NASA/CR–2013-217989

An Examination of Aviation Accidents Associated with Turbulence, Wind Shear and Thunderstorm

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May 2013

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Prepared for Langley Research Center
under Contract NNL12AA09C

May 2013

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Introduction

One of the technical challenges within the Atmospheric Environment Safety Technologies (AEST) Project is to "improve and expand remote sensing and mitigation of hazardous atmospheric environments and phenomena"[1]. Although numerous statistical studies of aviation accident and incident data have been conducted in the past regarding the accident categories of Turbulence and Windshear/Thunderstorm [2,3,4], AEST Project Management desired additional information regarding distinct subgroups of atmospheric hazards within those categories, in order to better focus their research portfolio toward the most common types of atmospheric hazards. The focal point of this study was the definition and examination of turbulence, wind shear and thunderstorm in relation to aviation accidents. Several literature sources were examined and influenced the study parameters. These include:

- Characterizing the Severe Turbulence Environments Associated with Commercial Aviation Accidents[5],
- A Federal Aviation Administration (FAA) Review of Aviation Accidents Involving Weather Turbulence in the United States 1992-2001[6],
- Aviation Occurrence Categories: Definitions and Usage Notes, Advisory Circular: Thunderstorms[7],
- A National Transportation Safety Board (NTSB) Study of Risk Factors Associated with Weather-Related General Aviation Accidents[4].

The paper by Michael Kaplan and several others[5] described the results of 44 case study analyses that defined the atmospheric structure prior to the development of accident-producing turbulence. His work resulted in the definition of a set of turbulence categories. Analyses by the FAA[6], NTSB[4] and others have similarly attempted to categorize turbulence and thunderstorms. Many of these have substantial overlap in their categories, but none are identical. For this study, we developed an atmospheric hazard taxonomy which draws on all of these papers, with the following categories:

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[1] Atmospheric Environment Safety Technologies (AEST) Project Plan. October 1, 2010 (Updated on October 21, 2011)

[2] Evans, J.K., "An Examination of Aviation Accidents and Incidents During the years 1989-2008 Associated with Technical Challenges within the Atmospheric Environment Safety Technologies (AEST) Project." Internal NASA Report; March 2012.

[3] Evans, J.K., "Frequency of Specific Categories of Aviation Accidents and Incidents During 2001-2010." Internal NASA Report; August 2012.

[4] National Transportation Safety Board. 2005. Risk Factors Associated with Weather-Related General Aviation Accidents Safety Study.

[5] Kaplan, M.L., Huffman, A.W., Lux, K.M., Charney, J.J., Riordan, A.J., Lin, Y.-L., "Characterizing the severe turbulence environments associated with commercial aviation accidents," Meteorology and Atmospheric Physics, Vol 88, 2005, pp. 129-152.

[6] National Aviation Safety Data Analysis Center (NASDAC) FAA Office of System Safety. 2004. Review of Aviation Accidents Involving Weather Turbulence in the United States 1992-2001. URL: http://www.asias.faa.gov/aviation_studies/turbulence_study/ turbulence_study _new.pdf.

[7] Federal Aviation Administration. 1983. Advisory Circular: Thunderstorms. URL: http://rgl.faa.gov/Regulatory_and_Guidance_Library/rgAdvisoryCircular.nsf/list/AC%2000-24A/$FILE/ac00-24b.pdf

1. Wake Turbulence (WAKE): Wake turbulence is a by-product of lift and is present behind every aircraft in flight. Once the aircraft is airborne, two counter rotating cylindrical vortices are created, which are hazardous to any trailing aircraft. This is particularly true during take-off, initial climb, final approach and landing, when the high angle of attack at which the aircraft operates maximizes the formation of strong vortices.

2. Mountain Wave Turbulence (MTN): Mountain wave turbulence occurs when air flows are forced to rise up the windward side of a mountain barrier, then as a result of certain atmospheric conditions, sink down the leeward side. This perturbation develops into a series of waves which may extend for hundreds of miles.

3. Clear Air Turbulence (CAT): Clear air turbulence typically occurs in cloud-free regions at higher altitude, widely separated from mountains, and often is associated with wind shear, particularly between the core of a jet stream and the surrounding air.

4. Cloud Turbulence (CLD): This turbulence phenomenon occurs in cloud covered regions without the requirements of convection or precipitation reaching the ground.

5. Convective Turbulence (CONV): An air mass which absorbs heat from the earth's surface will rise. As the air rises, it cools, and eventually the cooler air mass descends. This cycle of rising and falling air is known as convection. Convective turbulence occurs within, or in close proximity to, convective storms, particularly thunderstorms, which result in strong updrafts and downdrafts.

6. Thunderstorm, with no turbulence (TRW): This hazard category is restricted to thunderstorms, with or without microbursts or wind shear, but with no mention of turbulence.

7. Low Altitude Wind Shear, Microburst or Turbulence (LAWMT): This category consists of wind shear, microbursts or turbulence occurring at low altitude, with no mention of thunderstorms.

This report examines the historical aviation accidents, using the National Transportation Safety Board (NTSB) Aviation Accident and Incident Data System (restricted to 1987-2008). All US-based accidents with a cause or factor of turbulence, thunderstorm, wind shear or microburst were assigned to only one of the seven categories defined above, and this report summarizes the differences between the categories in terms of factors such as flight operations category, aircraft engine type, the accident's geographic location and time of year, degree of injury to aircraft occupants, aircraft damage, age and certification of the pilot and the phase of flight at the time the flight encountered severe weather. All percentages shown in tables or charts are based on the totals for the particular category listed above. Twelve accidents for which the accident report did not provide sufficient detail to classify the type of turbulence with confidence were eliminated from the analysis.

Methods

The National Transportation Safety Board is an independent Federal agency that investigates every civil aviation accident in the United States and significant accidents in the other modes of transportation, conducts special investigations and safety studies, and issues safety recommendations to prevent future accidents. The information the NTSB investigators collect during their investigations of these aviation events resides in the NTSB Aviation Accident and Incident Data System. A copy of this database in Microsoft Access format was obtained from the Aviation Safety Information Analysis and Sharing (ASIAS) department of the FAA's Office of Aviation Safety[8] in March 2010. At that point in time, the NTSB investigation was not complete for a substantial number of 2009 accidents, particularly those which occurred toward the end of the year. For this reason, all work on the database was restricted to 1987-2008, which was primarily an update of two years beyond the previous working version of the data. The update process requires several months of cross-checking various data elements and attempting to fill in any missing data, followed by the assignment of occurrence categories to each accident.

The NTSB database includes events involving a wide variety of aircraft (airplanes, helicopters, hot air balloons, gliders, ultralight, etc.) with operations conducted under various Federal Aviation Regulations (Part 91: General Aviation, Part 121: Commercial Air Carriers, Part 129: Foreign Air Carriers, Part 135: Commuters and On-Demand Air Taxis, Part 137: Agricultural Operations, etc.).

The NTSB considers each event to be either an accident or an incident, under the following definitions:[9]

Accident -	an occurrence associated with the operation of an aircraft, which takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage
Incident -	an occurrence other than an accident, associated with the operation of an aircraft, which affects or could affect the safety of operations

Any injury or aircraft damage which occurs when there was no intent for flight (high speed taxi tests, movement of the aircraft around the airfield, maintenance run-ups, etc) is, by definition, an incident.

All recorded accidents involving commercially built fixed-wing airplanes operating under FAR Part 121, Part 135 or Part 91 were included in these working datasets, regardless of whether the investigation is in a preliminary stage or finalized, and whether or not the event occurred within the United States. Amateur built or experimental aircraft were excluded, as were helicopters, ultra light aircraft, gliders and balloons.

[8] http://www.asias.faa.gov/portal/page/portal/asias_pages/asias_home/

[9] National Transportation Safety Board, "Government Information Locator Service (GILS): Aviation Accident Synopses"' http://ntsb.gov/Info/gils/gilssyn.htm

For every accident, the NTSB records a series of occurrence codes (e.g., In Flight Encounter with Weather, Loss of Control – In Flight, Hard Landing, etc.) and the associated phase of flight. They also record causes, factors and findings associated with each occurrence. Causes are actions or events that lead directly to the accident, while factors are actions or events that contributed to the accident. Each accident can have multiple causes and multiple factors[10]. Findings are actions or events that occurred in conjunction with the accident, but no determination was made that they contributed to the accident. For example, the aircraft might have flown in the area of a thunderstorm with lightning, but the lightning had no impact on the flight or the accident, so lightning is recorded as a finding. Similarly, the pre-flight weather briefing might have included turbulence, icing and low ceiling, but if there was no indication that the flight actually encountered turbulence, it would be considered only a finding.

Accidents were selected for inclusion in this study if turbulence, thunderstorm, wind shear or microburst was considered either a cause or a factor (but not a finding) in the accident report. The main interest in this analysis with regards to thunderstorms is the effect of turbulence and other types of wind. Five accidents in which the primary occurrence was a lightning strike or hail damage were excluded, despite the obvious connection to thunderstorm activity. These would be considered part of a separate category, based on the taxonomy described above. Similarly, accidents resulting from jet blast and propeller/rotor wash have been excluded, despite being included in the definition for wake turbulence from the Aeronautical Information Manual (AIM)[11]: "A phenomena resulting from the passage of an aircraft through the atmosphere. The term includes vortices, thrust stream turbulence, jet blast, jet wash, propeller wash, and rotor wash both on the ground and in the air." This study is interested in the more focused definition of "off the ground" wake turbulence that was provided in the introduction.

In order to describe the types of aircraft which were involved in these accidents, the specific aircraft make and model (and in many cases, aircraft series) was determined for each accident. For the vast majority of events, this information could be easily found in the data record. For some events it was necessary to consult the FAA's aircraft registry database, and to assume that the correct aircraft registration number was recorded in the data system. All aircraft in the data system for the chosen time period (1987-2008) were divided into groups based on some combination of engine type, aircraft use, aircraft size and aircraft complexity. The aircraft categories are as follows, and a list of the particular aircraft models (sometimes including series information) within each category can be found in Appendix A.

- Wide Body Jet Airliners
- Narrow Body Jet Airliners
- Regional Jets
- Medium Sized Business Jets
- Small Business Jets (maximum takeoff weight <= 12,500 lbs)

[10] https://asafe.larc.nasa.gov/DOC/definitions.html
[11] http://www.faa.gov/air_traffic/publications/ATpubs/AIM/aim.pdf; page PCG-W1.

- Large Turbo-props (maximum takeoff weight >= 32,000 lbs and more than 30 seats)
- Medium Turbo-props (12,500< maximum takeoff weight <32,000 lbs or 15-30 seats)
- Small Turbo-props (maximum takeoff weight <12,500 lbs and less than 15 seats)

- Heavier multiple reciprocating engines (maximum takeoff weight >15,000 lbs)
- Lighter multiple reciprocating engines (maximum takeoff weight < 15,000 lbs)
- Single reciprocating engine, retractable landing gear
- Single reciprocating engine, fixed landing gear
- Light Sport Aircraft (Rotax Engines)

Results and Discussion

Eight hundred sixty-four accidents were considered in this analysis; these were all affected by some sort of turbulence, thunderstorm, wind shear or microburst, or a combination thereof. In this report, these weather conditions will be referred to collectively as "Atmospheric Hazards." Each accident was assigned to only one hazard category. Sixty-nine of these flights (8.0%) encountered wake turbulence, sixty-eight (7.9%) were affected by mountain wave turbulence, one hundred thirteen (13.1%) encountered clear air turbulence, eighty-nine (10.3%) were affected by turbulence in clouds, one hundred fifty-six (18.1%) were classified as convective turbulence, one hundred seventy-seven (20.5%) encountered thunderstorms with no mention of turbulence, and one hundred ninety-two (22.2%) were affected by low altitude wind shear, turbulence or microburst with no mention of thunderstorm.

Flight Operations Category

Table 1 and Figure 1 show how these events were distributed among flight operations. Although wake turbulence is caused primarily by large jets[12], its effects are felt most among Part 91 flights (83%). Similarly, Part 91 flights account for nearly all accidents attributed to mountain wave turbulence (90%), thunderstorms with no turbulence (91%) and low altitude wind shear, turbulence or microburst (92%). Clear air turbulence primarily affects Part 121 (75%), while both cloud and convective turbulence are split more evenly between Part 121 and Part 91. Part 135 accidents accounted for between two and ten percent of the atmospheric hazards which were examined here (5% overall), and roughly five percent of all accidents in this time frame.

[12] Nelson, R.C., "The Trailing Vortex Wake Hazard: Beyond the Takeoff and Landing Corridors." American Institute of Aeronautics and Astronautics. 2004-5171.

Table 1. Flight operations among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Part 121	Part 135	Part 91	Total
Wake Turbulence	5 (7.2%)	7 (10.1%)	57 (82.6%)	69 (100%)
Mountain Wave Turbulence	4 (5.9%)	3 (4.4%)	61 (89.7%)	68 (100%)
Clear Air Turbulence	85 (75.2%)	3 (2.7%)	25 (22.1%)	113 (100%)
Cloud Turbulence	36 (40.4%)	6 (6.7%)	47 (52.8%)	89 (100%)
Convective Turbulence	61 (39.1%)	3 (1.9%)	92 (59.0%)	156 (100%)
Thunderstorm (no turbulence)	6 (3.4%)	10 (5.6%)	161 (91.0%)	177 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	4 (2.1%)	11 (5.7%)	177 (92.2%)	192 (100%)

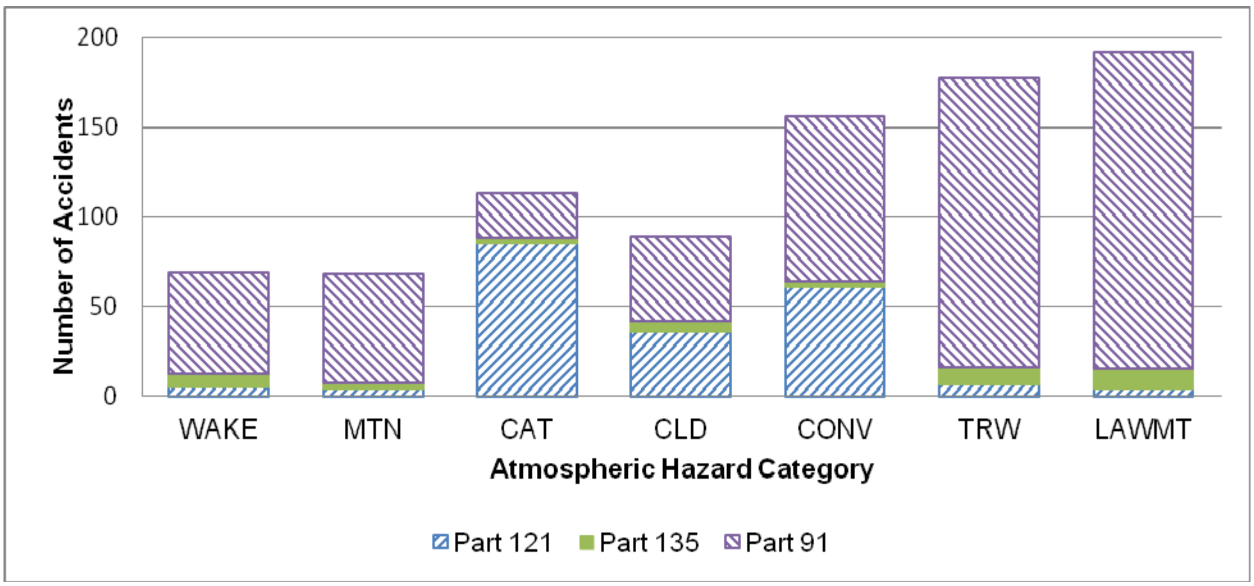


Figure 1. Flight operations among each type of atmospheric hazard (1987-2008).

Pilot Certification

Table 2 and Figure 2 show the distribution of pilot certification among each atmospheric hazard category. Eighty-four percent of those accidents which encountered clear air turbulence had an airline transport certificated pilot at the helm, along with fifty-two percent of the accidents affected by turbulence in clouds. Sixty-three percent of the pilots encountering thunderstorms had only a private license. Fourteen of the wake turbulence accidents had a student pilot in the aircraft. Five of the remaining “Other/Unknown” certifications were also student pilots, and three pilots had no license.

Table 2. Pilot certification among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Airline Transport	Commercial	Private	Other / Unknown	Total
Wake Turbulence	19 (27.5%)	18 (26.1%)	18 (26.1%)	14 (20.3%)	69 (100%)
Mountain Wave Turbulence	15 (22.1%)	18 (26.5%)	32 (47.1%)	3 (4.4%)	68 (100%)
Clear Air Turbulence	95 (84.1%)	6 (5.3%)	10 (8.8%)	2 (1.8%)	113 (100%)
Cloud Turbulence	46 (51.7%)	17 (19.1%)	25 (28.1%)	1 (1.1%)	89 (100%)
Convective Turbulence	68 (43.6%)	33 (21.2%)	53 (34.0%)	2 (1.3%)	156 (100%)
Thunderstorm (no turbulence)	24 (13.6%)	39 (22.0%)	112 (63.3%)	2 (1.1%)	177 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	32 (16.7%)	76 (39.6%)	83 (43.2%)	1 (0.5%)	192 (100%)

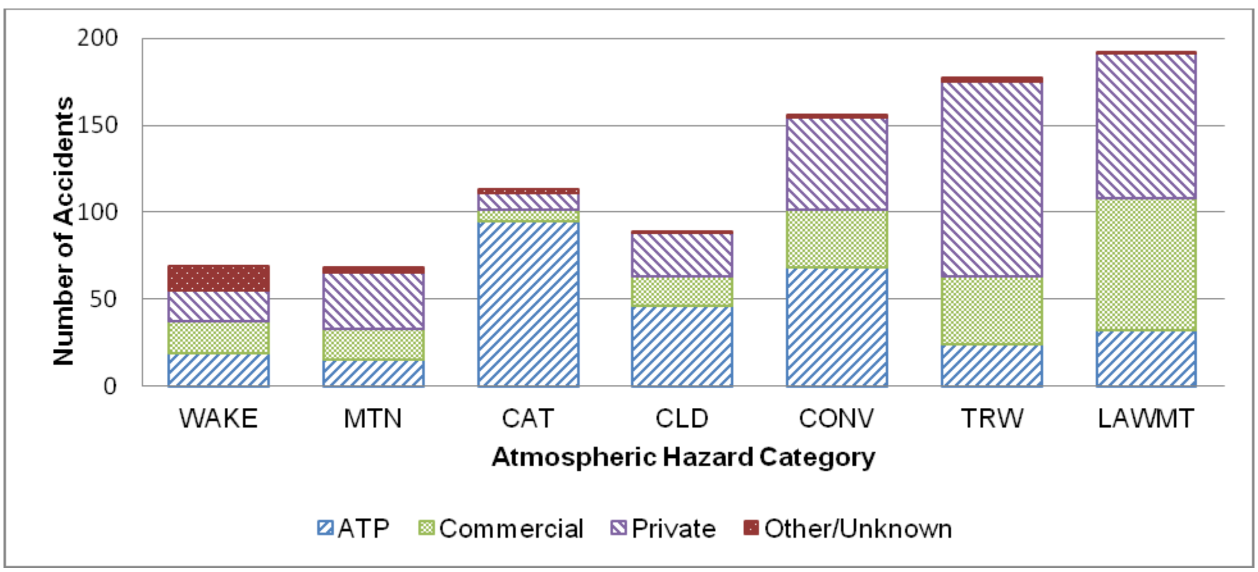
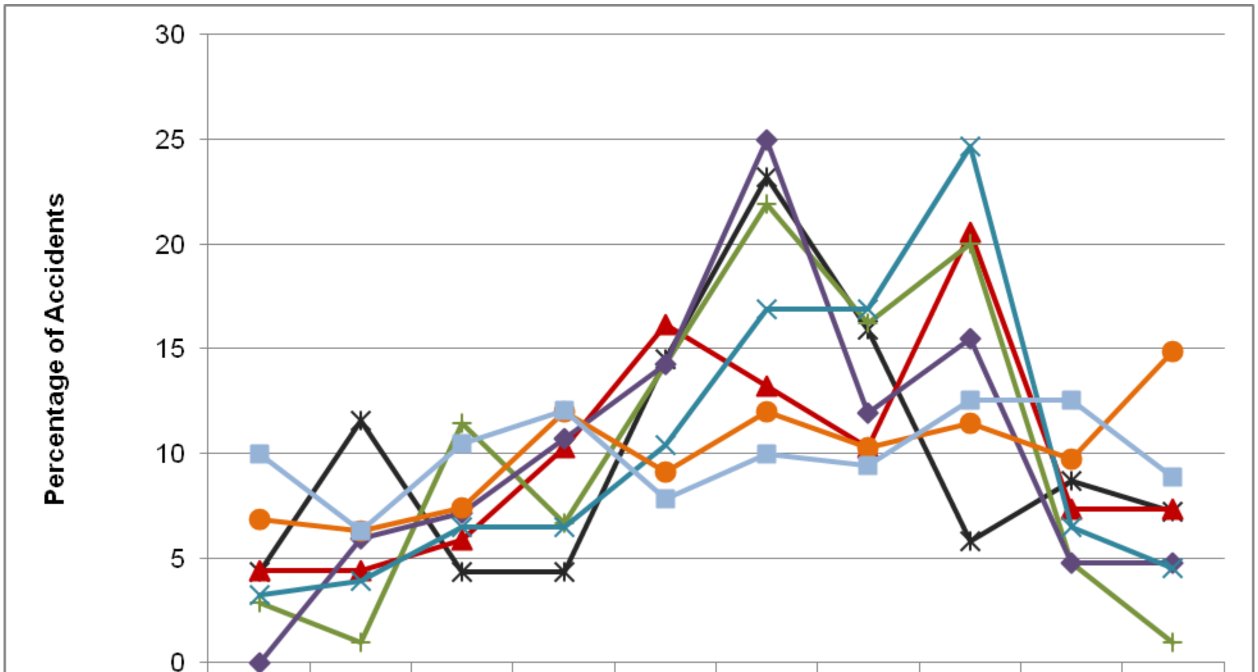


Figure 2. Pilot Certification among each type of atmospheric hazard (1987-2008).

Pilot Age

Figure 3 shows the percentage of accidents in each hazard category for ten groupings of pilot age. Not surprisingly, most of the pilots in accidents encountering clear air turbulence, turbulence in clouds and convective turbulence tend to be between forty-five and sixty years. According to the FAA, most active pilots are between the ages of 40 and 60. For every weather category except thunderstorm and low altitude wind shear, microburst or turbulence, the top three age groups were somewhere between forty and sixty years. However, fifteen percent of the accidents encountering thunderstorms were piloted by someone aged sixty-five or older; this was the largest percentage associated with any age grouping for that hazard. The age distribution among low altitude wind shear, microburst or turbulence was nearly uniform (with every age grouping representing 6-13%).

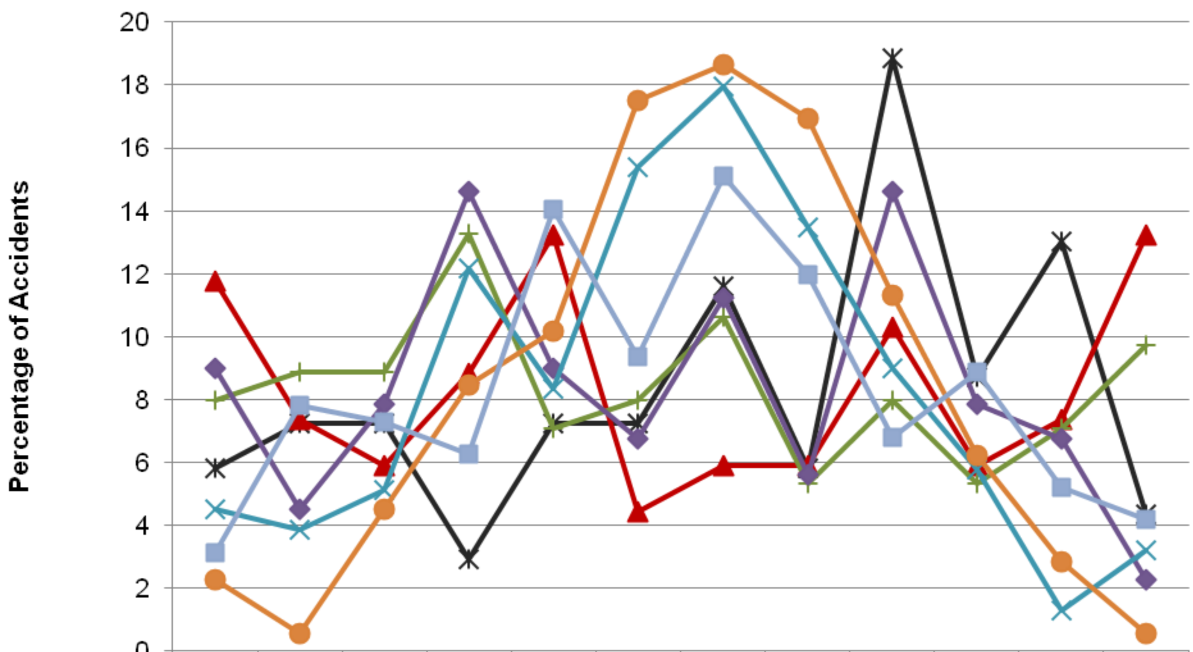


	<25	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65+
WAKE	4.3	11.6	4.3	4.3	14.5	23.2	15.9	5.8	8.7	7.2
MTN	4.4	4.4	5.9	10.3	16.2	13.2	10.3	20.6	7.4	7.4
CAT	2.9	1.0	11.4	6.7	14.3	21.9	16.2	20.0	4.8	1.0
CLD	0.0	6.0	7.1	10.7	14.3	25.0	11.9	15.5	4.8	4.8
CONV	3.2	3.9	6.5	6.5	10.4	16.9	16.9	24.7	6.5	4.5
TRW	6.9	6.3	7.4	12.0	9.1	12.0	10.3	11.4	9.7	14.9
LAWMT	9.9	6.3	10.5	12.0	7.9	9.9	9.4	12.6	12.6	8.9

Figure 3. Pilot Age among each type of atmospheric hazard (1987-2008).

Time of Year

Figure 4 shows the monthly trend for each type of atmospheric hazard. Thunderstorms and convective turbulence follow the same general pattern, peaking in July. Turbulence in clouds shows a lack of pattern, with peaks in April, July and September. Mountain wave turbulence peaks in December, January, May and September. Wake turbulence has a substantial peak in September and a big dip in April. Clear air turbulence peaks in April, and is lowest in August and October. Low altitude wind shear, microburst and turbulence tends to follow a similar pattern to thunderstorm, but the difference between the low months (December and January) and high months (May and July) is not as great.



	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
WAKE	5.8	7.2	7.2	2.9	7.2	7.2	11.6	5.8	18.8	8.7	13.0	4.3
MTN	11.8	7.4	5.9	8.8	13.2	4.4	5.9	5.9	10.3	5.9	7.4	13.2
CAT	8.0	8.8	8.8	13.3	7.1	8.0	10.6	5.3	8.0	5.3	7.1	9.7
CLD	9.0	4.5	7.9	14.6	9.0	6.7	11.2	5.6	14.6	7.9	6.7	2.2
CONV	4.5	3.8	5.1	12.2	8.3	15.4	17.9	13.5	9.0	5.8	1.3	3.2
TRW	2.3	0.6	4.5	8.5	10.2	17.5	18.6	16.9	11.3	6.2	2.8	0.6
LAWMT	3.1	7.8	7.3	6.3	14.1	9.4	15.1	12.0	6.8	8.9	5.2	4.2

Month of Accident

Figure 4. Month of Accident among each type of atmospheric hazard (1987-2008).

Aircraft Engine Type and Size

Aircraft engine types correlate strongly (although not perfectly) with flight operations categories, so it is not surprising that the distribution of atmospheric hazard by engine type (Table 3 and Figure 5) is very similar to that observed in Table 1 and Figure 1.

Table 3. Engine type among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Jet	Turbo-Prop	Reciprocating	Total
Wake Turbulence	7 (10.1%)	3 (4.3%)	59 (85.5%)	69 (100%)
Mountain Wave Turbulence	4 (5.9%)	4 (5.9%)	60 (88.2%)	68 (100%)
Clear Air Turbulence	81 (71.7%)	11 (9.7%)	21 (18.6%)	113 (100%)
Cloud Turbulence	33 (37.1%)	12 (13.5%)	44 (49.4%)	89 (100%)
Convective Turbulence	60 (38.5%)	13 (8.3%)	83 (53.2%)	156 (100%)
Thunderstorm (no turbulence)	7 (4.0%)	8 (4.5%)	162 (91.5%)	177 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	10 (5.2%)	9 (4.7%)	173 (90.1%)	192 (100%)

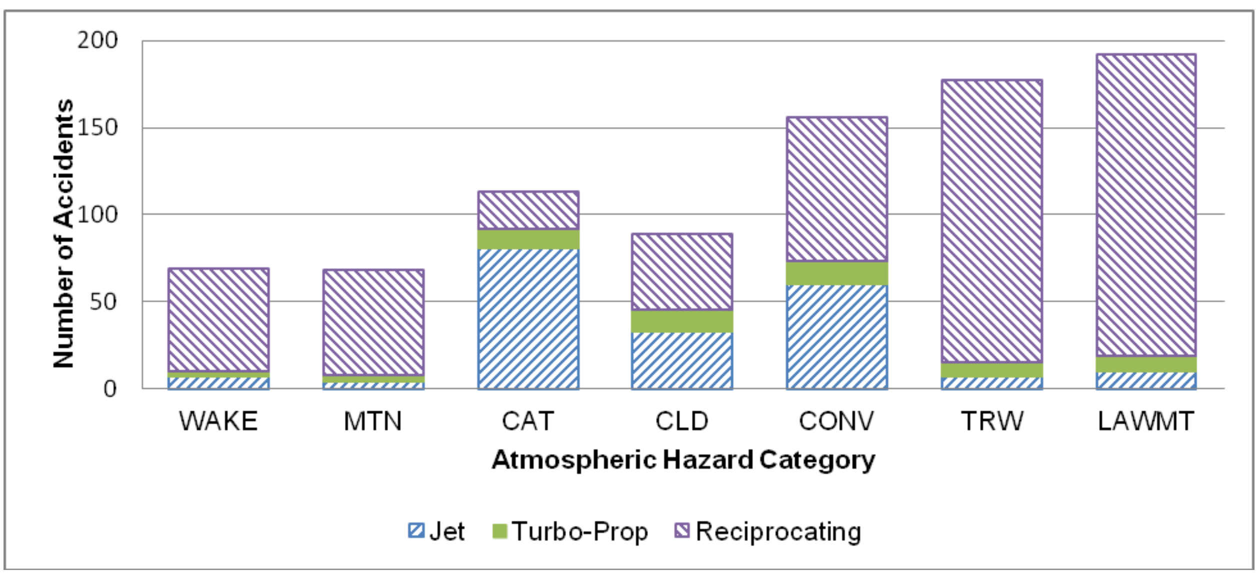


Figure 5. Engine type among each type of atmospheric hazard (1987-2008).

Among jet aircraft (Table 4), seventy percent of the low altitude events involved business jets, and seventy-five percent of mountain wave events involved narrow-body jets. In all other categories of atmospheric hazard accidents, between fifty-seven and sixty-seven percent of the jet aircraft were narrow-body jets.

Table 4. Aircraft Size (jet engines) among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Wide-Body	Narrow-Body	Regional	Business	Total
Wake Turbulence	0 (0.0%)	4 (57.1%)	0 (0.0%)	3 (42.9%)	7 (100%)
Mountain Wave Turbulence	0 (0.0%)	3 (75.0%)	0 (0.0%)	1 (25.0%)	4 (100%)
Clear Air Turbulence	22 (27.2%)	48 (59.3%)	8 (9.9%)	3 (3.7%)	81 (100%)
Cloud Turbulence	8 (24.2%)	21 (63.6%)	2 (6.1%)	2 (6.1%)	33 (100%)
Convective Turbulence	14 (23.3%)	40 (66.7%)	3 (5.0%)	3 (5.0%)	60 (100%)
Thunderstorm (no turbulence)	2 (28.6%)	4 (57.1%)	0 (0.0%)	1 (14.3%)	7 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	0 (0.0%)	3 (30.0%)	0 (0.0%)	7 (70.0%)	10 (100%)

Among turbo-props (Table 5), seventy-three percent of the CAT accidents were in large aircraft (maximum takeoff weight >= 32,000 lbs and more than 30 seats). For every other category of atmospheric hazard, at least half of the turbo-prop accidents involved small aircraft (maximum takeoff weight <12,500 lbs and less than 15 seats).

Table 5. Aircraft Size (turbo-prop engines) among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Large	Medium	Small	Total
Wake Turbulence	1 (33.3%)	0 (0.0%)	2 (66.7%)	3 (100%)
Mountain Wave Turbulence	1 (25.0%)	1 (25.0%)	2 (50.0%)	4 (100%)
Clear Air Turbulence	8 (72.7%)	0 (0.0%)	3 (27.3%)	11 (100%)
Cloud Turbulence	5 (41.7%)	0 (0.0%)	7 (58.3%)	12 (100%)
Convective Turbulence	4 (30.8%)	1 (7.7%)	8 (61.5%)	13 (100%)
Thunderstorm (no turbulence)	0 (0.0%)	1 (12.5%)	7 (87.5%)	8 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	0 (0.0%)	3 (33.3%)	6 (66.7%)	9 (100%)

Table 6. Aircraft Size (reciprocating engines) among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Single Engine, Fixed Gear	Single Engine, Retractable Gear	Multiple Engine	Total
Wake Turbulence	42 (71.2%)	7 (11.9%)	10 (16.9%)	59 (100%)
Mountain Wave Turbulence	26 (43.3%)	24 (40.0%)	10 (16.7%)	60 (100%)
Clear Air Turbulence	8 (38.1%)	9 (42.9%)	4 (19.0%)	21 (100%)
Cloud Turbulence	14 (30.8%)	20 (45.5%)	10 (22.7%)	44 (100%)
Convective Turbulence	27 (32.5%)	39 (47.0%)	17 (20.5%)	83 (100%)
Thunderstorm (no turbulence)	65 (40.1%)	55 (34.0%)	42 (25.9%)	162 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	112 (64.7%)	44 (25.4%)	17 (9.8%)	173 (100%)

Single-engine, retractable gear aircraft comprise the largest percentage (43%-47%) of piston-engine aircraft in clear air, cloud and convective turbulence (Table 6). In all other categories, the largest group was single-engine fixed gear aircraft.

Figure 6 shows the distribution of all engine-size combinations for each type of atmospheric hazard.

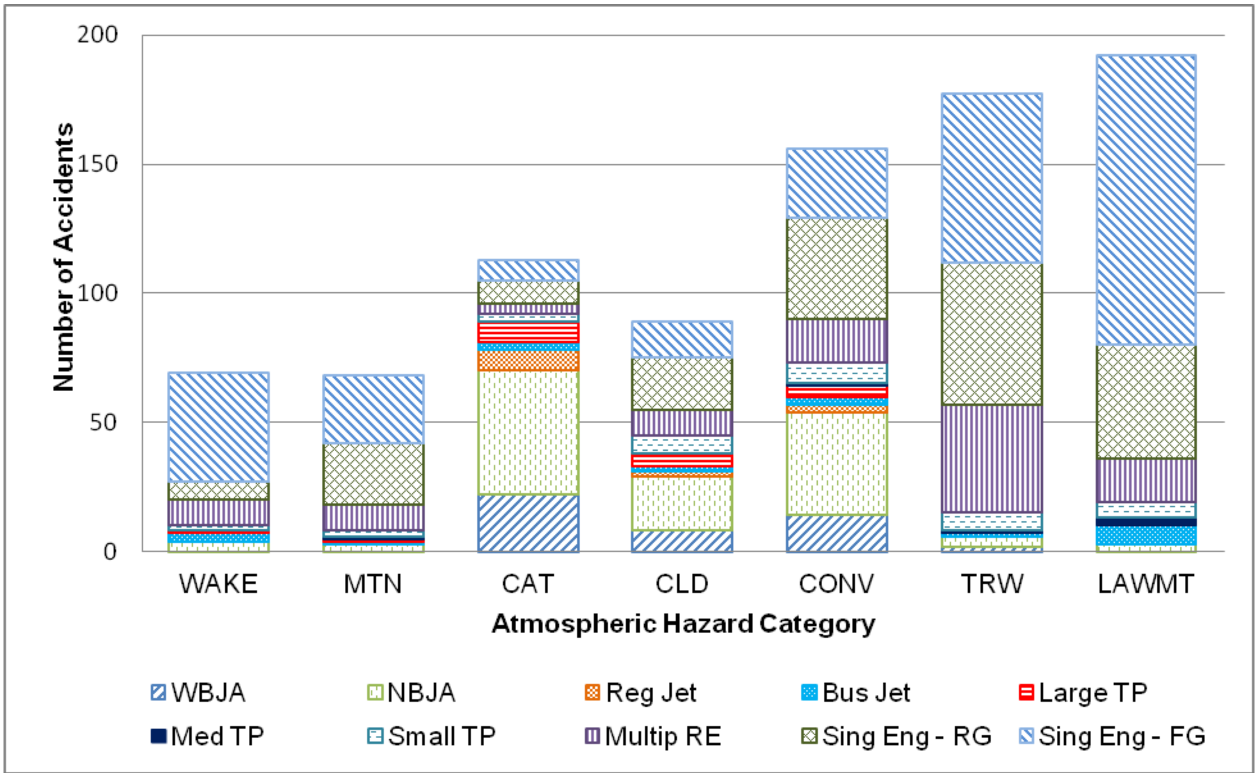
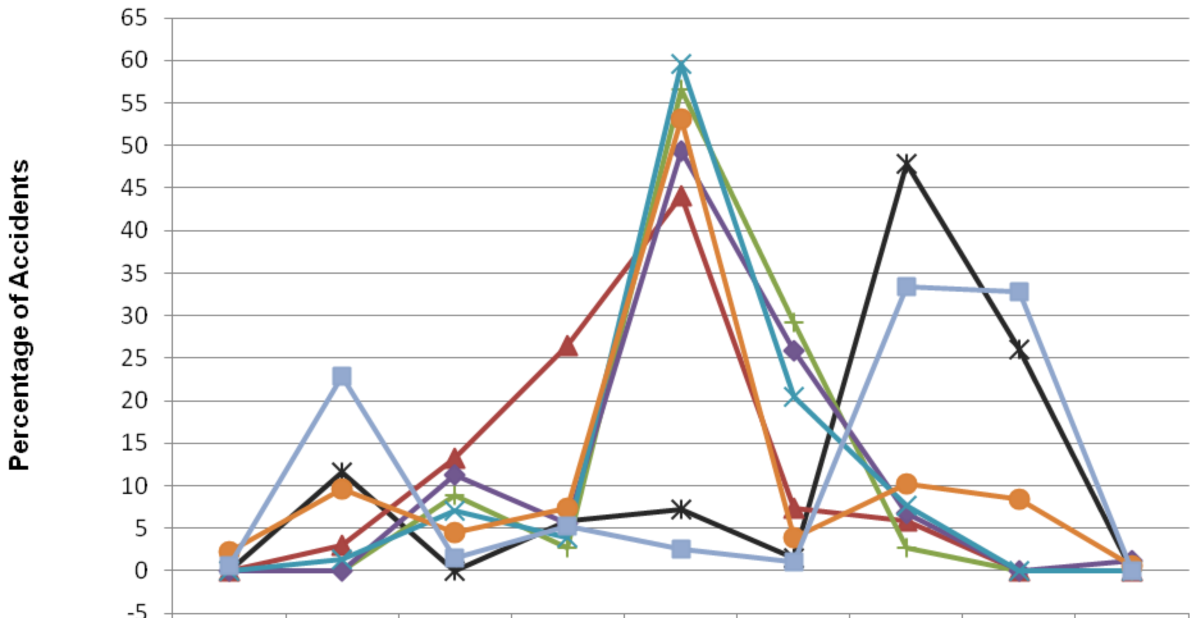


Figure 6. Aircraft engine/size grouping for each type of atmospheric hazard (1987-2008).

Phase of Flight

Figure 7 shows the phase of flight at the time the aircraft encountered each type of atmospheric hazard. All types except wake turbulence and low altitude wind shear, turbulence or microburst are most likely to occur during cruise flight. Wake turbulence is most likely during approach or landing, and by definition, low altitude wind shear, turbulence or microburst is most likely during approach, landing or takeoff.



	TAXI / STAND	TAKEOFF	CLIMB	MANEU-VERING	CRUISE	DESCENT	APP'CH	LAND	UNK
WAKE	0.0	11.6	0.0	5.8	7.2	1.4	47.8	26.1	0.0
MTN	0.0	2.9	13.2	26.5	44.1	7.4	5.9	0.0	0.0
CAT	0.0	0.0	8.8	2.7	56.6	29.2	2.7	0.0	0.0
CLD	0.0	0.0	11.2	5.6	49.4	25.8	6.7	0.0	1.1
CONV	0.0	1.3	7.1	3.8	59.6	20.5	7.7	0.0	0.0
TRW	2.3	9.6	4.5	7.3	53.1	4.0	10.2	8.5	0.6
LAWMT	0.5	22.9	1.6	5.2	2.6	1.0	33.3	32.8	0.0

Phase of Flight

Figure 7. Phase of flight at time of each type of atmospheric hazard (1987-2008).

Degree of Injury

Table 7 describes the highest level of injury sustained among the accidents in each category. Seventy-two percent of accidents in which thunderstorms were a factor included at least one fatality. Sixty-six percent of accidents in which the flight was caught in mountain wave activity were fatal, compared with only seven percent of accidents encountering clear air turbulence. However, roughly eighty-five percent of the clear air, cloud and convective turbulence categories included either a fatal or serious injury (81% for mountain wave, 75% for thunderstorm). Surprisingly, forty-two percent of the accidents affected by wake turbulence and fifty-two percent of those affected by low altitude wind shear, microburst or turbulence resulted in no injuries whatsoever.

Table 7. Degree of injury among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Fatal	Serious	Minor	None	Total
Wake Turbulence	11 (15.9%)	15 (21.7%)	14 (20.3%)	29 (42.0%)	69 (100%)
Mountain Wave Turbulence	45 (66.2%)	10 (14.7%)	5 (7.3%)	8 (11.8%)	68 (100%)
Clear Air Turbulence	8 (7.1%)	89 (78.8%)	1 (0.9%)	15 (13.3%)	113 (100%)
Cloud Turbulence	36 (40.4%)	41 (46.1%)	5 (5.6%)	7 (7.9%)	89 (100%)
Convective Turbulence	66 (42.3%)	65 (41.7%)	7 (4.5%)	18 (11.5%)	156 (100%)
Thunderstorm (no turbulence)	128 (72.3%)	5 (2.8%)	10 (5.6%)	34 (19.2%)	177 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	27 (14.1%)	33 (17.2%)	33 (17.2%)	99 (51.6%)	192 (100%)

Degree of Aircraft Damage

As shown in Table 8, nearly seventy-two percent of accidents encountering clear air turbulence suffered no damage to the aircraft. In more than ninety-two percent of accidents affected by wake turbulence, mountain wave turbulence, thunderstorm, or low altitude wind shear, microburst or turbulence, the aircraft was either destroyed or suffered substantial damage. In the categories of turbulence in clouds and convective turbulence, nearly equal numbers of aircraft suffered no damage as were destroyed.

Table 8. Aircraft damage among each type of atmospheric hazard (1987-2008)

Atmospheric Hazard	Destroyed	Substantial Damage	Minor Damage	No Damage	Total
Wake Turbulence	20 (29.0%)	45 (65.2%)	1 (1.4%)	3 (4.3%)	69 (100%)
Mountain Wave Turbulence	45 (66.2%)	18 (26.5%)	0 (0.0%)	5 (7.3%)	68 (100%)
Clear Air Turbulence	8 (7.1%)	16 (14.2%)	8 (7.1%)	81 (71.7%)	113 (100%)
Cloud Turbulence	35 (39.3%)	15 (16.9%)	0 (0.0%)	39 (43.8%)	89 (100%)
Convective Turbulence	67 (42.9%)	28 (17.9%)	6 (3.8%)	55 (35.3%)	156 (100%)
Thunderstorm (no turbulence)	121 (68.4%)	55 (31.1%)	0 (0.0%)	1 (0.6%)	177 (100%)
Low Altitude Wind Shear, Microburst or Turbulence	43 (22.4%)	149 (77.6%)	0 (0.0%)	0 (0.0%)	192 (100%)

Geographic Location

In order to examine the areas of the country more prone to specific types of atmospheric hazards, the author created regions based on the location of the aircraft at the time of the accident. These regions were defined as follows:

- Northeast: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Delaware, Maryland and the District of Columbia

- Southeast: North Carolina, South Carolina, Georgia, Florida, Alabama, Mississippi, Louisiana, Tennessee, Kentucky, Virginia and West Virginia

- Great Lakes: Ohio, Indiana, Illinois, Michigan, Wisconsin and Minnesota

- Plains: Iowa, Missouri, Arkansas, Oklahoma, Kansas, Nebraska, South Dakota and North Dakota

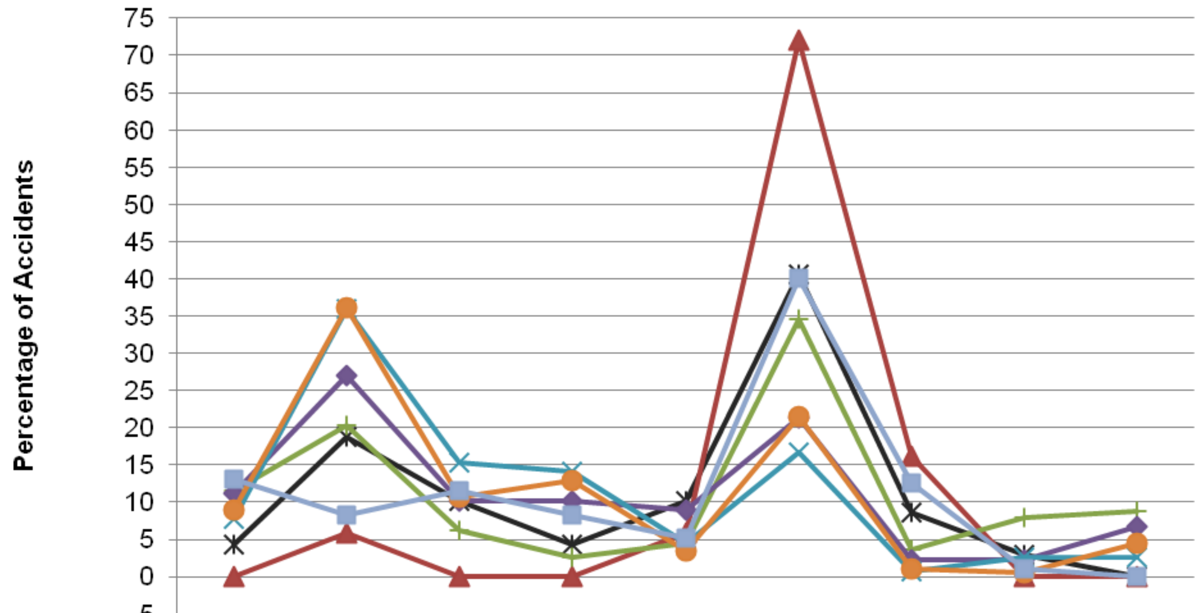
- Northwest: Montana, Wyoming, Idaho, Oregon and Washington

- Southwest: California, Utah, Nevada, Arizona, Colorado, New Mexico and Texas

- Alaska: Alaska

- Pacific Ocean: Generally flights to or from the US, Asia, Australia and New Zealand, including Guam and Hawaii

- Other: Generally flights in or near South America, the Caribbean and Europe



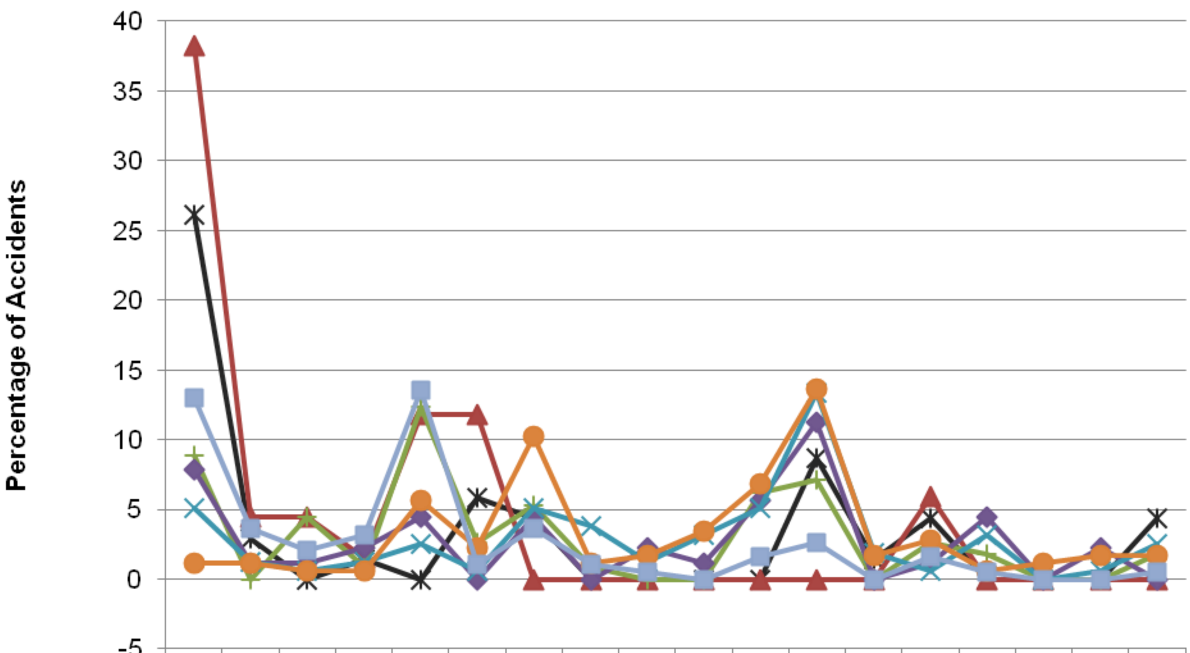
	North East	South East	Great Lakes	Plains	North West	South West	Alaska	Pacific Ocean	Other
WAKE	4.3	18.8	10.1	4.3	10.1	40.6	8.7	2.9	0.0
MTN	0.0	5.9	0.0	0.0	5.9	72.1	16.2	0.0	0.0
CAT	11.5	20.4	6.2	2.7	4.4	34.5	3.5	8.0	8.8
CLD	11.2	27.0	10.1	10.1	9.0	21.3	2.2	2.2	6.7
CONV	7.7	35.9	15.4	14.1	4.5	16.7	0.6	2.6	2.6
TRW	9.0	36.2	10.7	13.0	3.4	21.5	1.1	0.6	4.5
LAWMT	13.0	8.3	11.5	8.3	5.2	40.1	12.5	1.0	0.0

Figure 8. Geographic region at time of each type of atmospheric hazard (1987-2008).

Thunderstorms, convective turbulence and turbulence in clouds most often occur in the southeast United States (US), followed by the southwest US (see Figure 8). All other types of atmospheric hazards, particularly mountain wave activity, are most likely to occur in the southwest US. Mountain wave activity is rarely involved in accidents outside of Alaska and the Southwest. Low altitude wind shear, microburst or turbulence occurs most often in the southwest, but is just as likely in the northeast or great lakes regions as in Alaska. Thunderstorms and convective turbulence are least often involved in accidents in the northwest US, Alaska and the Pacific

Ocean. Forty percent of wake turbulence occurs in the southwest, compared with less than 20% in the southeast.

In order to further examine the location of accidents with a cause or factor of some type of atmospheric hazard, Figure 9 shows the percentage of each type of atmospheric hazard in the states which were defined as part of the southwest and southeast regions. In general, the states with the most events are California, Colorado, Texas and Florida. The most wake turbulence is in California, the most mountain wave activity is in California, Colorado and New Mexico, and the most low altitude wind shear, microburst or turbulence in California and Colorado. Clear air turbulence was felt most often in Colorado and Florida, turbulence in clouds was most often encountered in Florida and California, convective turbulence in Florida and thunderstorms in Florida and Texas.



	CA	AZ	NV	UT	CO	NM	TX	LA	MS	AL	GA	FL	SC	NC	VA	WV	KY	TN
WAKE	26.1	2.9	0.0	1.4	0.0	5.8	4.3	0.0	0.0	0.0	0.0	8.7	1.4	4.3	0.0	0.0	0.0	4.3
MTN	38.2	4.4	4.4	1.5	11.8	11.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.9	0.0	0.0	0.0	0.0
CAT	8.8	0.0	4.4	0.9	12.4	2.7	5.3	0.9	0.0	0.0	6.2	7.1	0.0	2.7	1.8	0.0	0.0	1.8
CLD	7.9	1.1	1.1	2.2	4.5	0.0	4.5	0.0	2.2	1.1	5.6	11.2	0.0	1.1	4.5	0.0	2.2	0.0
CONV	5.1	1.3	0.6	1.3	2.5	0.6	5.1	3.8	1.3	3.2	5.1	13.4	1.9	0.6	3.2	0.0	0.6	2.5
TRW	1.1	1.1	0.6	0.6	5.7	2.3	10.2	1.1	1.7	3.4	6.8	13.6	1.7	2.8	0.6	1.1	1.7	1.7
LLWMT	13.0	3.6	2.1	3.1	13.5	1.0	3.6	1.0	0.5	0.0	1.6	2.6	0.0	1.6	0.5	0.0	0.0	0.5

Southwest or Southeast State Nearest Atmospheric Disturbance

Figure 9. State nearest occurrence of each type of atmospheric hazard (1987-2008).

Summary

The purpose of this analysis was to compare the characteristics of accidents associated with seven categories of atmospheric hazard (mostly turbulence, thunderstorm and windshear). Eight hundred sixty-four accidents from 1987-2008 were selected from the NTSB accident database. All are considered US-based accidents, and were operating under FAR Part 121, 135 or 91 flight rules at the time.

Wake turbulence accounted for eight percent of the accidents selected. Although most wake turbulence is initiated by large jet aircraft, the resulting accidents are suffered mostly by single-engine, fixed gear aircraft (61%) operating under FAR Part 91 (83%). The pilots' certifications vary widely, with twenty-eight percent airline transport rated pilots, twenty-six percent commercial, twenty-six percent private and twenty percent student pilots. The pilot ages also vary, with twenty-five percent under age 40, fifty-four percent between 40 and 55, and the remaining twenty-two percent over 55. Forty-three percent of wake turbulence occurred in July, September or November, and all other months accounted for between three and nine percent of the events. Seventy-four percent of wake turbulence accidents occur during approach or landing, which in part explains why forty-two percent of the accidents result in no injury, even though ninety-four percent result in at least substantial damage to the aircraft. Twenty-six percent of wake turbulence accidents happen in California, and nine percent in Florida.

Sixty-two percent of accidents related to mountain wave turbulence occurred in California (38%), Colorado or New Mexico. Thirty-eight percent of the accidents occurred during December, January or May. Seventy-four percent of these accidents involved single piston-engine aircraft and ninety percent of the aircraft were operating under Part 91 rules. Forty-seven percent of the pilots had only a private license, and sixty percent of the pilots were between the ages of 40 and 60. Seventy percent of the accidents occurred during either cruise or maneuvering flight. Sixty-six percent of the mountain wave accidents resulted in a fatality and sixty-six percent resulted in destruction of the aircraft. Eight percent of the accidents selected for this report were affected by mountain wave turbulence.

Clear air turbulence represented thirteen percent of the atmospheric hazards in this analysis. Seventy-five percent of these flights were Part 121 flights, eighty-four percent of the pilots were licensed for airline transport flight, and seventy-two percent of the aircraft were jets (mostly narrow-body airliners). Seventy-two percent of the pilots were between 40 and 60 years of age. Thirteen percent of the accidents took place in April, and all other months accounted for between five and eleven percent of the accidents. Eighty-six percent of the encounters occurred during cruise or descent. Eighty-six percent of the accidents resulted in at least a serious injury but in seventy-two percent of the accidents there was no damage to the aircraft. Less than three percent of the clear air turbulence was encountered over the Plains states, compared with thirty-five percent in the southwest US.

Ten percent of the selected accidents involved turbulence in clouds. Forty-eight percent of that turbulence was encountered in the southwest or southeast United States. Nine percent of the flights were in the northwest US, which was the highest percentage in that region of any type of atmospheric hazard except wake turbulence. Fifty-three percent of the flights were Part 91 and forty-nine percent of the aircraft had reciprocating engines. Forty-four percent of the aircraft received no damage, but either a serious or fatal injury was recorded in eighty-six percent of the accidents. Fifty-two percent of the pilots had airline transport licenses, and two thirds of them were between 40 and 60 years of age. Seventy-five percent of the turbulence encounters were during cruise or descent. Less than three percent of these accidents occurred in December, with fifteen percent each in April and September.

One hundred fifty-six accidents (18%) were caused in part by convective turbulence. Nearly sixty percent of those flights were operating under Part 91 regulations and forty-two percent of the aircraft had a single reciprocating engine. Forty-four percent of the aircraft were destroyed, and a serious or fatal injury occurred in eighty-four percent of the accidents. Forty-four percent of the pilots were rated for airline transport, and fifty-eight percent were between 45 and 60 years old. Seventy-six percent of the accidents occurred from April through September and eighty percent occurred during cruise or descent. Thirty-six percent of the convective turbulence was encountered in the southeast US, with thirteen percent in Florida.

Roughly twenty percent of the accidents selected for this analysis encountered a thunderstorm but no mention of turbulence was made in the accident report. One might expect these accidents to be similar to those encountering convective turbulence, but the greatest similarities are in geography and time of the year. Thirty-six percent occurred in the southeast (14% in Florida) and, as with convective turbulence, only six percent of these accidents were outside the contiguous US. Sixty-three percent of the accidents occurred in June through August, and fifty-three percent occurred during cruise flight. Ninety-one percent of these were in Part 91 flights (versus 60% for convective turbulence), and ninety-two percent (versus 54%) of the aircraft had reciprocating engines. Sixty-three percent of the pilots had only a private license, and one-third of them were aged 45-60. Seventy-two percent of the accidents included at least one fatality (versus 43%), and the aircraft was destroyed sixty-eight percent of the time (versus 44%).

The largest category of atmospheric hazards was low altitude wind shear, microburst or turbulence (with no mention of thunderstorm) at twenty-two percent of the total. By a slight margin it had the largest percentage of Part 91 flights (92%), and was second to thunderstorms in the percentage of aircraft with reciprocating engines (90%). Fifty-two percent of these accidents resulted in no injury (the largest percentage of all types), but all resulted in at least substantial damage to the aircraft. Only seventeen percent of the pilots were rated for airline transport. This category also shows the most uniformity in the distribution of age (percentages in the ten groupings range from 6.3% to 12.6%). Twenty-nine percent of these accidents occurred in May or July, and more than one-quarter (26.5%) occurred in either California or Colorado. Eighty-nine percent of the accidents occurred during takeoff, approach or landing.

Each of these seven categories of atmospheric hazards has some characteristics in common with other categories, and some characteristics that separate them. The category of atmospheric hazards with the largest number of accidents was low altitude wind shear, microburst or turbulence (with no mention of thunderstorm). Clear air turbulence is the most frequent category among both Part 121 and jet aircraft, followed by cloud turbulence and convective turbulence. Flight into thunderstorms (no turbulence) is the category most likely to result in both fatalities and aircraft destruction, but 91% of those accidents were in Part 91 flights.

Appendix A

List of Specific Aircraft Make and Model within Each Aircraft Group

	Wide-Body Jet Airliner	**Narrow Body Jet Airliner**
Airbus	A300 A310 A330	A318 A319 A320 A321
Boeing	747 767 777	707 717 727 737 757
Lockheed		L-1011 TRISTAR
McDonnell-Douglas		DC-8 DC-9 DC-10 MD-11 MD-80 MD-90
HS-BAE Systems		BAE-146

Regional Jet

Bombardier	CRJ-100 CRJ-200 CRJ-700 CRJ-900 CRJ-5000
Embraer	ERJ-135 ERJ-140 ERJ-145 ERJ-170 ERJ-190
Fairchild	DO-328 (series 300)
Fokker	F-100 F-28

Medium Business Jet

Aero Commander	Jet Commander 1121
Aerospatiale	Corvette
Bombardier	Challenger DHC-112 (called the venom – military aircraft)
Cessna	CE-560 Citation II Citation III Citation Sovereign Citation X
Dassault	Falcon 10-100 Falcon 20-200 Falcon 50 Falcon 900 Falcon 2000
Douglas	A-4 (military)
Gulfstream	GA-1159 Gulfstream II Gulfstream III Gulfstream IV Gulfstream V
Hamburger Flugzeugbau	320
Beech	Hawker-800
HS-BAE Systems	125-HAWKER
Raytheon	125-HAWKER 400 Hawker-1000
Rockwell	Sabreliner
Israel Aircraft Industries	Astra Westwind

Medium Business Jet (continued)

Learjet	24 25 31 35 36 45 55 60
Lockheed	Jetstar
Mitsubishi	300

Small Business Jet

Cessna	Citation I CitationJet Mustang T-37 (military)
Eclipse	500
Learjet	23
Morane Saulnier	MS-760
Raytheon	390

Large Turbo-prop

ATR	42 72
Convair	CV-580 CV-600 CV-640
De Havilland	Dash 7 Dash 8
Fokker	F-27
HS-BAE Systems	BAE-ATP
Lockheed	L-188 L-382
NAMC	YS-11

Medium Turbo-prop

Aerospatiale	NORD-262
Air Tractor	602 802
Beech/Raytheon	BE-100 BE-200 BE-300 99 1900
CASA	212
De Havilland	DHC-6
Douglas	DC-3 (Turbo conversion)

Medium Turbo-prop (continued)

Embraer	EMB-110 EMB-120
Fairchild	DO-228 DO-328 (series 100)
Fairchild-Swearingen	SA-226 SA-227 Metro
GAF-ASTA	Nomad
Grumman	73-T
Gulfstream	Gulfstream I
Jetstream-BAE Systems	31 41
Rockwell	OV-10
Saab	340
Shorts	3-60 SC.7 Skyvan

Small Turbo-prop

Ayres	Turbo Thrush
Air Tractor	AT-400 AT-402 AT-503
Beech/Raytheon	BE-18 (conversions) BE-45 (T-34C) BE-60-T BE-90

Small Turbo-prop (continued)

Cessna	CE-208 CE-425 CE-441
De Havilland	DHC-2-MKIII DHC-3T
Fairchild-Swearingen	SA-26
Grumman	G-164
Gulfstream	GA-164 GA-680 GA-681 GA-690 GA-695
McKinnon	G-21
Mitsubishi	MU-2B
SIAI Marchetti	SF-260-TP
Partenavia	AP-68-TP
Piaggio	P180
Pilatus	PC-6 PC-7 PC-12
Piper	PA-31T PA-42 PA-46-310TP, PA-46-350TP, PA-46-500TP
Reims	F406
Socata	TBM-700
PZL-Mielec	M-18/T-45

Heavier Multi-Engine (Reciprocating)

Boeing	B-17 B-307
Convair	CV-240 CV-340 CV-440
Curtiss	C-46
De Havilland	DHC-4
Douglas	DC-3 DC-4 DC-6 DC-7 DC-A20 DC-A26
Fairchild	C-119
Grumman	C-1 HU-16 S-2F
Lockheed	L-1049 L-18 P-38
Martin	B26

Lighter Multi-Engine (Reciprocating)

Beagle	206
Beech	BE-18 BE-50, BE-55, BE-56, BE-58 BE-60, BE-65, BE-70, BE-76, BE-95

Lighter Multi-Engine (Reciprocating) (continued)

Britten-Norman	Islander Tri-Islander Defender
Stout Bushmaster	2000
Camair	480
Cessna	CE-303, CE-310, CE-320 CE-335, CE-336, CE-337, CE-340 CE-401, CE-402, CE-404 CE-411, CE-414, CE-421 T-50 (Military)
Champion	Lancer
De Havilland	DHC-90
Dornier	DO-28
Grumman	21, 44, 73
Gulfstream	GA-7 GA-500, GA-520, GA-560 GA-680, GA-685 GA-700, GA-720
Lockheed	L-12
Navion	D-16
Partenavia	P-68
Piper	PA-23 PA-30, PA-30A, PA-30B PA-31, PA-34, PA-39 PA-44, PA-60
STOL Aircraft Corp	UC-1
Wing Aircraft	D-1

Single-Engine (Reciprocating) Retractable Gear

Beech	BE-17 BE-23 (series codes 24R, A24R, B24R, C24R) BE-33, BE-35, BE-36 BE-45 (except BE-45-T34C)
Bellanca	BL-14, BL-17, BL-260
Cessna	CE-172-RG CE-177-RG CE-182-RG CE-182-TR CE-210
Colonial Aircraft	C-1, C-2
Culver	LCA, LFA, V
Curtiss-Wright	P-40
Douglas	A-1
Globe	GC-1
Grob	G-115, G-120
Grumman	Avenger
Gulfstream	GA-112, GA-114
Lake	LA-4
Meyers	Aero Commander 200 MAC-145
Mooney	M-18, M-20, M-22
North American	AT-6 SNJ-2, SNJ-4, SNJ-5, SNJ-6 Harvard
Navion	NAV-1 NAV-A, NAV-B, NAV-D NAV-G, NAV-H, NAV-L

Single-Engine (Reciprocating) Retractable Gear (continued)

Piper	PA-24, PA-28R, PA-28RT PA-32S-300 PA-32R, PA-46
Raytheon	Commander 114
Reims	FR-182
SIAI Marchetti	S-205 SF-260 FN-333
Socata	TB-9, TB-10, TB-20
Spartan	7W
STOL Aircraft	RC-3
Thurston	Teal TSC-1A
Yakovlev	Yak-3

Single-Engine (Reciprocating) Fixed Gear

Aero Mercantil	Gavilan 358
Air Tractor	AT-301 AT-401 AT-501 AT-502
AMD	Alarus-2000
American Legend	AL-11 AL-3
Avions Robin	R-2160
Arctic	S1A, S1B

Single-Engine (Reciprocating) Fixed Gear (continued)

Aeronca	AR-7, BL-7, AR-11, AR-15 AR-50, AR-58, AR-65 AR-C3, AR-K, AR-L3 Bubeck-Irving
Aviat	A-1
Ayres	Thrush
Bellanca	BL-7, BL-8 BL-DW1
Beech	BE-19, BE-23, BE-77
Boeing	B-75
Call Aircraft	A-2, A-3, A-9
Cavalier	Mustang
CASA	BU-131
Centaur	Longren
Cessna	CE-120, CE-140, CE-145, CE-150, CE-152 CE-170, CE-172, CE-175, CE-177 CE-180, CE-182, CE-185, CE-188 CE-190, CE-195, CE-205, CE-206, CE-207, CE-305
Champion	Champ-7, Champ-8
Cirrus	SR-20, SR-22
Columbia	XJ-7 350
Commonwealth	Skyranger, Sportster
Convair – General Dynamics	BT-13, BT-15, CV-L13
DeHavilland	DHC-1, DHC-2, DHC-3, DHC-82

Single-Engine (Reciprocating) Fixed Gear (continued)

Diamond	DA-20, DA-40, DA-42
ERCO	Alon-415 Ercoupe-415 Forney-415
Emigh	Trojan
Extra	EA
Fairchild	F-24, M-62 PT-19, PT-23, PT-26
Fieseler	Fi-156
Fleet	Model 2, Model 16
Found	FBA-2
Funk	Model B
Great Lakes	2T1
Grumman	G-164
Gulfstream	GA-AA, GA-AG
Helio	H-250, H-295, H-391, H-395 H-700, H-800
Helton	Lark-95
Howard	DGA-15
Indus	Thorp T-211
Lancair	LC-40, LC-41, LC-42
Liberty	XL-2
Lockheed	L-402
Luscombe	LL-8, LL-11 Phantom

Single-Engine (Reciprocating) Fixed Gear (continued)

Maule	M-4, M-5, M-6, M-7, M-8 MX-7, MT-7, MXT-7
MBB	BO-209
Meyers	OTW
Monocoupe	D-145
Morane-Saulnier	MS-880, MS-894
Mooney	M-10
Moravan	Zlin-242
Mudry	CAP-10
Naval Aircraft Factory	N3N-3
Noordyun	UC-64
OMF	Symphony
Pilatus	PC-6-350
Piper	L-21, L-4 PA-11, PA-12, PA-14, PA-15, PA-16, PA-17, PA-18, PA-19 PA-20, PA-22, PA-25, PA-28 PA-32, PA-36, PA-38 PA-J3, PA-J3C, PA-J3F, PA-J3L, PA-J4, PA-J5
Pitts	S-1, S-2
Porterfield	CP-55, CP-65, FP-65, LP-65
PZL-Mielec	M-18, M-104
Rawdon	T-1
Reims	FA-150, FR-172
Ryan	ST-A, ST-3

Single-Engine (Reciprocating) Fixed Gear (continued)

Socata	MS-Ralleye
Stinson	AT-19, SR-10, SR-V77, SR-JR, SR-L5, SR-108
Stearman	C-3
Sukhoi	SU-26, SU-29
SZD	Koliber-150
Taylorcraft	15A, 19, 20, 21 BC, BF, BL DC, DL
Tecnam	P-2002
Timm	N2T
Varga	2150A, 2180
Volaircraft	Aero Commander 100
WACO	AGC, AVN, ARE, HRE, SRE, UKS, QCF, UPF, YPF, YMF
Weatherly	201, 620
Zenair	CH-2000

Light Sport Aircraft (Rotax Engines)

Aero Ltd.	AT-4
Aeropro	Eurofox
Bush Caddy	LSA
Colyaer	Freedom
Czech Aircraft Works	Parrot Sport Cruiser
Evektor	Sportstar
Fantasy Air	Allegro 2000
Flight Design	CT
Higher Class Aviation	Sport Hornet
Iniziative	Sky Arrow 600
Jihlavan	KP-5
Moravan/Zlin	Savage
Tecnam	P-92
Zenair	CH-600

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01- 05 - 2013	Contractor Report	

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
An Examination of Aviation Accidents Associated with Turbulence, Wind Shear and Thunderstorm	NNL12AA09C
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Evans, Joni K.	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER
	284848.02.01.07.04

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
NASA Langley Research Center Hampton, Virginia 23681	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	NASA/CR-2013-217989

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 03
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES

Langley Technical Monitor: Sharon M. Jones

14. ABSTRACT

The focal point of the study reported here was the definition and examination of turbulence, wind shear and thunderstorm in relation to aviation accidents. NASA project management desired this information regarding distinct subgroups of atmospheric hazards, in order to better focus their research portfolio. A seven category expansion of Kaplan's turbulence categories was developed, which included wake turbulence, mountain wave turbulence, clear air turbulence, cloud turbulence, convective turbulence, thunderstorm without mention of turbulence, and low altitude wind shear, microburst or turbulence (with no mention of thunderstorms).More than 800 accidents from flights based in the United States during 1987-2008 were selected from a National Transportation Safety Board (NTSB) database. Accidents were selected for inclusion in this study if turbulence, thunderstorm, wind shear or microburst was considered either a cause or a factor in the accident report, and each accident was assigned to only one hazard category. This report summarizes the differences between the categories in terms of factors such as flight operations category, aircraft engine type, the accident's geographic location and time of year, degree of injury to aircraft occupants, aircraft damage, age and certification of the pilot and the phase of flight at the time of the accident.

15. SUBJECT TERMS

Aircraft accidents; Aircraft safety; Statistical analysis; Thunderstorms; Turbulence

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)***
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18