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3.6 A CASE STUDY OF MID-LEVEL TURBULENCE OUTSIDE REGIONS OF ACTIVE CONVECTION *†

Richard F. Ferris
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts

1. INTRODUCTION

Historically, the principal focus of research on clear-air turbulence of concern to aircraft has been on jet stream and mountain (orographic) induced turbulence. Relatively little research has focused on the turbulence hazard outside of, but in the vicinity of, convective storms, known as Convective Induced Turbulence (CIN). In this paper, we present our analysis requested by the National Transportation Safety Board (NTSB) of the meteorological conditions leading to severe turbulence and near loss of flight control of a commercial passenger jet and find that they fall into the CIN category.

On 12 May 1997, at approximately 1929 UT, an American Airlines Airbus A300 en route from Boston, MA to Miami, FL encountered severe turbulence off the coast of West Palm Beach, FL. Near the time of the incident the crew had been directed to hold at 16,000 ft because of weather and traffic near Miami International. While approaching the holding position, the aircraft experienced severe turbulence and dropped over 3000 vertical feet in 30 seconds. A detailed post-event analysis by the NTSB failed to find any causal evidence for the turbulence and no single sensor, data set, or pilot report examined by the NTSB provided justification for the magnitude of the event.

Our independent analysis of the incident was conducted primarily using recorded Miami WSR-88D base data. The analysis revealed a small-scale vertical shear zone may have emanated from a thunderstorm upstream of the Airbus. Animated cross-sectional images also suggested that a rotor may have propagated with the mean wind and intersected the flight path at the time the severe turbulence was reported. This paper will focus on meteorological conditions that led to the upset and provide evidence for several possible causes of the turbulence.

2. ENVIRONMENTAL CONDITIONS

The National Weather Service (NWS) surface analysis for 1800 UT, 12 May 97 showed an east-west stationary front located across south central Florida and adjacent Atlantic coast waters. A very moist tropical airmass was established over south Florida with broken to overcast multi-layered clouds and widespread convection. A strong southwesterly jetstream was present over the eastern Gulf of Mexico and southern Florida peninsula. At the time of the incident (29:29:11 UT), the nearest convective cell (42 dBZ) was 20 km southwest of the aircraft. A strong to severe line of thunderstorms was also located from approximately 30-80 km southwest or upstream of the flight path. Mean storm motion was from 250 degrees at 20 knots, with convective cloud tops up to 50 kft. The thunderstorms had a history of producing weak tornadoes in and around Miami (Figure 1), one of which was highly publicized as it moved through the city.

The 12 May 1200 UT sounding from Miami showed a Lifted Index of -4.6 and winds veering with height from 120 degrees at 8 knots at the surface to 245/23 at 16 kft to 255/68 at 30 kft. The 13 May 0000 UT sounding showed a Lifted Index of -4.4 and generally westerly winds from 290/06 at the surface to 245/42 at 16 kft to 260/38 at 30 kft. There was no significant vertical wind shear for either profile.

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† Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Air Force. Corresponding author address: Richard F. Ferris, Massachusetts Institute of Technology, Lincoln Laboratory, 244 Wood Street, Lexington, Massachusetts 02420-9185; e-mail: ferris@ll.mit.edu

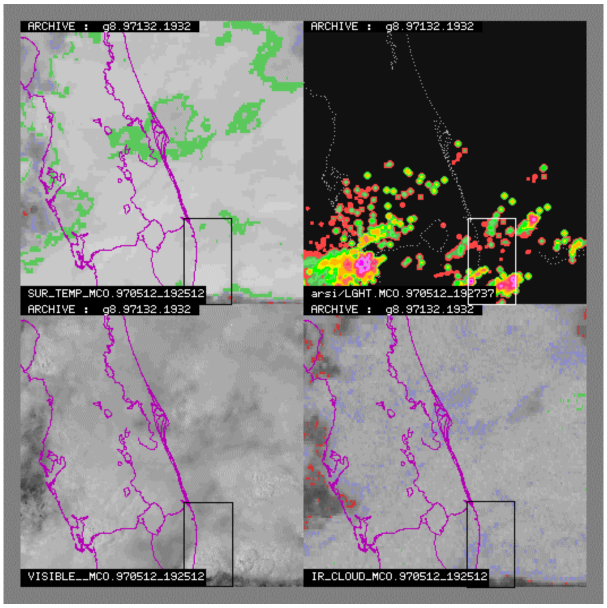


Figure 1. Panels showing conditions over southeast Florida at 1932UT, 12 May 1997. Box denotes mishap airspace. Top left: surface temperatures/clouds. Top right: lightning. Bottom left: visible clouds. Bottom right: IR clouds.

Per NTSB Factual Report [Skeen, 1998], a B727 aircrew in the accident area reported two or three cells converging on the navigation intersection HEATT (near the upset area). There were some scud clouds on the horizon at 19 kft, and visual contact could be maintained with the clouds through a turn (about 8.5 miles north of HEATT). The pilot also stated that they were in IFR conditions for about 30 seconds and did not encounter any icing or precipitation in clouds. The B727 pilot estimated the depth of the cloud deck around 5-6 kft feet and the ride was smooth at flight level. Weather information transmitted to the mishap crew of the Airbus A300 included numerous updates of the surface observations for Miami International and alternate airports, including a KMIA SPECI at 1907 UT which related the presence of a tornado in the vicinity of the airport.

3. FLIGHT DATA AND ANALYSIS

The Airbus A300 was en route from Boston, MA to Miami, FL (Figure 2). Just prior to the incident which occurred approximately 10 nmi and 16,000 feet abeam the coast of West Palm Beach Florida, the aircraft was heading 243 degrees and flight level winds were 254 degrees at 26 knots. Over the following 30 seconds, the aircraft appeared to encounter a rapid succession of strong right crosswinds followed immediately by left crosswinds. The oscillations may have been a result of aircrew flight control inputs and not purely wind fluctuations as extracted from the digital flight data recorder (DFDR). Table 1 shows the rapid descent rate experienced by the crew during the encounter and recovery from turbulent flight.

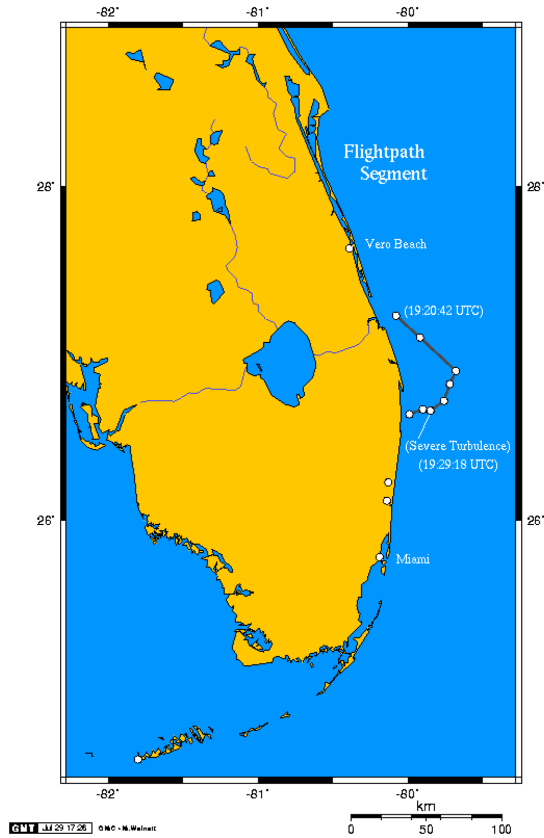


Figure 2. Flight path into severe turbulence.

Although DFDR information was useful for reconstructing the encounter and helping the NTSB analyze problems in aircraft control that arose during the disturbance [Lester, et al., 1989], it did not itself reveal the cause or existence of severe turbulence. In this regard, radar data from the closest available site was obtained for review.

It was unfortunate that the Melbourne WSR-88D was not operational on May 12th. Terminal Doppler Weather Radar (TDWR) data were also not available from West Palm Beach, Fort Lauderdale, or Miami. Radar data analysis (Table 2) is provided along the time- and altitude-phased flight path off the coast of West Palm Beach, FL and is based solely on data obtained from the Miami (KAMX) WSR-88D radar site.

Table 1.
(DFDR and Turbulence Encounter)

TIME (UT)	ALTITUDE (FT)	WINDS (DEG KTS)	COMMENTS
19:29:03	16,107	248 28	
19:29:07	16,103	254 26	Stable flight
19:29:11	16,099	265 28	**Start of incident**
19:29:15	16,099	301 30	
19:29:19	16,327	196 83	Dir and speed shear of 105 deg/53 kts
19:29:23	16,123	335 68	
19:29:27	16,015	232 53	
19:29:31	15,451	343 67	
19:29:35	15,027	219 74	
19:29:39	14,455	328 59	
19:29:43	13,667	240 41	Loss of 788 ft in 4 sec
19:29:47	13,075	325 32	
19:29:49	13,059	Unknown	Max loss of 3268 ft in 30 seconds, implying sink rate over 6000 ft/min– severe turbulence
19:30:00	13,399	250 32	
19:30:04	13,975	250 30	
19:30:12	15,263	248 32	Stable flight
19:30:16	15,839	249 25	

Table 2.
(Analysis of PLAN View Images)

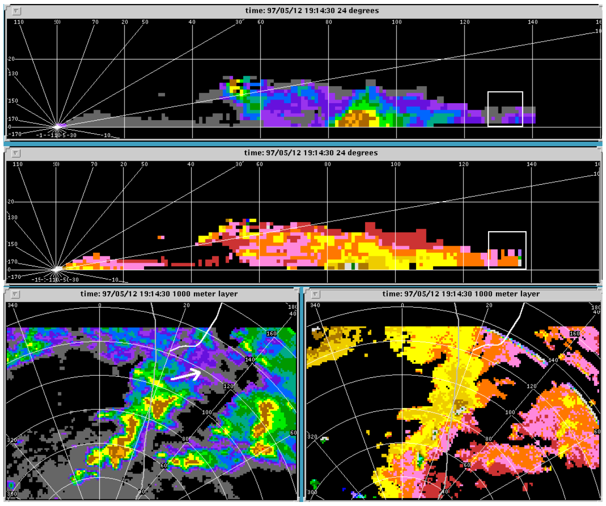
Time (Zulu)	Tilt (deg)	Alt. (m/ft)	Refl. (dBZ)	Vel. (m/s)	Spect. Width (m/s)
19:29:42	0.50	2411/ 7928	31	NA	
19:30:02	0.50	2398/ 7873	29.3	9.5	1.3
19:30:22	0.50	4290/ 14075	27.3	NA	NA
19:30:41	1.45	4224/ 13858	32.0	10.0	0.5
19:31:01	2.40	6314/ 20257	10.5	14.5	1.5

The incident began at 19:29:11 UT, or 31 seconds before the closest Miami WSR-88D volume scan. Given the spatial and temporal constraints, there was nothing in the PLAN view images or analysis to indicate that the aircraft encountered an exceptional vertical or horizontal shear, mesocyclone, tornado, or wind speed maxima. The fact that the low values of spectral widths were found was not completely unexpected. Doviak, et al. (1985) showed that spectral widths corresponding to turbulence greater than moderate were observed in only 30 percent of the volume of a tornadic storm, or that 70 percent of the storm may have only light to moderate turbulence.

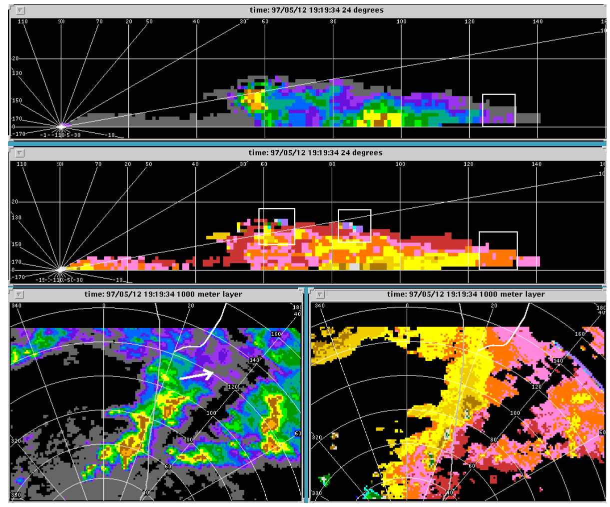
Since PLAN views did not reveal the existence of significant shear, Miami WSR-88D base data were regenerated and cross sectional images constructed in the region between the convection and aircraft flight tract. Vertical (i.e., RHI) images (Figure 3) were made every 5 - 6 minutes, every one degree from 0 degrees to 40 degrees from the Miami NEXRAD out to 140 km. The incident occurred at a range of 125 km - 129 km (67.5 nmi to 69.6 nmi), between an azimuth of 22-25 degrees, and an altitude of 3980 meters (13,059 ft) to 4900 meters (16,107 ft). At the time of the event (1929 UT) the radar scan strategy was VCP11, beam width of 0.95 degrees, and the aircraft was flying within the 0.50 degree and 1.45 degree tilt envelope. At the location of the incident, the long-range resolution was 250 m while the cross-beam (azimuthal/vertical) resolution was 2134 m.

At the time of the incident, the nearest convective cell (level 3/42 dBZ) was located approximately 20 km to the south-southwest, and a likely thunderstorm cell (level 5/54 dBZ) was located 25 km south of the aircraft. Over time, the reflectivity echoes indicated that all cells tracked to the east-northeast. This was the case at multiple levels and is consistent with Doppler velocity signatures and NWS wind field products.

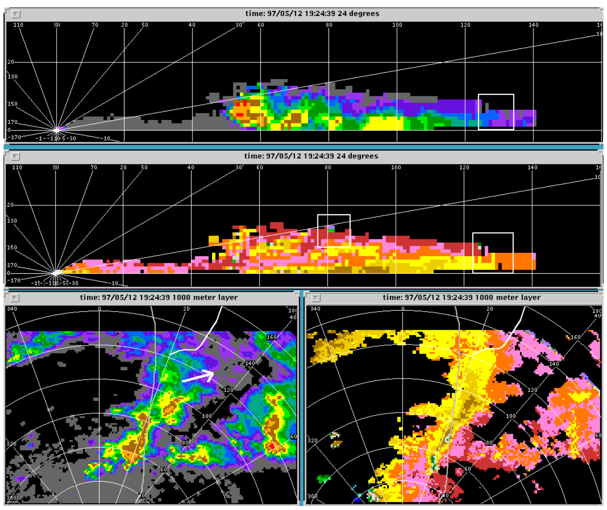
Table 3 was computed along a 24-degree radial from the Miami NEXRAD. The column “Couplet Distance from Airbus Upset” is the distance from the inbound/outbound velocity couplet to the position where the aircraft upset first started (26d 40'06"N 79d 50'30"W, altitude 16,099 ft (4907m), time 19:29:12 UT). The position corresponds to the 24 degree radial at 128 nmi from KAMX. Although certainly not conclusive by themselves, the series of animated cross-sections revealed the existence of a wave or rotor (in top velocity panels) that appeared to propagate towards the aircraft. Since data from only one radar was available, and that is at long ranges (with correspondingly poor spatial resolution), we cannot unambiguously determine that a rotor was present which could have caused the observed aircraft perturbations.



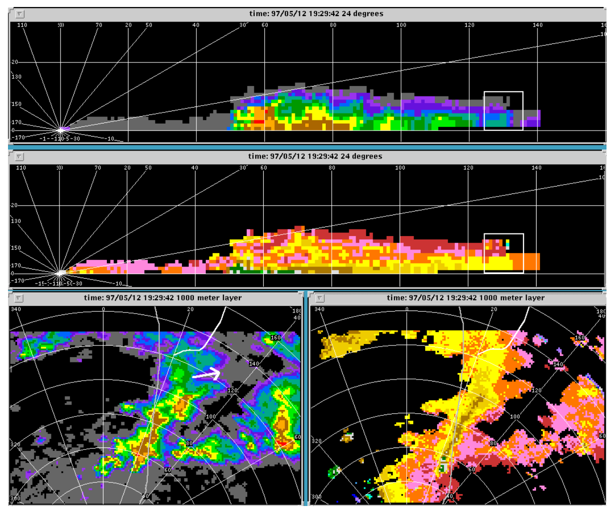
a) Cross section at 19:14:30 UT



b) Cross section at 19:19:34 UT



c) Cross section at 19:24:39 UT



d) Cross section at 19:29:42 UT

Figure 3. Cross-sectional analysis of mishap airspace along the 24-degree radial from 19:14:30 UT to 19:29:42 UT. The top two images within each panel show reflectivity and velocity (top-bottom) while the bottom left and right images show corresponding PLAN views of reflectivity and velocity. Arrow in bottom left image indicates direction of movement of convection.

Table 3.
(Analysis of Cross-sectional Images)

Time (UT)	Vertical Velocity Shear (m/s)		Couplet Alt. from Radar (km AGL)		Couplet Position from Radar (km) (range-altitude)		Couplet Dist. from Airbus Upset (km)
					Rng.	Alt.	
19:19:34	-28.0	+23.0	11.3	14.0	65.0	13.2	62
19:19:34	-25.5	+16.5	10.0	12.0	88.3	10.6	41
19:24:39	-7.5	+23.0	11.3	12.9	81.3	12.0	46
19:29:42	-8.0	+ 8.5	8.0	10.0	131.3	9.2	3

4. TURBULENCE THEORIES

Observations of interactions between convective and environmental flows are challenging because (1) the disturbing convective cells are changing in space and time and are themselves being influenced by the interaction and (2) Doppler radar observations of winds aloft outside of precipitation regions are difficult due to the very low reflectivity levels. Although severe turbulence is known to exist in strong updrafts associated with rapidly building thunderstorms (Kessler, 1985), satellite and radar imagery showed that the aircraft traversed beneath or along the edge of an anvil cloud and therefore may have been subjected to small-scale vertical motions due to condensation/evaporation rather than pure updraft.

Pantely and Lester (1990) and the references contained therein provide an excellent review of mechanisms causing turbulence near and around thunderstorms. Some evidence suggests that turbulence may occur in a three-dimensional wave downwind of individual, rapidly growing cells embedded in a squall line. Cross-sectional images as provided in this paper suggest that a similar wave or rotor may have been produced by upstream convection.

Additional evidence of turbulence can be seen in an experimental sounding generated by NOAA's Forecast Systems Laboratory. The experimental Interactive Aircraft Communications and Reporting System (ACARS) Display (Figure 4) indicates a significant wind shear between 500 mb and 600 mb, the envelope in which the Airbus was flying. The ascent sounding was produced at 2038 UT, lasted for 21 minutes, and covered 195 km.

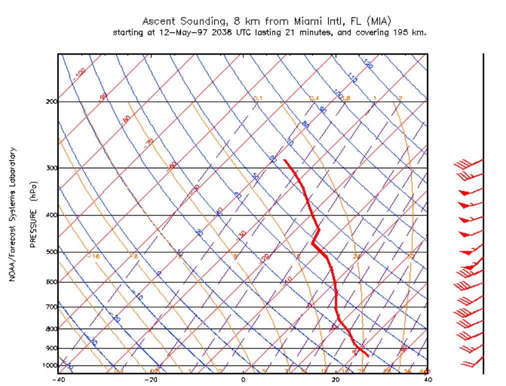


Figure 4. FSL experimental sounding showing wind shear between 600-500 mb, near Miami, FL.

Analysis showed a 21 knot and 25 degree speed/ directional shear (242 35 to 217 56) within 1971 vertical feet (15,649 ft to 17,620 ft). The shear was not detected by either the 12/1200 UT or 13/0000 UT NWS soundings from Miami.

5. CONCLUSIONS

It appears that the Airbus crew was flying in a relatively stable environment sufficiently downwind of active convection to avoid any significant hazards. However, based on the fact that the aircraft was flying downstream of vertically deep and intense convection, and also based on the radar data and theories presented, it is possible that the turbulence may have been induced by some sort of convectively-induced wave or rotor. It was obvious from the study that the true cause of the upset was illusive and not easily deduced by simple examination of aircraft or meteorological sensors or data sets. It may be possible to learn more about convection-induced turbulence through high-resolution numerical simulations such as the Advanced Regional Prediction System (Droegemeier, et al., 1997).

Until the intensity and location of thunderstorm-induced mid-level turbulence can be better detected or inferred through models in real time, general and commercial aviation pilots should continue to adhere to well known thunderstorm avoidance rules-of-thumb. However, it is apparent that even these guidelines may not have been conservative enough for the Airbus A300 flight crew.

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