Field measurements of Tropical Storm Aere (1619) via airborne GPS-dropsondes over the South China Sea

J. Y. Fu¹ | Z. R. Shu² | Q. S. Li³ | P. W. Chan⁴ | K. K. Hon⁴ | Y. C. He¹

¹Joint Research Center for Engineering Structure Disaster Prevention and Control, Guangzhou University, Guangzhou, China
²Department of Civil Engineering, University of Birmingham, Birmingham, UK
³City University of Hong Kong, Hong Kong (SAR), China
⁴Hong Kong Observatory, Hong Kong (SAR), China

Abstract

In the past two decades, Global Positioning System (GPS)-dropsonde has been developed as an effective tool to explore the internal structures of tropical cyclones (TCs). To facilitate the short-term forecasting of the TCs' intensity and track over the Hong Kong Flight Information Region (HKFIR), Hong Kong Observatory (HKO) launched in 2016 reconnaissance campaigns by using airborne GPS-dropsondes. On October 7, 2016, when Tropical Storm Aere (1619) got close to Hong Kong, 10 dropsondes were released from a reconnaissance aircraft at 10 km altitude to sample the TC at different storm-relative positions. This offers a valuable opportunity to examine the functional performance of the dropsonde system. In the study, the validity of dropsonde measurements is first examined, mainly by comparing the results with those collected contemporaneously by radiosonde balloons from a nearby station. Observational results of the structural characteristics are then discussed. Evidence was observed for the invasion of the storm's inner structure by background atmosphere, which was unfavourable for the intensification of Aere in the following time. Meanwhile, a height-resolving model of the TC's pressure field is proposed. It is also observed that the parachutes of two dropsondes failed to deploy during the descending period. The results presented here are expected to provide useful information for a better understanding of the in-situ measurements from dropsondes deployed over the HKFIR, and for advancing the knowledge on TC's inner structure.

KEYWORDS
airborne reconnaissance, GPS-dropsonde, Hong Kong Observatory (HKO), tropical cyclone

1 INTRODUCTION

Tropical cyclones (TCs) are one of most destructive natural phenomena in the world. To better facilitate the prevention and control of TC-related disasters, it is of great importance to explore TC characteristics as far as possible. During the last decades, continuous efforts have been made on this topic, based on ever-developing instruments. A majority of these studies rely on conventional observation equipment, such as ground-based meteorological masts/towers (Cao et al., 2009; Song et al., 2012). Researchers have also investigated TC features and
associated effects on civil structures with the help of structural health-monitoring systems established on high-rise buildings or long-span bridges (Li et al., 2020; Wang et al., 2020). However, these instruments can only detect a considerably limited portion of a TC. In this regard, remote-sensing devices (e.g., Doppler radar/lidar/sodar wind profilers) and radiosonde balloons have been increasingly adopted (He et al., 2018, 2020).

Global Positioning System (GPS)-dropwindsonde (or dropsonde for short) has been developed as an effective tool to explore the internal structures of TCs since its debut in the 1990s (Hock and Franklin, 1999). It has some overwhelming advantages against the aforementioned instruments. First, it allows flexible deployment at targeted storm-relative positions and different evolution stages of a TC, making it feasible to detect TCs strategically and systematically. Second, GPS-dropsondes can offer high-fidelity and high-resolution (along height) samplings of the inner structure of a TC (Hock and Franklin, 1999), which facilitates the resolving of detailed TC characteristics within a wide portion of the TC's depth.

Owing to the above features, GPS-dropsondes have been used extensively in TC surveillance campaigns to support operational weather forecasting and meteorological research. The earliest routine deployment of GPS-dropsondes started in 1997 from US hurricane reconnaissance aircraft (Aberson, 2010), with the vast majority of the devices released above the Atlantic TC basin and a small number above the eastern and central North Pacific basins. In 2002, researchers in Taiwan initiated the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSAR) experiment (Wu et al., 2007). Several reconnaissance missions were also conducted in the west Pacific Ocean (Aberson, 2011). Based on the collected data sets, typical TC characteristics have been analysed, including the surface wind factor (Franklin et al., 2003), air–sea interaction (Powell et al., 2003), low-level-jet of wind profiles (Kepert, 2006a, 2006b; Vickery et al., 2009; Giammanco et al., 2013), TC boundary layer depth (Zhang et al., 2011), TC outflow and warm core structures (Komaromi and Doyle, 2017), and so on. GPS-dropsonde data have been also used to improve the forecasting accuracy of TC track and intensity (Rappaport et al., 2009; Chen et al., 2013; Doyle et al., 2017). Comparison studies conducted by Wu et al. (2007) showed that the assimilation of GPS-dropsonde data could lead to an improvement of 22% in 72 hr average track forecasts.

Southeast China is located in a TC-prone region. The TCs can result in severe casualties and economic losses every year in this area. Currently, detections of the TCs in this region have been conducted mostly via ground-based instruments, while TC surveillance via aircraft is still limited (Chan et al., 2011, 2014). To facilitate the short-term forecasting of the TCs' intensity and track over the Hong Kong Flight Information Region (HKFIR), Hong Kong Observatory (HKO) in 2016 started to launch surveillance experiments by using airborne GPS-dropsondes, which was the first time a member of the Typhoon Committee of the World Meteorological Organization (WMO) had conducted routine typhoon surveillance using GPS-dropsonde over the South China Sea. On October 7, 2016, when Tropical Storm Aere (1619) got close to Hong Kong, a surveillance experiment was conducted on the storm. This offered a valuable opportunity to examine the functional performance of the GPS-dropsonde system.

In the study, the validity of collected GPS-dropsonde measurements is first examined. Observational results of Aere’s inner structure are then discussed. The results presented are expected to provide useful information for a better understanding of the in-situ measurements from GPS-dropsondes deployed over the HKFIR, and for advancing knowledge about the TC’s inner structure, especially at middle and upper TC depths.

2 | EXPERIMENT AND DATA SETS

2.1 | Tropical Storm Aere and the positions of the released dropsondes

Aere is the 19th TC storm that has developed over the western North Pacific (WNP). As shown in Figure 1, it formed as a tropical depression to the east of Dongsha on the afternoon of October 5, 2016. It then moved across the Luzon Strait and entered the northeastern South China Sea the next day, where it intensified into a tropical storm. After crossing the sea south of Dongsha in the early morning of October 7 Aere slowed down and drifted

FIGURE 1  Best crack of Aere (1619) issued by Hong Kong Observatory (HKO)
northwards during the day, reaching its peak intensity in the afternoon (10 min mean wind speed estimated to be 23.6 m\(\text{s}^{-1}\)).

The HKO deployed the reconnaissance campaign at the end of October 6. Between 0000 and 0200 UTC on October 7, 10 GPS-dropsondes were released successively at varied storm-relative positions from the flight level, that is, 10 km above mean sea level (AMSL). The satellite cloud snapshot captured at 0000 on October 7 and the positions of the launched dropsondes are shown in Figure 2, where the initially released locations of the dropsondes are marked by numbers 1–10. The solid square and solid circle in the zoom-in plot denote Dongsha and Haikou stations, respectively. Both stations are equipped with radiosonde balloons for detecting the upper atmosphere. In the study, the results from Dongsha station are used to examine the functional performance of the GPS-dropsonde through a comparison analysis, while those at Haikou station are adopted to provide reference information of the background environment for Aeré.

According to the best track records issued by the HKO, Japanese Meteorological Agency (JMA) and National Oceanic and Atmospheric Administration (NOAA), the geographical co-ordinates of Aeré’s centre at 0000 and 0600 on October 7 were [20.6°/20.4°/20.5° N, 116.4°/116.4°/116.5° E] (HKO/JMA/NOAA) and [20.7°/20.7°/20.6° N, 116.2°/116.0°/116.4° E], and the contemporary central pressures were 990/992/993 and 988/985/985 hPa, respectively. Based on the above information, it is thought that the location of the TC’s centre at 0000 on October 7 was [20.5° N, 116.4° E], whilst the contemporary translational speed and central pressure of the storm were 1.41 m\(\text{s}^{-1}\) and 991 hPa, respectively. It is stressed that the information of the TC’s centre location plays an important role in determining the storm-relative positions of the released dropsondes. Unfortunately, owing to the absence of related measurements, the accurate determination of such information is unavailable for the study. However, based on the best track data issued by different meteorological organizations, as introduced above, the location error should be < 12 km.

Figure 3 depicts the radial distance of each dropsonde from the TC’s centre during the descending period. For convenience, distances for dropsondes 1–6 are marked as positive, while those for the other dropsondes are marked as negative. Table 1 gives detailed information on the release times and release positions for the dropsondes. As shown, dropsonde 6 was selected to be released above the TC’s centre; the radial distance for this dropsonde was 11–19 km.

### 2.2 Introduction of the data sets

Typically, a GPS-dropsonde mainly consists of a GPS receiver to derive information on horizontal wind speed and direction, and sensors for measurements of pressure, temperature and humidity. It is usually released from a reconnaissance aircraft. As the dropsonde descends, it
relays the sampling data to the aircraft by radio transmission until hitting the Earth’s surface.

The dropsonde adopted in the study belongs to the Vaisala RD94 type, whose weight is 350 g. It samples the atmosphere at 0.25 s intervals for wind measurement and at 0.5 s intervals for temperature, pressure and humidity. On average, the dropsondes dropped at a speed of approximately 13 m·s⁻¹ and lasted for about 12 min before hitting the sea surface. During the descent, the dropsondes drifted both tangentially and radially with the TC’s winds. The maximum drifting distance was approximately 10 km. The measurement information archived automatically by the dropsonde system includes approximately 10 km of wind measurement; and (2) comparing the measurement results from dropsondes with those from radiosonde balloons released at Dongsha station (Figure 2).

Three key parameters were recalculated, that is, horizontal wind speed (U), direction (θ) and relative humidity (RH), via the following equations:

\[
U = \sqrt{U_\phi^2 + U_\lambda^2}, \quad U_\lambda = \frac{d\lambda}{dt} \cdot R\pi/180, \quad U_\phi = \frac{d\phi}{dt} R \cos(\lambda)/180
\]

\[
\theta = \begin{cases} 
\arccos(U_\phi/U), & \text{for } U_\lambda \geq 0; \\
360 - \arccos(U_\phi/U), & \text{for } U_\lambda < 0.
\end{cases}
\]

\[
RH = 100 \cdot \exp\left(\frac{17.625 T_d}{243.04 + T_d} - \frac{17.625 T}{243.04 + T}\right)
\]

where φ, λ are the longitude (φ) and latitude (λ) co-ordinates (°); U_φ, U_λ are the speed components owing to the variation of latitude and longitude; t is time (s); R is the radius of the Earth; and \(\text{mod}(A, B)\) means the modulus of A after division by B (A and B are two real numbers). This operation aims to convert the geometric angle θ obtained mathematically to wind direction θ. Note that θ is defined as θ′ for a wind blowing from the north and as 90° for a wind blowing from the east; while θ′ is defined as an angle anticlockwise from the line pointing to the east. RH (%) was computed via the August–Roche–Magnus approximation (Alduchov and Eskridge, 1996), based on the measurements of dry-bulk temperature (T) and dew point (T_d).

### Table 1: Information about the launched Global Positioning System (GPS)-dropsondes

| No. | Starting launching | Ending receiving |
|-----|-------------------|------------------|
|     | Time (UTC)        | Latitude (°)     | Longitude (°) | Distance (km) | Time (UTC)        | Latitude (°) | Longitude (°) | Distance (km) |
| 1   | 00:42:38          | 21.97158         | 117.0232     | 176           | 00:55:09        | 22.00253      | 116.9184     | 165           |
| 2   | 00:53:40          | 21.50862         | 116.9922     | 128           | 01:01:24        | 21.5454       | 116.941      | 129           |
| 3   | 01:01:38          | 21.00011         | 116.9953     | 83            | 01:14:36        | 21.0828       | 116.9386     | 86            |
| 4   | 01:12:40          | 21.5048          | 116.4881     | 112           | 01:24:30        | 21.52678      | 116.401      | 114           |
| 5   | 01:20:22          | 20.99815         | 116.4917     | 56            | 01:32:44        | 21.04616      | 116.3717     | 61            |
| 6   | 01:25:50          | 20.49997         | 116.503      | 11            | 01:37:56        | 20.59991      | 116.5521     | 19            |
| 7   | 01:31:17          | 20.49212         | 115.9901     | 43            | 01:43:37        | 20.42829      | 116.0807     | 34            |
| 8   | 01:37:06          | 19.97486         | 116.0006     | 72            | 01:49:33        | 19.95685      | 116.0744     | 69            |
| 9   | 01:44:05          | 19.49526         | 115.4943     | 146           | 01:56:49        | 19.47062      | 115.5305     | 146           |
| 10  | 01:50:30          | 20.0042          | 115.5003     | 119           | 01:57:59        | 19.97805      | 115.5297     | 107           |

*All times are for October 7, 2016.

*Distance denotes that between a dropsonde and the tropical cyclone’s centre.*
Figure 4 compares the recalculated and automatically generated results. Basically, the two results show good agreement. It should be noticed that due to the absence of time information at some altitudes for some profiles, the results of recalculated $U$-values contain several spikes. By contrast, the results of the autogenerated RH suffer from a series of unrealistic breakpoints. Therefore, the records of $U$ and $\theta$ automatically generated by the dropsonde system and the recalculated RHs will be adopted in the following analysis.

Figure 5 compares the measurement results from dropsonde 5 and a balloon released about 1 hr ahead of the dropsonde at Dongsha station. The horizontal distance between the two devices was 40 km. Measurements from the two devices show good agreement for $T$ and $T_d$. For wind measurements, the results differed more evidently, mostly owing to the discrepancy of the released positions between the dropsonde and the balloon, as well as the large gradient of the wind field in the TC’s inner region. Despite these differences, the profiles of $U$ from the two devices agree with each other in a large portion of the observed depth. In sum, the comparison results reflect the credibility of the collected measurements from the dropsondes.

4 | RESULTS AND DISCUSSION

4.1 | Thermodynamic characteristics

Figure 6 depicts the vertical profiles of temperature ($T$) and potential temperature ($\theta$) for the storm. Also
presented are the ensemble-mean results from Haikou station (denoted as “Ref”) which are computed based on balloon sounding records during the first one-third of each October between 1981 and 2010 (http://www.nmic.cn/data/detail/dataCode/B.0011.0001C.html). As the TC's centre was situated at a consistent latitude with Haikou station during the studied period (Figure 2), the results from this station are used to account for the background environment. The \( \theta \)-values are computed based on measurements of \( T \) and \( P \):

\[
\theta = T \left( \frac{P_0}{P} \right)^{\frac{R}{C_P}}
\]

where \( P_0 \) (\( \approx 1,010 \) hPa) denotes the sea-level atmospheric pressure; \( R \) (\( = 8.314 \text{ J mol}^{-1} \text{ K}^{-1} \)) is the universal gas constant; and \( C_P \) is the specific heat capacity (\( R/C_P = 0.286 \)).

As demonstrated, the ensemble-mean atmospheric temperature decreased almost linearly with the increase of altitude. The lapse rate \( (\mu) \) below 7 km was 5.1 K km\(^{-1} \), compared with that of 6.3 K km\(^{-1} \) at the upper portion (i.e. 7–10 km) and the mean of 5.4 K km\(^{-1} \) throughout the whole detection range. On the other hand, the ensemble-mean \( \theta \)-values increased linearly with increasing altitude, with a rate of 5.0 K km\(^{-1} \).

From the results of dropsonde 6 (around the TC's eye), the atmospheres in the range of 1.5–4.0 km were distinctly warmer than those associated with other dropsondes, which reflects the warm-core feature of the TC. Meanwhile, there was an inversion layer of \( T \) at about 1.5 km, beneath which the profiles varied insignificantly among different dropsondes. Note that the inversion layer at low altitudes has been reported as a typical feature of the TC's structures (Aberson, 2010). By contrast, the atmospheres in a range of 5.0–6.5 km associated

**FIGURE 5** Comparison of measurements from dropsonde 5 and a contemporaneously released balloon at Dongsha station: (a) wind measurements; and (b) dry-bulb temperature and dew point

**FIGURE 6** Vertical profiles of atmospheric temperature (a) and potential temperature (b)
with dropsonde 6 were even colder than the others. As to be further demonstrated, this is due to the effects of wind shear which steered colder background flows to invade the TC’s inner region. Atmospheres in the range of 6–8 km detected by dropsonde 4 were distinctly warmer than the others. In the following, it will be shown that atmospheres at this area were dominated by intense convections through which warmer and meanwhile more humid flows at a lower portion were transported to upper altitudes.

Figure 7 presents the results of the RH in forms of vertical profile and filled contour plot. The atmospheres beneath the inversion layer (about 1.5 km) are found to be considerably humid (ensemble-mean RH = 90%), regardless of the storm-relative positions of the released dropsondes. Between 1.5 and 4.0 km, as dropsonde 6 was located around the TC’s centre, atmospheres there were distinctly drier than those associated with other dropsondes or the background environment (i.e. “Ref”). However, the results in range of 6–8 km from this dropsonde suggest the atmospheres in Aere’s most inner region were more humid than the background atmosphere. There are two potential reasons for this strange phenomenon, both of which are closely related to the wind-shear effects of the background environment. First, the TC’s centre was twisted vertically by environmental wind-shear, and dropsonde 6 was located closer to the TC’s eyewall or the inner end of the primary rainbands in a range of 6–8 km. Second, the TC’s centre was invaded by a relatively more humid background environment. Actually, Figure 2 provides visual evidence for the existence of significant wind shear for Aere, in which the TC’s cloud seems to be steered northwards with respect to the TC’s centre. By contrast, the RHs from dropsondes 3, 9 and 10 at upper altitudes were much smaller. From Figure 2, all these dropsondes were released at a cloudless position just beyond the main body of the TC’s cloud.

Results from observational studies have shown that atmospheres in such peripheral areas are dominated by downward (therefore, hot and dry) flows that outflow from the TC’s inner region (He et al., 2020).

Figure 8 exhibits the results of equivalent potential temperature $\theta_e$, which denotes the potential temperature that a parcel would reach if all involved water vapour were condensed and rained out by raising the parcel upwards and then lowering it to the mean sea level adiabatically. This quantity is more conserved than potential temperature in the case with changes of air pressure, as the effects of water vapour and phase change have been further taken into account. In the study, the method recommended by Bolton (1980) is adopted to calculate $\theta_e$. Figure 8 also depicts the results of $\Delta \theta_e$, which is defined as the contrast in $\theta_e$ between the TC’s atmosphere and the background environment. Here, a positive $\Delta \theta_e$ means the TC’s atmosphere had a larger $\theta_e$ than the background environment. This parameter is widely adopted to investigate the warm-core feature of the TCs.

Overall, the TC atmospheres were distinctly warmer than the background environment. The maximum $\Delta \theta_e$ was measured as 19 K at 3 km from dropsonde 4. However, the maximum $\theta_e$ and $\Delta \theta_e$ observed were noticeably smaller than those for other TC events (e.g. He et al., 2019b, 2020), which can be well explained by the weak intensity of Aere. Meanwhile, the results of $\theta_e$ collectively demonstrate a trend that $\theta_e$ first increased and then decreased along with altitudes. Despite such common features, the details associated with varied profiles differed markedly.

First, the results from dropsonde 6 reveal that $\theta_e$ around the TC’s centre was abnormally smaller than those in other areas. In consideration of the fact that the $\theta_e$-values at some portions of this profile were comparable with those of the background environment, it is reasonable to speculate that environmental flows had
invaded the inner core of Aere. More specifically, results shown in Figure 8b,d suggest that environmental flows invaded Aere from the southern sector of the storm, mostly in the range of 5–8 km. The colder and, therefore, heavier environmental flows tended to sink as they invaded inward. Because atmospheric density was lightest at the TC's centre, the invasion extended most downward at this area (dropsonde 6). Apparently, such invading flows would be unfavourable for the intensification of the storm.

Second, for the results from dropsonde 4, $\theta_e$ decreased sharply in the region of 3–5 km, while the values in other portions almost remained unchanged (about 355 K). Meanwhile, the $\theta_e$-values in the ranges of 1–3 and 6–8 km from this dropsonde were distinctly larger than those from other dropsondes. Previous studies (e.g. He et al., 2020) have shown that profiles of $\theta_e$ at different radial distances with respect to the TC's centre possess different trending features. While those at more peripheral regions demonstrate a similar pattern to that of the background environment, the one around the eyewall tends to be distributed as a straight line along altitude (i.e. $\theta_e$ remains unchanged), which suggests atmospheres at such intense-convection featured zones tend to ascend adiabatically. Thus, it is more likely that the atmospheres in the ranges of 1–3 and 6–8 km associated with dropsonde 4 were dominated by intense convection in Aere's inner region. This speculation is further supported by the results the of vertical wind speed, which will be demonstrated in the following section. On the other hand, the portion below about 6 km associated with dropsonde 4 should be influenced more significantly by the invading flows, which resulted in the decrease of $\theta_e$ in the range of 3–6 km.

It is emphasized that TC intensity depends upon many factors, including sea-surface temperature, the translational speed of the storm, interactions of the TC's internal structures, and so on, besides environmental wind shears that are discussed herein. Till now, it has been challenging to predict a TC's intensity accurately. Actually, a comparison of the best-track data of Aere issued by different meteorological organizations reveals that there are evident discrepancies of the TC's intensity among varied sources. According to the information issued by the HKO, after two days' development, Aere intensified from a tropical depression into a tropical
storm at 0000 on October 7, with the central pressure estimated at 990 hPa. It then reached the peak intensity at 0600 with the central pressure estimated as 988 hPa, which lasted for 24 hr. After that, it started to decay consistently. Thus, Aere had almost not intensified further after the observational period (during which the central pressure of the storm was estimated as about 989 hPa via interpolation). This is consistent with the unfavourable effects of the invasion of the storm by environmental flows, as discussed above.

4.2 Pressure field

The vertical profiles of atmospheric pressure \( P \) and the pressure deficit \( \Delta P \) of the TC’s atmosphere compared with the environment are shown in Figure 9. The environmental pressure is calculated via Equation 1, rather than using the reference records at Haikou station, as there are only a few pressure level records available from this site. As reflected in Figure 9, the barometric formula (“Fit”) is found to fit the measurements well:

\[
P(z) = P_0(1 - \mu z/T_0)^{gM/g\mu}
\]  

where \( T_0 \) (≈300 K) is the atmospheric temperature at mean sea level; \( \mu \) is the lapse rate of temperature; \( z \) denotes altitude; \( g \) (= 9.807 m s\(^{-2}\)) is the acceleration of gravity on the Earth’s surface; and \( M \) (= 0.02896 kg mol\(^{-1}\)) is the molar mass of dry air.

It is also observed that \( \Delta P \) becomes insignificantly small above about 5 km (550 hPa). To explore the detailed characteristics of \( \Delta P \), Figure 10a shows the vertical profiles of this parameter. As reflected, \( \Delta P \) increased almost linearly with the increase of barometric altitude:

\[
\Delta P(z) = \Delta P_0 - k \cdot P(z)
\]  

where \( \Delta P_0 \) denotes the pressure deficit at mean sea level; and \( k \) is the slope of the profile that can be determined by fitting the data via the least-square technique.

Figure 10b examines the correlation between \( k \) and \( \Delta P_0 \). It is interesting to find that the two parameters are linearly correlated with each other:

\[
k = c \cdot \Delta P_0
\]  

where \( c \) is a constant and determined as 0.00223 hr Pa\(^{-1}\) through fitting.

Equations 5–7 provide an empirical model for the vertical profile of the TC’s pressure deficit, which can be used to generate a two-dimensional TC pressure field model in conjunction with an existing radial profile model, for example, that proposed by Holland (1980). This is of great interest for developing height-resolving models for TC wind fields (Snaiki and Wu, 2017; Fang et al., 2018; He et al., 2019a). It is noted that the profile model of \( \Delta P \) depicted by Equation 6 differs slightly from that documented in He et al. (2019a, 2019b). Here, \( \Delta P \) is quantified as a function of barometric height, that is, \( P(z) \), compared with that for of altitude (m or km) in He et al. The reason for this discrepancy is twofold. First, the environmental pressure in He et al. is computed based on long-term pressure records at the study site, while that in the study is determined by using Equation 5. Second, as discussed previously, Aere was invaded by environmental flows at the upper portion of the TC’s depth. As a result, \( \Delta P \) tended to decrease more significantly along a height at middle and upper altitudes compared with the cases in He et al., which are associated with much stronger TC events.
4.3 Horizontal wind

Results for horizontal wind speed ($U$) and direction ($\theta$) as well as the corresponding radial ($U_{\text{rad}}$) and tangential ($U_{\text{tang}}$) wind components are depicted in Figure 11. Here a negative $U_{\text{rad}}$ means the TC’s atmosphere flows toward the TC’s centre. Because the vertical profile of Aere’s centre is unavailable, a fixed co-ordinate of the TC’s centre from the best track data is adopted when computing $U_{\text{rad}}$ and $U_{\text{tang}}$.

From Figure 11b, the wind direction varied sharply around the TC’s centre, which is consistent with expectations. However, the results in Figure 11a demonstrate that the strongest TC winds (27 m·s$^{-1}$ at 6 km) existed around the TC’s centre. Although this abnormal phenomenon may be partially explained by environmental wind shear, specific reasons still remain unclear. In reference to the radial wind component, results from dropsondes 5–7 show that $U_{\text{rad}}$ exceeded 20 m·s$^{-1}$ in the range of 4–7 km above Aere’s most inner region. Meanwhile,
results from the middle portion of the profiles associated with dropsondes 5 and 7 indicate the TC's atmosphere was respectively dominated by extremely strong inflowing winds and outflowing winds at these zones. Again, it is still unclear whether such findings are artificially caused by using inaccurate information for the TC's centre when computing \( U_{rad} \) and \( U_{tang} \), or if they were physically induced by the invading environment.

To examine the turbulent characteristics of horizontal wind speed, the vertical profile of \( U \) is stratified into 50 bins along heights at 200 m intervals, with each bin containing about 10 samplings. The bin wind turbulent intensity \( T_{I_b} \) is then defined as the ratio of the standard deviation \( \sigma_b \) to the bin-mean speed \( U_b \). The equivalent turbulent intensity \( T_{I_e} \) for each TC wind profile is then defined as the median of \( T_{I_b} \). In consideration of the non-stationary features of the TC's wind, \( T_{I_b} \) and \( T_{I_e} \) are computed via two methods which are based on originally collected wind profile records (Method 1) and the high-pass-filtered records (Method 2). The empirical modal decomposition (EMD) technique (Huang et al., 1998) is adopted for the filtering process involved in Method 2. This technique has the merit of self-adaption for non-stationary signals. Through the EMD manipulation, the original signal can be decomposed into a group of intrinsic model functions (IMFs). In the study, only the first three IMFs are selected and combined to create the high-pass-filtered profile. By doing this, the trending components involved in each profile can be well removed.

Figure 12 depicts the results of \( T_{I_b} \) and \( T_{I_e} \), where \( T_{I_b} \) is calculated on the basis of filtered speed profiles, while \( T_{I_e} \) is computed via the aforementioned two methods. In Figure 13a, the two ends of the error bar stand for the 25th and 75th percentiles, while the markers denote 50th percentiles, or \( T_{I_e} \). These results reveal that \( T_{I_e} \) in the TC's most inner region (roughly within 90 km from the TC's centre) was generally smaller than that in relatively outer areas, and the \( T_{I_e} \) values for the strongest winds were in the range of 1–3%. There were two large \( T_{I_e} \)-featured zones, that is, the zones associated with dropsondes 8–10 and then 4 and 2. As the parachutes of dropsondes 2 and 10 failed to work effectively during the descending period (see the next section), the results of \( T_{I_b} \) and \( T_{I_e} \) from these two dropsondes tend to be less consistent with those from other dropsondes. The situations at these two zones are discussed under the context of dropsondes 8 and 9 (for the first zone, or Zone 1) and dropsonde 4 (for the other zone, or Zone 2), respectively. As discussed previously, Zone 1 was featured by severe invasion of environmental flows. Meanwhile, the wind
strength was overall much weaker. Thus, the atmospheres there were most turbulent in terms of $T_l_0$ and $T_l$. By contrast, the TC’s atmospheres at Zone 2 were featured by intense convections. The results shown in Figure 12 also demonstrate that the $T_l$ computed via the two introduced methods may differ moderately, which further reveals the non-homogeneous and non-stationary features of the TC’s wind.

### 4.4 Falling speed and vertical wind speed

The falling speed of the released GPS-dropsondes $W$, whose positive direction is defined to point upward, consists of two parts: the falling speed in still atmosphere $W_d$ and the vertical wind speed $VV$ (Wang et al., 2009):

$$W = W_d + VV$$

where $W_d$ can be calculated via (Hock and Franklin, 1999; Wang et al., 2009):

$$W_d \approx -\sqrt{2mg/(C_dA\rho)}$$

where $m = 0.350\text{kg}$ is the weight of the adopted GPS-dropsonde; $g (= 9.807 \text{m} \cdot \text{s}^{-2})$ is the acceleration of gravity; $C_d = 0.61$ is the drag coefficient; $A = 0.0676\text{m}^2$ is the projection area of the parachute; and $\rho$ is the air density calculated via:

$$\rho = \frac{P_dM_d + P_vM_v}{RT}$$

where $P_d$ and $P_v$ are the partial pressure of dry air and water vapour, respectively; and $M_d = 0.028964 \text{kg} \cdot \text{mol}^{-1}$ and $M_v = 0.018016 \text{kg} \cdot \text{mol}^{-1}$ are the molar mass of dry air and water vapour, respectively.

The profiles of $W$ and $VV$ are shown in Figure 13. For $W$, the results from dropsondes 2 and 10 differ from the others distinctly in that they suggest a nearly doubled falling speed of the dropsondes with respect to other dropsondes. Apparently, the parachutes of these two dropsondes failed to deploy during the descending period. The results of $VV$ reveal an ensemble-mean upward speed of about 2 m·s$^{-1}$ for the TC’s atmosphere, which is less consistent with one’s expectation. It is still unclear whether this result should be attributed to the convective movement of the TC’s atmosphere or if it might be due to computational errors. Despite the above uncertainties, the results of $VV$ provide useful information to further understand the local characteristics of the TC. Specifically, the large vertical wind speeds in the region of 6–8 km from dropsonde 4 reveal the existence of intense convection at this area, which is consistent with the discussions on the equivalent potential temperature (Figure 8).

### 5 CONCLUSIONS

Routine reconnaissance campaigns for tropical cyclones (TCs) over the South China Sea by using airborne Global Positioning System (GPS)-dropsondes were initiated from 2016. The study presents the preliminary results for a sampled tropical storm, that is, Aere in 2016, based on measurements collected by 10 GPS-dropsondes released at selected storm-relative positions from the flight level. The validity of the collected measurements was examined by comparing the archived records respectively with the recalculated results for some key weather elements and those collected from a radiosonde balloon. The overall good agreement between these results enhances our confidence in the credibility and accuracy of the dropsonde measurements. Meanwhile, observational results also suggest that the parachutes of two dropsondes failed to work during the descending period. Thus, special efforts are required to explore the reasons and to avoid such issues in following campaigns.

In reference to the TC’s structure, several interesting findings have been observed. (1) Both the ensemble-mean profiles of dry-bulb temperature ($T$) and potential temperature ($\theta$) were linearly distributed along altitude. The lapse rate for $T$ was 5.4 K·km$^{-1}$ and the increasing rate for $\theta$ was 5.0 K·km$^{-1}$. (2) The ensemble-mean profile of air pressure was found to follow the barometric formula. More interestingly, the profiles of the TC’s pressure deficit were linear along barometric altitude, with the amplitude of the slope increasing linearly with the increase of the pressure deficit at mean sea level. An empirical model for the vertical profile of the TC’s pressure deficit was established and used to generate a two-dimensional TC pressure field model in conjunction with an existing radial profile model. (3) The background environment can influence the TC’s structure significantly. Severe environmental wind shears could twist the TC’s structure and steer colder atmospheric flows to invade the vortex’s warm core. In the present study, evidence was observed that suggests Aere was invaded by environmental flows. Such findings are consistent with the best track information issued by Hong Kong Observatory (HKO) that Aere stopped intensifying into a stronger storm after the surveillance experiment, even when it moved over a vast area of warm sea.

In consideration of the significant role of the TC’s centre co-ordinates and the thermodynamic characteristics of background atmospheres when analysing the
inner structures of the TCs, it is suggested that corresponding instruments be mounted in the reconnaissance aircraft during the following surveillance experiments.

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ORCID
P. W. Chan DOI: https://orcid.org/0000-0003-2289-0609
Y. C. He DOI: https://orcid.org/0000-0002-6639-5901

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