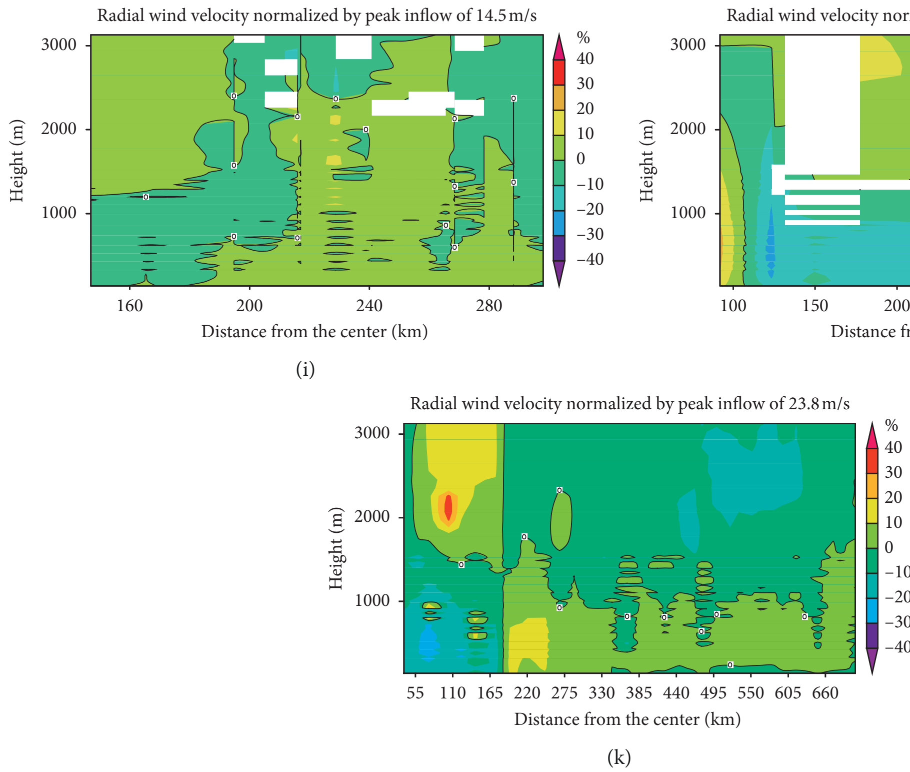
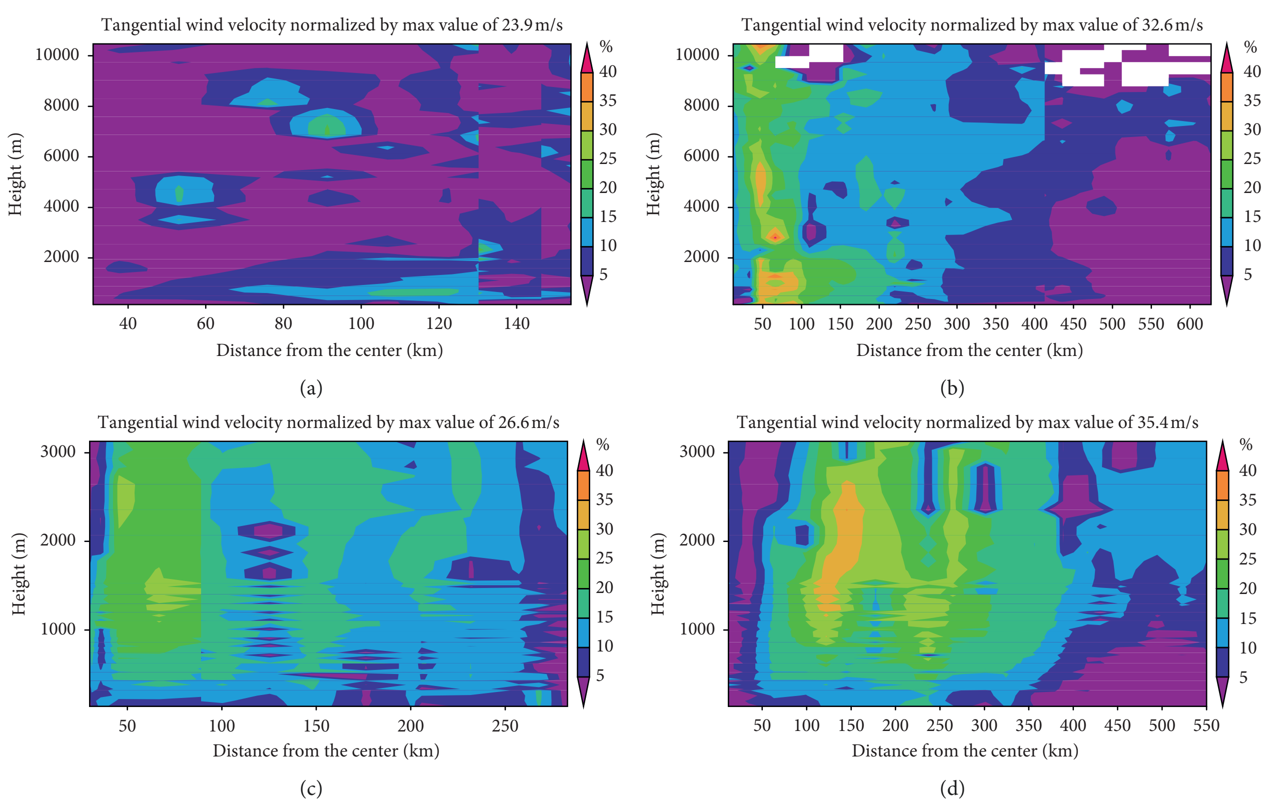


Figure 4: Distributions of the radial velocity relative to the radius of the typhoon as obtained by wind profilers ((a)–(k) are consistent with the numbers in Table 1).



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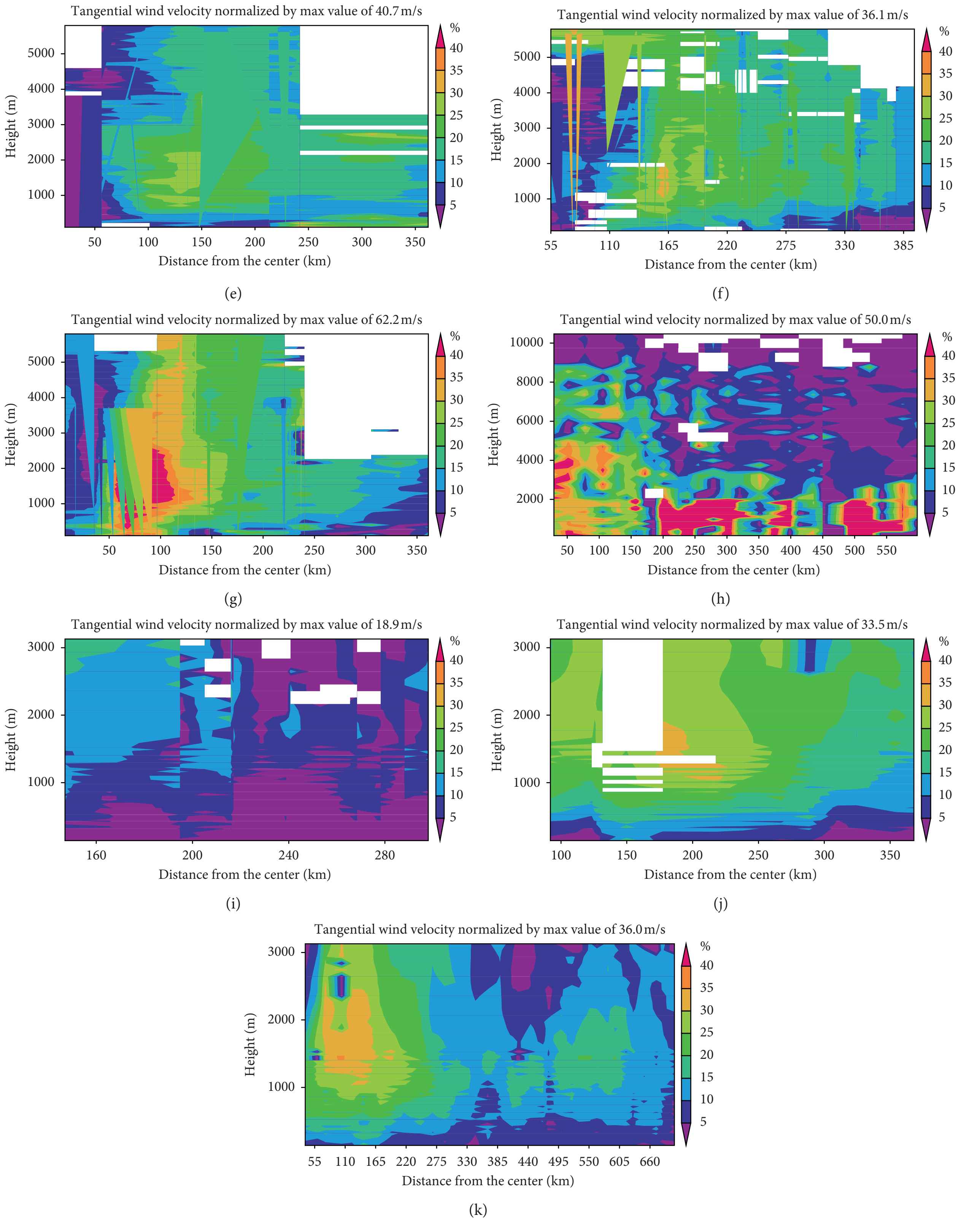

Figure 5: Distributions of the tangential velocity relative to the radius of the typhoon as obtained by wind profilers ((a)–(k) are consistent with the numbers in Table 1).

strengthening of the intensity is the intensification from a severe tropical storm to a typhoon. The maximum wind velocity range of "Vicente" is located at 1-2 km, essentially at the radial air inflow, and it eventually intensified from severe tropical storm to typhoon and finally to intense typhoon. "Pakhar" (Figure 5(e)), "Hato" (Figure 5(g)), and "Mujigae"

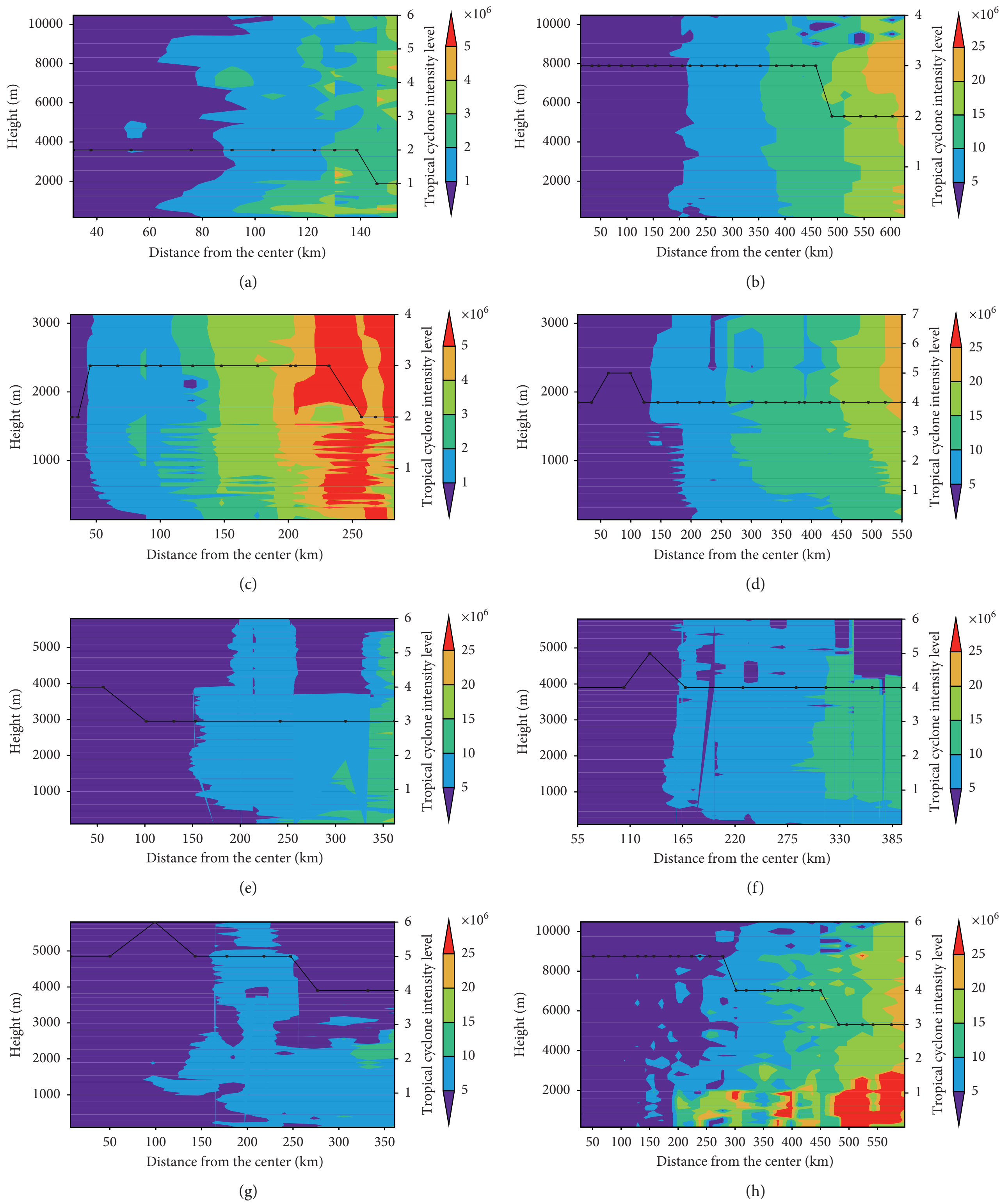

Figure 6: Continued.

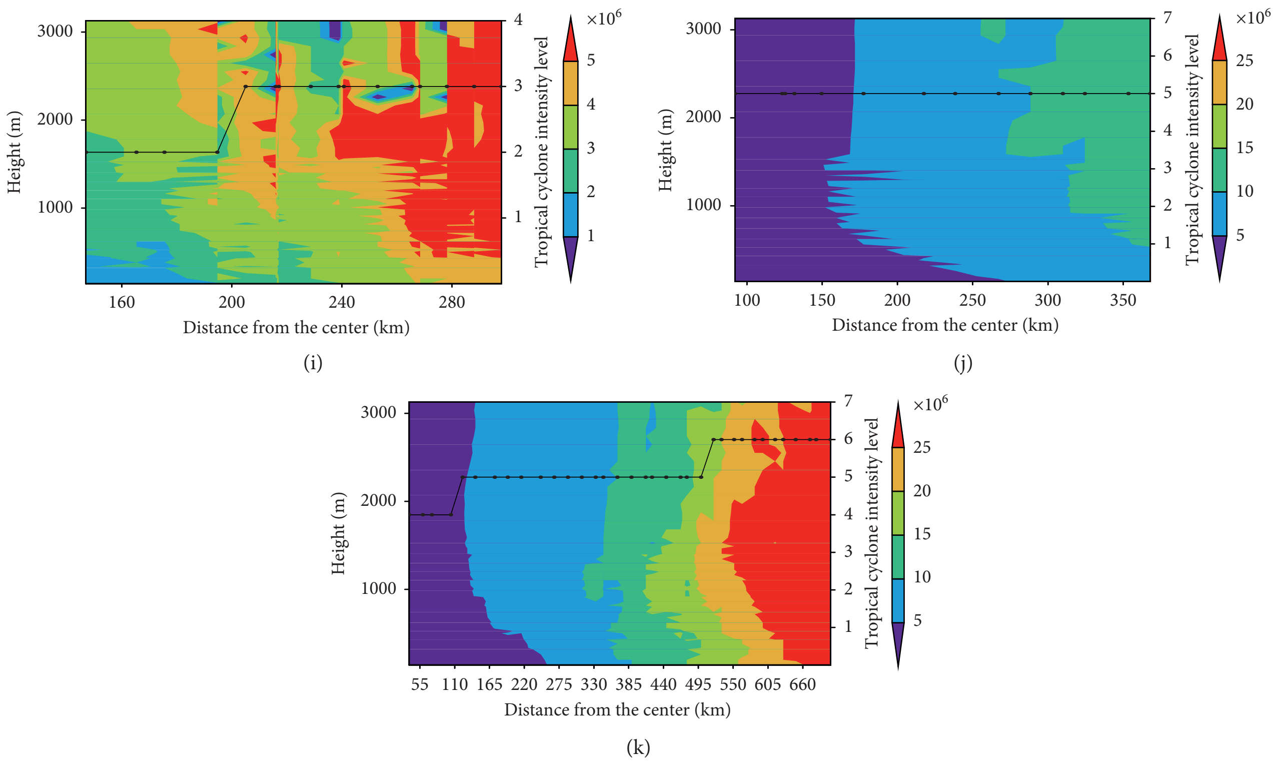

Figure 6: Distributions of the absolute angular momentum relative to the radius of the typhoon as obtained by wind profilers. (a)–(k) are consistent with the numbers in Table 1, and the black dotted solid lines are the strength grades of a tropical cyclone. The numbers on the right represent the tropical cyclone category as judged by its intensity [20]: 1 is tropical depression, 2 is tropical storm, 3 is severe tropical storm, 4 is typhoon, 5 is intense typhoon, and 6 is superintense typhoon.

(Figure 5(h)) are also similar to "Nida" in that the maximum tangential wind velocity range is not completely located in the radial inflow. However, because their maximum tangential wind velocities are above 40 m/s, the intensities persistently strengthen. Therefore, the strong tangential wind velocity range and its location in the radial inflow region are both conducive to the intensification of the tropical cyclone strength.

The distribution of the maximum tangential wind velocity for the weakened tropical cyclone is similar to that of the strengthened tropical cyclone. That is, the maximum tangential wind velocity range is located at the approximately 100–150 km radius of the typhoon. However, if the maximum tangential wind velocity appears at the inflow layer, the tropical cyclone is prone to strengthen; in contrast, the maximum tangential wind velocity range of "Haima" (Figure 5(j)) is located at 1.2–2 km, which is essentially in the radial outflow region; the maximum tangential wind velocity range (located at 1–2.5 km) of "Usagi" (Figure 5(k)) is also essentially located in the air outflow; and the characteristics of "Mawar" (Figure 5(i)) are also similar. Therefore, the maximum tangential wind velocity range located in the radial outflow region of a tropical cyclone is detrimental to the intensification of the cyclone.

4.2.3. Distribution Characteristics of Angular Momentum. The magnitude of the angular momentum is directly correlated with the tangential wind velocity and the distance from the centre of a tropical cyclone. Generally, if the angular momentum increases as the radius increases at every height, the tropical cyclone has a very good inertial equilibrium structure [18]. If the radial inflowing air transports the angular momentum towards the centre of a tropical cyclone, the maximum wind velocity range is formed and developed [6].

For a strengthened or weakened tropical cyclone, the distribution of the angular momentum at different radii has similar characteristics: the maximum range of the angular momentum is about twice the radius of the maximum tangential wind, and the angular momentum first increases, then decreases as the height increases, and gradually decreases as the radius decreases. Therefore, the angular momentum does not always increase as the radius increases. The maximum angular momentum of a tropical cyclone could exist at any radius. From the maximum angular momentum to the centre of a tropical cyclone, the angular momentum gradually decreases. Therefore, the relatively large angular momentum at the periphery of a tropical cyclone is gradually lost during the continuous transfer process towards the centre.

Based on the comparison between strengthened and weakened tropical cyclones, the height of the maximum angular momentum is often consistent with the height of the maximum tangential wind in strengthened cyclones, while for weakened cyclones, there is some deviation between the heights. As mentioned above, when the height of the maximum angular momentum is in the range of radial inflow, the horizontal inward transport of the momentum is relatively smooth. Then, the maximum tangential wind velocity and the maximum angular momentum are located at the same height; for example, in "Vicente" (Figure 6(f)), the maximum tangential wind and maximum angular momentum are at the same height. If the range of the maximum angular momentum falls within the range of the radial outflow when the intensity of a tropical cyclone is relatively weak, the range of the maximum tangential wind could exceed the height of the maximum angular momentum, whereas the height of the maximum tangential wind for a relatively intense tropical cyclone could be less than the height of the maximum angular momentum. These results also indicate that the angular momentum transports energy towards the centre by the convergence of the radial inflow, causing the maximum tangential wind to form.

As a tropical cyclone moves, the radar observations of the coastal wind profile can be vertically continuous from the outside to the inside, and the range of the maximum angular momentum is usually more than twice the radius of the maximum tangential wind velocity. Therefore, an analysis of the angular momentum and radial airflow (inflow/outflow) can determine the direction of the intensity change in a tropical cyclone and the height of the maximum tangential wind velocity.

5. Conclusions

Eleven cases of tropical cyclones whose intensities change over the offshore area of Guangdong Province were selected to study the evolution characteristics of the radial wind, tangential wind, and angular momentum during intensity changes. The observation data are mainly observations of wind profile radars along the coast of Guangdong Province, as well as aircraft observations of the No. 1604 "Nida" storm. The wind profile radar stations that were nearest to the landing points of 11 tropical cyclones were selected, and their continuous observations every 6 minutes can capture the continuous variation of the wind field in the tropical cyclone boundary layer. Aircraft observations have three hours of observation time, and observations via horizontal and vertical flights are carried out 260–400 km away from the centre of Nida. The wind direction, wind velocity, temperature, and pressure of the atmosphere are acquired by aircraft observations.

For a tropical cyclone strengthened offshore, there was an obvious supergradient wind in the maximum wind velocity radius in its boundary layer. The maximum wind velocity appeared within a height of 1–2 km, and the wind velocity generally exceeded 200% of the velocity of the corresponding gradient wind. Montgomery et al. [6] observed that the maximum wind velocity exceeded 20–60% of the velocity of the gradient wind, which was lower than our observations, indicating that different tropical cyclones had different characteristics; however, supergradient winds were always present during the strengthening of tropical cyclones. The observation results also show that if there was a relatively consistent radial air inflow in the lower layer and the height of the supergradient wind was consistent with that of the radial air inflow flow, then the intensity of the tropical cyclone is enhanced. In contrast, if part or all of the maximum tangential wind area was located in the radial outflow area, then the intensity of the tropical cyclone was continuously weakened.

The radial inflow is the main feature of the intensification of a tropical cyclone. However, different intensified tropical cyclones have different inflow features. Some tropical cyclones have consistent air inflows in the boundary layer, such as the No. 1306 "Rumbia," and some exhibit the strengthening and expansion of air inflows close to the centre, such as the No. 1702 "Merbok"; however, in all cases, the air inflows are strengthened and gradually expand to the entire boundary layer. In contrast, when the airflow in the boundary layer of a tropical cyclone is mainly radial outflow, the intensity tends to clearly decrease.

The range of the maximum angular momentum is more than twice the maximum wind velocity radius. The lower-layer air inflow during the strengthening of a tropical cyclone will cause angular momentum to be transported towards the centre, and the maximum angular momentum and the maximum wind velocity are at the same height (mainly below 2 km). If the range of the maximum angular momentum falls within the range of the radial outflow, then the intensity of the tropical cyclone will decrease. These observations confirm that the main mechanism of typhoon strengthening is the vortex intensification caused by the radial convergence of the angular momentum in the boundary layer, as pointed out by Smith and Thomsen [12] in a numerical simulation study. The observations are also similar to those discovered by Montgomery et al. [6].

These observations indicate that different dynamic characteristics of the boundary layer result in different intensity changes in tropical cyclones, and the formation of a supergradient wind and radial inflow play important roles in the intensification of tropical cyclones. However, the characteristics of the boundary layers of tropical cyclones strengthened offshore were different. For instance, while "Nida," "Pakhar," and "Vicente" all intensified from severe tropical storm to typhoon, the vertical distributions of their radial inflows showed significant inconsistencies. The effect of the inconsistencies on the development of the tropical cyclones remains unclear. However, it is certain that the radial outflow in the boundary layer of the weakened tropical cyclone is more obvious than that of the intensified tropical cyclone, and thus the characteristics of the radial outflow and inflow are critical to the intensity changes of tropical cyclones. In addition, only 11 cases of tropical cyclones were selected in this study. This sample number is not enough to obtain a universal result to determine the trend of the intensity changes of tropical cyclones, and more samples are needed to collect further evidence that support our results.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (grant nos. 41305029 and 41775140), Special Fund for Meteorology-Scientific Research in the Public Interest (GYHY201406033-05), Guangzhou Municipal Science and Technology Planning Project (grant no. 907158342066), and Science and Technology Research Projects of the Guangdong Meteorological Service (grant no. GRMC2017Q12).

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