10.9 LOW ALTITUDE BUOYANCY WAVE TURBULENCE – A POTENTIAL AVIATION SAFETY THREAT

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1. INTRODUCTION†

Weather comprises one of the most signficant safety hazards facing civilian aviation today. This hazard has been signficantly reduced by the development and use of microburst wind shear detection technologies such as the Low Level Wind Shear Alert System (LLWAS), the Terminal Doppler Weather Radar (TDWR), the ASR-9 Weather Systems Processor (WSP) and the Integrated Terminal Weather System (ITWS). Each was designed to detect and warn for the presence of low altitude wind shear resulting from microburst and gust fronts. These systems have made an unquestionable improvement in aviation safety; however, there are other forms of low altitude wind shear hazardous to aviation.

This paper provides a description of a low altitude buoyancy wave (BW) induced turbulence phenomena that appears to also be a significant hazard to aviation. Buoyancy wave turbulence can be particularly dangerous since it often occurs outside regions containing intense precipitation where pilots typically expect to encounter thunderstorm induced wind shear conditions. Section 2 of this paper contains a general description of BW phenomena based on laboratory and observational studies. Section 3 will briefly summarize several incidents where commercial and civilian aircraft have encountered buoyancy waved induced turbulence. A summary and conclusions are made in section 4.

2. BACKGROUND

Buoyancy waves, often referred to as gravity waves, are a general description given to an atmospheric phenomena, which forms in response to a perturbation of an air parcel in a thermodynamically stable environment. This phenomenon can occur acorss a relatively broad spectrum of scales ranging from 10's of km to 100's of meters. The present study examines buoyancy waves that form at the smaller end of this spectrum. These waves form on the density discontinuity along the upper surface of a thunderstorm outflow. The instability that causes these waves develops in response to vertical shear in the horizontal winds in the boundary layer. Figure 1 illustrates an idealized thunderstorm outflow encountering vertical shear in the horizontal winds and depicts the type of conditions that would support BW development.

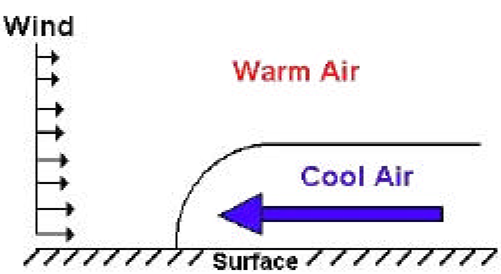

Figure 1. An idealized thunderstorm outflow encountering vertical shear in the environmental winds.

2.1 LABORATORY AND THEORETICAL STUDIES

The formation of buoyancy waves along the density discontinuity between two fluids is a fairly well understood physical process. Much of the physical understanding of this type of wave disturbance was gained from laboratory experiments. These experiments examined fluid motions resulting from the introduction of a more dense fluid into a lower density fluid environment. Similar processes occur in the atmosphere when cool, more dense air from a thunderstorm downdraft is introduced into an environment of warmer, less dense air. Simpson (1969) utilized a saline solution and pure water to examine this type of fluid interaction and compared them to observations of atmospheric density flows. His study provided physical descriptions and photographed examples of turbulence that develops along the upper boundary of the density current. Figure 2 is a photograph of a density current in a transparent tank from Simpson (1969).

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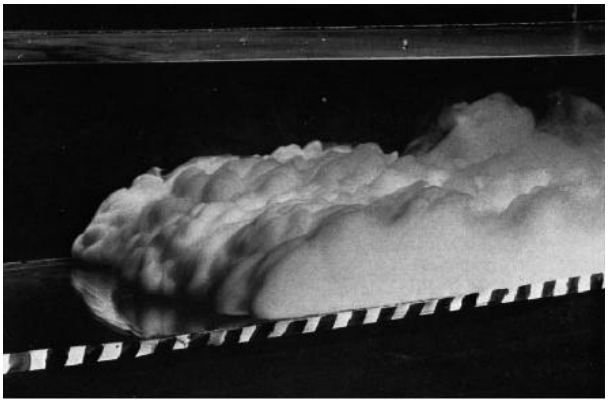

Figure 2. Density current in a transparent tank. The strip at the bottom is marked in intervals of 1 cm. (Simpson, 1969)

Subsequent studies using two-dimensional atmospheric numerical models have provided additional insights into the interactions that occur in a two fluid system. Simulations by Xue et. al. (1996) also showed that instabilities can develop along the density discontinuity at the upper surface of a density current and vary in response to the vertical environmental shear that they encounter. These findings confirmed earlier work by Droegemeier and Wilhelmson (1987), which indicated that vigorous Kelvin-Helmhotz (KH) waves develop along the upper surface of the density current associated with the thunderstorm outflow. Their work showed that the KH wave development on thunderstorm outflows can result in strong low level turbulent mixing.

2.2 BUOYANCY WAVE OBSERVATIONS

Buoyancy waves similar to those described earlier by laboratory and numerical modeling studies are frequently observed in the atmosphere. This class of atmospheric wave disturbance forms in a vertically stratified stable environment. The stable stratification in the lower atmosphere provides a wave-guide along which the energy propagates horizontally. The stability also inhibits much of the vertical dissipation of wave energy. In this situation, atmospheric stability acts as the restoring force since more [less] dense air displaced up [down] tends to return to its original altitude. This type of situation commonly occurs following the passage of a thunderstorm outflow or a sea breeze.

This study examines the BW turbulence that forms behind thunderstorm outflows. Data used in this study were collected at the MIT Lincoln Laboratory ITWS field sites located in Dallas, TX, Memphis, TN and Orlando, FL. Detailed analyses of thunderstorm outflow induced BW turbulence have been documented by Meuse et. al. (1996), Miller et. al., (1997) and Miller (1999). These studies identified numerous cases in which BW turbulence impacted air traffic operations at the ITWS field sites. All of these studies primarily used radial wind and radar reflectviity data from the TDWR; however, the Meuse et. al. (1996) and Miller et. al., (1997) studies also utilized surface pressure and wind data to verify the presence of buoyancy waves. In cases where both wind and pressure data were available, fluctations in speed and direction of the wind were compared to oscillations in surface pressure. Pressure jumps of up to 2.6 mb occurred in conjuction with wind speed changes of 10 m/s and 40° directional shifts in wind direction. Similar patterns between correponding wind speed/directional shifts and pressure jumps/falls were consistently seen in all of the analyzed cases.

In the presence of adequate scatters, BW turbulence can be detected in the radial velocity data from Doppler weather radars. The phenomenon appears as a succession of increasing and decreasing radial velocity “waves”. An example of the BW turbulence is shown in Figure 3. Here a 0.3° elevation, planned position indicator (PPI) velocity field detected by the Memphis International Airport (MEM) TDWR on January 15, 1997 illustrates a typical BW turbulence signature.

In this figure the warmer colors (i.e. reds and yellow’s) represent outbound velocities while the cooler colors (i.e. blue and greens) indicate inbound radial velocities. The BW turbulence signature can be seen to the west of the MEM TDWR located on the right hand side of the image. These images portray the characteristic signature of oscillating radial winds found in most radar detected BW turbulence. Although not shown in this paper, localized maximums of radar reflectivity coincide with the maximums of inbound velocity and correspond with the BW wave crests.

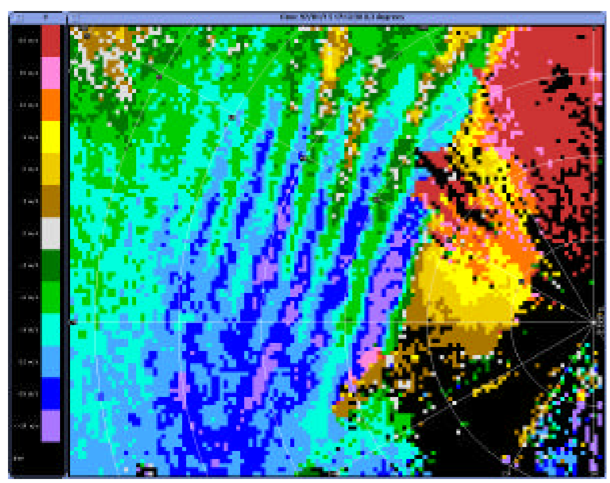

Figure 3. Radial velocity image of a buoyancy wave event from the MEM TDWR. This image represents the event at 1712 GMT on January 15, 1997.

A cross-sectional view of the same case is shown in Figure 4. Here the radial winds are shown for radar cross-section through the BW feature along the 285° radial. The data in this cross-section are from the 0.1°, 0.3°, 1.0° and 2.3° elevation tilts and again the warm colors represent outbound winds and cool colors represent inbound winds. Vertical soundings of temperature and dew point temperature based on data from MDCARs aircraft reports indicate that at the time of the gust frontal passage, the stable layer depth in this case extended from the surface to approximately 730 m. This is consistent with the cross-section showing BW waves at nearly the same altitude. The cross-sectional representation highlights that this is indeed a shallow phenomena whose depth is related to the depth of the thunderstorm outflow.

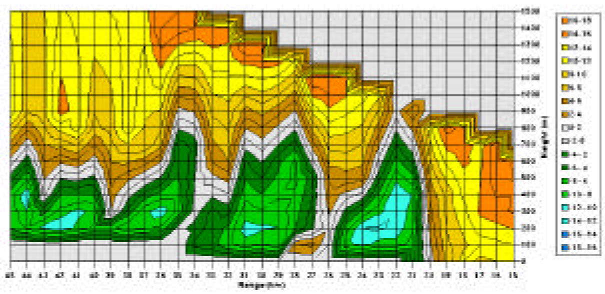

Figure 4. A vertical cross-section of MEM TDWR radial velocity data along the 285° radial. The cross-section represents the conditions collected at approximately the same time as the data displayed in figure 3.

The effect of wind shear on aircraft is often measured in terms of horizontal shear encountered over a prescribed distance. Shear in the environmental winds causes the aircraft to experience dangerous airspeed fluctuations, which are particularly hazardous during approaches or initial climbout. A shear in the horizontal winds of at least 7.5 m/s per km is requied by the TDWR and ITWS systems to issue a wind shear alert. This type of alert indicates moderate wind shear is present and that caution should be taken when attempting to land. A horizonal wind shear of 15 m/s per km or greater is used to indicate dangerous wind shear conditions. In this case, hazardous wind shear conditions are present and aircraft approach and landing is not advised.

Buoyancy wave induced wind shear can cause similar wind speed fluctuations. An analysis of cases collected from June of 1994 through August of 1998 by Miller (1996) found that a vast majority of the identified cases that he analyzed contained wind shear in excess of 7.5 m/s per km. His study only utilized wind shear measurements behind the initial gust front boundary since algorithms currently exist to warn for dangerous wind shear associated with gust front passages. Figure 5 shows a graph depicting the frequency of occurrence in a data set versus the intensity of the BW wind shear (Miller, 1999).

3. THREAT TO AVIATION

Observational data suggests that BW induced turbulence is capable of producing sufficient horizontal wind shear to be potentially hazardous to aviation. Furthermore, this phenomenon occurs at low altitudes where wind shear of this magnitude from thunderstorm microbursts has caused numerous aviation fatalities. Commercial and civilian aircraft typically avoid the well-known wind shear hazards posed by microbursts and gust fronts; however, few are aware of the potential threat of BW wind shear behind the initial gust front. This wind shear hazard is typically present outside of regions where pilots have been trained to anticipate low altitude wind shear.

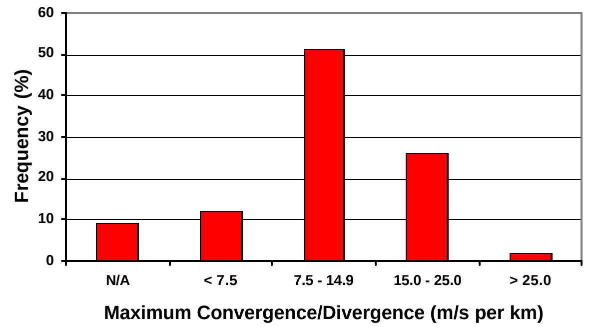

Figure 5. Percentage of analyzed gravity wave cases with maximum values of convergence and divergence. Data in this figure excludes that found along the leading edge of the initial gust front.

Numerous commercial encounters with BW turbulence have been documented at the MIT/LL ITWS field sites. Pilot reports (PIREPS) and aircraft to tower communications have ben examined when buoyancy waves were present in the flight path. Pilots commonly reported airspeed losses from +/- 10 knots to +/- 50 knots during critical phases of flight. The most hazardous occurred on approaches at altitudes below 1000 feet. The airspeed gains and losses often persisted until aircraft touchdown. On several occasions the airspeed fluctuations were severe enough to warrant aborting the approach.

Buoyancy wave induced wind shear can also impact departing aircraft. Over the past 4 years several incidents have occurred that can be attributed to BW turbulence encounters. On April 12, 1996 a MD80 operated by a major US airline encountered severe wind shear during takeoff from the Dallas-Ft. Worth International Ariport (DFW). The aircraft experienced in excess of a 40-knot loss in airspeed and 60° roll during the encounter. The flight crew engaged a full-throttle, nose up escape maneuver that allowed them to successfully escape the wind shear.

Immediately following the wind shear encounter, the MD80 was diverted to Tulsa, OK for a precautionary inspection. It was found that the aircraft sustained considerable damage from engine overspeed during the escape maneuver. A meteorological post analysis of the event revealed that it was likely that the aircraft encountered BW wind shear and not microburst induced wind shear as earlier suspected. The Aviation Safety Institute cited this incident as one of the "Accidents That Didn't Happen" in 1996.

A similar encounter occurred at DFW on November 6, 1996. In this case, a commercial aircraft encountered a 40-knot airspeed loss shortly after takeoff. The incident alarmed the flight crew to such an extent that they did not raise the landing gear until the airplane reached

5000 ft. A post analysis of this event attributed the wind shear encounter to BW turbulence (Miller, 1999).

To date there have been no fatal commercial airline crashes that have been attributed to this type of wind shear. Unfortunately the same cannot be said for general aviation. MIT/LL was involved in an investigation of the crash of a twin engine Beech Baron that occurred near Max Westheimer Airport (OUN) at Norman, Oklahoma. The initial NTSB investigation indicated that it was possible that the crash was a result of an encounter with adverse weather conditions. The nature of the weather that was encountered was not clear since the crash occurred outside of any significant weather echoes. A subsequent analysis of the meteorological data surrounding the time of the crash indicated that there was BW turbulence in the vicinity of OUN. This data, in conjunction with the flight track and aircraft-tower communcations indicate that it is highly probable that the Beech Baron encountered BW turbulence during the last several minutes of the flight.

4. CONCLUSIONS

Aviation safety has been the beneficiary of significant advancements in the understanding of mesoscale wind shear phenomena. The discovery and research into microburst and gust front wind shear led to the development of wind shear detection and warning systems which have unquestionably saved lives and made air travel safer. It appears; however, that there are other forms of wind shear and turbulence which may also be a significant hazard to aviation. Prior to its identification, researchers did not realize the significant threat that microburst wind shear posed to flight safety. Unfortunately many people lost their lives prior to the discovery of this phenomena and the development of tools to detect and warn of its presence. In an analogous sense, wind shear attributed to BW turbulence is just now being recognized as a potentially significant hazard to flight safety. It frequently occurs in regions of airspace typically considered to be safe from low altitude wind shear. Current wind shear detection systems are not designed to detect and warn for this phenomenon. To date there have fortunately been no major aviation disasters attributed to this phenomena. Evidence from the incidents that have occurred, suggest however that BW turbulence is capable of producing dangerous wind shear conditions during critical phases of flight.

Further research into BW turbulence is required to better understand the conditions in which it forms, and the extent of the hazard that it poses to aviation safety. This BW induced wind shear hazard assessment will require a determination of wind shear magnitude that can be expected along with frequency of occurrence. The meteorological assessment should be then combined with aircraft performance characteristics to identify which aircraft would be most affected and the likelihood of a potentially dangerous encounter. Many similarities exist between BW turbulence and microburst wind shear. Initially both were poorly understood and early research indicated that they posed a threat to aviation safety. It is now time to determine whether BW turbulence poses enough of a threat to aviation safety to warrant the development and deployment of a detection and warning system.

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