Building Resilience in Aviation: Economic Impacts of Disasters and Future Adaptations

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This paper examines typical disruptions to aviation caused by natural disasters. While there are many disruptions that impact aviation, this paper will primarily cover flooding, severe weather storms, extreme temperatures, and clear air turbulence across the United States. The paper also presents initial economic assessment methodology for understanding the economic impact of these disruptions on the aviation ecosystem. Furthermore, adaptation strategies to minimize the impact will be explored. The paper will make a case that a coordinated national strategy at federal, regional, and local levels that could benefit from a resiliency assessment and management of the aviation system.

I. Nomenclature and Acronyms

ARMD = NASA Aeronautics Research Mission Directorate
BEARS = Building Enhanced Aviation Resilience Systems
BWB = Blended Wing Body aircraft concept
CAS = Convergent Aeronautics Solutions project
CTOL = Conventional takeoff and landing
IFAR = International Forum for Aviation Research
NAS = National Airspace System
RIA = Resilience in Aviation
STOL = Short takeoff and landing
TBW = Truss Braced Wing aircraft concept
VSTOL = Vertical and/or short takeoff and landing
VTOL = Vertical takeoff and landing
WHDA = Weather hazard and disaster adaptation

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II. Introduction

The NASA ARMD Convergent Aeronautics Solution (CAS) project [1], a part of the Transformative Aeronautics Concept Program (TACP) [2], has been acting as an innovation incubator by encouraging speculative high risk and high payoff projects for over a decade. Recently, the CAS project has initiated the Building Enhanced Aviation Resilience Systems (BEARS) study which seeks to systematically consider the impact of natural disasters on aviation and, further identifies what sorts of weather adjustment/adaptation approaches that might be needed. These adaptation strategies include (a) airspace CONOPS and overall network design/evolution, (b) aerospace technologies and aircraft design, and (c) airport infrastructure improvements.

Figure 1 illustrates an informal view of Resilience in Aviation (RIA) as a potential new area of research study being introduced in this paper; resilience engineering in general, though, has been an established field for some time [3]. There are many study domains that could fall within RIA. The potential study domains highlighted in Fig. 1 include: (a) weather hazard adaptation (in Aviation); (b) economy/disaster-proofed growth; (c) adaptation to, or incorporation of, disruptive aerospace technologies; and (d) highly productive aircraft development. The BEARS study primarily focuses on the first RIA study domain, i.e. weather hazard adaptation in aviation. The notional study domain of economy/disaster-proofed growth would seek to address the problem where, historically, the aerospace sector has been particularly susceptible to economic downturns as well as disaster impacts; addressing this problem could potentially be done through advances in automation, manufacturing, design tool accessibility and flexibility, and the opening of new application domains/markets to preserve, or sustain, aerospace sector economic growth irrespective of global or overall strength of the economy (or disasters disrupting that strength). The notional study domain of adaption to, or incorporation of, disruptive aerospace technologies would seek to address the problem wherein several general classes of technology are in the process of being introduced that could have profound implications as to the strength, safety, and reliability of the aerospace sector over the next two to three decades (e.g., telework/telepresence, self-driving/autonomous vehicles, online/virtual manufacturing of parts, and various advanced air mobility platforms and networks); addressing this problem could entail conducting (periodic/ongoing) high-level system-of-systems architecture analysis and review(s) whose primary goal would be to provide an independent assessment of the interrelated disruptive effect of novel technologies while seeking to harmonize those technologies as best as possible. Finally, the notional study domain of highly-productive aircraft would seek to study the problem of how to maximize productivity for aircraft for complete life cycles, while at the same recognizing the need to develop new air transportation networks; there are many ways of potentially addressing this problem including (a) expanding capability by going to higher-speeds, carrying the right number of passengers to optimize load factor, increasing aircraft performance efficiency, increasing throughput and (b) through reducing the 'costs' of operating such aircraft by reducing emissions, reduce manufacturing costs, reducing airport and air traffic management infrastructure, reducing delays/cancelations, etc.. These other notional study domains will hopefully be studied in future work; again, the focus of this paper will be the study domain of weather hazards adaptation.

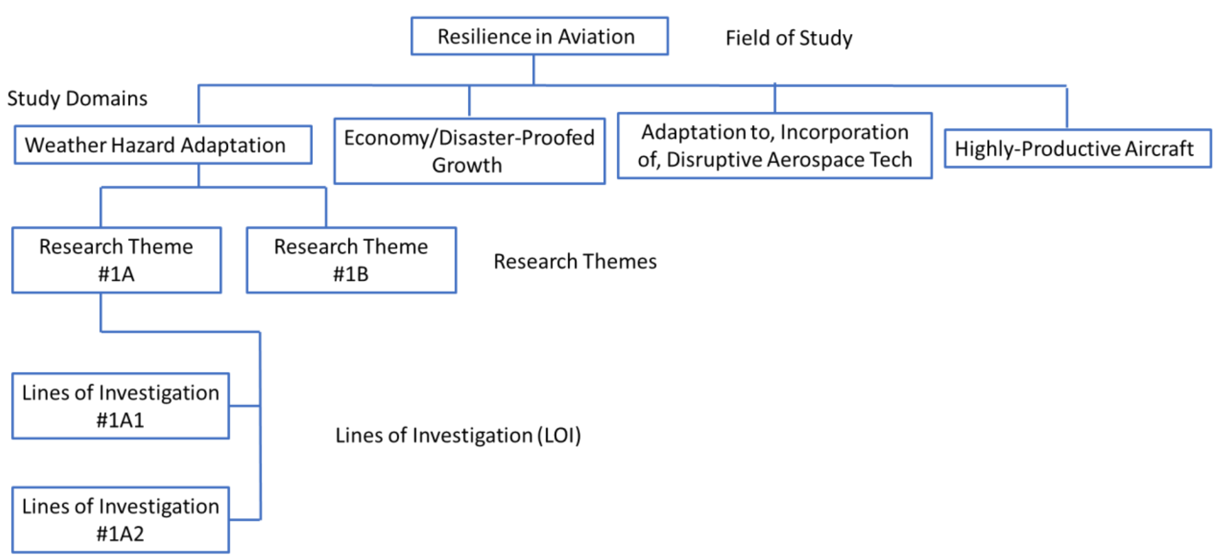

Figure 1. Resilience in Aviation as a Research Theme (and proposed associated study domains)

Figure 2 presents a high-level summary of some of the research themes that are a part of the weather hazard adaptation study domain. These research themes include: (a) flood-proofed infrastructure; (b) strengthened aircraft and airports to severe storms; (c) insulating (literally and figuratively) aviation assets and people against extreme temperatures; (d) cushioning (or rather protecting) passengers, possessions, and cargo against severe clear-air turbulence. (Note that these research themes are aspirational in nature, e.g., it is unclear whether fully flood-proofed infrastructure is economically or physically feasible but from an aspirational standpoint it reflects the overarching 'goal' of the research theme.) It is anticipated that there should be a significant amount of commonality between lines of investigation for all the research themes but there will also likely be a unique/singular line of investigation for aspects of each research theme.

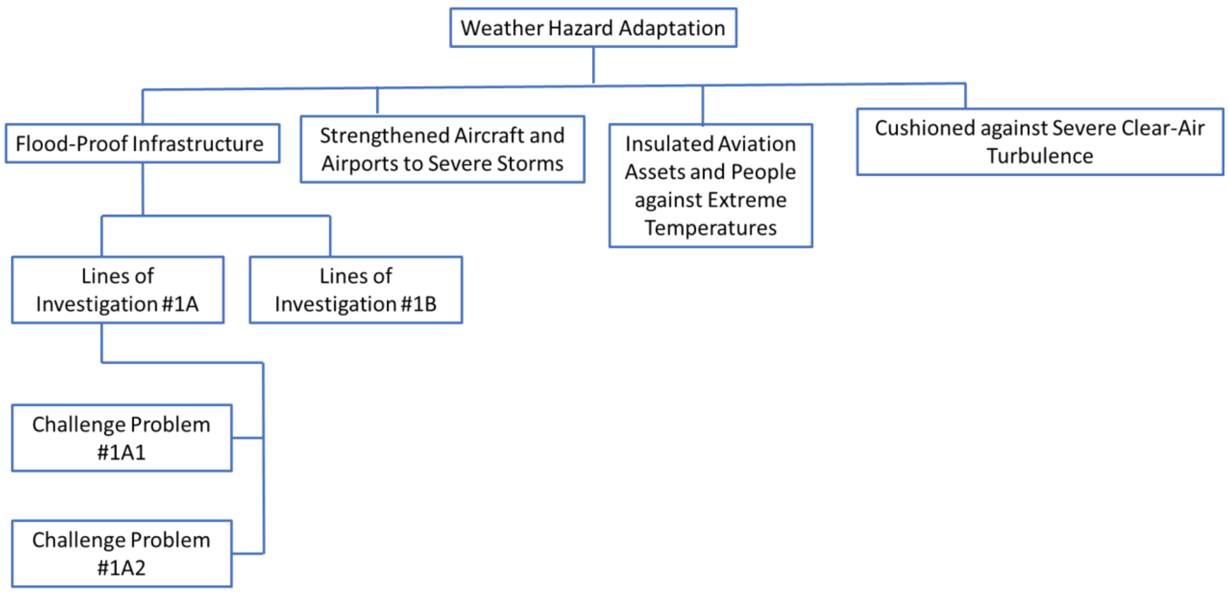

Figure 2. Weather Hazard Adaptation (focus of this paper) as the Study Domain

BEARS is still in its early stages, but a substantial amount of literature review, problem scope definition, and high-level planning discussion have already occurred. This includes definition of possible deliverables for the BEARS effort such as:

- Understanding natural disasters that typically impact the aviation system
- Understanding the economic impact of disruptions caused by selected disasters on aviation across the United States
- Examining opportunities to mitigate the impact of, or adapt to, these disruptions by increasing the resiliency of the United States aviation system
- Collaborate with national, regional, and local entities to plan for managing a coordinate mitigation/adaptation strategy

III. Background on Economic Impacts of Disruptions to the Aviation System

We will build upon existing academic literature surveys, e.g., [4-5], foundational reports, e.g., [6], and literature within each potential weather hazard area, such as flooding, e.g., [7]. In addition to providing results from a literature review, there will be discussion related to what we have learned from conducting interviews across a wide set of stakeholders and subject matter experts (researchers, airports, airlines, policy makers, etc.). Perhaps most importantly, a preliminary analysis/assessment of the literature and stakeholder interviews will be performed and presented. In particular, the literature review and stakeholder interview findings will sorted, summarized, and assessed in terms of four key focus areas: (1) organizing the literature into four sub-areas of weather hazards to be considered by the BEARS effort, i.e., (a) flooding, (b) extreme heat/temperature, (c) extreme weather (i.e. storms, hurricanes) and (d) clear-air turbulence; (2) further subdividing the areas of interest into airports, infrastructure, air traffic management and airspace operations, aircraft design and technologies, and overarching social and economic impacts; (3) identifying prior works related to weather hazards impact on aviation modeling and proposals for future work in such modeling; (4) identifying current and future stakeholders and their potential for future collaborations with respect to paving a path forward on weather hazard and natural disaster adaptation for aviation.

An important outcome of this survey will be a gap analysis for all potential stakeholders to consider in potentially devising plans – both technological, programmatic, regulatory, and operational – that can be responsive by the 2050 timeframe. Given the complexity of the aviation sector, and weather hazards itself, it is important to consider the overall problem of weather adaptation now rather than later.

The extreme storm weather hazard encompasses several phenomena: hurricanes or tropical storms, tornadoes and other high wind events, thunderstorms, lightning and electrical storms, blizzards and ice/winter storms, volcanic ash storms or aerosol particulate dispersal.

The flooding weather hazard includes storm surge, sea level rise, and inland flooding due to rainfall and river spillover.

The extreme temperature weather hazards considers both extreme high and cold temperatures events both on the ground and inflight. Accordingly, for on the ground extreme temperatures, the safety of passengers and airport staff needs to be considered. In the case of inflight extreme temperatures, the safe takeoff and landing during high and hot conditions need to be considered as well as wing/aircraft icing under very cold conditions. Hailstorm damage to the aircraft can also be considered a part of the extreme temperature hazard.

The severe clear-air turbulence weather hazard considers several inflight turbulence occurrences including shifts in the jet streams, increased crosswinds during takeoff and landing, severe midflight gusts/turbulence that jeopardize the safety of crew and passengers (and in the most severe cases can damage aircraft).

The appendix of this paper presents a high-level summary of an impact assessment of weather hazards and natural disasters.

Figures 3-4 present some initial first-order, high-level macroeconomic assessment of some of the impacts that have been noted from past historical weather hazards and natural disasters. Figures 3-4 focus only on four US airports and, first, note the magnitude of air traffic out of those airports during a given period of time and, second, provide estimates of the impact of flooding on those operations. A more detailed economic analysis, based on air traffic and weather databases, is currently ongoing and will be described in a later Analysis, Modeling, and Tool development subsection.

Past studies, e.g. [8], have shown that studying the northeast corridor, particularly the main three airports in New York, shows that whatever happens there ripples to the rest of the country.

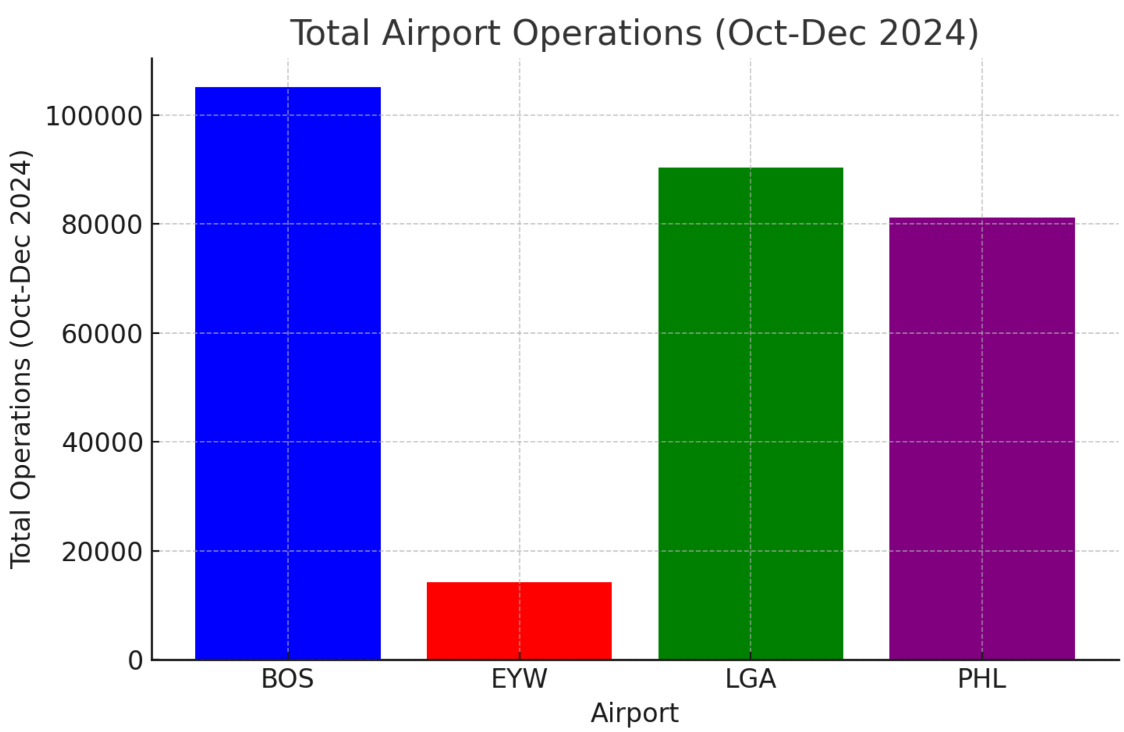

Figure 3. Total number of operations in four select airports in the northeast region of the US

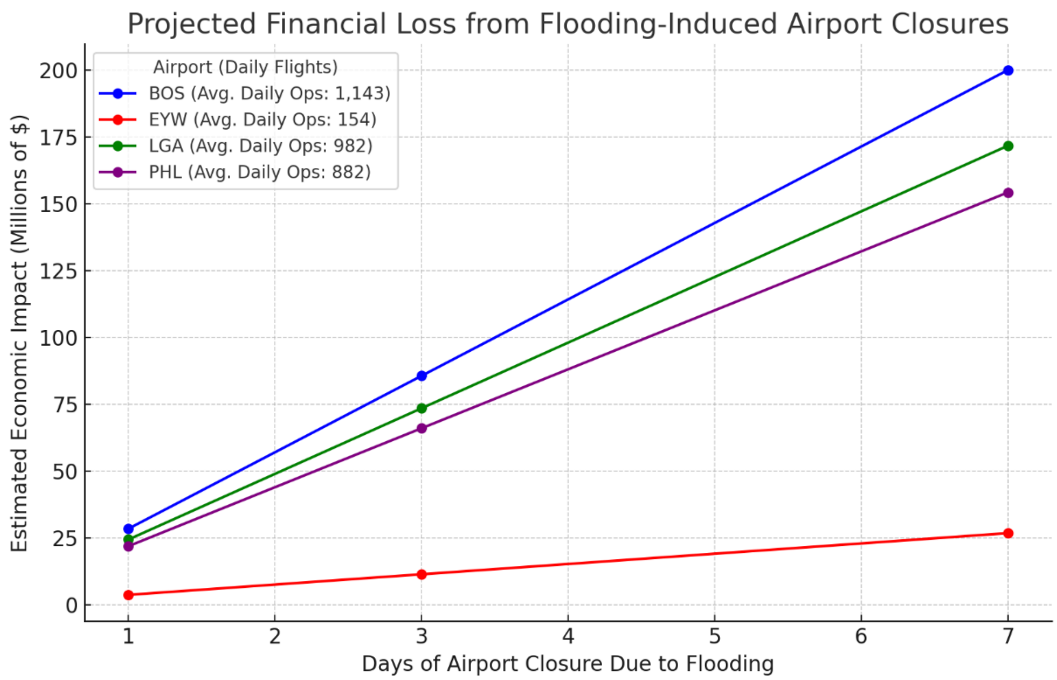

Figure 4. First order estimates of regional financial loss due to notional levels of airport closures by any type of disruption

Using the flight operations data from FAA's Air Traffic Activity Data System (ATADS) from October 1-December 31, 2024, a first-order economic analysis was conducted. The traffic included both IFR and VFR operations [9]. The analysis estimates a high-level economic impact of flooding-related airport shutdowns at four U.S. airports known to be at risk due to their low elevation and proximity to the coast as well as having experienced known flooding incidents in the past: Boston Logan International Airport (BOS); Key West International Airport (EYW); LaGuardia Airport (LGA); Philadelphia International Airport (PHL).

Average Daily Operations = Total Operations / 92 Days (i.e., October 1 to December 31)

Disruption Scenarios and Assumptions: full airport closures ("shutdown") due to flooding were modeled for durations of 1, 3, and 7 days, assuming 100% of flights (arrivals and departures) are canceled during each day of disruption and no mitigation or rerouting measures are assumed due to flooding making runways or other critical airport infrastructure unusable or inaccessible. The number of disrupted flights is therefore:

Disrupted Flights = Avg. Daily Operations × Days of Shutdown

A benchmark value of $25,000 per disrupted flight was used in the above estimates, derived as a midpoint of industry-wide estimates. According to a 2022 AirHelp report, total U.S. flight disruption costs exceeded $30–34 billion, with approximately 1.2 to 1.5 million flights disrupted [10]. This yields a per-flight economic impact range of approximately $20,000 to $28,000, accounting for airline operating costs, crew and aircraft delays, passenger time losses, and downstream effects on business and tourism.

The value of $25,000 per flight was chosen as a representative value, acknowledging that this is a rough estimate and does not account for variations in aircraft size or passenger load, which further would be a consideration in the airports analyzed above especially given the heterogeneity of aircraft size, flight schedules, and passenger loads for the airports listed above. The total estimated economic loss for each scenario was calculated as: Total Economic Impact = Disrupted Flights × 25,000.

Even from this limited, partial first-order assessment, airport closures stemming from major weather events or disasters can have a major economic impact on regions of the US, i.e., literally hundreds of millions of USD of financial cost.

IV. A Fifty States Survey of Economic Impacts of Disasters and Extreme Weather on Aviation

Statistics on weather related cancellations and delays were sources from the FAA's Airline Service Quality Performance System (ASQP). The number of cancellations and delays for all commercial airports available were retrieved for January 2015 – January 2025. There are no airports in Delaware listed in the data source. The aggregate number of weather-related cancellations and delays as reported by the FAA for airports in each state are shown in Figs. 5-6. As shown in the figures, airports in New York, Texas, Illinois, and California attribute to the largest number of cancellations due to weather disruptions. These states along with New Jersey and New Mexico are also attributed to the highest number of weather related delays. These cancellations and delays carry an economic cost carries by the airlines, airports, municipalities, states, and federal governments.

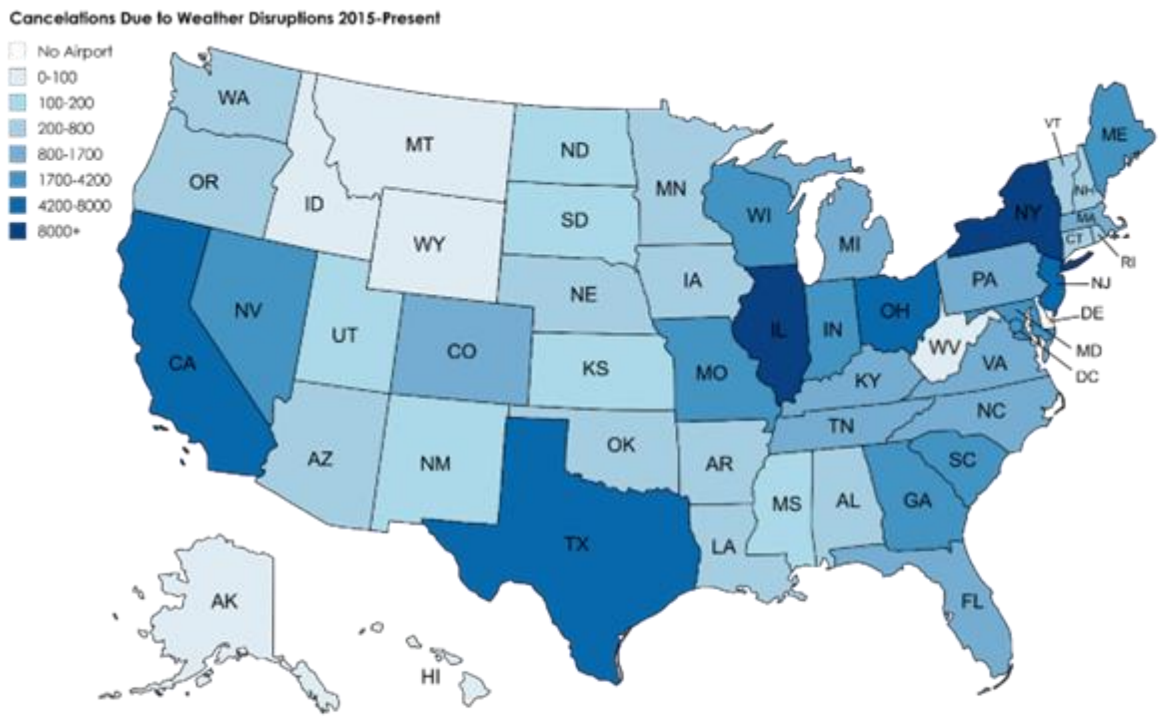

Figure 5. Flight Cancellations in the CONUS 50-States Due to Weather Hazards or Natural Disasters

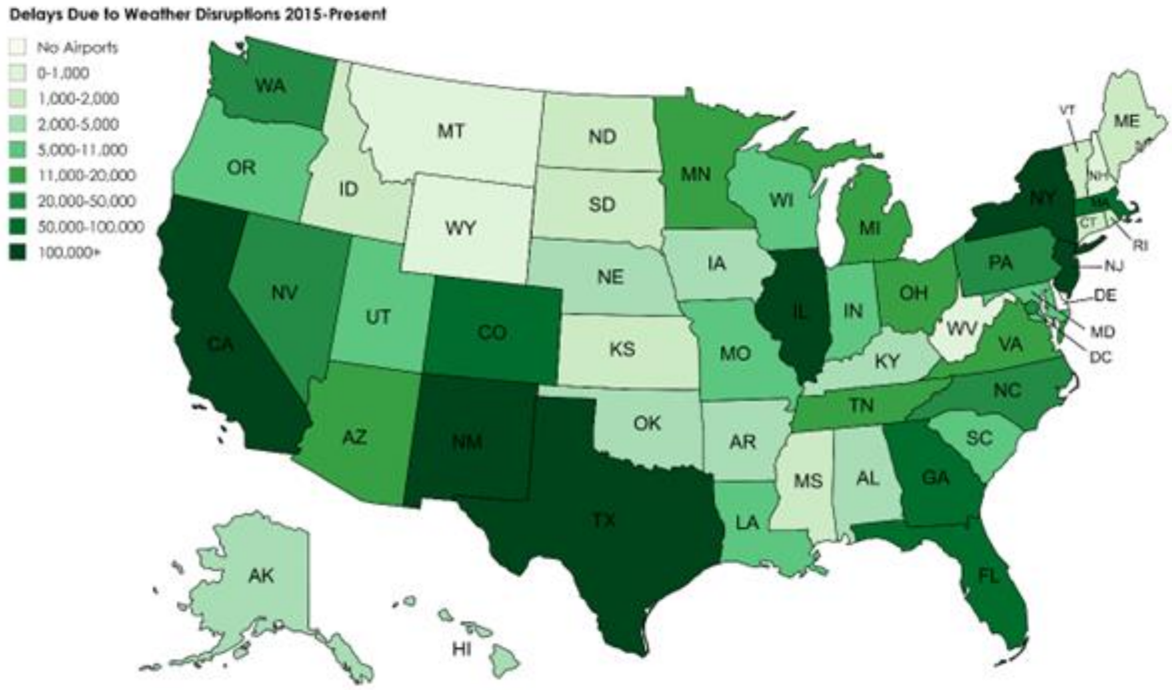

Figure 6. Flight Delays in the CONUS 50-States Due to Weather Hazards or Natural Disasters

To get a better understanding of the potential patterns present, the reported weather cancellations and delays were normalized by the total number of operations in each airport to calculate the percent of cancellations and delays caused by weather disruptions. The data was organized into eight total groups, representative of the rounded square root of the number of data points as a common method for histograms. The lower and upper limits of each bin was determined using k-mean clustering algorithm. This allowed the data points that are nearest to each other based on the Euclidian distance to be grouped together such that patterns within the data can emerge. The percentage of cancellations and delays for each state are shown in Figs. 5-6. Regional clustering for the cancellations and delays emerges from this method, indicating a potential relationship between weather hazard and aviation operational effects.

The causes of the cancellations and delays in each state can be understood by the types of weather hazards present in each state. An initial list of the weather hazards present in each state was created using Chat GPT. This list was then verified by two researchers on the team familiar with the major historical weather events across the United States. Figure 7 shows the presence of weather hazards, along with their level of risk, for each state. This can be used to begin to develop a correlation with the percentage of cancellations and delays observed across the United States. For instance, the northeast can be attributed to the highest percentage of cancellations and delays. This could be caused by weather hazards such as winter storms and cold temperatures.

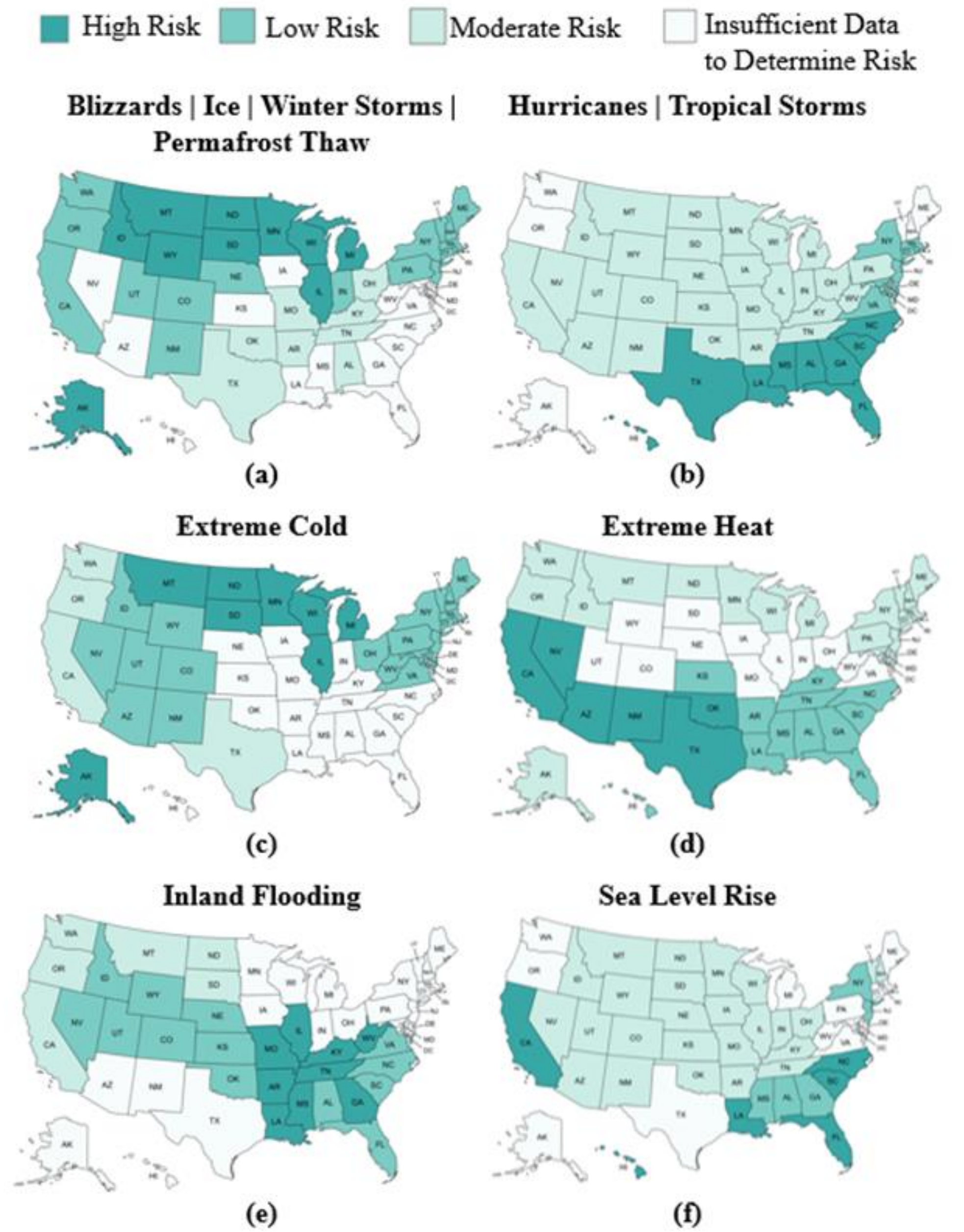

Figure 7. Weather hazard risk-level by state: (a) blizzards, ice, winter storms, and permafrost thaw, (b) hurricanes, typhoons, cyclones, and tropical storms, (d) extreme cold, (d) extreme heat, (e) inland flooding and (f) seal level rise

V. Aviation Disruptions

The effects of the weather disruptions on airport operations and infrastructure are shown in Figure 8. The darker the shading the greater the delay, cancellations, infrastructure/aircraft damage, and/or multi-day recovery from the major weather event. Depending on location, the effects of each weather hazard can be more extreme. For example, a winter storm in Texas will have a greater effect on aviation systems compared to one in states that frequently experience snow and ice and are therefore equipped to handle those weather events. In general, this is a qualitative assessment of the impact of a wide array of disruptions as to their relative severity on the aviation systems. This qualitive assessment will be a good guide for future work making more quantitative assessments of economic impact.

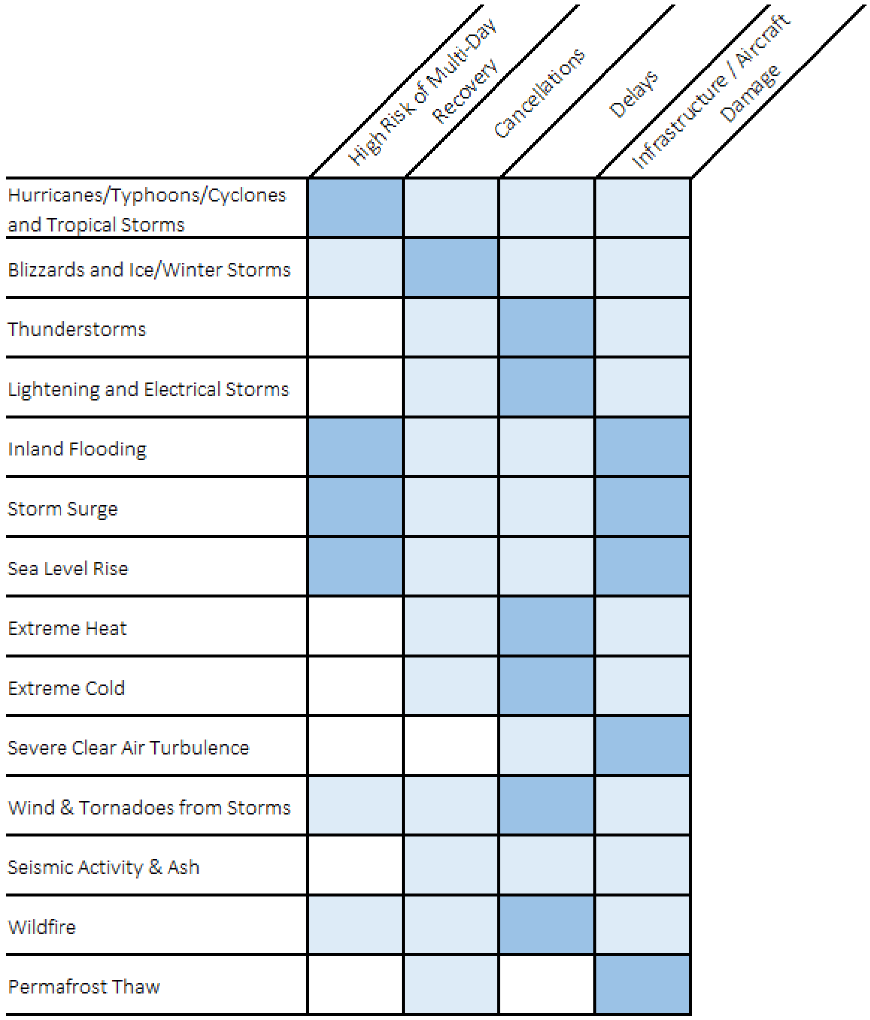

Figure 8. Effects of the weather disruptions on airport operations and infrastructure

The impact of individual historical weather/disaster events on aviation and the overall community economics can also be presented in the form of 'score cards'. Figures 9-10 present two examples of such score cards that were developed by the BEARS team.

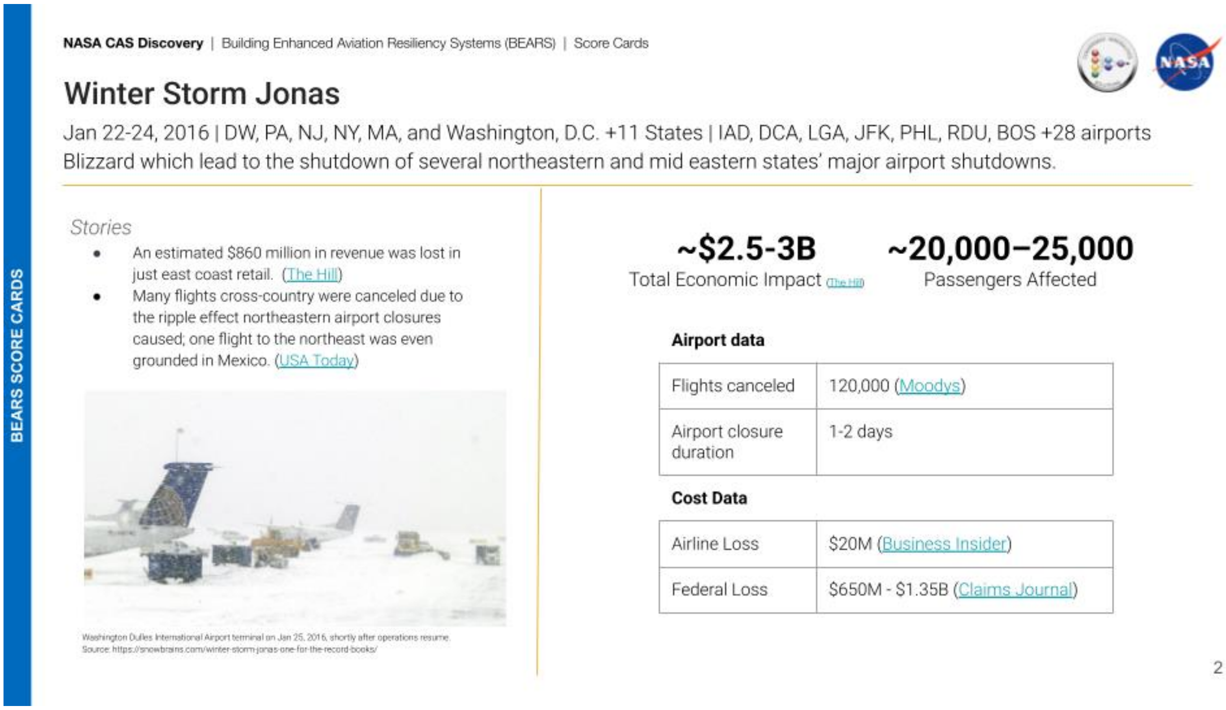

Figure 9. Score card showing the impact of Winter Storm Jonas on Aviation

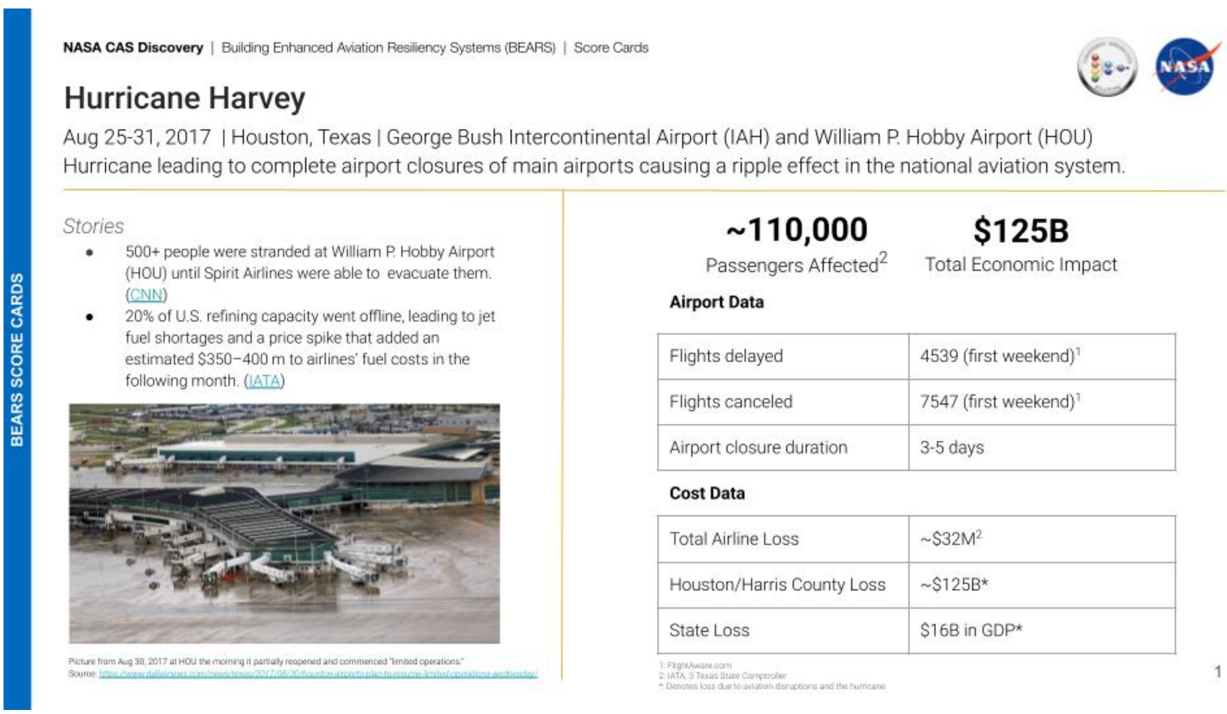

Figure 10. Score card showing the impact of Hurricane Harvey on Aviation

Such score cards are intended to be a quick accessible means of communicating to many stakeholders the importance, or rather necessity, of developing resiliency in aviation, especially with respect to weather hazard and natural disaster adaptation.

VI. Toward a Framework for Aviation System Resilience

The overall approach taken with the BEARS project is to define the overall aviation weather hazard adaptation problem, perform information from a wide range of sources and stakeholders, perform initial assessments of the economic impact of these hazards/disruptions, and then finally make recommendations to build a framework for enhancing Aviation system resilience.

A. Potential National and International Collaboration

Defining roadmaps to enhanced Aviation resilience will not merely involve US stakeholders but, ultimately, international participants/collaborators as well. The BEARS project has begun initial steps toward U.S. stakeholder outreach and engagement. A part of this potential strategy would be to build a community that takes actionable steps towards weather adaptation for aviation.

As an initial phase of the BEARS project a series of stakeholder interviews were conducted. Several half-hour-to hour-long interviews were conducted virtually from stakeholders ranging from technical society leaders, aviation researchers, economics professors, municipal/airport planners. In general, there was great initial enthusiasm voiced for the overarching goal of the BEARS study and its potential implications for future aerospace technology efforts. Additionally, several specific interview comments led to revisiting some of the BEARS study objectives and approaches. Figure 11 is an illustrative example of one of the stakeholder interview summary 'cards' that were used by the BEARS team to document all the interviews conducted.

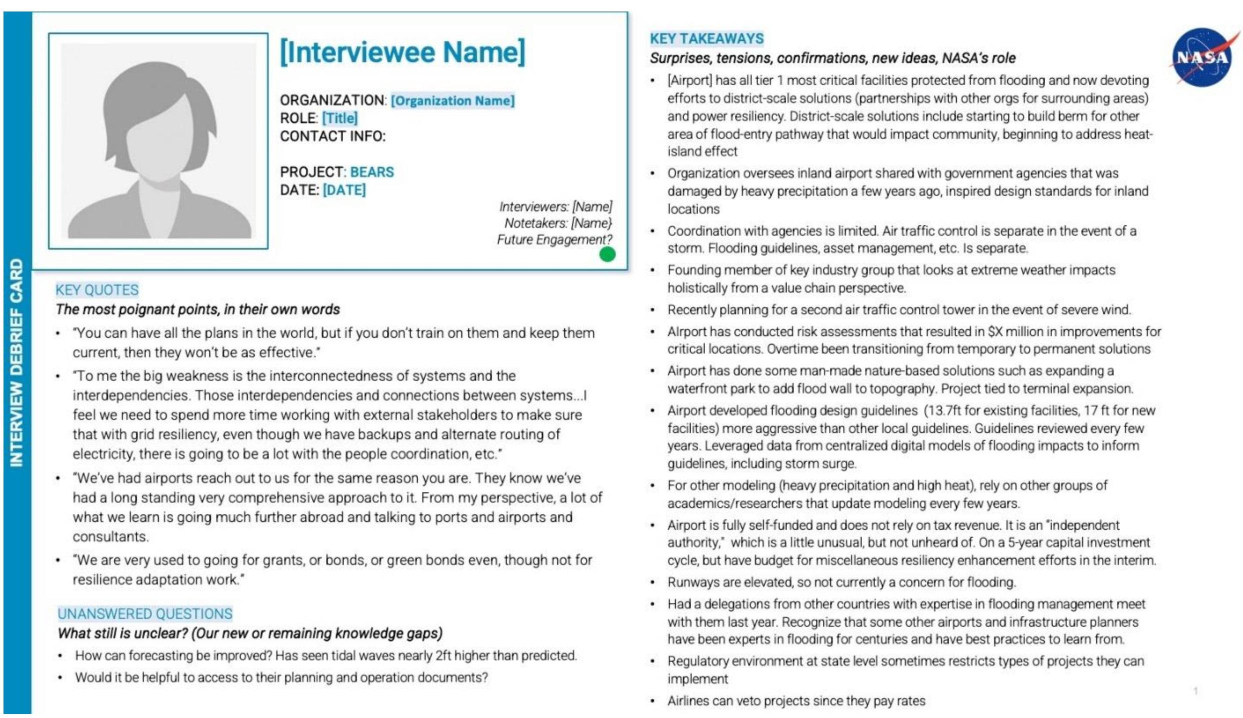

Figure 11. Sample anonymized stakeholder interview summary card

Initial planning has also been conducted as to using NASA crowdsourcing initiatives to employ internal (aerospace technologist) subject matter expertise to refine the objectives of the BEARS study as well as consider that input in the potential context of Delphi-method-like forecasting of both future hazards and disrupters for Aviation as well better brainstorming and assessing potential future technological adaptations to those disruptors to maximize Aviation resiliency.

Initial planning has also been conducted as to defining/scoping potential NASA-sponsored and/or technical-society-sponsored student design competitions on the topic(s) of how to build systems that can enhance Aviation resiliency, particularly with respect to increasing Aviation robustness to weather hazards and natural disasters.

B. Analysis, Modeling, and Tool Development

A key element of our work is to develop a data modeling environment to conduct robust data mining and data translation from NASA and other organizations' weather model predictions to develop the inputs required for NASA ARMD airspace and aircraft analysis tools. While we can draw from existing weather models and scenarios, there are limited existing models that translate between different levels of weather hazards (e.g., flooding, amounts of clear air turbulence, etc.) into technical, social, and economic impacts on the global air transportation system. A key effort for our team in this early 'Discovery' phase is the development of new analysis tools and, overall, a toolchain to translate recognized weather hazards model output to aerospace analysis tool input; for example, refer to Fig. 12.

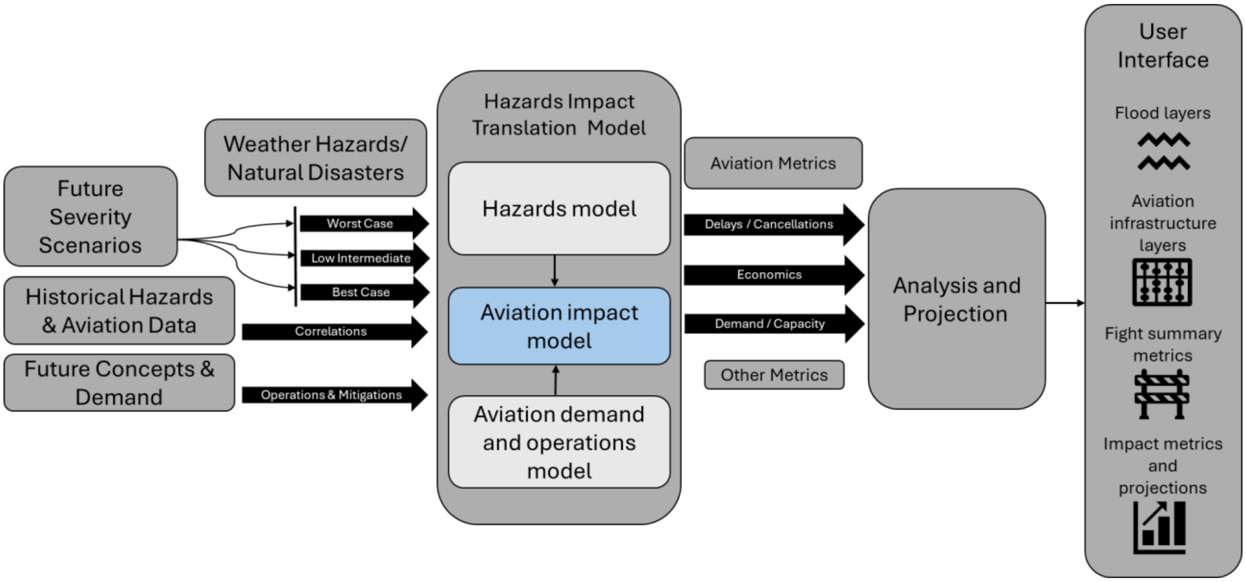

Figure 12. Representative Data Modeling Tool Flow Chart

Identifying impacted areas (operations, infrastructure, leases, insurance claims and compensation, etc.) within the aviation industry and aviation systems will be critical for directing future investments to build hazard resilience. There is currently no established way to understand the magnitude of the economic and infrastructural impacts that weather hazards and natural disasters have on aviation systems is the CONUS nor is there a consistent data source tracking the impacts of these events. The BEARS team is creating the Vulnerability Assessment for Aviation Systems Tool (VAAST) to address this gap. This software tool helps visualize these hazards and the associated impacted aviation infrastructure and is also integrated with aviation operations data. This enables the outputting of projected impacts to aviation systems based on the severity and type of hazards. The current minimum viable product iteration of tool development is focused on quantifying the impacts of coastal flooding on aviation infrastructure, which will be expanded to flooding and other hazards. VAAST will enable decision making for stakeholders across aviation systems by aiding in the visualizing and quantifying of hazard(s) exposure and allowing for the analysis of what-if scenarios to craft appropriate response and resilience strategies.

Figure 13 is an illustrative representative example of the output of the in-development data modeling tool for weather hazard projections and their economic impact assessment for the CONUS. The output from this data modeling tool will be tailored for different Aviation stakeholders to maximize the value of the results presented.

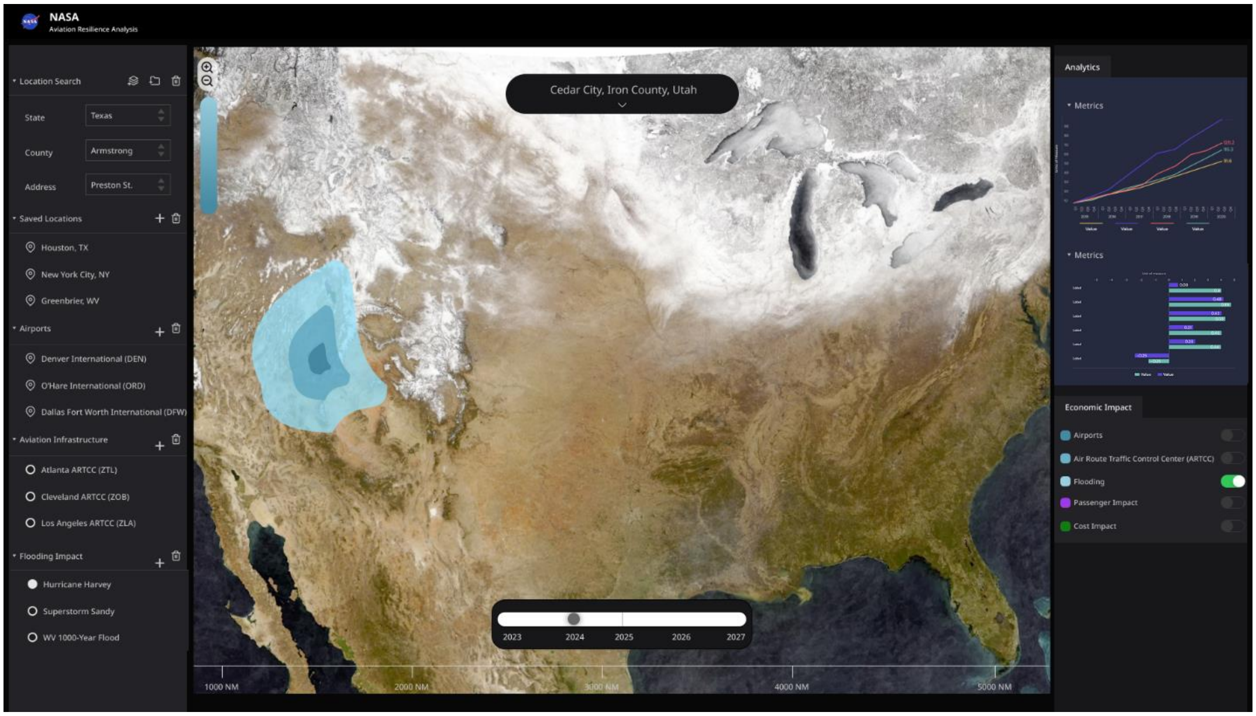

Figure 13. Visualization output from the BEARS VAAST weather hazard data modeling tool

C. Reexamination of Design Standards and the Examination of the Resilience of Current and Next-Generation Aircraft Designs to Weather hazards Impacts

Ultimately, this effort is more than just estimating/projecting an assessment of the potential impact of weather hazards or other natural disasters on aviation. It should ultimately aid the definition of new aircraft design standards and ongoing assessments/examination of the system-of-systems resilience of current and next-generation aircraft and operations. Examples of possible aircraft design standards that may need to be reexamined include:

1. Evaluate aircraft design standards for takeoff 'high and hot' conditions in the world of 2050 (or some other agreed upon target date).
2. Evaluate aircraft design standards for aircraft structure load limits and handling qualities for increased clear-air turbulence and other extreme weather fallouts in the world of 2050.
3. Evaluate aircraft design standards for landing-gear and tires for airport runways with increase water build-up during flooding or increased heavy water runoff in the world of 2050.

Next-generation aircraft designs might need to be examined for their resilience to weather hazards impacts (e.g., potential increased clear-air turbulence).

D. New Airspace Network Concepts and Operational Models

Weather hazards, or other natural disasters, impact to airports, aviation infrastructure, and airspace (network) operations could be profound. This paper provides discussion and suggestions on how resilience to weather hazard impacts might be assessed against current and next generation airports, infrastructure, and airspace/network operations. For example, is the current hub-and-spoke network model adequately resilient to air traffic disruption – with attendant increases in delay and reductions in throughput – due to anticipated weather hazards?

From an airspace operations and airport network perspective, a new type of airport network system (as distinguished from the current hub and spoke type networks) may need to be developed. Alternate airport networks might need to be proposed such as: decentralized/distributed networks; incorporating small airports and vertiports and VSTOL (aka Runway Independent Aircraft) into large airport networks; amphibious 'airfields' and amphibious aircraft integrated into airport networks; and/or other multimodal network solutions. Such novel airport network concepts should be explored to increase airspace transportation system resilience in the 2050 and beyond time frame that adapts the airspace system to projected weather disruptions.

E. New Aircraft Design Concepts

New types of aircraft specifically tailored for weather-adaptation will likely be required in the 2050 and beyond timeframe to successful adapt to weather hazards that might still occur despite ongoing research and development efforts into sustainable aviation by NASA, other governmental research organizations, and industry. NASA has a long history of studying 'runway independent aircraft' (RIA) – i.e., VTOL (vertical takeoff and landing) and STOL (short takeoff and landing) aircraft of various types. But such studies haven't directly considered the implication of RIA in the context of weather mitigation and weather adaption. Hybrid electric regional CTOL (conventional takeoff and landing) aircraft are currently being studied by NASA ARMD, but only a very small amount of research is currently being conducted for hybrid-electric large, regional VTOL and/or STOL aircraft.

F. Potential Future NASA Aeronautics Technology Portfolio Investments

The BEARS effort is a small first step to address a potentially very large societal problem. To fully address some of the questions being raised in the CAS BEARS effort, it might be necessary to revisit the NASA technology portfolio and determine if, and how, the portfolio investments need to be rebalanced. The study is just a small step toward considering this possibility and sparking discussion around what a rebalanced technology portfolio might be.

VII. Future Economic Impact Modeling

The three key disruptors of extreme weather, disruptive technologies, and novel design to the national aviation system each require a different approach for economic modeling and damage estimation. Economic analysis of future aviation disruptions can take advantage of previous weather events and historical damages to create a model based on backcasting methods. Emerging threats can leverage benchmark events to create damage scenarios. Novel design and technologies will rely on technological assumptions and market projections, as they do not have reliable precedence or historical data. The latest advances in machine learning models and Bayesian statistical methods can be helpful for rapid deployment, recalculation, and discovery. However, network complexity and data availability remain significant obstacles to economic modeling efforts.

Changing extreme weather leads to significant economic damages in the national aviation system, ranging from direct damage to airport property and aviation infrastructure, airline and associated business losses, passenger delay and cancellation nuisance cost, physical injury, as well as insurance costs. The economic damages to aviation as a result of extreme weather are part of the "billion-dollar US weather disasters" [11]. Different types of extreme weather call for different types of economic modeling strategies. For increasing severe clear air turbulence, the main economic harm are to do with injury and mortality damages. As such, the appropriate economic models would apply here include mortality measures to estimate excess deaths (see [12]) and applying measures like the value of statistical life (VSL), or in the case of injuries, the value of a quality-adjusted life year (QALY).

For airports experiencing extreme heat, the economic model will focus on the costs associated with potential runway extensions, economic impact of weight-restricted loadings, and the cost of increased cooling for airports and aircraft. Ground staff may also be impacted and incur both defensive expenditures (such as cooling gear, fans, and other apparatus on the tarmac), more frequent water breaks and mandatory rests, as well as potential injury costs. For extreme cold, the economic model will focus on additional costs associated with deicing, snow clearance, and other planning and defensive costs for personnel.

The economic damages of increasing severe storms and severe weather, on the other hand, can leverage backcasting from previous episodes of severe weather and see how those have impacted aviation performance and operations. Using supervised machine learning methods and Bayesian statistics, the relationship between past severe weather events and aviation performance can be inferred, even without strong functional form assumptions. The costs of delays and cancellations can be measured by nuisance costs, lost wages, and direct airline losses [13, 14]. However, any backcasting model faces challenges. First, it is costly and challenging to obtain granular airline performance data, which are highly proprietary and protected. Second, the model is likely to best predict damages of origin or destination weather. En-route weather would be challenging due to possibilities of rerouting. Additionally, severe weather results in National Aviation Systems (NAS) delays, which means that there is a degree of cascading network delay effects that are conflated with weather in the data as well [13]. Similar approaches can be applied to study the effects of jetstream changes including ENSO and AO [15], though stronger assumptions about flight times and performance will have to be made. For rising sea levels, the economic analysis can focus on shutdown and recovery scenarios weighted against costs of defensive and adaptive measures such as flood proofing or sea walls.

Thus far, the economic damage models outlined above only cover short-run direct impacts. Aviation, however, also benefits regions through its positive spillovers by fostering long-run innovation, enhancing business connections, boosting tourism, and strengthening social capital [13].

For disruptive technologies such as eVTOL, electric propulsion, and hydrogen, the economic modeling will focus on the infrastructure costs - both for operations and for the users, as well as the economic cost of additional complexity in the aviation system. New charging stations, battery maintenance, hydrogen refueling stations will have to be installed and regulated. The additional airspace complexity will require enhanced FAA capacity projections and staffing. New training protocols and operational optimization will incur additional costs. Considerations on airspace congestion and new access corridors will add additional burden to the aviation management systems.

New wing and body designs and the return of supersonic aircraft will also incur different economic costs. New standards in noise mitigation, specialized route planning and ATC, as well as upgraded infrastructure at the airport design level will all incur significant costs to the aviation system.

To conclude, the economic modeling effort presents several challenges and opportunities. First, many of the source data that are important inputs to several economic model relies on granular data on flight performance. Airlines or other companies such as FlightAware are unlikely to provide these data due to their propriety nature. Currently, there are no publicly available historical records of the paths and their associated weather. Records related to international flights are likely restricted. While this is an opportunity for next-generation data collection effort to safeguard aerospace intelligence and understand aviation risks, the aforementioned models will likely benefit from quality historical data. Second, the aviation network as well as demand complexity continue to evolve. Demand structures have shifted significantly in the past decade, and next-generation aircraft that can serve long-distance, lower capacity routes will mean that the demand and network structures may look rather different in the future. Finally, advances in machine learning, artificial intelligence, and other advanced computational techniques could enhance the economic modeling efforts. For example, advances like the Tabular Prior-data Fitted Network (TabPFN) can boost rapid economic data analysis in the context of aviation resilience [16], and rapid updates can accelerate scientific discovery and enhance important decision-making for the nation's aeronautic systems.

VIII. Conclusion

The Building Enhanced Aviation Resilience Systems (BEARS) effort seeks to consider both near-term and mid- to long-term steps that could be taken by national and international stakeholders to enable aircraft and airspace adaptation to the projected impacts of weather hazards. Ultimately, the NASA CAS project's BEARS effort might be the catalyst that helps make the world's aviation systems more resilient to weather hazards, disasters, and other major societal disruptors. However, to meet that goal, it is crucial to begin to build a community of stakeholders who are actively engaged in attempted to understand and address this problem.

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References

[1] NASA Convergent Aeronautics Solution (CAS) project; https://www.nasa.gov/directorates/armd/tacp/cas/; last accessed April 15, 2025.

[2] NASA Transformative Aeronautics Concept Program (TACP); https://www.nasa.gov/directorates/armd/tacp/; last accessed April 15, 2025.

[3] Resilience engineering; https://www.resilience-engineering-association.org/; last accessed May 6, 2025.

[4] R. Burbidge, C. Paling, and R. M. Dunk, "A systematic review of adaption to weather hazards impacts in the aviation sector," *Transp. Rev.*, vol. 44, no. 1, pp. 8–33, Jan. 2024, doi: 10.1080/01441647.2023.2220917.

[5] A. Voskaki, T. Budd, and K. Mason, "The impact of weather hazards to airport systems: a synthesis of the implications and risk mitigation trends," *Transp. Rev.*, Jul. 2023, Accessed: Oct. 09, 2024. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/01441647.2022.2163319

[6] "EUROCONTROL study on weather hazards risks for European aviation," EUROCONTROL, Sep. 2021. Accessed: Oct. 09, 2024. [Online]. Available: https://www.eurocontrol.int/publication/eurocontrol-study-weather-change-risks-european-aviation

[7] M. C.-P. Poo, Z. Yang, D. Dimitriu, and Z. Qu, "Review on Seaport and Airport Adaptation to Weather hazards: A Case on Sea Level Rise and Flooding," *Mar. Technol. Soc. J.*, vol. 52, no. 2, pp. 23–33, Mar. 2018, doi: 10.4031/MTSJ.52.2.4.

[8] Saraf, A., et al, "Benefits Assessment of Integrating Arrival, Departure, and Surface Operations with ATD-2," IEEE/AIAA 36th Digital Avionics Systems Conference, DASC 2017, September 17-21, 2017.

[9] Federal Aviation Administration. Air Traffic Activity Data System (ATADS). Available at: https://aspm.faa.gov/opsnet/sys/airport.asp

[10] AirHelp (2022). The Economic Cost of Flight Disruptions. Available at: https://img.airhelp.com/Documents/AH_disruption_economic_cost.pdf

[11] Smith, A. B., and Katz, R. W., "US billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases," Natural Hazards, Vol. 67, 2013, pp. 387–410. https://doi.org/10.1007/s11069-013-0566-5.

[12] Young, R., and Hsiang, S., “Mortality caused by tropical cyclones in the United States,” Nature, 2024. https://doi.org/10.1038/s41586-024-07945-5.

[13] Wong, J. C. Y., “Essays on Aviation, Infrastructure, and Sustainable Development,” Ph.D. thesis, Columbia University, 2019; https://doi.org/https://doi.org/10.7916/d8-rhwk-vg95, URL https://doi.org/10.7916/d8-rhwk-vg95.

[14] Borsky, S., and Unterberger, C., “Bad weather and flight delays: The impact of sudden and slow onset weather events,” Economics of Transportation, Vol. 18, 2019, pp. 10–26. https://doi.org/10.1016/j.ecotra.2019.02.002, URL https://doi.org/10.1016/j.ecotra. 2019.02.002.

[15] Karnauskas, K. B., Donnelly, J. P., Barkley, H. C., and Martin, J. E., “Coupling between air travel and climate,” Nature Climate Change, 2015, pp. 1–6. https://doi.org/10.1038/nclimate2715, URL http://www.nature.com/doifinder/10.1038/nclimate2715.

[16] Hollmann, N., Müller, S., Purucker, L., Krishnakumar, A., Körfer, M., Hoo, S. B., Schirrmeister, R. T., and Hutter, F., “Accurate predictions on small data with a tabular foundation model,” Nature, Vol. 637, 2025, pp. 319–326. https://doi.org/10.1038/s41586-024-08328-6.

[17] Shireen Khalil, “New Zealand Plane Struck by Lightning Forced to Turn Back,” New York Post, Dec 10 2024. Retrieved 15 April 2025. https://nypost.com/2024/12/10/world-news/new-zealand-plane-struck-by-lightning-forced-to-turn-back/

[18] Steiner, M., Wiebke Deierling, Kyoko Ikeda, and Randall G. Bass, “Ground Delays from Lightning Ramp Closures and Decision Uncertainties,” *Air Traffic Control Quarterly*, Vol. 22, No. 3, 2016. https://doi.org/10.2514/atcq.22.3.223

[19] Keith, R., and Leyton, S. M., “An Experiment to Measure the Value of Statistical Probability Forecasts for Airports,” 2007. https://doi.org/10.1175/WAF988.1

[20] ICAO, “Effects of Climate Change on Aviation Business and Economics,” 2020.

[21] O’ Connor, A., and Kearney, D., “Evaluating the Effect of Turbulence on Aircraft During Landing and Take-Off Phases,” *International Journal of Aviation, Aeronautics, and Aerospace*, Vol. 5, No. 4, 2018. https://doi.org/10.15394/ijaaa.2018.1284

[22] Syme, P., “Severe Turbulence That Injured 17 People on a Delta Flight Is a Stark Reminder of Why You Need to Wear Your Seatbelt,” Business Insider, Dec 17 2024. Retrieved 15 April 2025. https://www.businessinsider.com/delta-turbulence-injured-17-istark-reminder-to-wear-seatbelt-2024-12

[23] Casto, D., “Weather Challenges Airport Operations Year-Round,” DTN, Apr 14 2023. Retrieved 15 April 2025. https://www.dtn.com/weather-challenges-airport-operations-year-round/

[24] “Airport Infrastructure: Selected Airports’ Efforts to Enhance Electrical Resilience,” GAO-23-105203, United States Government Accountability Office, August 2023.

[25] N.I. Petrov, A. Haddad, G.N. Petrova, H. Griffiths, and R.T. Waters, “Study of Effects of Lightning Strikes to an Aircraft,” *Recent Advances in Aircraft Technology*, 2012.

[26] Patrick Veillette, “Increased Lightning Will Affect Aviation, Part 1 | Aviation Week Network,” Aviation Week, May 04 2023. Retrieved 23 April 2025. https://aviationweek.com/business-aviation/safety-ops-regulation/increased-lightning-will-affect-aviation-part-1?check_logged_in=1

[27] “Saffir-Simpson Hurricane Wind Scale.” Retrieved 15 April 2025. https://www.nhc.noaa.gov/aboutsshws.php

[28] Alemazkoor, N., Rachunok, B., Chavas, D. R., Staid, A., Louhghalam, A., Nateghi, R., and Tootkaboni, M., “Hurricane-Induced Power Outage Risk under Climate Change Is Primarily Driven by the Uncertainty in Projections of Future Hurricane Frequency,” *Scientific Reports*, Vol. 10, 2020, p. 15270. https://doi.org/10.1038/s41598-020-72207-z

[29] Feng, K., Ouyang, M., and Lin, N., “Tropical Cyclone-Blackout-Heatwave Compound Hazard Resilience in a Changing Climate,” *Nature Communications*, Vol. 13, 2022, p. 4421. https://doi.org/10.1038/s41467-022-32018-4

[30] Chen, Y., Yang, S., and Yu, J., “A Quantitative Research on Climate Resilience in Coastal Airports from the Perspective of Adaptation,” *Environmental Systems Research*, Vol. 13, No. 1, 2024, p. 29. https://doi.org/10.1186/s40068-024-00362-7

[31] “Operating Near Hurricane Recovery Efforts | Federal Aviation Administration.” Retrieved 15 April 2025. https://www.faa.gov/air_traffic/flight_info/hurricane_season/operating-near-hurricane-recovery-efforts

[32] Chang, D., Bu, N., Zhang, N., and Xiao, H., “Climate Change and Tourism Demand: Risks for Extreme Heat?,” *Heliyon*, Vol. 10, No. 17, 2024, p. e37186. https://doi.org/10.1016/j.heliyon.2024.e37186

[33] “FSF ALAR Briefing Note 8.3- Landing Distances,” Flight Safety Foundation - Flight Safety Digest, 2000.

[34] Suzanne Rowan Kelleher, “Winter Storms: 8,600+ Flight Cancellations And Delays Today,” Forbes. Retrieved 15 April 2025. https://www.forbes.com/sites/suzannerowankelleher/2025/02/13/winter-storms-disrupted-flights-today/

[35] Jose A. Algarin Ballesteros and Nathan M. Hitchens, “Meteorological Factors Affecting Airport Operations during the Winter Season in the Midwest,” *Weather, Climate, and Society*, Vol. 10, No. 2, 2018, pp. 307–322. https://doi.org/10.1175/WCAS-D-17-0054.1

[36] “How Weather Impacts Major Airports in the United States - AMS Weather Band,” Aug 28 2023. Retrieved 15 April 2025. https://www.amsweatherband.org/weatherband/articles/how-weather-impacts-major-airports-in-the-united-states/

[37] “Large Aircraft Ground Deicing,” Federal Aviation Administration, Sep 30 1992.

[38] “Let It Snow: Airports Across U.S. Receive FAA Funding to Tackle Winter Weather | Federal Aviation Administration,” Nov 23 2022. Retrieved 15 April 2025. https://www.faa.gov/newsroom/let-it-snow-airports-across-us-receive-faa-funding-tackle-winter-weather

[39] Blake, D. M., Deligne, N. I., Wilson, T. M., Lindsay, J. M., and Woods, R., “Investigating the Consequences of Urban Volcanism Using a Scenario Approach II: Insights into Transportation Network Damage and Functionality,” *Journal of Volcanology and Geothermal Research*, Vol. 340, 2017, pp. 92–116. https://doi.org/10.1016/j.jvolgeores.2017.04.010

[40] Song, W., Lavallée, Y., Hess, K.-U., Kueppers, U., Cimarelli, C., and Dingwell, D. B., “Volcanic Ash Melting under Conditions Relevant to Ash Turbine Interactions,” *Nature Communications*, Vol. 7, No. 1, 2016, p. 10795. https://doi.org/10.1038/ncomms10795

[41] Vogel, A., Durant, A. J., Cassiani, M., Clarkson, R. J., Slaby, M., Diplas, S., Krüger, K., and Stohl, A., “Simulation of Volcanic Ash Ingestion Into a Large Aero Engine: Particle–Fan Interactions,” *Journal of Turbomachinery*, Vol. 141, No. 011010, 2018. https://doi.org/10.1115/1.4041464

[42] Drummelsmith, M., “How Weather Events Impact Aviation Insurers,” Aviation Specialty Insurance, Feb 24 2021. Retrieved 16 April 2025. https://aviationspecialtyinsurance.com/2021/02/24/how-weather-events-impact-aviation-insurers/

[43] Mike Gavin, “Why Can’t Firefighting Planes Fly When the Wind Gusts? – NBC Los Angeles,” NBC Los Angeles, Jan 13 2025. Retrieved 16 April 2025. https://www.nbclosangeles.com/news/local/fire-fighting-planes-grounded-due-to-wind-gusts/3603767/

[44] Sampson, H., Andrade, S., and Cappucci, M., “Is Your Plane Safe from a Tornado?,” *The Washington Post*, Jul 17 2024.

[45] Markolf, S. A., Hoehne, C., Fraser, A., Chester, M. V., and Underwood, B. S., “Transportation Resilience to Climate Change and Extreme Weather Events – Beyond Risk and Robustness,” *Transport Policy*, Vol. 74, 2019, pp. 174–186. https://doi.org/10.1016/j.tranpol.2018.11.003

[46] Zhou, L., and Chen, Z., “Measuring the Performance of Airport Resilience to Severe Weather Events,” *Transportation Research Part D: Transport and Environment*, Vol. 83, 2020, p. 102362. https://doi.org/10.1016/j.trd.2020.102362

[47] Malandri, C. <1990>, “How to Cope with Air Transport Disruptions: Airport Airside Resilience and Vulnerability,” Doctoral Thesis. Alma Mater Studiorum - Università di Bologna, 2020. https://doi.org/10.48676/unibo/amsdottorato/9480

[48] Glass, C., Davis, L., and Watkins-Lewis, K., “A Visualization and Optimization of the Impact of a Severe Weather Disruption to an Air Transportation Network,” *Computers & Industrial Engineering*, Vol. 168, 2022, p. 107978. https://doi.org/10.1016/j.cie.2022.107978

[49] Gu, Y., Wiedemann, M., Freestone, R., Rothe, H., and Stevens, N., “The Impacts of Shock Events on Airport Management and Operations: A Systematic Literature Review,” *Transportation Research Interdisciplinary Perspectives*, Vol. 27, 2024, p. 101182. https://doi.org/10.1016/j.trip.2024.101182

[50] Veli Ahmet Çevik, “Impacts of Climate Change on Logistics and Supply Chains,” *Afet ve Risk Dergisi Journal of Diaster and Risk*, Vol. 7, No. 2, 2024, pp. 368–391.

[51] Blanc-Brude, F., Nugier, F., and Marcelo, D., “Physical Risks & the Cost of Capital of Infrastructure Investments - Flood Damage Factor Estimation and Bond Yields in U.S. Airports.” https://doi.org/10.2139/ssrn.4695330

[52] Yesudian, A. N., and Dawson, R. J., “Global Analysis of Sea Level Rise Risk to Airports,” *Climate Risk Management*, Vol. 31, 2021, p. 100266. https://doi.org/10.1016/j.crm.2020.100266

[53] Zhou, Y., Zhang, N., Li, C., Liu, Y., and Huang, P., “Decreased Takeoff Performance of Aircraft Due to Climate Change,” *Climatic Change*, Vol. 151, No. 3, 2018, pp. 463–472. https://doi.org/10.1007/s10584-018-2335-7

[54] Thompson, T. R., “Climate Change Impacts Upon the Commercial Air Transport Industry: An Overview,” *Carbon & Climate Law Review*, Vol. 10, No. 2, 2016, pp. 105–112.

[55] Budd, L., and Ryley, T., “Chapter 3 An International Dimension: Aviation,” *Transport and Climate Change*, Vol. 2, Emerald Group Publishing Limited, 2012, pp. 39–64. https://doi.org/10.1108/S2044-9941(2012)0000002006

[56] Barbi, P., Tavassoti, P., Tighe, S., and Baaj, H., “Implications of Climate Variation in Flexible Airport Pavement Design and Performance,” 2021.

[57] Burbidge, R., “Adapting Aviation to a Changing Climate: Key Priorities for Action,” *Journal of Air Transport Management*, Vol. 71, 2018, pp. 167–174. https://doi.org/10.1016/j.jairtraman.2018.04.004

[58] Coffel, E., Thompson, T., and Horton, R., “The Impacts of Rising Temperatures on Aircraft Takeoff Performance,” *Climatic Change 144*, Vol. 144, 2017, pp. 381–388. https://doi.org/10.1007/s10584-017-2018-9

[59] Ren, D., Dickinson, R., Fu, R., Bornman, J., Guo, W., Yang, S., and Leslie, L., “Impacts of Climate Warming on Maximum Aviation Payloads,” *Climate Dynamics*, Vol. 52, 2019, pp. 1711–1721.

[60] Lee, J., Marla, L., and Vaishnav, P., "The Impact of Climate Change on the Recoverability of Airline Networks," *Transportation Research Part D: Transport and Environment*, Vol. 95, 2021, p. 102801. https://doi.org/10.1016/j.trd.2021.102801

[61] Minoretti, P., Serrano, M. G., Liaño Riera, M., Sáez, A. S., and Martín, Á. G., "Occupational Health Challenges for Aviation Workers Amid the Changing Climate: A Narrative Review," *Cureus*, Vol. 16, No. 3, 2024. https://doi.org/10.7759/cureus.55935

[62] Gultepe, I., "A Review on Weather Impact on Aviation Operations: Visibility, Wind, Precipitation, Icing," *Journal of Airline Operations and Aviation Management*, Vol. 2, No. 1, 2023, pp. 1–44. https://doi.org/10.56801/jaoam.v2i1.1

[63] Borsky, S., and Unterberger, C., "Bad Weather and Flight Delays: The Impact of Sudden and Slow Onset Weather Events," *Economics of Transportation*, Vol. 18, 2019, pp. 10–26. https://doi.org/10.1016/j.ecotra.2019.02.002

[64] Leung, A. C. W., Gough, W. A., and Mohsin, T., "Analysing Historical and Modelling Future Soil Temperature at Kuujjuaq, Quebec (Canada): Implications on Aviation Infrastructure," *Forecasting*, Vol. 4, No. 1, 2022, pp. 95–125. https://doi.org/10.3390/forecast4010006

[65] Uzarowski, L., Musial, M., and Rizvi, R., "Challenge of Permafrost Degradation Impact on Airport and Road Pavements," presented at the TAC 2018: Innovation and Technology: Evolving Transportation - 2018 Conference and Exhibition of the Transportation Association of Canada, 2018.

[66] McBeath, J., "Institutional Responses to Climate Change: The Case of the Alaska Transportation System," *Mitigation and Adaptation Strategies for Global Change*, Vol. 8, No. 1, 2003, pp. 3–28. https://doi.org/10.1023/A:1025840627213

[67] Hinkel, K., Nelson, F., Parker, W., Romanovsky, V., Smith, O., Tucker, W., Vinson, T., and Brigham, L., "Climate Change, Permafrost, and Impacts on Civil Infrastructure," Special Report 01-03, U.S. Arctic Research Commission Permafrost Task Force Report, December 2003.

[68] Melvin, A., Larsen, P., Boehlert, B., and Marchenko, S., "Climate Change Damages to Alaska Public Infrastructure and the Economics of Proactive Adaptation | PNAS," *Environmental Sciences*, Vol. 114, No. 2, pp. E121–E131. https://doi.org/10.1073/pnas.1611056113

[69] Foudad, M., Sanchez-Gomez, E., Jaravel, T., Rochoux, M. C., and Terray, L., "Past and Future Trends in Clear-Air Turbulence Over the Northern Hemisphere," *Journal of Geophysical Research: Atmospheres*, Vol. 129, No. 13, 2024, p. e2023JD040261. https://doi.org/10.1029/2023JD040261

[70] Evans, J. K., "An Examination of Aviation Accidents Associated with Turbulence, Wind Shear and Thunderstorm," 20130013459, Langley Research Center, May 2013.

[71] Williams, P., "Transatlantic Flight Times and Climate Change," *Environmental Research Letters*, Vol. 11, No. 2, 2016. https://doi.org/10.1088/1748-9326/11/2/024008

[72] Storer, L., Williams, P., and Joshi, M., "Global Response of Clear-Air Turbulence to Climate Change," *Geophysical Research Letters*, Vol. 44, No. 19, 2017, pp. 9976–9984.

[73] Prosser, M. C., Williams, P. D., Marlton, G. J., and Harrison, R. G., "Evidence for Large Increases in Clear-Air Turbulence Over the Past Four Decades," *Geophysical Research Letters*, Vol. 50, No. 11, 2023, p. e2023GL103814. https://doi.org/10.1029/2023GL103814

[74] Jiang, W., Chang, R. C., Yang, N., and Ding, M., "An Investigation of Sudden Plunging Motion Mechanisms for Transport Aircraft during Severe Clear-Air Turbulence Encounter," *Journal of Aerospace Engineering*, Vol. 36, No. 3, 2023. https://doi.org/10.1061/JAEEEZ.ASENG-449

[75] Storer, L., Williams, P., and Gill, P., "Aviation Turbulence: Dynamics, Forecasting, and Response to Climate Change," *Pure and Applied Geophysics*, Vol. 176, 2018, pp. 2081–2095.

[76] FAA, "AC 120-88A - Preventing Injuries Caused by Turbulence," 120–88A, FAA, January 2006.

[77] Williams, P. D., and Joshi, M., "Chapter 23: Clear-Air Turbulence in a Changing Climate," *Aviation Turbulence*, Springer International Publishing Switzerland, 2016, pp. 465–480.

Appendix – Summary of Impact Assessment of Weather Hazards and Natural Disasters

To understand the resilience of aviation against extreme weather hazards, the top four occurring weather patterns were investigated with respect to their effect on aviation:

Extreme Storms: several categories of severe storms that are widespread across the United States including thunderstorms, lightening and electrical storms, hurricanes and tropical storms, blizzards and ice/winter storms, seismic activity & ash, fire, wind & tornadoes from storms.

Flooding: effects of different forms of flooding such as inland flooding, storm surge, and sea level rise.

Extreme Temperatures: includes extreme heat, extreme cold, permafrost thaw for higher temperatures.

Clear Air Turbulence: occurs in clear skies that cannot be detected by pilots or traditional aviation equipment.

To effectively address extreme weather hazards, the following key impact dimensions are examined. Understanding these dimensions is crucial for developing coordinated strategies to enhance aviation system resilience:

Infrastructure: Examines the physical resilience of airports, runways, and terminals facing extreme weather threats, emphasizing structural adaptations

Operations: Focuses on the effect on air traffic management, flight scheduling, and ground operations under extreme weather conditions.

Aircraft Design: Involves the structural integrity and propulsion systems during severe environmental conditions.

Economics: Investigates the financial implications on aviation systems and the costs associated with disruptions caused by extreme weather conditions.

Health and Safety: Evaluates existing safety protocols in the aviation context, including guidelines for operation under extreme conditions and emergency response strategies.

	Hazard	Infrastructure	Operations	Aircraft Design	Economics	Health & Safety
Extreme Storms	**Thunderstorms**	- aircraft damage from lightning and hail [17]	- flight & ground delays [18] - holding & diversions leading to additional fuel burn [19] - runway closures due to rainfall [20] - difficulty landing due to wind [21]	- aircraft materials to withstand lightning and hail	- cancellations and delays - increased fuel [19]	- injuries caused by turbulence [22] - lightening and hail dangerous for ground personnel - injuries caused by strong wind gusts at takeoff/landing
	Lightening and Electrical Storms	- aircraft damage from lightning [17] - disrupted communication and measurement networks from electrical surge	- in-flight diversions - delays due to pause in ground crew operations [23] - power outages [24] - affected navigation and autopilot systems from lightening	- aircraft materials to withstand lightning strikes	- lightening related inspection and maintenance [25] - revenue loss from grounded damaged aircrafts [26] - backup power demands [24]	- lightning strikes dangerous for ground personnel [23] - lightening induced surges disrupt cockpit instrumentation
	Hurricanes and Tropical Storms	- aircraft damage from flooding and winds [27] - damages to terminals, runways, hangers [28,29] - power outages - radar and navigation system failures [28]	- cancellations and delays [30] - multi-day airport closures [31] - reduced airport capacity [31] - navigational errors from crosswinds	- aircraft materials to withstand flooding and winds [27]	- aircraft repair - infrastructure repair and maintenance - cancellations and delays [30] - passenger compensation for cancelled flights - tourism drop [32]	- injuries caused by strong wind gusts - risk of injuries and contaminants carried in floodwaters
	Blizzards and Ice/Winter Storms	- ice and snow on runways, taxiways - increased landing distances due to ice [33]	- cancellations [34] - delays for de-icing -reduced airport capacity [35,36] - decreased aircraft efficiency, increased fuel burn - disrupted ground crew operations, longer turnaround times - longer time for baggage handling	- ice accumulation on wings reduces lift and increases drag [37] - reduced fuel efficiency	- cancellations and delays - passenger compensation for cancellations - maintenance and repairs - runway de-icing [38]	- reduced visibility - ice and snow on surfaces increase risk of falls, vehicle collisions, skidding off runways
	Seismic Activity & Ash	- ashfall on runways - infrastructure damage from seismic shocks	- cancellations and delays - multi day disruptions or closures - cleaning ash from runways	- engine failure from ash [40] - reduced engine lifespan [41]	- cancellations and delays	- emergency landings from engine failures - reduced outdoor air quality harmful to passengers and personnel

		- disrupted ground navigation and communications from ash [39]				
	Fire, Wind & Tornadoes from Storms	- infrastructure damage from strong winds and tornadoes [42]	- cancellations and delays - winds affect aircraft ability to takeoff and land safely [43]	- aircraft materials to withstand strong winds - aircrafts such as UAS to pinpoint fire and tornado location	- cancellations and delays - maintenance and repairs	- reduced outdoor air quality harmful to passengers and personnel - injuries or fatalities caused by strong wind gusts at takeoff/landing [44]
Flooding	**Inland Flooding, Storm Surge, and Sea Level Rise**	- drainage system overload - runway, terminals, and equipment damages - structural degradation and permanent structural loss from chronic flooding - subsurface erosion - radar and navigation system failures	- cancellations and delays [45–47] - rerouted flights - large scale evacuations - multi day disruptions or closures - supply chain disruptions [48–50]	- material degradation, especially in prolonged exposure [51] - wet surfaces suboptimal for landing gear - compromised electrical systems in saltwater [52] - humidity and mold in aircraft ventilation systems	- cancellations and delays - maintenance and repairs - insurance claims	- harmful contaminants carried in floodwaters - risk of injuries to passengers and personnel - mold and mildew - contaminated drinking water supply - increased wildlife and pests
Extreme Temperatures	**Extreme Heat**	- higher takeoff speeds, longer runways [53] - heat damage to runways [54–56] - fuel flashpoint exceeded [54] - overheating equipment [57] - increased cooling requirements [57] - lack of infrastructure to protect outdoor personnel from heat	- cancellations and delays [58] - weight restrictions leading to reduced passenger and cargo capacity [58] - shift in tourism and passenger demand [58]	- higher takeoff speed increased fuel burn and engine wear [55] - speed limitations from engine and tires - decreased engine efficiency [59]	- cancellation and delays [60] - reduced capacity from weight restrictions - increased cooling costs [54] - maintenance - infrastructure improvements such as lengthening runways	- high cockpit temperatures affect pilots physically and cognitively [61] - fuel spills ignite if flashpoint temperature is exceeded - high temperatures dangerous to ground crew, passengers [55] - increased noise pollution in cooler hours
	Extreme Cold	- increased landing distances due to ice [55] - freezing equipment	- cancellations - delays from ice removal [63]	- ice accumulation on sensors [55] - engine power loss [62]	- cancellation and delays - de-icing - maintenance and repairs - increased heating costs	- ice and cold temperatures risk to ground personnel - vehicle collisions from ice [55]

		- engine power loss due to icing [62] - inaccurate altitude and airspeed measurements due to icing sensors [62]	- increased drag and decreased lift from ice on wings			- planes skid off runways from ice - engine power loss [62] - inaccurate altitude and airspeed measurements due to icy sensors [55]
	Permafrost Thaw	- settlement of runways, taxiways, roads [64,65] - rough, bumpy pavements [65] - settlement of airport buildings [65]	- disruptions to airport significantly impact rural communities that are inaccessible by roadways [66,67]	- rough runways damage aircrafts	- repairs to damaged infrastructure [68] - relocation of buildings, runways in the case of ground settlement [68]	- rough runways hazard during landing, taxiing, and take off
Turbulence	**Clear Air Turbulence**	- aircraft damaged from strong turbulence [69,70] - traditional radar systems cannot detect clear air turbulence	- longer flight times for diversions [71]	- material fatigue due to repeated turbulence [69]	- fuel cost from longer flight times [71,72] - maintenance [73] - accident compensations [72]	- plunging aircrafts from strong wind shear [74] - engine stall [74] - injuries to passengers and crews [75–77] - rare but possible fatalities [70] - heightened stress and mental impacts [69,70]