The Eyewall-Penetration Reconnaissance Observation of Typhoon Longwang (2005) with Unmanned Aerial Vehicle, Aerosonde

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ABSTRACT

In this paper, a successful eye-penetration reconnaissance flight by an unmanned aerial vehicle, Aerosonde, into Typhoon Longwang (2005) and the preliminary analyses of the collected data are presented. The 10-h flight is diagnosed through four flight legs. The wind field measured along flight leg 1 provides the tangential and radial wind profiles from the outer perimeter into the eye of the typhoon at the 700-hPa layer. A vertical sounding was taken in the eye along flight leg 2 and the derived surface pressure in the eyewall is close to the estimates made by the local weather agencies. Along flight leg 3, the strongest winds during the whole flight mission were measured. These in situ wind measurements by Aerosonde are consistent with the winds observed by the Hua-lien Doppler weather radar. The maximum 10-min (1 min) wind along flight leg 3 when Aerosonde was flying around the eyewall region is 58.6 m s⁻¹ (62 m s⁻¹). The maximum sustained surface wind derived from this maximum wind speed is also close to the estimates made by the local weather agencies. In conclusion, this successful mission demonstrates that the Aerosonde with a trained crew can play a role in severe weather monitoring and the Aerosonde’s measurement can serve as an independent check for Doppler radar wind retrieval.

1. Introduction

The in situ measurements of typhoon characteristics, such as the radius of the gale force winds and the minimum central pressure, are important to the study of typhoon dynamics, operational forecasting, and disaster reduction. They can also serve as the ground truth to validate the model simulations or the wind fields retrieved from the Doppler radar observations. From the mid-1970s to September 1987, reconnaissance flights into tropical storms over the western North Pacific to obtain in situ data were carried out continuously by the United States Air Force (USAF) C-130 aircraft fleet based in Guam (Weatherford and Gray 1988). Since 1987 the U.S. National Hurricane Program only focuses on hurricane observations over the eastern Pacific and the North Atlantic using the Air Force C-130 and National Oceanic and Atmospheric Administration (NOAA) P-3 aircraft with dropsonde facility (OFCM 2002; Hock and Franklin 1999). Hurricane reconnaissance flights are costly, and a potential threat to the onboard crew still exits under dangerous conditions. These have motivated several programs to suggest the cheaper but potentially effective solution of using unmanned aerial vehicles (UAVs; Langfold and Emanuel 1993; Bluth et al. 1996).

A small robotic UAV called Aerosonde (Fig. 1) designed by the InSitu Corp. (McGeer and Holland 1993) has been proposed or used recently in the studies of local circulation, thunderstorm environment, and sea surface temperature in the Arctic (McGeer and Holland 1993; Holland et al. 2001; Holland 2002; Lin et al. 2003; Curry et al. 2004; Soddell et al. 2004). The UAV reconnaissance project in Taiwan was started in 1998 under the support of Taiwan’s National Science Council, with the second (first) author as the principal investigator of the first (second) 3-yr phase. A technical group called the Taiwan Aerosonde Team (TAT) led by the first author obtained complete technical transfer from the Aerosonde Ltd. in 1999 regarding the Aerosonde operation. The TAT has performed 12 flights into typhoons from 2000 to 2004 using six Aerosondes (Mark-I version). These six UAVs all crashed in the rainband regions of typhoons and none of them ever penetrated through the eyewall of a typhoon.
phoon. In the winter of 2004, TAT obtained two new Aerosondes (Mark-III version) with Iridium satellite phone communication capability and a stronger engine than that of Mark-I.

On 16 September 2005, an Aerosonde flight was conducted at a 2500-ft height circling around the outer rainband of Hurricane Ophelia over the Atlantic by NOAA and the Aerosonde Ltd.; it measured winds up to 38 m s$^{-1}$ (Rogers et al. 2006). However, no eyewall penetration was performed in this mission. On 1 October 2005, an Aerosonde operated by TAT flew into the inner region of Typhoon Longwang and performed continuous measurements for about 10 h. Overlapping the flight track on the radar reflectivity images indicates that the Aerosonde had penetrated through the eyewall of Longwang—the first successful eyewall penetration by a UAV. This flight provides the environmental information in Longwang—a 3000-m constant height (∼700 hPa) path and a vertical sounding inside the eye. Most importantly, this flight has demonstrated that the Aerosonde can be an effective tool to take in situ measurements of meteorological parameters under severe weather conditions.

In this paper, we describe the Aerosonde reconnaissance flight into Typhoon Longwang in more detail and present the preliminary results of data analyses. In section 2, the characteristics of Aerosonde and the Aerosonde operation in Taiwan are described briefly. The detail flight mission into Longwang is presented in section 3. The preliminary analysis of the in situ measurements in this flight mission is shown in section 4. Finally, section 5 is the discussion and conclusions.

2. Features of Aerosonde and the Aerosonde operation in Taiwan

The Aerosonde is the smallest and simplest platform for weather mission among those surveyed by The Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) at the Naval Postgraduate School in Monterey, California, which operates manned, instrumented research aircraft in support of the science community (Bluth et al. 1996). Table 1 shows the detailed specifications of Aerosonde version Mark-III. The most notable features of the Mark-III version include the 30-h sustainable capability in the air and the Iridium satellite communication. There was also an earlier version of Aerosonde, Mark-I, which we had used before. The major disadvantage of Mark-I was its limited maximum range of very high frequency (VHF) radio communication (only 150 km), which had severely limited our previous field operations. The long-range reconnaissance flight became possible only after 2004 when the Iridium satellite communication module on the Mark-III started to work successfully. The onboard instrument, Vaisala RSS901, is a new fast-response pressure–temperature–humidity (PTU) sensor made by the Vaisala Company (Finland). This sensor is also used in the RS92 balloon radiosonde (Währn et al. 2004), which is widely used in the atmospheric science com-

Fig. 1. A photo of Aerosonde Mark-III taken at Heng-Chun airport, Taiwan.
Table 1. The specifications of Aerosonde Mark-III.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing length</td>
<td>3 m</td>
</tr>
<tr>
<td>Weight</td>
<td>13 kg</td>
</tr>
<tr>
<td>Engine</td>
<td>24 cc unleaded petrol</td>
</tr>
<tr>
<td>Operation</td>
<td>Manual mode during takeoff and landing, and remote mode for out of vision under autopilot and GPS navigation of flight computer</td>
</tr>
<tr>
<td>Speed</td>
<td>17–40 m s⁻¹</td>
</tr>
<tr>
<td>Navigation</td>
<td>GPS</td>
</tr>
<tr>
<td>Endurance</td>
<td>Up to 30 h</td>
</tr>
<tr>
<td>Range of reconnaissance</td>
<td>150 km (UHF) to 3000 km (satellite)</td>
</tr>
<tr>
<td>Altitude</td>
<td>300–4000 m</td>
</tr>
<tr>
<td>Radio frequency</td>
<td>400–406 MHz</td>
</tr>
<tr>
<td>Variables recorded</td>
<td>Pressure, air temperature, humidity, wind speed and direction, altitude, latitude/longitude, flight status, airspeed, engine temperature, and RPM</td>
</tr>
</tbody>
</table>

Community for vertical sounding measurements. Table 2 lists the accuracy of parameters for the RSS901 sensor. Two RSS901 sensors are installed under the Aerosonde’s wings. Before the sensors are installed on board, ground calibration with the reference glass temperature, dry chamber, and digital barometer is performed. This calibration procedure is similar to that performed in the synoptic weather stations for daily balloon radiosonde observation. For more details about Aerosonde, please refer to Holland et al. (2001).

TAT is formed by teaming three organizations together. The first one is the Department of Atmospheric Sciences, National Taiwan University (NTU), which is in charge of the scientific mission and the operational plan. The second member, the Central Weather Bureau (CWB), is responsible for applying for the aviation space permission and providing supporting facilities from its local weather stations. The third member, the Chung-shang Institute of Scientific Technology (CSIST), is responsible for the control of the Aerosonde in the air, the maintenance of Aerosonde, and the ground check on site. TAT generally starts to prepare for a flight mission before the CWB issues a typhoon sea warning (the “near gale” force wind is about to affect the inshore area within 100 km from the coast of Taiwan in 24 h), because a 48-h lead time for airspace clearance is necessary for each flight. Once a flight mission is planned, the field operation team, including five members led by the first author, will drive to one of the two Aerosonde field operation bases, Il-lan (24.75°N, 121.83°E) and Heng-chun airport (22.04°N, 120.72°E), located at the northeastern coast and the southern coast of Taiwan, respectively. Generally, there are only 24 h available for TAT to transport, assemble, and launch the Aerosonde for each flight mission.

To launch the Aerosonde, we first loaded it on a specially designed cradle that is fixed on the roof of a car. The Aerosonde is then launched by the lifting force of the air when the car is running at a speed of ~80 km h⁻¹ on a 400-m-long runway. Once launched, the Aerosonde can fly by manual control or automatically according to the preloaded flight plan. A flight plan includes the waypoints, flight altitude, and cruise speed. If desired, the flight plan can be changed in real time via radio or the satellite phone communication. At the ground control station, the GPS location of Aerosonde is continuously marked on the radar reflectivity images taken by the land-based weather radar to illustrate the location of Aerosonde with respect to the moving typhoon center. The in situ measurements of pressure, wind speed and direction, temperature and humidity by the Aerosonde and the flight status of Aerosonde [such as the GPS position, pitch and yaw rate, throttle, engine temperature, and engine rotations per minute (RPM)] are transmitted to the ground control station automatically during the entire flight. Depending on the weather and the communication condition, the length of each data segment recorded during the flight operation ranges from 10 s to several hundred seconds. One laptop computer is used to monitor the flight condition and to store the real-time data. The real-time data (including the location of the Aerosonde) are also posted on a Web page at 10-min sampling intervals. The forecasters at CWB can refer to this information during the real-time typhoon forecast operation.

3. The flight mission of Aerosonde into Longwang

Figure 2 shows the track of Typhoon Longwang from 26 September to 3 October 2005. Typhoon Longwag reached Saffir–Simpson category 4 intensity at 1200 UTC 31 September and remained as a category 4 system until 1800 UTC 1 October. According to the TAT Aerosonde operation record, Longwang’s flight is the 15th reconnaissance flight using the 8th Aerosonde owned by TAT. The Aerosonde took off from the Heng-chun airport at 1000 UTC 1 October 2005 when...
The center of Longwang was located at about 300 km east of Taiwan, with a moving speed of 6–7 m s\(^{-1}\) toward the island. At this moment, Longwang was a category 4 system with the radius of “near gale” force wind (\(\sim 15\) m s\(^{-1}\)) of 200 km. (Note that the CWB official warning includes the radius of \(\sim 15\) m s\(^{-1}\) wind or the Beaufort wind scale 7). The Aerosonde was navigated to climb up to a 1500-m height and to fly around the field operation base for about 2 h before it started the reconnaissance flight at 1200 UTC. The Aerosonde climbed up to a 3000-m height at about 1300 UTC (point 1 in Fig. 3a) and then started its constant height flight (see Fig. 4) to approach the inner region of the typhoon. This flight level is the same as that used by the USAF C-130 reconnaissance missions in the North Atlantic. When the Aerosonde arrived at the point 22°N, 123°E (point 2 in Fig. 3a) at about 1400 UTC, it began turning cyclonically and heading toward the eye of the typhoon as shown in Fig. 3a.

After 1430 UTC 1 October, the Aerosonde was steered by a strong cyclonic inflow, which helped Aerosonde to fly into the eye of Longwang. The measured wind speed was about 35 m s\(^{-1}\) at 1430 UTC but increased almost continuously for the following hour (Fig. 4). At about 1515 UTC, the measured wind speed increased to over 50 m s\(^{-1}\) and maintained at 52–54 m s\(^{-1}\) for more than 20 min. After 1540 UTC, the measured wind speed dropped from over 50 m s\(^{-1}\) to less than 10 m s\(^{-1}\) in about 15 min, indicating that the Aerosonde was located inside the eye (which was also confirmed by the radar images). At this time, Longwang was located at about 180 km east of Taiwan’s coast. The flight level of Aerosonde from 1300 to 1555 UTC was maintained mostly at 3000 m, and this track segment (called flight leg 1) is shown in Figs. 3a,b.

Figure 3 shows the flight track segments at various time periods and a selective composite radar reflectivity image corresponding to each track segment. For example, Fig. 3b shows the track segment at 1450–1555 UTC and the radar images at 1540 UTC 1 October 2005. Note that the location of Aerosonde at the time corresponding to the radar image (1540 UTC in Fig. 3b) is marked by a black “X” in Fig. 3. Examining the radar images and the Aerosonde locations at a 10-min interval shows that Aerosonde flew through a convective area with maximum reflectivity over 45 dBZ at 1300–1450 UTC. After 1450 UTC, the Aerosonde kept flying cyclonically toward the center and penetrated through a developing rainband (or outer eyewall) as shown in Figs. 3a,b. At 1540 UTC, the Aerosonde reached the dissipating inner eyewall (Fig. 3b) at where the maximum wind speed (\(\sim 55\) m s\(^{-1}\)) along leg 1 was measured (Fig. 4).

The Aerosonde stayed inside the eye from 1555 to 1720 UTC (flight leg 2) as shown in Fig. 3c. During this period, the Aerosonde performed a 5-km square box of spiral vertical sounding from 3490 down to 1240 m at 1630–1650 UTC. After 1720 UTC, the Aerosonde flew...
Fig. 3. The composite radar reflectivity with Aerosonde location marked by the black “X” at time (UTC) shown at the bottom left of 1 Oct 2005. The blue curve shows the flight track during the period (UTC) shown at the upper left, and the corresponding flight leg is shown at the bottom right. Numbers 1, 2, 3, and 4 show the locations of Aerosonde at 1300, 1400, 1430, and 1510 UTC, respectively. The letters “H,” “F,” and “B” show the location of Hua-lien radar, Tai-tung, and the ground base, respectively.
cyclonically outward at a 3000-m height and took a second penetration through the eyewall located at the rear of the center (Fig. 3d). From 1720 to 1930 UTC (flight leg 3), the Aerosonde flew cyclonically from the rear left to the front left of the center as shown in Figs. 3d,e. To prevent Aerosonde from crashing onto the mountain, the Aerosonde was navigated to climb up to 4000 m at 1845–1900 UTC. Note that the Doppler radial wind measurements taken at the Hua-lien Doppler weather radar (marked by the letter “H” in Fig. 3a) are collected during this flight leg to compare against the wind measurements taken by the Aerosonde.

Unfortunately, the Aerosonde lost its power because of an engine failure likely caused by a malfunctioning spark plug at 1930 UTC, and had to perform a gliding flight from a 4000-m height down to the sea surface (flight leg 4) as shown in Fig. 3f. The Aerosonde probably crashed into water (where it is only 170 km away from the ground base) at 1950 UTC. This Aerosonde reconnaissance flight lasts for almost 10 h and is the first ever eyewall-penetration flight conducted by a small UAV equipped with meteorological instruments, according to the available information (Becker et al. 2006).

Six track segments of entire flight paths overlaid on the corresponding radar reflectivity images of Longwang have been shown in Fig. 3, in which the 25-dBZ contour of radar reflectivity is used to indicate the boundary of the rainband surrounding the eye (Barnes et al. 1983). Analyzing the radar reflectivity reveals that the stronger echoes were located mostly on the left-hand side of the typhoon at 1650 UTC (Fig. 3c), but extended counterclockwise afterward to surround the center of the typhoon at 1930 UTC (Fig. 3f). During this period, the Aerosonde penetrated through the eyewall and flew around the inner region of the typhoon, completing more than three-quarters of a circle surrounding the typhoon center. During a period of more than 10 min around 1630 UTC, quite a few measured wind speeds exceed 60 m s$^{-1}$ (the strongest winds along the entire flight track) as shown in Fig. 4. Figures 3d,e show that the Aerosonde was flying along a developing rainband (or eyewall) surrounding the center at this period. A measure of disequilibrium, $q^2 - r \times gv^{-1}$ (where $q$ and $r$ are the pitch and yaw rate, respectively; $g$ is the gravity acceleration; and $v$ is the airspeed), should normally be kept near zero under steady flight status. But the time series of disequilibrium parameter (not shown) shows that the Aerosonde was flying in the rainband with significant turbulence in flight legs 3 and 4 until it crashed.

4. The structures of Longwang as observed by the Aerosonde

Flight leg 1 of this Aerosonde flight mission provides continuous measurements at a 3000-m height from a radius greater than 250 km inward to inside the eyewall of Longwang. Figure 5 shows the specific humidity and the air temperature along leg 1 as a function of radius from the typhoon center. Using the sharp gradient of specific humidity as guidance, we can identify the inner boundary of the eyewall at the radius of 30–35 km. The observed specific humidity is much higher (~12 g kg$^{-1}$ or higher) at radii from 35 to about 70–75 km, and drops to about 10 g kg$^{-1}$ at radius of ~100 km. The specific humidity maintains at about the same value outward to ~160-km radius and decreases to below 8 g kg$^{-1}$ outside 170-km radius. These results are consistent with the radar reflectivity as shown in Figs. 3a,b. At about 1400 UTC (~170-km radius) the Aerosonde flew into a convective area thus the measured mixing ratio increased from ~8 to ~10 g kg$^{-1}$. The higher mixing ratio at radii from 35 to 70–75 km is because that the
Aerosonde was flying through a developing rainband (eyewall) after 1450 UTC. Unfortunately, the humidity sensors on board the Aerosonde appeared to malfunction and reported missing data after the inward eyewall penetration. It is quite likely that the rainwater somehow entered either the sensor connection and/or sensor electronics and caused the failure of the humidity sensor.

The temperature measurements show a more complicated structure when the Aerosonde flew inward, penetrating through the rainband and the eyewall along flight leg 1. At the convective region outside the eyewall (~80–160-km radius), the temperature is higher at 140-km radius where the specific humidity is slightly lower. The temperature at radius of 40–70 km (eyewall region) is slightly higher than that at 80–160-km radius (the convective region outside the eyewall). However, moving inward from 45-km radius, the measured temperature increases by about 4°C (from 12° to 16°C) in 15 km. Halverson et al. (2006) presented a temperature composite for Hurricane Erin (2001) using data taken during the Convection and Moisture Experiment (CAMEX)-4. Results showed that the warm core existed at the 500-hPa level (temperature deviation was 11°C) and extended downward to 700 hPa where the core region was 3°–7°C warmer than the environment. In the Longwang case, at a 3000-km height (~700 hPa) the significant warm core exists only inside a 40-km radius. The temperature inside the eye is about 4.5°C higher than that in the environment (~11.5°C, which is the average outside a 200-km radius). The variations of the moisture and temperature patterns at radius of 40–170 km (or the eyewall and the convective region) indicate complicated 3D structures of the convections at the inner region of a typhoon. Although the measurements taken by a small UAV with limited instruments along a constant level flight cannot be expected to depict well the 3D structure of the system, this in situ horizontal slice view of the typhoon structure still provides unique and useful information.

The Aerosonde-measured wind is an average along an S-shape flight path segment (~5 km in the Longwang flight; see Holland et al. (2001) for the detail of the wind measurement procedure). Soddell et al. (2004) found that the wind field measured by the Aerosonde using the S-shape methodology is comparable to that measured by the balloon radiosonde using the GPS-finding method. As shown in Fig. 4, the Aerosonde-measured wind speed along flight leg 1 (after 1300 UTC) generally increases with time until 1540 UTC. This wind pattern appears to be quite realistic especially inside the eyewall where the wind speed decreases almost linearly with time.

Before the Aerosonde-measured winds are further analyzed, they are compared against those measured by the CWB Doppler weather radar (model: SELEX Geomatronik METEOR 1000S) located at Hua-lien (24.99°N, 121.62°E), which is 40 km north of the landfall point of Longwang. The Doppler radial wind is presented in the constant altitude plan position indicator (CAPPI) format from a 6-min volume scan with 250-m spatial resolution in radial direction. As an example, the Doppler radial wind at a 3-km height at 1848 UTC 1 October when the maximum wind speed (66.5 m s⁻¹) along the entire flight track was observed is shown in Fig. 6, in which the location of Aerosonde is marked by an “X.” At this moment, Aerosonde was flying at a 3320-m height and the toward-radar component of the Aerosonde-measured wind is 56.6 m s⁻¹, which is about the same as the radar-measured Doppler radial wind speed.

When analyzing the Aerosonde-measured winds, we compute the tangential and radial wind components with respect to the moving typhoon center or the storm-relative tangential and radial winds (Fig. 7). Because the computed tangential and radial winds are sensitive to the center position, the center of the typhoon at each moment is linearly interpolated from the hourly center positions determined according to the radar images. Results show that the tangential wind speed measured along flight leg 1 generally increases with decreasing radius and can be fitted by a power law curve, which is also shown in Fig. 7. The maximum tangential wind speed \(V_{\text{max}}\) of the fitted curve is 46.8 m s⁻¹ at the radius of 30 km [often referred to as the radius of max-

![Diagram](image-url)
mum wind (RMW)]. The radial profile of tangential wind is important to typhoon study, such as that the initial vortex for a model simulation is often assumed to be similar to a Rankine vortex. The tangential wind profile generally takes the form \( V / H_{1100} \), where \( V / H_{1100} \) equals to \( V / H_{925} \) at radius \( R \) for a Rankine vortex. Different values of \( V / H_{925} \) were used in the literature, such as \( V / H_{1100} \) in Low-Nam and Davis (2001) and \( V / H_{1100} \) in Riehl (1963). In the case of Longwang, the optimal fit (minimum root-mean-square of \( V / H_{1100} \)) is roughly \( 0.4 \). Note that strong tangential winds occur at radius around 175 km (inside the rainband) and make the power-law curve rise slightly. The radial wind pattern implies that strong convergence occurs at radii of 30–50 km and 75–100 km, corresponding to the dissipating inner eyewall and the developing outer eyewall as revealed in Fig. 3, respectively. Another strong convergence occurs at a 160–180-km radius, where the tangential wind is also stronger, indicating the existence of the rainband. Barnes et al. (1983) suggested that rainband around the eyewall could act as a partial barrier to the inflow below 3 km for Hurricane Floyd (1981) in the Atlantic.

When Longwang was approaching the eastern coast of Taiwan, CWB Hua-lien weather radar scanned the typhoon continuously with a 6-min volume scan. The radar data show that the Doppler radial wind is stronger (about 50–60 m s\(^{-1}\)) on the right-hand side of the eyewall. In flight legs 1 and 3 (refer to Fig. 3), Aerosonde flew through the right-hand side of the eye-wall and measured wind speeds comparable to those observed by the Doppler radar (around 1530 and 1830 UTC in Fig. 4). As mentioned before, the strongest Aerosonde-measured wind speeds occurs at around 1830 UTC along flight leg 3. The 10-min average wind speed from 1825 to 1835 UTC is 58.6 m s\(^{-1}\), while the maximum 1-min wind speed during this period is 62 m s\(^{-1}\). Note that the sampling period of the wind measurements or the time period of an S-shape flight path is from 7 to 30 s during this period because of the strong steering flow. Since the Aerosonde was flying around

![Fig. 6. The Doppler radial winds (m s\(^{-1}\)) at a 3-km height taken by the Hua-lien weather radar (marked by the cross sign) at 1848 UTC 1 Oct 2005. The “X” marks the location of Aerosonde where the toward-radar component of the Aerosonde-measured wind is 56.6 m s\(^{-1}\). Counters start at wind speed of 25 m s\(^{-1}\) in 10 m s\(^{-1}\) intervals with negative values toward radar and positive values away from radar.](image-url)

![Fig. 7. The storm-relative tangential (dots) and radial winds (circle) along flight leg 1 plotted as a function of radius from the center of Longwang. The dashed curve is the optimal power fitting curve (\( \alpha = -0.4 \)) of tangential wind with \( V_{\text{max}} \) of 46.8 m s\(^{-1}\) and RMW of 30 km. The numbers inside the rectangular show the observation time (UTC).](image-url)
the outer edge of eyewall during 1800–1900 UTC (as shown in Fig. 3d), it is quite likely that the Aerosonde was near the strongest wind region.

It is also customary for the forecast center to use the $V_{\text{max}}$ at the 700-hPa level to estimate the maximum sustained surface wind. Franklin et al. (2003) suggested to multiply the $V_{\text{max}}$ at 700 hPa measured by the conventional C-130 reconnaissance flights by 0.9 (used by the Tropical Prediction Center) to obtain the maximum sustained surface wind. Taking 58.6 m s$^{-1}$ as the maximum wind at 700 hPa, the maximum sustained surface wind of Longwang computed in this way is about 52.7 m s$^{-1}$ ($= 58.6 \times 0.9$). This number is close to the official reports of Japan Meteorological Agency (JMA) and CWB, or 49 and 51 m s$^{-1}$, respectively. However, it has to be noted that the maximum sustained surface winds of JMA and CWB are satellite based.

During flight leg 2, a vertical sounding from 3490- to 1240-m height was performed to estimate the sea surface pressure in the eye. However, the communication interference makes the data below 1416 m unusable. At the lowest height with observed data (1416-m height), the measured pressure is 786 hPa. Assuming that the temperature lapse rate to be the same as that of the standard atmosphere gives a mean sea level pressure of 924.5 hPa. This number is close to the minimum sea surface central pressures of Longwang estimated by JMA and CWB at this time period (930 and 925 hPa, respectively). Results also show that the measured temperature inside the eye (Fig. 8) decreases at a rate of 5.3°C km$^{-1}$ from 1416 to 2900 m, and remains at about the same value up to 3490 m.

In the final 20-min flight before crashing into the water from a 4000-m height (flight leg 4), the Aerosonde took a lower atmospheric sounding measurement near the edge of the rainband located to the left of the eye (see Fig. 3f). The temperatures measured along flight leg 4 are also shown in Fig. 8. Results show that the average temperature lapse rate from the surface to a 4000-m height is 5.0°C km$^{-1}$, which is smaller than 6.5°C km$^{-1}$ for the standard atmosphere (or more stable than the standard atmosphere). However, temperature lapse rate varies significantly from the surface to 4000 m. The lapse rate is 7.5 and 8.3°C km$^{-1}$ at layers of the surface to 300 m and a 700–2000-m height, respectively, while the temperature does not change much from 300 to 700 m and from 2500 to 4000 m. Such a complicated structure is likely a result of various effects, including the convective activities in the rainband and the subsidence warming. Note that there was a foehn surface weather report from the coastal city, Taitung, located 80 km west of the Aerosonde crash site (shown by the letter “T” in Fig. 3a).

5. Discussion and conclusions

Before the Longwang flight, we have carried out the Aerosonde program for 8 yr including 2 yr (1998–1999) of operation training and 6 yr (2000–2005) of field experiments (14 typhoon reconnaissance flights) in Taiwan. The TAT was well trained and had good experience in Aerosonde operation. All these had led to the final successful Aerosonde eyewall-penetration flight in Typhoon Longwang on 1 October 2006. Based on our previous experience in Aerosonde operation and the Longwang’s reconnaissance flight, several salient observations and comments are summarized below for this Aerosonde program.

1) The rainband and eyewall-penetration flight in Typhoon Longwang with UAV Aerosonde at the 700-hPa level provides unique in situ measurements of the tangential wind, radial wind, temperature, and specific humidity in the eye and the eyewall regions. The Aerosonde measurements provide reasonable estimates of the maximum sustained surface wind and the central pressure of the eye, which are comparable to the reports of local weather agencies. This kind of information is provided by C-130 reconnaissance flights over the Atlantic, and this Aerosonde experiment demonstrates that Aerosonde has potential to provide such information. Measurements of wind fields in flight leg 3 agree well with Hua-lien weather radar measurements.
that strong winds occur to the right-hand side of the eye. These results suggest that the Aerosonde data can serve as an independent check for Doppler radar wind retrieval.

2) The 10-h-long reconnaissance flight indicates that the new model of Aerosonde, Mark-III, is likely capable of taking a typhoon reconnaissance flight. The Vaisala PTU sensors carried by the Aerosonde at \(~70 \text{ km h}^{-1}\) cruise speed seems to perform reasonably well (even though one of them malfunctioned during the flight for unknown reasons) and the measured data show a severe atmospheric environment in the typhoon. Therefore, Aerosonde can be considered as an effective observation platform for a special-purpose field experiment.

3) A well-trained team is necessary to operate Aerosonde in order to meet the scientific expectation. Through 6 yr of operation, we find that a successful recovery of Aerosonde during a typhoon flight mission depends heavily on the expertise of the team members. In addition, technical maintenance of Aerosonde requires considerable engine knowledge, and experience in operating miniature aircraft is helpful in controlling the takeoff and landing of Aerosonde. At the same time, a meteorological team is necessary for weather information management, like typhoon prediction and data quality control on PTU sensors. Multiple ground bases for Aerosonde operation are also desirable for flexible choice of optimal launch/recovery site. Although the Aerosonde Ltd. has been developing the ejector and autolanding software for a while, at the current stage the visual flight for Aerosonde takeoff or landing by an expert pilot is still needed. This implies that the Aerosonde launch and recovery have to be carried out during the daytime.

4) If the Aerosonde recovery in typhoon reconnaissance flight is not a great concern, then Aerosonde can play a role in severe weather monitoring. For example, the Aerosonde can stay inside the eye and measure the intensity change for several hours. In general nonsevere weather conditions, Aerosonde can make significant contributions to the in situ measurements during the field experiments of the marine boundary layer study, the lower cloud entrainment dynamics, and the land–sea circulation evolution studies.

The risk of losing Aerosonde is a great concern in the scientific field experiments, because the wind shear and heavy rainfall in typhoon circulation pose a continuous challenge to this kind of lightweight UAV platform. Nevertheless, the NOAA Hurricane Research Division conducted a Hurricane Unmanned Aircraft Systems (UAS) Demonstration Project at Key West, Florida, in September of 2006, after the National Aeronautics and Space Administration's (NASA) Wallops Flight Facility operation from 2001 to 2005 in CAMEX. In addition, Aerosonde was proposed in the “Global Hawk” (MacDonald 2005) and used in the “Altair” NOAA and NASA demonstration project 2005–2006 (more information is available online at http://uas.noaa.gov/projects/demos/altair/). All of these have shown the potential role of UAV platform in weather and climate researches.

Another typhoon field program that uses a Gulfstream-100 jet plane for the synoptic surveillance of typhoons near Taiwan [Dropsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR)] started in 2003, and has provided contribution to the analysis of typhoons in the western North Pacific (Wu et al. 2005). It is likely that the joint observations of dropsonde surveillance in DOTSTAR and Aerosonde reconnaissance in the future will provide better in situ measurements of atmospheric conditions in a typhoon.

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