Preventing Turbulence-Related Injuries in Air Carrier Operations Conducted Under Title 14 *Code of Federal Regulations* Part 121

Safety Research Report

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Preventing Turbulence-Related Injuries in Air Carrier Operations Conducted Under Title 14 *Code of Federal Regulations* Part 121

National Transportation Safety Board

490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

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Abstract: This safety research report examines the prevalence and risk factors of turbulence-related accidents in Title 14 *Code of Federal Regulations* Part 121 air carrier operations; assesses the effectiveness of policies, programs, technologies, and other applicable safety countermeasures; and makes recommendations for improving turbulence avoidance and injury mitigation. To conduct this research, the National Transportation Safety Board (NTSB) used both quantitative and qualitative methods, including a literature review, aggregate analysis of aviation accident data, and interviews with a broad selection of government, industry, and other stakeholders. In addition, the NTSB conducted 10 detailed investigations of turbulence-related Part 121 accidents over the course of this research. The NTSB identified the following safety issues: (1) insufficient submission and dissemination of turbulence observations, (2) a lack of shared awareness of turbulence risks, (3) the need for mitigation of common turbulence-related injury circumstances, and (4) the need for updated turbulence guidance. As a result of this safety research, the NTSB makes 18 new recommendations to the Federal Aviation Administration (FAA), 2 new recommendations to the National Weather Service, and 1 new recommendation to Airlines for America, the National Air Carrier Association, and the Regional Airline Association. The NTSB also reiterates three recommendations to the FAA and classifies and reiterates one additional recommendation to the FAA.

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Acronyms and Abbreviations

AC	advisory circular
ACARS	aircraft communications addressing and reporting system
ADS-B	automatic dependent surveillance-broadcast
ADS-B Wx	automatic dependent surveillance-broadcast weather
AIREP	air report
AIRMET	airmen's meteorological information
ARTCC	air route traffic control center
ATC	air traffic control
CFR	*Code of Federal Regulations*
CG	center of gravity
CRS	child restraint system
CWA	center weather advisory
EDR	eddy dissipation rate
EWINS	enhanced weather information system
FAA	Federal Aviation Administration
GTG	graphical turbulence guidance
GTGN	graphical turbulence guidance nowcast
JSAT	Joint Safety Analysis Team
JSIT	Joint Safety Implementation Team
NAS	National Airspace System
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NTSB	National Transportation Safety Board
NWS	National Weather Service

PIREP	pilot weather report
RA	resolution advisory
SIGMET	significant meteorological information
SOP	standard operating procedure
TCAS	traffic collision avoidance system
TRACON	terminal radar approach control

Glossary

The following is a glossary of key aviation and turbulence-related terms used in this report. Several of the terms are also defined as they appear in the report.

Accident: An occurrence associated with the operation of an aircraft that 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. This definition is derived from Title 49 *Code of Federal Regulations* (*CFR*) 830.2.

Child restraint system: A device manufactured to transport children in a motor vehicle or aircraft to restrain, seat, or position children who weigh 80 pounds or less. This definition is derived from 49 *CFR* 571.213.

Defining event: One event occurring in an aircraft accident sequence that is used to categorize the accident type. The NTSB has used this accident categorization approach since 2008. Before 2008, the NTSB categorized aviation accidents by the first event, which refers to the initial event occurring in an aircraft accident sequence.

Dispatcher: A person certificated under 14 *CFR* Part 65 who shares responsibility with the pilot-in-command for the operational control of a flight. Dispatcher duties include planning and monitoring flights under their control.

Flight crew: Crewmembers assigned to duty in an aircraft during flight time, such as a pilot or a flight engineer.

General aviation: All US civil aviation operations except those conducted under Part 121 air carrier operations or Part 135 commuter and on-demand air carrier operations; this primarily includes noncommercial operations regulated by 14 *CFR* Part 91.

Part 121: Air carrier operations involving airplanes with a passenger-seat configuration of more than nine passenger seats or, in the case of cargo operations, airplanes having a payload capacity of more than 7,500 pounds. These operations are regulated by 14 *CFR* Part 121.

Part 135: Commuter and on-demand air carrier operations not meeting the passenger seat or payload requirements of Part 121. These operations are regulated by 14 *CFR* Part 135.

Phase of flight: A specific period during the duration of flight, such as climb, cruise, and descent.

Ride conditions: The quality of a flight as affected by weather and aircraft accelerations and as experienced by the flight crew, flight attendants, and passengers.

Serious injury: Any injury that (1) requires hospitalization for more than 48 hours, commencing within 7 days from the date the injury was received; (2) results in a fracture of any bone, except simple fractures of fingers, toes, or nose; (3) causes severe hemorrhages, nerve, muscle, or tendon damage; (4) involves any internal organ; or (5) involves second- or third-degree burns, or any burns affecting more than 5% of the body surface. This definition is based on 49 *CFR* 830.2.

Turbulence: An atmospheric phenomenon that causes changes in aircraft altitude, attitude, and/or airspeed with aircraft reaction depending on intensity.

Turbulence-related accident: An accident for which turbulence was the defining event or found to be a causal or contributing factor in the accident.

Executive Summary

Safety Research Topic

Turbulence-related accidents are the most common type of accident involving air carriers operating under Title 14 *Code of Federal Regulations* Part 121. From 2009 through 2018, the National Transportation Safety Board (NTSB) found that turbulence-related accidents accounted for more than a third of all Part 121 accidents; most of these accidents resulted in one or more serious injuries but no aircraft damage. This NTSB safety research report examines the prevalence and risk factors of turbulence-related accidents in Part 121 air carrier operations; assesses the effectiveness of policies, programs, technologies, and other applicable safety countermeasures; and makes recommendations for improving turbulence avoidance and injury mitigation.

Turbulence arises from eddies in the atmosphere and is typically categorized by its source, such as convection, nonconvective wind shears in clear air, mountain waves, surface features, and aircraft wake vortices. Like many accidents in aviation, turbulence-related accidents can often be influenced by multiple human, aircraft, environmental, and organizational factors. Over the past decade, the NTSB has determined the probable cause for numerous turbulence-related accidents and has issued safety recommendations for improving weather forecasting, dissemination of weather reports, and air traffic management practices to reduce the likelihood of aircraft encounters with turbulence. More recently, in 2017, the NTSB issued several recommendations addressing safety issues related to turbulence as part of its special investigation report *Improving Pilot Weather Report Submission and Dissemination to Benefit Safety in the National Airspace System*, SIR-17/02.

Despite steady improvements in the overall accident rate for Part 121 air carrier operations, turbulence continues to be a major cause of accidents and injuries. This research examined safety issues related to the turbulence problem from a systemwide perspective. The NTSB's research goals were to (1) summarize the basic types and causes of turbulence; (2) describe the safety impacts of turbulence, including characteristics of and trends in turbulence-related accidents and injuries across Part 121 air carrier operations; (3) examine methods used to reduce the likelihood of turbulence encounters and turbulence-related injuries in Part 121 air carrier operations; and (4) identify proven and emerging best practices and safety countermeasures. To accomplish these goals, the NTSB used both quantitative and qualitative methods, including a literature review, aggregate analysis of aviation accident data, and interviews with a broad selection of government, industry, and other stakeholders. In addition, the NTSB conducted 10 detailed investigations of turbulence-related Part 121 accidents over the course of this research to provide relevant and timely case studies.

Safety Issues

The safety issues identified in this report include the following:

- **Insufficient submission and dissemination of turbulence observations.** Improving the accuracy and frequency of turbulence observations is needed (1) to generate and validate more predictive turbulence forecasts, (2) to enhance flight planning and the management of the safe and efficient flow of air traffic, and (3) to improve pilot opportunities for avoiding turbulence and informing passengers and flight attendants when turbulence is likely to be encountered. Such increased sharing of turbulence observations can help reduce turbulence-related accidents and injuries in Part 121 air carrier operations but that shared information also needs to be widely and commonly understood.

- **Lack of shared awareness of turbulence risks.** Many different turbulence forecasting products are available to meteorologists, dispatchers, air traffic controllers, and pilots. However, many of these products are proprietary, and they vary considerably in their capabilities, which limits a shared awareness and common understanding of forecasted turbulence risks across all key stakeholder groups involved in Part 121 air carrier operations.

- **Need for mitigation of common turbulence-related injury circumstances.** Being seated with the seat belt fastened is the most effective way to prevent a turbulence-related injury. However, there are authorized movements and activities within the passenger cabin during flight, and unexpected turbulence encounters can occur. From 2009 through 2018, about half of the turbulence-related accidents in Part 121 air carrier operations occurred during the descent or approach phases of flight; 60% of these accidents occurred below 20,000 feet, and flight attendant was the most commonly injured person type. Within the aircraft, turbulence-related injuries were most prevalent in the aft section, accounting for more than three-quarters of flight attendant injuries.

- **Need for updated turbulence guidance.** The most recent Federal Aviation Administration guidance to Part 121 air carriers on preventing turbulence-related injuries was published in 2007. Since then, the NTSB has investigated numerous accidents and incidents involving turbulence and industry groups have also studied the issue. Updated guidance should incorporate best practices and lessons learned from these activities; reflect technological advancements occurring in the last 14 years; and promote the findings and, eventually, the outcomes of the safety recommendations in this report.

Findings

- Wearing a seat belt reduces the risk of serious injury for all aircraft occupants during turbulence-related accidents in Title 14 *Code of Federal Regulations* Part 121 air carrier operations.

- Air traffic control procedures for processing pilot weather reports remain time-consuming and nonstandardized, which continues to prevent safety-critical turbulence observations from being shared throughout the National Airspace System.

- Air carriers continue to share turbulence observations with only their personnel but not throughout the National Airspace System, limiting opportunities for awareness of adverse weather phenomena that can negatively affect the safety of flight.

- Developing methods to translate between eddy dissipation rate (EDR) values calculated by different algorithms would produce consistent results, enable the maximum sharing of EDR data among air carriers, and ensure that turbulence forecast products are appropriately using these data.

- Because objective, in situ turbulence observations are not shared publicly to the greatest extent possible, air traffic control, weather forecasters, and other National Airspace System users lack access to important flight safety data.

- Due to their large size, airmen's meteorological information advisories are currently of limited value to Title 14 *Code of Federal Regulations* Part 121 air carrier pilots and air traffic controllers.

- Providing graphical airmen's meteorological information (AIRMET) advisories, significant meteorological information (SIGMET) advisories, and center weather advisories (CWAs) to air traffic controllers as controller-selectable layers on current and future controller displays in air route traffic control centers and terminal radar approach control facilities would increase shared awareness among controllers of AIRMET advisory, SIGMET advisory, and CWA locations.

- A frequently updated, short-term forecasting product known as a turbulence nowcast would provide more complete and accurate tactical information to help pilots, dispatchers, and air traffic controllers effectively respond to turbulence.

- Total lightning and hail information provide useful indicators for areas of convection and convective turbulence.

- Having flight attendants seated with their seat belts fastened during additional portions of the descent phase of flight would reduce the rate of flight attendant injuries due to turbulence and the rate of turbulence-related accidents overall.

- Assessing how aircraft accelerations resulting from turbulence vary along the length of the aircraft would improve understanding of the risk of injury due to turbulence, especially for occupants not wearing a seat belt.

- Researching the factors that affect caregivers' decisions about whether to use a child restraint system (CRS) when traveling on a Title 14 *Code of Federal Regulations* Part 121 air carrier airplane with children under the age of 2 would inform and improve government and industry efforts to increase the voluntary use of CRSs.

- Advisory Circular 120-88A, "Preventing Injuries Caused by Turbulence," does not contain information about the current available technologies and best practices for avoiding turbulence encounters and turbulence-related injuries, which could be used by Title 14 *Code of Federal Regulations* Part 121 air carriers to improve the safety of their flights.

Recommendations

New Recommendations

To the Federal Aviation Administration:

Work with stakeholders to standardize the distribution of pilot weather reports (PIREPs) across and within air traffic control facilities to ensure they are disseminated to only those facilities and air traffic controller positions for which each PIREP applies. (A-21-25)

As a condition of enhanced weather information system approval, require Title 14 *Code of Federal Regulations* Part 121 air carriers to disseminate all turbulence observations to the National Airspace System as pilot weather reports, as well as reports of smooth ride conditions. (A-21-26)

Determine how to harmonize current and future eddy dissipation rate algorithm performance in operational environments and publish the results of this determination. (A-21-27)

Incorporate the automatic dependent surveillance-broadcast weather capability in the next version of the automatic dependent surveillance-broadcast technical standard order. (A-21-28)

After the automatic dependent surveillance-broadcast (ADS-B) technical standard order is revised as recommended in Safety Recommendation A-21-28, require that aircraft flown in Title 14 *Code of Federal Regulations* Part 121 air carrier operations be retrofitted with automatic dependent surveillance-broadcast weather capable ADS-B equipment. (A-21-29)

Require automatic dependent surveillance-broadcast weather (ADS-B Wx)-equipped aircraft to broadcast ADS-B Wx information when operating in airspace requiring automatic dependent surveillance-broadcast capability as defined by Title 14 *Code of Federal Regulations* 91.225. (A-21-30)

In collaboration with the National Weather Service, modify airmen's meteorological information (AIRMET) advisory issuing practices to include graphical AIRMET advisories with higher granularity, taking into account the effect it would have on all National Airspace System users. (A-21-31)

Distribute graphical airmen's meteorological information advisories, significant meteorological information advisories, and center weather advisories to air traffic controllers as controller-selectable layers on current and future controller radar displays in air route traffic control centers and terminal radar approach control facilities. (A-21-32)

Work with local safety councils to develop training on the use of the advisories developed for Safety Recommendation A-21-32. (A-21-33)

In collaboration with the National Weather Service, operationalize a turbulence nowcast, such as the graphical turbulence guidance nowcast. (A-21-34)

Develop air traffic control guidelines for use of the turbulence nowcast operationalized in accordance with Safety Recommendations A-21-34 and A-21-44. (A-21-35)

Incorporate total lightning and hail information as selectable layers on air traffic controller radar displays in air route traffic control centers and terminal radar approach control facilities. (A-21-36)

After the action in Safety Recommendation A-21-36 is completed, provide training to air traffic controllers on the use of the controller-selectable total lightning and hail information. (A-21-37)

Based on National Transportation Safety Board data on turbulence-related Title 14 *Code of Federal Regulations* Part 121 accidents, include in the revisions to Advisory Circular 120-88A, "Preventing Injuries Caused by Turbulence," in Safety Recommendation A-21-42 the phases of flight and associated altitudes at which flight attendants should be secured in their seats during Part 121 air carrier operations, including in particular the descent phase of flight. (A-21-38)

Conduct a study of how aircraft accelerations vary along the length of the aircraft during turbulence encounters, including differences among aircraft types operated by Title 14 *Code of Federal Regulations* Part 121 air carriers, and publish the study findings. (A-21-39)

Conduct a study to determine the factors that affect caregivers' decisions about the use of child restraint systems (CRSs) when traveling on a Title 14 *Code of Federal Regulations* Part 121 air carrier airplane with children under the age of 2 and to understand the challenges associated with using CRSs; publish the study findings. (A-21-40)

After the action in Safety Recommendation A-21-40 is completed, use the study findings to direct the Federal Aviation Administration's efforts to increase child restraint system usage. (A-21-41)

Revise Advisory Circular 120-88A, "Preventing Injuries Caused by Turbulence," to reflect current best practices and the findings of this research report, such as new turbulence forecasting and warning technologies; training methods; in-flight communications between pilots and flight attendants, procedures, and available information for predicting turbulence; and altitudes at which flight attendants should be secured in their seats. (A-21-42)

To the National Weather Service:

Work with the Federal Aviation Administration to modify airmen's meteorological information (AIRMET) advisory issuing practices to include graphical AIRMET advisories with higher granularity, taking into account the effect it would have on all National Airspace System users. (A-21-43)

Work with the Federal Aviation Administration to operationalize a turbulence nowcast, such as the graphical turbulence guidance nowcast. (A-21-44)

To Airlines for America, the National Air Carrier Association, and the Regional Airline Association:

Coordinate with your member airlines to develop and implement a program to increase child restraint system (CRS) usage in airplanes; this effort should include collecting data to determine the program's effectiveness at increasing CRS usage. (A-21-45)

Previously Issued Recommendations Reiterated in This Report

To the Federal Aviation Administration:

Provide air traffic controllers with automated pilot weather report (PIREP) data-collection tools that incorporate design elements to prevent input errors, increase quantity, and improve the timeliness of PIREPs disseminated to the National Airspace System. (A-17-21)

> Incorporate automation technology that captures data elements from air traffic controllers' displays, including aircraft type, time, location, and altitude, to automatically populate these data into a pilot weather report (PIREP)-collection and -dissemination tool that will enable controllers to enter the remaining PIREP elements and disseminate PIREPs through a common exchange model directly to the National Airspace System. (A-17-22)

> Provide a reliable means of electronically accepting pilot weather reports directly from all users who are eligible to submit reports, and ensure that the system has the capacity to accept and make available all such reports to the National Airspace System. (A-17-26)

Previously Issued Recommendation Classified and Reiterated in This Report

To the Federal Aviation Administration:

> Encourage industry safety efforts, such as the Commercial Aviation Safety Team and the General Aviation Joint Steering Committee, to identify, develop, and implement incentives for 14 *Code of Federal Regulations* Part 121, 135, and 91K operators and the general aviation community to freely share pilot weather reports (PIREPs), including braking action or runway condition reports filed as PIREPs, to the National Airspace System to enhance flight safety. (A-17-25)

Safety Recommendation A-17-25 is classified "Open—Unacceptable Response" in section 4.1.1 of this report.

1 Introduction

Turbulence-related accidents are the most common type of accident involving air carriers operating under Title 14 *Code of Federal Regulations* (*CFR*) Part 121.[1] From 2009 through 2018, the National Transportation Safety Board (NTSB) found that turbulence-related accidents accounted for more than a third of all Part 121 accidents; most of these accidents resulted in one or more serious injuries but no aircraft damage. This NTSB safety research report examines the prevalence and risk factors of turbulence-related accidents in Part 121 air carrier operations; assesses the effectiveness of policies, programs, technologies, and other applicable safety countermeasures; and makes recommendations for improving turbulence avoidance and injury mitigation.[2]

Like many accidents in aviation, turbulence-related accidents can often be influenced by multiple human, aircraft, environmental, and organizational factors. Over the past decade, the NTSB has determined the probable cause for numerous turbulence-related accidents and has issued safety recommendations for improving weather forecasting, dissemination of weather reports, and air traffic management practices, to reduce the likelihood of aircraft encounters with turbulence.[3] More recently, in 2017, the NTSB issued several recommendations addressing safety issues related to turbulence as part of its special investigation report *Improving Pilot Weather Report Submission and Dissemination to Benefit Safety in the National Airspace System* (NTSB 2017).[4] Despite steady improvements in the overall accident rate for Part 121 air carrier operations, turbulence continues to be a major cause of accidents and injuries.

1.1 Scope

This research focused on reducing crew and passenger injuries resulting from atmospheric turbulence encounters in Part 121 air carrier operations. Specifically, the NTSB examined the accuracy of turbulence prediction and detection technologies and their use in avoiding turbulence

[1] (a) Title 49 *CFR* 830.2 defines an *accident* as an occurrence associated with the operation of an aircraft that 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. A turbulence encounter becomes an accident if the airplane is substantially damaged or a person on board sustains a serious or fatal injury. (b) Title 14 *CFR* Part 121 regulates air carrier operations involving airplanes with a passenger-seat configuration of more than nine passenger seats, or, in the case of cargo operations, airplanes having a payload capacity of more than 7,500 pounds. (c) For the remainder of this report, air carrier operations regulated by 14 *CFR* Part 121 are referred to as *Part 121 air carrier operations*, and accidents involving such operations are referred to as *Part 121 accidents*.

[2] Additional information about this safety research can be found in the NTSB Accident Docket Search system using NTSB docket DCA18SS003.

[3] For example, Safety Recommendations A-12-18 through A-12-20, A-14-13 through A-14-16, and A-14-17 through A-14-21 concern topics such as the content of preflight weather briefings, the incorporation of weather data into air traffic controller and pilot displays, controller training on weather-related capabilities, the consistency of aviation weather products, aviation meteorologist responsibilities, and communication protocols among aviation meteorologists (NTSB 2012, 2014a, 2014b). See appendix A for more information concerning these safety recommendations and all NTSB safety recommendations referenced in this report. Additional information about safety recommendations referenced in this report is also available via the CAROL Query Tool.

[4] See section 1.4 of this report for further discussion of the 2017 special investigation report. See also appendix A for more information.

encounters, the utility of turbulence-related resources for planning and conducting flights, and the overall effectiveness of air carrier and air traffic control (ATC) training, policies, and procedures for avoiding turbulence and minimizing occupant injuries when turbulence is encountered. Also, the outcomes of recent industry efforts to address the safety risks of turbulence and aircraft technologies for mitigating turbulence-related injuries were assessed.

1.2 Goals

This research examined safety issues related to the turbulence problem from a systemwide perspective. The NTSB's research goals were to (1) summarize the basic types and causes of turbulence; (2) describe the safety impacts of turbulence, including characteristics of and trends in turbulence-related accidents and injuries across Part 121 air carrier operations; (3) examine methods used to reduce the likelihood of turbulence encounters and turbulence-related injuries in Part 121 air carrier operations; and (4) identify proven and emerging best practices and safety countermeasures. To accomplish these goals, the NTSB used both quantitative and qualitative methods, including a literature review, aggregate analysis of aviation accident data, and interviews with a broad selection of government, industry, and other stakeholders. In addition, the NTSB conducted 10 detailed investigations of turbulence-related Part 121 accidents over the course of this research to provide relevant and timely case studies.

1.3 Basics of Aviation Turbulence

Turbulence arises from eddies in the atmosphere and is typically categorized by its source, such as convection, nonconvective wind shears in clear air, mountain waves, surface features, and aircraft wake vortices (Sharman 2016).[5] (See figure 1.) Turbulence intensity is typically reported using a four-level subjective scale of light, moderate, severe, or extreme.[6] The light and moderate levels of turbulence can also be reported as "chop," which is distinguished by "slight, rapid, and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude" (FAA 2019). Turbulence duration may be reported as occasional, intermittent, or continuous.[7] The reported turbulence type, intensity level, and duration are determined by the pilot and are based on the aircraft response and the response inside the aircraft cabin. Table 1 shows the Federal Aviation Administration (FAA) guidance for pilots when reporting turbulence types and intensities (FAA 2019). Pilot observations of turbulence are most often disseminated via voice communication with air traffic controllers.

[5] (a) *Eddies* are circular air currents typically moving in a different direction than the main air current. (b) *Convection* refers to the vertical transport of heat and moisture in the atmosphere, especially by updrafts and downdrafts. The terms convection and thunderstorms are often used interchangeably, although thunderstorms are only one form of convection. (c) *Nonconvective wind shears in clear air* refers to wind shear not associated with thunderstorms or other forms of atmospheric convection. (d) *Mountain waves* are disturbances in the horizontal air flow that result in oscillations to the downwind side of mountains and other high ground. (e) *Surface features* refer to turbulence caused by friction between the air and irregular terrain or human-made structures. (f) *Aircraft wake vortices* are disturbances in the atmosphere that form behind an aircraft as it passes through the air.

[6] *Turbulence intensity* may be reported as a range of levels, such as "light to moderate."

[7] *Occasional turbulence* is defined as occurring less than one-third of the time. *Intermittent turbulence* is defined as occurring between one-third to two-thirds of the time. *Continuous turbulence* is defined as occurring more than two-thirds of the time.

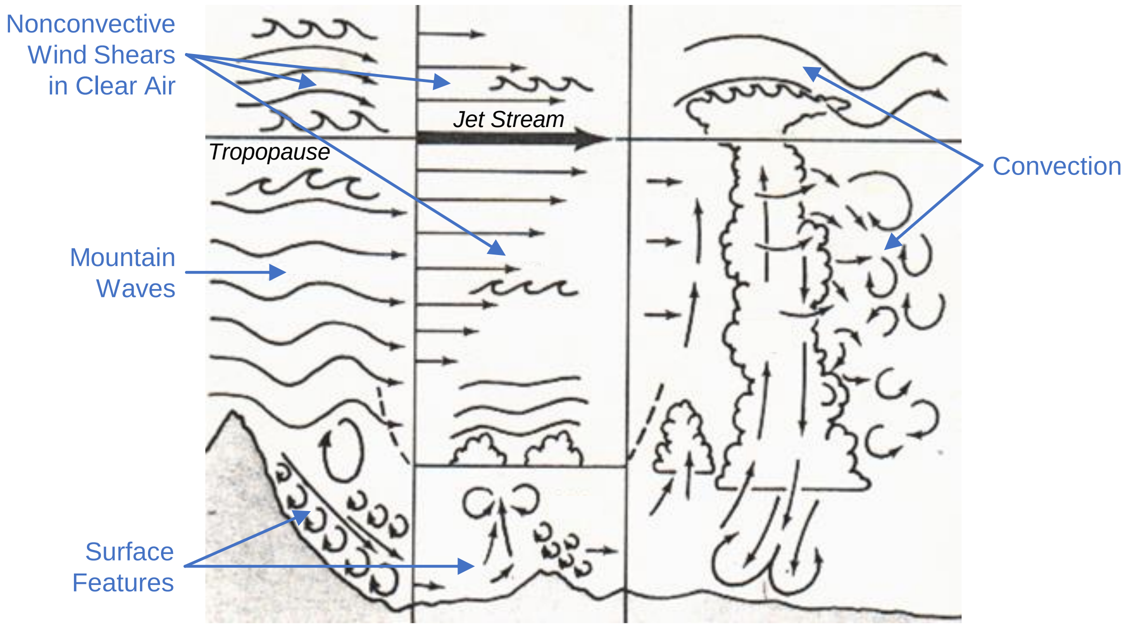

Figure 1. Illustration showing sources of turbulence (adapted from Lester 1994).

Table 1. FAA turbulence reporting criteria.

Intensity	Aircraft Reaction	Reaction Inside Aircraft
Light	Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw). Report as **Light Turbulence** Or Turbulence that causes slight, rapid, and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude. Report as **Light Chop**.	Occupants may feel a slight strain against seat belts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encountered in walking.
Moderate	Turbulence that is similar to Light Turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed. Report as **Moderate Turbulence** or Turbulence that is similar to Light Chop but of greater intensity. It causes rapid bumps or jolts without appreciable changes in aircraft altitude or attitude. Report as **Moderate Chop**.	Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult.
Severe	Turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control. Report as **Severe Turbulence**.	Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about. Food service and walking are impossible.
Extreme	Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. Report as **Extreme Turbulence**.	—

Part 121 air carriers began using methods of objectively calculating turbulence intensity level in 1997. These calculations use aircraft sensors to calculate a turbulence value based either on the aircraft response or an aircraft-independent measure of the turbulent state of the atmosphere.[8] An example of the former is root mean square acceleration, and an example of the latter is the eddy dissipation rate (EDR). Root mean square acceleration is a measure of vibration. The EDR is typically represented as a scale of the rate at which energy dissipates in the atmosphere. The EDR is the official atmospheric turbulence intensity metric recognized by the International Civil Aviation Organization (ICAO 2010).[9]

The National Weather Service (NWS) produces aviation turbulence forecast products, such as significant meteorological information (SIGMET) advisories, airmen's meteorological information (AIRMET) advisories, center weather advisories (CWAs), high-level significant weather charts, and graphical turbulence guidance (GTG).[10] SIGMET advisories provide information about widespread weather that is potentially hazardous to all aircraft, including severe or extreme turbulence. SIGMET advisories are valid for up to 4 hours for conditions estimated to have a significant impact on the safety of aircraft operations. AIRMET advisories are issued when weather phenomena that do not meet the requirements for a SIGMET advisory are affecting or, in the forecaster's estimation, are expected to affect an area having a significant impact on the safety of aircraft operations, such as moderate turbulence. AIRMET advisories are issued in graphical and text forms.[11] Graphical AIRMET advisories are valid at discrete times in 3-hour intervals. Text AIRMET advisories are valid for 6 hours and describe a larger area than graphical AIRMET advisories because they encompass all the graphical AIRMET advisories valid during the 6-hour period (FAA 2019). Figure 2 shows an example of a graphical AIRMET advisory. See also appendix B for a table summarizing all turbulence-related weather products discussed in this report.

[8] An aircraft-independent measure of turbulence is analogous to a "sea state." That is, it does not depend on the characteristics of the aircraft experiencing the turbulence, much like wave height does not depend on the size of a ship when used to describe marine surface conditions.

[9] The International Civil Aviation Organization is a United Nations specialized agency that develops and supports the implementation of global standards and recommended practices applicable to international aviation.

[10] The NWS is part of the National Oceanic and Atmospheric Administration (NOAA).

[11] Graphical AIRMET advisories are issued as polygons with minimum and maximum altitudes.

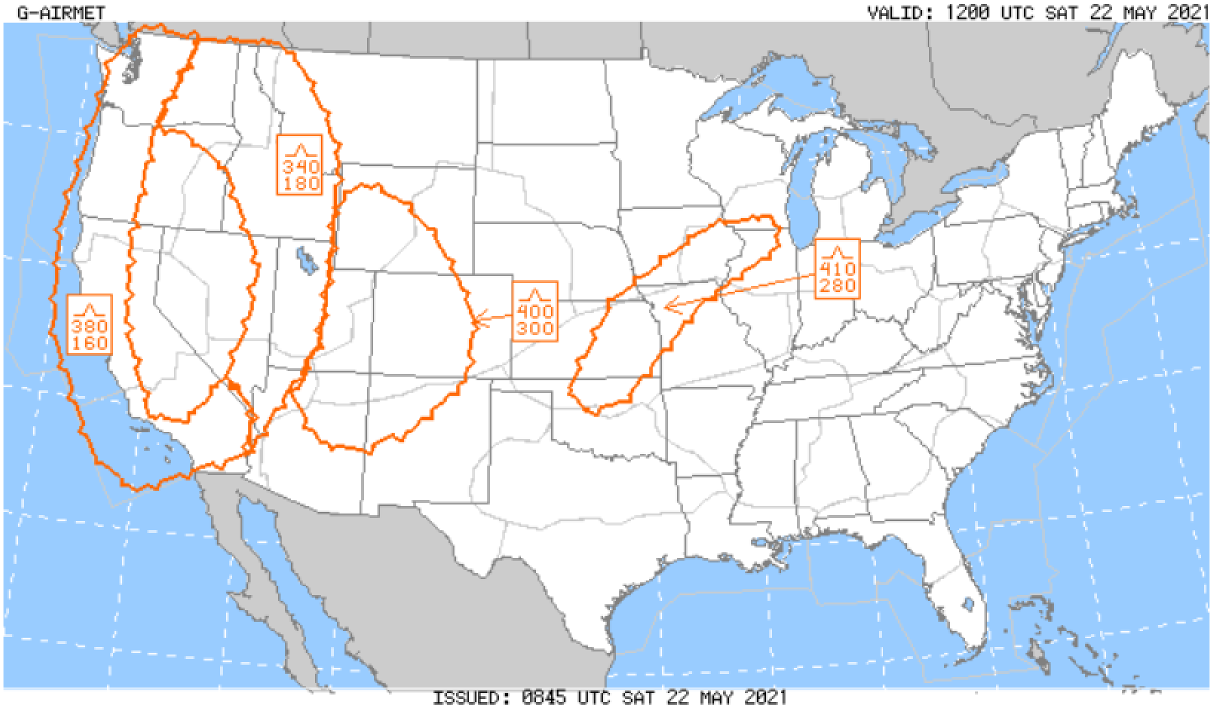

Figure 2. Example graphical AIRMET advisory showing areas with the potential for moderate turbulence.

CWAs are unscheduled weather advisories for conditions meeting or approaching AIRMET advisory or SIGMET advisory criteria and are issued by a center weather service unit. High-level significant weather charts show significant en route weather phenomena over a range of flight levels across the United States and the world with associated surface weather features shown and areas of convection and moderate or severe turbulence highlighted. They are valid at discrete times in 6-hour intervals.

The GTG is a relatively newer turbulence forecast product that has been used since the early 2000s. The current version of the GTG provides forecasts of clear air and mountain wave turbulence at multiple altitudes from the surface to flight level 500 and for lead times ranging from 0 to 18 hours, displayed as a potential EDR with an 8-mile horizontal resolution. It is updated hourly (NWS 2021a). Figure 3 shows an example of a GTG forecast. In this example, the GTG provides a 6-hour lead-time forecast showing the potential of encountering combined clear air and mountain wave turbulence at flight level 230.

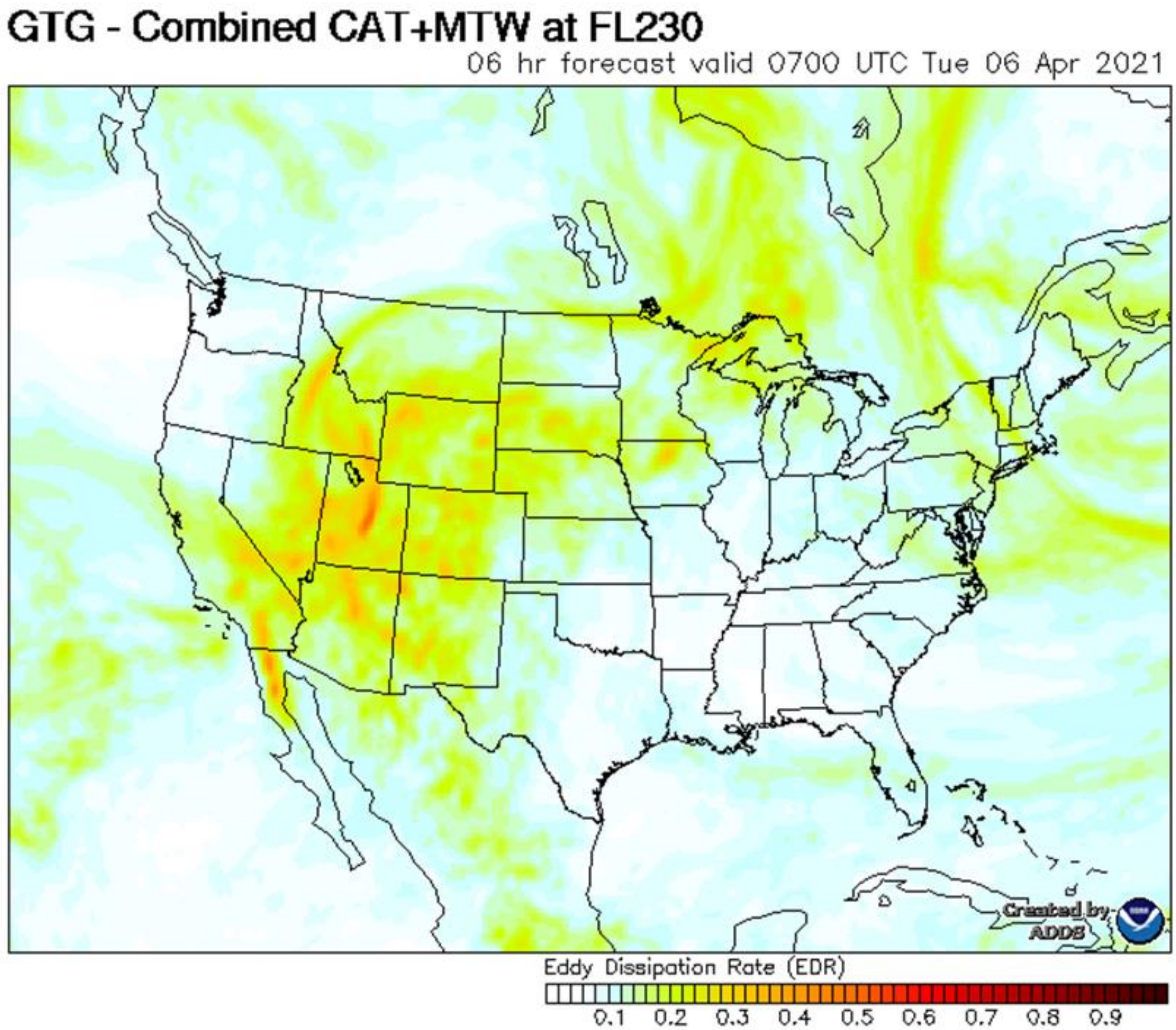

Figure 3. Example GTG forecast for combined clear air and mountain wave turbulence.

1.4 Previous NTSB Reports and Recommendations

The NTSB has conducted work on turbulence beyond its investigations of turbulence-related accidents. The NTSB first comprehensively examined the risks of turbulence to air carrier operations in a 1971 report, *Study of Lessons to be Learned from Accidents Attributed to Turbulence* (NTSB 1971). In this report, the NTSB focused on airborne weather radar training, operation, and maintenance; forecasting and detection of clear air turbulence; and the need for pilots to have real-time weather information.

More recently, in September 2014, the National Center for Atmospheric Research (NCAR) organized a 2-day workshop on turbulence impact mitigation, which the NTSB hosted at its boardroom and conference center in the District of Columbia (NCAR 2014). The workshop included expert panelists involved in ongoing research and safety initiatives focused on how turbulence affects different elements of the National Airspace System (NAS). The workshop highlighted a number of safety issues associated with turbulence in aviation operations, such as the importance of developing and improving turbulence mitigation capabilities across the NAS and new strategies for government and industry to work together on reducing turbulence-related accidents and injuries.[12]

In June 2016, the NTSB held a 2-day forum, "PIREPs: Pay it Forward…Because Weather for One is Weather for None," to facilitate information sharing among various users of pilot weather reports (PIREPs) and to discuss ways to improve the effectiveness of the PIREP system. A PIREP describes a pilot's observations about in-flight weather conditions. (See figure 4.) The forum examined the ways in which weather services, ATC, industry, and researchers use PIREPs and the safety issues related to the quantity, quality, and distribution of PIREPs across the NAS. Although not specifically focused on turbulence, the forum identified standard reporting criteria for PIREPs as an area for future improvement.[13]

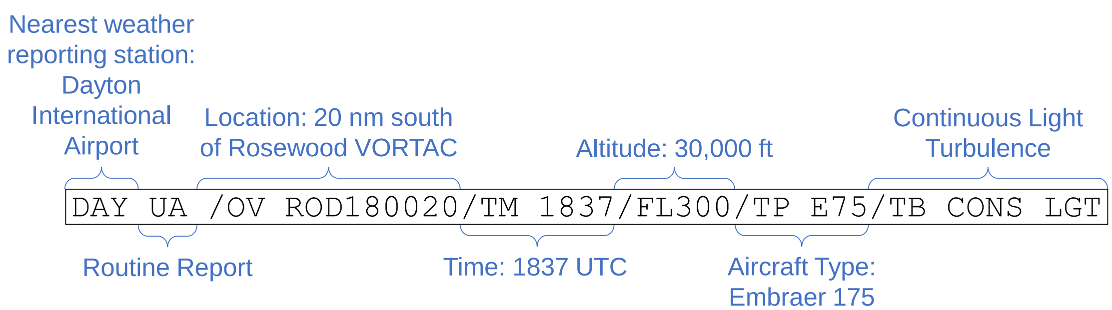

Figure 4. Example PIREP and explanation of coded text.

[12] NCAR held a follow-on workshop in 2018, which the MITRE Corporation hosted at its Center for Advanced Aviation System Development in McLean, Virginia (NCAR 2018).

[13] More information about this forum, including presentations and transcripts, can be found in the NTSB Accident Docket Search system using NTSB docket DCA15SR001.

In March 2017, the NTSB made several recommendations addressing safety issues related to turbulence as part of its special investigation report *Improving Pilot Weather Report Submission and Dissemination to Benefit Safety in the National Airspace System* (NTSB 2017).[14] Because they provide in situ observations, PIREPs were identified as an important source of information for weather forecasters when assessing the quality of their forecasts and for improving graphical weather products used by pilots and others to avoid weather hazards in the NAS.[15] As a result, the NTSB issued Safety Recommendation A-17-18 to the FAA and a companion Safety Recommendation A-17-29 to the NWS recommending that they harmonize PIREP guidance in the *Aeronautical Information Manual* and Advisory Circular (AC) 00-45H, "Aviation Weather Services," including the guidance and criteria for reporting fair weather, low-level windshear, and turbulence. In addition, the NTSB issued Safety Recommendation A-17-19 to the FAA and a companion Safety Recommendation A-17-30 to the NWS calling for comprehensive PIREP-coding guidance and standard criteria for reporting mountain wave activity, including parameters for classifying the intensity level of turbulent and smooth wave encounters and the threshold at which PIREPs for each type of encounter, such as turbulent or smooth, should be coded as urgent. In response to these recommendations, the NWS added mountain wave and low-level windshear reporting criteria to the NWS Aviation Weather Center electronic PIREP submission tool, and the FAA reflected these changes in revisions to AC 00-45H and the *Aeronautical Information Manual*.[16]

[14] (a) See pages 47 through 50 of the report, SIR-17/02; also see appendix A for more information. (b) For the remainder of this report, this special investigation will be referred to as the NTSB's 2017 PIREP special investigation report.

[15] An *in situ observation* refers to a real-time weather observation made in the original place where it is occurring.

[16] Safety Recommendations A-17-18 and A-17-19 to the FAA are classified "Open—Acceptable Response." The companion Safety Recommendations A-17-29 and A-17-30 to the NWS are also classified "Open—Acceptable Response." See appendix A for more information.

2 Methodology

The NTSB used a combination of quantitative and qualitative methods to conduct this research, including a literature review, aggregate analyses of accident data, interviews with government and industry stakeholders, and detailed investigations of turbulence-related Part 121 accidents that occurred during the research period. While conducting this research, the NTSB also participated in several conferences and forums focused on aviation weather and turbulence.

2.1 Literature Review

The NTSB reviewed relevant scientific literature concerning turbulence and its effect on flight operations, methods for detecting and forecasting turbulence, and in-flight injuries resulting from turbulence encounters. The NTSB also reviewed government and industry guidance, policies, and procedures regarding turbulence, including the outcomes of past industry efforts to address the safety risks of turbulence. Information gathered from the literature review provided context for the safety issues discussed in section 4 and informed the recommendation development process.

2.2 Data Analysis

To understand the frequency, trends, and common characteristics of turbulence-related Part 121 accidents, the NTSB analyzed data from its Aviation Accident Database.[17] This database contains more than 350 possible data elements describing all civil aviation accidents occurring in the United States since 1983 and limited data on foreign accidents involving US-registered aircraft. The NTSB Aviation Accident Database also includes narrative fields, coded data elements categorizing the accident sequence, and the NTSB's findings of probable cause and contributing factors. Using these data, the NTSB produced descriptive statistics pertaining to the following:

- prevalence of turbulence-related Part 121 accidents
- yearly trends in Part 121 accident counts, 1989 through 2018
- yearly trends in Part 121 accident rates, 1989 through 2018
- turbulence type
- seasonality of turbulence-related Part 121 accidents
- reported turbulence intensity
- phase of flight
- aircraft damage
- number of injuries
- type of person injured (crewmember or passenger)

[17] The NTSB has deployed a new Case Analysis and Reporting Online tool, commonly known as the CAROL Query Tool, to help users find information about accidents and recommendations. Until CAROL is completely integrated, aviation investigations occurring before 2008 can be found using the Aviation Accident Database. Also, accident docket information can be found using the NTSB Accident Docket Search system.

Most analyses summarize the 10-year period from 2009 through 2018; some analyses of accident trends are shown for the 30-year period from 1989 through 2018 to illustrate accident trends more clearly.

The NTSB reviewed the text of accident reports and used background materials found in investigation dockets, such as flight crewmember statements, to extract additional data not available in the NTSB's Aviation Accident Database. These data were used to produce descriptive statistics pertaining to the following:

- altitude at which Part 121 accidents occurred
- flight crew awareness of turbulence risks prior to each Part 121 accident
- location within the aircraft of each injured person
- activity of each injured person at the time of injury
- restraint usage
- region of the body that was injured

The results of these analyses are shown in section 3.1.

2.3 Stakeholder Interviews

To complement the quantitative data analysis, the NTSB conducted interviews with subject matter experts and other stakeholders.[18] All subject matter experts and stakeholders were either directly involved in Part 121 air carrier operations or conducting work in areas critical to the safety of such operations. The purpose of these interviews was to gather qualitative data on the latest developments in turbulence forecasting and reporting, operational practices related to turbulence, areas of common concern among stakeholders, and best practices. The following is a list substantively grouping and summarizing the types of subject matter experts and stakeholders the NTSB interviewed and the topics typically covered:

- **ATC:** The NTSB conducted interviews at 11 FAA ATC facilities, including five air route traffic control centers (ARTCCs), five terminal radar approach control (TRACON) facilities, and the Air Traffic Control System Command Center. These interviews typically included air traffic controllers, supervisors, labor union representatives, support staff, and traffic managers. At the ARTCCs, the NWS center weather service unit personnel were also interviewed. Interview topics included the following:
    - sources of turbulence information
    - training
    - procedures for soliciting and disseminating PIREPs
    - traffic management practices when turbulence is forecast or reported

[18] Semi-structured interviews consisting of open-ended questions were used. With this type of interview technique, the topics and potential questions are developed beforehand. However, the order and wording of the questions may vary among interview subjects, and questions may be added as the interview progresses to explore topics in greater detail (Britten 2006).

Most interviews conducted at ATC facilities also included site visits and observations of operations.

- **Air Carriers:** The NTSB conducted interviews with personnel from 10 Part 121 air carriers, including 4 regional air carriers. These interviews typically included dispatchers, flight attendants, pilots, labor union representatives, and representatives of corporate safety departments. Interview topics included the following:

    - trends in turbulence encounters and injuries, and practices for tracking these events
    - internal initiatives for reducing turbulence-related injuries
    - dispatcher, pilot, and flight attendant training
    - policies for dispatching flights when turbulence is forecast
    - tools for determining the risk of turbulence to a flight, including dispatcher flight planning software, airborne weather radar, and electronic flight bag applications[19]
    - fleet equipment for objective turbulence measurement
    - preflight and in-flight communications among dispatchers, pilots, flight attendants, passengers, and ATC

    Several interviews also included observations of air carrier flight dispatchers and operations centers.

- **Meteorologists and Commercial Weather Information Providers:** The NTSB conducted interviews with personnel from the FAA NextGen Aviation Weather division, aviation turbulence researchers at NCAR, meteorologists at the NWS Aviation Weather Center, and two commercial providers of weather and flight planning software for Part 121 air carriers. Interview topics included the following:

    - FAA research activities involving turbulence
    - how the research community, the NWS, and the FAA work together
    - sharing of in situ turbulence observations
    - new weather models
    - training on the use of turbulence forecast products
    - EDR reports

[19] An *electronic flight bag* is a device that hosts applications that replace or extend the paper documents traditionally carried by a pilot. An electronic flight bag may be installed on the flight deck of an airplane or be a portable device, such as a tablet computer. Examples of electronic flight bag applications include electronic operations manuals to replace paper manuals, electronic airspace and procedure charts to replace paper charts, and real-time graphical weather products to replace paper charts and supplement textual weather products (FAA 2017).

- **Other Stakeholders:** The NTSB conducted interviews with representatives from one pilot union, one flight attendant union, one aircraft manufacturer, one airborne radar manufacturer, and one RTCA committee.[20] Interview topics included the following:
  - international interoperability of safety recommendations
  - phase of flight and turbulence-related accidents
  - emerging techniques for turbulence detection
  - sharing of EDR data
  - turbulence detection in airborne weather radars

Summaries of the stakeholder interview responses are provided in section 3.2.

2.4 Case Studies

To strengthen this research, the NTSB conducted 10 detailed investigations of turbulence-related Part 121 accidents between February 2019 and February 2020. These case studies were used to provide further evidence and context for the safety issues discussed in section 4. As part of each case study investigation, the NTSB produced a meteorology factual report and an operational factors factual report. The NTSB also collected supporting materials, including operations manuals, training records, ATC data and documentation, and crewmember statements. A brief overview of the 10 case studies is provided in section 3.3, and further details about each case study investigation are provided in appendix C.

[20] Formerly known as the Radio Technical Commission for Aeronautics, the RTCA is a private, not-for-profit association that develops aviation performance standards.

3 Results

This section discusses the results of the turbulence-related accident and injury data analyses conducted from the NTSB's Aviation Accident Database, highlights the emergent stakeholder interview themes, and provides an overview of 10 recent turbulence-related Part 121 case studies.

3.1 Data Analysis

This section provides a retrospective analysis of the characteristics of turbulence-related accidents in US civil aviation operations with a focus on accidents and injuries occurring in Part 121 air carrier operations.

For this research, the accident data were obtained from the NTSB's Aviation Accident Database, and the flight activity data were obtained from the FAA. Most analyses summarize the 10-year period from 2009 through 2018; some analyses of accident trends are shown for the 30-year period from 1989 through 2018 to illustrate accident trends more clearly. These accident data were current as of September 24, 2020.

For some of the analyses presented in this section, particularly those concerning injury types and circumstances, the NTSB categorized information found in textual narratives and other accident docket materials to augment the quantitative data obtained from its Aviation Accident Database. The NTSB also reviewed accident narratives to identify accidents that were clearly turbulence-related but did not otherwise meet the defining event and probable cause criteria for a turbulence-related Part 121 accident that occurred from 1989 through 2018, such as foreign accidents for which the NTSB did not determine the probable cause.[21] This review resulted in eight accidents being added to the set of turbulence-related Part 121 accidents analyzed in this section.[22]

3.1.1 Accident Characteristics

To illustrate why the NTSB focused this research on Part 121 air carrier operations, table 2 shows the number of turbulence-related accidents involving different segments of US civil aviation operations from 2009 through 2018. During this period, there were a total of 197 turbulence-related accidents, accounting for 1.4% of all US civil aviation accidents. The involvement of turbulence in aviation accidents was not evenly distributed across operation types. However, turbulence was much more likely to be involved in Part 121 accidents than Part 135 or general aviation accidents, accounting for 37.6% of all Part 121 accidents during this period. There are many possible reasons for this, including the different operational environments, aircraft sizes, and the number and type of aircraft occupants typically involved in Part 121 air carrier operations compared with other aviation operations. It should be noted that Part 121 air carrier operations have a lower overall

[21] The *defining event* refers to one event occurring in an aircraft accident sequence that is used to categorize the accident type. The NTSB has used this accident categorization approach since 2008. Before 2008, the NTSB categorized aviation accidents by the *first event*, which refers to the initial event occurring in an aircraft accident sequence.

[22] The eight additional accidents are listed here by their NTSB investigation number along with the year in which each accident occurred: LAX92WA091, 1992; MIA95LA133, 1995; LAX96LA035, 1995; CHI01WA014, 2000 (two serious injuries); ATL01WA106, 2001; MIA03WA084, 2003; DFW07WA178, 2007; and ANC11CA101, 2011. Except where noted otherwise, all accidents resulted in one serious injury and no aircraft damage.

accident rate than Part 135 commuter and on-demand air carrier operations and general aviation operations.[23]

Table 2. Accidents by US civil aviation operations segment, 2009–2018.

US Civil Aviation Operations Segment	Turbulence-Related Accidents	Total Accidents	Percent Turbulence-Related
Part 121	111	295	37.6%
Part 135	7	443	1.6%
General Aviation	79	13,297	0.6%
Total	**197**	**14,028[a]**	**1.4%**

[a] The total number of accidents is less than the sum of accidents in each segment because some accidents involve multiple aircraft operating in different segments.

To further illustrate the prevalence of turbulence in accidents involving Part 121 air carrier operations, table 3 shows the top five defining events for Part 121 accidents occurring from 2009 through 2018. Turbulence was the most common defining event for Part 121 accidents, accounting for more than one-third of all Part 121 accidents during this period.[24]

Table 3. Top five defining events for Part 121 accidents, 2009–2018.

Defining Event	Accidents	Percent
Turbulence Encounter	109	36.9%
Abnormal Runway Contact	36	12.2%
Cabin Safety Events	33	11.2%
Ground Collision	31	10.5%
Ground Handling	24	8.1%

[23] The NTSB's Annual Summary of US Civil Aviation Accidents provides additional details on accident trends, accident rates, and accident types involving Part 121 air carrier operations, Part 135 commuter and on-demand operations, and general aviation operations.

[24] The percentage of turbulence-related accidents in table 2 does not match the percentage of turbulence-related accidents in table 3 because some turbulence-related accidents analyzed do not have a defining event of turbulence, as noted in section 3.1.

Figure 5 shows yearly trends in Part 121 accidents from 1989 through 2018. The number of turbulence-related Part 121 accidents varied between 4 and 18 accidents occurring each year. However, the percent of Part 121 accidents that were turbulence-related was generally highest in the most recent decade shown, from 2009 through 2018, due to a decrease in non-turbulence-related accidents.

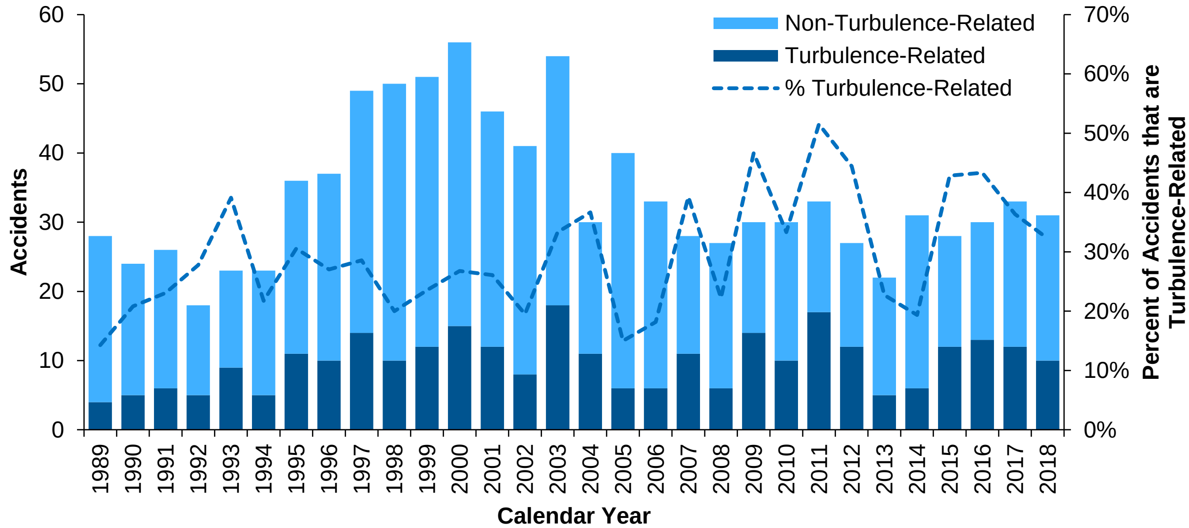

Figure 5. Turbulence-related and non-turbulence-related Part 121 accidents, 1989–2018.

Figure 6 shows yearly trends in Part 121 accident rates from 1989 through 2018. After normalizing the data by annual flight hours, there was no obvious trend over time for turbulence-related Part 121 accidents during this period.[25]

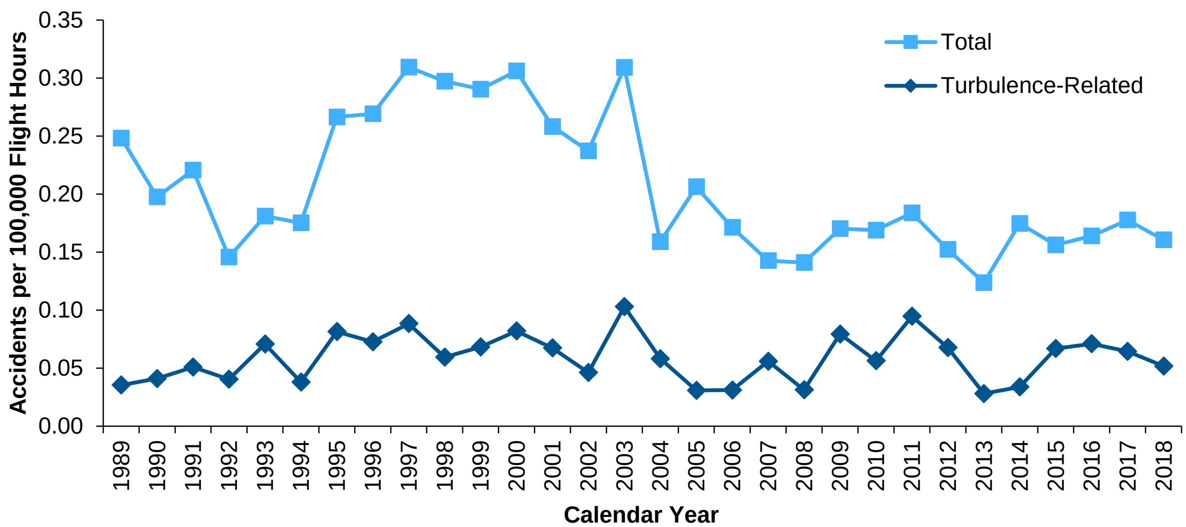

Figure 6. Total and turbulence-related Part 121 accident rates, 1989–2018.

[25] Normalizing data refers to converting data expressed in counts, such as the number of accidents, into a common reference scale, such as an accident rate, to make more meaningful comparisons during analysis.

As shown in figure 7, convective turbulence was present in 57.7% (64 of 111) of all turbulence-related Part 121 accidents from 2009 through 2018, and clear air turbulence was present in 28.8% (32 of 111). Smaller percentages of accidents involved mountain wave turbulence, wake turbulence, or mechanical turbulence. The turbulence type was not reported or unknown in 3.6% of accidents (4 of 111).[26]

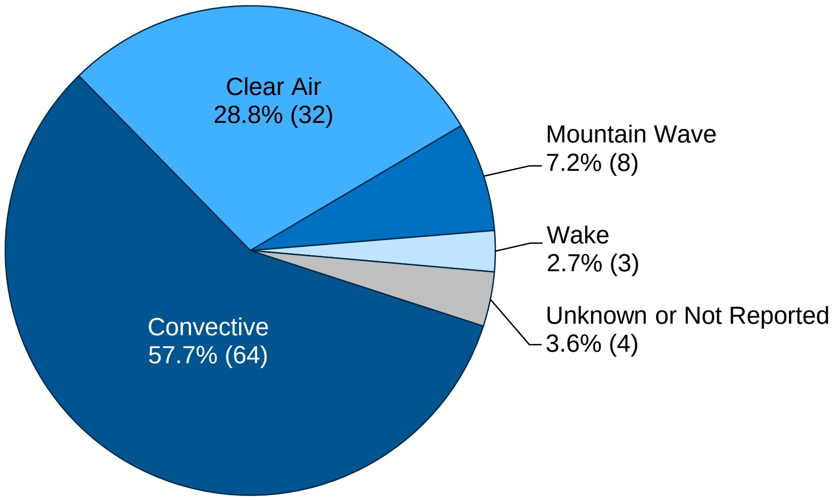

Figure 7. Turbulence-related Part 121 accidents by turbulence type, 2009–2018.

[26] The NTSB reviewed the turbulence-related accidents and defined a *convective turbulence encounter* as an event in the immediate proximity of strong radar reflectivities and/or visible indication of cumulonimbus or cumulus congestus type clouds in the immediate vicinity of the aircraft, even if it was being overflown. A *clear air turbulence encounter* was typically associated with the jet streams or in the immediate vicinity of the tropopause or other upper-level fronts, which could include flight into cirriform or other stratiform clouds not associated with cumulonimbus clouds. *Mountain wave turbulence encounters* were defined as directly associated with mountains with defined wind and thermal patterns to create breaking waves. *Wake turbulence* was defined as being associated with the wing tip vortices created with the generation of lift on an airfoil, which could be typically encountered following another aircraft or operating below its altitude.

Figure 8 shows the distribution of turbulence-related Part 121 accidents by month of occurrence and turbulence type from 2009 through 2018. The accident levels showed some seasonality, with more accidents involving convective turbulence occurring during the summer months in the northern hemisphere, which is when there is a greater number of thunderstorms.[27]

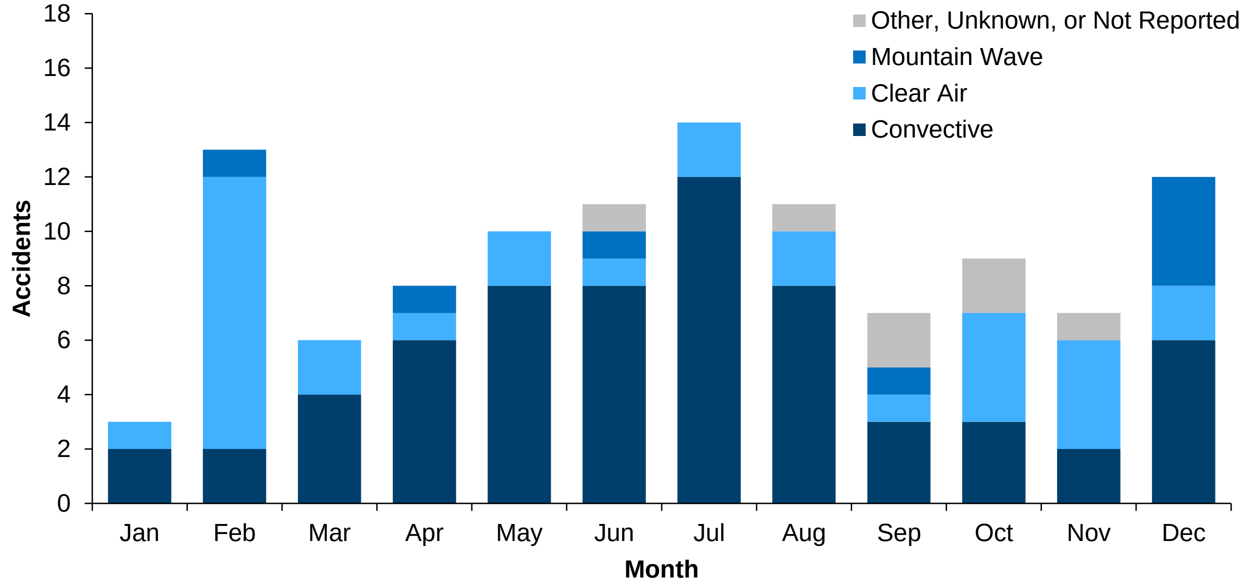

Figure 8. Turbulence-related Part 121 accidents by month of occurrence, 2009–2018.

[27] (a) In contrast, Part 121 accidents that were not turbulence related did not show this seasonality. (b) This analysis did not account for other seasonal variations that may affect turbulence-related accidents, such as changes in flight activity, aircraft types, or flight routes.

As shown in figure 9, turbulence intensity was reported in 86.5% of turbulence-related Part 121 accidents (96 of 111). The most commonly reported intensity levels were severe turbulence (44.1%) and moderate turbulence (41.4%).

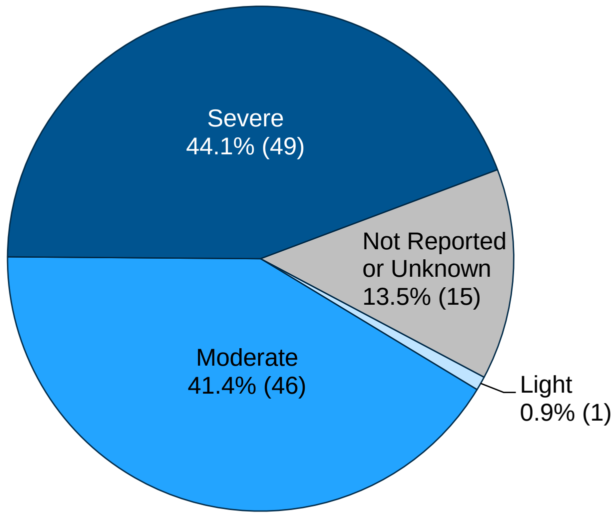

Figure 9. Turbulence-related Part 121 accidents by reported turbulence intensity, 2009–2018.

Figure 10 shows the distribution of turbulence-related Part 121 accidents by the phase of flight associated with the defining event from 2009 through 2018.[28] The most common phase of flight associated with the defining event of turbulence-related Part 121 accidents was en route–descent, which accounted for 36.0% of accidents (40 of 111), followed by en route–cruise, which accounted for 30.6% of accidents (34 of 111). The descent and approach phases of flight, from en route–descent to approach–instrument flight rules final approach, accounted for about half of the accidents (50.5%, 56 of 111) and serious injuries (49.6%, 61 of 123).[29] However, it is worth noting that these data do not account for the proportion of time typically spent in each phase of flight. For example, the initial climb phase of flight only contains the portion of flight after takeoff when an aircraft is between 35 feet and 1,000 feet above runway elevation. These data also do not account for the requirements for aircraft occupants to be seated with their seat belts fastened in each phase of flight. For example, passengers are usually instructed to remain seated throughout the takeoff, initial climb, and en route–climb to cruise phases of flight,

[28] The phases of flight used in this report are categorized according to the Commercial Aviation Safety Team and the International Civil Aviation Organization Common Taxonomy Team's Phase of Flight: Definitions and Usage Notes, April 2013 (1.3). Hyphenated phases of flight are subcategories of a more general phase. For example, en route–climb to cruise is a subcategory of the en route phase. The general phases of flight—initial climb, en route, and approach—are used when investigators are unable to determine a more specific phase of flight.

[29] In contrast, for non-turbulence-related Part 121 accidents occurring during this period, the most common phases of flight associated with the defining event were standing, taxi, and landing. For non-turbulence-related Part 121 accidents occurring while airborne, the most common phase of flight associated with the defining event was en route-cruise.

but flight attendants often get up from their jumpseats earlier during the en route–climb to cruise phase.[30]

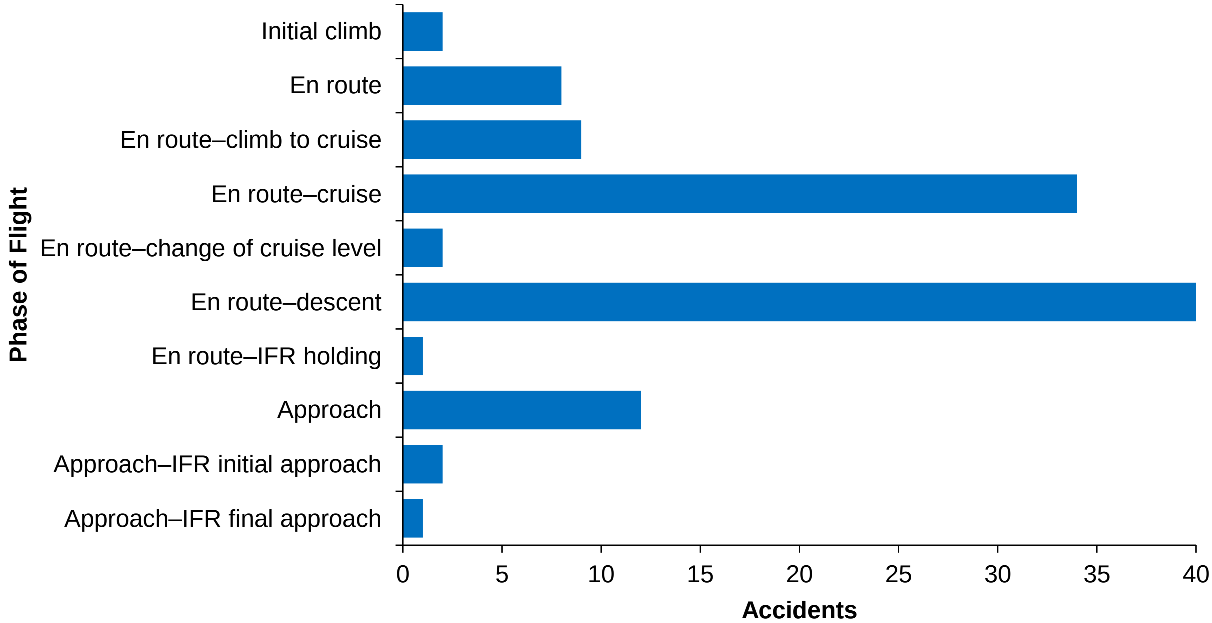

Figure 10. Turbulence-related Part 121 accidents by phase of flight, 2009–2018.

Note: In figure 10, IFR refers to instrument flight rules.

Figure 11 shows the distribution of turbulence-related Part 121 accidents by 5,000-foot altitude increments and by broad phase of flight, from 2009 through 2018. For figure 11, the 10 phases of flight shown in figure 10 were grouped into 3 broad phase of flight categories—climb, cruise, and descent—as shown in the list below:

- **Climb**
  - initial climb
  - en route–climb to cruise
- **Cruise**
  - en route
  - en route–cruise
  - en route–change of cruise level
- **Descent**
  - en route–descent
  - en route–instrument flight rules holding
  - approach
  - approach–instrument flight rules initial approach
  - approach–instrument flight rules final approach

[30] A *jumpseat* is seat on an aircraft located on the flight deck or in the aircraft cabin available for use by pilots, flight attendants, or other authorized personnel.

In the climb phase of flight, no accidents occurred below 10,000 feet. Among accidents occurring in the descent phase of flight with known altitude, 65.3% (32 of 49) occurred below 20,000 feet.

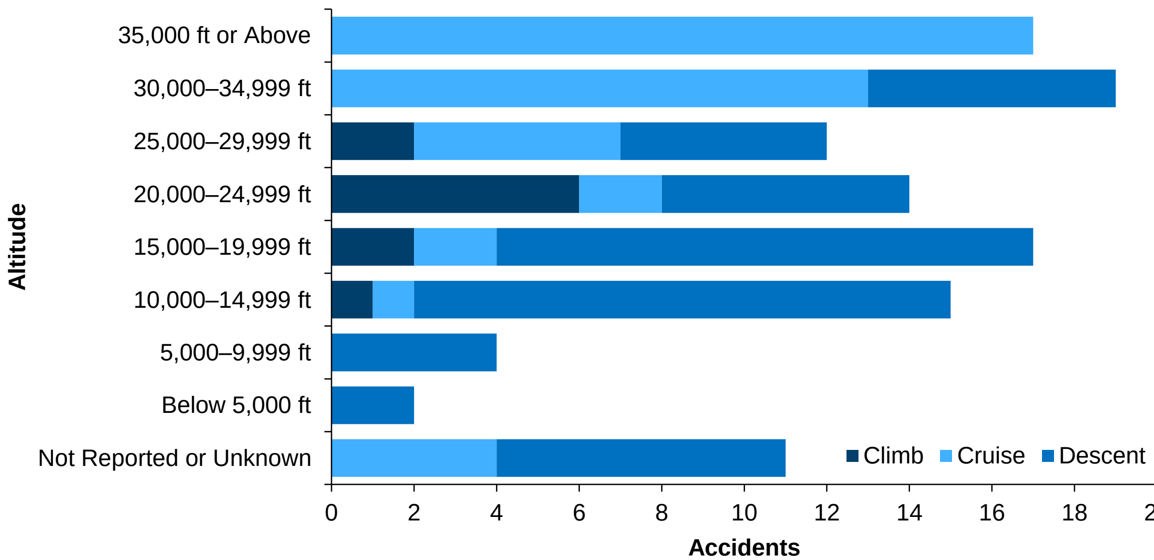

Figure 11. Turbulence-related Part 121 accidents by altitude and phase of flight, 2009–2018.

The NTSB analyzed investigation materials for evidence that flight crews were aware of the risk of encountering turbulence on accident flights, such as holding a preflight briefing, mentioning a weather report, hearing reports from ATC, seeing convective weather on radar, or experiencing light turbulence/chop. As shown in figure 12, in 53.2% of turbulence-related Part 121 accidents from 2009 through 2018 (59 of 111), the flight crew was aware of the risk of encountering turbulence before the accident occurred. In 29.7% of the accidents (33 of 111), the flight crew was not aware, and in the remaining accidents, flight crew awareness was unknown or not reported.

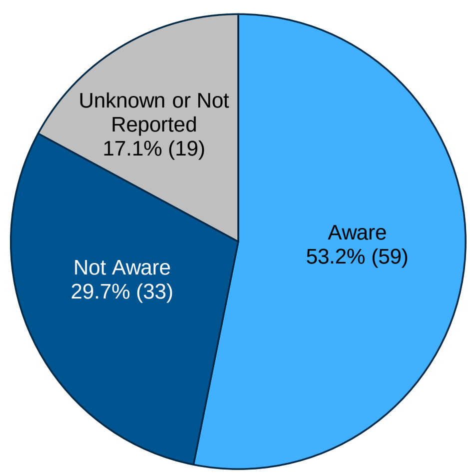

Figure 12. Flight crew awareness of turbulence risk prior to turbulence-related Part 121 accidents, 2009–2018.

3.1.2 Injury Characteristics

A turbulence encounter becomes an accident if the airplane is substantially damaged or a person on board sustains a serious or fatal injury.[31] As shown in figure 13, from 2009 through 2018, no event qualified as a turbulence-related Part 121 accident based on substantial damage to the airplane. For the five minor damage accidents that occurred, the damage mainly involved cabin components, such as seats, ceiling panels, overhead bins, and passenger-service units.

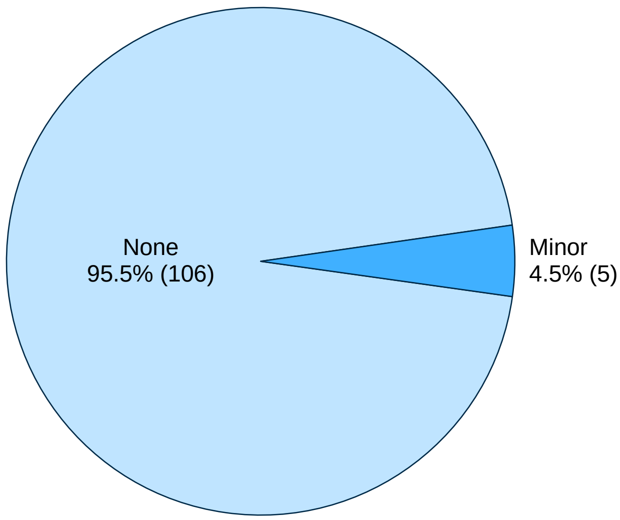

Figure 13. Turbulence-related Part 121 accidents by aircraft damage level, 2009–2018.

In contrast, of the 111 turbulence-related Part 121 accidents that occurred from 2009 through 2018, all resulted in at least one serious injury.[32] Figure 14 shows that most turbulence-related Part 121 accidents resulted in a serious injury to only one occupant.

[31] See the glossary in this report for the definition of the term *serious injury*.

[32] The most recent turbulence-related Part 121 accident that resulted in a fatality occurred on December 28, 1997. A Boeing 747 experienced severe turbulence en route from Narita, Japan, to Honolulu, Hawaii. Of the 374 passengers (including 5 infants) and 19 crewmembers on board, 15 passengers and 3 flight attendants were seriously injured, and 1 passenger died. See NTSB investigation DCA98MA015 for more information.

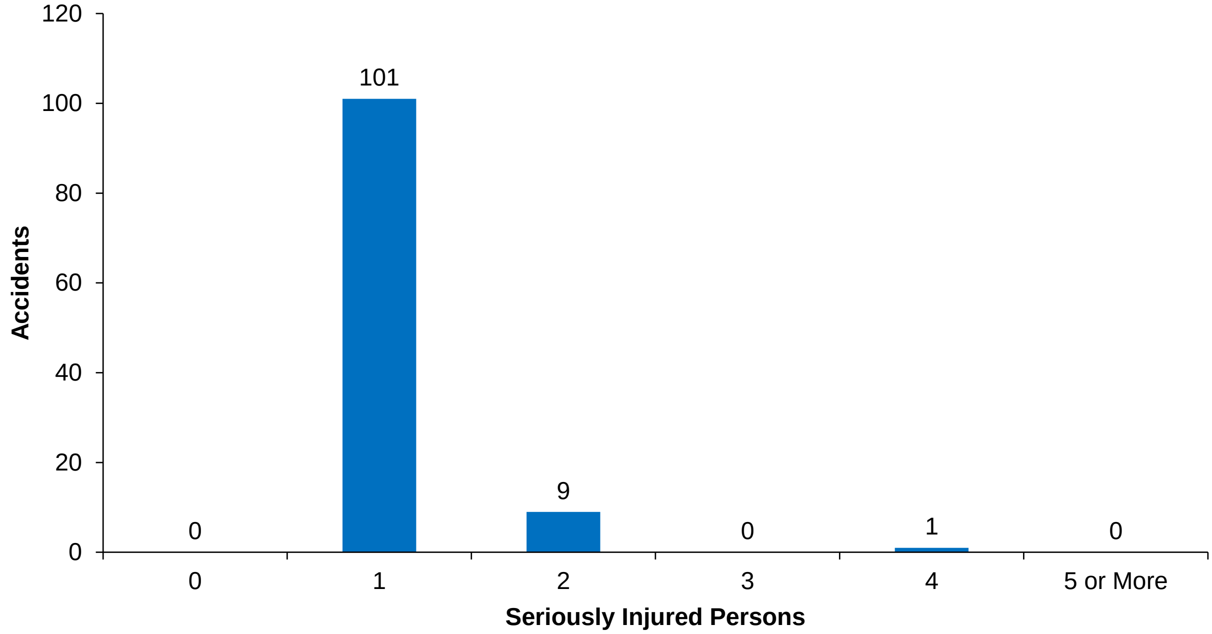

Figure 14. Number of persons seriously injured per turbulence-related Part 121 accident, 2009–2018.

As shown in figure 15, from 2009 through 2018, flight attendant was the most commonly injured person type in turbulence-related Part 121 accidents, accounting for 78.9% of seriously injured persons (97 of 123). Passengers accounted for 21.1% of seriously injured persons (26 of 123). No flight crewmembers were seriously injured in turbulence-related Part 121 accidents during this time.

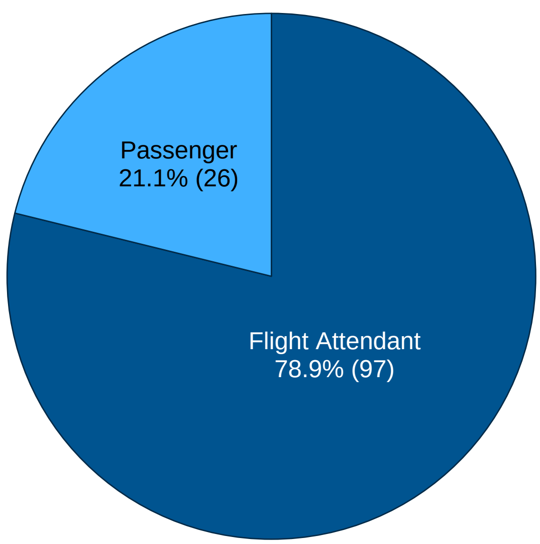

Figure 15. Type of person seriously injured in turbulence-related Part 121 accidents, 2009–2018.

Table 4 shows the location within the airplane where flight attendants were seriously injured in turbulence-related Part 121 accidents. First, the location is given in terms of the general cabin section, that is, forward, middle, or aft. Second, the location is given in terms of the specific area of the cabin, such as an aisle, a galley, or a jumpseat. These location descriptors were derived from flight attendant statements or interviews. Seventy-four of 84 flight attendant injuries with known cabin section (88.1%) occurred in the aft section of the airplane, and, more specifically, 56 of those 74 injuries (75.7%) occurred in the aft galley area.

Table 4. Location of flight attendants within airplane at time of serious injury during turbulence-related Part 121 accidents, 2009–2018.

Specific Area	Forward Cabin	Middle Cabin	Aft Cabin	Not Reported	Total
Galley	2	0	56	3	61
Aisle	3	1	5	0	9
Jumpseat	1	0	7	1	9
Lavatory	1	0	2	0	3
Crew Rest Area	0	0	0	1	1
Not Reported	1	1	4	8	14
Total	**8**	**2**	**74**	**13**	**97**

Figure 16 shows the activity that seriously injured flight attendants were performing at the time of the injury.[33] The most commonly reported activities were as follows:

- preparing the cabin for landing (39.2%, 38 of 97), which includes securing the galleys and performing passenger safety checks
- conducting cabin service (13.4%, 13 of 97), which includes serving food or beverages, collecting trash, and distributing customs forms
- preparing for cabin service (9.3%, 9 of 97), which includes preparing food or beverages for distribution and stocking the serving cart

[33] The category designated as "other" in figure 16 includes standing near a jumpseat, galley, or closet; making an announcement to passengers; cleaning the galley after a previous turbulence encounter; and attempting to sit in a jumpseat.

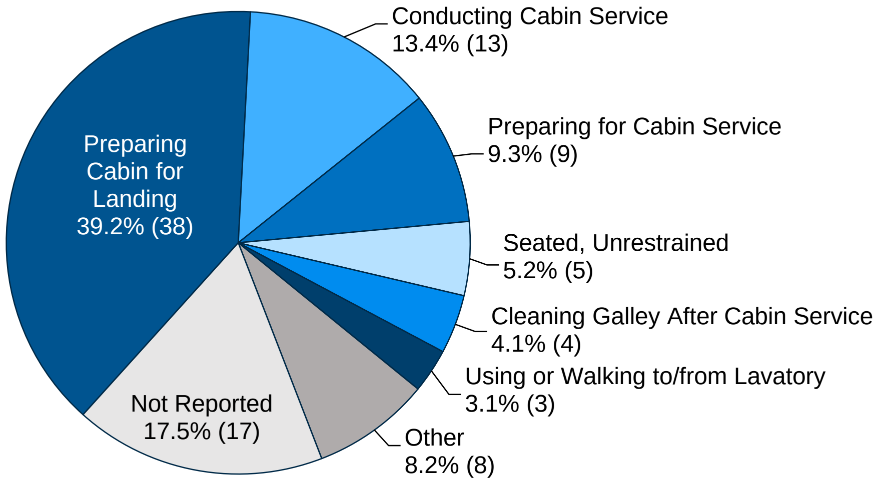

Figure 16. Flight attendant activity at time of serious injury, turbulence-related Part 121 accidents, 2009–2018.

Table 5 shows the location within the airplane where each passenger was seriously injured in turbulence-related Part 121 accidents. For 17 of 26 passengers injured, the general cabin section could be determined. Most of these injuries occurred in the aft section of the cabin (82.4%, 14 of 17). Eight of 17 serious injuries (47.1%) occurred in or near a lavatory.

Table 5. Location of passenger within airplane at time of serious injury during turbulence-related Part 121 accidents, 2009–2018.

Specific Area	Forward Cabin	Middle Cabin	Aft Cabin	Not Reported	Total
Lavatory	0	2	6	0	8
Seat	1	0	4	0	5
Aisle	0	0	1	0	1
Not Reported	0	0	3	9	12
Total	**1**	**2**	**14**	**9**	**26**

Figure 17 shows the activity that seriously injured passengers were performing at the time of the injury. The most commonly reported activity was using, waiting for, or walking to or from the lavatory (26.9%, 7 of 26).[34] However, in half of the accidents (50.0%, 13 of 26), this information was not available.

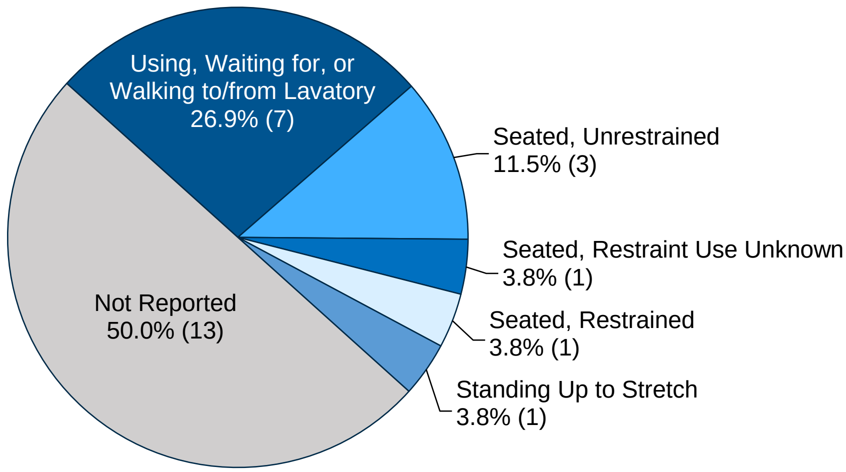

Figure 17. Passenger activity at time of serious injury, turbulence-related Part 121 accidents, 2009–2018.

Of the 123 passengers and flight attendants who were seriously injured in turbulence-related Part 121 accidents occurring from 2009 through 2018, only 1 passenger was documented as having used a seat belt during the turbulence event. As shown in figure 18, among injured flight attendants, 81 out of 97 (83.5%) were documented as not wearing seat belts, and seat belt usage for the remainder was unknown or not reported. Of the 26 injured passengers, 1 was wearing a seat belt, 17 were not wearing a seat belt, and seat belt usage for the remaining 8 was unknown or not reported.

[34] Note that the number of passengers using, waiting for, or walking to/from a lavatory in figure 17 does not equal the number of passengers injured in or near a lavatory in table 5. In some cases, investigative records indicated a passenger was injured near a lavatory but did not indicate if the passenger was using a lavatory. Likewise, other records indicated a passenger was returning to a seat from a lavatory but did not indicate where in the airplane cabin the passenger was injured, or the records indicated that the passenger had already walked to a different location within the airplane when the passenger was injured.

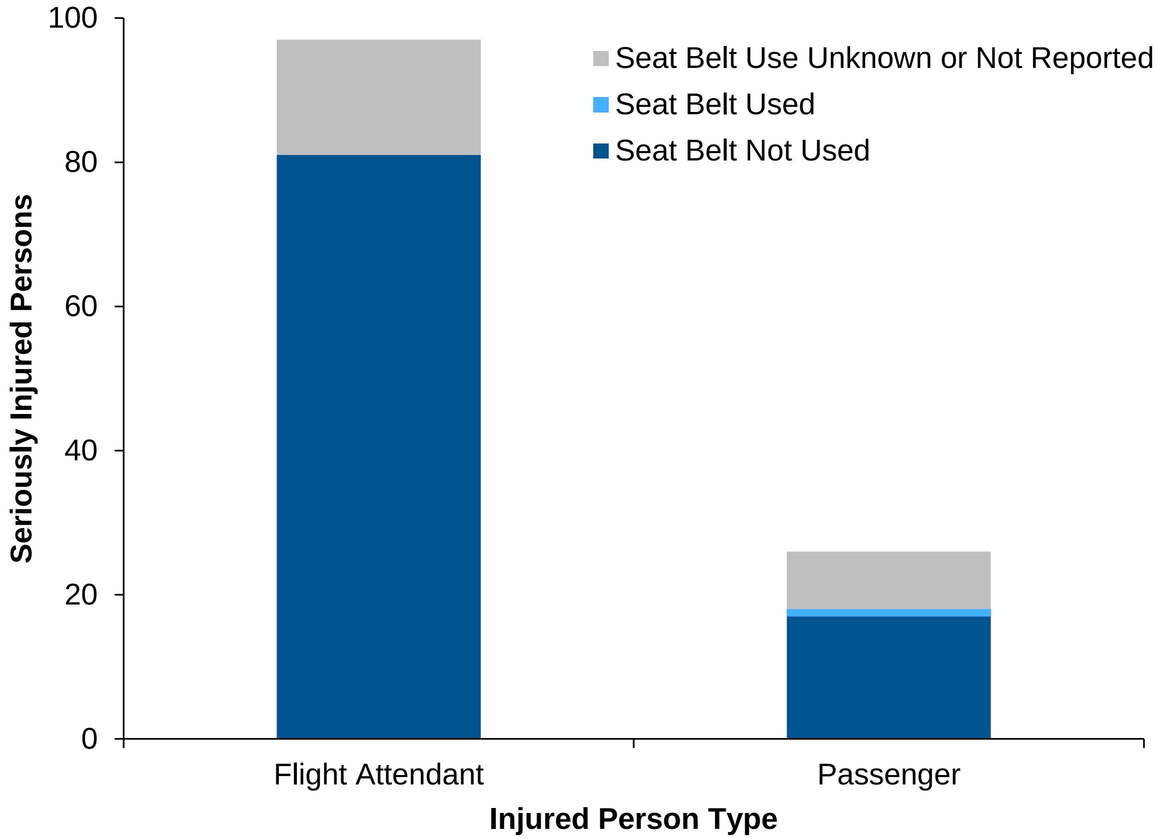

Figure 18. Seat belt use for persons seriously injured in turbulence-related Part 121 accidents, by injured person type, 2009–2018.

This analysis shows that, in general, aircraft occupants who were wearing their seat belt at the time of a turbulence-related Part 121 accident were not seriously injured. Therefore, the NTSB concludes that wearing a seat belt reduces the risk of serious injury for all aircraft occupants during turbulence-related accidents in Part 121 air carrier operations.

The NTSB categorized the injuries sustained by persons involved in turbulence-related Part 121 accidents by the body region that was injured. The injuries were described for 83.7% of seriously injured persons (103 of 123). As shown in figure 19, the most commonly injured body region for flight attendants was lower extremity, accounting for 57.8% of known injuries (48 of 83). The second most commonly injured body region for flight attendants was upper extremity, accounting for 14.5% of known injuries (12 of 83). For passengers, the most commonly injured body region was lower extremity, accounting for 40.0% of known injuries (8 of 20), and the second most commonly injured body region was the spine, accounting for 30.0% of known injuries (6 of 20).

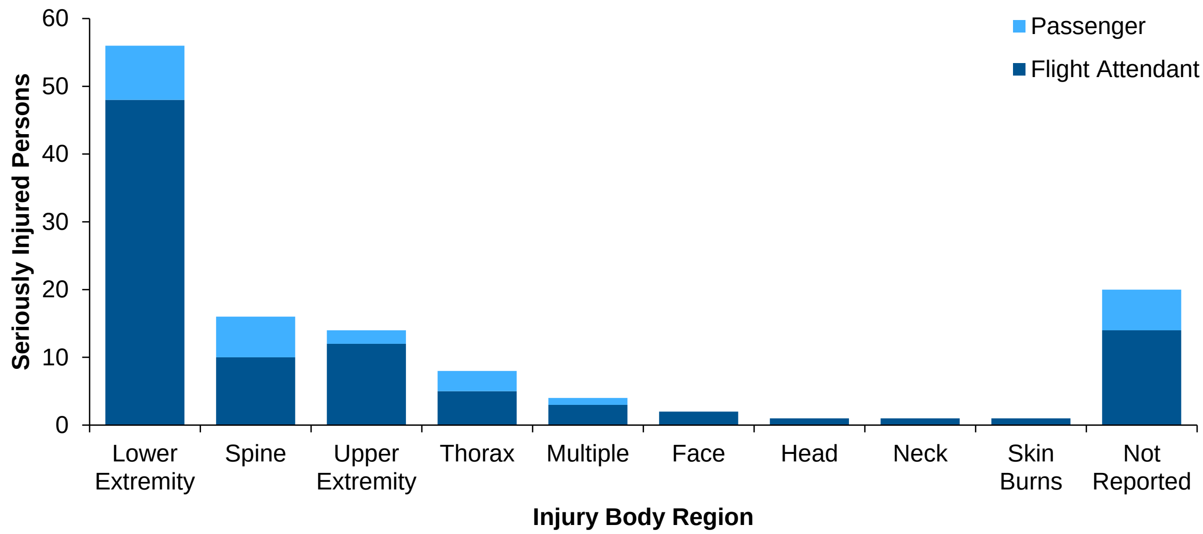

Figure 19. Body region injured for persons seriously injured in turbulence-related Part 121 accidents, 2009–2018.

The quantitative data presented in these sections—accident and flight activity trends; turbulence-related accident characteristics; and the types and mechanisms of turbulence-related injuries as well as the region of bodily injury—provide informative initial insights about the turbulence problem and its potential impacts on Part 121 air carrier operations. However, to gain a better understanding of the most effective means of avoiding turbulence encounters or mitigating turbulence-related injuries, the NTSB also applied a diverse qualitative research approach. Specifically, the NTSB collected qualitative information through document reviews, site visits, and stakeholder interviews. This entailed conducting detailed examinations of air carrier and ATC policies, procedures, and training materials; aircraft technologies aimed at reducing the risks of turbulence; and methods for detecting and predicting turbulence. These efforts are discussed in section 3.2, and the results are used to supplement the safety issue discussions in section 4.

3.2 Stakeholder Interviews

This section summarizes the statements made in semi-structured interviews the NTSB conducted with stakeholders. Each interview session involved groups of 1 to 20 individuals and was from 1 to 8 hours long. Most interviews were conducted in person; several were conducted virtually. All stakeholders were either directly involved in Part 121 air carrier operations or conducting work in areas critical to the safety of such operations.

3.2.1 ATC

The NTSB conducted interviews with air traffic controllers, supervisors, traffic managers, and on-site meteorologists supporting ATC operations. The most common emergent interview themes follow.

When asked how they assessed the risk of turbulence in their area of responsibility before starting a shift, air traffic controllers reported that the position relief briefing from the previous controller was most helpful.[35] Controllers also reported being required to watch a preduty weather briefing before their shift.[36] Controller opinions of the preduty weather briefing were uniformly negative. The most common complaints were that the preduty weather briefing was outdated and that it was not well aligned with controllers' work hours. Non-ARTCC controllers also frequently stated that the material contained in the preduty weather briefing was not relevant. At many facilities, for controllers starting their shift in the early morning, the most recent preduty weather briefing was generated the previous evening.[37]

When asked how PIREPs were made available to air traffic controllers, responses varied by facility. At ARTCCs, PIREPs were generally displayed on the en route decision support tool until acknowledged by the controller.[38] At some facilities, PIREPs were also displayed graphically at a single display within each control area, not in the controllers' line of sight. When asked if they would like PIREPs to be graphically shown directly on their radar display, controllers were generally in favor of such a capability, provided that clutter issues could be resolved and that it could be an option selected as needed and not permanently displayed.

When asked how PIREPs were processed in their facility, air traffic controllers at all facilities described a multistep process involving the relaying of information via several controllers or personnel before disseminating a PIREP within a facility or into the NAS. Controllers at multiple facilities volunteered that they did not understand why they should play such a central role in PIREP processing, as they had heard that turbulence PIREPs could be generated automatically using sensors on the aircraft or manually input by pilots via their onboard equipment. Controllers also expressed frustration at the subjective nature of turbulence PIREPs; in their view, some air carriers uniformly reported higher levels of turbulence intensity than other air carriers. When asked if they would like to be able to input PIREPs directly via their radar displays with known information, such as aircraft type and location, prefilled, controllers were generally in favor of such a capability.

Air traffic controllers described their control actions in the presence of turbulence as being largely reactive in response to pilot-reported turbulence and pilot-requested deviations. Controllers stated that their dependence on PIREPs for knowing where turbulence was present created difficulties. They said it was difficult to know for how long the turbulence reported in a PIREP might still be present and, as a result, this required an aircraft to test for the presence of turbulence by flying through the same area for which the original PIREP was issued. When asked if they would like to provide more proactive traffic management regarding turbulence if a high-quality turbulence forecast were available—for example, advising aircraft of forecast areas of turbulence

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[35] A *position relief briefing* is a process used by air traffic controllers to transfer position responsibility from one controller to another.

[36] A *preduty weather briefing* is a recorded briefing developed several times per day by each ARTCC's center weather service unit for the entire ARTCC and its underlying facilities, including TRACON facilities, airport traffic control towers, and FAA contract towers.

[37] The NTSB notes that, since the ATC stakeholder interviews were conducted, the FAA has addressed this problem by modifying requirements for the times that preduty weather briefings are issued.

[38] According to the FAA, the *en route decision support tool* uses flight plan data, forecast winds, aircraft performance characteristics, and position data to develop expected aircraft trajectories and predict potential conflicts between aircraft and between aircraft and specific types of airspace, such as special use or designated airspace. Air traffic controllers use the tool for strategic planning.

or vectoring aircraft around areas of forecast turbulence—opinions were varied. Some controllers were in favor of this, while others thought that turbulence was inherently unpredictable and would always require reactive actions. Finally, when asked about the "20-mile rule" that many air carriers use for thunderstorm avoidance, TRACON controllers stated that adhering to this rule was often not possible when trying to maintain throughput in highly constrained airspace.[39]

3.2.2 Air Carriers

The NTSB interviews with air carrier stakeholders typically included dispatchers, flight attendants, pilots, labor union representatives, and representatives of corporate safety departments. Common interview discussion themes follow.

In interviews with representatives of corporate safety departments, representatives from all air carriers reported that turbulence-related injuries were an area of concern. Representatives of corporate safety departments from most air carriers reported that they had tracked turbulence-related injuries and had conducted some type of internal turbulence-related injury reduction effort, such as establishing a cross-functional turbulence task force, revising in-flight communication procedures, or modifying aircraft interiors. These efforts were primarily focused on reducing flight attendant injuries.

In interviews, dispatchers from all air carriers reported they primarily relied on commercially provided weather information, including turbulence forecasts, for flight planning rather than NWS products. In particular, NWS AIRMET advisories and SIGMET advisories were generally reported to be of limited use compared to the turbulence forecast products available commercially, which are tailored to Part 121 air carrier operations.[40] At all air carriers, dispatchers were prohibited from routing aircraft into areas of forecast severe turbulence, but few air carriers had defined policies or procedures for routing aircraft into areas of forecast light or moderate turbulence. Preflight, dispatchers and flight crews primarily communicate via a paper or electronic dispatch release. With few exceptions, such as for international flights, preflight verbal discussions between dispatchers and flight crews are rare. In flight, dispatchers are required by 14 *CFR* 121.601 to provide flight crews with updated information on meteorological conditions that may affect the safety of flight. They reported frequently using the aircraft communications addressing and reporting system (ACARS), a datalink system for transmitting short, text-based messages between aircraft and ground stations, to communicate with flight crews, including sharing turbulence reports. One air carrier stakeholder found that shortcomings in this en route flight-following function contributed to turbulence injuries. Most dispatchers had access to the NWS website for submitting PIREPs received from flight crews via ACARS. However, dispatchers generally preferred to instead enter PIREPs into their commercial flight planning software, viewing it as a simpler, faster process, and they said PIREPs would then still be shared internally. No air carrier stakeholders reported conducting joint turbulence-related training with dispatchers and flight crews. Although conducting joint turbulence-related training was seen as

[39] The *20-mile rule* refers to FAA guidance for aircraft to avoid by at least 20 miles any thunderstorm identified as severe or giving an intense radar echo (FAA 2013).

[40] Examples of commercial weather software packages that include turbulence forecast products are WSI Fusion and WSI Pilotbrief from IBM and Jeppesen FlightDeck Pro.

potentially beneficial, it was also understood to be logistically difficult because dispatchers and flight crews have different training schedules and often train in different locations.

Pilots interviewed at all air carriers reported using tablets with graphical weather applications to familiarize themselves with turbulence risks prior to a flight.[41] These applications were generally viewed as easier to use than the information contained in text-based dispatch releases provided for each flight.[42] In-flight access to weather applications varied widely; most mainline air carriers provided such access, while most regional air carriers did not. Pilots at all air carriers stated that they attempted to conduct preflight briefings with all flight attendants but that this was not always possible; in such situations, the pilot would brief the lead flight attendant, who would in turn brief the other flight attendants. All pilots indicated that weather conditions, including turbulence, were an expected part of all preflight briefings. Pilots reported varying use of their tablets for preflight briefings with flight attendants; some thought the graphical products available on tablets helped convey information, and some thought that flight attendants were uninterested in that level of detail. Pilots stated that practices for using the seat belt sign for turbulence varied among individual pilots, with some being more conservative than others. However, few pilots reported using the seat belt sign for reasons unrelated to safety, such as to keep passengers seated during in-flight service. Pilots generally believed that this was a technique that had been used in the past but was now rarely used. Regarding turbulence PIREPs, pilots stated that they would often provide or solicit verbal ride quality reports when checking in with a new ATC sector, but they did not usually formally submit PIREPs or expect that these verbal ride reports would be disseminated as PIREPs by air traffic controllers. Regarding use of weather radar, pilots reported that use of weather radar was covered in training but that it was mostly learned on the job during initial operating experience and that weather radar training quality depended on the trainer. Pilots at several air carriers mentioned the descent phase of flight as a time of particular risk of flight attendant injury due to turbulence. Pilots at multiple air carriers also mentioned that the effects of turbulence are most pronounced in the aft section of the aircraft.

Flight attendants interviewed at all air carriers reported that their primary preflight source of information regarding the turbulence risks of a flight was the preflight briefing from the captain. In flight, the primary sources of turbulence information were calls and public address announcements from the flight crew. Flight attendants at several air carriers stated that turbulence-related announcements from the flight crew carried more weight with passengers than announcements from the flight attendants. Flight attendants at multiple air carriers expressed a desire for better in-flight turbulence information. No flight attendants had in-flight access to weather applications, but flight attendants at one air carrier reported using the flight map feature of the air carrier's application for passengers. Flight attendants generally stated that they did not believe passenger compliance with the seat belt sign was a large problem. Flight attendants at all

[41] These applications were usually developed by the same vendor that provided the flight planning software for dispatchers.

[42] According to 14 *CFR* 121.687, a *dispatch release* contains, at a minimum, the following information for each flight: the identification number of the aircraft; trip number; departure airport, intermediate stops, destination airports, and alternate airports; a statement of the type of operation, for example, instrument flight rules or visual flight rules; minimum fuel supply; the extended-range twin-engine operations performance standards diversion time for which the flight is dispatched, if applicable; and weather reports, available weather forecasts, or a combination thereof, for the destination airport, intermediate stops, and alternate airports, that are the latest available at the time the release is signed by the pilot-in-command and dispatcher.

air carriers stated that they were empowered to suspend service when turbulence was encountered. However, flight attendants also stated that their profession was generally service-oriented, and it would be difficult to change the mindset of flight attendants to be more concerned with their personal safety. Regarding flight attendant procedures in the descent phase of flight, the policy of most air carriers was for flight attendants to perform a final cabin walkthrough and be seated for landing when descending through 10,000 feet. However, flight attendants acknowledged that the actual altitude at which they were seated could be much lower than this. Stakeholders at one air carrier reported that the air carrier used a “gear down, sit down” mnemonic.

3.2.3 Meteorologists and Commercial Weather Information Providers

The NTSB conducted interviews with personnel from the FAA NextGen Aviation Weather division, aviation turbulence researchers at NCAR, meteorologists at the NWS Aviation Weather Center, and representatives from two commercial providers of weather and flight planning software for Part 121 air carriers. Concerns raised in the FAA NextGen Aviation Weather interviews included making EDR reports freely available to all stakeholders and operationalizing new weather models in a timely fashion. NCAR researchers were concerned about different EDR algorithms using different scales, and they believed that more in situ turbulence observations should be shared because they are safety data. They also stated that there was a need to educate users on how to use turbulence forecast products, including ATC.

NWS meteorologists stated that most turbulence SIGMET advisories are only issued after a PIREP is reported. They expressed a desire for more EDR reports and more upper-air soundings.[43] They believed that the information provided by the GTG was very good, but they were unsure who the end user for the GTG was supposed to be, and they wondered if the FAA had provided training to ATC personnel or air carriers about how to use the product.

NWS meteorologists also pointed out that it is difficult for meteorologists to refine their turbulence forecasting techniques because of the lack of adequate verification of turbulence forecasts due to the subjective nature of turbulence reporting from pilots along with limited availability of objective, in situ turbulence observations. They further stated that increasing the dissemination of proprietary turbulence observations from air carriers would improve turbulence forecasts and AIRMET advisory resolution.

The representatives from the two commercial providers of weather and flight planning software for Part 121 air carriers stated that the number of different turbulence metrics, including different objective turbulence measures, used in the industry was frustrating. They stated that they see the biggest turbulence issues during the climb and descent phases of flight. One provider stated that they had planned to disseminate turbulence reports entered by users of their software into the NAS, but that customers stopped expressing a desire for this capability, so they discontinued its development.

[43] *Upper-air soundings* are measurements of atmospheric conditions above the effective range of a surface weather observation.

3.2.4 Other Stakeholders

The NTSB conducted interviews with representatives from one pilot union, one flight attendant union, one aircraft manufacturer, and one airborne radar manufacturer. One aim of the union interviews was to hear from representatives of organizations that have unique perspectives into turbulence-related issues across air carriers. The representatives from the pilot union expressed a concern that any NTSB recommendations should consider international interoperability. The representatives from the flight attendant union expressed a concern that many turbulence-related injuries occurred at lower altitudes in the descent phase of flight. Seating flight attendants and passengers earlier during the descent phase of flight was suggested as a simple fix to this problem.

The interview with the aircraft manufacturer representatives focused on the practicalities of equipping aircraft with EDR reporting, the use of airborne weather radar for turbulence avoidance, emerging techniques for turbulence detection, aircraft control approaches to improve ride quality in turbulence, cabin design approaches to mitigate turbulence-related injuries, and aircraft certification requirements related to cabin safety in turbulence. The aircraft manufacturer representatives described recent research initiatives regarding turbulence, including using LIDAR, to detect impending turbulence.[44] Although they did not see this as a capability ready for implementation anytime soon, the aircraft manufacturer representatives did think it could enhance gust suppression systems as current systems rely on the angle-of-attack sensor and it only takes about one-tenth of a second for a gust to travel between the angle-of-attack vane and the wing.[45] Regarding sharing of EDR data, the aircraft manufacturer representatives believed that the ultimate goal should include data sharing among air carriers, weather services, and ATC. Finally, the focus of the interview with the radar manufacturer representatives was to learn about current capabilities for turbulence detection in airborne weather radars. Many aircraft operated by Part 121 air carriers are equipped with weather radars that display a single level of convective turbulence corresponding to severe turbulence.[46]

3.3 Case Studies

Table 6 lists the 10 case study investigations of turbulence-related Part 121 accidents the NTSB conducted between February 2019 and February 2020. Each of the 10 case studies resulted in 1 serious injury, and 4 of the case studies resulted in additional minor injuries. Only one case study resulted in aircraft damage. Six of the 10 case studies occurred in the descent or approach phases of flight, and 8 of the 10 case studies involved convective turbulence. Further details about each case study investigation are provided in appendix C.

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[44] *LIDAR*, or light detection and ranging, is a system that is similar to radar but uses light from a laser instead of radio waves.

[45] (a) *Angle of attack* is an aerodynamic term in aviation that refers to the angle at which the chord of an aircraft's wing meets the wind. The chord is a straight line from the leading edge to the trailing edge of the wing. (b) An *angle-of-attack vane* is a small external probe used to measure the angle of attack.

[46] Several manufacturers have recently introduced or are developing airborne weather radars capable of displaying two levels of turbulence. Performance standards for airborne weather radar systems specify that at least one displayed level must correspond to severe turbulence, which is defined as 0.3*g* root mean square vertical acceleration (RTCA 2018).

Table 6. Turbulence-related Part 121 case study investigations.

NTSB Investigation Number	Date	Location	Phase of Flight	Altitude	Aircraft	Injuries	Damage
DCA19CA081	2/13/2019	Reno, NV	En route–cruise	FL340	E170	1 serious, 4 minor	None
DCA19CA091	2/17/2019	Franklin, TN	En route–descent	FL345	737-800	1 serious, 1 minor	None
DCA19CA151	5/25/2019	Waycross, GA	En route–descent	12,000 ft	737-800	1 serious, 1 minor	None
DCA19CA208	8/26/2019	Chicago, IL	Approach	14,000 ft	MD-88	1 serious	None
DCA19CA206	8/27/2019	Denver, CO	Approach	15,000 ft	A320	1 serious	None
DCA19CA213	9/6/2019	Fort Myers, FL	En route–descent	12,000 ft	A319	1 serious	None
DCA20CA038	12/16/2019	Alexandria, LA	En route	FL370	ERJ135	1 serious	None
DCA20CA043	12/18/2019	Disputanta, VA	En route	FL180	E190	1 serious	None
DCA20CA058	1/10/2020	New Orleans, LA	En route–climb	FL305	A320	1 serious	None
DCA20CA071	2/7/2020	Waynesville, NC	En route–descent	FL185	CRJ900	1 serious, 22 minor	Substantial

4 Safety Issues

As a result of this research, the NTSB identified the following safety issues: (1) insufficient submission and dissemination of turbulence observations, (2) a lack of shared awareness of turbulence risks, (3) the need for mitigation of common turbulence-related injury circumstances, and (4) the need for updated turbulence guidance.

4.1 Insufficient Submission and Dissemination of Turbulence Observations

Accurate and frequent turbulence observations, including observations of smooth air, were important to many stakeholders interviewed. Meteorologists and researchers found such observations to be important for generating and validating turbulence forecasts. Dispatchers found them to be critical for flight planning and flight following. Air traffic controllers found them to be essential for managing the safe and efficient flow of traffic. Pilots found these observations to be particularly crucial for mitigating the effects of turbulence during flight, which they considered to be the final preventative step. For example, pilots reported that such observations informed when they should operate the airplane at turbulence penetration speed.[47] Pilots also reported that such observations helped them better inform passengers and flight attendants when turbulence was likely to be encountered, thereby helping passengers and flight attendants know when to secure the cabin before a turbulence event.

Turbulence observations generally fall into two categories: (1) PIREPs and (2) objective, in situ observations, such as automated EDR reports. The utility of PIREPs is limited by their subjectivity, accuracy, and timeliness. For example, one study comparing a sample of PIREPs to EDR data found that the location of turbulence as reported in PIREPs differed from the locations in EDR reports by an average of 25 miles (Sharman and others 2014). Another study found that between 10% and 20% of turbulence PIREPs had data entry errors that were not in accordance with FAA guidelines for PIREP formatting (Bhatt 2020). Nevertheless, PIREPs are an important source of turbulence observations that nearly all NAS users already have the capability to submit and receive, as the only equipment required to do so is a radio for communicating with ATC.

Objective, in situ turbulence observations overcome many of the limitations of PIREPs. They do not rely on a subjective evaluation of turbulence intensity by a pilot; instead, onboard equipment provides an objective calculation of turbulence intensity and an accurate location and timestamp for each observation. Further, they are automatically disseminated without requiring action on the part of an air traffic controller or pilot, who may be preoccupied with other duties during a turbulence encounter. However, existing EDR implementations have hardware and sensor requirements, EDR software must be tuned for each aircraft type, and there are challenges to sharing this information. In interviews, most Part 121 air carrier stakeholders expressed enthusiasm for objective, in situ turbulence data, but they also believed that such turbulence

[47] *Turbulence penetration speed* refers to the maximum airspeed at which an airplane should be flown in turbulent air.

observations were unlikely to completely replace PIREPs.[48] Thus, even as Part 121 air carrier stakeholders make greater use of objective, in situ turbulence observations, improvements to the submission and dissemination of PIREPs can yield additional safety benefits.

4.1.1 PIREPs

In its 2017 PIREP special investigation report, the NTSB identified shortcomings with PIREP submission and dissemination (NTSB 2017). Several safety issues identified in that report remain unresolved. For example, it is common for Part 121 air carrier pilots to solicit and report ride conditions when communicating with ATC, but this information often does not become a PIREP that is disseminated into the NAS. In interviews with Part 121 air carrier stakeholders, pilots stated that, although they often informally discussed ride conditions with ATC and found such exchanges to be valuable, it was rare to explicitly submit formal PIREPs to ATC, and they almost never submitted PIREPs for smooth ride conditions. In interviews with ATC stakeholders, controllers stated that they rarely entered reports of smooth ride conditions or light turbulence as PIREPs, and pilots stated that they had no expectation that ATC would enter these informal ride condition reports as PIREPs.

In an analysis of voice communications from pilots to ATC, the MITRE Corporation estimated that 10 million transmissions occurred in 2018 that contained weather information of value to the NAS, but less than 900,000 PIREPs were submitted that year (Kopald 2020). The majority of these communications were reports of smooth ride conditions or light chop. However, as noted in the NTSB's 2017 PIREP special investigation report, even PIREPs of smooth ride conditions are valuable in determining where turbulence is not present. Not sharing all relevant weather information can lead to safety-of-flight issues not only because other pilots do not have the information, but also because weather forecasters and researchers do not receive it either and, therefore, cannot effectively update existing turbulence products and algorithms or develop new ones. In addition, as mentioned in interviews with FAA Air Traffic Control System Command Center personnel, the insufficient submission of turbulence PIREPs could lead to issues with the safe routing of aircraft through the NAS.

Discussions with air traffic controllers from ATC facilities across the NAS revealed that PIREP dissemination by ATC remained inefficient and prone to errors. Although the FAA has tried to standardize the way controllers disseminate PIREPs into the NAS, controllers still expressed the desire for more technology that would allow them to disseminate PIREP information directly from the controller's workstation. For example, controllers sought the ability to access a drop-down menu on their radar display that would be associated with the radar data block of an aircraft and that would allow them to directly enter data based on a series of selections. All aircraft, altitude, and position information is already attached to that data tag, potentially making such a capability a more accurate and efficient means of data entry and dissemination.[49] In contrast, controllers are now required to take their attention away from the aircraft to which they are providing services to write down on a piece of paper or manually type all of the applicable

[48] See section 2.3 for an overview of the various stakeholders interviewed. See also section 3.2 for summaries of the common themes discussed during the stakeholder interviews.

[49] On a radar display, a *data tag* refers to a small block of text associated with each aircraft that follows the aircraft as it moves on the display. The data tag contains information such as the aircraft's call sign, altitude, and type.

information separately; then, they forward that information to a supervisor or other entity within the facility for further dissemination into the NAS. With better technology, information that is sometimes not being disseminated or that currently takes between 10 minutes to an hour to disseminate would take only seconds to disseminate, while also decreasing the potential for error and relieving controllers of the need to take their attention away from their air traffic.

Additionally, PIREPs coming to some ARTCCs from other facilities were not consistently distributed. All PIREPs for all areas were disseminated to all control positions within a facility, requiring controllers to "sift through" PIREPs and determine what PIREPs may apply to their airspace. However, controllers from at least one ARTCC stated that their PIREPs were sorted prior to being internally disseminated, with controllers only receiving those PIREPs that applied to their areas of responsibility. For those facilities at which PIREPs were not sorted, controllers stated that they pay less attention to the PIREPs due to lack of consistent relevancy to the airspace they were working.

As a result of its 2017 PIREP special investigation report, the NTSB made the following recommendations to the FAA:

> Provide air traffic controllers with automated pilot weather report (PIREP) data-collection tools that incorporate design elements to prevent input errors, increase quantity, and improve the timeliness of PIREPs disseminated to the National Airspace System. (A-17-21)
>
> Incorporate automation technology that captures data elements from air traffic controllers' displays, including aircraft type, time, location, and altitude, to automatically populate these data into a pilot weather report (PIREP)-collection and -dissemination tool that will enable controllers to enter the remaining PIREP elements and disseminate PIREPs through a common exchange model directly to the National Airspace System. (A-17-22)
>
> Provide a reliable means of electronically accepting pilot weather reports directly from all users who are eligible to submit reports, and ensure that the system has the capacity to accept and make available all such reports to the National Airspace System. (A-17-26)

In response to these recommendations and others resulting from the 2017 PIREP special investigation report, the FAA established a team of subject matter experts to analyze the recommendations and determine the feasibility of adopting them. This team created an Operational Needs Assessment that addresses the need for improved automation of PIREP collection, entry, and dissemination. On November 5, 2019, the FAA told the NTSB that the Operational Needs Assessment was submitted to the FAA's Air Traffic Organization's Operational Concepts, Validation, and Requirements Group, which planned to determine the feasibility of adopting the Operational Needs Assessment recommendations. In response to Safety Recommendations A-17-21 and A-17-22, the FAA also published changes to two FAA orders to align PIREP guidance.[50] On February 24, 2020, the NTSB replied that the review by the FAA's Operational Concepts, Validation, and Requirements Group was a necessary first step to addressing these recommendations. Pending future updates and completion of the recommended actions, Safety Recommendations A-17-21, A-17-22, and A-17-26 remained classified "Open–Acceptable Response."[51]

However, due to the concerns expressed by air traffic controllers regarding PIREP processing and recent analysis showing that PIREPs only capture a small fraction of the weather-related information communicated by pilots to ATC, the NTSB concludes that ATC procedures for processing PIREPs remain time-consuming and nonstandardized, which continues to prevent safety-critical turbulence observations from being shared throughout the NAS. Therefore, the NTSB reiterates Safety Recommendations A-17-21, A-17-22, and A-17-26 to the FAA. The NTSB also recommends that the FAA work with stakeholders to standardize the distribution of PIREPs across and within ATC facilities to ensure they are disseminated to only those facilities and air traffic controller positions for which each PIREP applies.

Most Part 121 air carrier stakeholders stated that their air carrier was approved by the FAA to use an enhanced weather information system (EWINS), which allows an air carrier to use weather forecasts from commercial weather information providers rather than NWS products (FAA 2007a). Although EWINS and NWS products use the same underlying NWS data, the integration and presentation of the data to the user can vary. Commercial weather information providers create products that are tailored for the unique requirements of Part 121 air carrier operations. The FAA-required functions for an EWINS are performed by an integrated suite of operations management software that combines flight planning, flight following, and weather reporting and forecasting functions. Although some Part 121 air carriers use the same EWINS provider, others use unique systems that are not shared with other air carriers. Therefore, not every air carrier uses a shared common reference point regarding turbulence.

Although ride conditions reported by Part 121 pilots are rarely disseminated to the NAS as PIREPs, they are frequently shared within each air carrier via its EWINS software. Pilots typically communicate ride conditions to dispatchers via ACARS. Dispatchers can then enter this information into their operations management software for dissemination to other dispatchers within the same air carrier or other users of the same software at other air carriers. However, a majority of these proprietary PIREPs are not distributed throughout the NAS. All 10 Part 121 air carrier stakeholders interviewed used proprietary software to view and enter ride condition information.

The NWS provides a website where users, such as dispatchers, can enter PIREPs (NWS 2021b). Although dispatchers at several Part 121 air carriers reported using this website to submit PIREPs for dissemination throughout the NAS while, in parallel, also entering the PIREP into their commercial flight planning software, dispatchers generally reported that they used the NWS website much less often than their own software for ride condition information entry. User interface challenges were cited as the reason for not submitting reports to the NWS website.

[50] The updates are reflected in FAA Order JO 7210.3BB, Facility Operation and Administration, effective August 15, 2019, and FAA Order JO 7110.10AA, Flight Services, effective August 15, 2019.

[51] See appendix A for more information.

Specifically, dispatchers noted that the ride condition information entry function in their commercial software was well integrated and could prefill some data fields, but the NWS website required a separate browser window and individual login permissions. They also noted that the NWS website used a rudimentary text form interface that does not prefill data or perform error checking.

As discussed in the NTSB's 2017 PIREP special investigation report, when ride condition information is available but is kept proprietary and not made available to all NAS users, it creates a lack of shared awareness and safety-of-flight concerns. As a result of its 2017 PIREP special investigation report, the NTSB recommended that the FAA

> Encourage industry safety efforts, such as the Commercial Aviation Safety Team and the General Aviation Joint Steering Committee, to identify, develop, and implement incentives for 14 *Code of Federal Regulations* Part 121, 135, and 91K operators and the general aviation community to freely share pilot weather reports (PIREPs), including braking action or runway condition reports filed as PIREPs, to the National Airspace System to enhance flight safety. (A-17-25)[52]

In its July 10, 2017, initial response to Safety Recommendation A-17-25, the FAA only discussed recent revisions related to runway condition PIREPs. Although the FAA reported that it was considering ways to improve PIREP sharing, it did not state its plan for doing so. On October 26, 2017, the NTSB replied that the intent of this recommendation was to break down the proprietary walls that exist between operators and weather service providers when it comes to sharing PIREP information, and the NTSB believed that unrestricted sharing of PIREP information should be encouraged as a standard operating procedure (SOP) for all operators to improve flight safety in the NAS. Although the use of takeoff and landing performance assessments discussed in the FAA's July 10, 2017, letter was an improved way to assess runway conditions, it did not address important aspects of this recommendation. Although it said it was considering ways to improve PIREP sharing among commercial operators and the general aviation community, the FAA did not discuss its plan, nor did it provide information about actions that it had taken or that it planned to take to address the recommendation. Pending the NTSB's review of such a plan and completion of the recommended action, Safety Recommendation A-17-25 remained classified "Open—Await Response." On April 26, 2018, the NTSB reiterated Safety Recommendation A-17-25 as a result of its investigation of the October 2, 2016, accident involving Ravn Connect Flight 3153 in Togiak, Alaska (NTSB 2018).

On May 5, 2021, the FAA provided a further response to Safety Recommendation A-17-25. The FAA acknowledged the intent of this safety recommendation and the importance of sharing PIREPs, including braking action or runway condition reports. In order to "holistically address the intent of the Board's safety recommendations pertaining to its special investigation report," the FAA placed an emphasis on braking action or runway condition reports by focusing specifically on its new Takeoff and Landing Performance Assessment requirements and its impact. The FAA also stated it would address the overall PIREP improvement effort through other NTSB recommendations, such as Safety Recommendations A-17-17 through A-17-24.[53] The remainder

[52] See appendix A for more information.

[53] See appendix A for more information.

of the FAA's letter focused exclusively on including pilot braking action reports in its Takeoff and Landing Performance Assessment program, rather than the subject of Safety Recommendation A-17-25. The FAA's letter concluded that, with the implementation of the Takeoff and Landing Performance Assessment program, the FAA believed that it had effectively addressed this recommendation and considered its actions complete.[54]

The NTSB disagrees with the FAA that it has addressed this recommendation. Because the FAA's response to Safety Recommendation A-17-25 has only addressed pilot braking reports on contaminated runways, rather than the proprietary walls between operators and weather service providers when it comes to sharing PIREP information and the unrestricted sharing of PIREP information, the NTSB classifies Safety Recommendation A-17-25 "Open—Unacceptable Response."

This report documents the continuing problem with turbulence-related ride condition reports being included in commercial flight planning and weather forecasting software used by Part 121 carriers but not being shared in PIREPs available to the NAS. The NTSB concludes that air carriers continue to share turbulence observations with only their personnel but not throughout the NAS, limiting opportunities for awareness of adverse weather phenomena that can negatively affect the safety of flight. Therefore, the NTSB reiterates Safety Recommendation A-17-25 to the FAA. The NTSB also recommends that the FAA, as a condition of EWINS approval, require Part 121 air carriers to disseminate all turbulence observations to the NAS as PIREPs, as well as reports of smooth ride conditions.

4.1.2 Objective, In Situ Turbulence Observations

Objective, in situ turbulence observations overcome many of the limitations of PIREPs. Although different methods for objectively measuring turbulence have been developed, the EDR is the official atmospheric turbulence intensity metric recognized by the International Civil Aviation Organization (ICAO 2010). Part 121 air carriers currently use three algorithms for calculating the EDR.[55] NCAR developed one of the algorithms, and commercial organizations developed the other two. In addition, new groups are developing other methods for calculating objective turbulence measures, such as using accelerometers on electronic flight bag tablets instead of installed aircraft sensors (Yamasee SkyPath LLC 2020).[56] However, there is no guarantee that these different EDR algorithms would produce the same EDR values in an operational environment. In interviews with the FAA, air carrier stakeholders, and aviation weather researchers, it was repeatedly stated that the lack of standardization or interoperability among these algorithms limited the utility of sharing EDR data among NAS stakeholders.

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[54] At a 2020 Virtual PIREPs Summit hosted by the FAA Civil Aerospace Medical Institute, FAA staff described additional actions taken by the FAA that the NTSB believes are relevant to Safety Recommendation A-17-25, including the development of a capability for users to electronically submit PIREPs (Moosakhanian 2020). However, these actions were not included in the FAA's official correspondence to the NTSB.

[55] An *algorithm* refers to a specific set of instructions to be followed in mathematical calculations or other problem-solving operations.

[56] An *accelerometer* is an instrument used to measure acceleration.

In 2017, the RTCA published guidelines for EDR algorithm performance (RTCA 2017). However, in interviews with representatives from multiple government, meteorology, and industry organizations, it was stated that these guidelines only applied to a test environment and did not fully address differences in EDR algorithm performance. It is unlikely that the industry will coalesce around a single EDR algorithm, as several Part 121 air carriers have already invested significant time and funds either adapting particular EDR algorithms to their aircraft and equipping their fleets with EDR reporting capability or implementing different turbulence reporting approaches. The NTSB concludes that developing methods to translate between EDR values calculated by different algorithms would produce consistent results, enable the maximum sharing of EDR data among air carriers, and ensure that turbulence forecast products are appropriately using these data. Therefore, the NTSB recommends that the FAA determine how to harmonize current and future EDR algorithm performance in operational environments and publish the results of this determination.

Although the use of automated, objective, in situ turbulence observations is increasing, not all Part 121 air carriers are generating these observations, and some air carriers that have equipped their aircraft with this technology do not share their observations widely across the NAS. Air carriers realize the importance of sharing turbulence observations among all stakeholders to improve safety but expressed concerns that any data sharing be done equitably, given the substantial cost to equip aircraft to generate objective turbulence observations and to transmit these data. In the absence of FAA action, the International Air Transport Association, an industry trade group, has established an online platform for sharing EDR data (IATA 2021). However, only entities that have established an agreement with the International Air Transport Association have access to these data, which does not include the weather forecast or ATC communities.

Stakeholders at every ATC facility where the NTSB conducted interviews confirmed that ATC currently has no way of receiving or analyzing objective, in situ turbulence observations for their strategic or tactical use. Many stakeholders at the ATC and NWS facilities the NTSB visited were very discouraged to hear of the abundance of turbulence information that was available to operators but was not shared with them. For example, one weather forecast office was located in the same room as a proprietary turbulence data holder, yet the weather forecast office staff did not have access to the same turbulence decision-making tools for the NAS. The NTSB concludes that because objective, in situ turbulence observations are not shared publicly to the greatest extent possible, ATC, weather forecasters, and other NAS users lack access to important flight safety data.

One of the reasons EDR data are not shared more broadly is because there is not a method in place to easily share the information in a consistent manner nor is there a common source from which all relevant stakeholders can access the data. One potential method for achieving increased generation and wider dissemination of turbulence observations is via automatic dependent surveillance-broadcast (ADS-B), a datalink system for broadcasting and receiving data from aircraft. Since 2020, most aircraft have been required to be equipped with some components of

ADS-B to operate in most controlled airspace in the United States.[57] ADS-B is a critical component of the NAS that is used to provide position, velocity, and other aircraft data.

Automatic dependent surveillance-broadcast weather (ADS-B Wx) is a proposed addition to ADS-B. It includes ADS-B Wx PIREP, a capability for on-condition broadcast of PIREP data when integrated with an electronic flight bag application, and ADS-B Wx air report (AIREP), a capability for continuous, automated broadcast of weather-related data from sensors on board equipped aircraft via the ADS-B datalink. Such data will be received via the ADS-B ground receiver network already in place. Using ADS-B to transmit EDR data would eliminate per-message costs of transmitting these data from aircraft and make EDR data publicly available.[58]

The RTCA and the European Organization for Civil Aviation Equipment have developed the requirements for ADS-B Wx, which are incorporated into version 3 of the ADS-B minimum operational performance standards as optional capabilities (RTCA 2020). These standards include data elements to convey turbulence PIREPs and EDR-based, objective, in-situ turbulence observations. In 2021, the FAA is expected to publish a revised technical standard order for aircraft manufacturers to build ADS-B hardware or, where feasible, develop software updates that conform to the updated ADS-B minimum operational performance standards.

ADS-B Wx AIREPs will provide automated weather information directly from aircraft every 2.2 seconds for some weather variables and every 5.0 seconds for all other weather variables. With areas of moderate or greater turbulence often being transient, the frequent reporting of weather information via aircraft every 2.2 to 5.0 seconds will provide a great deal of weather information to help detect and forecast transient turbulence weather features. Such weather information could be provided to all users via the NWS's existing Meteorological Assimilation Data Ingest System and would make significantly more turbulence information available to operators, weather forecasters and researchers, ATC facilities, and others that would find use for the high frequency weather information.[59] In addition, ADS-B Wx can support better weather forecasts and real-time awareness of hazardous weather, which would facilitate better ATC and operator tactical responses and strategic planning to mitigate turbulence encounters more successfully. Therefore, the NTSB recommends that the FAA incorporate the ADS-B Wx capability in the next version of the ADS-B technical standard order. The NTSB further recommends that, after the ADS-B technical standard order is revised as recommended in Safety Recommendation A-21-28, the FAA require that aircraft flown in Part 121 air carrier operations be retrofitted with ADS-B Wx capable ADS-B equipment. The NTSB also recommends that the FAA require ADS-B Wx-equipped aircraft to broadcast ADS-B Wx information when operating in airspace requiring ADS-B capability as defined by 14 *CFR* 91.225.

[57] Title 14 *CFR* 91.225 lists airspace in which ADS-B Out—that is, the capability to broadcast data from aircraft—is required. Equipment with ADS-B In—that is, the capability to receive data from other aircraft—are available, but this capability is not currently required to operate aircraft in the United States.

[58] Most objective, in situ observations are transmitted via ACARS, which charges for each message.

[59] The Meteorological Assimilation Data Ingest System is a meteorological observational database and data delivery system. It ingests data from NOAA data sources and non-NOAA providers, decodes the data, performs quality checks, and encodes the data into a common format with uniform observational units and time stamps.

4.2 Lack of Shared Awareness of Turbulence Risks

Although increased sharing of turbulence observations is necessary for better turbulence avoidance, it is not sufficient. Stakeholders stated that, as the sharing of objective, in situ turbulence observations increases, it is unreasonable to expect pilots, dispatchers, and air traffic controllers to manually interpret and integrate "thousands of dots" into a mental model of turbulence risk. Further, the turbulence forecast products available to stakeholders vary considerably in their capabilities. This limits the ability to establish a common understanding of turbulence risks across stakeholder groups.

The majority of the turbulence encounters analyzed in the 10 case study investigations conducted for this research occurred within regions where the NWS or the air carrier's EWINS provider had forecast moderate or greater turbulence, thunderstorms or strong convection, or both. However, some of the flight crewmembers involved reported being unaware of the existence of the advisories at the time of the turbulence encounter. For example, in three of the convectively induced turbulence encounters analyzed in the case study investigations, the pilots had no knowledge of any advisories concerning turbulence when overflying and deviating around the strong convection, which further highlights the disconnect.[60]

4.2.1 NWS Turbulence Forecast Products

Most Part 121 air carriers are approved by the FAA to use forecasts from commercial weather information providers via an EWINS rather than NWS products. These proprietary products include turbulence forecasts that are tailored to Part 121 air carrier operations. In contrast, air traffic controllers and the NWS center weather service unit meteorologists that support them are limited to using NWS products, such as AIRMET advisories, SIGMET advisories, and CWAs.

AIRMET advisories are the primary NWS product used for forecasting moderate turbulence, and Part 121 air carriers generally try to avoid moderate turbulence if possible. For example, one interviewed stakeholder stated the air carrier's dispatcher policy was to consider using additional contingency fuel and selecting a different altitude or route of flight, or both, if greater than light turbulence was expected. However, dispatchers, pilots, and air traffic controllers uniformly stated in interviews that AIRMET advisories were of little use for avoiding turbulence, given their large size, both laterally and vertically.

Meteorologists at the NWS Aviation Weather Center indicated in interviews that users perceive AIRMET advisories as large for the following reasons:

- Given its complex nature, multiple-generation mechanisms, and uncertainty, turbulence is difficult to capture within the limited AIRMET advisory formats required by the FAA.[61]
- Forecasters need to consider numerous aircraft types and operations, not just Part 121.

[60] See NTSB investigations DCA19CA081, DCA19CA208, and DCA20CA038 for more information. See also appendix C.

[61] *Turbulence generation mechanisms* refer to underlying atmospheric processes that produce turbulence, such as breaking gravity waves associated with convection.

Aviation Weather Center meteorologists also stated that ATC and other users primarily use the lower resolution text AIRMET advisory instead of the higher resolution graphical AIRMET advisory.

Until 2019, AIRMET advisories covered a minimum area of 3,000 square nautical miles. Although this minimum area requirement is no longer applicable, AIRMET advisories continue to often cover a much larger area.[62] NWS Aviation Weather Center meteorologists stated that one reason for this was that all text products transmitted via the weather message switching center replacement system are subject to a character limit.[63] This limit then restricts the granularity of AIRMET advisories by limiting the number of corners in each AIRMET advisory polygon, leading to larger AIRMET advisory polygons with fewer corners. However, the FAA is currently considering a proposal to discontinue text AIRMET advisories in the continental United States and retain only graphical AIRMET advisories, which would remove the character limitation. Although this presents an opportunity to modify graphical AIRMET advisory issuing practices to better enable air traffic controllers to assist Part 121 flight crews with avoiding turbulence, air traffic controllers currently only receive text AIRMET advisories at their workstations, and the FAA has no plans for controllers to receive graphical AIRMET advisories if text AIRMET advisories are discontinued. The FAA has stated that one reason for this is that pilots rarely ask for AIRMET advisories from air traffic controllers. (As stated above, pilots reported that AIRMET advisories were of little use because they covered such a large area.) However, the FAA also acknowledges that ATC uses AIRMET advisories for other purposes. For example, air traffic controllers are required to solicit PIREPs when certain weather conditions exist or are forecast for their area of jurisdiction, including turbulence of moderate degree or greater. ATC facilities use AIRMET advisories to determine when controllers should solicit PIREPs from pilots under this criterion, and some ATC facilities have developed decision support tools for PIREP solicitation that use AIRMET advisories as inputs. Still, if ATC relies on the broad boundaries of text AIRMET advisories and Part 121 air carriers rely on the more granular reports from commercial forecast products, this can lead to both parties having a different awareness of where moderate turbulence is likely to exist.

The NTSB concludes that, due to their large size, AIRMET advisories are currently of limited value to Part 121 air carrier pilots and air traffic controllers. The NTSB believes that modifying AIRMET advisories to include more granularity would improve their usefulness. Further, any changes to AIRMET advisories would also need to consider the safety effects for other NAS users, such as operators of lighter, general aviation aircraft. Therefore, the NTSB recommends that the FAA, in collaboration with the NWS, modify AIRMET advisory issuing practices to include graphical AIRMET advisories with higher granularity, taking into account the effect it would have on all NAS users. The NTSB further recommends that the NWS work with the FAA to modify AIRMET advisory issuing practices to include graphical AIRMET advisories with higher granularity, taking into account the effect it would have on all NAS users.

[62] AIRMET advisories are now issued for weather phenomena that are affecting or, in the forecaster's estimation, are expected to affect an area having a significant impact on the safety of aircraft operations.

[63] FAA personnel confirmed that the limit is about 3,480 characters, including spaces and punctuation.

In addition to concerns about the large areas that AIRMET advisories cover, air traffic controllers also expressed a concern in interviews that they often did not share a common understanding about which turbulence advisories were valid for which regions or areas in their airspace. When an ATC facility received an AIRMET advisory, SIGMET advisory, or CWA, it was received via a text printout that controllers were required to broadcast over the radio frequency. However, in some ATC facilities, it would be up to the individual controller to interpret whether an advisory's specific boundaries and altitudes applied to the controller's area of responsibility because all these advisories were distributed facility-wide without regard for area or altitude. Having a graphical representation of an AIRMET advisory, SIGMET advisory, or CWA available for toggle view on a controller's radar display would improve a controller's awareness of and the relevancy of weather information available to aid flights within or about to enter the advisory's graphical region.[64]

The NTSB concludes that providing graphical AIRMET advisories, SIGMET advisories, and CWAs to air traffic controllers as controller-selectable layers on current and future controller displays in ARTCCs and TRACON facilities would increase shared awareness among controllers of AIRMET advisory, SIGMET advisory, and CWA locations. Therefore, the NTSB recommends that the FAA distribute graphical AIRMET advisories, SIGMET advisories, and CWAs to air traffic controllers as controller-selectable layers on current and future controller radar displays in ARTCCs and TRACON facilities. The NTSB believes the FAA should work with local safety councils to develop training to further this effort. Local safety councils are collaborative teams made up of local union representatives and management at all FAA ATC facilities. These councils encourage facilities to mitigate hazards and share safety information (FAA 2020). Therefore, the NTSB further recommends that the FAA work with local safety councils to develop training on the use of the advisories developed for Safety Recommendation A-21-32.

4.2.2 Availability of Tools to Support Tactical Decision-Making

In interviews, pilots and air traffic controllers repeatedly mentioned that a disadvantage of relying on turbulence observations, both subjective and objective, to avoid turbulence is that such observations only provide information for a particular point in time and space. It does not provide much information about how extensive turbulence conditions are or how they are expected to change over time. Although many controllers expressed a desire to provide more proactive service to help pilots avoid turbulence, they believed they did not have the tools to do so. The GTG is available for operational use by dispatchers, pilots, and ATC. However, given its hourly update rate, it is best suited for route planning and strategic decision-making rather than tactical turbulence avoidance.

NCAR has developed a companion product to the GTG, known as the graphical turbulence guidance nowcast (GTGN), that is designed to support tactical decision-making and provide a prediction of convective turbulence.[65] The GTGN combines a short-term GTG forecast with PIREPs, EDR reports, and information from the Next Generation Radar Turbulence Detection

[64] *Toggle view* refers to a selectable button that allows a user to easily switch between two different view options on a system display screen.

[65] (a) The GTGN is a *turbulence nowcast*, which is a frequently updated, short-term forecasting product. (b) See appendix B for a table summarizing all turbulence-related weather products discussed in this report.

Algorithm to produce a short-term estimate of turbulence that is updated every 15 minutes (NCAR 2021).[66] A National Oceanic and Atmospheric Administration (NOAA) assessment of the GTGN algorithm found that it outperformed the GTG algorithm at forecast time scales less than 1 hour, resulting in fewer missed detections of turbulence and fewer false alarms (Wandishin and others 2016). The NWS has not yet made the GTGN fully operational, but one Part 121 air carrier has provided GTGN graphics to its pilots on their electronic flight bag devices to support in-flight turbulence avoidance, and the general feedback from pilots has been positive.[67] No other similar product providing near-real-time awareness of turbulence is currently available.

The GTGN is now available as a semi-operational product. Recognizing the value of the GTGN, the FAA convened a safety risk management panel in 2019 to analyze the safety impacts of making the GTGN available to users who have signed a license agreement and to whom NCAR would provide only raw GTGN data—that is, without graphics and without data availability guarantees. Although this is an atypical arrangement, the FAA established the semi-operational GTGN data feed as an interim solution because the FAA anticipated that the NWS would not have the resources to fully operationalize the GTGN for several years. However, the FAA's safety risk management panel was largely focused on air carriers' use of GTGN data; the panel did not consider ATC usage, as it was explicitly outside the scope of its mission. Also, FAA researchers stated in stakeholder interviews that little thought has been given to how ATC would make use of products such as the GTGN or EDR data in general.

In the case study investigations conducted during the course of this research, the NTSB found that the GTGN for convectively induced turbulence encounters would have provided critical information about the potential for turbulence over the area prior to an event.[68] However, not all aircraft or air carrier operations centers had the capability to view the data in real time through use of the internet or via electronic flight bags.

The NTSB concludes that a frequently updated, short-term forecasting product known as a turbulence nowcast would provide more complete and accurate tactical information to help pilots, dispatchers, and air traffic controllers effectively respond to turbulence. Therefore, the NTSB recommends that the FAA, in collaboration with the NWS, operationalize a turbulence nowcast, such as the GTGN. The NTSB further recommends that the NWS work with the FAA to operationalize a turbulence nowcast, such as the GTGN. In addition, the NTSB recommends that the FAA develop ATC guidelines for use of the turbulence nowcast operationalized in accordance with Safety Recommendations A-21-34 and A-21-44.

[66] (a) Next Generation Radar is a network of high-resolution weather radars operated by NOAA's NWS. (b) The Next Generation Radar Turbulence Detection Algorithm produces estimates of in-cloud turbulence.

[67] Only *operational* products can be used as official sources of weather information for meeting aviation weather regulatory requirements. The process for developing, testing, and operationalizing new weather products is described in NWS Instruction 10-102, "Products and Services Change Management" (NWS 2018).

[68] See NTSB investigations DCA19CA091, DCA19CA213, DCA20CA038, DCA20CA043, DCA20CA058, and DCA20CA071 for more information. See also appendix C.

4.2.3 Proxies for Convective Turbulence

One of the advantages of the GTGN is that it integrates multiple indicators of turbulence into a single product. However, considering its current update rate and spatial resolution, the optimal ATC users for the GTGN are likely area supervisors and traffic management coordinators, who are primarily concerned with traffic flows and balancing capacity and demand, rather than individual air traffic controllers. Other weather data are available that indicate areas of convective turbulence with higher update rates and spatial resolutions that would be more appropriate for inclusion on controllers' radar displays. For example, total lightning—that is, both in-cloud and cloud-to-ground lightning—has been shown to be associated with the presence of convective turbulence (Deierling and Williams 2016). Although many Part 121 dispatchers have access to real-time lightning data, this information is not available to air traffic controllers at their workstations. Hail is another indicator of convection.

In 2012, the NTSB issued recommendations to the FAA in which the NTSB maintained that ATC and pilots should be aware of areas where lightning was occurring in real time and should avoid them because lightning itself can damage an aircraft, and thunderstorms are known areas where severe turbulence and other hazards exist (NTSB 2012). As a result, the NTSB issued Safety Recommendation A-12-18 to the FAA.[69]

> Study the technical feasibility of presenting, through the use of the weather and radar processor system or other means, real-time total lightning data on controller displays at both air route traffic control centers and terminal radar approach control facilities, and, if feasible, incorporate real-time total lightning data on controller displays and in associated weather products for current and future display systems. (A-12-18)

As of 2008, the FAA had developed software for sending lightning data to ARTCC controller displays and an algorithm for displaying user-selectable weather data layers. However, this work was halted until a new flight and radar data processor, the En Route Automation Modernization system, was put into use (Stobie and others 2008). Since the 2012 recommendations were issued, the FAA has also incorporated lightning information into aviation products that assist in the recognition of hazardous convection where weather radar is not available, for example, in some oceanic airspaces. However, after evaluating Safety Recommendation A-12-18, the FAA determined that adding the recommended information to a controller's display would result in a deterioration of safety services, erode controller situational awareness, and increase aircraft delays and potential FAA liability, while providing no benefit. The FAA stated that despite the use of real-time lightning data, some controllers might continue to route traffic through lightning and thunderstorm areas. In addition, the FAA stated that its current budget was not able to provide the needed funds to develop and implement the recommended display systems. As a result, the FAA disagreed with Safety Recommendation A-12-18 and did not plan to take the recommended action. On January 24, 2018, the NTSB replied that it believed that the FAA's evaluation of presenting real-time total lightning data on controller displays and its determination that this presentation was not feasible were counter to the NTSB's understanding of these systems' capabilities and how they

[69] See appendix A for more information.

would be used. However, because the FAA clearly stated it would not take the action, Safety Recommendation A-12-18 was classified "Closed—Unacceptable Action."

The NTSB continues to believe that the FAA's concerns about presenting lightning data on controller displays are unfounded or addressable. For example, the erosion of situational awareness due to display clutter could be addressed by configuring lightning data as a controller-selectable layer on displays. In stakeholder interviews, some controllers voiced concerns about additional weather data leading to display clutter, but controllers uniformly stated that having lightning data available on their radar displays would be beneficial if it were implemented as a controller-selectable layer. Concerns about the interpretation, use, and communication of lightning data could be addressed through training and the development of appropriate policies, procedures, and phraseology. Liability issues concerning lightning data that are displayed to controllers but not communicated to pilots are already present with other weather data that are available to controllers, and they could be dealt with similarly. Further, the NTSB continues to investigate accidents for which ATC access to lightning data could have been beneficial.[70]

In addition to lightning strikes, encounters with hail aloft can be damaging to aircraft and often occur in or near an environment characterized by strong convective activity, such as thunderstorms. Weather forecasters often look specifically for the potential for deep convection when forecasting for hail, and the NWS defines hail as ice falling from a cumulonimbus cloud.[71] Like lightning, hail can act as a proxy for regions of deep and/or vigorous convection and/or thunderstorms and the hazards associated with them. Regions of hail must also be avoided to (1) prevent damage to aircraft by the hail itself and (2) mitigate encounters with severe turbulence and other hazards associated with convection. The NTSB has investigated the following two incidents where en route aircraft have encountered severe or moderate turbulence and hail in the same area.

On April 29, 2014, near Powhatan, Virginia, the pilots of a Boeing 757 air carrier flight reported to ATC that they had encountered severe turbulence while en route in instrument flight.[72] The Boeing 757 indicated that the turbulence occurred between flight level 370 and flight level 360; after landing, all four flight attendants and several passengers on board the aircraft were transported to the hospital. None of the reported injuries met the standard for an aircraft accident; however, two of the flight attendants remained in a nonduty status for at least 3 weeks after the incident. A postflight examination of the airplane revealed hail damage, which required the radome to be replaced.[73]

[70] For example, see NTSB investigation DCA20CA038 for more information. See also appendix C.

[71] (a) More specifically, the NWS defines hail as "showery precipitation in the form of irregular pellets or balls of ice more than 5 mm in diameter, falling from a cumulonimbus cloud." See the NWS glossary. (b) For the purposes of this report, although hail is defined as a type of precipitation, which by definition must reach the ground, the NTSB considers hail aloft—that is, large chunks of ice that have not yet reached the ground or may not reach the ground—to also be hail.

[72] See NTSB investigation OPS14IA007 for more information.

[73] A *radome* is an assembly that protects the weather radar housed in the nose of an aircraft.

On August 11, 2016, an Airbus A320 air carrier flight encountered severe turbulence at flight level 320 near Wood, South Dakota, and diverted to Rapid City, South Dakota.[74] Of the 151 passengers and crew on board, 31 sustained minor injuries. According to interviews, the flight crew observed cumulonimbus clouds and deviated to the left; however, the airplane encountered turbulence as it flew through the edge of the clouds. The captain described the turbulence as "very violent and very quick" and stated that, at the time of the turbulence encounter, the airborne weather radar only displayed indications of light rain. However, the aircraft had entered or was very near an area characterized by hail activity according to the Cooperative Institute for Mesoscale Meteorological Studies' severe hail index, as shown in figure 20.[75]

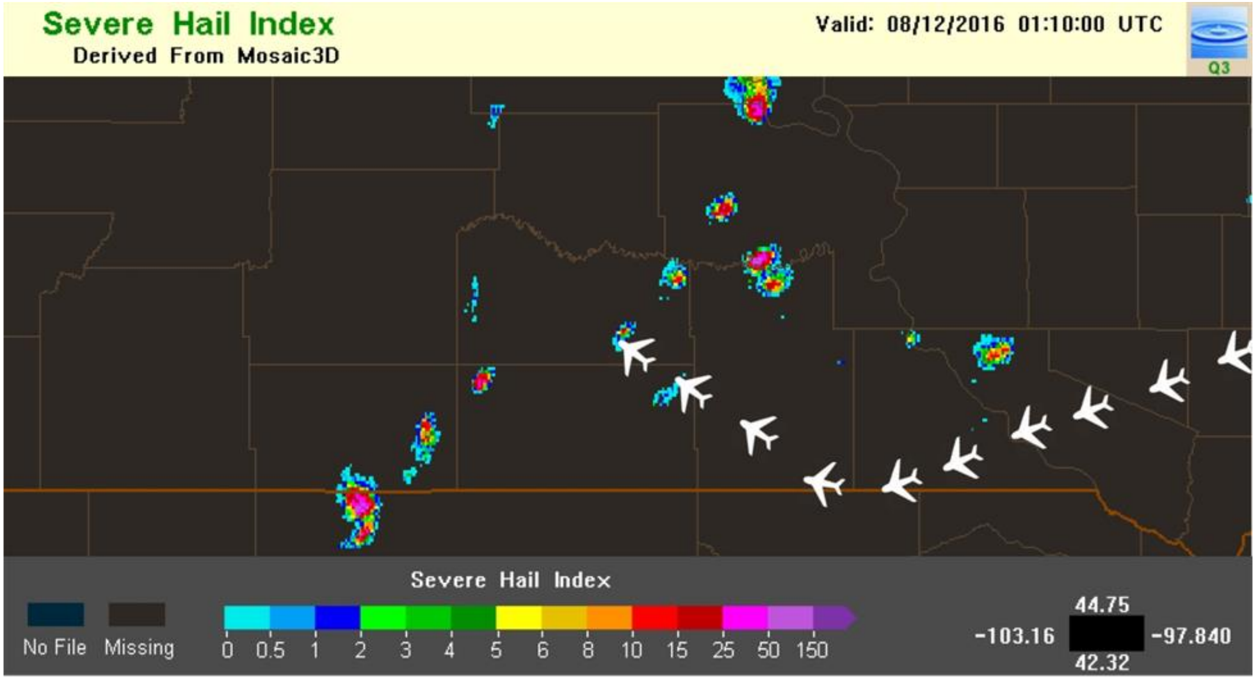

Figure 20. Cooperative Institute for Mesoscale Meteorological Studies' severe hail index plot from the time of the incident. Approximate aircraft position through incident time plotted by white airplane symbols.

Numerous weather radar-derived products exist that can alert to the potential presence of hail aloft. Like total lightning data, real-time information about the presence of, or potential for, hail aloft can also help flight crews and ATC identify areas characterized by severe turbulence as well as other convective hazards. Therefore, the NTSB concludes that total lightning and hail information provide useful indicators for areas of convection and convective turbulence.

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[74] See NTSB investigation DCA16IA215 for more information.

[75] (a) The Cooperative Institute for Mesoscale Meteorological Studies is a research organization created in 1978 by a cooperative agreement between the University of Oklahoma and NOAA. (b) The severe hail index is a radar-derived parameter that can be a good indicator of strong vertical updrafts.

The FAA is currently updating the En Route Automation Modernization system hardware and software (DOT OIG 2020). Thus, it may be an opportune time to reconsider weather-related enhancements to controller displays. Therefore, the NTSB recommends that the FAA incorporate total lightning and hail information as selectable layers on air traffic controller radar displays in ARTCCs and TRACON facilities. The NTSB further recommends that, after the action in Safety Recommendation A-21-36 is completed, the FAA provide training to air traffic controllers on the use of the controller-selectable total lightning and hail information.

4.3 Need for Mitigation of Common Turbulence-Related Injury Circumstances

The recommendations discussed in sections 4.1 and 4.2—concerning processes and tools for reporting and forecasting turbulence—largely aim to reduce turbulence-related Part 121 accidents by improving knowledge about turbulence risks so that turbulence encounters can be avoided. However, there are situations for which turbulence is difficult to identify. For example, embedded convection may not be easily detected by onboard or ground-based weather radar, and when not visible outside the aircraft windows, this class of convective activity can act as a hidden source of severe turbulence encounters within an otherwise benign-looking cloud mass.[76]

As shown in figure 12, from 2009 through 2018, in 28.7% of turbulence-related Part 121 accidents, the flight crew had no advance warning of the potential for encountering turbulence. In these situations and in situations where the risk of turbulence is known but cannot be avoided, accident reduction depends on mitigating the risk of injury.

The recommendations in this section address injury mitigation by focusing on the following patterns observed in the accident data analyzed in section 3.1:

- Nearly all turbulence-related injuries are sustained by occupants who are not wearing their seat belts.
- Many injuries occur during the descent phase of flight.
- Injuries are not uniformly sustained throughout the aircraft cabin.

[76] The NTSB has recently investigated several accidents that were outside the time period for this study involving turbulence and embedded convection. For example, on February 13, 2019, a Compass Airlines Embraer ERJ 175 encountered turbulence while in cruise flight at flight level 340 and subsequently diverted to the Reno-Tahoe International Airport in Reno, Nevada. Of the 75 passengers and crew on board, 1 flight attendant sustained serious injuries while 1 flight attendant and 2 passengers sustained minor injuries. The airplane sustained minor damage. About 1 hour into the flight, the aircraft encountered an area of severe turbulence that lasted about 8 seconds. Postaccident examination of the weather satellite data depicted cloud patterns aloft consistent with the presence of a convective updraft coincident with the flight's location at the time of the turbulence encounter. The convection appeared to be embedded with stratiform clouds and may not have been visually identifiable by the flight crew. See NTSB investigation DCA19CA081 for more information. See also appendix C.

4.3.1 Flight Attendant Injuries in the Descent and Approach Phases of Flight

Flight attendants are recognized as being at higher risk of sustaining turbulence-related injuries. In 2001, the Commercial Aviation Safety Team Joint Safety Analysis Team (JSAT) analyzed turbulence-related accidents and concluded that the risk of serious injury in turbulence was nearly 24 times higher for flight attendants compared to passengers (CAST 2001). This may be attributed to flight attendants spending more time in the cabin unseated and therefore not wearing their seat belts.

As described in section 3.1, there has been no overall reduction in the annual rate of turbulence-related Part 121 accidents over the past three decades. Yet, figure 21 shows there have been reductions in turbulence-related passenger injury rates since the 1983–1999 period examined in the JSAT study while flight attendant injury rates have not shown a similar decrease.

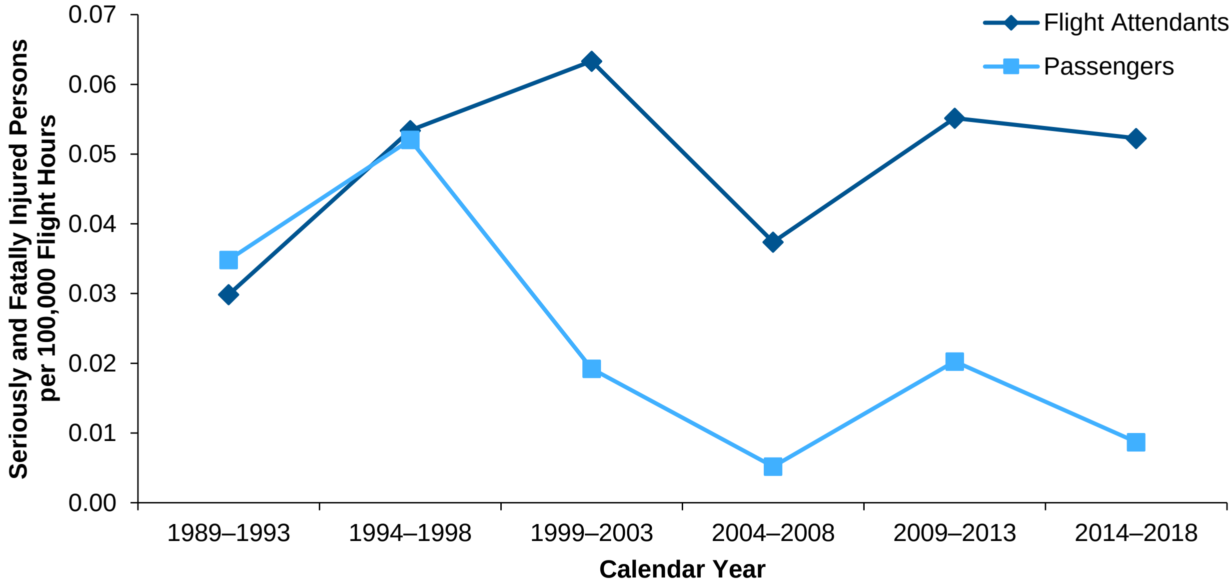

Figure 21. Rates of serious and fatal turbulence-related injuries in Part 121 accidents for flight attendants and passengers, 1989–2018.

During the 2009–2018 period examined, there were 111 turbulence-related Part 121 accidents. Most of these events involved flight attendant injuries only, with no serious passenger injuries nor damage to the aircraft. It is clear that flight attendants continue to be at higher risk for turbulence-related injuries.

The 2001 JSAT report provided 30 potential interventions to address turbulence-related accidents. Three of those interventions specifically addressed flight attendant safety and are listed here as follows:

- To reduce flight attendants' exposure to turbulence, during climb and descent, air carriers should establish and implement a policy and related SOPs that require all flight attendants and passengers to be seated with their seat belts fastened from takeoff to cruise altitude and from flight level 200 through landing. (Intervention 622)

- To reduce flight attendants' exposure to turbulence while performing seat belt monitoring, the FAA should require, and air carriers should develop and implement, clearly stated policies and SOPs to be included in flight attendant manuals. These policies and SOPs should allow flight attendants to prioritize, without repercussion, immediate duties and cabin service schedules, including the option to be seated while making seat belt announcements in response to anticipated turbulence hazards or warnings. (Intervention 623)
- To equip flight attendants with the insights and knowledge required to prioritize cabin duties versus the risk of turbulence-related injuries, the FAA should require air carriers to develop and implement training for flight attendants in turbulence hazards, aircraft behavior in turbulence, and the need to ensure their own safety. (Intervention 624)

After publication of the 2001 JSAT report, the Commercial Aviation Safety Team chartered the Turbulence Joint Safety Implementation Team (JSIT), which evaluated the proposed JSAT interventions, prioritized them based on their safety benefits and feasibility, and developed implementation plans for the high-priority items (CAST 2004). With respect to the interventions listed above, the JSIT report noted that their implementation costs were low and that the interventions were already practiced by some air carriers. As potential impacts of these three interventions, the report listed fewer injuries, resulting in reductions of lost work time and reduced litigation. The JSIT report also noted that the interventions would result in changes to company manuals and procedures and increased FAA oversight. Finally, the report mentioned that there may be concerns from air carriers about limiting crew availability for cabin service, particularly for certain flights that would require sitting during the entire flight.

The JSIT report grouped the interventions into seven proposed areas, two of which concerned cabin safety during turbulence. The first proposed area, "Implement Cabin Injury Reduction During Turbulence," included the following action items:

- evaluating and developing consensus on industry best practices
- creating an AC and updating FAA Order 8400.10 to be consistent with the new AC
- creating and conducting training for pilots and flight attendants based on the new AC
- identifying cabin interior products, such as handholds that can improve flight attendant stability during turbulence, and installing or retrofitting those products

The second proposed area, "Reduce Cabin Injuries During Turbulence—Research and Development," included the following action items:

- conducting research on best practices for increasing passenger seat belt use and developing an implementation plan
- developing and providing to the Commercial Aviation Safety Team a plan to use existing technology to facilitate instant aircraft-wide communications

The Commercial Aviation Safety Team documents safety enhancements that have been accomplished as well as safety enhancements reserved for future implementation. There is one turbulence-related safety enhancement listed on its website as completed, and there are 12 enhancements mentioning turbulence that are listed as safety enhancements reserved for future implementation. The completed safety enhancement, "SE078: Turbulence Procedures for

Reducing Cabin Injuries," lists the publication of the FAA AC 120-88A, "Preventing Injuries Caused by Turbulence," as its related accomplishment. AC 120-88A was originally published in 2005 and was updated in 2006 and 2007 (FAA 2007b). Several pages of the AC are dedicated to turbulence avoidance. With respect to preventing injury in the event of turbulence, the AC states that one of the most effective measures is to have occupants seated with seat belts fastened. The AC suggests that air carriers conduct training to emphasize the importance of conducting preflight briefings about the potential for turbulence on each portion of a flight, prioritizing safety when there is a risk of turbulence and using standard phraseology and SOPs. The AC also suggests operating procedures such as clearly communicating with passengers about turbulence advisories, emphasizing to passengers the benefits of keeping seat belts fastened at all times, and providing an announcement in advance of illuminating the seat belt sign. The AC suggests that air carriers gather information about their turbulence encounters and injuries and then review them to identify prevention strategies. It also suggests cabin modifications such as adding grab bars or handholds and minimizing angular surfaces or protrusions in the cabin.

One section of AC 120-88A focuses on how air carriers can design training to prevent or mitigate turbulence-related injuries to flight attendants. It states that "flight attendant injuries occur at a disproportionately high rate compared to other crewmembers and other cabin occupants because flight attendants spend more time in the passenger cabin unseated and, therefore, unbelted." To address this problem, the AC recommends training crewmembers in the air carrier's SOPs and conducting training that emphasizes to flight attendants that they are "not invincible" and that focuses on tools available to increase safety, such as the effective use of the public address system, the locations of handholds, and techniques for securing a service cart or galley in minimum time. The AC does not include a recommendation that flight attendants sit and use seat belts during certain phases of flight when there is a risk of turbulence.

During interviews, several Part 121 air carrier stakeholders described their efforts to reduce turbulence-related flight attendant injuries. Every air carrier stakeholder noted that it empowers flight attendants to sit and wear their seat belts when they feel unsafe during turbulence, regardless of instructions from the flight crew. Several air carrier stakeholders referred to specific guidance that directs flight attendants to be seated during moderate or higher turbulence or when such turbulence is anticipated. Some of the air carrier stakeholders developed other efforts, such as the following:

- using specific phrases to instruct flight attendants to be seated based on turbulence levels
- installing handholds in galley areas or head pads near flight attendant jumpseats, or both
- encouraging flight attendants to check a turbulence forecasting website
- establishing a set of 12 "early sit" airports in their route structure for which flight attendants are advised to be seated earlier than usual during descent because their data showed higher potential for turbulence encounters

AC 120-88A and air carrier practices in recent years appear to be consistent with two of the three flight attendant safety interventions suggested by the 2001 JSAT report. Current efforts emphasize training, focus on standardized communication, and prioritize flight attendant safety during turbulence or when moderate or severe turbulence is forecast. However, the data suggest that, overall, there has been little change in flight attendant injury rates since the mid-1990s.

The 2001 JSAT report also included a safety enhancement that air carriers should establish and implement a policy and related SOPs that require all flight attendants and passengers to be seated with their seat belts fastened from takeoff to cruise altitude and from flight level 200 through landing to reduce flight attendants' exposure to turbulence during climb and descent. Although it is established that being seated with the seat belt fastened is an effective method to prevent turbulence-related injuries, the NTSB is not aware of any air carriers that have implemented such a policy.

Others have also noted the turbulence risk of these phases of flight. For example, one air carrier analyzed the objective, in situ turbulence observations from its fleet and found that in 2018, 55% of all moderate-or-greater turbulence observations occurred below 15,000 feet and an additional 17% occurred between 15,000 feet and flight level 200 (Abelman 2018). Additionally, during their interviews, several Part 121 air carrier stakeholders mentioned descent as a phase of flight susceptible to turbulence events, and one air carrier stakeholder noted that more flight attendants are injured in turbulence events considered light or moderate than in the rare event classified as severe. Finally, it was the position of the flight attendant union representatives that, due to the frequency of turbulence-related injuries in the descent phase of flight, it should be required that all service items and carts be stowed, and flight attendants and passengers be seated with their seat belts fastened at and below 18,000 feet in the descent phase of flight. The union representatives did not believe that efforts to encourage air carriers to voluntarily implement such policies would be successful; it was stated that one air carrier rejected a proposed change in the altitude at which flight attendants were seated from 10,000 to 18,000 feet because it was perceived as leading to a competitive disadvantage for in-flight service.

In sum, it is understood that being seated with the seat belt fastened below a certain altitude is an effective countermeasure to preventing turbulence-related injuries; however, air carriers have not implemented such measures. Current efforts, which rely on anticipating turbulence or reacting quickly enough in the event of unanticipated turbulence to prevent injury, have not yielded reductions in the rate of flight attendant injuries. This NTSB research found that most turbulence-related Part 121 accidents occurred during the descent phase of flight or when the airplane was below flight level 200. The NTSB concludes that having flight attendants seated with their seat belts fastened during additional portions of the descent phase of flight would reduce the rate of flight attendant injuries due to turbulence and the rate of turbulence-related accidents overall. Therefore, the NTSB recommends that the FAA, based on NTSB data on turbulence-related Part 121 accidents, include in the revisions to AC 120-88A, "Preventing Injuries Caused by Turbulence," in Safety Recommendation A-21-42 the phases of flight and associated altitudes at which flight attendants should be secured in their seats during Part 121 air carrier operations, including in particular the descent phase of flight.

4.3.2 Turbulence Variations Within the Aircraft Cabin

Analysis of NTSB accident data shows that most serious injuries in turbulence-related Part 121 accidents are sustained by occupants in the aft section of the aircraft cabin. Using information from crewmember statements and interviews from turbulence-related Part 121 accident investigations occurring from 2009 through 2018, the NTSB categorized the location within the cabin where each serious injury was sustained, including the general cabin section (forward, middle, or aft) and the specific area (such as aisle, crew rest area, lavatory, or galley). As shown in table 4, for 84 of the 97 flight attendant injuries, the general cabin section could be determined. Seventy-four injuries (88.1% of injuries with known cabin section) occurred in the aft section of the cabin, and 56 of these injuries (75.7%) occurred in or near an aft galley. As shown in table 5, for 17 of 26 passenger injuries, the general cabin section could be determined; 14 injuries (82.3% of injuries with known cabin section) occurred in the aft section of the cabin, and 7 of these injuries occurred in or near an aft lavatory.

By themselves, these data do not necessarily indicate a safety issue with the aft cabin. Rather, the statistics are likely biased by differences in risk exposure—that is, they might reflect where aircraft occupants tend to spend the greatest amount of time when not wearing their seat belts. About half of the injuries for the passengers occurred in or near an aft lavatory, which is one reason passengers may be in this area of the cabin unsecured. Likewise, the fact that the majority of the flight attendant injuries occurred in or near an aft galley might reflect that the service-related duties of flight attendants often require them to spend more time working unrestrained in the galley area.

To account for risk exposure, the NTSB also analyzed the locations of flight attendants who were not wearing seat belts and not seriously injured during turbulence-related Part 121 accidents to determine if the rate of serious injury differed throughout the aircraft cabin. Of the 449 flight attendants involved in these accidents, seat belt use and general cabin section could be determined for 233 flight attendants; of these, 216 were not wearing their seat belt at the time of the accident. Six of 45 flight attendants in the forward section of the cabin were seriously injured (13.3%); 2 of 42 flight attendants in the middle section of the cabin were seriously injured (4.8%); and 67 of 129 flight attendants in the aft section of the cabin were seriously injured (51.9%).

In stakeholder interviews, pilots and flight attendants consistently mentioned that the effects of turbulence were usually worst in the aft section of the cabin. They described this as common knowledge and believed that the behavior was more pronounced for certain aircraft types. Stakeholders from one Part 121 air carrier reported that a key finding from analyzing the air carrier's internal safety data was that flight attendants perceived turbulence as more pronounced in aft galleys. Stakeholders from three other air carriers reported that their air carriers had made modifications to aircraft interiors in an attempt to reduce flight attendant injuries in the aft section of particular aircraft types, including adding handholds to galleys and adding padding to door mechanisms that protruded near flight attendants' heads when seated in their jumpseats. However, no air carrier stakeholders reported having quantitative data showing differences in how turbulence was experienced, such as through accelerations, at different locations within an aircraft.[77]

The accelerations experienced by an aircraft occupant can be described in terms of load factor, which is defined as the ratio of the total aerodynamic forces acting on an aircraft to the aircraft's weight.[78] During a turbulence encounter, at points away from an aircraft's center of gravity (CG), which the aircraft rotates around, the rotational components of the aircraft's motion will result in the load factor varying with distance from the CG. As the linear and rotational motion of the aircraft change over time throughout a turbulence encounter, their combined effects may result in different load factors at different locations along the length of the aircraft.

In the early 2000s, as part of a research program concerning weather-related accident prevention, the National Aeronautics and Space Administration developed a generic model of the effects of turbulence on aircraft occupants. This model showed that differences between accelerations occurring at the CG and in the aft cabin depended on wind gust characteristics, finding that "at the shorter [gust] wavelengths, the aft cabin accelerations are significantly higher. Part of this increase is due to the pitching motion of the simulated airplane, but a significant part is due to the excitation of the structural mode of the tail" (Stewart 2005). However, little published data exist showing load factor variations occurring within aircraft cabins in real-world turbulence encounters. As part of the same research program, the National Aeronautics and Space Administration conducted flight tests involving intentional turbulence encounters (Hamilton and Proctor 2006). One of the researchers involved in this work stated to the NTSB that the Boeing 757-200 research aircraft used in the flight tests was equipped with accelerometers at the pilot station, the CG, and the aft galley. Analysis showed that load factors occurring at the pilot station were 12% higher than those occurring at the CG, and load factors occurring at the aft galley were 40% higher than those occurring at the CG. However, these results were never published, and the observed load factor differences may not be generalizable to other aircraft types.

To illustrate variations in aircraft responses to turbulence, figures 22 and 23 show plots of normal load factors versus time for two recent turbulence-related Part 121 accidents investigated by the NTSB.[79] The NTSB used information from the flight data recorders to estimate the normal load factors during each turbulence encounter at three different locations within the aircraft: at the CG, at a point approximating the pilots' seating position, and at a point approximating the rear cabin door.[80] For the accident shown in figure 22, which involved a Boeing 737-900ER, the estimated normal load factors in the aft cabin peaked about -0.4*g* and then at 2.0*g*, about 0.2*g* higher in magnitude than at the CG; for this accident, the pilot station generally experienced the lowest normal load factor variations. However, for the accident shown in figure 23, which involved

[77] *Accelerations* refer to the time rate of change of the magnitude or direction of velocity, or both. Aircraft accelerations result in loads (perceived forces) on occupants, making them feel heavier, lighter, or pushed from side to side.

[78] In general, the *load factor* on an object refers to the ratio of the total forces (other than gravity) acting on the object to its weight. Accelerations resulting from forces on an aircraft are transmitted to the occupants through the airplane structure, such as the floor and seats, and are perceived as load factors by the occupants.

[79] (a) *Normal load factor* refers to the component of load factor along the aircraft's vertical axis. (b) See NTSB investigations DCA16CA010 and DCA20CA043 for more information. See also appendix C for additional details concerning DCA20CA043.

[80] This evaluation did not include factors such as the structural vibration of the airplane.

an Embraer 190, the differences among the aft, the CG, and the pilot station normal load factors were smaller. Although the rear of the aircraft initially experienced marginally higher loads than the front of the aircraft, there were also times when the front of the aircraft had a higher normal load factor.

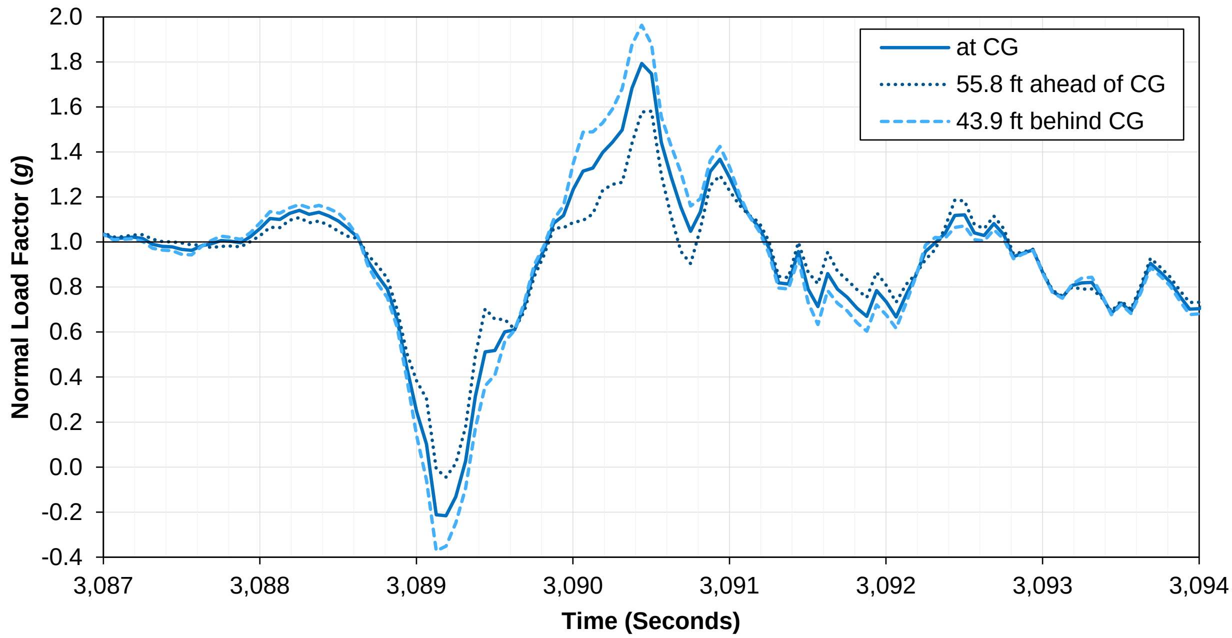

Figure 22. Estimated load factors during DCA16CA010 accident.

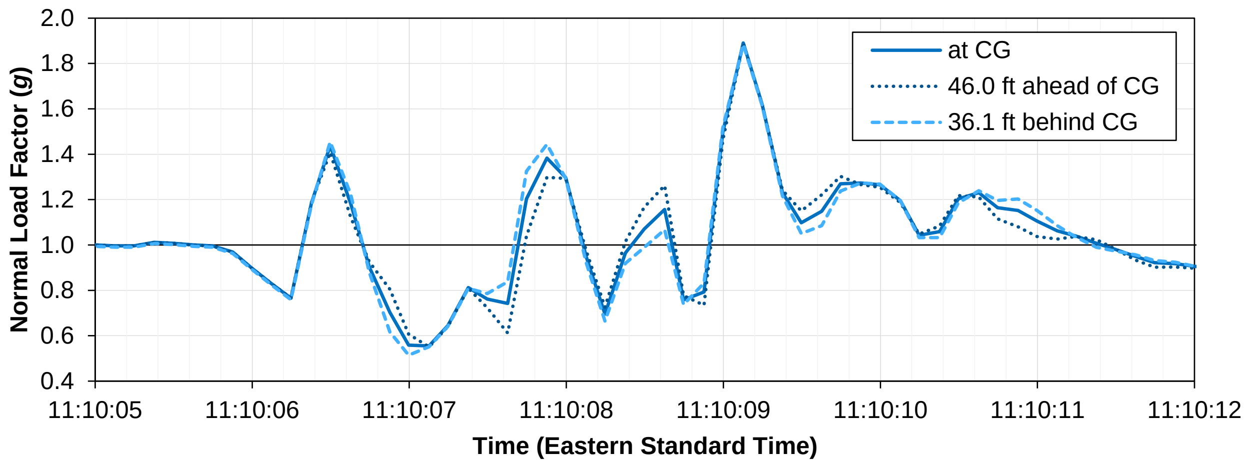

Figure 23. Estimated load factors during DCA20CA043 accident.

An evaluation of how aircraft accelerations resulting from turbulence vary along the length of an aircraft would provide air carriers with information needed to develop policies and procedures that account for worst-case turbulence impacts and minimize the risk of turbulence-related flight attendant injuries. This information could also influence future aircraft design and cabin layouts. The NTSB concludes that assessing how aircraft accelerations resulting from turbulence vary along the length of the aircraft would improve understanding of the risk of injury due to turbulence, especially for occupants not wearing a seat belt. Therefore, the NTSB recommends that the FAA conduct a study of how aircraft accelerations vary along the length of the aircraft during turbulence encounters, including differences among aircraft types operated by Part 121 air carriers, and publish the study findings.

4.3.3 Unrestrained Aircraft Occupants

Most passengers seriously injured in turbulence-related Part 121 accidents are either out of their seats or seated with their seat belts unfastened. As shown in figure 18, of 26 aircraft passengers seriously injured in turbulence-related Part 121 accidents between 2009 and 2018, only 1 person was documented as having used a seat belt; the remainder either were not wearing a seat belt or seat belt usage was not reported.[81]

The FAA recognizes the safety benefits of seat belt usage during turbulence. FAA AC 120-88A states

> The data strongly suggest that having passengers and [flight attendants] seated with seat belts fastened is an effective measure during a turbulence encounter. From 1980–2003, only four people who were seated with seat belts fastened received serious injuries during turbulence, excluding cases of other people falling onto and injuring properly secured occupants (FAA 2007b).

The AC further emphasizes the importance of occupants being seated and wearing a seat belt, recommending that air carriers implement procedures to promote voluntary seat belt use, compliance with the seat belt sign, and keeping seat belts fastened.

From a regulatory standpoint, per 14 *CFR* 121.311, separate seats and seat belts are required for each person traveling on board an aircraft in Part 121 air carrier operations. This regulation can help mitigate turbulence-related injuries when occupants have their seat belts fastened. However, this regulation contains an exception for children under the age of 2 that allows such children to be held on an adult's lap. This exception prevents children under the age of 2 from benefitting from the protection a seat belt affords.

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[81] (a) The one injury to a passenger wearing a seat belt occurred on Northwest Airlines flight 2, which encountered severe turbulence on descent to Narita International Airport, Narita, Japan, on February 20, 2009. This accident was investigated by the Japan Transport Safety Board. A total of 4 passengers sustained serious injuries; 27 other passengers and 7 flight attendants sustained minor injuries. In its accident report, the Japan Transport Safety Board stated that the serious injuries probably occurred because the passengers "were not seated or did not fasten their seat belts, or even if they did, it was done inappropriately" (JTSB 2011). (b) Among the case study accidents analyzed in this report, one passenger sustained a serious injury while wearing a seat belt with extender; see NTSB investigation DCA20CA038 for more information. See also appendix C.

Turbulence-related accidents have occurred with children under the age of 2 on board who are not in a separate seat, otherwise known as lap-held infants, in which caregivers have been unable to hold the infants securely during the turbulence encounter. Other aircraft occupants during these turbulence-related accidents did sustain serious injuries, but the lap-held infants were not seriously injured.[82] Although these events are infrequent and have not resulted in serious or fatal injuries to infants, they demonstrate that a turbulence encounter may exceed the ability of a caregiver to safely restrain a lap-held infant and therefore the potential for more severe outcomes remains.

There is widespread consensus among the transportation safety and medical communities, including the American Academy of Pediatrics, the Aerospace Medical Association, and the Centers for Disease Control and Prevention, that it is safest for children less than 2 years old to be seated in their own seat on an airplane, using an appropriate child restraint system (CRS), such as a car seat that is also approved for airplane use (AAP 2015, 2019; AsMA 2013; CDC 2017). For example, the American Academy of Pediatrics states, "the safest place for a child under 2 on an airplane is in a car seat, not on a parent's lap"; it further states, "if there is turbulence, or worse, you may not be able to protect your baby in your arms" (AAP 2015, 2019). Also, in its *Manual on the Approval and Use of Child Restraint Systems*, the International Civil Aeronautical Organization states that

> States and industry should encourage the use of CRS by passengers traveling by air with infants or children. Proper use of restraints is one of the most basic and important factors in surviving an accident. It is not possible for a parent to physically restrain an infant or child, especially during a sudden acceleration or deceleration, unanticipated or severe turbulence, or impact. The use of CRS provides an equivalent level of safety to infants and children as that afforded to adult passengers wearing seat belts (ICAO 2019).

Although it does not require using a CRS for children under the age of 2, the FAA does acknowledge that using a CRS is the safest option, especially during unexpected turbulence.[83] In 1996, the FAA issued a brochure, titled "Childproof Your Flight," which discussed turbulence and provided the following warning:

[82] For example, see NTSB investigation DCA14LA060 concerning United Airlines flight 1676 that encountered severe mountain wave turbulence while in cruise flight with the seat belt light off. Of the 114 passengers and 5 crewmembers, there were 2 serious injuries and 9 minor injuries, which included 1 lap-held infant. See also NTSB investigation DCA17CA155 concerning Republic Airlines flight 4678 that encountered turbulence 25 miles from its destination. During the encounter, several passengers were thrown into their passenger service units and one lap-held child was thrown several rows away from her mother but was uninjured.

[83] Outside the United States, the European Union Aviation Safety Agency strongly recommends the use of approved child seats on board an aircraft, and the Transportation Safety Board of Canada has recommended that Transport Canada mandate the use of CRSs for infants and young children traveling on commercial aircraft (EASA 2021, 2019; TSB 2015).

> The Federal Aviation Administration (FAA) strongly urges you to secure your child in an appropriate restraint based on weight and size. Turbulence can happen with little or no warning. And when it does, the safest place for your child is in a CRS, not in an adult's lap. Your arms just aren't capable of holding your child securely, especially when turbulence is unexpected. Keeping your child in a CRS for the duration of the flight is the smart and right thing to do so that everyone in your family arrives safely at your destination (FAA 1996).

In its 1996 brochure and on its 2021 website, the FAA suggests that, as an alternative to purchasing a separate ticket for children under the age of 2, caregivers should "ask if your airline will allow you to use an empty seat" (FAA 1996, 2021). However, because the percentage of passenger seats occupied can vary across flights and throughout the year, suggesting that a caregiver depend on the availability of an empty seat in which to install a CRS is not a reliable safety strategy.

For more than three decades, the NTSB has recommended that the FAA require children under the age of 2 to be appropriately restrained during takeoff, landing, and during a turbulence encounter in Part 121 air carrier operations.[84] The NTSB continues to believe that all occupants, including children under the age of 2, should be afforded the same level of protection when traveling on board Part 121 air carrier airplanes. Most recently, in 2010, the NTSB issued Safety Recommendation A-10-123 to the FAA to "amend 14 *CFR* Parts 121 and 135 to require each person who is less than 2 years of age to be restrained in a separate seat position by an appropriate CRS during takeoff, landing, and turbulence."[85]

Over the years, in response to the NTSB's safety recommendations, the FAA has consistently declined to mandate CRS usage for children under the age of 2. Instead, the FAA has emphasized the actions it has taken to increase voluntary CRS usage, including providing information on the FAA website and conducting outreach via social media. However, because the FAA has not evaluated the effects of its public education campaign, it is difficult to accurately determine trends in the amount of voluntary CRS usage, to identify operational impediments to CRS usage, or to evaluate the effects of public education or industry efforts on CRS usage. Such analyses require applicable data. Therefore, the NTSB concludes that researching the factors that affect caregivers' decisions about whether to use a CRS when traveling on a Part 121 air carrier airplane with children under the age of 2 would inform and improve government and industry efforts to increase the voluntary use of CRSs.

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[84] Safety Recommendation A-90-78, issued May 30, 1990, recommended that the FAA "revise 14 *CFR* 91, 121, and 135 to require that all occupants be restrained during takeoff, landing, and turbulent conditions, and that all infants and small children below the weight of 40 pounds and under the height of 40 inches be restrained in an approved child restraint system appropriate to their height and weight." This recommendation was superseded by Safety Recommendation A-95-51 in 1995, which recommended that the FAA "revise 14 *CFR* Parts 91, 135, and 121 to require that all occupants be restrained during takeoff, landing, and turbulent conditions, and that all infants and small children be restrained in a manner appropriate to their size." Safety Recommendation A-95-51 was classified "Closed—Unacceptable Action" on December 13, 2006. See appendix A for more information.

[85] Safety Recommendation A-10-123 was classified "Closed—Unacceptable Action" on November 4, 2013. See appendix A for more information.

Gathering and analyzing such data would critically inform the FAA's and the industry's understanding of the factors associated with why a caregiver does or does not choose to use a CRS as well as the challenges a caregiver might encounter when using a CRS. These data would be most valuable if they were obtained from caregivers who recently traveled with children under the age of 2—that is, passengers who made decisions concerning CRS usage on a given trip. Surveying such passengers would provide useful information about actual challenges they encountered. These real-life decisions and experiences, as compared to hypothetical or intended decisions, would provide precise insights about the factors influencing CRS use. Further, there are numerous points of access to caregivers traveling with children under the age of 2 in airport terminals that could provide opportunities to conduct this type of research without undue delay in the caregiver's travel itinerary, for example, in the baggage claim or gate areas. Therefore, the NTSB recommends that the FAA conduct a study to determine the factors that affect caregivers' decisions about the use of CRSs when traveling on a Part 121 air carrier airplane with children under the age of 2 and to understand the challenges associated with using CRSs; publish the study findings. Subsequent targeted actions could then be taken to implement key study findings. Therefore, the NTSB further recommends that after the action in Safety Recommendation A-21-40 is completed, the FAA use the study findings to direct the FAA's efforts to increase CRS usage.

Further, the NTSB believes that the safest place for a child under the age of 2 is in a CRS. This is reflected in airline industry advice for customers traveling with children. On its website, Airlines for America states that "the safest place for your child is in a government approved child safety restraint system" (A4A 2014). However, the NTSB notes that Part 121 air carriers do not consistently recommend (for example, via their websites) that customers use a CRS or inform customers of the safety benefits of CRS usage. Therefore, the NTSB recommends that Airlines for America, the National Air Carrier Association, and the Regional Airline Association coordinate with their member airlines to develop and implement a program to increase CRS usage in airplanes; this effort should include collecting data to determine the program's effectiveness at increasing CRS usage. For example, the program could include a long-term communication effort by air carriers to educate parents and caregivers, clearly explaining that it is safest for children less than 2 years old to be seated in their own seat on an airplane, using an appropriate CRS approved for airplane use.

4.4 Need for Updated Turbulence Guidance

In 2007, the FAA published the most recent update to AC 120-88A, "Preventing Injuries Caused by Turbulence" (FAA 2007b). Although some of the guidance provided in the AC remains relevant, since its publication, the NTSB has investigated numerous accidents and incidents involving turbulence, and industry groups have also studied the issue of turbulence resulting in lessons learned and best practices. Additionally, technology has improved significantly in the past 14 years, and guidance regarding the use of innovative, engaging techniques for presenting information on turbulence is important information for air carriers. For example, tools for virtual meetings have been greatly enhanced in recent years and could address the logistical difficulties associated with joint turbulence-related training.

An NTSB review of AC 120-88A revealed that certain sections of the AC are outdated. For example, the AC's figures depicting the rates of turbulence-related accidents use data from 1982 through 2003. Also, since the AC's publication in 2007, there have been improvements to in-flight internet and real-time graphical depictions of weather using electronic flight bags. In stakeholder interviews, pilots often highlighted the value of real-time electronic flight bag weather forecasts, but some pilots noted that not all aircraft are equipped with flight deck internet access and, in those instances, they would wind up relying on outdated turbulence information. A revised AC could emphasize the value of in-flight internet to facilitate transmission of weather updates and identify a minimum set of real-time weather data that Part 121 pilots should have access to in-flight, such as a turbulence nowcast, total lightning, and hail information.

Stakeholders also shared examples of best practices during interviews. For example, one air carrier stakeholder's turbulence injury reduction program included changes to gathering and tracking turbulence-related data and revising its turbulence action guides to simplify and streamline procedures for turbulence-related public address system commands. The air carrier stakeholder also launched a new PIREP processor, initiated a turbulence line operations safety audit, and pilot tested a turbulence-sensing electronic flight bag application. The air carrier stakeholder's data showed reductions in flight attendant injury reports, flight attendant injury rates, and passenger injury claims between 2017 and 2018. Examples of successful programs such as these could be added to the AC so that all air carriers can be aware of promising practices.

Also, after the FAA completes the study called for in Safety Recommendation A-21-39, the AC should be updated with the findings about how turbulence might be experienced differently in different parts of the aircraft cabin. Based on the results of the study, the AC should include countermeasures to minimize the risk of injury in areas that may experience greater accelerations. Further, after completing the study called for in Safety Recommendation A-21-40 in this report, the FAA should update the AC to provide guidance on the most effective means to increase CRS usage for children under the age of 2.

The NTSB concludes that AC 120-88A, "Preventing Injuries Caused by Turbulence," does not contain information about the current available technologies and best practices for avoiding turbulence encounters and turbulence-related injuries, which could be used by Part 121 air carriers to improve the safety of their flights. Therefore, the NTSB recommends that the FAA revise AC 120-88A, "Preventing Injuries Caused by Turbulence," to reflect current best practices and the findings of this research report, such as new turbulence forecasting and warning technologies; training methods; in-flight communications between pilots and flight attendants, procedures, and available information for predicting turbulence; and altitudes at which flight attendants should be secured in their seats.

5 Conclusions

5.1 Findings

- Wearing a seat belt reduces the risk of serious injury for all aircraft occupants during turbulence-related accidents in Title 14 *Code of Federal Regulations* Part 121 air carrier operations.

- Air traffic control procedures for processing pilot weather reports remain time-consuming and nonstandardized, which continues to prevent safety-critical turbulence observations from being shared throughout the National Airspace System.

- Air carriers continue to share turbulence observations with only their personnel but not throughout the National Airspace System, limiting opportunities for awareness of adverse weather phenomena that can negatively affect the safety of flight.

- Developing methods to translate between eddy dissipation rate (EDR) values calculated by different algorithms would produce consistent results, enable the maximum sharing of EDR data among air carriers, and ensure that turbulence forecast products are appropriately using these data.

- Because objective, in situ turbulence observations are not shared publicly to the greatest extent possible, air traffic control, weather forecasters, and other National Airspace System users lack access to important flight safety data.

- Due to their large size, airmen's meteorological information advisories are currently of limited value to Title 14 *Code of Federal Regulations* Part 121 air carrier pilots and air traffic controllers.

- Providing graphical airmen's meteorological information (AIRMET) advisories, significant meteorological information (SIGMET) advisories, and center weather advisories (CWAs) to air traffic controllers as controller-selectable layers on current and future controller displays in air route traffic control centers and terminal radar approach control facilities would increase shared awareness among controllers of AIRMET advisory, SIGMET advisory, and CWA locations.

- A frequently updated, short-term forecasting product known as a turbulence nowcast would provide more complete and accurate tactical information to help pilots, dispatchers, and air traffic controllers effectively respond to turbulence.

- Total lightning and hail information provide useful indicators for areas of convection and convective turbulence.

- Having flight attendants seated with their seat belts fastened during additional portions of the descent phase of flight would reduce the rate of flight attendant injuries due to turbulence and the rate of turbulence-related accidents overall.

- Assessing how aircraft accelerations resulting from turbulence vary along the length of the aircraft would improve understanding of the risk of injury due to turbulence, especially for occupants not wearing a seat belt.

- Researching the factors that affect caregivers' decisions about whether to use a child restraint system (CRS) when traveling on a Title 14 *Code of Federal Regulations* Part 121 air carrier airplane with children under the age of 2 would inform and improve government and industry efforts to increase the voluntary use of CRSs.

- Advisory Circular 120-88A, "Preventing Injuries Caused by Turbulence," does not contain information about the current available technologies and best practices for avoiding turbulence encounters and turbulence-related injuries, which could be used by Title 14 *Code of Federal Regulations* Part 121 air carriers to improve the safety of their flights.

6 Recommendations

As a result of this safety research report, the National Transportation Safety Board makes the following new safety recommendations.

6.1 New Recommendations

To the Federal Aviation Administration:

Work with stakeholders to standardize the distribution of pilot weather reports (PIREPs) across and within air traffic control facilities to ensure they are disseminated to only those facilities and air traffic controller positions for which each PIREP applies. (A-21-25)

As a condition of enhanced weather information system approval, require Title 14 *Code of Federal Regulations* Part 121 air carriers to disseminate all turbulence observations to the National Airspace System as pilot weather reports, as well as reports of smooth ride conditions. (A-21-26)

Determine how to harmonize current and future eddy dissipation rate algorithm performance in operational environments and publish the results of this determination. (A-21-27)

Incorporate the automatic dependent surveillance-broadcast weather capability in the next version of the automatic dependent surveillance-broadcast technical standard order. (A-21-28)

After the automatic dependent surveillance-broadcast (ADS-B) technical standard order is revised as recommended in Safety Recommendation A-21-28, require that aircraft flown in Title 14 *Code of Federal Regulations* Part 121 air carrier operations be retrofitted with automatic dependent surveillance-broadcast weather capable ADS-B equipment. (A-21-29)

Require automatic dependent surveillance-broadcast weather (ADS-B Wx)-equipped aircraft to broadcast ADS-B Wx information when operating in airspace requiring automatic dependent surveillance-broadcast capability as defined by Title 14 *Code of Federal Regulations* 91.225. (A-21-30)

In collaboration with the National Weather Service, modify airmen's meteorological information (AIRMET) advisory issuing practices to include graphical AIRMET advisories with higher granularity, taking into account the effect it would have on all National Airspace System users. (A-21-31)

Distribute graphical airmen's meteorological information advisories, significant meteorological information advisories, and center weather advisories to air traffic controllers as controller-selectable layers on current and future controller radar displays in air route traffic control centers and terminal radar approach control facilities. (A-21-32)

Work with local safety councils to develop training on the use of the advisories developed for Safety Recommendation A-21-32. (A-21-33)

In collaboration with the National Weather Service, operationalize a turbulence nowcast, such as the graphical turbulence guidance nowcast. (A-21-34)

Develop air traffic control guidelines for use of the turbulence nowcast operationalized in accordance with Safety Recommendations A-21-34 and A-21-44. (A-21-35)

Incorporate total lightning and hail information as selectable layers on air traffic controller radar displays in air route traffic control centers and terminal radar approach control facilities. (A-21-36)

After the action in Safety Recommendation A-21-36 is completed, provide training to air traffic controllers on the use of the controller-selectable total lightning and hail information. (A-21-37)

Based on National Transportation Safety Board data on turbulence-related Title 14 *Code of Federal Regulations* Part 121 accidents, include in the revisions to Advisory Circular 120-88A, "Preventing Injuries Caused by Turbulence," in Safety Recommendation A-21-42 the phases of flight and associated altitudes at which flight attendants should be secured in their seats during Part 121 air carrier operations, including in particular the descent phase of flight. (A-21-38)

Conduct a study of how aircraft accelerations vary along the length of the aircraft during turbulence encounters, including differences among aircraft types operated by Title 14 *Code of Federal Regulations* Part 121 air carriers, and publish the study findings. (A-21-39)

Conduct a study to determine the factors that affect caregivers' decisions about the use of child restraint systems (CRSs) when traveling on a Title 14 *Code of Federal Regulations* Part 121 air carrier airplane with children under the age of 2 and to understand the challenges associated with using CRSs; publish the study findings. (A-21-40)

After the action in Safety Recommendation A-21-40 is completed, use the study findings to direct the Federal Aviation Administration's efforts to increase child restraint system usage. (A-21-41)

> Revise Advisory Circular 120-88A, "Preventing Injuries Caused by Turbulence," to reflect current best practices and the findings of this research report, such as new turbulence forecasting and warning technologies; training methods; in-flight communications between pilots and flight attendants, procedures, and available information for predicting turbulence; and altitudes at which flight attendants should be secured in their seats. (A-21-42)

To the National Weather Service:

> Work with the Federal Aviation Administration to modify airmen's meteorological information (AIRMET) advisory issuing practices to include graphical AIRMET advisories with higher granularity, taking into account the effect it would have on all National Airspace System users. (A-21-43)

> Work with the Federal Aviation Administration to operationalize a turbulence nowcast, such as the graphical turbulence guidance nowcast. (A-21-44)

To Airlines for America, the National Air Carrier Association, and the Regional Airline Association:

> Coordinate with your member airlines to develop and implement a program to increase child restraint system (CRS) usage in airplanes; this effort should include collecting data to determine the program's effectiveness at increasing CRS usage. (A-21-45)

6.2 Previously Issued Recommendations Reiterated in This Report

The National Transportation Safety Board reiterates the following safety recommendations.

To the Federal Aviation Administration:

> Provide air traffic controllers with automated pilot weather report (PIREP) data-collection tools that incorporate design elements to prevent input errors, increase quantity, and improve the timeliness of PIREPs disseminated to the National Airspace System. (A-17-21)

> Incorporate automation technology that captures data elements from air traffic controllers' displays, including aircraft type, time, location, and altitude, to automatically populate these data into a pilot weather report (PIREP)-collection and -dissemination tool that will enable controllers to enter the remaining PIREP elements and disseminate PIREPs through a common exchange model directly to the National Airspace System. (A-17-22)

> Provide a reliable means of electronically accepting pilot weather reports directly from all users who are eligible to submit reports, and ensure that the system has the capacity to accept and make available all such reports to the National Airspace System. (A-17-26)

6.3 Previously Issued Recommendation Classified and Reiterated in This Report

The National Transportation Safety Board classifies and reiterates the following safety recommendation.

To the Federal Aviation Administration:

> Encourage industry safety efforts, such as the Commercial Aviation Safety Team and the General Aviation Joint Steering Committee, to identify, develop, and implement incentives for 14 *Code of Federal Regulations* Part 121, 135, and 91K operators and the general aviation community to freely share pilot weather reports (PIREPs), including braking action or runway condition reports filed as PIREPs, to the National Airspace System to enhance flight safety. (A-17-25)

Safety Recommendation A-17-25 is classified "Open—Unacceptable Response" in section 4.1.1 of this report.

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

BRUCE LANDSBERG
Acting Chairman

JENNIFER HOMENDY
Member

MICHAEL GRAHAM
Member

THOMAS CHAPMAN
Member

Report Date: August 10, 2021

Board Member Statement

Member Chapman filed the following concurring statement on August 12, 2021; Acting Chairman Landsberg and Members Homendy and Graham joined in this statement.

Thomas B. Chapman
Statement of Concurrence

Safety Research Report—*Preventing Turbulence-Related Injuries in Air Carrier Operations Conducted Under Title 14 Code of Federal Regulations Part 121*

I concur and join in the Board's unanimous adoption of the safety research report.

The report includes an important discussion of the risk to unrestrained occupants onboard aircraft, including flight attendants – who account for nearly 80% of those seriously injured in turbulence-related accidents. Key recommendations in the report are intended to help ensure better protections for flight attendants.

I have also taken a special interest in the risk to young children, who often fly unrestrained in the lap of a parent or another older passenger.

On its website, the Federal Aviation Administration strongly urges parents to secure children in a child restraint system. FAA says it's the smart and right thing to do.

Indeed, it is. There is widespread consensus among the transportation safety and medical communities that it is safest for children less than two years old to be seated in their own seat on an airplane, using an appropriate child restraint system.

Yet FAA has long declined to require child restraint systems. By regulation, the FAA *explicitly* says it's okay for young children to travel by air while seated unsecured in an older passenger's lap. For parents lacking further information, FAA's explicit regulatory authority allowing lap children to fly unsecured implies the practice is safe – because, after all, the agency responsible for regulating air safety says it's okay.

The existing regulatory structure calls on parents or other caregivers to override FAA's implied safety judgment and substitute their own. Unfortunately, families can only make the safest choice if they know enough to understand the risk. And FAA has made little effort to educate the public about the risk – a risk which FAA acknowledges but has declined to regulate.

For price sensitive families traveling with children, the opportunity to avoid purchasing an additional seat is an appealing way to save money. If it's "safe," why spend the money for an additional seat? Yet many parents have little or no knowledge of the serious risk to which they are exposing their children.

As adopted, the report includes an additional safety recommendation which I hope will help address this dangerous lack of knowledge. Our recommendation encourages the leading airline industry trade associations to coordinate with their member airlines to develop and implement a program to increase usage of child restraint systems. Such a program should include mechanisms for collecting data to determine the program's effectiveness.

FAA has a very poor track record in addressing this issue over the past quarter century. A premise of our newly adopted recommendation is that we can't count on FAA to do the right thing. We should therefore look directly to the airlines to help better inform parents and caregivers of the risks associated with young children flying unsecured.

Congratulations to our team for the fine job done on this safety research report. It is an important contribution which I believe will result in fewer turbulence-related injuries in Part 121 airline operations.

Appendixes

Appendix A: Previously Issued Recommendations Referenced in This Report

Table A-1 provides the number, classification, date closed, and recommendation text for all recommendations referenced in this report. Further information about these recommendations can be found using the CAROL Query Tool or by clicking on the hyperlinks provided below.

Table A-1. Previously issued recommendations referenced in this report.

Number	Classification	Date Closed	Recommendation
A-90-78	Closed—Unacceptable Action/Superseded	5/15/1995	**To the Federal Aviation Administration:** Revise 14 *CFR* 91, 121 and 135 to require that all occupants be restrained during takeoff, landing, and turbulent conditions, and that all infants and small children below the weight of 40 pounds and under the height of 40 inches be restrained in an approved child restraint system appropriate to their height and weight. (Superseded by A-95-50 and A-95-51)
A-95-51	Closed—Unacceptable Action	12/13/2006	**To the Federal Aviation Administration:** Revise 14 *Code of Federal Regulations* part 91, 135, and 121 to require that all occupants be restrained during takeoff, landing, and turbulent conditions, and that all infants and small children be restrained in a manner appropriate to their size. (Supersedes A-90-78)
A-10-123	Closed—Unacceptable Action	11/04/2013	**To the Federal Aviation Administration:** Amend 14 *Code of Federal Regulations* Parts 121 and 135 to require each person who is less than 2 years of age to be restrained in a separate seat position by an appropriate child restraint system during takeoff, landing, and turbulence.
A-12-18	Closed—Unacceptable Action	1/24/2018	**To the Federal Aviation Administration:** Study the technical feasibility of presenting, through the use of the weather and radar processor system or other means, real-time total lightning data on controller displays at both air route traffic control centers and terminal radar approach control facilities, and, if feasible, incorporate real-time total lightning data on controller displays and in associated weather products for current and future display systems.
A-12-19	Closed—Unacceptable Action	1/24/2018	**To the Federal Aviation Administration:** To the extent practicable, incorporate direct center weather service unit briefings on new weather-related air traffic control equipment and information services into controller training.
A-12-20	Closed—Acceptable Action	9/18/2020	**To the Federal Aviation Administration:** Incorporate real-time total lightning data into the products supplied to pilots through the flight information services – broadcast data link.

Number	Classification	Date Closed	Recommendation
A-14-13	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** Ensure that all Federal Aviation Administration (and contracted) preflight weather briefings include any products modified or created by the National Weather Service in response to Safety Recommendation A-14-17.
A-14-14	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** Require that the National Weather Service (NWS) provide a primary aviation weather product (as recommended in Safety Recommendation A-14-18 to the NWS) that specifically addresses the potential for and existence of mountain wave activity and its associated aviation weather hazards.
A-14-15	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** In cooperation with the National Weather Service (NWS), revise the Interagency Agreement between the Federal Aviation Administration and the National Oceanic and Atmospheric Administration/NWS for the center weather service units (CWSU) and its accompanying Statement of work if needed to add the new responsibilities of CWSU personnel in response to Safety Recommendations A-14-17 and/or A-14-18 to the NWS, which are in addition to the other responsibilities currently performed by the NWS under this agreement.
A-14-16	Closed—Acceptable Action	4/20/2020	**To the Federal Aviation Administration:** Include center weather advisories in the suite of products available to pilots via the flight information services-broadcast data link.
A-14-17	Open—Acceptable Response	N/A	**To the National Weather Service:** Modify National Weather Service (NWS) aviation weather products to make them consistent with NWS nonaviation-specific advisory products when applicable, so that they advise of hazardous conditions including aviation hazards less than 3,000 square miles in area that exist outside of terminal aerodrome forecast coverage areas.
A-14-18	Open—Acceptable Response	N/A	**To the National Weather Service:** Provide a primary aviation weather product that specifically addresses both the potential for and the existence of mountain wave activity and the associated aviation weather hazards (as recommended in Safety Recommendation A-14-14 to the Federal Aviation Administration).
A-14-19	Open—Acceptable Response	N/A	**To the National Weather Service:** In cooperation with the Federal Aviation Administration (FAA), revise the Interagency Agreement between the FAA and the National Oceanic and Atmospheric Administration/National Weather Service (NWS) for the center weather service units (CWSU) and its accompanying Statement of work if needed to add the new responsibilities of CWSU personnel in response to Safety Recommendations A-14-17 and/or A-14-18 to the NWS, which are in addition to the other responsibilities currently performed by the NWS under this agreement.

Number	Classification	Date Closed	Recommendation
A-14-20	Open—Acceptable Response	N/A	**To the National Weather Service:** Establish a protocol that will enhance communication among meteorologists at the center weather service units, the Aviation Weather Center, and, as applicable, other National Weather Service facilities to ensure mutual situation awareness of critical aviation weather data among meteorologists at those facilities.
A-14-21	Open—Acceptable Response	N/A	**To the National Weather Service:** Establish standardized guidance for all National Weather Service aviation weather forecasters on the weighting of information reported in pilot reports (PIREPs) that will (1) promote consistent determination of hazard severity reported in a PIREP and (2) assist in aviation weather product issuance.
A-17-17	Closed—Unacceptable Action	5/28/2020	**To the Federal Aviation Administration:** Develop and distribute information that emphasizes the safety importance of hazardous-weather pilot weather reports (PIREPs) and explains examples of regulatory violations in which the Federal Aviation Administration may use PIREPs in enforcement action, as well as the potential protection from sanction under the aviation safety reporting system.
A-17-18	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** In collaboration with the National Weather Service, (1) revise and harmonize the pilot weather report (PIREP) guidance in the *Aeronautical Information Manual* (*AIM*) and Advisory Circular (AC) 00-45H, including but not limited to the guidance and criteria for reporting low-level windshear (to specify airspeed gain or loss), turbulence (to specify in-cloud or out-of-cloud), and fair weather; and (2) revise the *AIM* to either include comprehensive PIREP-Coding guidance or to clearly reference AC 00-45H as the source of this information.
A-17-19	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** In collaboration with the National Weather Service, revise the Aeronautical Information Manual and Advisory Circular 00-45H to define standard criteria for reporting mountain wave activity in pilot weather reports (PIREPs) that include (1) consideration that not all hazardous mountain wave encounters involve turbulence; (2) airspeed fluctuation range, altitude fluctuation range, and any other information needed to adequately describe the effects of the mountain wave activity on the aircraft; (3) parameters for classifying the intensity level of the conditions for a turbulent wave encounter and a smooth wave encounter; and (4) the threshold at which the PIREP for each type of encounter (turbulent or smooth) should be coded as urgent.

Number	Classification	Date Closed	Recommendation
A-17-20	Closed—Acceptable Action	2/24/2020	**To the Federal Aviation Administration:** In collaboration with the National Air Traffic Controllers Association, develop and distribute to all air traffic control (ATC) facilities best practices guidance for the solicitation and dissemination of pilot weather reports for each type of ATC facility.
A-17-21	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** Provide air traffic controllers with automated pilot weather report (PIREP) data-collection tools that incorporate design elements to prevent input errors, increase quantity, and improve the timeliness of PIREPs disseminated to the National Airspace System.
A-17-22	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** Incorporate automation technology that captures data elements from air traffic controllers' displays, including aircraft type, time, location, and altitude, to automatically populate these data into a pilot weather report (PIREP)-collection and -dissemination tool that will enable controllers to enter the remaining PIREP elements and disseminate PIREPs through a common exchange Model directly to the National Airspace System.
A-17-23	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** Revise Federal Aviation Administration Orders JO 7110.65W, "Air Traffic Control"; JO 7110.10Y, "Flight Services"; and JO 7210.3Z, "Facility Operation and Administration," to ensure that the chapters of the orders that address pilot weather reports (PIREPs) include improved and consistent guidance about PIREP Coding, handling, solicitation, and dissemination.
A-17-24	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** Review and revise air traffic controller training to ensure that it provides scenario-based education, relevant to the controller's specific facility type and location, that includes real-world examples that demonstrate the value of both fair-weather and adverse-weather pilot weather reports (PIREPs) to weather forecasters and that shows how location inaccuracies and common collection and dissemination errors, including the consolidation of multiple PIREPs, adversely affect the usefulness of the reports to all National Airspace System users.
A-17-25	Open—Await Response	N/A	**To the Federal Aviation Administration:** Encourage industry safety efforts, such as the Commercial Aviation Safety Team and the General Aviation Joint Steering Committee, to identify, develop, and implement incentives for 14 *Code of Federal Regulations* Part 121, 135, and 91K operators and the general aviation community to freely share pilot weather reports (PIREPs), including braking action or runway condition reports filed as PIREPs, to the National Airspace System to enhance flight safety.

Number	Classification	Date Closed	Recommendation
A-17-26	Open—Acceptable Response	N/A	**To the Federal Aviation Administration:** Provide a reliable means of electronically accepting pilot weather reports directly from all users who are eligible to submit reports, and ensure that the system has the capacity to accept and make available all such reports to the National Airspace System.
A-17-27	Closed—Acceptable Action	2/24/2020	**To the Federal Aviation Administration:** Remove the 1-hour age limitation for accepting pilot weather reports.
A-17-28	Open—Unacceptable Response	N/A	**To the Federal Aviation Administration:** Maintain a database of pilot weather reports that archives the data for at least 1 year and that provides search and retrieval capabilities to support meteorological, research, and other uses.
A-17-29	Open—Acceptable Response	N/A	**To the National Weather Service:** Work with the Federal Aviation Administration to (1) revise and harmonize the pilot weather report (PIREP) guidance in the Aeronautical Information Manual (AIM) and Advisory Circular (AC) 00-45H, including but not limited to the guidance and criteria for reporting low-level windshear (to specify airspeed gain or loss), turbulence (to specify in-cloud or out-of-cloud), and fair weather; and (2) revise the AIM to either include comprehensive PIREP-Coding guidance or to clearly reference AC 00-45H as the source of this information.
A-17-30	Open—Acceptable Response	N/A	**To the National Weather Service:** Work with the Federal Aviation Administration to revise the Aeronautical Information Manual and Advisory Circular 00-45H to define standard criteria for reporting mountain wave activity in pilot weather reports (PIREPs) that include (1) consideration that not all hazardous mountain wave encounters involve turbulence; (2) airspeed fluctuation range, altitude fluctuation range, and any other information needed to adequately describe the effects of the mountain wave activity on the aircraft; (3) parameters for classifying the intensity level of the conditions for a turbulent wave encounter and a smooth wave encounter; and (4) the threshold at which the PIREP for each type of encounter (turbulent or smooth) should be coded as urgent.
A-17-31	Open—Acceptable Response	N/A	**To the National Air Traffic Controllers Association:** Work with the Federal Aviation Administration to develop and distribute to all air traffic control (ATC) facilities best practices guidance for the solicitation and dissemination of pilot weather reports for each type of ATC facility.
A-17-32	Closed—Acceptable Action	10/26/2017	**To the Cargo Airline Association:** Encourage your members to provide more pilot weather reports (PIREPs) during overnight flight hours, either by increased reporting by flight crews or by increased solicitation by dispatch or other personnel, and ensure that those PIREPs are submitted for dissemination to the National Airspace System.

Appendix B: Turbulence-Related Weather Products Discussed in This Report

Table B-1 lists and describes the different types of turbulence-related weather products discussed in this report.

Table B-1. Turbulence-related weather products discussed in this report.

Product	Description	Format	Frequency of Issuance	Period of Validity
AIRMET Advisory	Advisory of weather that does not meet the requirements for a SIGMET advisory but has a significant impact on the safety of aircraft operations, such as moderate turbulence.	Polygon with minimum and maximum altitudes.	Four times per day (continental United States and Hawaii), three times per day (Alaska), and as needed	Up to 6 hours (text, continental United States and Hawaii), up to 8 hours (text, Alaska); 12 hours, in 3-hour increments (graphical)
SIGMET Advisory	Advisory of weather that is judged to have significant impact on the safety of aircraft operations, including severe or extreme turbulence.	Polygon with minimum and maximum altitudes.	As needed	Up to 4 hours
Convective SIGMET Advisory	Advisory of thunderstorm activity that is judged to have significant impact on the safety of aircraft operations.	Polygon with minimum and maximum altitudes.	As needed	Up to 2 hours
CWA	Unscheduled aviation weather warning for conditions meeting or approaching AIRMET advisory or SIGMET advisory criteria within an ARTCC's area of responsibility.	Polygon with minimum and maximum altitudes.	As needed	Up to 2 hours
GTG	Forecast of potential turbulence due to clear air and mountain wave turbulence.	Grid of potential EDR values with a horizontal resolution of about 8 miles and a vertical resolution of 1,000 feet from the surface to flight level 450.	Hourly	18 hours, in 1-hour increments through the first 3 hours and 3-hour increments from the 3rd through 18th hours
GTGN	Nowcast of turbulence due to convective, clear air, and mountain wave turbulence.	Grid of potential EDR values with a horizontal resolution of about 8 miles and a vertical resolution of 1,000 feet from the surface to flight level 450.	Every 15 minutes	Valid at the time of issuance

Appendix C: Part 121 Air Carrier Accident Case Studies

The following are brief summaries of the 10 NTSB case study accident investigations discussed throughout this report. The complete reports for each case study accident investigation can be found using the CAROL Query Tool or by clicking on the hyperlinks provided below.[1]

DCA19CA081: February 13, 2019, Reno, Nevada

Background

On February 13, 2019, about 1232 Pacific standard time, Compass Airlines flight 5763, an Embraer 175, N613CZ, encountered turbulence while in cruise flight at flight level 340 and subsequently diverted to Reno-Tahoe International Airport in Reno, Nevada. The flight departed out of the Santa Ana, California, Airport en route to the Seattle, Washington, Airport, and it operated as a regularly scheduled passenger flight from the John Wayne-Orange County Airport in Santa Ana, California, to the Seattle-Tacoma International Airport in Seattle, Washington.

Accident Summary

Upon reaching cruise altitude of 34,000 feet, the aircraft was experiencing intermittent light-moderate chop, and after 40 minutes, it turned to smooth with occasional light chop. It was at this time that the pilots released the flight attendants to begin service, while still leaving the seat belt sign illuminated.

The flight remained smooth until about 1 hour into the flight. The aircraft encountered severe turbulence causing a sharp increase in vertical speed, which triggered a “Descend” traffic collision avoidance system (TCAS) resolution advisory (RA) command due to another aircraft passing above. The pilot flying disconnected the autopilot and responded to the RA by pushing the yoke forward; the severe turbulence (updraft), however, prevented the pilot flying from complying with the RA. The pilot monitoring got on the controls to assist in responding to the RA, then the updraft subsided and resulted in a sharp drop of the aircraft. Once the RA cleared, the flight crew returned to the assigned altitude and reported the TCAS RA and turbulence to ATC.

Injuries

Of the 75 passengers and crew on board, 1 flight attendant sustained serious injuries while 2 flight attendants and 2 passengers sustained minor injuries. The pilots checked back with the flight attendants and were notified of multiple injuries to passengers and crew. At this point, the pilots elected to declare an emergency and decided to divert to Reno-Tahoe International Airport in Reno, Nevada. Once on the ground, medics met the aircraft and took care of the injured passengers. Two passengers were transported to the hospital, treated for minor injuries, and released that day.

[1] Minor editorial changes have been made to these reproduced but abbreviated accident investigation summaries to make some of the language consistent with that used throughout this report. However, all probable cause statements appear exactly as written in the original NTSB accident reports.

Aircraft Damage

The aircraft experienced minor damage to the overhead bins and lavatory.

Probable Cause

The NTSB determined the probable cause of this accident was an inadvertent encounter with convective turbulence that resulted in a TCAS RA, which required an abrupt control input by the flight crew to resolve the conflict.

DCA19CA091: February 17, 2019, Franklin, Tennessee

Background

On February 17, 2019, about 1804 central standard time, Delta Air Lines flight 957, a Boeing 737-800, N3730B, encountered turbulence during descent into the Atlanta Hartsfield-Jackson International Airport in Atlanta, Georgia. The flight was a regularly scheduled passenger flight from the Bozeman Yellowstone International Airport in Bozeman, Montana, to the Atlanta Hartsfield-Jackson International Airport.

Accident Summary

According to the flight crewmembers, ATC informed them to expect light and occasional moderate turbulence during the descent. About 10 minutes before beginning their descent, the flight crew illuminated the seat belt sign and instructed the flight attendants to stow the carts and take their seats.

Shortly after departing flight level 350 for flight level 250, the airplane encountered two "rapid-bumps of light, moderate turbulence" about flight level 345. The flight crewmembers slowed the airplane and contacted the flight attendants, and they were then informed that the aft flight attendant was injured. According to the flight attendants, the flight had been routine, having experienced only occasional light turbulence. The two aft flight attendants had finished their meal service and secured the galley. The two flight attendants were making their final walkthrough of the cabin when the turbulence was encountered, and the captain made the public address announcement to discontinue cabin service. The flight crew declared an emergency and requested paramedics meet the flight at the gate.

Postaccident examination of the weather data determined that the accident flight was in instrument meteorological conditions in an area of convectively induced turbulence due to embedded rain shower activity when the turbulence was encountered. Although there was no lightning activity around the accident site at the accident time, there were pockets of strong-rain shower cells within the complex of precipitation. The area where the accident occurred was covered by an AIRMET advisory that warned of moderate turbulence conditions.

Injuries

Of the 145 passengers and crew on board, 1 flight attendant sustained serious injuries and another flight attendant sustained minor injuries. The two aft flight attendants reported they were thrown up to the ceiling and then came "crashing back down" onto the galley floor. One flight attendant was in intense pain and was transported to the hospital; the flight attendant was diagnosed with a fractured vertebra.

Aircraft Damage

The aircraft sustained no damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with convective turbulence during descent.

DCA19CA151: May 25, 2019, Waycross, Georgia

Background

On May 25, 2019, about 1715 eastern daylight time, Southwest Airlines flight 2842, a Boeing 737-8H4, N8697C, encountered turbulence during descent into the Jacksonville International Airport in Jacksonville, Florida. The flight was a regularly scheduled passenger flight from the Chicago Midway International Airport in Chicago, Illinois, to the Jacksonville International Airport.

Accident Summary

According to the captain, as the flight approached 15,000 feet, he noticed there was a scattered layer of clouds they needed to descend through, and so he elected to provide the 10,000-foot chime to the flight attendants early, which indicated they should begin preparing the cabin for landing.

As the flight descended through the layer at about 12,000 feet, the airplane encountered moderate turbulence. The seat belt sign was off, and the flight crewmembers had turned off the weather radar about 5 minutes before because they had observed no weather between the airplane and the Jacksonville International Airport. According to the flight attendants, the turbulence was encountered shortly after they received the 10,000-foot chime and had begun their final walkthrough of the cabin. The two flight attendants in the aft cabin were thrown into the air and then struck the floor.

Postaccident examination of the weather data determined that the turbulence was encountered in the vicinity of the sea breeze front and localized convergence where towering cumulus clouds were depicted on the satellite imagery. There was no lightning detected, and there were no PIREPs or in-flight advisories for convection or turbulence current for the area.

Injuries

Of the 128 passengers and crew on board, 1 flight attendant sustained serious injuries and one flight attendant sustained minor injuries. One of the injured flight attendants was transferred to a passenger seat for the remainder of the flight. The flight crewmembers were notified of the injury, and they requested that paramedics meet the airplane at the gate. After landing, the two aft flight attendants were transported to the hospital where one was diagnosed with a fractured ankle.

Aircraft Damage

The aircraft sustained no damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with convectively induced turbulence while penetrating cumulus clouds during descent.

DCA19CA208: August 26, 2019, Chicago, Illinois

Background

On August 26, 2019, about 2037 central daylight time, Delta Airlines as flight 805, a Boeing MD-88, N911DL, encountered turbulence during descent to the Chicago O'Hare International Airport in Chicago, Illinois. The flight was operating as a regularly scheduled passenger flight from the Atlanta Hartsfield-Jackson International Airport in Atlanta, Georgia.

Accident Summary

According to the flight crewmembers, during initial descent, they heard reports of moderate turbulence from preceding airplanes on arrival. The captain contacted the flight attendants and informed them of the upcoming moderate turbulence and instructed them to be seated. Shortly after, while deviating around an area of weather, the airplane encountered about 10 to 15 seconds of moderate turbulence.

According to flight attendant statements, they had finished service and had stowed everything they needed to in the galley. The captain notified them that turbulence "was coming in three to five minutes." The aft flight attendant was returning to his jumpseat when the turbulence was encountered, and he was unable to maintain his balance and fell to the floor. After the turbulence had subsided, the injured flight attendant was able to make it back to his jumpseat and immobilize his ankle.

Injuries

Of the 152 passengers and crew on board, 1 flight attendant was seriously injured. The flight attendants informed the flight crew of the injury, and medical personnel met the airplane at the gate. A subsequent x-ray indicated the flight attendant sustained a fractured distal fibula.

Aircraft Damage

The aircraft sustained no damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with convective turbulence during descent.

DCA19CA206: August 27, 2019, Denver, Colorado

Background

On August 27, 2019, about 0650 mountain daylight time, Frontier Airlines as flight 461, an Airbus A320, N328FR, encountered turbulence while on descent to the Denver International Airport in Denver, Colorado. The flight was operating as a regularly scheduled passenger flight from the Minneapolis/St. Paul International Airport in Minneapolis, Minnesota, to the Denver International Airport. Visual flight conditions prevailed at the time of the accident.

Accident Summary

According to the flight crew, as the flight was approaching 15,000 feet, the captain, who was the pilot monitoring, identified a single cumulus cloud in front of them with the tops about 15,000 feet and informed the first officer of possible turbulence. The first officer reduced airspeed to 250 knots in anticipation of the turbulence, and the captain advised the flight attendants to take their seats. The airplane then entered moderate turbulence for about 10 seconds.

According to the flight attendants, very shortly after being notified by the captain, the turbulence was encountered. The aft flight attendant was returning to her jumpseat when the turbulence occurred, and she was thrown to the floor. After the encounter, she was helped back to her jumpseat by another flight attendant, and they informed the flight crew.

An NTSB weather study indicated likely mountain wave conditions between 11,000 feet and 14,000 feet with cloud formation near the accident site and points eastward and cloud tops near 15,000 feet.

Injuries

One flight attendant sustained a serious injury. The flight was met at the gate by medical personnel, and the flight attendant was transported to the hospital and diagnosed with a broken left ankle.

Aircraft Damage

The aircraft sustained no damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with mountain wave turbulence.

DCA19CA213: September 6, 2019, Fort Myers, Florida

Background

On September 6, 2019, about 1600 eastern daylight time, Spirit Airlines flight 967, an Airbus A319, N515NK, encountered turbulence during descent into the Fort Myers Southwest Florida Airport in Fort Myers, Florida. The airplane was not damaged. The flight was operating as a regularly scheduled domestic passenger flight from the Cleveland Hopkins International Airport in Cleveland, Ohio, to the Fort Myers Southwest Florida Airport.

Accident Summary

According to the flight crew, the flight was descending through about 12,000 feet when the captain made the arrival announcement on the public address system "in anticipation of encountering turbulence due to a scattered layer of cumulous clouds." The seat belt sign was illuminated.

According to the flight attendants, the turbulence was encountered shortly after the captain's announcement on the public address system, while the flight attendants were conducting final compliance checks in the cabin. One of the aft flight attendants fell to the floor during the encounter. She was unable to return to her jumpseat due to her injury and was assisted to a passenger seat in the aft cabin for landing. The flight crew was notified of the flight attendant's injury, and the flight crew requested that paramedics meet the airplane at the gate.

Postaccident examination of the weather data determined that the turbulence occurred during day visual meteorological conditions when the airplane entered scattered cumulus congestus clouds (towering cumulus) associated with heavy rain showers and a sea breeze front. There was no lightning detected, and there were no PIREPs or in-flight weather advisories current for the area.

Injuries

Of the 108 passengers and crew on board, 1 flight attendant sustained a serious injury. After landing, the injured flight attendant was transported to the hospital where she was diagnosed with a fractured ankle.

Aircraft Damage

The aircraft sustained no damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with convectively induced turbulence associated with towering cumulus clouds during descent.

DCA20CA038: December 16, 2019, Alexandria, Louisiana

Background

On December 16, 2019, about 1323 central daylight time, Envoy flight 3960, an EMB140, N805AE, encountered severe turbulence during cruise flight while en route to the Gainesville Regional Airport in Gainesville, Florida. The flight was operating as a regularly scheduled domestic passenger flight from the Dallas-Fort Worth International Airport in Dallas, Texas, to the Gainesville Regional Airport.

Accident Summary

According to the flight crewmembers, as the flight was cruising at flight level 370 in visual meteorological conditions, they could see convective activity ahead. ATC informed them that PIREPs along their route of flight had reported "nothing worse than moderate chop" with one report of "severe turbulence" from another aircraft that was an hour old. Prior to the turbulence encounter, the captain made an announcement to the passengers about impeding weather and possible turbulence and requested that the flight attendant take her seat.

The seat belt sign was illuminated. As the flight approached the weather, the first officer, who was the pilot flying, began to maneuver around several cells visually. The airplane radar did not show any returns. Upon entering visible moisture, moderate rain and turbulence began immediately but increased rapidly in intensity. Airspeed and altitude began fluctuating rapidly and upon receiving an overspeed warning, the first officer brought the thrust levers to idle and deployed the speed brakes. Large fluctuations in vertical speed continued to occur, and the autopilot automatically disengaged simultaneously with stick shaker activation. Shortly after, the first officer returned the airplane to a normal flight condition and returned to flight level 370. The captain informed ATC that the flight had encountered severe turbulence and then contacted the flight attendant to check if there were any injuries.

At that time, the flight attendant reported no injuries; however, about 5 minutes later, the captain was informed that a passenger had been injured. According to the flight attendant and deadheading crewmembers, all passengers and the flight attendant were seated with their seat belts fastened when the turbulence was encountered. After the turbulence stopped, drinks covered the walls and ceiling, and magazines and electronic devices were located multiple rows from their original location.

Postaccident examination of the weather data determined that the flight encountered convectively induced turbulence after penetrating cumulonimbus clouds, with tops near flight level 400, while attempting to overfly a large area of known convection. In the area of the encounter, weather surveillance radar depicted extreme echoes at lower altitudes with lighter echoes at the airplane's altitude, with lightning in the vicinity. The NWS Convective Outlook forecast had warned of a moderate risk of severe thunderstorms over the area. In addition, there was an NWS tornado watch and a convective SIGMET advisory current for severe embedded thunderstorms in the area.

Injuries

Of the 39 passengers and crew on board, 1 passenger sustained serious injuries. The injured passenger indicated that her seat belt, with extender, was fastened; however, she had hit her head "pretty hard" and had back and neck pain. The captain notified the air carrier operations center and ATC of the injury and requested that paramedics meet the airplane at the gate. After landing the injured passenger was transported to a local hospital and diagnosed with two small neck fractures.

Aircraft Damage

The aircraft sustained no damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with convectively induced turbulence while overflying an area of known convective activity.

DCA20CA043: December 18, 2019, Disputanta, Virginia

Background

On December 18, 2019, about 1109 eastern standard time, American Airlines flight 2247, an Embraer ERJ190, N959UW, encountered turbulence while en route to the Raleigh-Durham International Airport in Morrisville, North Carolina. The flight was operating as a regularly scheduled domestic passenger flight from LaGuardia Airport in Queens, New York, to the Raleigh-Durham International Airport.

Accident Summary

According to the flight crewmembers, the flight was initially in cruise at flight level 200 with the seat belt sign off because ATC had reported all PIREPs as "smooth" and "no complaints."

About 1 hour into the flight, the flight crew encountered a brief duration of light to moderate chop and illuminated the seat belt sign. The flight crew requested a descent to flight level 180. The seat belt sign was turned off after the flight reached flight level 180 because the skies were clear, they were experiencing a smooth ride, and there were no PIREPs of turbulence.

A short time later, the flight encountered light to moderate chop turbulence that lasted 20 seconds to a minute. The flight crew then received a call from the cabin advising them that a flight attendant had been injured. The injured flight attendant was transferred to a passenger seat for the remainder of the flight. Upon being notified of the injury, the flight crew declared a medical emergency and requested paramedics meet the flight at the gate.

One nonrevenue crewmember described the turbulence encountered as "moderate to severe." Postaccident examination of the weather data determined that the airplane was passing through the lower boundary of a strong jet stream that was associated with significant shear. Moderate turbulence had been forecast for the area of the encounter, and there were no previous PIREPs of severe turbulence.

Injuries

Of the 48 passengers and crew on board, 1 flight attendant sustained a serious injury. At the time of the second turbulence event, the flight attendants were conducting drink service in the cabin, and the flight attendant in the aft cabin was thrown to the floor, injuring her foot. After landing, the flight attendant was transported to a local hospital where she was diagnosed with a fractured foot.

Aircraft Damage

The aircraft sustained no damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with clear air turbulence during cruise flight.

DCA20CA058: January 10, 2020, New Orleans, Louisiana

Background

On January 10, 2020, about 2245 universal coordinated time, United Airlines flight 1754, an Airbus A320, N1902U, encountered turbulence near the top of climb from the New Orleans International Airport in New Orleans, Louisiana. The flight was operating as a regularly scheduled passenger flight from the New Orleans International Airport to the Newark Liberty International Airport in Newark, New Jersey.

According to the flight crewmembers, they advised the flight attendants to expect some light turbulence during the climb out and stated they would leave the seat belt sign illuminated for passengers until they had reached smooth air. During the climb to their assigned altitude of flight level 370, the weather radar was active, and ATC advised of weather directly in front of the flight.

Accident Summary

As the flight was climbing through about flight level 305, the flight was in clear air, but the crew realized they were not going to stay above the clouds ahead of the airplane and requested, and were approved, to deviate to the right to avoid them. During the turn, the captain made an announcement on the public address system for the flight attendants to "take their jumpseats," and the flight subsequently encountered "a couple bumps of light chop."

Almost immediately after, the flight crew received a call from the cabin, reporting that the purser had been injured. Postaccident examination of the weather data determined that the turbulence was encountered when the airplane was flying over an area of general thunderstorms. Cloud tops up to flight level 400 were located within 10 miles of the turbulence encounter, but there were no PIREPs in the vicinity indicating turbulence prior to the event. There was a CWA current for the area for isolated thunderstorms, which had been included in the flight's weather briefing.

Injuries

Of the 159 passengers and crew on board, 1 flight attendant sustained serious injuries. According to the flight attendants, they were preparing for cabin service when the turbulence was encountered. The forward flight attendant fell to the floor as she was walking through the first-class cabin. Subsequently, the flight crew's announcement for the "flight attendants take your jumpseats" came over the public announcement system. The injured flight attendant was assisted by medically qualified passengers and stayed in a passenger seat for the remainder of the flight. Paramedics met the airplane at the gate, and the flight attendant was transported to the hospital where she was diagnosed with a fractured ankle.

Aircraft Damage

The airplane was not damaged.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with convectively induced turbulence while overflying an area of known convective activity.

DCA20CA071: February 7, 2020, Waynesville, North Carolina

Background

On February 7, 2020, about 0105 eastern standard time, PSA Airlines flight 5634, a Canadair CRJ-900, N610NN, encountered turbulence during en route descent to the McGhee Tyson Airport in Knoxville, Tennessee. The regularly scheduled domestic passenger flight was from the Charlotte Douglas International Airport in Charlotte, North Carolina, to the McGhee Tyson Airport. The flight departed 4 hours late due to the late arrival of the inbound airplane in the Charlotte Douglas International Airport because of persistent severe weather that had been in the area. According to the flight crewmembers, they kept the seat belt sign illuminated for the entire flight because of the late night and weather in the area.

Accident Summary

The flight crew indicated that the takeoff, climb, and cruise were uneventful. Most of the flight was conducted at flight level 220 in clear air with clouds beneath. As they approached the McGhee Tyson Airport, the flight was cleared to descend at the pilot's discretion to 13,000 feet. During the descent, the onboard radar was on but did not depict any precipitation in the cloud layer below them. In the early stages of the descent, the flight began entering and exiting various cloud layers and experienced very light/intermittent chop.

About flight level 185, the flight went into a cloud and encountered severe turbulence, causing the autopilot to disengage and the airplane to pitch nose down rapidly. The pilot flying reduced power and leveled the wings, and the airplane quickly exited the clouds into visual meteorological conditions again. The flight continued to experience moderate turbulence during the descent. The captain called back to check on the flight attendants and passengers but initially received no reply.

A short time later, the captain called back again and was informed by a deadheading flight attendant that both flight attendants had been injured.[2]

Injuries

Of the 73 passengers and crewmembers on board, 1 flight attendant sustained serious injuries and there were 22 minor injuries. At the time of the turbulence encounter, the forward flight attendant was preparing the galley for landing and was thrown to the ceiling and back to the floor, injuring both ankles. The flight attendant could not stand, and a deadheading pilot helped her to a passenger seat. The aft flight attendant was conducting final compliance checks in the cabin and was also thrown to the ceiling and back to the floor, causing her to black out for a short time. Multiple passengers sustained various injuries, including head bumps/bruises and scrapes. Some passengers experienced anxiety issues. Two deadheading flight attendants assumed the duties of the two injured flight attendants for the remainder of the flight. After landing, paramedics

[2] *Deadheading* refers to the air carrier practice of carrying its own employees, free of charge, on a normal passenger flight to make sure its employee can be in the right place to begin their duties.

met the airplane at the gate, and the two flight attendants and several passengers were transported to the hospital. The forward flight attendant was diagnosed with fractures in both ankles. Postaccident examination of the weather data determined that the turbulence encounter occurred in a strong sheared environment with a 155-knot jet stream. There were several PIREPs of moderate to severe turbulence in the area, and there was a SIGMET advisory current for severe turbulence in the area.

Aircraft Damage

The aircraft sustained substantial damage.

Probable Cause

The NTSB determined the probable cause of this accident was an encounter with severe convective turbulence associated with a strong sheared environment associated with the jet stream.

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