In-Flight Decision-Making by General Aviation Pilots Operating in Areas of Extreme Thunderstorms

Douglas D. Boyd

BACKGROUND: General aviation (comprised mainly of noncommercial, light aircraft) accounts for 94% of civil aviation fatalities in the United States. Although thunderstorms are hazardous to light aircraft, little research has been undertaken on in-flight pilot decision-making regarding their avoidance. The study objectives were: 1) to determine if the thunderstorm accident rate has declined over the last two decades; and 2) assess in-flight (enroute/landing) airman decision-making regarding adherence to FAA separation minima from thunderstorms.

METHODS: Thunderstorm-related accidents were identified from the NTSB database. To determine en route/arriving aircraft real-time thunderstorm proximity/relative position and airplane location, using a flight-tracking (Flight Aware®) website, were overlaid on a graphical weather image. Statistics employed Poisson and Chi-squared analyses.

RESULTS: The thunderstorm-related accident rate was undiminished over the 1996–2014 period. In a prospective analysis the majority (enroute 77%, landing 93%) of flights violated the FAA-recommended separation distance from extreme convection. Of these, 79 and 69% (en route and landing, respectively) selected a route downwind of the thunderstorm rather than a less hazardous upwind flight path. Using a mathematical product of binary (separation distance, relative aircraft-thunderstorm position) and nominal (thunderstorm-free egress area) parameters, airmen were more likely to operate in the thunderstorm hazard zone for landings than en route operations.

DISCUSSION: The thunderstorm-related accident rate, carrying a 70% fatality rate, remains unabated, largely reflecting nonadherence to the FAA-recommended separation minima and selection of a more hazardous route (downwind) for circumnavigation of extreme convective weather. These findings argue for additional emphasis in ab initio pilot training/recurrency on thunderstorm hazards and safe practices (separation distance and flight path).

KEYWORDS: convective weather, pilot decision-making, human factors, aviation accidents.

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General aviation, mostly comprised of piston engine powered aircraft,[20] is classified as all civil aviation excluding passenger/freight transport and regulated by a set of rules enshrined in the Code of Federal Regulations (14 CFR Part 91).[14] In contrast, commercial transportation by air carriers and charter operations are governed by a more stringent set of rules (14 CFR Part 121 and 14 CFR Part 135).[14] Although accidents for the latter group have dramatically declined over the last few decades,[8] only a very modest decrease has been witnessed for general aviation, the latter accounting for 94% of civil aviation fatalities in the United States.[28] Indeed, the fatality rate for general aviation is 23 times higher than that of the air carriers.[8]

While there have been a plethora of studies identifying risk factors for general aviation accidents over the last two decades (see review[8]), little research has been undertaken on in-flight pilot decision-making related to convective weather (thunderstorms) avoidance. By virtue of their violent turbulence, hail, and windshear,[19] thunderstorms pose extreme hazards to light aircraft, often resulting in a fatal outcome.[26] Importantly, such adverse weather conditions can prevail some distance from the visible thunderstorm. Indeed, moderate to severe turbulence has been reported in regions of low radar reflectivity with eddy dissipation rate studies demonstrating a fourfold increased relative risk of moderate or greater turbulence some 16 nmi from a

From GSBS, University of Texas, Houston, TX.

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Address correspondence to: Douglas Boyd, Ph.D., Retired, University of Texas, 1515 Holcombe Blvd., Houston, TX 77054; dboyd.academic.aviation@gmail.com.

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thunderstorm.[27] In addition, gust fronts (outflow) may lead the visible thunderstorm by up to 15 mi.[19,27]

Unlike transport category aircraft, which are mandated[3] to have onboard radar which provides real-time reflectivity data, no such requirement exists for general aviation. Additionally, wind-shear alert systems pertinent to safe operations for arriving/departing aircraft are mandatory for air carrier operations under 14 CFR Part 121.358,[3,16] but again no comparable requirement exists for general aviation. Moreover, major airports serving commercial operators in thunderstorm-prone areas, unlike aerodromes commonly used by general aviation, often are equipped with Terminal Doppler radar or low-level windshear systems[3,29] which can also provide advance warning of windshear. Nevertheless, and notwithstanding a lag period inherent to the weather products, the increasing availability of onboard data-linked weather has provided airmen the ability to determine the location of thunderstorms, allowing for strategic circumnavigation.[12,32]

In view of the aforementioned thunderstorm-associated hazards, the Federal Aviation Authority (FAA) has long advised airmen to maintain a 20-mile separation from convective activity characterized as "extreme" (≥50 dBZ radar reflectivity or echo tops of ≥35,000 ft[18,19]) and to avoid landing or departure in the face of an approaching thunderstorm.[19] Operations ahead (downwind) of an advancing thunderstorm are regarded as more hazardous than those to the rear (upwind) of the convective weather due to the potential of hail and gust fronts.[17–19] With this in mind, the objective of this study was twofold. First, has the thunderstorm accident rate declined over the last two decades? Second, in a prospective analysis of in-flight operations in a thunderstorm environment, did airmen adhere to FAA-recommended separation minima for en route and landing operations?

METHODS

Sources of Data

The National Transportation Safety Board (NTSB) accident database (March 2017 release)[31] was used to identify thunderstorm-related general aviation accidents. Annual fleet flight time used, as denominator, to determine accident rate was obtained from the FAA general aviation survey.[20] NEXt generation RADar (NEXRAD, representing modernization of the U.S. National Weather Service system partly via deployment of WSR-88D Doppler radars across the country[32]) weather data (vertically integrated liquid content, projected storm track, lightning strikes, echo tops) were from the Consolidated Storm Prediction for Aviation web-based application (CoSPA).[10,13] Vertically integrated liquid content was converted to reflectivity values (dBZ) as described elsewhere.[10] Aircraft make/model, flight position (latitude/longitude), ground speed, and altitude were obtained from a commercial source (FlightAware®[20]). Prevailing aerodrome weather data (MEteorological Terminal Aviation routine weather Report) within 10 min prior to the time of aircraft landing [either per the instrument flight rules (IFR) flight plan or the most current at the time of the actual landing] were obtained from either https://mesonet.agron.iastate.edu/request/download.phtml or https://www.aopa.org/airports/.

General Aviation Thunderstorm-Related Accident Rates

To determine general aviation accident rates the NTSB Access database was queried for mishaps occurring over the period spanning 1996–2014 involving aircraft (with 1–2 engines) operating under 14 CFR Part 91 regulations. To restrict the query to thunderstorm-related accidents, the narrative cause was searched for any of the following terms: "thunderstorm," "cumulus," "*convective,*" "inflight breakup," "hail," "heavy rain," "extreme precipitation," "lightning." Data were exported to Excel and records manually inspected to confirm that accidents were thunderstorm-related. Annual fleet flight time for piston-powered aircraft, used as denominator to calculate an accident rate over multiyear periods, represented the sum of fleet time across the time span specified.

Determination of Aircraft Proximity/Relative Position to Extreme Convective Weather

The study period for the prospective analysis of general aviation flight operations conducted under IFR spanned November 1, 2016, through June 9, 2017. All flight operations were during daylight hours, i.e., between the beginning of morning civil twilight and the end of evening civil twilight.[15] The following procedure was used to determine the distance and relative position of aircraft or airport of intended landing to extreme convection. The evening preceding the search, the 48 contiguous states of the United States were checked for areas at elevated risk for convective activity using the Aviation Weather Center website (Convective Outlook product).[33] The following day, the so-identified geographical areas were then manually scanned in CoSPA for extreme convective weather over the course of the day. Note that although the FAA defines 50+ dBZ reflectivity as extreme convection,[19] "bright-banding" phenomena[12] may over-estimate thunderstorm severity. Consequently, a radar reflectivity of 50+ dBZ in conjunction with either the presence of concurrent lighting strikes or echo tops of 35,000 ft or greater was operationally used to define extreme convection herein.

In parallel, U.S.-registered light aircraft (<12,500 lb) operating under IFR whose projected flight path (shown as a dashed line) would, in the future, intersect with the aforementioned extreme convection were identified using FlightAware®.[23] To be included in the study, aircraft had to be a minimum of 50 nmi from convective weather at the time of selection and not be exceeding a ground speed of 180 and 120 kn (en route and during the approach phase, respectively) per FlightAware®. The latter criterion was employed to include a margin of error (see below for explanation). Aircraft operated for paid passenger transportation were excluded on the basis of being identified as "airline" or having a non-N-prefixed registration per FlightAware®. Note that no aircraft was represented more than one time for either en route or arrivals based on its N-registration.

Time-stamped latitude/longitude coordinates (from FlightAware®) of a selected aircraft, at its closest proximity to extreme convective weather, was used to overlay its position on a 6-min delayed CoSPA image, also time-stamped. This procedure was performed to take into account the 4–6 min volume scan of the NEXRAD radar in precipitation mode over the various tilt angles.[32,35] To further reduce the chance of error in determining whether an aircraft had violated the recommended distance from the extreme convection, a 3-min margin of error, converted to distance, was applied as follows. Thus, for aircraft traveling at a maximum of 180 (3 nmi/min en route) and 120 kn (2 nmi/min landing), a 3-min margin of error corresponds to a covered distance of 9 and 6 nmi, respectively, thus reducing the FAA-recommended 20-nmi separation to a more conservative 11 and 14 nmi, respectively. For convenience, the safe distances from extreme convection (inclusive of the aforementioned margin of error) were arbitrarily set at 10 and 14 nmi for en route and arriving aircraft, respectively.

CoSPA images, with the plotted FlightAware® aircraft position, were exported to a vector-based graphics program (CorelDraw v. X7) and a circle, whose center was positioned on the aircraft or landing airport, was constructed with a radius of 10 or 14 nmi for en route and arriving traffic, respectively. Aircraft were defined as violating the FAA-prescribed separation distance if any extreme convective weather (as defined above) lay within the defined circle (**Fig. 1**; solid line).

Thunderstorm-Free Egress Area

For aircraft which operated in contravention to the FAA-recommended separation distance, a lateral area described by a 20-nmi radius circle centered on the airplane was used to identify the surrounding thunderstorm-free airspace. This circle was segmented into 8 × 45° "pie slices." An "egress" (escape) segment was defined as any 45° pie slice absent for reflectivity ≥30 dBZ (Fig. 1; grey solid lines in the top left quadrant of the circle).

Risk Exposure Category

To quantify the level of thunderstorm-related risk for en route and landing aircraft, a metric was constructed using the following dichotomous or ordinal parameters per **Table I**: 1) violation of the FAA-prescribed distance for extreme convection; 2) thunderstorm location relative to the aircraft; and 3) the number of thunderstorm-free egress segments. A risk exposure score (on a scale of 0–6) representing the product of these three measures was then calculated (Table I; column 7). For each flight, one of four risk exposure categories (None, Low, Medium, High) was then assigned based on this score (Table I; Column 8).

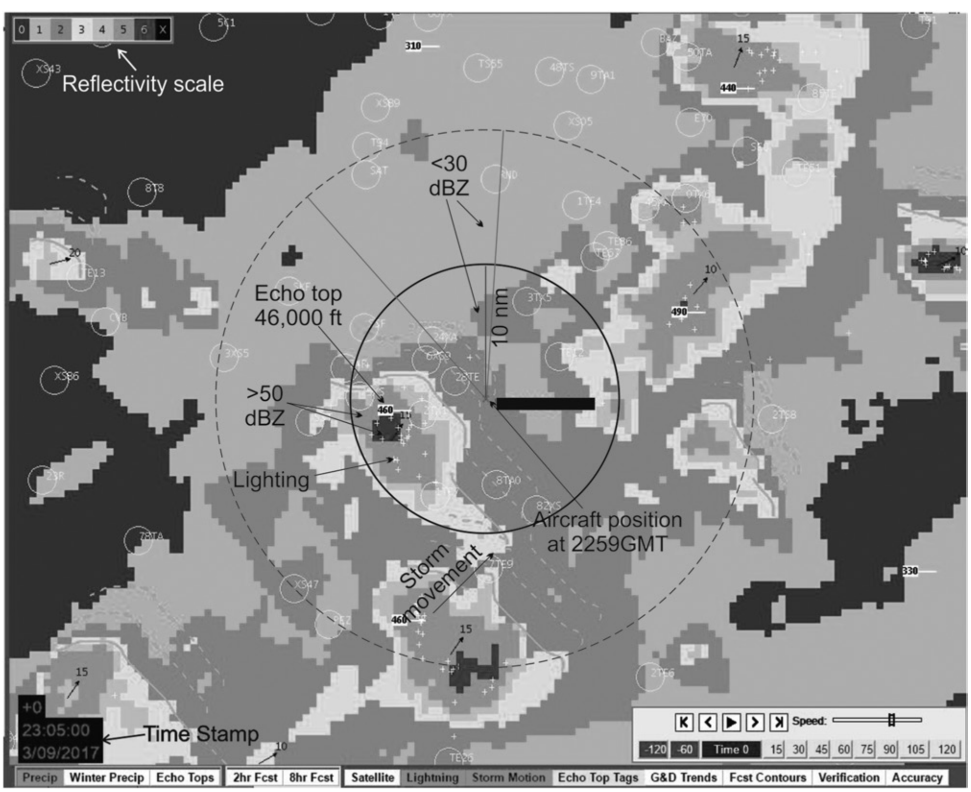

Fig. 1. Visual depiction of measurements and weather phenomena used for aircraft separation from extreme convection. A CoSPA image of extreme convection captured with aircraft position overlaid. The inner ring (solid line), adjusted for a margin of error, describes an area for which en route aircraft adhering to the separation distance prescribed by the FAA should be free of extreme convective weather. The outer ring (dashed line) represents a circle of 20 nmi radius. Reflectivity, echo tops, storm movement, and lightning strikes are shown. Note that the CoSPA image capture is delayed by 6 min to take into account the multiple rotations of the radar at the various tilt angles. Aircraft registration is redacted (black rectangle).

Statistical Analysis

A Poisson probability distribution analysis[11] was used to determine if the thunderstorm-related accident rate changed over time using piston-powered general aviation aircraft fleet times (natural log) as an offset for the respective periods. A Chi-squared test[21] was employed to assess differences in proportions. All statistical analyses were performed using the SPSS program (v. 24; IBM, Armonk, NY).

RESULTS

Thunderstorm-Related Accident Rate

A query of the NTSB aviation accident database indicated a total of 141 thunderstorm-related accidents over the period spanning 1996–2014, an average of 7 mishaps per year. Of these, 71% had a fatal outcome (i.e., at least one occupant perished per

Table I. Description of Risk Exposure Analyses.

COLUMN							
1	2	3	4	5	6	7	8
Violation of FAA Prescribed Distance from Extreme Convection	Assigned Score	Location of Extreme Convection Relative to Aircraft	Assigned Score	Thunderstorm-Free (<30 dBZ) Egress Pie Slice Count	Assigned Score	Risk Exposure Score (0–6)	Risk Exposure Category
Yes	1	Upwind	2	0–2	3	0	None
No	0	Downwind	1	3–5	2	1–2	Low
				6–7 or N/A	1	3–4	Medium
						5–6	High

Each aircraft, at its closest proximity to extreme convective weather, was assigned scores based on: 1) whether the aircraft had violated the FAA-recommended separation distance from extreme convection; 2) the position of the aircraft relative to the thunderstorm; and 3) the number (0–7) of thunderstorm-free egress "pie slices." A risk exposure score, representing the product of these three parameters, was assigned to one of four risk categories (column 8).

accident), substantially higher than the 14–23% cited for non-thunderstorm-related general aviation mishaps.[7,28,34]

The accident rate showed an initial increase (**Fig. 2**) from the earliest (1996–2000) to the subsequent period (2001–2005). However, this increase was not statistically significant per a Poisson rate analysis ($P = 0.083$). Although a decrease was evident thereafter, again, however, using the initial period as referent, this difference was not statistically significant ($P = 0.163$). Additionally, using the 2006–2010 period as referent, the apparent reduction in accident rate for the most recent period was also not statistically significant ($P = 0.155$). Note that 2014 was chosen as the most recent year analyzed since the average time to completion of an NTSB accident investigation is 13 mo.[22] These data indicate that accidents related to convective activity still continue to pose a hazard to general aviation operations.

In-Flight Decision-Making for Enroute Operations

Over the period spanning November 1, 2016–June 8, 2017, 112 en route general aviation flights whose projected IFR route intersected with extreme convection were captured. Regarding thunderstorm circumnavigation, the majority (69%) of aircraft did not observe the FAA-recommended separation distance from extreme convection (**Table II**). Moreover, for aircraft violating the FAA-prescribed distance, 79% were located downwind of the thunderstorm—a region characterized as more hazardous compared with the upwind sector.

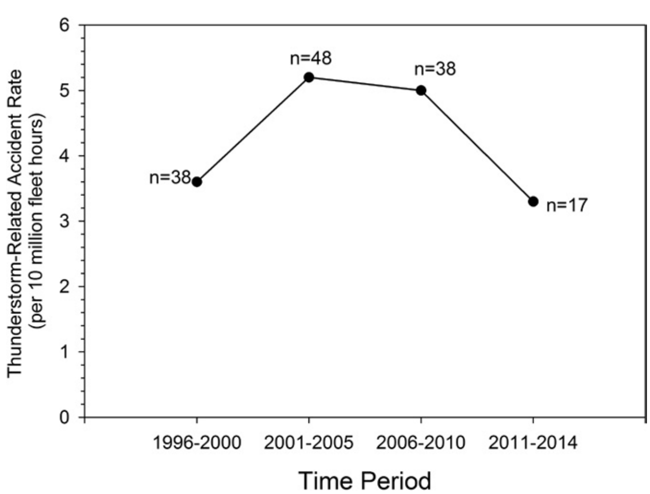

Fig. 2. Thunderstorm-related general aviation accident rate for the period spanning 1996–2014; n: accident count.

In-Flight Decision-Making for Landing Aircraft

Over the identical period, 54 general aviation flights were identified whose projected arrival/landing coincided with extreme convection within the FAA-recommended distance from the airport. Of these, 45 (83%) aircraft landed, whereas the remaining diverted to an alternate airport. For the aircraft which elected to land, 93% operated in contravention with the recommended distance prescribed by the FAA for extreme convection (Table II). Moreover, despite the potential for gust fronts and windshear, of the landing aircraft violating the recommended distance from extreme convection, 69% arrived in the path (downwind) of the advancing thunderstorm.

Risk Exposure for En Route and Landing Operations

An aggregate risk exposure was calculated for en route and landing operations based on whether the recommended distance from extreme convection was compromised, aircraft location relative to the thunderstorm, and the enumeration of thunderstorm-free 45° egress segments (allowing airmen a thunderstorm-free zone of airspace for egress). Based on a metric of these parameters, over 40% of landings were characterized as high risk (**Fig. 3**) compared with one fifth for enroute operations.

Importantly, only a modest proportion of general aviation airmen exercised safe practices with respect to negotiating extreme convection. Thus, 31% (en route) and 7% (landings) of operations were categorized in the "None" risk category. Proportion analysis (χ^2 $P < 0.001$) indicated that airmen were more likely to operate in a thunderstorm-associated high-risk environment for the landing phase compared with en route operations.

DISCUSSION

The study herein demonstrates an undiminished thunderstorm-related general aviation accident rate over the last two decades. Importantly, these types of mishaps carry a high

Table II. Summary of Aircraft Proximity and Location Relative to Extreme Convection.

EN ROUTE				LANDED			
AIRCAFT DISTANCE FROM EXTREME CONVECTION ($N = 112$) LESS THAN FAA-PRESCRIBED DISTANCE		AIRCRAFT < PRESCRIBED DISTANCE FROM EXTREME CONVECTION ($N = 77$), THUNDERSTORM LOCATED UPWIND		AIRCAFT DISTANCE FROM EXTREME CONVECTION ($N = 45$) LESS THAN FAA- PRESCRIBED DISTANCE		AIRCRAFT < PRESCRIBED DISTANCE FROM EXTREME CONVECTION ($N = 42$), THUNDERSTORM LOCATED UPWIND	
N	**%**	***N***	**%**	***N***	**%**	***N***	**%**
77	69	61	79	42	93	29	69

Data collected over the 7-mo period for en route and landing aircraft are summarized; *N*: count.

fatality rate, ranging from 70% (in the current study) to 100%,[26] well in excess of the 14–23% for nonweather related accidents.[25,28] With almost certainty, the unchecked thunderstorm-related accident rate is likely due to a disregard (by design or ignorance) by a subset of general aviation airmen of the FAA-recommended separation distance from extreme convection as well as selection of a route downwind of the approaching thunderstorm.[18,19]

A major question arising is why these recommendations are not adhered to. Several possibilities, as discussed below, exist. The first of these could reflect a limited understanding of thunderstorm hazards, as reported elsewhere.[6,9] A second possibility, considering the increasing availability of onboard data-linked weather, is data misinterpretation.[6,9] A third plausible explanation is human factors[4,36,37] driving the decision-making process.

As to a limited comprehension of thunderstorm dangers, anecdotally, a not uncommon perception among general aviation airmen is that visual separation from convective activity suffices in keeping one out of the "hazard zone." However, convective-induced turbulence may prevail some distance from the thunderstorm and, importantly, in areas of low radar reflectivity.[2,27] Indeed, examples of thunderstorm-related

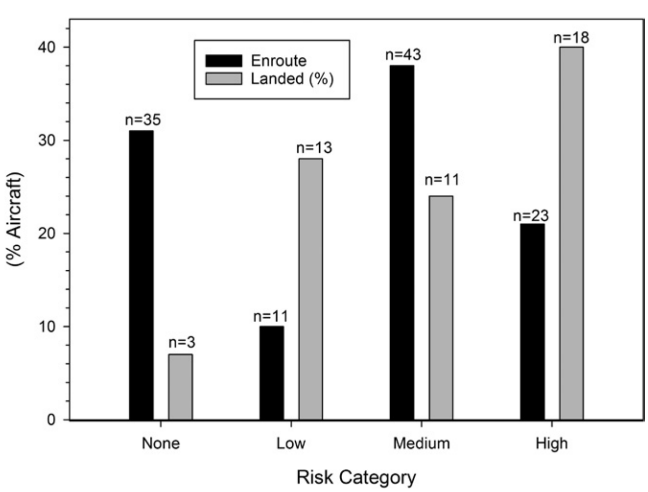

Fig. 3. Summary of risk exposure for en route and landing operations. The percentage of flights within the binned risk exposure category is shown for each phase of operation (en route and landing) over the 7-mo study period. For each phase of operation, the percentage sum across the four risk categories equals 100. n: aircraft count. Risk exposure categories were determined as described in Table I. Proportion analysis was with a 2 × 2 Chi-squared test (None/high risk vs. en route/landing).

accidents illustrate this point. Reconstruction of two recent general aviation thunderstorm-related fatal accidents (NTSB CEN14FA300 and CEN15FA268)[39] demonstrated that in both cases airmen were either visually navigating a route between cloud build-ups or were operating in an area of light precipitation. Control upset due to windshear and structural failure ultimately led to these accidents.[39] As to thunderstorm hazards relating to arriving aircraft, general aviation airmen may also be unaware that automated surface observation systems[30] located at the airport of intended landing are incapable of windshear detection. In contrast, a low-level windshear detection system and/or Doppler radar[3,29] are commonly installed at major airports serving air carriers, not to mention the requirement for comparable equipment on transport category aircraft.[16] Another misconception is that the 20-nmi prescribed limit simply reflects an arbitrary, conservative value chosen by the FAA. However, this separation distance is rooted in sound scientific observations. Eddy dissipation rate studies have demonstrated that moderate or greater turbulence, generated by horizontally propagating gravity waves, can be elevated over 20 nmi from visible storms.[27]

The current study did not evaluate the extent to which onboard data-linked weather was used for weather circumnavigation. However, the increased accessibility of NEXRAD products (radar reflectivity, lightning strikes, echo tops) and associated hardware, commonly with a distance measurement scale, is well recognized for this aviation sector. Indeed, near real-time weather (due to the ~6-min delay associated with completion of multiple radar tilt angles) has proven efficacious in improving weather awareness[1] for general aviation pilots, albeit in a flight simulated environment. If indeed such weather products were used, a second plausible explanation for the infringement of the thunderstorm hazard zone could lie in the inadequate interpretation of such data coupled with their inappropriate usage for tactical (rather than strategic) avoidance.[6,9] Conversely, the possibility that at least a subset of flights captured in the current study lacked weather data/equipage must be entertained. The author is unaware of published data on usage of onboard weather data by general aviation pilots. Therefore, in instances where airmen lack such in-flight information, estimating separation distances between aircraft and convective weather could prove difficult. That said, en route air traffic control (ATC) are capable (all IFR operations are mandated to be in communication with ATC) of providing at least a distance estimate upon request.

Human factors may also contribute to the decision of general aviation airmen to violate the prescribed separation distance from extreme convection. In a web-based questionnaire conducted by the FAA,[24] it was shown that risk-tolerant pilots elected to navigate through increasingly shorter gaps between two thunderstorms compared with their less risk-tolerant counterparts. In addition, the opportunity for financial gain can also weigh in on the decision of the general aviation pilot to negotiate adverse weather.[38] Finally, the disproportionate number of landing operations categorized as high risk compared with those for the en route phase echoes previous findings showing that airmen are more likely to complete a flight after the midpoint.[4,37]

This study was not without limitations. For example, only IFR-general aviation traffic was studied, reflecting the flight-tracking source (FlightAware®) not tracking visual flight rules (VFR) operations. A second limitation was that pilots who elected not to depart due to forecast convective weather would have escaped capture in the present research. Third, in a few cases airmen cancelled their IFR flight plan en route and may have diverted under VFR to an airport unaffected by thunderstorms, maintaining, at all times, a safety zone per the FAA-recommended distance. Such cases were, therefore, lost (since FlightAware® does not track VFR aircraft). The consequence of the latter in our analyses would be to decrease the count of airmen who, in fact, were adhering to the FAA-recommended distances, thereby artificially yielding a higher percentage of aircraft infringing the hazard zone. Fourth, the flight experience (total flight time) of the airmen involved was not determined. This could be relevant since a previous study reported that a higher flight time increased the probability of an adverse weather encounter (albeit VFR to IFR),[36] while a separate investigation identified greater experience as a risk factor for a fatal accident.[5] Finally, the imprecise nature of radar (due to the time for a single 360° sweep) in determining aircraft location necessitated the inclusion of a margin of error, thus precluding an analysis of varying distance from extreme convection as a risk factor. However, such a study is warranted in the future with a shift to the more precise satellite-based system for U.S. air traffic control planned for the year 2020.

In conclusion, the overwhelming majority of general aviation pilots operating in an IFR environment intrude into potentially hazardous areas of extreme convection in contravention to FAA-recommended separation distances. Such unsafe practices presumably are a major contributing factor to the undiminished thunderstorm-related general aviation accident rate evident over the past two decades. These findings advocate the wide dissemination of training courses on thunderstorm hazards and avoidance strategies[6,9] for both the ab initio airman as well as those engaged in recurrency training in geographical areas prone to such adverse weather. Importantly, such training should emphasize knowledge on the hazards of windshear and the paucity of corresponding weather data relevant to arriving and departing aircraft at the majority of airports serving general aviation.

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Author and affiliation: Douglas D. Boyd, Ph.D., Retired, GSBS, University of Texas, Houston, TX.

REFERENCES

1. Ahlstrom U, Ohneiser O, Caddigan E. Portable weather applications for general aviation pilots. Hum Factors. 2016; 58(6):864–885.
2. Ahmad N, Proctor F. Large eddy simulations of severe convection induced turbulence. Reston (VA): American Institute of Aeronautics and Astronautics; 2011.
3. Airbus, adverse weather operations: windshear awareness. [Accessed Jan. 2016]. Available from https://skybrary.aero/bookshelf/books/164.pdf.
4. Batt R, O'Hare D. Pilot behaviors in the face of adverse weather: a new look at an old problem. Aviat Space Environ Med. 2005; 76(6):552–559.
5. Bazargan M, Guzhva VS. Impact of gender, age and experience of pilots on general aviation accidents. Accid Anal Prev. 2011; 43(3):962–970.
6. Blickensderfer EL, Lanicci JM, Vincent MJ, Thomas RL, Smith MJ, Cruit JK. Training general aviation pilots for convective weather situations. Aerosp Med Hum Perform. 2015; 86(10):881–888.
7. Boyd DD. General aviation accidents related to exceedance of airplane weight/center of gravity limits. Accid Anal Prev. 2016; 91:19–23.
8. Boyd DD. A review of general aviation safety (1984–2017). Aerosp Med Hum Perform. 2017; 88(7):657–664.
9. Cobbett EA, Blickensdorfer EL, Lanicci JM. Evaluation of an education/training module to foster knowledge of cockpit weather technology. Aviat Space Environ Med. 2014; 85(10):1019–1025.
10. Crowe BA, Mills WD. The benefits of using NEXRAD vertically integrated liquid water as an aviation weather product. Proceedings of the 8th Conference on Aviation, Range, and Aerospace Meteorology; 10-15 January, 1999; Dallas, TX. Boston (MA): American Meteorological Society; 1999.
11. Dobson AJ, Barnett AG. Poisson regression and log-linear models. In: Carlin BP, Faraway JJ, Tanner M, Zidek Jan. Introduction to generalized linear models. Texts in Statistical Science Series; 3(9):165–171. Boca Raton (FL): Chapman and Hall/CRC; 2008.
12. Duda J. How to use and interpret Doppler weather radar. [Accessed 10-22-2016]. Available from http://www.d4n.nl/files/docs/How%20to%20read%20and%20interpret%20weather%20radar.pdf.
13. Dupree W, Morse D, Chan M, Tao X, Iskenderian H, et al. The 2008 CoSPA Forecast Demonstration (Collaborative Storm Prediction for Aviation). ARAM Special Symposium on Weather-Air Traffic; January 2009; Phoenix, AZ. Boston (MA): American Meteorological Society; 2009.
14. Electronic Code of Federal Regulation. General operating and flight rules. 2015. [Accessed Oct. 2015]. Available from https://www.ecfr.gov/cgi-bin/text-idx?node=14:2.0.1.3.10.
15. Electronic Code of Federal Regulation. Definitions and abbreviations. 2017. [Accessed June 2017]. Available from https://www.ecfr.gov/cgi-bin/text-idx?SID=c35945ba15391aa67d353624f324f09d&mc=true&node=se14.1.1_11&rgn=div.
16. Electronic Code of Federal Regulation. Low-Altitude Windshear System Equipment Requirements. 2017. [Accessed Jun, 2017]. Available from https://www.ecfr.gov/cgi-bin/text-idx?SID=8ff829dfb88994c67fef346d2b7e4932&mc=true&node=pt14.3.121&rgn=div5#se14.3.121_1358.
17. Federal Aviation Administration. Pilot windshear guide. AC 00-54, 1-64. Washington (DC): U.S. Department of Transportation; 1988.

18. Federal Aviation Administration. Thunderstorms- don't flirt…skirt 'em. FAA-P-8740-12, 1–6. Washington (DC): U.S. Department of Transportation; 2008.
19. Federal Aviation Administration. Thunderstorms. AC 00-24C. Oklahoma City (OK): U.S. Department of Transportation Federal Aviation Administration; 2013.
20. Federal Aviation Administration. General aviation and part 135 activity surveys. [Accessed Jan. 2017]. Available from http://www.faa.gov/data_research/aviation_data_statistics/general_aviation.
21. Field A. Discovering statistics using IBM SPSS Statistics, 3rd edition. Thousand Oaks (CA): Sage Publications; 2009.
22. Fielding E, Lo AW, Yang JH. The National Transportation Safety Board: a model for systemic risk management. Journal of Investment Management. 2011; 9:17–49.
23. Flight Aware. [Accessed Nov. 2016–June 2017]. Available from http://flightaware.com/.
24. Hunter DR. Risk perception and risk tolerance in aircraft pilots. AM-02/17. Oklahoma City (OK): U.S. Department of Transportation, Federal Aviation Administration; 2002.
25. Kenny D. 24th Joseph T. Nall Report. Frederick (MD): Air Safety Foundation, AOPA; 2015.
26. Kenny D. 25th Joseph T. Nall Report. General aviation accidents in 2013. Frederick (MD): Air Safety Foundation, AOPA; 2016.
27. Lane TP, Sharman RD, Trier SB, Fovell RG, Williams JK. Recent advances in the understanding of near-cloud turbulence. Bulletin of the American Meteorological Society. 2012; 93(4):499–515.
28. Li G, Baker SP. Crash risk in general aviation. JAMA. 2007; 297(14): 1596–1598.
29. National Centers for Environmental Information. Terminal Doppler weather radar. [Accessed Dec. 2016]. Available from https://www.ncdc.noaa.gov/data-access/radar-data/tdwr.
30. National Oceanic and Atmospheric Administration. Automated Surface Observing System. 1998. [Accessed Aug. 2001]. Available from www.nws.noaa.gov/asos/aum-toc.pdf.
31. National Transportation Safety Board. NTSB Accident Database. [Accessed Oct. 2015]. Available from http://app.ntsb.gov/avdata/Access/.
32. National Weather Service. Doppler radar. [Accessed Oct. 2016]. Available from http://www.srh.noaa.gov/jetstream/doppler/doppler_intro.html.
33. National Weather Service. Aviation Weather Center-convective outlook. [Accessed Nov. 2016–June 2017]. Available from https://www.aviationweather.gov/convection.
34. Neuhaus C, Dambier M, Glaser E, Schwalbe M, Hinkelbein J. Probabilities for severe and fatal injuries in general aviaton accidents. J Aircr. 2010; 47:2017–2020.
35. NOAA. Jetstream max: volume coverage patterns (VCPs). [Accessed Feb. 2017]. Available from http://www.srh.noaa.gov/jetstream/doppler/vcp_max.html.
36. O'Hare D, Hunter DR, Martinussen M, Wiggins M. Classification and prediction of pilot weather encounters: a discriminat function analysis. Aviat Space Environ Med. 2011; 82(5):543–549.
37. O'Hare D, Owen D. Cross-country VFR crashes: pilot and contextual factors. Aviat Space Environ Med. 2002; 73(4):363–366.
38. Pauley K, O'Hare D, Wiggins M. Risk tolerance and pilot involvement in hazardous events and flight into adverse weather. J Safety Res. 2008; 39(4):403–411.
39. Vasquez T. Stormy encounters. IFR. 2017; 2017(April):20–22.