Air Crash Case Study: Icing Event over the Taiwan Strait

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Abstract. Various meteorological data charts derived from in situ observations, satellite imagery, soundings near an air crash site and the Tropical Rainfall Measuring Mission Microwave Imager (TMI) level 2A hydrometeor profile product were used to investigate the synoptic and mesoscale environment of an icing event (IE) over the Taiwan Strait on 20 December 2002. The IE occurred in a frontal cloud system. A series of meteorological chart analyses shows that the relative humidity at the 850 and 700 hPa levels reached 80% and 90%, respectively. In addition, there was an occurrence of small-scale negative vorticity (shear vorticity). The sounding observations revealed widespread light to moderate icing over the crash site. The TMI level 2A hydrometeor profile product provided further evidence of the existence of icing. The intensity of the icing was 0.3 gm⁻³, the vertical thickness reached 4 km, and the icing duration exceeded 24 h.

Keywords: TMI, hydrometeor profile, icing event, sounding observation

1. Introduction

According to the accident report of the Aviation Safety Council, details of the air crash investigated in this study are as follows: TransAsia Airways cargo GE791 was an ATR 72-200 aircraft that took off at 1704 UTC on 20 December in 2002. At 1725 UTC, the flight altitude was 18,000 ft (approximately 5500 m). The captain visually detected icing at 1732 UTC. Activation of the icing removal mechanism first occurred during 1734–1737 UTC. The second occurrence started at 1741 UTC, and the captain informed the traffic control tower that the aircraft had descended to an altitude of 16,000 ft (approximately 4900 m). Contact with the aircraft was lost at 1752 UTC. The icing removal mechanism was still active at this time. Ultimately, the cargo aircraft crashed 27 km southwest of Penghu.

Aircraft icing is one of the most critical factors that affect flight safety. Bernstein et al. (2005) argued that analysis of aircraft icing is crucial because of the numerous air crashes it has caused over recent decades [1]. Therefore, since the 1990s, many studies on aircraft icing have been conducted. For example, Rasmussen et al. (1992) improved forecasts of aircraft icing by studying the processes leading to the formation and depletion of supercooled liquid water [2]. This technique was used to analyze the weather data associated with the crash of an ATR 72 aircraft on 31 October 1994. Stankov and Bedard (1994) used various combinations and arrays of remote sensors to successfully predict icing conditions when an aircraft was aloft [3]. Relevant research continues to investigate aircraft icing concerns. Cober and Isaac (2012) analyzed an aircraft icing environment by collecting instrumented data from 134 flights during six field programs in three geographic regions of North America [4]. Fernández-González et al. (2014) simulated synoptic and mesoscale meteorological conditions by using numerical models, and indicated that icing conditions may arise locally, even when the synoptic situation indicates no risk [5]. This paper analyzed the icing conditions of a TransAsia Airways plane crash that occurred in the Taiwan Strait.

In Section 2, we provide information regarding the various data used in this study. Section 3 presents an overview of the atmospheric environment, including the synoptic, meso-, and convective scales.
discusses evidence of icing when the crash occurred. The final section draws conclusions.

2. Data and Methods

In this study, we employed both surface observation and upper air radiosonde sounding data for analysis.

Synoptic weather charts, relative humidity, vorticity distribution, and atmospheric sounding diagrams were produced using conventional surface and upper air observation data. In situ observations were used to obtain information on the synoptic environment of the crash. Because of the lack of data from the Penghu radiosonde station, we used three sounding stations located near the crash site: Taipei, Shantou, and Ishigakijima Island. Additional details regarding the radiosonde observation used in this study are shown in Table 1.

Satellite data included MTSAT, satellite cloud imagery and the Tropical Rainfall Measuring Mission (TRMM) 2A12. The satellite images were infrared images taken from MTSAT, a geostationary satellite positioned above the equator at 140°E. The TRMM is a joint U.S.–Japan satellite mission to monitor tropical and subtropical precipitation and to estimate their associated hydrometeor profiles. This research used precipitation ice data with a vertical resolution of 0.5–18.0 km from the surface. Spatial coverage was between 38°N and 38°S. The horizontal resolution was 5.1 km, and the swath width reached 878 km.

In this case study, we used weather maps and relative humidity charts to locate the frontal position, the extent of the continental high pressure, and the relative humidity and distribution of atmospheric dynamics at the crash site at 1200 UTC on 20 December 2002. Infrared imagery was used to observe the structure, distribution, and movement of clouds. Finally, satellite image loops from the TRMM satellite’s two-swath scan over the crash site was analyzed to gain insight into the weather conditions of the aircraft flight altitude. Additional details regarding the TRMM swath used in this study are shown in Table 2.

Table 1: A list of radiosonde used in this study.

<table>
<thead>
<tr>
<th>Name of the station</th>
<th>WMO</th>
<th>Lat</th>
<th>Lon</th>
<th>Station height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taipei</td>
<td>58968</td>
<td>25.03°N</td>
<td>121.53°E</td>
<td>9</td>
</tr>
<tr>
<td>Shantou</td>
<td>59316</td>
<td>23.24°N</td>
<td>116.41°E</td>
<td>3</td>
</tr>
<tr>
<td>Ishigakijima Island</td>
<td>47918</td>
<td>24.33°N</td>
<td>124.17°E</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 2: A list of TRMM swaths in this study

<table>
<thead>
<tr>
<th>Data file name</th>
<th>Date / Time (UTC)</th>
<th>Path Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>2A12.20021220.29054.6.HDF</td>
<td>Dec. 20 / 0043</td>
<td>29054</td>
</tr>
<tr>
<td>2A12.20021220.29058.6.HDF</td>
<td>Dec. 20 / 0652</td>
<td>29058</td>
</tr>
<tr>
<td>2A12.20021221.29069.6.HDF</td>
<td>Dec. 20 / 2349</td>
<td>29069</td>
</tr>
<tr>
<td>2A12.20021221.29073.6.HDF</td>
<td>Dec. 21 / 0558</td>
<td>29073</td>
</tr>
</tbody>
</table>

3. Synoptic Overview

The synoptic weather conditions are shown in Fig. 1. The surface weather charts were at 0000 UTC, from 19 to 21 December 2002. The separated cold high-pressure center was located in Mongolia, and its pressure level was 1042 hPa, moving southeastward. Taiwan was affected by a frontal system, and there were clouds over the south of mainland China and the Taiwan area. The separated cold high-pressure moved toward the northeast of mainland China at 0000 UTC on 20 December. The frontal system remained near east Taiwan. When the separated cold high-pressure moved to the east of the Japan Sea at 0000 UTC on 21 December, the frontal system started to move away from Taiwan.

The cold, dry air from the high-pressure system located over mainland China began to weaken on 20 December. Fig. 2 shows that the 850–700 hPa level was affected by cold advection. Although humidity levels at the 850 hPa level began to decrease over the Taiwan Strait and southern Taiwan, the overall relative humidity reached 80%. Meanwhile, the cold advection area was limited to 700 hPa. Only a small portion of
the cold advection remained over the eastern coast of Taiwan. All other areas experienced warm advection; thus, the 700 hPa relative humidity increased to 90% over both the Taiwan Strait and Taiwan (Fig. 3). South China, the Taiwan Strait, and the Taiwan area all exhibited warm advection in the 500 hPa range. The southwest wind at the 500 hPa level reached 45 kn at the Taipei station. Concurrently, the cloud amount and water content increased sharply from 300 to 500 hPa, and small-scale negative vorticity was present at 500 hPa over Taiwan. Wind shear vorticity was inferred from wind distribution, which also indicated wind shear turbulence over the Taiwan Strait (Fig. 4).

Fig. 5: (a) and (b) respectively show two infrared images, (a) at 1730 UTC, and (b) at 1830 UTC on 20 December 2002. The satellite images of the East Asian region were taken before and after the crash. These figures show that the low-pressure system in the frontal cloud band extended southwest from Japan to the South China Sea. The crash site was located within the range of the frontal cloud band.

Fig. 1: Surface chart at 0000 UTC (a) 19, (b) 20, and (c) on 21 December 2002. (JMA)

Fig. 2: (a) 850 hPa, and (b) 700 hPa temperature advection chart at 1200 UTC on 20 December 2002.

Fig. 3: (a) 850 hPa and (b) 700 hPa chart at 1200 UTC on 20 December 2002. (Shaded area is the relative humidity ≥ 80%)
4. Observational Evidence for the Existence Of ice

We conducted our analysis according to the vertical distribution curves of temperature and dew point at 1200 UTC on 20 December 2002. The skew-T diagram and the vertical moisture distribution reached 350 hPa (Fig. 6). The strong southwest wind conveyed an abundance of water vapor near the vicinity of Taiwan. Despite the cold air advection at the bottom from 850 to 700 hPa, the temperature and dew point curves were extremely close, from 700 to 350 hPa. The abundance of water vapor resulted in the 850 hPa relative humidity to reach 80% in the Taiwan area (Fig. 2); at 700 hPa, the relative humidity was within the 90% range.

At 1200 UTC on 20 December 2002 (Fig. 6), analysis of the 1000–925 hPa, 850–700 hPa, and 400–300 hPa levels from the Taipei sounding station indicated unstable conditions. Other atmospheric layers were relatively more stable. The freezing height reached 3916 m (approximately 12,922 ft) at the time, and the lifting condensation level (LCL) was 244 m (805 ft). This meant that the low-cloud height was approximately 800 ft, and the height of the middle-high level clouds ranged from 3100 m (10,230 ft) to 8000 m (26,400 ft). The altitude of the TransAsia Airways GE791 flight was 18,000 ft (5454 m). The aircraft was flying in the clouds, where the temperature was approximately -9 °C. Within these clouds, the temperature of the supercooled water (0 °C–15 °C) represented the largest distribution (Huschke, 1959 [6]); therefore, the sounding chart analysis revealed a rime-icing phenomenon. In addition to the Taipei sounding station, the Shantou and Ishigakijima Island sounding stations observed a rime-icing phenomenon near 500 hPa. The freezing level was between 3532 and 4134 m. Measurements from the three stations indicated a low-cloud height between 200 and 300 m, and cloud thickness greater than 10 km. These measurements indicated unstable weather conditions during that evening.

Two sounding stations near the crash site and data interpolation from the two stations closest to the crash site (Fig. 7) were used to conduct a cross-sectional analysis to observe the icing and cloud water distribution. Fig. 8 shows the vertical distribution of ice, approximately 4–8 km, and the icing strength, ranging from mild to moderate. From the 1- to 13-km vertical distribution of cloud water, the maximum content was located
within 5–8 km, and the liquid water content (LWC) was approximately 0.005–0.006 gm$^{-3}$. This value is consistent with the findings of Cober, S., and G. Isaac (2012), who showed that the average LWC of aircraft icing environment conditions are $> 0.005$ gm$^{-3}$ [4]. The LWC of clouds near the crash site was 0.006 gm$^{-3}$, indicating moderate icing conditions.

Fig. 6: Taipei radiosonde sounding at 1200 UTC on 20 December 2002.

Fig. 7: Geographical location map of radiosonde sounding.

Fig. 8: Cross section of icing and cloud water.
The TRMM 2A12 of standard figure production is able to show the vertical distribution of ice up to 18 km from the surface. The aircraft was flying at an altitude of 5500 m, which corresponded to the ninth layer (5–6 km) according to the 2A12. Fig. 9 shows the water content of the ninth layer observed by the TRMM satellite before and after the crash time. Fig. 9 (a) and (b) shows that there was an icing layer extending from the Taiwan Strait to the South China Sea during the morning of the crash. Clouds were moving from southwest to northeast, indicating that these winds carried a significant icing layer above the South China Sea to the vicinity of the Taiwan Strait. Fig. 9 (c) shows a significant icing layer at 2349 UTC that day, which did not weaken until the morning of 21 December.

Fig. 10 shows the 2A12 icing information closest to the crash point. Fig. 10 (a) presents the icing distribution at the 4- to 5-km flight level. Fig. 10 (b) depicts the icing distribution at the 5- to 6-km flight level. Fig. 10 (c) presents the icing distribution at the 6- to 8-km flight level. The red square corresponds to the crash site. Fig. 10 shows evident icing during that time.

Fig. 11 depicts the progression of the icing intensity at the crash site for different heights. Before the crash, the icing strength was 0.15 gm-3. The arrow represents an interpolation of the icing strength at the time of the crash. From a flight level perspective, the icing intensity reached more than 0.3 gm-3, and the vertical thickness of the icing exceeded 4 km.

![Fig. 9: Precipitation ice at (a) 0043, (b) 0652, and (c), 2349 UTC, on Dec. 20, and (d) 0558 UTC on 21 December 2002.](image1)

![Fig. 10: Precipitation ice at (a) 4–5 km, (b) 5–6 km, and (c) 6–8 km at 2349 UTC on December 20, 2002.](image2)
5. Conclusions

According to the synoptic weather map analysis, a frontal system affected Taiwan on 20 December 2002. Considerable cloudiness over southern China and Taiwan was observed. The relative humidity exceeded 80% at 850–700 hPa, and wind shear turbulence was present over the Taiwan Strait. Thick clouds from the frontal cloud system extended from the southwest of Japan to the South China Sea, covering the vicinity of the crash site. Analysis of the aforementioned environment indicated that both the thermal and dynamic conditions induced unstable atmospheric conditions.

The sounding curve distribution analysis showed strong southwest winds conveying moisture above 700 hPa. From the dew point temperature curve, water vapor was abundant (300–700 hPa). The relative humidity reached 90% in the range of 700 hPa. The cloud height observed by the three stations reached 250 m on the day of the crash, and cloud thickness ranged 8–10 km, indicating that the aircraft was flying in the clouds. Because the three stations near the 0 °C isotherm were only within 3500–4000 m, the flight altitude was still at a level where the temperature was below 0 °C. Icing conditions occurred during a flight altitude of 5500 m over the three stations.

This study employed a cross-sectional observation of icing distribution and cloud water content. Slight to moderate icing was observed at an altitude of 4–8 km. The maximum amount of cloud water also existed within this range. An evident distribution of drop icing was observed from the South China Sea to the Taiwan Strait during the morning of the crash, which continued to occur for more than 24 h. Despite the aircraft descending to an altitude of 16000 ft (4877 m) before the crash, a high degree of slight icing was observed according to the TRMM satellite. Analysis of the upper air radiosonde sounding data and precipitation ice information indicated that icing occurred within the cloud distribution at the flight altitude during that evening, reaching a strength of 0.3 gm⁻³. Encountering icing was unavoidable, regardless of a change in flight altitude.

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7. References


