Acta Oceanol. Sin., 2017, Vol. 36, No. 9, P. 39–44
DOI: 10.1007/s13131-017-1109-9
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The research on boundary layer evolution characteristics of Typhoon Usagi based on observations by wind profilers

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Received 1 June 2016; accepted 9 December 2016

Abstract

Vertically exploring the characteristics of the typhoon boundary layer (TBL) plays an important role in recognizing typhoon structure. The boundary layer radial direction and tangential wind characteristics of Typhoon Usagi based on the observational data of three boundary layer wind profiler stations along the route of Typhoon Usagi (No. 1319) and by combining with sounding data. The results show that: (1) maximum tangential wind appears in the vicinity of the eye area of Usagi, and it basically maintains a height of around 1 800 m when Usagi keeps a strong typhoon level, with the rapidly decreasing strength of Usagi after it lands, the speed of the maximum tangential wind and its vertical range both decrease; (2) the height of the maximum tangential wind is close to that of the inflow layer top of the typhoon, and is greater than that of the boundary layer estimated on the basis of Richardson number or potential temperature gradient, while the height of mixed layer judged on the basis of the signal-to-noise ratio (SNR) or its gradient is usually low; (3) the the boundary layer height can reach higher than 2 100 m before Usagi lands. When the typhoon level or above is achieved, the boundary layer height observed by various stations does not change much, basically staying at between 1 200 and 1 600 m. With the decreasing strength of Usagi after its landfall, the boundary layer height rapidly drops.

Key words: typhoon, boundary layer height, wind profiler, sounding

Citation: Liao Fei, Deng Hua, Gao Zhiqiu, Chan Pak-wai. 2017. The research on boundary layer evolution characteristics of Typhoon Usagi based on observations by wind profilers. Acta Oceanologica Sinica, 36(9): 39–44, doi: 10.1007/s13131-017-1109-9

1 Introduction

The typhoon boundary layer is an important part of the structure of a typhoon. It is long since the scholars began to conduct numerical theory researches by utilizing numerical models (e.g., Emanuel, 1986; Li et al., 2015). Early typhoon simulation studies usually set the boundary layer height in the model as a fixed value (Smith, 2003). The model can simulate the vortex structure and airflow radial distribution inside the boundary layer, and the simulated supergradient wind develops at the maximum wind radius (this result is similar to the observations of Kepert (2006)). However, an unreasonable set value of the boundary layer height will lead to distinct deviations in the physical quantities calculated by the model. When the set value of the boundary layer height is small, the phenomenon of the big super-gradient wind will develop easily, and inflow airflow will quickly weaken (Smith and Vogl, 2008). Therefore, Smith (2003) comes up with the parameterization plan of the boundary layer height with the change of radiuses; when simulating typhoons, the values of the heights of the boundary layer set by Smith and Montgomery (2008) decrease with the drop of radiuses, and the simulated maximum speed vertical distribution is more reasonable compared with the adoption of a fixed boundary layer height; the parameterization plan of the boundary layer height based on helicity proposed by Ma and Bao (2016) has substantially improved the simulation of Typhoon Morakot. Obviously, reasonable determination of the boundary layer height of a typhoon is crucial to the simulation results of the typhoon structure (Kepert, 2012).

The precise definition of the atmospheric boundary layer height is that it is the maximum height where turbulence exists. At present, for the heights of the stable boundary layer, the convective boundary layer and the cloud-covered boundary layer, Dai et al. (2014) have provided judgment methods based on single-station sounding data. However, due to the lack of direct observations of turbulence vertical distribution under the condition of high-speed wind during typhoons, non-direct turbulence momentum observations are also very few. Therefore, traditional

Foundation item: The National Natural Science Foundation of China under contract Nos 41305029 and 41475014; the Science and Technology Planning Project of Guangdong Province of China under contract No. 2013B020200013; the Guangzhou Municipal Science and Technology Planning Project of China under contract No. 201604020069; the Meteorological Key Technology Integration and Application Projects of China Meteorological Administration under contract No. CMAGJ2015M42.

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method for defining the boundary layer height is not applicable to the judgment of the boundary layer height of a typhoon. Opinions still vary as to how to determinate the boundary layer height of a typhoon in practice. For the exploring of the boundary layer of a typhoon, balloon sounding is still used more frequently at present. Different opinions still exist as to how the boundary layer height of typhoon is defined by the sounding data, for instance, Moss and Merceret (1976) took the conversion layer based on the definition of a potential temperature profile as the boundary layer height of typhoon; Rotunno et al. (2009) defined the maximum wind speed height as the boundary layer height of typhoon; Smith et al. (2009) thought that the inflow layer top could be taken as the boundary layer height of typhoon since it was the highest place that ground friction effects can reach; observations also showed that the minimum values of momentum and water vapor flux usually appear at the inflow layer top (Zhang et al., 2009), and this was consistent with the analysis result of a model simulation (Kepert, 2013). On the basis of model analysis result, Kepert et al. (2016) also thought that compared with the height of mixed layer, the height of the inflow layer could more accurately reflect the boundary layer height of a typhoon. But Zhang et al. (2011) pointed out that there were significant differences among the boundary layer heights of a typhoon given by different judgment methods.

However, due to the bad weather brought by a typhoon, it is extremely difficult to carry out relevant observations on the boundary layer of a typhoon. Moss (1978) and Zhang et al. (2009) have subsequently conducted observations on the boundary layer turbulence of a typhoon with airplanes several times. Therefore, it is relatively rare to determine the boundary layer height of a typhoon by analyses of observations. Over the past decades, with the development of remote sensing and exploring technologies, vertical exploring equipment (such as wind profilers) capable of conducting continuous upper-air observations on the atmosphere has emerged, thus becoming a new way in the determination and research of the atmospheric boundary layer. The drastic changes of turbulence pulsation of the temperature and humidity existing on the top of the boundary layer will make the signal-to-noise ratio (SNR) detected by the wind profiler show a maximal value (Angevine et al., 1994). The vertical gradient changes of the SNR can in turn reflect the strength of the turbulence. Thus, the boundary layer height can be judged by taking the exploring information as a supplement. With the gradual networking and use of wind profilers in China, the judgment method of probing the boundary layer height of a typhoon based on the wind profilers has become the main method in the research of the boundary layer structure of a typhoon at present by combining with the vertical distribution of wind despite the lack of observation data by turbulence flux airplanes, given that the vertical gradient change of the SNR detected by the wind profilers can reflect the strength of the turbulence.

2 Overview of typhoon case

At 02:00 o'clock (Universal Time Coordinated (UTC)) of September 17, Usagi, No. 19 tropical cyclone of 2013, was generated on the surface of Northeast Pacific, east of the Philippines. It evolved into a strong tropical storm at 05:00 o'clock of September 18, a typhoon at 20:00 o'clock of the same day, further developed into a strong typhoon at 11:00 o'clock of September 19 and a super typhoon (Grade 1 760 m/s) at 17:00 o'clock of the same day. It only took 20 h from the beginning to a typhoon, and only 40 h from the beginning to a super typhoon. It landed in the coastal areas of Shanwei (Zhelang Peninsula) at 19:40 of September 22. The maximum wind near the center during landing reached Grade 14 (45 m/s), and the minimum pressure at the center was 935 hPa. After landing, Usagi continued to move toward the west-northwest by passing through the Zhujiang Delta (Fig. 1). It weakened into a typhoon inside Huizhou City, Guangdong Province, China, at 23:00, a strong tropical storm inside Guangzhou City at 05:00 o'clock, a tropical storm inside Qingyuan City at 06:00 o'clock, and further weakened into a tropical depression inside Zhaoqing City at 08:00 o'clock. It moved from

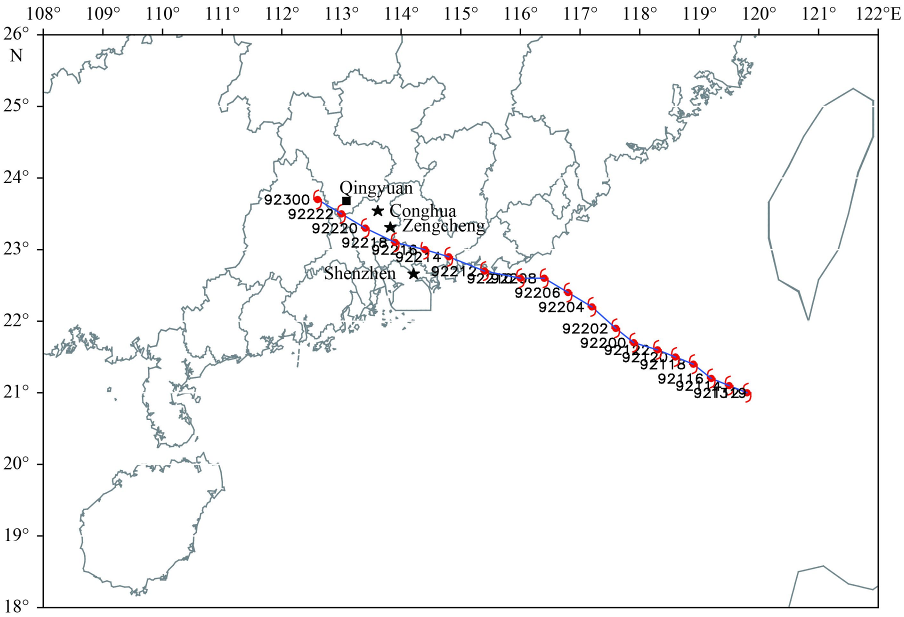

Fig. 1. Path diagram of Typhoon 1319 hour-by-hour (The black star represents the location of wind profiler station, and the black round point represents Qingyuan sounding station. Various hours of the moving path are of UTC; for instance, 92112 represents 12:00 UTC of September 21).

Huaiji County of Zhaoqing City in Guangdong Province to Hezhou City of Guangxi Zhuang Autonomo Region, China at 12:00 o'clock, and further weakened until it disappeared.

3 Data and methods

On the basis of the moving path of Usagi, by combining with the actual working conditions of business wind profilers, three wind profilers set in Shenzhen, Zengcheng and Conghua respectively are chosen since their locations are in the vicinity of the moving path. These three wind profilers are all boundary layer wind profilers (the one set at Shenzhen station is produced by Vaisala of Finland, model: LAP3000; the rest set at Zengcheng and Conghua stations are produced by Beijing Metstar Radar Co., Ltd, model: TWP3). The intervals of wind profile real-time data sampling is 6 minutes. Owing to certain impacts of the rain on the wind profilers, the quality control on the data of the wind profilers is first conducted by adopting the method of Liao et al. (2016). On the basis of this, Fig. 2 also provides comparison diagrams of Qingyuan sounding station and Conghua wind profiler station at 00:00 UTC of September 22 and 23.

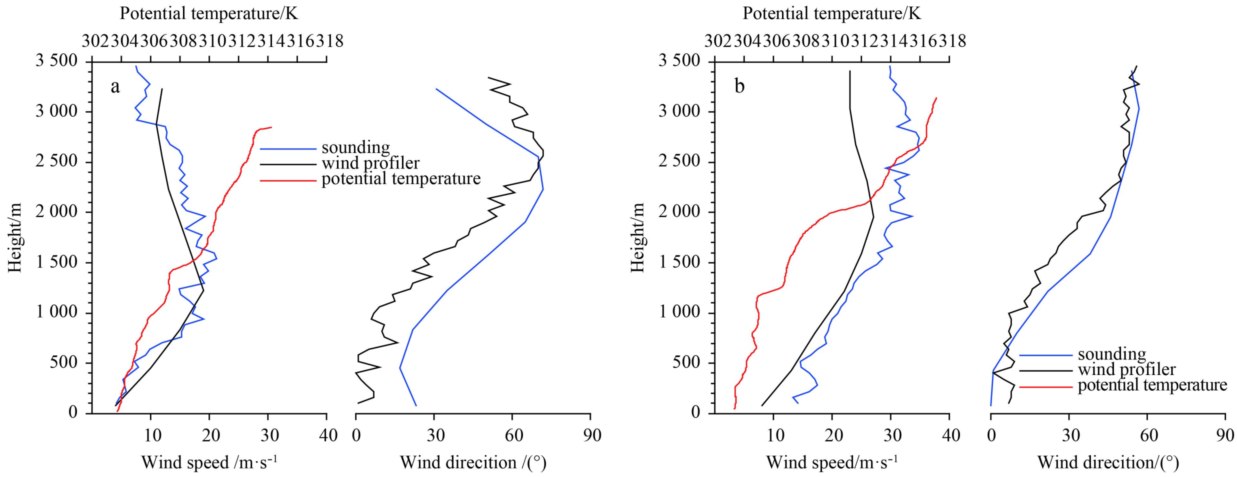

Fig. 2. Comparisons of the wind speeds and directions of Qingyuan sounding station and Conghua wind profiler station at 00:00 UTC (a) and 12:00 UTC (b) of September 22. (The blue solid line represents the sounding data, the black solid line represents the wind profiler data, and the red solid line represents the potential temperature calculated based on the sounding data).

At 00:00 UTC of September 22, Usagi is at 21.7°N, 117.9°E, about 470 km from the Conghua wind profiler station; at 12:00 UTC of September 22, Usagi is at 22.7°N, 115.4°E, about 200 km from the Conghua wind profiler station. At 00:00 UTC of September 22, the Conghua wind profiler station is far from the typhoon center, and the wind speed observed by the wind profiler is quite close to that observed by the sounding, with the maximum wind speed at 1 000–1 500 m, while the wind direction distribution trends observed by the two are also close. At 22:00 UTC of September 22, the Conghua wind profiler station is near the typhoon center, and the wind speed increases with the rising height. In addition, the maximum wind speed (about 30 m/s) increases remarkably, while the height (about 2 km) at which the maximum wind speed appears also gradually lifts. From the comparisons of wind speeds and wind direction distributions of the two periods of time, it is obvious that the observations of the wind profiler and the sounding are quite close. However, due to the longer distance between the two observation stations, and the much rapid change of the path of the sounding balloon during ascending under the conditions of typhoon, there are definitely certain differences between the observations made by the two stations, but it can be generally ascertained that the observational results of the wind profiler are credible.

Owing to the influence of ground friction effects, super geostrophic wind often appears in the typhoon boundary layer, and this is shown in that radial airflows exist in the typhoon boundary layer. To study the characteristics of the boundary layer of typhoon, the method of coordinate rotation is adopted (Fig. 3). The observational data from horizontal U and V wind fields obtained from three wind profiler stations are respectively broken down based on the radial and tangential winds by taking the typhoon center as the dot for coordinate transformation equation:

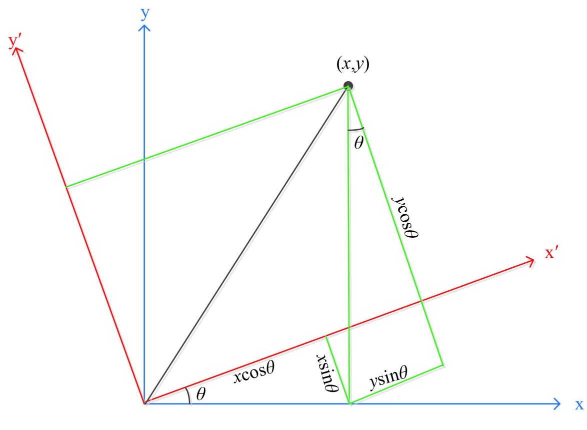

Fig. 3. Schematic diagram of coordinate rotation.

$$x' = x\cos\theta + y\sin\theta, \tag{1}$$

$$y' = y\cos\theta - x\sin\theta. \tag{2}$$

Since the typhoon path is presented by means of hourly positioning data, the wind fields of the wind profilers are broken down hour by hour at each hour. If the radial wind thus resulted in movement towards the typhoon center, it will be the inflow airflow; otherwise, it will be an outflow airflow.

4 Characteristics of typhoon boundary layer

4.1 *Distribution characteristics of tangential airflow*

During the process when Usagi moves toward the northwest, from 12:00 o'clock of September 21 to 15:00 o'clock of September 22, the level of Usagi was a strong typhoon (wind speed exceeds 41.5 m/s); from 15:00 to 20:00 o'clock of September 22, it became a typhoon (wind speed exceeds 32.7 m/s); at 21:00 o'clock, it became a strong tropical storm (wind speed exceeds 24.5 m/s); from 22:00 to 23:00 o'clock, it became a tropical storm (wind speed exceeds 17.2 m/s); from 00:00 o'clock of September 23, it weakened into a tropical depression until it disappears later.

A boundary layer jet stream generally exists within the boundary layer of typhoon. This is an important characteristic of the boundary layer of typhoon, and with the distribution profiles of the typhoon radius, the speed of the tangential wind directly influences the path and strength of typhoon (Ma et al., 2003). Figure 4 shows the sectional views of the heights of different time of the tangential winds of Usagi observed at the three wind profiler stations. It is obvious that there is a distinct field with the maximum wind speed on the periphery of the eye of typhoon. But the vertical distributions of the tangential winds of Usagi observed at different stations have different characteristics, with the maximum wind speeds appearing at heights of 1 500–2 100 m (Conghua station), 2 000–2 700 m (Zengcheng station) and 1 800–3 000 m (Shenzhen station). This observational result is higher than that (400–1 300 m) of Zhang et al. (2009) by using sounding data. In addition, when Usagi maintains the level of a strong typhoon, the heights at which the maximum tangential wind speeds appear observed by the three stations are basically stable (approximately 1 800 m). When the strength of Usagi drops rapidly after landing, the maximum wind speed also obviously decreases correspondingly, and no longer maintains at a certain height.

In addition, the differences of the vertical distributions of the maximum tangential wind speeds observed at the three stations also indicate the asymmetry of the structure of Usagi. When the strength of Usagi drops after landing, the vertical range of the field with the maximum tangential wind speed also gradually decreases, and this is shown in that the tangential wind speed at the back of the moving path is obviously weakened compared with that at the front.

4.2 *Heights and variations characteristics of typhoon boundary layer*

The wind profilers obtain a set of wind vertical profiles every 6 min, and horizontal wind fields of various heights are broken down based on the radial wind and the tangential wind accordingly to get the time-height distributions of radial winds of the typhoon observed by the stations (Fig. 5). Meanwhile, the corresponding heights of the boundary layer are also given based on the maximum value or gradient of SNR. Conghua station is near Qingyuan sounding station. Figure 5 shows the heights of the boundary layer defined by the Richardson number (R_i>0.25) calculated by the sounding data at Qingyuan station; in addition, the thickness of the mixed layer can also be estimated by the vertical profiles of the potential temperature given by Fig. 2 (reaching the lowest height of $d\theta/dz \geqslant 3$ K/km).(Zeng et al., 2004)

At 00:00 UTC of September 22, the height at which the maximum wind speed appears is 1 200 m (Fig. 2a), and the height of inflow layer is around 1 500 m, basically consistent with the height of boundary layer determined by the Richardson number; the height of boundary layer determined by the SNR or its gradient is around 1 200 m, and it's obvious that the gradients only change slightly under 1 400 m from the vertical distributions of potential temperature (Fig. 2a). At 12 UTC, the height at which the maximum wind speed appears lifts slightly, and is 1 900 m based on the observations of Conghua wind profiler, while the maximum height of the inflow layer can reach 1 800 m; but the

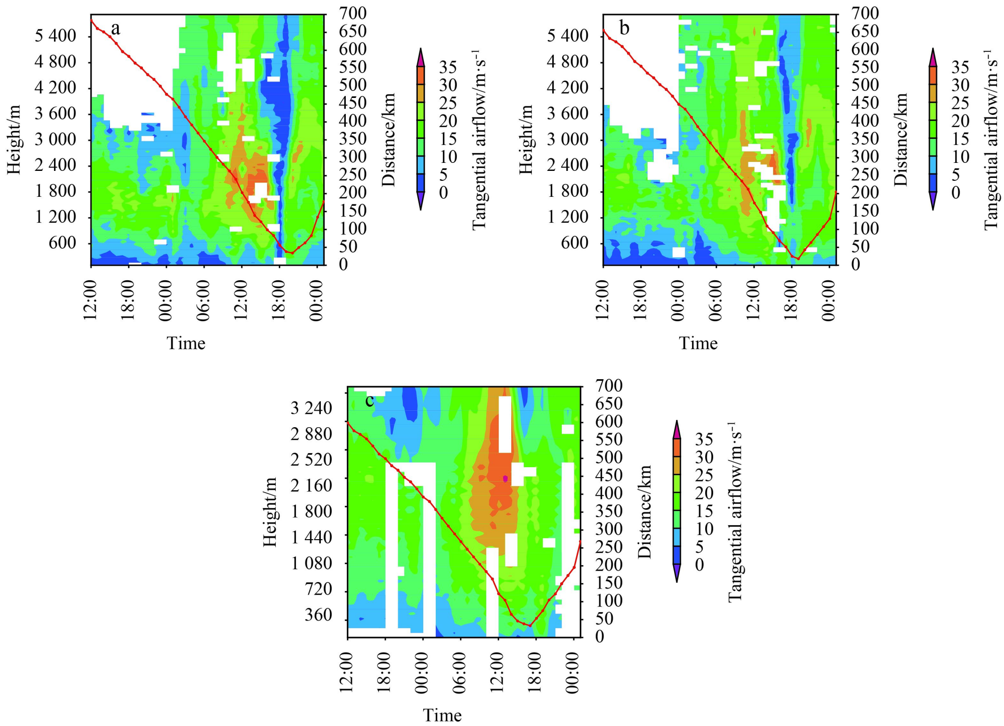

Fig. 4. Distributions of tangential airflows of Conghua (a), Zengcheng (b) and Shenzhen (c) over time. (The counterclockwise one represents a positive value while the clockwise one represents a negative one.)

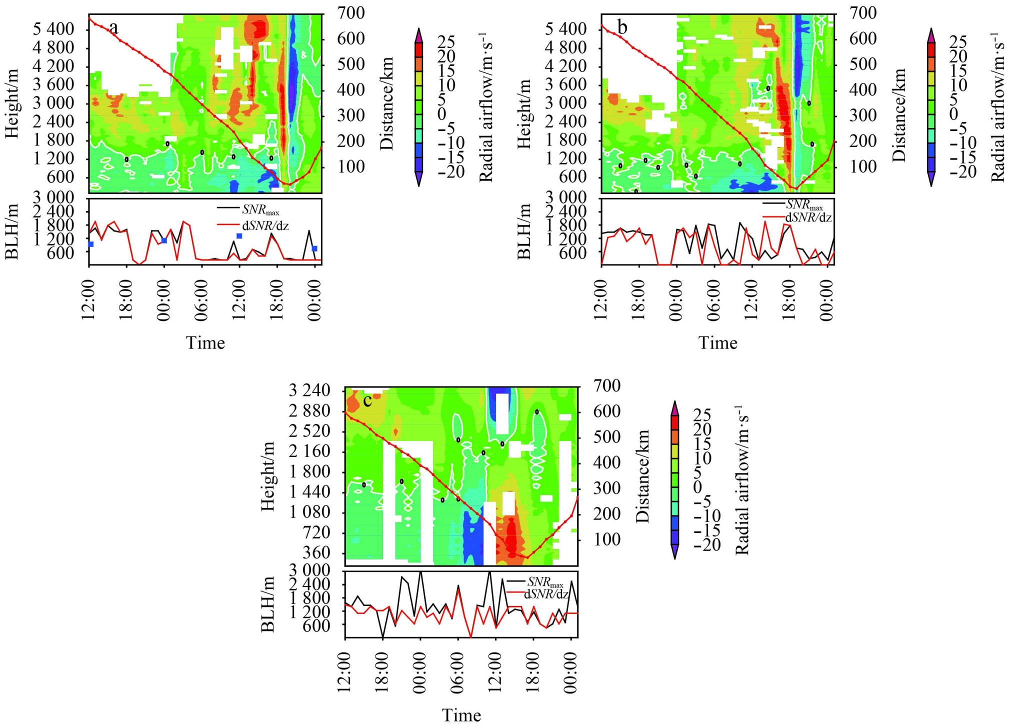

Fig. 5. Distributions of the radial airflows of Conghua (a), Zengcheng (b) and Shenzhen (c) (a negative value represents the inflow while a positive one represents the outflow) over time. Distributions of the boundary layer heights (BLH) based on the wind profiler SNR or SNR gradients; the red dot solid line represents the distance between the station and the eye of typhoon; Conghua station also provides the Richardson number (R_i) calculated by utilizing the sounding data obtained from Qingyuan station (00:00 and 12:00 UTC), and it will be the boundary layer height if R_i>0.25 (the blue square point).

height of boundary layer based on the Richardson number is around 1 200 m (Fig. 2b also shows that the gradients only change slightly under 1 200 m), and is only 300 m based on the SNR or its gradient. Therefore, the boundary layer heights of typhoon determined by different judgment methods are different. However, the results of judgments based on the height of the maximum wind speed and the height of the inflow layer top are very close, and those based on the Richardson number or gradient variations of the potential temperature are also close, but the boundary layer height determined by SNR or its gradient is often low (therefore, SNR mostly reflects the maximum height of the mixed layer, and the maximum height of the inflow layer is bigger than the height of the mixed layer (Kepert et al., 2016)). Thus, it is rather suitable to adopt the inflow layer top to determine the height of boundary layer of typhoon.

Since the wind profilers can continuously obtain vertical observational data of high temporal and spatial resolutions (the interval is 6 min, and the vertical distance is 60 m), the research of the boundary layer heights of the typhoon is provided with excellent data. Usagi has subsequently blew through Shenzhen Station (coastal area), Conghua and Zengcheng Stations (inland), and Fig. 5 shows that the characteristics of the boundary layer heights of the typhoon reflected by these two types of stations are also different.

During the course when Usagi moves toward northwest, Shenzhen Station is first affected. From Figs 1 and 5c, it can be seen that when the distance between Shenzhen station and the eye of typhoon is within about 170 km, only outflow airflows exist; when it exceeds 170 km, only inflow airflows exist; when it is between 170 and 250 km (07:00–11:00 UTC of September 22), the height of the inflow layer top reaches 2 100 m; and when it exceeds 250 km, the height of the inflow layer top fluctuates between 1 200 and 1 600 m.

For Conghua and Zengcheng Stations, the characteristics of the boundary layer and inflow layer of the typhoon observed by the inland stations are different. Before 18:00 UTC of September 22, the heights of the inflow layer top observed by the two stations are at least 1 200 m, and the height of the inflow layer top observed by Conghua station is obviously between those observed by Zengcheng and Shenzhen stations.

Therefore, when Usagi continues to move toward northwest and approach Guangdong, the height of the inflow layer rapidly drops due to the gradually increased influence of the underlying surface of the land. In other words, it is obvious that: (1) before the typhoon lands, its boundary layer height can reach higher than 2 100 m; (2) before landing, the boundary layer height of the typhoon does not change dramatically along with the change of radius; (3) after landing, with the decreasing of the strength of the typhoon, the outflows of the boundary layer takes a leading position, and the boundary layer height of the typhoon drops rapidly; and (4) outflow airflows are rather obvious at the typhoon center, and the outflow layer is quite thick.

5 Conclusions

Understanding the characteristics of the boundary layer of the typhoon is a crucial factor in enhancing the capacity of a typhoon numerical model. On the basis of the observational data of continuous, high temporal and spatial resolutions obtained by the wind profilers, Typhoon Usagi (No. 1319) is analyzed and studied.

(1) According to the results of continuous vertical observations on the wind fields, the maximum tangential wind speed ap-

pears in the vicinity of the eye area of Usagi, and it basically maintains at a height of around 1 800 m at all time when Usagi keeps a strong typhoon level. With the rapidly decreasing strength of Usagi after it lands, the maximum tangential wind speed and its vertical range both decrease.

(2) According to the time-height data analysis on the wind fields observed by the wind profilers, the height at which the maximum tangential wind speed appears is basically close to that of the inflow layer top of the typhoon, and is higher than that of the boundary layer estimated according to Richardson number or potential temperature gradient, while the height of mixed layer based on the SNR or its gradient is usually low. The study by Zhang et al. (2009) also points out that the difference of the boundary layer heights outside the eye of typhoon determined by different judgment methods is quite distinct, but it is rather suitable to adopt the height of the inflow layer to determine the boundary layer height of the typhoon.

(3) Therefore, the height of the boundary layer can reach higher than 2 100 m before Usagi lands. When Usagi is of the typhoon level and above, the heights of the boundary layer observed by various stations do not change much, basically maintaining between 1 200 and 1 600 m. With the decreasing strength of Usagi after it lands, the boundary layer height rapidly drops.

At present, during parameterization of the boundary layer height of the typhoon in typhoon model, it is usually set to gradually increase with the enlarging radius of the typhoon, with the maximum wind speed existing in the range of 1.0–1.5 km around the eye area (for instance: Franklin et al., 2003). This is somewhat different from the observations on Usagi. However, the radial wind and tangential wind of the typhoon obtained in this article are based on the breakdown of the horizontal *U* and *V* wind components on the assumption that the typhoon is circular. This will lead to certain differences between the results of breakdown and the actual situation. Therefore, it is necessary to use more observational cases to study and verify the observational characteristics of the boundary layer of typhoon.

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