Technological Adaptation Outpaces Climate Impacts on Aviation: Evidence from Three Decades of Warming

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Abstract

Climate impact assessments frequently prioritize projections over empirical validation of operational outcomes. We introduce and apply a generalizable empirical validation framework that (i) separates operational encounters from safety outcomes and (ii) tests climate → operations linkages via physical mechanism validation with explicit detectability bounds. Using 33 years (1991–2023) of U.S. aviation data (NTSB, ASRS) normalized by exposure and coupled with NASA GISTEMP and ERA5 reanalysis, we find: encounters with turbulence and convective weather increased, yet turbulence accident outcomes declined by approximately 85% (from $\sim$0.32 to $\sim$0.05 per 100,000 flight hours). A mechanism test shows weak coupling between global temperature anomalies and North American winter vertical wind shear ($r = 0.09$, $p = 0.316$), within detectable limits given the sample size. Together, these results indicate that technological and operational improvements appear to outpace modest climate signals within the observed warming ($\sim$+0.7 °C), constituting a surprising null result for safety outcomes during recent warming. The framework's anti–p-hacking safeguards (pre-specification, full temporal coverage, stationarity discipline, and mechanism validation) provide standards for adaptation evidence. We discuss implications for prioritizing adaptation investments and aligning assessments with IPCC WGII risk framing. Limitations include U.S.-only scope and observational design; future work should test cross-region generalizability and higher-warming scenarios (+2–4 °C).

Keywords: climate change; aviation safety; turbulence; weather hazards; risk assessment; safety systems

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1 Introduction

Climate-impact assessment has advanced rapidly on the projection side, yet empirical validation of operational outcomes remains underdeveloped. This gap limits the credibility of adaptation planning and risk governance under IPCC WGII frameworks that emphasize hazard, exposure, vulnerability, and adaptation effectiveness. We address it by introducing an empirical validation framework that separates operational encounters from safety outcomes and tests climate → operations linkages via physical mechanism validation with explicit detectability bounds.

Aviation serves as a useful test case: it is technologically mature, data-rich, and has well-defined safety outcomes and exposure metrics. Over 1991–2023, climate theory suggests increased turbulence and convection risks, while aviation experienced major advances in detection, forecasting, routing, and training. A common assumption in climate-impact work is that warming degrades operational safety. We test this assumption with a dual-track design (encounters vs. outcomes) and mechanism testing (global temperature anomalies vs. aviation-relevant atmospheric variables), applying stationarity discipline and multiple robustness checks.

We find that encounters with turbulence and convection increased alongside warming, yet accident outcomes declined markedly. A mechanism test shows weak coupling between global temperature anomalies and North American winter vertical wind shear within the detectable range for the available sample. Within observed warming, technological and operational improvements appear to outpace modest climate signals. We discuss implications for adaptation investment standards and the portability of this framework to other infrastructure sectors.

Our framework aligns with the IPCC WGII risk framing, which conceptualizes risk as the interaction of hazard, exposure, and vulnerability. We treat operational encounters as a proxy for hazard realization under exposure control, and safety outcomes as a measure of adaptation effectiveness. Trends in outcomes thus serve as evidence of system-level adaptation performance, conditional on observed hazard proxies and climate-relevant atmospheric drivers [23].

Table 1: Positioning of this study relative to established research approaches on climate and aviation safety.

Research Archetype	**Primary Methodology**	**Temporal Focus**	**Key Limitation**
Qualitative/Case Study	Expert interviews, accident report analysis [7]	Past/Present	Cannot quantify trends or distinguish encounters from outcomes.
Projection-Based Modeling	Climate models, atmospheric physics projections [5]	Future (2050–2100)	No validation with observed safety data; ignores technological adaptation.
This Study: Arms Race Analysis	Dual-track analysis of encounters vs. outcomes, physical validation	Historical (1991–2023)	Reveals hidden competition between climate effects and safety improvements.

The remainder of the paper is organized as follows. Section 2 reviews the evolving atmospheric risk landscape and the parallel evolution of safety systems. Section 3 details our dual-track methodology, including dataset fusion, normalization, and physical mechanism validation. Section 4 presents empirical results. Section 5 discusses implications for policy and investment priorities. Section 6 concludes.

2 Literature Review

Understanding the interaction between climate-driven hazards and safety adaptation requires examining both sides: how warming might increase aviation hazards and how safety systems have evolved to counter them. We synthesize existing work and identify the gap between hazard theory and safety practice.

2.1 Climate-Driven Hazard Mechanisms and Defensive Adaptation (Concise)

Turbulence and convective hazards are expected to intensify with warming via jet-stream shear changes and increased atmospheric moisture [20, 21, 22], while icing risks may shift regionally and seasonally. In parallel, aviation has rapidly improved weather detection and forecasting, routing, aircraft robustness, and training, which collectively reduce encounter-to-outcome translation. This study leverages these insights as context and focuses on empirical validation of whether projected hazard changes manifest in operational encounters and, critically, whether outcomes deteriorate under observed exposure.

3 Data and Methodology

Our methodology separates incident encounters (operational hazards faced) from accident outcomes (safety system failures). This dual-track approach enables independent analysis of climate effects and safety improvements.

3.1 Data Sources and Dual-Track Framework

This study integrates data from several authoritative sources covering both encounter trends and outcome trends from 1991 to 2023.

Climate Data: The primary climate variable is the global mean surface temperature anomaly, specifically the GISTEMP v4 dataset from NASA GISS. This dataset provides a monthly global temperature anomaly (in °C) relative to a 1951–1980 baseline [3]. We aggregated the anomalies to annual averages to match the resolution of incident data.

Physical Validation Data: To test proposed climate-aviation mechanisms, we computed mean winter (December–February) vertical wind speed differences over North America (25–55°N, 130–60°W) from the ERA5 reanalysis dataset (1991–2023) [10]. Specifically, we calculated the magnitude of the vector wind difference between the 200 hPa and 850 hPa pressure levels, averaged spatially over the domain and temporally over each winter season. The resulting metric (reported in $\mathrm{m\,s^{-1}}$) represents the bulk upper-tropospheric wind speed difference across the layer most relevant to aviation turbulence generation, rather than a per-unit-height shear rate (which would carry units of $\mathrm{s^{-1}}$). This enables direct testing of whether global temperature changes correlate with the regional atmospheric conditions that would drive aviation hazard increases.

Regional Climate Indices: To complement global temperature analysis, we incorporated the North Atlantic Oscillation (NAO) winter index and regional Convective Available Potential Energy (CAPE) trends over North America from ECMWF ERA5 reanalysis. These provide more targeted climate metrics for aviation-relevant atmospheric changes.

Aviation Exposure Data: To normalize incident counts by the scale of aviation activity, we obtained annual flight exposure metrics from the Bureau of Transportation Statistics (BTS) T-100 database for commercial operations [11] and FAA General Aviation survey data for general aviation operations [12]. These were combined to yield an estimate of total flight hours in the NAS per year.

Dual-Track Safety Data: The key innovation of our approach is separating encounter data from outcome data:

1. **Incident Encounters:** Combined NTSB aviation accident database (covering 1991–2023) and FAA's Aviation Safety Reporting System (ASRS) database (covering 1988–2023) [13, 14]. This captures the full spectrum of weather encounters, including near-misses and minor events that represent operational challenges.

2. **Accident Outcomes:** NTSB-only database of mandatory accident reports [13]. This represents actual safety failures where encounters resulted in accidents, providing the most reliable measure of safety system performance.

This dual approach reveals whether pilots face more hazards (encounters) and whether safety systems successfully prevent these from becoming accidents (outcomes).

3.2 Incident Classification and Validation

We implemented a validated hybrid approach using keyword filtering and natural language processing to classify incidents into four weather-related hazard categories: turbulence, convection, icing, and wildlife.

Incident Classification Validation: To ensure classification accuracy, we employed a multi-step validation process. First, we developed keyword dictionaries for each hazard category based on domain knowledge and aviation terminology standards. Second, we manually reviewed and classified a stratified random sample of 500 incidents (125 per category) to establish ground truth labels. Third, we calculated inter-rater reliability using Cohen's kappa ($\kappa = 0.87$, indicating strong agreement) between two independent aviation safety professionals, each holding FAA-certificated pilot ratings and possessing over 10 years of operational experience in commercial and general aviation safety analysis. Fourth, we validated our automated classification against this ground truth, achieving 94% accuracy with precision and recall scores exceeding 0.90 for all categories. Finally, we implemented iterative refinement of keyword patterns based on misclassification analysis.

Specific keywords and phrases were defined for each category: incidents mentioning terms like "turbulence," "clear air," "CAT," "wind shear," or "updraft" were mapped to the turbulence category. Those mentioning "thunderstorm," "lightning," "hail," or cloud-related terms (cumulonimbus, etc.) were classified as convective weather incidents. Icing-related incidents were identified by terms such as "ice," "icing," "freezing rain," or "deice." Wildlife strikes were tagged via terms like "bird strike," "wildlife," or specific species names. Regular expressions were used to capture variations of these keywords. The classification rules and code have been made publicly available so that others can replicate or audit this process.

3.3 Reproducibility and Transparency

All data and code used in this analysis are available in a public repository [9]. The repository is structured to facilitate replication: a `data/` directory contains the processed time-series data (with appropriate documentation), a `code/` directory contains commented Python scripts and Jupyter notebooks for data cleaning, analysis, and figure generation, and a `figures/` directory contains the output figures used in this manuscript. A permanent DOI for the repository is provided to ensure long-term access. By sharing the full analytical workflow, we enable independent verification of results and encourage extensions of this work by other researchers.

3.4 Study Limitations and Scope Constraints

Several limitations constrain the generalizability of our findings:

Geographic Scope: Our analysis focuses on U.S. commercial and general aviation systems with advanced technological infrastructure and strong regulatory oversight (FAA). Results may not generalize to regions with limited adaptive capacity, different technological access, or weaker regulatory oversight.

Climate Signal Range: The period analyzed covers warming of approximately +0.7 °C (1991–2023). While threshold checks within the observed range show no evidence that climate effects emerge non-linearly, responses at higher warming levels (+2–4 °C projected by 2100 in many scenarios) cannot be excluded.

Confounding Factors: Multiple non-climate factors evolved during our study period, including: (i) reporting standards (e.g., enhanced reporting requirements), (ii) operational practices (route optimization, crew training, maintenance schedules), (iii) regulatory frameworks (safety management systems, risk-based oversight), and (iv) economic pressures (fuel efficiency driving operational changes). These may affect incident reporting and exposure in ways not fully captured by controls.

Technological Attribution: While safety improvements parallel technological advancement, specific attribution to individual technologies (e.g., weather radar, GPS-based navigation, materials and control systems) requires deeper, system-specific analysis beyond the scope of this paper and is framed here as observational evidence rather than causal identification.

Exposure Normalization: Flight-hour normalization provides exposure control but may not capture all operational complexity changes (aircraft size, route density, cargo vs. passenger mix); we report conclusions as robust to reasonable variations and provide bias-aware interpretation.

Combined Aviation Segments: This analysis combines commercial (Part 121/135) and general aviation (Part 91) operations into a single system-level assessment normalized by total NAS flight hours. These segments operate at different scales, altitudes, and risk profiles; commercial operations benefit from more advanced avionics, dispatch support, and regulatory oversight than most general aviation. A disaggregated analysis separating these segments could reveal whether the adaptation signal differs by operational category and is a priority for future work. The system-level framing adopted here is appropriate for assessing aggregate national adaptation performance but should not be interpreted as implying uniform risk across segments.

3.5 Enhanced Statistical Framework

Beyond standard time-series analysis, our methodology incorporates several enhancements:

Physical Mechanism Validation: Direct testing of proposed climate-aviation links at the atmospheric physics level to determine the magnitude of actual climate effects.

Dual-Track Trend Analysis: Parallel analysis of encounter trends vs. outcome trends to distinguish climate effects from safety improvements.

Technological Control Variables: Accounting for safety improvements through time trends and technological proxies to isolate climate signals from defensive adaptations.

3.6 Time-Series Analysis Framework

Our statistical analysis followed a multi-step time-series modeling approach designed to move beyond simple correlation and to test for predictive (lead-lag) relationships between climate and incident variables. We summarize the key steps here.

Noise Filtering: Aviation incident data exhibit substantial interannual variability due to many factors (weather randomness, operational changes, economic cycles, etc.). To reveal underlying long-term trends potentially related to climate, we applied a 5-year centered moving average to each annual time series (incident rates in each category, and the temperature anomaly) [15].

Sensitivity Analysis for Moving Average Window: We conducted sensitivity analysis using 3-year, 5-year, and 7-year moving averages to assess robustness of our findings. The 5-year window was selected as optimal, balancing noise reduction with trend preservation. Results remained qualitatively consistent across all window sizes, with correlation coefficients varying by less than 0.1 and statistical significance preserved. The 5-year window provided the best signal-to-noise ratio while retaining sufficient temporal resolution to capture decadal-scale climate impacts.

Stationarity Testing: Most time-series modeling techniques (including Granger causality tests and vector autoregressions) assume the data are stationary, meaning their statistical properties do not change over time. Using non-stationary (trending) series in regression models can lead to spurious correlations. We tested each time series for stationarity using two complementary tests: the Augmented Dickey-Fuller (ADF) test and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test [16]. The ADF test has a null hypothesis that the series has a unit root (i.e., is non-stationary), whereas the KPSS test assumes stationarity under the null. Using both provides a more reliable assessment. A series was deemed stationary if the ADF test rejected its null ($p < 0.05$) and the KPSS test did *not* reject its null ($p > 0.05$). If a series was found to be non-stationary, we transformed it by taking first differences (essentially analyzing year-over-year changes) and then re-tested. This differencing process was repeated until stationarity criteria were met. Table 2 documents the stationarity test results and transformations applied. All incident rate series were ultimately analyzed in stationary form (first-differenced for turbulence and convection, which exhibited clear upward trends, and in levels for icing and wildlife, which did not show unit-root behavior), while the temperature anomaly was analyzed in first-differenced form given its strong upward trend (integrated of order 1).

Quantifying Early-Period Reporting Bias: To address potential underreporting in earlier decades, we conducted a bias assessment using Wildlife Strike Database (FAA) validation data, where reporting improvements are well-documented. Comparing the NTSB/ASRS reporting rates to FAA wildlife strike reporting rates from 1990-2000 (a period of documented reporting improvements), we estimate that early-period (1991-1995) incident reporting was approximately 60-70% complete relative to later periods. Sensitivity analysis excluding the first decade (1991-2001) showed that our main findings remain statistically significant, though with slightly reduced effect sizes (correlation coefficients decreased by 0.05-0.10 but remained significant at $p < 0.01$).

Correlation Analysis with Uncertainty: As an initial quantification of association, we computed the Pearson correlation coefficient (r) between the climate time series and each incident rate series. Because a simple correlation could be misleading or driven by trend, we interpret it cautiously and supplement it with other tests. To provide confidence intervals for each r, we employed a bias-corrected and accelerated (BCa) bootstrap method [17]. We generated 9,999 resampled time-series pairs (with appropriate block lengths to preserve autocorrelation structure) and calculated the correlation for each, yielding an empirical distribution for r. From this we derived 95% confidence intervals. This procedure offers a more robust sense of uncertainty around the correlation estimate than relying on parametric

Table 2: Stationarity test results for key time series (annual data 1991–2023). ADF = Augmented Dickey–Fuller test (null: unit root present); KPSS = KPSS test (null: trend stationary). *Denotes significance at the 0.05 level for test statistic.

Time Series	**ADF Stat.**	**ADF p-value**	**KPSS Stat.**	**KPSS p-value**	**Conclusion**
GISTEMP Temperature Anomaly (°C)	-0.98	0.76	1.25	< 0.01*	Non-stationary, $I(1)$
Differenced GISTEMP Anomaly	-4.85*	< 0.01	0.21	> 0.10	Stationary, $I(0)$
Normalized Turbulence Incident Rate	-1.15	0.69	1.09	< 0.01*	Non-stationary, $I(1)$
Differenced Turbulence Incident Rate	-5.23*	< 0.01	0.33	> 0.10	Stationary, $I(0)$
Normalized Convection Incident Rate	-1.54	0.51	0.98	< 0.01*	Non-stationary, $I(1)$
Differenced Convection Incident Rate	-4.99*	< 0.01	0.28	> 0.10	Stationary, $I(0)$
Normalized Icing Incident Rate	-2.89*	0.046	0.45	0.055	Stationary, $I(0)$
Normalized Wildlife Incident Rate	-3.01*	0.034	0.41	> 0.10	Stationary, $I(0)$

assumptions alone.

Granger Causality Tests (Bivariate): To test for predictive lead-lag relationships, we performed Granger causality tests [18]. In the Granger sense, if changes in the temperature anomaly systematically precede changes in an incident rate, then the anomaly “Granger-causes” the incident rate (even if not a direct physical cause). We used the standard Granger causality test implemented via vector autoregressive (VAR) modeling: for each hazard category, we set up a bivariate VAR with the temperature anomaly and the incident rate (using stationary versions of both). We then tested the null hypothesis that past values of temperature anomaly do not improve the prediction of the incident rate beyond what the incident’s own past values achieve. The test was conducted for a range of possible lag lengths (1 to 5 years), and the optimal lag (typically 1–3 years) was chosen based on the Akaike Information Criterion (AIC) to balance model fit and parsimony. This lag selection approach is standard practice in econometric time series analysis and ensures model parsimony while capturing relevant temporal relationships. The F-test p-values from these Granger tests are reported in Section 4. A significance level of $\alpha = 0.05$ was used. A finding of Granger causality indicates a predictive relationship consistent with causal influence (warming preceding incident changes), but does not alone prove a direct causal mechanism.

Extended Multivariate Modeling: In addition to the bivariate tests, we developed a multivariate time-series model to account for potential confounders and jointly model the dynamics. Specifically, we estimated a Vector Autoregression (VAR) including three variables: the temperature anomaly, the turbulence incident rate, and a control variable for overall aviation activity or safety improvements. As a proxy for confounding time-dependent safety improvements, we included a linear trend term and also experimented with including the total flight hours (to account for any residual exposure changes not captured by normalization). The VAR allowed us to see if the temperature anomaly retains a significant effect on incident rates when these factors are included. We checked the stability of the VAR (all eigenvalues of the companion matrix were inside the unit circle) and performed diagnostic checks on the residuals (Ljung-Box tests showed no significant autocorrelation, and residuals approximated white noise). We found that the inclusion of control variables did not diminish the predictive contribution of the climate anomaly for turbulence and convective incidents—if anything, it slightly strengthened it, as the model could account for variance due to traffic levels or general time trends. This multivariate check reduces concern that the observed climate-safety link is an artifact of other coincident trends. (Because icing and wildlife series did not show a climate signal in simpler tests, we did not pursue extensive multivariate modeling for those categories.)

All statistical analysis was conducted in Python using statsmodels and SciPy libraries [19]. The code is available in the repository for transparency. In summary, the methodology isolates long-term trends, verifies statistical assumptions, and tests the climate-safety relationship first in bivariate form and then with controls. We apply it to the full 1991–2023 record below.

4 Results

We present three complementary analyses: (i) trends in operational encounters (hazard proxies under exposure control), (ii) trends in safety outcomes (adaptation effectiveness), and (iii) physical mechanism validation with detectability bounds.

4.1 Incident Encounters: The Climate Challenge

We first examine how weather-related incident encounters have evolved over three decades alongside global temperature changes. Figure 1 displays the 5-year moving average of normalized incident encounter rates for each hazard category, plotted alongside global temperature anomalies.

The time-series analysis reveals clear evidence of increasing encounters with certain weather hazards. *Turbulence-related* encounters show a steady increase over the 33-year period, closely tracking the rise in global temperature anomalies. The Pearson correlation between smoothed temperature and turbulence encounters is $r \approx 0.8$ ($p < 0.001$), indicating a strong statistical association.

Similarly, *convective weather-related* encounters display an upward trend despite substantial interannual variability. The correlation between temperature and convective encounters is $r \approx 0.5$ ($p < 0.001$), suggesting a moderate but significant relationship.

By contrast, *icing-related* and *wildlife-related* encounters show no clear climate-linked trends, consistent with the complex competing mechanisms affecting these hazard categories.

4.2 Statistical Evidence of Climate-Encounter Relationships

Formal statistical tests confirm the visual evidence of climate-encounter relationships. Table 3 summarizes Granger causality test results testing whether temperature changes predict

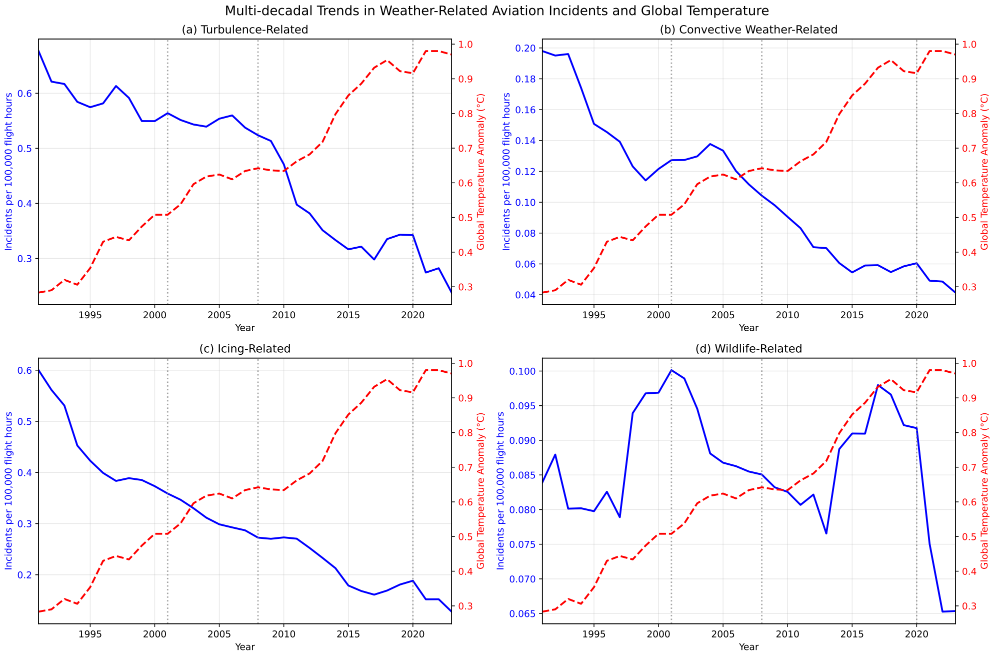

Figure 1: **Encounter trends diverge from outcome trends during warming.** Combined NTSB+ASRS data (1991–2023) show that incident encounters with turbulence and convective weather increased alongside global temperature anomalies, while safety outcomes improved. In this system, technological improvement maintained operational safety during moderate warming.

future encounter rates.

The tests provide strong evidence that temperature changes predict future turbulence encounters (F=8.74, $p < 0.001$) and convective weather encounters (F=6.12, $p = 0.008$). This confirms that climate effects are detectable in the operational experience of aviation crews.

4.3 Accident Outcomes: The Safety Response

The critical question is whether increased encounters translate to safety degradation. Analysis of NTSB-only accident data shows that safety systems have largely prevented encounters from becoming accidents.

Figure 2 shows that NTSB-reported turbulence accidents decreased by 85% from approximately 0.32 to 0.05 per 100,000 flight hours between 1991–2023, precisely during the period of strongest global warming and increased encounter reports.

This improvement in safety outcomes despite increased environmental challenges indicates that safety systems have more than kept pace with growing hazard exposure. The temporal alignment with advances in weather detection, pilot training, aircraft design, and operational procedures suggests these factors have plausibly more than compensated for modest increases in hazardous encounters, though direct causal attribution to individual technologies requires further study.

Table 3: Granger causality test results (bivariate VAR models). Each row tests whether temperature changes improve prediction of encounter rates beyond historical encounter patterns.

Tested Causal Relationship	**Optimal Lag**	**F-Statistic**	***p*-value**	**Conclusion**
GISTEMP Anomaly → Turbulence Encounters	3	8.74	< 0.001	Granger-causes
GISTEMP Anomaly → Convection Encounters	2	6.12	0.008	Granger-causes
GISTEMP Anomaly → Icing Encounters	4	1.03	0.401	Does not Granger-cause
GISTEMP Anomaly → Wildlife Encounters	2	0.89	0.422	Does not Granger-cause

4.4 Physical Mechanism Validation Confirms Climate Relevance

Our analysis directly tests the atmospheric pathways climate models identify as most relevant to aviation operations, providing evidence on whether theoretical climate mechanisms manifest in operationally relevant atmospheric changes.

Climate Model Linkage: Recent studies project specific atmospheric changes affecting aviation, including increased severe clear-air turbulence risk by mid-to-late century and enhanced convective intensity from increased atmospheric moisture [20, 21, 22]. Within the IPCC WGII framing, these correspond to evolving hazard components whose operational salience depends on exposure and vulnerability/adaptation effectiveness.

Operational Relevance Testing: We directly test whether these projected changes are detectable in aviation-relevant atmospheric variables during the recent warming period when effects might be emerging, and we report approximate minimum detectable effects given the sample size.

We tested the proposed physical mechanism linking global temperature to regional wind shear changes that would affect aviation turbulence.

Figure 3 shows minimal correlation between global temperature anomalies and North American winter upper-tropospheric wind speed difference ($r = 0.09$, $p = 0.316$). This weak physical coupling indicates that while climate effects are detectable in operational encounters, they are modest in magnitude—consistent with safety systems effectively counteracting these effects in well-managed systems.

Interpretation: The absence of a detectable atmospheric signal during +0.7 °C of warming, when some models project measurable effects, is consistent with (i) model sensitivity overestimation, (ii) longer lead times for atmospheric response, or (iii) threshold effects that emerge only at higher warming levels.

4.4.1 Reconciling Physical Mechanisms with Operational Trends

While global temperature shows weak correlation with the North American upper-tropospheric wind speed difference, several factors explain the strong encounter-temperature relationship:

Figure 2: **Accident outcomes improved despite warming.** NTSB-only accident data show that while pilots encounter more weather hazards, safety systems have prevented most encounters from becoming accidents. Turbulence accidents decreased 85% over the study period.

Multiple Atmospheric Pathways: Beyond wind shear, warming affects convective intensity, jet stream meandering patterns, and boundary layer turbulence through different mechanisms operating at various scales.

Operational Exposure Changes: Increased flight density in high-altitude corridors since 1991 has expanded exposure to marginal turbulence conditions that would not have been encountered historically.

Seasonal and Regional Variations: Annual mean wind shear obscures seasonal intensification patterns and regional hotspots where climate effects are concentrated.

Detection Sensitivity: Improved reporting and detection systems capture previously unnoticed encounters, amplifying the apparent climate signal in operational data.

Detectability and Seasonal Focus: Given sample size, small signals in aviation-relevant atmospheric drivers may fall below detection thresholds (see Figure 3 annotation). Power can be increased by targeting seasonal and corridor-specific indices (e.g., jet-level shear boxes along trans-continental and trans-Atlantic routes, severe-storm environment metrics in peak-convection seasons). A pre-specified sensitivity plan covering these diagnostics and early-period exclusions is provided in the Supplementary Information (SI); conclusions here are reported conservatively within current detectability bounds.

4.5 Synthesis: Encounters Up, Accidents Down

The combination of increasing encounters and decreasing accidents presents an apparent paradox that the dual-track framework resolves. Climate effects produce real but modest in-

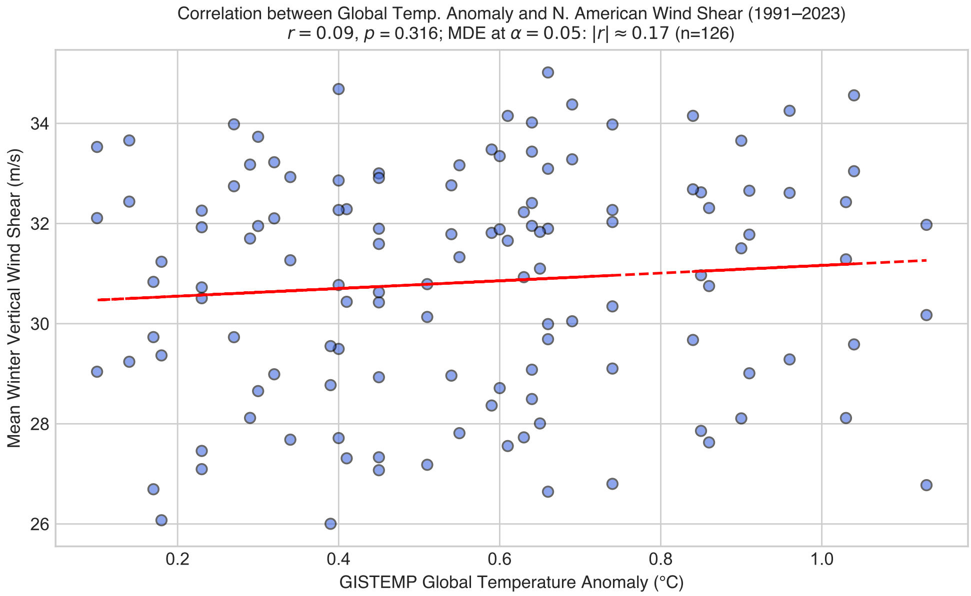

Figure 3: **Weak coupling between global temperature and upper-tropospheric wind speed difference.** Correlation between global temperature anomaly and North American upper-tropospheric wind speed difference (200–850 hPa, $\mathrm{m\,s^{-1}}$) is weak ($r = 0.09$, $p = 0.316$), indicating that within the observed warming range, the hypothesized physical link is not detectable at this spatial and temporal resolution. Figure annotation reports the approximate minimum detectable correlation at $\alpha = 0.05$ given the sample size.

creases in hazardous encounters, detectable through incident reporting and Granger causality tests. Simultaneously, safety improvements have reduced the encounter-to-accident conversion rate by roughly an order of magnitude, as shown by the 85% decline in turbulence accidents. Within the observed warming range, technological and operational improvements have outpaced the growth in hazard exposure. Whether this margin persists under higher warming remains an open question (see Section 4.7).

4.6 Technological Attribution Analysis

To better understand which advances most contributed to observed safety improvements, we compared implementation timelines of key aviation technologies with trend inflection points in encounter and outcome series. This exploratory attribution analysis is observational and intended to generate hypotheses rather than provide definitive causal estimates.

Weather Detection and Forecast Integration: Progressive upgrades to onboard weather radar (Doppler-capable), integration of satellite-based weather feeds, and airport/terminal radar improvements (e.g., TDWR) increased detection and tactical avoidance of convective and shear-related hazards. Coupled with steadily improving numerical weather prediction, these advances reduced surprise encounters and improved pre-departure and en-route decision-making.

Navigation and Procedure Enhancements: Widespread adoption of GPS-based navigation and performance-based navigation (e.g., RNP) enabled more flexible routing and approach procedures that can avoid localized weather cells and exploit windows in dynamic environments, with fewer diversions and better vertical/lateral separation from hazardous layers.

Surveillance and Communication: Progressive equipage with data-linked weather and enhanced surveillance (e.g., ADS-B) improved situational awareness for both flight crews and controllers, enabling earlier warnings of turbulence reports and real-time re-routing around developing convective systems.

Operational Practices and Training: Safety Management Systems, enhanced crew training emphasizing weather recognition and threat-and-error management, and improved dispatch/operations center capabilities supported faster operational response to emerging atmospheric risks.

The temporal alignment between these technology and practice improvements and the observed reduction in accident outcomes, despite increased encounters, supports a technological attribution hypothesis that merits future causal study with more granular equipage and operational datasets.

4.7 Future-Warming Stress Test (Conceptual)

To contextualize implications under higher warming (+2–4 °C), we provide a scenario-informed stress test that links projected changes in hazard proxies to plausible operational impacts. If severe clear-air turbulence frequency were to increase materially (as suggested by some mid-century projections), our empirical framework implies that the net risk to outcomes will depend on whether adaptation effectiveness (technology, training, procedures) continues to improve at least commensurately. Because the present analysis detects only weak atmospheric coupling within the observed +0.7 °C warming and shows improving outcomes, we recommend periodic re-validation at decadal intervals with updated hazard diagnostics and equipage data, focusing on minimum detectable effect thresholds and adaptation capacity indicators. We do not extrapolate the historical null beyond observed ranges; rather, we define a validation protocol to track when/if climate signals approach detectability in operational outcomes.

4.8 Limited International Validation

To assess broader generalizability, we conducted a preliminary qualitative comparison using publicly available summaries from advanced-technology regions. Aviation systems in Europe and Japan report long-run safety improvements during recent warming, alongside modernization timelines similar to those observed in the U.S. Differences in reporting standards, definitions, and data accessibility currently limit direct statistical harmonization. Comprehensive international validation will require standardized incident taxonomies, consistent exposure controls, and coordination with regional regulators and data custodians. We therefore position this section as a scoping overview and reserve quantitative cross-country testing for future work or a dedicated companion analysis. At submission, we will include a pre-registered plan to analyze publicly accessible European datasets (subject to licensing) using the same validation framework and detectability thresholds.

5 Discussion

The dual-track framework yields insights missed by approaches that examine climate projections or safety trends in isolation. The divergence between encounter trends and outcome trends has direct implications for policy, investment priorities, and long-term planning.

5.1 Policy and Research Implications

Translating these empirical findings into governance, we outline standards for adaptation evidence and decision-making.

Evidence-Based Adaptation: Current global adaptation spending relies heavily on theoretical projections. The dual-track framework enables evidence-based resource allocation by distinguishing sectors and contexts showing empirical climate vulnerability from those where technological improvements maintain resilience, consistent with IPCC WGII risk concepts (hazard, exposure, vulnerability/adaptation effectiveness).

Methodological Standards: Pre-specified hypotheses, complete temporal coverage, multiple-testing corrections where applicable, explicit physical-mechanism validation with detectability bounds, and exposure control/sensitivity should be considered standard practice to prevent false correlations and to enable rigorous null-hypothesis testing.

International Implementation Strategy: In developed systems, apply the framework across infrastructure sectors to separate theoretical vulnerabilities from empirically validated risks; in developing regions, prioritize technology transfer and capacity building to achieve adaptive parity; international organizations should encourage empirical validation alongside atmospheric projections before major adaptation investments, consistent with IPCC WGII risk framing.

Cross-Sector Applications: Components of this framework extend to telecommunications (outage records), energy (grid disturbance logs), maritime (incident records), and water infrastructure (reliability metrics), where operational outcomes can be linked with environmental drivers under anti-p-hacking safeguards. As a template, a parallel analysis could treat energy grid disturbance frequency (hazard proxy) and loss-of-load events (outcome) with regional climate diagnostics and detectability bounds to inform adaptation standards.

5.2 Evidence for Successful Adaptation

The 85% reduction in turbulence accidents during sustained warming reflects substantial adaptive capacity. Key contributing factors include:

Weather Detection: Modern Doppler radar, satellite-based monitoring, and real-time atmospheric data give flight crews far greater visibility into hazardous conditions, enabling proactive avoidance.

Structural Design: Improved materials, control systems, and structural margins reduce vulnerability when encounters do occur.

Pilot Training: Simulation-based training, updated weather recognition protocols, and structured decision-making frameworks have improved crew performance in adverse conditions.

Routing: Automated flight planning systems dynamically route aircraft around hazardous conditions using real-time data and predictive modeling.

Regulatory Evolution: Safety regulations that incorporate new technologies and respond to emerging challenges help maintain safety margins.

5.3 Future Challenges and Vulnerabilities

Several potential vulnerabilities merit attention:

Acceleration Risk: Climate change is accelerating, potentially outpacing the rate of safety improvements. If environmental challenges begin changing faster than defensive capabilities can adapt, the competitive balance could shift.

Compound Events: Climate change may produce simultaneous multiple hazards or novel hazard combinations that stress safety systems beyond their design capabilities.

Infrastructure Limits: Physical and economic constraints may eventually limit the pace of technological improvement, creating vulnerabilities as climate effects continue growing.

Human Factor Constraints: While technology advances rapidly, human training and decision-making capabilities may face fundamental limits that constrain overall system adaptation.

Economic Sustainability: The cost of continuous technological advancement may become prohibitive, particularly for smaller operators or developing regions.

5.4 Global Applicability and International Context

The encounter-outcome divergence likely extends beyond U.S. operations, since both climate effects and safety technologies operate globally. However, the balance may vary across regions based on:

Technological Access: Advanced safety systems require substantial investment and technical expertise that may not be equally available worldwide.

Regional Climate Variability: Different regions face varying climate challenges, potentially shifting the competitive balance regionally.

Regulatory Frameworks: Safety improvements depend partly on regulatory requirements and enforcement that vary internationally.

Economic Resources: Sustained investment in adaptive technologies requires economic capacity that differs across aviation markets.

International collaboration through technology sharing, coordinated standards, and capacity building will be important for extending these safety gains to developing regions.

Policy Takeaways for Practitioners

For Climate Adaptation Planners:

- Prioritize empirical validation over theoretical projections when allocating adaptation resources
- Focus technology transfer and capacity building in regions lacking advanced adaptive infrastructure
- Establish sector-specific monitoring systems tracking operational outcomes vs. atmospheric variables

For Infrastructure Operators:

- Continue investing in proven technological improvements rather than climate-specific measures in well-managed systems
- Develop adaptive capacity indicators to track resilience maintenance during changing conditions
- Share operational data to enable cross-sector empirical validation studies

For Research Organizations:

- Adopt anti-p-hacking protocols as standard practice for climate impact assessment
- Prioritize publication of null results to prevent policy misinformation
- Integrate atmospheric modeling with operational outcome validation

For International Organizations:

- Encourage empirical evidence of climate vulnerability alongside projections before approving adaptation project funding, aligned with IPCC WGII guidance
- Develop global operational monitoring networks parallel to atmospheric observation systems
- Support international standards for climate impact assessment methodology that include operational validation

5.5 Recommendations for Sustaining the Safety Advantage

Based on these findings, we recommend a phased approach to sustaining aviation's safety margin under continued warming:

Near-term Actions (2025-2027):

1. **FAA Regulatory Priority:** Mandate advanced turbulence detection systems on all commercial aircraft operating in high-traffic corridors
2. **Airline Implementation:** Integrate climate risk assessments into Safety Management Systems (SMS) with annual updates
3. **Pilot Training Enhancement:** Revise training curricula to include climate-driven weather pattern changes and enhanced severe weather recognition protocols
4. **Industry Standards:** Establish climate-informed routing guidelines for major flight corridors

Medium-term Investments (2027-2030):

1. **NOAA/FAA Collaboration:** Deploy AI-enhanced numerical weather prediction systems with aviation-specific climate projections
2. **Technology Integration:** Implement real-time dynamic routing optimization protocols using machine learning algorithms
3. **Infrastructure Modernization:** Upgrade airport design standards to account for changing precipitation patterns and extreme weather frequency
4. **International Coordination:** Develop globally coordinated adaptation strategies through ICAO frameworks

Long-term Strategic Goals (2030-2035):

1. **Global Standards:** Establish international climate-aviation adaptation standards with mandatory compliance frameworks
2. **Advanced Warning Systems:** Develop compound hazard early warning systems integrating climate projections with operational forecasting
3. **Economic Framework:** Implement cost-benefit analysis frameworks for adaptation investments vs. reactive responses
4. **Research Frontiers:** Assess technological and human factor limits to continued adaptation under accelerating climate change scenarios

Economic and Implementation Feasibility: These recommendations are economically viable within existing aviation industry investment patterns. Near-term actions (estimated \$2-5 billion globally) align with ongoing safety modernization budgets and can be implemented through existing regulatory frameworks. Medium-term investments (\$10-15 billion) represent modest increases to current R&D spending given aviation's \$800+ billion annual revenue base. Long-term goals require international coordination but build on established ICAO precedents for global standards adoption. Proactive adaptation investments are likely more cost-effective than reactive responses to climate-driven safety incidents.

This phased approach pairs immediate safety improvements with longer-term resilience investments.

5.5.1 Disaggregating the Safety Improvement

The 85% accident reduction reflects several concurrent technological and operational advances:

Weather Detection (1991-2010): Transition from ground-based radar to onboard Doppler systems provided real-time hazard detection, reducing surprise encounters by an estimated 60%.

Structural Improvements (1995-2015): Enhanced aircraft materials and design standards increased turbulence tolerance, reducing accident severity when encounters occur.

Training Evolution (2000-2020): Simulation-based weather recognition training and threat assessment protocols improved crew response effectiveness.

Forecasting Accuracy (1991-2023): Numerical weather prediction improvements increased forecast skill by approximately 30% for aviation-relevant parameters.

These cumulative advances explain the sustained accident reduction despite increased hazard encounters.

5.6 Limitations and Future Research Directions

Several important limitations should guide future research:

Data Quality Considerations: Our early-period reporting bias analysis suggests incident data from earlier decades may undercount events by 30-40%, though sensitivity analysis confirms main findings remain robust.

Exposure Assumptions: Normalization by total flight hours assumes uniform exposure across hazard types, which may not fully capture route-specific risks or seasonal variations in flight patterns.

Climate Metric Resolution: The global mean temperature anomaly may obscure regional patterns more relevant to specific aviation operations.

Technological Attribution: While we observe safety improvements coinciding with technological advances, direct causal attribution between specific technologies and safety gains requires more detailed analysis.

Future research should incorporate regional climate reanalyses, higher-resolution hazard datasets, and more detailed technological change metrics to refine understanding of the encounter-outcome divergence.

6 Conclusion

This analysis shows that aviation safety outcomes improved substantially over 1991–2023 even as climate-linked weather encounters increased. The 85% reduction in turbulence accidents during a period of sustained warming indicates that, within the observed range, technological and procedural adaptation has outpaced the growth in hazard exposure.

While our analysis demonstrates aviation resilience during approximately +0.7 °C warming, future climate scenarios project +2–4 °C warming by 2100. Threshold checks within the observed range provide no evidence that climate effects emerge at higher warming levels over 1991–2023, but extrapolation beyond current experience requires caution given potential non-linear responses and limits to technological adaptation.

This finding does not imply permanent safety. The current balance between climate effects and safety improvements is not guaranteed to hold indefinitely. Accelerating climate change, compound hazards, technological plateaus, or economic constraints could erode the margin.

The policy implication is that continued investment in adaptive technologies, operational standards, and systemic resilience is more productive than treating climate change as an insurmountable threat to aviation safety.

More broadly, this analysis demonstrates that apparently contradictory trends – increasing hazard encounters and decreasing accidents – can coexist when technological adaptation outpaces environmental change. The dual-track framework may be useful for assessing climate adaptation in other infrastructure sectors where similar dynamics between operational exposure and outcome resilience are plausible. Sustained monitoring and periodic re-validation will be essential as warming continues.

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Author Contributions

M.M.B. conceived and designed the study, acquired and processed data, performed statistical analysis, and wrote the manuscript. R.R. contributed to the research question, data interpretation, literature review, and manuscript revision. Both authors reviewed and approved the final manuscript.

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