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7.2 THUNDERSTORM INDUCED GRAVITY WAVES AS A POTENTIAL HAZARD TO COMMERCIAL AIRCRAFT *†

David W. Miller
Massachusetts Institute of Technology
Lincoln Laboratory
244 Wood Street
Lexington, Massachusetts 02420–9185

1. INTRODUCTION

Under certain atmospheric conditions, thunderstorm development can induce a phenomenon known as gravity waves (i.e., buoyancy or density waves). These waves are characterized by alternating regions of convergence and divergence over a relatively short distance. Such aerodynamic shear can become hazardous to air traffic if the shear contained within the waves surpasses the threshold for air traffic safety. Gravity waves are particularly hazardous because they develop in seemingly benign weather surrounding the parent thunderstorm and in many cases are not associated with any visual storm feature. Several cases have been studied in which commercial aircraft have encountered gravity waves and have been adversely affected by their encounters. The purpose of this study is to show how gravity waves can have a detrimental effect on aircraft in flight, how gravity waves can be detected, and that need for a detection algorithm exists.

With the development of the National Weather Service's Next Generation Radar (WSR–88D NEXRAD) and the Federal Aviation Administration's Terminal Doppler Weather Radar (TDWR), the ability to detect gravity waves exists near many of America's major airports. Since gravity waves are a low–level phenomenon (generally below 2 km), their presence should be of interest to aircraft in the takeoff and landing stages of flight. During operations at Lincoln Laboratory's Integrated Terminal Weather System (ITWS) prototype field site in Dallas, there have been at least two incidents in which commercial aircraft experienced wind shear of at least 40 knots on takeoff, possibly caused by single or multiple gravity wave bands.

This study will look at 57 cases of gravity wave formation within the terminal areas of Dallas–Ft. Worth International, Memphis International, and Orlando International airports. Statistics will be compiled to determine the frequency and severity of the gravity waves as well as their duration. The study will include Pilot Reports (PIREPS) from a few of these cases in which aircraft experienced wind shear due to suspected encounters with gravity waves. It is the hope of the author that this study will lead to the development of a detection algorithm that will increase the safety of America's commercial air traffic.

2. GRAVITY WAVE CHARACTERISTICS

When the vertical atmospheric profile contains a strongly stratified stable layer capped by a weakly stratified neutrally stable layer, the conditions exist that allow for the development and propagation of gravity waves to occur. The atmosphere acts to constrain the vertical dispersion of wave energy and thus produces a horizontal wave–guide, (Fulton, et al., 1990). Cool thunderstorm downdrafts help to increase the stability of the boundary layer and thus increases the likelihood for gravity wave development.

In a typical gravity wave event, downbursts from the parent thunderstorm produces an outward moving gust front. As the air mass behind the initial gust front grows more stable, gravity waves begin to develop along the density boundary. The subsequent gravity wave train is basically horizontally symmetrical with uniform wavelengths and wave speeds. The wavelength and wave speeds of the ensuing waves are governed by the depth and stability of the stable layer, (Haase and Smith, 1989) and (Lindzen and Tung, 1976).

The vertical structure of the waves resembles a sinusoidal wave pattern. Above the density boundary the wind direction is that of the environmental winds while the wind direction below this boundary is set forth by the direction of the initial downdraft. The undulating nature of the waves causes downdrafts on the lee side of the troughs above the density boundary and updrafts below the boundary. On the windward side of the troughs, updrafts are produced above the density boundary while downdrafts occur below the boundary (see figure 2). Therefore, the wind speed and direction above the waves can be greatly different from those below the wave train. When most gravity wave trains are viewed using Doppler radar, the direction of the wind in the peaks is opposite in direction to the winds in the troughs. This leads to alternating areas of convergence and divergence assuming a direct path through the waves (such as commercial aircraft would). To illustrate the characteristics of the gravity wave train, figures 1 and 2 depict the Doppler radar signature of a gravity wave train. Figure 1 is the PPI scan from the the MEM TDWR and figure 2 is a vertical cross section along a perpendicular radial to the wave train. In both figures, the light shaded areas are velocities directed towards the radar while the darker shading denotes velocities directed away from the radar.

Corresponding author information:
David W. Miller
MIT Lincoln Laboratoy
DFW ITWS field site
P.O. Box 1957
Grapevine, TX 76099–1957
email dwmiller@ll.mit.edu
Phone: (972) 574–4800 Fax: (972) 574–4724

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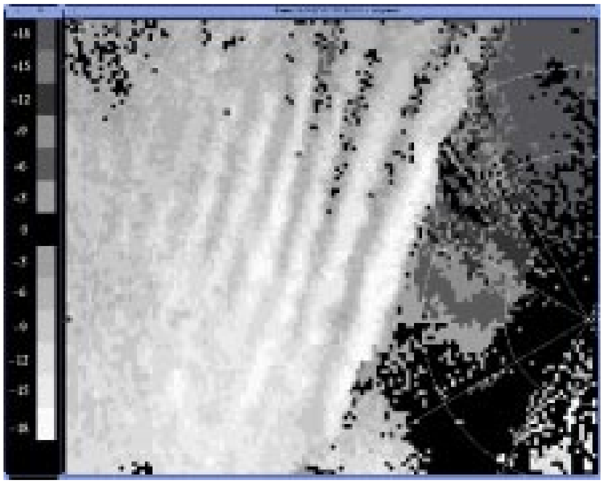

FIGURE 1. *Gray–scale adaptation of the MEM TDWR velocity filed from Memphis, TN at 17:12 UT on January 15, 1997.*

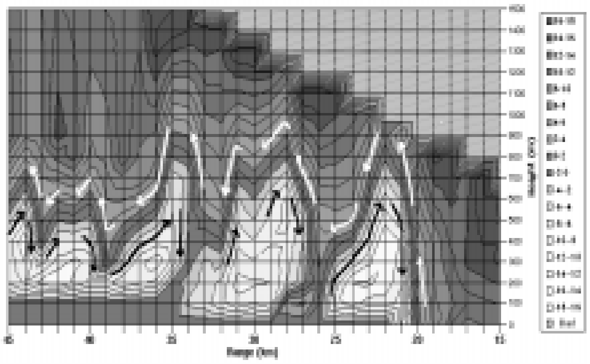

***FIGURE 2**. Compiled vertical cross section of TDWR radar velocity field along the 285 radial using scans from 17:12 to 17:17 UT on January 15, 1997. The white and black arrows indicate the updrafts and downdrafts caused by the undulating waves both above (white) and below (black) the density boundary.*

3. CASE STUDIES – RESULTS

This paper describes the results of 57 gravity wave cases that occurred within the Terminal areas of the Dallas–Ft. Worth International, Memphis International and Orlando International airports. These three airports coincide with Lincoln Laboratory ITWS prototype sites.

Over the course of five years, Lincoln Laboratories have operated field sites at the three airports mentioned above. During this time, gravity waves have appeared at various times and dates at all three sites. In order to analyze the individual cases, information was obtained from such sources at the FAA's TDWR and Low Level Windshear Alert System (LLWAS) as well as the National Weather Service (NWS). Data were also obtained from meteorological sensors positioned on 150–foot towers at both the Memphis and Dallas airports.

Table 1 lists the most recent gravity wave cases used in the study. All together, there are gravity wave cases dating back to June of 1994 and as recently as August of 1998. The table includes the date and location of the gravity waves as well as the wavelength (km) and wave speed (m/s) for each case.

Table 1.
Recent Gravity Wave Cases.

Date	Site	Wavelength (km)	Wave Speed (m/s)
8/8/98	MEM	5.13	10.22
8/7/98 (1)	DFW	5.90	5.26
8/7/98 (2)	DFW	4.23	9.30
8/7/98 (3)	DFW	4.30	5.27
8/6/98	MEM	4.32	3.99
8/3/98	DAL	6.35	7.77
7/13/98	DFW	6.43	9.24
7/8/98	DAL	6.11	9.93
5/26/98 (1)	DFW	5.25	3.31
5/26/98 (2)	DFW	4.94	10.69
5/26/98 (3)	DFW	6.11	14.05
5/7/98	MEM	3.83	6.93
4/26/98 (1)	DFW	3.67	8.02
4/26/98 (2)	DFW	5.01	10.52
4/26/98 (3)	DFW	3.97	6.97
2/17/98	MEM	4.13	6.15
1/22/98 (1)	DFW	13.54	12.01
1/22/98 (2)	DFW	4.86	2.94
1/22/98 (3)	DFW	11.85	10.36
1/6/98	DFW	4.78	7.16
12/24/97 (1)	MEM	6.34	5.56
12/24/97 (2)	MEM	3.36	5.70
12/7/97	DFW	8.25	19.25
12/2/97	DFW	7.31	7.87
10/31/97	MEM	4.78	6.24
10/13/97	MEM	3.35	10.11

***TABLE 1**. Gravity wave cases since October of 1997. Numbers in parenthesis indicate more than one incident on the given date. Site names correspond to the airport TDWR that was used (DFW = Dallas–Ft. Worth; MEM = Memphis; DAL = Dallas–Love). The wavelength is given in km while the wave speed is in m/s.*

Table 1 shows that on five of the 17 dates listed, there were multiple incidents of gravity wave trains. On these days, the atmospheric conditions were very conducive to gravity wave formation. As the atmosphere remained stratified, the further development of thunderstorms gave way to the formation of additional gravity wave trains.

Table 1 reflects a lack of cases from MCO. In total there were only four gravity wave cases observed in Orlando, with one of the days containing multiple cases. Since Orlando is located in a sub–Tropical climate, the atmospheric profile is nearly always conditionally unstable and conditions for the genesis of gravity waves is a relatively infrequent occurrence.

For each case, the wavelength and wave speed were determined from multiple volume scans of the TDWR using the 0.3° tilts. The 0.3° tilt was used since this is the lowest tilt in which a full 360° azimuthal sweep is made.

For each of the cases, the time in which the wave train first appeared on radar as well as when they departed was noted. The time of occurrence for each gravity wave case was placed into hourly bins to determine the most like times of occurrence. This data was then separated in bins of 4 hours each. The results of the time occurrences appears in figure 3.

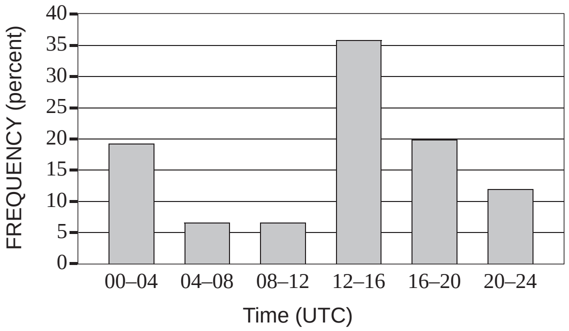

***FIGURE 3**. Percentage of gravity wave cases occurring in the given time bins. Some cases may exist in more than one bin.*

Figure 3 shows that the vast majority of gravity wave cases occurred between the hours of 12Z and 16Z. This is intuitive since maximum surface cooling has peaked and the morning inversion leads to the strongest diurnal stability of the boundary layer. However, during this time period, thunderstorm activity is at a relative minimum.

Gravity waves have occurred during every month of the year, with the largest number of occurrences in late summer (the peak of thunderstorm activity). The frequency of gravity wave cases for each month of the year appears in figure 4.

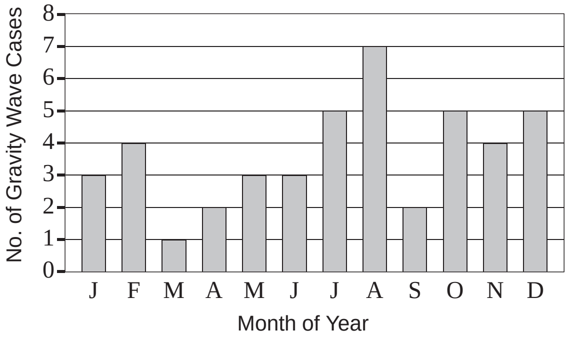

***FIGURE 4**. Number of gravity wave cases occurring during the given months. Multiple cases of gravity waves in a single day count as only one case.*

4. AIR TRAFFIC HAZARDS

Since the atmospheric profile that exists for the formation of gravity waves, dampens the vertical dispersion of the wave energy (Fulton, et al.,1989), the life span of the gravity wave train can last for several hours, allowing the gravity wave train to propagate large distances away from the parent thunderstorm. With the exception of the initial gust front, the gravity wave train usually does not form a cloud structure unless the entire wave train is embedded in a stratus cloud layer. Therefore, there usually is no visual guidance to alert commercial pilots to the existence of gravity waves.

Of the 57 gravity wave cases studied, 31 directly impacted the airports. For each of the cases, the distance from the gravity wave train to the parent thunderstorm was calculated. The results of this are shown in figure 5.

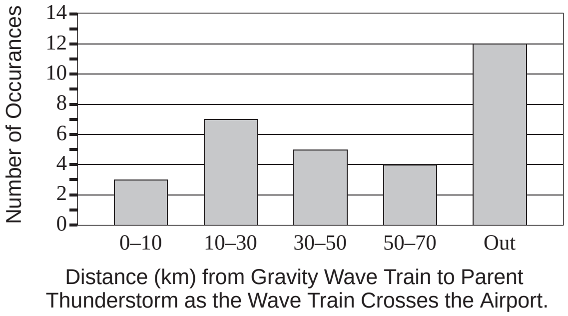

***FIGURE 5**. Number of airport–impacting gravity wave cases at the given distance away from the parent thunderstorm. The category titled "Out" represents cases in which the parent thunderstorm was outside of the range of the radar or the parent thunderstorm had dissipated by the time the waves had reached the airport.*

In this study, most of the gravity wave cases occurred when the parent thunderstorm was far enough away that pilots of commercial aircraft would not expect to experience any thunderstorm–induced wind shear during approach or departure from the airport. Thus, it is important to understand whether the strength of shear when flying through a gravity wave train is enough to cause alarm for the pilots. For each gravity wave case, the maximum shear was calculated between the peak and trough of the wave train (a half–wavelength). Although this does not represent true airspeed losses, it does give an idea of the overall strength of the the gravity waves. Figure 6 shows the strength of the gravity waves as a function of the frequency of occurrence.

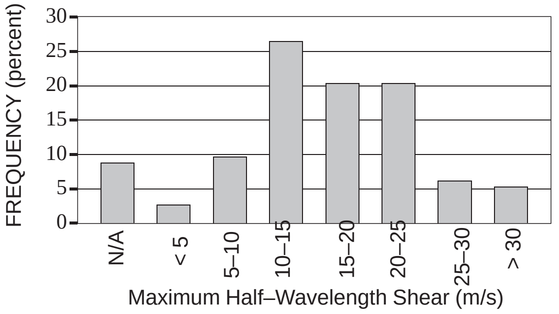

***FIGURE 6**. Percentage of gravity wave cases with the maximum value of shear between the trough and the peak (half–wavelength).*

The shear values in figure 6 and the convergence values in figure 7 were calculated using both the 0.3° and 1.0° tilts of the TDWR (the lowest two tilts with a 360° azimuthal sweep). The N/A represents the percentage of occurrences that failed to appear on the 1.0° tilt.

To determine the actual air speed fluctuations that would be experienced by commercial aircraft, the convergence and divergence values were calculated for each case. The convergence and divergence values were calculated by determining the greatest shear found within a horizontal distance of 1 km. Shear values of 7.5 m/s/km correspond to an air speed fluctuation of 15 knots and are the minimum criteria for issuing alerts over the runways. Shear values of 15 m/s/km or more correspond to air speed fluctuation of greater than 30 knots and constitute dangerous shear over the runways. Figure 7 shows the frequency of occurrence for given values of convergence and divergence. These values were separated according to the criteria for wind shear. Values of less than 7.5 m/s/km are considered weak shear with no alerts; values of 7.5 to 14.99 m/s/km are considered moderate shear with wind shear alerts produced. Values of greater than 15 m/s/km are considered strong shear with microburst alerts issued and values of greater than 25 m/s/km are considered severe shear with microburst alerts issued.

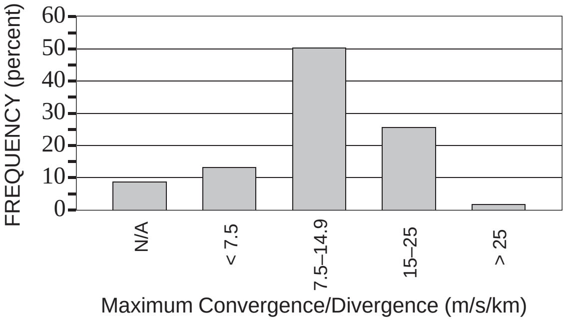

FIGURE 7. *Percentage of gravity wave cases with the maximum values of convergence or divergence found within the wave train excluding that found along the leading edge of the initial gust front.*

For this study, the convergence found along the leading edge of the gust front is excluded from the data set. The reasons for this is twofold. Current algorithms are already in place to detect the convergence associated with the initial gust front. Also, the initial gust front is not considered as part of the gravity wave train since the gust front is a factor in the creation of gravity waves. Thus, the convergence is not included so as not to skew the results.

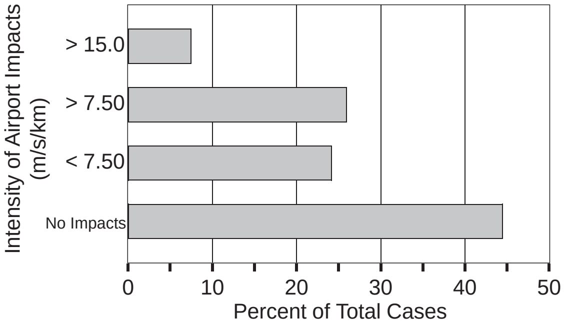

FIGURE 8. *Percentage of gravity wave cases inducing wind shear impacts at the airport.*

The results in figure 7 show that the vast majority of gravity wave cases would cause a commercial aircraft to experience airspeed losses of at least 15 knots (7.5 m/s/km). More importantly, it must be determined how many of the total gravity wave cases actually impacted the airport and to determine the strength of these impacts. Figure 8 shows the percentage of gravity wave cases that exhibited various wind shear strengths as they impacted the airport. In 44% of the cases, the gravity wave train never impacted the airport.

During the course of operations at the ITWS prototype sites, it is common practice to record Air Traffic Control (ATC) communications at times when the airport is impacted by heavy weather. On several occasions, recordings were made as gravity waves impacted the airports. Table 2 shows a sampling of PIREPS for 6 cases in which pilots reported wind shear as they passed through gravity waves. In all 6 cases, gravity waves impacted the airport when they were within 15 km of the parent thunderstorm. Therefore, recordings of ATC communications were underway. However, as shown in figure 5, most of the gravity wave cases impacted the airport when they were a great distance from the parent thunderstorm. This resulted in the lack of additional recorded PIREPS from the other airport–impacting cases.

Table 2.
PIREPS from Several Gravity Wave Cases

Date	Site	PIREP
2/16/96	MEM	1458: –10 kts @ 200 ft
6/18/96	MEM	1220: + 10kts @ 400 ft till landing
1/15/97	MEM	1723: – 10kts @ 100 ft
		1731: – 20kts @ 500 ft
		1733: – 10kts, fluctuated up and down the whole way down
		1801: +/– 10kts
		1809: +/– 10kts @ 500 ft till landing
2/27/97	MEM	0337: +/– 10kts @ 100 ft
		0353: –10kts @ 2100 ft
		0407: +10kts @ 500 ft
12/12/97	MCO	1540: + 50kts then –50kts. Aircraft windshear warning issued. Missed approach
		1543: +20kts @ 1000 ft to 500 ft
12/24/97	MEM	0722: +/– 10kts
		0728: –25kts on final
		0743: –25 to –27kts

TABLE 2. *Selected PIREPS from airport–impacting gravity wave cases. Times are given in UTC.*

In addition to the ATC recordings obtained at the ITWS prototype sites, 2 additional incidents occurred in which serious consequences were narrowly averted when commercial aircraft encountered thunderstorm–induced gravity waves. On April 12, 1996, a commercial aircraft encountered a gravity wave train as it was departing from the Dallas–Ft. Worth Airport, (Meuse, et al.,1996). The aircraft experienced a 40 knot loss shortly after leaving the runway, which resulted in the pilots using full throttle. This forced the plane to make an unscheduled landing in Tulsa, OK in order to inspect the engines. The pilot reported that the airplane experience a 60° roll as he encountered the waves. Voice communications between the pilots and the tower indicated that they “thought we were going to lose it.” Prior to this incident, an intense squall line had moved through the area. The incident occurred when the squall line was about 40 km east of the airport. Although skies remained overcast, precipitation had ended at the airport.

Another incident occurred on November 6, 1996 at the Dallas–Ft. Worth airport. Thunderstorms located 35 km northwest of the airport produced a gust front that tracked southeastward across the airport. An intense gravity wave train formed behind the initial gust front. An aircraft experienced a 40 knot loss shortly after takeoff. The incident alarmed the pilots so much that the landing gear was not raised until they had reached 5000 ft.

Since there have been several incidents in which aircraft have experienced wind shear due to gravity waves, it is prudent that an algorithm be developed to detect these potentially hazardous features. Currently, algorithms exist to detect the initial gust front which has long been identified as a region of low altitude wind shear dangerous to safe flight, (Doviak and Christie,1989). However, there are several factors that inhibit the detection of the gravity waves. The initial gust front is oftentimes associated with a distinct thin–line reflectivity feature that aids in the detection of the gust front. With gravity wave trains, there is not always a defining thin–line reflectivity feature.

In addition, the initial gust front is often moving against the environmental flow. This results in a well distinguished feature in the velocity field. Although a similar feature occurs with gravity waves, it is not always as distinct. The ITWS gust front detection algorithm could be changed to be more sensitive to detect these weaker features but this would result in an unacceptably high false–alarm rate.

Another problem occurs because there is also a divergent signature associated with gravity waves. The divergent feature is most similar to a microburst signature. Currently, the ITWS microburst detection algorithm is incapable of detecting the divergence within the gravity wave train. The reason for this is that the ITWS microburst detection algorithm uses a threshold on associated vertically integrated liquid water content (VIL) to diminish the chances for false alarms. Since gravity waves form away from the convective activity, the algorithm would ignore the divergence found within the gravity waves.

Since neither of these algorithms are designed to detect the gravity wave feature, a new algorithm needs to be developed specifically to detect these features. A hybrid of the two algorithms with feature detectors designed to detect gravity waves is feasible. With the addition of a detector to identify the atmospheric profile necessary for gravity wave formation, the instances of false alarms can be greatly reduced.

5. CONCLUSIONS

Gravity waves have been shown to be a potential hazard to commercial aircraft. With the use of the TDWR and other meteorological instrumentation, gravity waves can be readily detected. A viable algorithm to detect these waves is not only feasible but is necessary to protect the safety of commercial aircraft from this potentially hazardous phenomenon.

6. ACKNOWLEDGEMENTS

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