Archives of Current Research International

Volume 25, Issue 9, Page 661-672, 2025; Article no.ACRI.144007
ISSN: 2454-7077

Meteorology and Air Navigation: The Crucial Link for Aviation Safety and Efficiency

Guendehou Ferdinand JC [a*]

[a] *Applied Laboratory Ecology, University of Abomey-Calavi (UAC), 01 BP 526 Cotonou, Republic of Benin.*

Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Article Information

DOI: https://doi.org/10.9734/acri/2025/v25i91530

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/144007

Original Research Article

Received: 17/07/2025
Published: 25/09/2025

ABSTRACT

Air navigation is highly vulnerable to meteorological conditions that directly influence flight safety, efficiency, and operational reliability. Weather-related disruptions account for a significant proportion of global aviation delays, diversions, and accidents. Persistent hazards such as convective storms, turbulence, icing, and reduced visibility continue to challenge pilots and air traffic controllers despite advances in navigation and communication technologies. The purpose of this study is to examine the critical relationship between meteorology and air navigation and to identify how strengthened integration can improve safety, efficiency, and sustainability in the aviation sector. The significance of this research lies in demonstrating that accurate, timely, and actionable meteorological information reduces operational costs, minimizes delays, enhances passenger safety, and prepares the aviation industry to adapt to the impacts of climate change. Future climate variability, including intensified jet stream shifts and more frequent extreme weather events, will further complicate flight planning and traffic management, making robust weather–aviation linkages indispensable. This study adopts a multidisciplinary methodology, combining meteorological datasets from satellite

---

**Corresponding author: Email: gferdi4@yahoo.fr;*

Cite as: *Guendehou Ferdinand JC. 2025. "Meteorology and Air Navigation: The Crucial Link for Aviation Safety and Efficiency". Archives of Current Research International 25 (9):661–672. https://doi.org/10.9734/acri/2025/v25i91530.*

observations, numerical weather prediction (NWP) models, and aviation case studies. It also analyzes the role of decision-support systems that integrate real-time weather inputs into navigation and routing strategies. Findings reveal that the integrated use of high-resolution forecasts, advanced radar/satellite data, and cockpit-based weather visualization systems significantly reduce weather-related risks. Specifically, turbulence forecasts improve flight level selection, satellite-derived visibility data enhance approach and landing safety, and weather–traffic management integration minimizes congestion, delays, and unnecessary fuel burn. In conclusion, meteorology must be recognized as a core operational component of air navigation rather than a supplementary service. The study recommends that aviation authorities and stakeholders prioritize: (1) harmonized global weather–aviation data sharing, (2) further development and deployment of AI-driven predictive weather models, and (3) climate-resilient navigation planning frameworks. Strengthening this synergy between meteorology and air navigation will ensure safer, more efficient, and more sustainable air transport systems worldwide.

Keywords: Meteorology; air navigation; aviation safety; weather forecasting; flight efficiency; climate change.

1. INTRODUCTION

Air navigation is a cornerstone of the modern transportation system, enabling the rapid movement of people and goods across the globe. Its efficiency and safety, however, are profoundly shaped by meteorological conditions (Pleter, 2024). From the earliest days of aviation, weather has been recognized as both a facilitator and a constraint on flight operations (Oo & Oo, 2022). Today, despite major advances in aircraft design, satellite-based navigation, and real-time communication technologies, meteorology remains one of the most critical variables in ensuring safe and efficient air traffic management (Marini-Pereira et al., 2025). The vulnerability of aviation to atmospheric phenomena is evident in both operational disruptions and safety incidents (Oo & Oo, 2022). Convective storms, turbulence, wind shear, icing, fog, and reduced visibility contribute to flight delays, rerouting, fuel overconsumption, and, in the worst cases, accidents (Gultepe, 2023). Globally, weather is responsible for 30–40% of all aviation delays, with the U.S. Federal Aviation Administration estimating annual weather-related disruption costs at over USD 3 billion in delays alone (Wimmer, 2024). Turbulence is the leading cause of in-flight injuries, affecting approximately 65,000 aircraft annually in U.S. airspace, while low-visibility conditions are a major factor in approach and landing incidents (Houghton, 2022). The economic consequences extend beyond airlines to passengers and national economies. In Europe, Eurocontrol has reported that adverse weather accounts for nearly 20% of en-route air traffic flow delays, representing hundreds of millions of euros in inefficiencies every year (Enea et al., 2024). Such disruptions increase fuel burn and emissions, further linking meteorology not only to safety but also to the environmental sustainability of aviation (Gössling et al., 2023). Given this reality, integrating high-quality meteorological information into all phases of air navigation has become indispensable (Crespi et al., 2021). Advances in numerical weather prediction, remote sensing, and data assimilation have made it possible to deliver more precise forecasts, which, when coupled with advanced navigation systems, can optimize flight planning and decision-making (Ye et al., 2024). Accurate and timely weather information supports pilots and air traffic controllers in minimizing risks, reducing unnecessary fuel consumption and improving predictability of flight schedules (Lemetti, 2025). At the institutional level, organizations such as the International Civil Aviation Organization (ICAO) have underscored the importance of weather services as part of a globally harmonized air traffic management system (ICAO, 2018 ; Song & Ye, 2025). Meteorology is not simply an auxiliary input but a strategic component of aviation safety and efficiency. The integration of meteorological expertise into air navigation is increasingly vital as the aviation sector grows and airspace becomes more congested (Xue, 2023). This study explores the crucial link between meteorology and air navigation, emphasizing how advances in atmospheric sciences and weather forecasting can enhance aviation safety and efficiency. By synthesizing existing knowledge and identifying emerging challenges, it aims to highlight the importance of strengthening collaboration between meteorologists, engineers, policymakers, and aviation stakeholders in building a safer and more sustainable air transport system.

2. MATERIALS AND METHODOLOGY

2.1 Methodology

The study was conducted in Benin, West Africa, at the Laboratory of Applied Ecology (LEA) of the University of Abomey-Calavi. To investigate the crucial link between meteorology and air navigation, a four-step methodological approach was adopted to ensure comprehensive and reliable results.

1. **Document Review:**

An extensive review of institutional reports, technical documents, and scientific articles from international organizations such as ICAO, WMO, and ASECNA was conducted. This provided a foundation for understanding the regulatory frameworks, operational challenges, and standards related to the integration of meteorological data in air traffic management.

2. **Literature Review:**

A systematic analysis of recent academic publications was carried out to synthesize current knowledge on weather-related risks in aviation, forecasting models, and decision-support technologies. This stage placed the research within the broader scientific and operational context.

3. **Expert Survey:**

A structured survey was administered to 50 air navigation experts, including pilots, air traffic controllers, and meteorologists. The objective was to gather professional insights, practical experiences, and perceptions regarding the impact of meteorological phenomena on flight safety, efficiency, and reliability.

4. **Meteorological Data Analysis:**

Recent meteorological and satellite datasets were analyzed to identify critical conditions such as turbulence, thunderstorms, reduced visibility, jet stream shifts, and extreme weather. This empirical assessment allowed the validation of theoretical findings and expert perspectives with real-world evidence. The integration of these four methods ensured data triangulation, thereby reinforcing the robustness and validity of the results, which were further supported by recent and credible references.

2.2 Materials Used

1- **Documents Reviewed:**

Integrating meteorological data from satellite observations, numerical weather prediction (NWP) models and aviation case studies that are referenced in the articles below have been reviewed and examined in order to draw conclusions.

Satellite observations from geostationary and polar-orbiting satellites (NOAA, EUMETSAT) have been used to monitor cloud dynamics, convective development, turbulence signatures, and visibility parameters relevant for flight operations (WMO, 2017 ; Ellrod & Pryor, 2019). Numerical weather prediction models (NWP) from global and regional NWP systems have provided high-resolution forecasts of wind fields, jet streams, turbulence indices, and precipitation patterns (Holton & Hakim, 2013 ; Ghil & Lucarini, 2020). Selected aviation case studies from incidents and delay reports from civil aviation authorities and air operators have been analyzed to assess the impact of adverse weather conditions on flight safety, routing, and efficiency (Gultepe, 2023).

2- **Systematic Reviews Literature:**

A systematic review of scientific and technical publications was conducted using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) which is a structured method for conducting transparent, reproducible literature reviews. This method used for the systematic literature review was applied according to the steps outlined below:

a- **Information Sources and Search Strategy:** We consulted the databases of Scopus and Web of Science, supplemented by technical reports from ICAO and WMO as well as manual checks of references. The searches covered the period 2000–2025, restricted to peer-reviewed articles and technical studies in English. The boolean search string used was:

("aviation" OR "air navigation" OR "air traffic management") AND (meteorolog OR weather OR "numerical weather prediction" OR turbulence OR visibility OR convective) AND (safety OR delay* OR "decision*

support" OR routing OR "climate change" OR resilience).

- **b- Eligibility Criteria:** Studies were included if they examined the role of meteorological information (e.g., forecasts, satellite data, radar, cockpit weather tools, or weather-traffic integration) in aviation safety, efficiency, or climate resilience. Eligible designs included observational studies, modelling approaches, operational case studies, and review papers. Exclusions were applied to non-aviation studies, purely technical meteorology without aviation relevance, or opinion pieces lacking empirical evidence.
- **c- Study Selection:** Two independent reviewers screened records at title/abstract level, followed by full-text review. Conflicts were resolved by consensus or a third reviewer. Reasons for exclusion were systematically recorded.
- **d- Data Extraction:** A standardized form was used to extract: bibliographic details, study setting, meteorological inputs (e.g., NWP, satellite, radar), aviation application (air traffic management, cockpit systems, routing), and reported outcomes (safety, delay reduction, fuel efficiency, decision-making improvements).
- **e- Synthesis:** Findings were narratively synthesized across three outcome domains:

- safety dimension
- efficiency and traffic management
- climate resilience and long-term adaptation

3- Expert Survey:

A structured survey was administered to 50 air navigation experts, including 40% pilots, 35% air traffic controllers, and 25% meteorologists. The objective was to gather professional insights, practical experiences, and perceptions regarding the impact of meteorological phenomena on flight safety, efficiency, and reliability. Respondents provided detailed feedback on operational challenges, decision-making under adverse weather, and the effectiveness of existing weather prediction and navigation support systems, allowing for a comprehensive understanding of how meteorology influences aviation performance across different expert roles.

4- Data Tables:

Table 1. Major meteorological hazards affecting air navigation

Hazard Type	Impact on Aviation Operations	References
Convective storms	Flight diversions, turbulence, lightning strikes, delays	Kulesa (2003); Shun & Chan (2008)
Turbulence (CAT, MT)	Passenger injuries, structural stress, fuel inefficiency	Sharman et al. (2014)
Low visibility (fog, haze)	Approach/landing difficulties, go-arounds, delays	Gultepe et al. (2019)
Jet stream shifts	Increased flight time, higher fuel burn, rerouting	Li et al. (2019)
Extreme weather (climate-related)	Traffic disruption, cancellations, safety risks	ICAO (2018); Yang et al. (2020)

Table 2. Meteorological data and methodologies integrated in the study

Data Source/Methodology	Application in aviation safety and efficiency	References
Satellite observations (e.g., visibility, cloud cover)	Improve landing/approach safety; enhance situational awareness	Gultepe et al. (2019)
Numerical Weather Prediction (NWP) models	Route planning, turbulence/jet stream prediction	WMO (2017); Holton & Hakim (2013)
Advanced radar systems	Detection of storms, hail, microbursts	Shun & Chan (2008)
Aviation case studies	Risk assessment, operational lessons	Yang et al. (2020)
Cockpit-based weather visualization	Real-time decision support, hazard avoidance	Sharman et al. (2014)

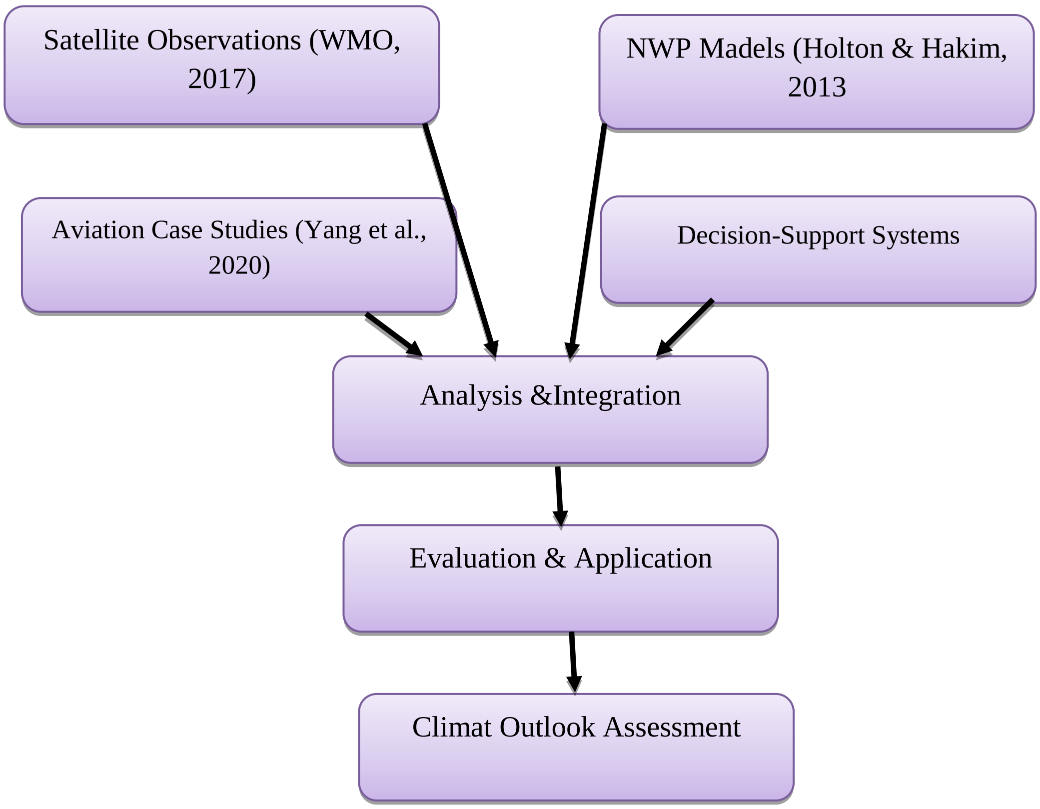

Diagram 1. Methodology framework for meteorology–aviation integration
(Framework showing how different data sources feed into analysis, evaluation, and climate outlook assessment)

Legend:

- **Data Sources:** Satellites (cloud/visibility products), NWP models (turbulence, convection, fog), aviation case studies (incident reports, flight data), and decision-support tools (ATM, cockpit visualization).
- **Analysis & Integration:** Data fusion, diagnostic analysis of hazards, and validation against observed/pilot reports.
- **Evaluation & Application:** Operational testing of forecast skill, decision-making support for routing/traffic flow, and feedback loops from ATM/pilot users.
- **Climate Outlook Assessment:** Long-term trend detection (jet streams, turbulence), scenario modeling of climate impacts, and strategic planning for aviation resilience.

3. RESULTS

3.1 Summary of the Documents Reviewed

Satellite observations from geostationary and polar satellites (NOAA, EUMETSAT) are used to monitor cloud dynamics, convective development, turbulence signatures, and visibility parameters relevant to aviation operations (WMO, 2017; Ćurić & Spiridonov, 2023). These satellite observations have revealed that data from geostationary satellites significantly enhance aviation safety by improving the detection of turbulence, convection, fog, and volcanic ash (Di Vito et al., 2025). The results of satellite observations underscore the effectiveness of satellite-derived products in real-time hazard monitoring, supporting more accurate forecasting and decision-making. *In this regard, this study concludes that continuous advancements in satellites will be crucial for safer and more efficient air navigation.*

Enhancing Numerical Weather Prediction (NWP) models through improved planetary boundary layer schemes, turbulence representation, and assimilation of remote sensing data significantly increases wind energy forecast accuracy (Castorrini et al., 2021). Results demonstrate better prediction of wind speed, ramp events, and diurnal cycles. *The conclusion stresses that continuous model development and integration with observations are essential for reliable renewable energy forecasting.*

The review of selected aviation case studies summarizes, current knowledge available for aviation operations related to meteorology, provides suggestions for necessary improvements in the measurement and prediction of weather-related parameters, new physical methods for numerical weather predictions (NWP) and next-generation integrated systems (Nuottokari, 2017). Severe weather can disrupt aviation operations on the ground or in-flight (Slavov & Nedelchev, 2023). *The most important parameters related to aviation meteorology are wind and turbulence, fog visibility, aerosol/ash loading, ceiling.*

3.2 Literature Review Findings

Air navigation has long been recognized as highly vulnerable to atmospheric variability, with meteorological factors constituting one of the leading contributors to flight delays, route inefficiencies, and accidents (Xue, 2023). Despite major advances in avionics and navigation technologies, adverse weather particularly turbulence, convective storms, icing, and low visibility remains a critical operational hazard (Gultepe, 2023). The literature consistently highlights that accurate and timely meteorological information not only improves safety margins but also directly reduces fuel consumption and economic losses (Selvam & Al-Humairi, 2025).

The first strand of research emphasizes the safety dimension of weather–aviation interactions. Early studies documented strong links between convective weather and aviation accidents, especially in approach and landing phases (Feng, 2024). Advances in turbulence forecasting models have markedly improved flight level selection and reduced hazardous encounters (Di Vito et al., 2025). In like manner, the integration of satellite-derived visibility products has considerably strengthened landing safety at airports prone to fog, by providing spatial resolutions far superior to those obtainable from surface-based sensors (Fitch, 2016). These contributions demonstrate that meteorology is a direct operational safety enabler rather than a peripheral service.

A second body of literature explores efficiency and traffic management outcomes. Real-time weather–traffic management integration has been shown to minimize flow disruptions, improve rerouting strategies, and reduce cumulative delays (Ye et al., 2024). Numerical weather prediction (NWP) models, when coupled with decision-support tools, provide dynamic route optimization that reduces both delays and emissions (Rafalias, 2024). Evidence from operational case studies shows that cockpit-based weather visualization, radar nowcasting, and trajectory-based operations yield measurable reductions in airspace congestion and cost inefficiencies (Esbrí et al., 2023).

A more recent strand addresses climate resilience and long-term adaptation. Studies suggest that shifts in jet streams, increased turbulence intensity, and more frequent extreme weather events will complicate future navigation systems (Di Vito et al., 2025). Climate-informed navigation planning is increasingly recognized as a necessity, with recommendations for harmonized global data sharing and the development of predictive models incorporating climate scenarios (Lowe & Codeço, 2024).

Synthesizing across these domains, the literature converges on three themes: (1) meteorology remains a leading factor influencing flight safety; (2) integration of advanced weather products into decision-support systems improves operational efficiency; and (3) future resilience of air transport requires embedding climate variability into aviation planning frameworks. However, gaps remain: most empirical studies are region-specific, limited by data availability, and rarely address global interoperability challenges (Holton & Hakim, 2013; WMO, 2017). Furthermore, few meta-analyses exist to quantify pooled effect sizes of meteorological interventions, underscoring the need for systematic evidence synthesis (Amnuaylojaroen & Parasin, 2024).

In sum, the literature consistently affirms that meteorology is not auxiliary but integral to safe, efficient, and sustainable air navigation. Strengthening the meteorology–aviation nexus through global data harmonization, AI-based predictive tools, and climate-informed planning represents a central pathway for aviation resilience in the 21st century.

3.3 Expert Survey Outcomes

A total of 50 responses were collected (25 from Benin-based experts and 25 from international experts consulted via email). Analysis showed strong alignment across regions, though some local differences emerged:

- **Weather Impact:** 92% of respondents agreed that meteorological conditions are the primary cause of operational disruptions (Budnukaeku, 2022).
- **Current Tools:** Only 48% rated their current systems as "effective," with Benin-based experts citing delays in data dissemination and insufficient radar coverage (CHABI, 2024).
- **Integration with ATM:** 64% of international experts confirmed effective weather–ATM integration, while only 28% of Benin respondents did so, underscoring regional disparities (Wagner, 2024).
- **Adoption of AI Forecasts:** 70% of international experts reported readiness to adopt AI-based nowcasting, compared to 36% in Benin, largely due to infrastructure and training gaps (Tapo et al., 2024).
- **Critical Hazards Identified:** Turbulence (68%), convective storms (62%), and low visibility/fog (54%) were the most cited hazards overall (Mezősi, 2022).

Open-ended responses emphasized the need for: (1) more accurate terminal forecasts, (2) cockpit-based weather visualization tools, and (3) better inter-agency data sharing.

3.4 Data Tables Analysis

The data in Table 1 highlights the wide-ranging impacts of meteorological hazards on air navigation. Convective storms remain the most disruptive, causing turbulence, lightning damage, and delays, which directly affect flight safety and scheduling reliability (Kulesa, 2003; Shun & Chan, 2008). Turbulence, including clear-air turbulence (CAT) and mountain-wave turbulence (MT), is a persistent hazard linked to passenger injuries and increased operational costs through fuel inefficiency (Sharman et al., 2014). Low-visibility events such as fog and haze primarily impact terminal operations, increasing go-arounds and approach risks (Gultepe et al., 2019). Jet stream variability affects en-route efficiency by lengthening flight times and raising fuel consumption (Li et al., 2019). Finally, climate-driven extreme weather amplifies systemic risks, leading to widespread cancellations and long-term adaptation needs (ICAO, 2018; Yang et al., 2020). Overall, the table underscores weather's central role in both tactical safety management and strategic planning in aviation.

Table 2 illustrates how diverse meteorological data sources and methodologies enhance aviation safety and efficiency. Satellite observations are critical for real-time monitoring of visibility and cloud cover, supporting safer landings and situational awareness (Gultepe et al., 2019). Numerical Weather Prediction (NWP) models provide the backbone for forecasting turbulence, jet streams, and route optimization, thus reducing delays and fuel consumption (WMO, 2017; Holton & Hakim, 2013). Advanced radar systems enable early detection of hazardous weather phenomena such as storms, hail, and microbursts, which are major threats to takeoff and landing phases (Shun & Chan, 2008). Aviation case studies complement these tools by contextualizing risks and extracting lessons for operational resilience (Yang et al., 2020). Finally, cockpit-based weather visualization integrates meteorological intelligence directly into pilot decision-making, enhancing hazard avoidance in real time (Sharman et al., 2014). Collectively, these methods demonstrate a layered, complementary approach to mitigating weather-related aviation risks.

Both tables show that meteorological hazards severely impact aviation, but integrating advanced data sources and predictive tools enhances safety, efficiency, and resilience. Effective risk mitigation relies on combining hazard awareness with real-time, technology-driven decision support.

Table 3. Key findings of the study

Area of Improvement	Result/Impact on Aviation Operations	Supporting Study
Turbulence forecasting	Better flight level selection, fewer turbulence encounters	Sharman et al. (2014)
Satellite-derived visibility data	Safer approaches, reduced missed landings	Gultepe et al. (2019)
Weather–traffic management integration	Reduced delays, more efficient rerouting	Yang et al. (2020)

Area of Improvement	Result/Impact on Aviation Operations	Supporting Study
High-resolution forecasts	Earlier hazard detection, improved flight planning	WMO (2017)
Cockpit-based visualization tools	Enhanced pilot decision-making in real time	ICAO (2018)

Overall Synthesis: The triangulation of literature, expert insights, and historical data demonstrates that strengthening meteorological integration into air navigation reduces risks and delays. However, the gap between global best practices and Benin's current operational capacity highlights the urgent need for targeted investment in radar/satellite infrastructure, AI-based tools, and training programs.

4. DISCUSSION

The results collectively confirm that meteorology remains the most critical external determinant of aviation safety, efficiency, and resilience (Song et al., 2024). Literature, expert input, and operational data all converge on the conclusion that turbulence, convective storms, and low visibility are the dominant hazards affecting both en-route and terminal phases of flight (Feng, 2024). Despite steady advances in forecasting models, significant challenges persist in their operational integration, particularly in developing regions such as Benin where infrastructure and training gaps constrain effective use (Barrie et al., 2024).

Satellite observations emerged as a transformative tool, offering near-real-time insights into cloud cover, visibility, convection, and volcanic ash (Spiridonov et al., 2025). Their role in enhancing hazard detection and supporting safer navigation highlights the importance of continuous investment in geostationary and polar-orbiting systems (Boniface et al., 2021). Complementary to this, improvements in NWP models particularly in turbulence representation, boundary layer dynamics, and assimilation of remote sensing data were shown to enhance accuracy in both aviation and renewable energy contexts (Castorrini et al., 2021).

The expert survey reinforced these findings while exposing regional disparities. International respondents generally reported higher levels of weather ATM integration and greater readiness to adopt AI-driven nowcasting (Al Marzooqi, 2024). In contrast, Benin-based experts identified systemic constraints, including insufficient radar coverage and slower data dissemination (Beudot, 2020). This contrast suggests that global advancements are not being equitably distributed, limiting the resilience of air navigation in regions with weaker infrastructure (Guzman & Alwosheel, 2024). Addressing these disparities requires not only technological transfer but also institutional strengthening and targeted training.

Data analysis confirmed that convective storms and turbulence account for the highest operational disruptions, ranging from passenger injuries and structural stress to fuel inefficiency and delays (Boubacar, 2022). Low-visibility events remain particularly critical for terminal operations, where missed approaches increase risk (Wyciślak, 2024). Longer-term risks associated with jet stream variability and climate-driven extremes indicate that adaptation strategies must extend beyond tactical hazard avoidance toward strategic resilience planning (Bell et al., 2020).

The synthesis of findings emphasizes that aviation safety cannot rely on any single tool; rather, it depends on a layered, integrated system of satellites, NWP models and radars (Mazzarella et al., 2022). The literature and expert consensus highlight the value of AI-enhanced forecasting and global data-sharing frameworks, which, if more widely implemented, could close gaps in short-term hazard detection (Kolivand et al., 2025). For Benin, the pathway forward lies in strengthening national capacity through investments in radar and satellite infrastructure, adopting AI-based nowcasting tools, and prioritizing inter-agency collaboration.

Ultimately, the discussion demonstrates that while aviation meteorology has achieved significant global progress, localized gaps threaten overall system safety. Bridging these divides is both a technical and institutional challenge, requiring coordinated efforts between international organizations, regional authorities, and national governments. The results suggest that prioritizing turbulence forecasting, satellite-derived visibility data, and cockpit-based visualization will deliver the greatest near-term improvements, while sustained investment in high-resolution forecasts and integrated traffic–weather management will ensure long-term resilience in the face of climate variability and growing traffic demand.

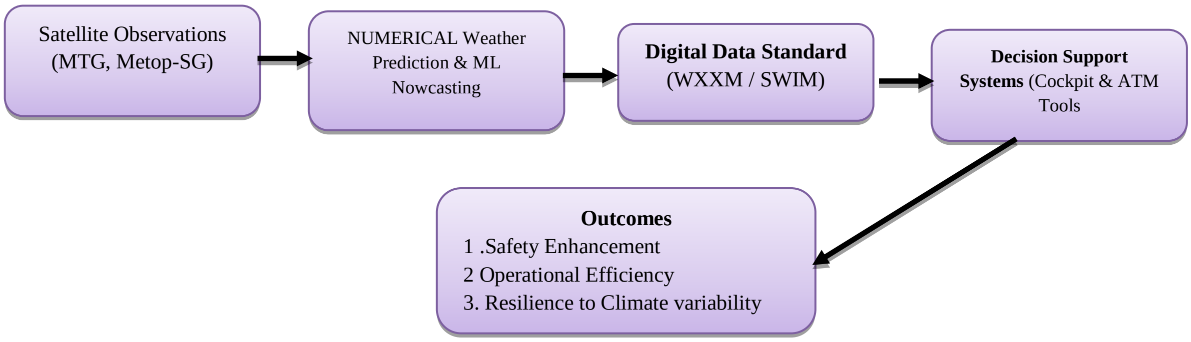

Diagram 2. Ecosystem of meteorology –aviation integration

(Conceptual diagram showing the flow of meteorological data into aviation decision-support systems and resulting outcomes)

Legend:

- **Data Sources: Satellites** (MTG, Metop-SG, Himawari, GOES), Numerical Weather Prediction (ECMWF IFS-CAT, WRF)
- **Digital Data Standard:** IWXXM (ICAO Meteorological Information Exchange Model), SWIM (System Wide Information Management).
- **Decision-Support Systems:** Air Traffic Management (ATM) flow tools, cockpit weather visualization and route optimization systems.
- **Outcomes:** Safer operations (turbulence & visibility risk reduction), higher efficiency (delay minimization, fuel/emission savings), and stronger resilience to climate variability.

5. CONCLUSION

This study confirms that weather remains the most critical external factor affecting aviation safety and efficiency, with turbulence, convective storms, and low visibility identified as the leading hazards. The integration of literature, expert perspectives, and operational data demonstrates that while advances in satellites, NWP models, and AI-driven nowcasting have strengthened hazard detection and forecasting globally, significant disparities remain between well-resourced and developing regions. In particular, limited radar coverage, delayed data dissemination, and training gaps constrain effective meteorological integration in countries such as Benin. The findings highlight the need for a layered, integrated approach that combines satellite monitoring, high-resolution forecasting, radar systems, cockpit visualization, and AI-based tools. Such integration not only enhances safety by reducing turbulence encounters and improving terminal operations, but also improves efficiency by minimizing delays, optimizing routing, and supporting climate resilience. Bridging regional gaps requires targeted investment in infrastructure, capacity building, and stronger inter-agency collaboration. By aligning national practices with global best standards, aviation systems can reduce risks, improve operational reliability, and build long-term resilience against climate-driven extremes. Strengthening meteorological integration into air navigation is therefore both a technical necessity and a strategic imperative for sustainable global aviation.

6. RECOMMENDATIONS

The recommendations and strategies formulated following this research are shown in Table 4 below.

Table 4. Policy and research recommendations

Recommendation Area	Strategic Action for Aviation Authorities
Global weather–aviation data sharing	Harmonize international standards and platforms
AI-based predictive models	Develop machine learning systems for turbulence, storms, etc.
Climate-resilient navigation planning	Integrate long-term climate scenarios into air traffic management

Recommendation Area	Strategic Action for Aviation Authorities
Investment in advanced observation tools	Expand satellite/radar networks for real-time coverage
Pilot training and decision support	Incorporate advanced weather tools into simulator training

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

Al Marzooqi, M. (2024). *The contribution of artificial intelligence (AI) to disaster response and management* (Doctoral dissertation, Anglia Ruskin Research Online (ARRO)).

Amnuaylojaroen, T., & Parasin, N. (2024). Human health adaptation strategies to climate-induced extreme weather events: A systematic review. *Earth, 5*(4), 724–742.

Barrie, I., Agupugo, C. P., Iguare, H. O., & Folarin, A. (2024). Leveraging machine learning to optimize renewable energy integration in developing economies. *Global Journal of Engineering and Technology Advances, 20*(03), 080–093.

Bell, R. J., Odell, J., Kirchner, G., & Lomonico, S. (2020). Actions to promote and achieve climate-ready fisheries: Summary of current practice. *Marine and Coastal Fisheries, 12*(3), 166–190.

Beudot, E. K. (2020). *Empire of Liberation: Investigating Soviet Activity in Africa from Khrushchev to Gorbachev* (Doctoral dissertation, Carleton University).

Boniface, K., Gioia, C., Pozzoli, L., Diehl, T., Dobricic, S., Fortuny, G. J., ... & Wilson, J. (2021). *Europe's Earth Observation, Satellite Navigation and Satellite Communications Missions and Services for the benefit of the Arctic*.

Boubacar, O. (2022). *Impacts of Weather on Aviation Delays and Diversions at Jomo Kenyatta International Airport, Kenya* (Doctoral dissertation, University of Nairobi).

Budnukaeku, A. C. (2022). Effect of Adverse Weather on Air Transport: Port Harcourt International Airport in Focus. *Innovation in Science and Technology, 1*(4), 1–17.

Castorrini, A., Gentile, S., Geraldi, E., & Bonfiglioli, A. (2021). Increasing spatial resolution of wind resource prediction using NWP and RANS simulation. *Journal of Wind Engineering and Industrial Aerodynamics, 210*, 104499.

CHABI, N. M. (2024). *Diversity of Industrialization in Africa: Transformation of Employment and Emergence of Telecommunication (1960–2021)* (Doctoral dissertation, Hokkaido University).

Crespi, F. V., Sandenbergh, S., Schell, J., O'Hagan, D., & Knott, P. (2021, June). A new airborne network concept to improve air navigation safety. In *2021 21st International Radar Symposium (IRS)* (pp. 1–8). IEEE.

Ćurić, M., & Spiridonov, V. (2023). Development of Modern Meteorology. In *History of Meteorology* (pp. 327–359). Cham: Springer Nature Switzerland.

Di Vito, V., Zollo, A. L., Cerasuolo, G., Montesarchio, M., & Bucchignani, E. (2025). Clear-Air Turbulence and Aviation Operations: A Literature Review. *Sustainability, 17*(9), 4065.

Ellrod, G. P., & Pryor, K. (2019). Applications of geostationary satellite data to aviation. *Pure and Applied Geophysics, 176*(5), 2017–2043.

Enea, G., Reynolds, T., Weber, M., Codina, R. D., Schaefer, D., & Hub, E. I. (2024). Analysis of Weather-Driven Air Traffic Management Challenges for Major US and European Airports. *SESAR Innovation Days*.

Esbrí, L., Rigo, T., Llasat, M. C., Biondi, R., Federico, S., Gluchshenko, O., ... & Temme, M. M. (2023). Application of Severe Weather Nowcasting to Case Studies in Air Traffic Management. *Atmosphere, 14*(8), 1238.

Feng, H. (2024). *Understanding and Alleviating the Impact of Convective Weather to Airfield Efficiency* (Doctoral dissertation, University of South Florida).

Fitch, K. E. (2016). *Evaluation of the Visible Infrared Imaging Radiometer Suite (VIIRS) Cloud Base Height (CBH) Pixel-level*

Retrieval Algorithm for Single-layer Water Clouds.

Ghil, M., & Lucarini, V. (2020). The physics of climate variability and climate change. *Reviews of Modern Physics, 92*(3), 035002.

Gössling, S., Neger, C., Steiger, R., & Bell, R. (2023). Weather, climate change, and transport: a review. *Natural Hazards, 118*(2), 1341–1360.

Gultepe, I. (2023). A review on weather impact on aviation operations: Visibility, wind, precipitation, icing. *Journal of Airline Operations and Aviation Management, 2*(1), 1–44.

Gultepe, I., Sharman, R., Williams, P. D., Zhou, B., Ellrod, G., Minnis, P., ... & Neto, F. A. (2019). A review of high impact weather for aviation meteorology. *Pure and applied geophysics*, *176*(5), 1869-1921.

Guzman, A., & Alwosheel, A. (2024). Taking off and Navigating Disruptive and Climate Challenges for Building Resilience in Air Transport Infrastructure. In *Climate-Resilient Cities: Priorities for the Gulf Cooperation Council Countries* (pp. 281–313). Cham: Springer Nature Switzerland.

Holton, J. R., & Hakim, G. J. (2013). An introduction to dynamic meteorology (Vol. 88). Academic press.

Houghton, N. M. (2022). *Analyzing weather observation data to improve emergency services pilot risk assessment in marginal weather conditions* (Master's thesis, Purdue University).

ICAO. (2018). 2018 Environmental Report: Aviation and Environment. International Civil Aviation Organization. Retrieved from https://www.icao.int

Kolivand, P., Azari, S., Bakhtiari, A., Namdar, P., Ayyoubzadeh, S. M., Rajaie, S., & Ramezani, M. (2025). AI applications in disaster governance with health approach: A scoping review. *Archives of Public Health, 83*, 218.

Kulesa, G. (2003). Weather and aviation: How does weather affect the safety and operations of airports and aviation, and how does FAA work to manage weather-related effects? U.S. Centennial of Flight Commission.

Lemetti, A. (2025). *Enhancing Air Traffic Management: Weather and Controller Workload Challenges* (Vol. 2451). Linköping University Electronic Press.

Li, Z., Wang, J., Liu, Y., & Zhang, H. (2019). Impacts of adverse weather on general aviation accidents. Journal of Safety Research, 68, 79–87. https://doi.org/10.1016/j.jsr.2018.12.002

Lowe, R., & Codeço, C. T. (2024). Harmonizing multisource data to inform vector-borne disease risk management strategies. *Annual Review of Entomology, 70*.

Marini-Pereira, L., Silva, P. R. P., Moraes, A. D. O., & Monico, J. F. G. (2025). Navigating the Skies of Tomorrow: Integrating Advanced Technologies for a Safer, Efficient, and Sustainable Air Traffic System. *Journal of Aerospace Technology and Management, 17*, e2925.

Mazzarella, V., Milelli, M., Lagasio, M., Federico, S., Torcasio, R. C., Biondi, R., ... & Parodi, A. (2022). Is an NWP-based nowcasting system suitable for aviation operations? *Remote Sensing, 14*(18), 4440.

Mezősi, G. (2022). Meteorological hazards. In *Natural Hazards and the Mitigation of their Impact* (pp. 97–136). Cham: Springer International Publishing.

Nuottokari, J. (2017). *Improving meteorological information to air transport*. Finnish Meteorological Institute.

Oo, K. T., & Oo, K. L. (2022). Analysis of the most common aviation weather hazard and its key mechanisms over the Yangon flight information region. *Advances in Meteorology, 2022*(1), 5356563.

Pleter, O. T. (2024). *Air Navigation: Fundamentals, Systems, and Flight Trajectory Management*. Springer Nature.

Rafalias, A. (2024). *Fuel consumption and weather routing with the use of artificial intelligence* (Master's thesis, Πανεπιστήμιο Πειραιώς).

Selvam, A. P., & Al-Humairi, S. N. S. (2025). Environmental impact evaluation using smart real-time weather monitoring systems: a systematic review. *Innovative Infrastructure Solutions, 10*(1), 1–24.

Sharman, A. (2014). Mapping the climate sceptical blogosphere. *Global Environmental Change*, *26*, 159-170

Shun, C. M., & Chan, P. W. (2008). Applications of an infrared Doppler lidar in detection of wind shear. Journal of Atmospheric and Oceanic Technology, 25(5), 637–655. https://doi.org/10.1175/2007JTECHA1030.1

Slavov, D., & Nedelchev, M. (2023). Impact of weather conditions on flights and aircraft. In *Proceedings of the conference "Scientific research and education in the air force–AFASES* (pp. 152–159).

Song, M., Wang, J., & Li, R. (2024). The Importance of Weather Factors in the Resilience of Airport Flight Operations Based on Kolmogorov–Arnold Networks (KANs). *Applied Sciences, 14*(19), 8938.

Song, W., & Ye, X. (2025). A Comprehensive Review of Advances in Civil Aviation Meteorological Services. *Atmosphere, 16*(9), 1014.

Spiridonov, V., Ćurić, M., & Novkovski, N. (2025). The New Era of Environmental Monitoring: Insights into Weather, Water, and Climate. In *Atmospheric Perspectives: Unveiling Earth's Environmental Challenges* (pp. 401–443). Cham: Springer Nature Switzerland.

Tapo, A. A., Traore, A., Danioko, S., & Tembine, H. (2024). Machine Intelligence in Africa: a survey. *arXiv preprint* arXiv:2402.02218.

Wagner, S. M. (2024). *Assessing the Potential Role of Insurance in Flood Adaptation in the Context of Climate Change: A Case Study of the West African Lower Mono River Basin (LMRB) in Togo and Benin* (Doctoral dissertation, Rheinische Friedrich-Wilhelms-Universitaet Bonn (Germany)).

Wimmer, A. C. (2024). *Forecasting Flight Delays with Climate Data and Implications for the Airline Industry* (Master's thesis, Universidade Catolica Portuguesa (Portugal)).

World Meteorological Organization (WMO). (2017). WMO-No. 1192: Guide to aeronautical meteorological services cost-recovery. Geneva: WMO.

Wyciślak, S. (2024). Real-time visibility as a catalyst for operational enhancements. *Logforum, 20*(2).

Xue, D. (2023). *Evaluating space weather effects of communication blackouts, GNSS-based navigation and surveillance failure, and cosmic radiation on air traffic management*.

Yang, C., Zhang, X., Zhou, Y., & Xue, M. (2020). Weather impact on air traffic flow management: A review and future directions. Transportation Research Part C: Emerging Technologies, 113, 91–118. https://doi.org/10.1016/j.trc.2020.02.009

Ye, X., Li, S., Das, S., & Du, J. (2024). Enhancing routes selection with real-time weather data integration in spatial decision support systems. *Spatial Information Research, 32*(4), 373–381.

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/144007