The Netherlands Press

Journal of Airline Operations and Aviation Management

Article

Aviation and Climate Change: Challenges and the Way Forward

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DOI: https://doi.org/10.56801/jaoam.v2i1.5

Abstract.

There is a broad scientific consensus that the phenomenon of global warming is very likely driving a global climate change. There is also a developing understanding that climate change and air transport have a two-way relationship. This paper aims to identify the possible impacts of climate change on the aviation sector and to discuss adaptation plans that will address the vulnerabilities and will ensure safe aviation-related operations. Climate change is known to cause disruptions in airport operations due to greater and more frequent temperature extremes and changes in precipitation and wind that are very possible to demand increased take-off distances and decreased climb rates. Extreme rainfall and rising sea levels may threaten coastal and low-lying airports with flooding. Changes in biodiversity and wildlife patterns intensify the bird strike hazard. Disruptions also occur in air operations. Increasingly frequent extreme weather events are responsible for air traffic delays. Changing atmospheric patterns and icing conditions challenge aircraft performance and rise flight duration and flight costs. The above risks may have a direct impact on travel and tourism, affecting destination favorability and the duration of the tourism season. All the above concerns call for urgent actions from the policymakers and the industry. Adaptation measures include the development of risk-assessment frameworks and action plans for the major stakeholders, technology advancements to deal with gas emissions and oil depletion, long-range infrastructure planning and investment, the introduction of climate-related regulations, as well as raising awareness and promoting collaboration as key steps in building climate change resilience for the global aviation sector.

Keywords: adaptation, airports, aviation, climate change, tourism.

Journal of Airline Operations and Aviation Management Volume 2 Issue 1

Received Date 24 January 2023
Accepted Date 05 May 2023
Published Date 15 August 2023

1. Introduction

According to an abundance of scientific evidence, the Earth's climate is changing due to increasing greenhouse gas concentrations in the atmosphere. The connection between modern climate change and emissions from human activity is widely recognized, and policymakers are becoming more cognizant of it. The recent commitment of the European Green Deal to attain carbon neutrality in Europe by 2050 is cause for optimism. The latest analysis from the United Nations Intergovernmental Panel on Climate Change (IPCC) indicates that the global average surface temperature is likely to reach 1.5°C above pre-industrial levels, the optimal target set by the Paris Agreement, within the next 20 years, regardless of any actions taken by the European Union to reduce greenhouse gas emissions. If no mitigation measures are implemented, global temperatures could rise by more than 5°C above pre-industrial levels by the end of the century [1].

Therefore, it is envisaged that the effects of climate change will intensify throughout the century. The melting of land ice and the warming of the oceans poses a hazard to the world's coastlines as sea levels rise. The resilience of infrastructure, transportation, supply chains, communities, and the global economy is threatened by these effects. Positively, although it may seem counterintuitive, the climate in certain regions may be more conducive to particular activities. This, however, would not be sufficient to mitigate the damage that climate change is likely to inflict [2].

There is a growing awareness that climate change and air travel are interdependent in multiple ways. On the one hand, aircraft and ground infrastructure emissions contribute to human-caused climate change. Aircraft, particularly, operate entirely within the troposphere and lower stratosphere, and thus may be directly affected by any changes to these layers of the atmosphere [3]. While the aviation industry has been cited for a long time as a contributor to the causes of climate change through greenhouse gas emissions, the need for the aviation industry to adapt to the effects of climate change has not been adequately studied or considered [4]. Adaptation considers how climate change-related impacts and risks can be mitigated and managed, whereas emission reductions are intended to mitigate the causes of climate change.

To prepare for these potential impacts, it is essential that the European aviation industry comprehends the nature and magnitude of the risks posed by climate change, and that it adapts and constructs resilience proportionally and expeditiously. This paper investigates the potential impacts of climate change on aviation and the development of adaptation strategies that address vulnerabilities and guarantee the safety of aviation-related operations.

1.1. Climate change impact on aviation and tourism

The International Civil Aviation Organization surveyed its 193 member states in 2019 to determine their understanding of climate change adaptation and related plans. Sixty-five percent of responding states believed that climate change had already had an impact on air transportation in their states, with an additional 15% anticipating an impact by 2030 [5]. As reported by Ryley et al. [4], the impact of climate change on air travel has three dimensions. First, ground operations will be disrupted by climate change as a result of more frequent and severe temperature extremes, changes in precipitation and wind, and rising sea levels. Second, air operations will be disrupted by altered atmospheric patterns and less predictable extreme weather events. Thirdly, there will be additional disruptions caused by varying passenger demand patterns, as climate impacts can render vacation destinations less desirable and sometimes inaccessible.

1.2. Climate change impact on airport operations

Climate change is known to cause disruptions in airport operations due to greater and more frequent temperature extremes and changes in precipitation and wind that are very possible to demand increased take-off distances and decreased climb rates. Extreme rainfall and rising sea levels may threaten coastal and low-lying airports with flooding. Changes in biodiversity and wildlife patterns intensify the birdstrike hazard.

Coastal flooding is made more likely by the thermal expansion of seawater and the thawing of glaciers, as well as the altering of storm patterns. Gratton [3] and Eurocontrol [6] estimate that the Global Mean Sea Level (GMSL) has risen by 0.2m since 1900 and is projected to rise by up to 0.84m by 2100, compared to 1986–2005. This would not only increase the risk for airports that are already at risk, but it would also endanger airports that are not at risk at present. More than 270 coastal and low-lying airports (aerodromes and aerodromes with heliports) were evaluated. Two-thirds of airports (178 out of 273) are expected to be at risk of marine inundation due to storm surges until 2090. Eurocontrol projects that by 2090, the number of ECAC airports at risk of severe or total flooding will increase by slightly more than 20%, posing significant operational and financial hazards [6]. The cost of diverted and canceled flights could range between €3 million (for medium airports) and €18 million (for large airports) in the event of a one-day closure due to total flooding. Pejovic et al. [7] evaluated the effects of a brief closure at London Heathrow Airport. A one-hour airport closure was estimated to cost between €700,000 and €1.250,000. Carbon costs associated with the closure could contribute between 230,000 and 340,000 euros, while estimates of external costs can reach up to 1,400,000 euros.

In addition, 91% of the airports identified as being at risk of inundation are small airports with fewer than 10,000 annual passenger movements. These minor airports may serve the local community, the military, the tourism industry, and the community of General Aviation (GA). Although the direct costs associated with flight disruptions at these airports may be minimal, it is anticipated that the indirect costs to the local or regional economies due to secondary effects will be significantly higher. At certain locations, ground transportation links to the airport may also be susceptible to flooding [8].

Wind velocities are also being altered at both the surface and altitude [6]. This is the result of a combination of rising temperatures, diminishing wind strength, and altering wind vectors. From the perspective of air transportation, near-surface winds are only significant near a runway. At airports with extensive runway length, the primary effect is increased takeoff distances; at airports with shorter runways, the payload is restricted [9]. Coffel & Horton[10] examined the effects of climate change and extreme temperatures on aviation and concluded that airports will generally need longer runways, and space-constrained airports are projected to have a significant increase in days with weight restrictions. Coffel et al. [11] examined the effects of increasing temperatures on the takeoff performance of aircraft. Rising temperatures have the greatest impact on medium/long-range aircraft and airports with limited runways at high altitudes. Gratton et al. [9] demonstrated that since at least 1955, climate change has gradually degraded the performance of aircraft departing from the ten evaluated Greek airports on both the turboprop and turbofan airliner scales. For airports where aircraft maximum take-off mass is a performance-limited function of runway length and where minimum temperatures have increased and/or mean headwind components have decreased, these results indicate that climate change has already had a significant impact on the airline industry's economic activity. Zhou et al. [12] conducted a study of the decreased take-off performance of aircraft as a result of climate change quantifying the effects of climate change on aircraft take-off performance, including take-off distance and climb rate. They concluded that changes in temperature and pressure altitude as a result of global warming will increase takeoff distances and decrease ascent rates. In the future summers, the Boeing 737-800 aircraft will require an additional 3.5–168.7 meters of launch distance.

Climate change along with other anthropogenic factors alters the distribution of bird populations and other animal migration patterns, posing a negative impact on aviation safety. Biodiversity challenges will differ based on the existing local ecosystem and the manner in which the regional climate changes. For instance, the number and types of bird species around an airport may alter. Changes in migratory patterns could affect aircraft operations and increase the risk of bird collisions, especially if heavyweight migratory bird populations increase in the area [8]. Dolbeer [13] reported an increasing trend of damaging bird strikes with aircraft outside the airport boundary. Flight routes and safety recommendations are based on known bird behaviors; however, bird migratory patterns are changing – for instance, in the Pacific due to El Niño altering foodsource availability, and southern species have been expanding their territory northwards; spring migrations have been occurring earlier in the year. Existing bird strike avoidance measures will be rendered ineffective by alterations in avian behavior until those alterations are understood and compensated for [3].

Climate change has a multifold impact on overall airport operability. Probably the nation that has examined the impact of climate change on national infrastructure the most closely is the United Kingdom, which, under the 2008 Climate Change Act, mandated that providers of major national infrastructure report periodically on their identified susceptibility to climate change and the mitigation measures they have implemented [3]. According to the most recent available climate impact reports of UK aviation infrastructure providers, as summarized by Gratton et al. [3], airports' operability is threatened by infrastructure devastation from flooding/drainage failure, flood damage to infrastructure, failure of pollution containment or balancing pond or pollution lagoon, sea-level increase, spontaneous fuel storage fires, heat deterioration of runway surfaces, water deficits, pollution due to the increased use of de-icing substances, high-temperature working conditions, future requirements for heating and air-conditioning, energy and water supply security risks, frequent fog interference with flight operations, increased adverse weather events causing runway closures and traffic delays, climate-driven market shifts, all of them describing the different dimensions of airport operations that can be affected by climate change.

1.3. Climate change impact on air operations

Climate-driven disruptions also occur in air operations. Increasingly frequent extreme weather events are responsible for air traffic delays. Changing atmospheric patterns and icing conditions challenge aircraft performance and rise flight duration and flight costs.

According to Federal Aviation Administration (FAA) statistics, approximately 70% of the US National Airspace System delays are caused by the weather [14]. Similarly in Europe, a very strong relationship was found between Significant Weather Days (SWDs) and the most major en-route ATFM delays, confirming that convection is responsible for a large proportion of the major en-route ATFM delay days [6]. Using extreme daily rainfall as a proxy for convective activity, it is projected that extreme rainfall days will increase in northern Europe, but decrease in southern Europe. Across northern and western Europe, weather patterns characterized by deep low-pressure systems are associated with a higher probability of ATFM delays due to disruptive high surface wind velocities [6]. Additionally, Pejovic, et al. [15] developed a climate model for London Heathrow Airport through 2050 which demonstrates that extreme weather conditions (thunderstorms, snow, and fog) increase the likelihood of weather-related delays by more than 25%, and an increase of 1 knot in wind speed above the mean increases the likelihood of delay by 8%. Flight delays also concern airports, since the latter serves as a hub for supplying passengers to airlines. Therefore, en-route delays can affect airport scheduling and berth management, while late arrivals can affect noise quotas and curfews [8].

Climate change seems to have a relationship with volcanism [16]. The isostatic discharge of glaciers may increase volcanic activity, resulting in aviation disruptions (e.g., ash clouds). Volcanic ash consists of crushed granite which is primarily composed of substances with a melting point lower than the operating temperature of an aircraft engine at cruise altitude. At cruise altitudes, the combination of pulverized rock and acidic gases can have a significant impact on the efficacy of jet engines. Mount Pinatubo's 1991 eruption resulted in ash that circled the globe in a matter of days and disrupted a multitude of air traffic routes because aircraft traversing this thin layer of ash required additional maintenance. Globally, there are 575 active volcanoes, which contribute an average of 50 eruptions per year, culminating in 50-75 "danger days" per year, according to statistics [16].

Climate change is also connected with in-flight icing. From 1989 to early 1997, in-flight icing contributed to or caused approximately 11% of all weather-related accidents involving general aviation aircraft in the USA [14]. Icing during flight is not only hazardous but also has a significant impact on flight operations efficacy. The rerouting and delays of commercial carriers, especially regional and commuter airlines, to avoid freeze conditions result in late arrivals, whereas all aircraft types incur additional fuel and other expenses due to route deviations. Structural icing on wings and control surfaces increases aircraft weight, reduces drag, produces erroneous instrument readings, and jeopardizes aircraft control [17]. Mechanical frost in carburetors, engine air intakes, and fuel cells impairs engine performance, resulting in a decrease in output. Small aircraft operate habitually at altitudes where temperatures and clouds are most conducive to ice formation, making them susceptible to icing for extended periods. Larger aircraft are most at risk during takeoff and landing in terminal locations [14].

An additional threat connected with changing climate is reduced ceiling height and visibility which poses safety risks for all forms of aviation [14]. Between 1989 and 1997, ceiling and visibility were cited as contributing factors in 24% of all general aviation accidents. They were also cited as contributing factors in 37% of commuter/air taxi accidents during the same period. Accidents involving low ceiling and poor visibility occur when unqualified pilots or pilots operating an aircraft without the necessary instrumentation encounter such conditions, leading to loss of control or controlled flight into terrain [14].

Climate change is associated with changes in wind patterns (en-route winds). The jet stream is a characteristic of high-altitude winds that significantly affect transatlantic flights. The jet stream is projected to strengthen and migrate poleward as a result of climate change, influencing the routing and duration of transatlantic flights [3]. The effect of weather patterns on flight duration is expected to be greatest in winter and least in summer [6]. Moreover, eastbound flights can benefit from stronger winds, while westbound flights can avoid harsher headwinds. This has a particularly strong impact on transatlantic flights, but it is anticipated that this effect will mostly influence flights between Europe and Asia [6]. Similarly, Williams [18] and Lee et al. [19] demonstrated a substantial increase in track-averaged tailwinds on eastbound transatlantic flights (and headwinds on westbound transatlantic flights) and calculated the effects of these altered winds on flight duration, fuel consumption, and CO2 emissions. Overall, these effects tend to indicate a 2% average increase in transatlantic travel durations due to changes in the mean wind speed. These variations are negligible in the time average, but they can be substantial on individual days. Although the average impact of altering wind patterns on a single flight may appear negligible, the impact of all aircraft operating on the global traffic flows is significantly greater [6].

Changes are occurring in jet streams and stationary wave pattern winds at cruising altitudes, particularly as a result of increased carbon dioxide forcing [3]. Since satellites began observing it in the late 1970s, the subpolar jet stream over the North Atlantic Ocean at flight cruising altitudes has become 15% more sheared [19]. Consequently, stronger wind shears increase both the intensity and frequency of clear-air turbulence (CAT). Non-convective turbulence poses a significant threat to aviation. The effects of turbulence range from mildly uncomfortable jostling of the aircraft for passengers and crews to severe injuries and transient loss of aircraft control caused by sudden accelerations. In addition to being hazardous, clear-air turbulence has a significant impact on the efficacy of flight operations due to aircraft rerouting and delays [14]. Storer et al. [20] conducted a study of the global response to climate-induced clear-air turbulence using climate model simulations for the years 2050 to 2080. They found that large relative increases in clear-air turbulence are particularly prevalent in the midlatitudes of both hemispheres, with several hundred percent more turbulence in certain regions. The busiest international airspace also experiences the greatest increases.

Convective storms, in which flight is frequently hazardous due to turbulence, icing, wind shear, and lightning, are also predicted to increase in frequency due to climate change [3]. Eurocontrol analyzed the impact of storms on the airspace above Maastricht and forecasted an increase in spring and summer storms through 2050 [6]. It is impossible for aircraft to fly above these cyclones, which can extend over 17 km, with the majority of airliners limited to 12 km or below. This necessitates longer routes, steeper climbs and descents, and less efficient airspeeds, all of which hurt emissions, flight durations, and costs, and force more aircraft into certain portions of airspace, posing potential safety concerns that must be mitigated [3]. Lightning and hail damage can render an aircraft inoperable, resulting in revenue losses and increased maintenance costs. Weather is a major contributing factor in 23% of all aviation accidents. Depending on the type of aircraft involved, between 1989 and early 1997, the National Aviation Safety Data Analysis Center (NASDAC) identified thunderstorms as a contributing factor in 2% to 4% of weather-related incidents [14].

1.4. Climate change impact on tourism

The above risks may have a direct impact on travel and tourism, affecting destination favorability and attractiveness and the duration of the tourism season. Tourism is considered to be a highly climate-sensitive industry both contributing to human-induced climate change and strongly affected by the ecological and socioeconomic changes caused by climate change [21]. The increasing impact of climate change on temperatures, weather patterns, and the environment around the world can change the attractiveness (and thus demand) of existing tourist destinations geographically, temporally, or both. There is evidence that European tourism flows may shift from South East to North West coupled with an appetite for domestic resorts in tourist-origin countries [6]. Coastal and maritime tourism has a high possibility to be negatively affected in favor of higher altitudes. Loss of attractiveness of the marine environment may happen due to beach availability reduction caused by sea level rise and beach erosion; species loss, increase in alien invasive species, or landscape degradation; the increased danger of forest fires in tourism areas; increased damages to infrastructures and facilities; reduced availability of domestic water; thermal stress and heat waves; health problems caused by emerging infectious diseases and loss of cultural heritage [22]. Climate change risks also affect winter sports tourism reducing natural snow availability. The final impact on ski resorts however will depend on their technical snowmaking capabilities [21].

1.5. Adaptation measures

All the above concerns call for urgent actions from the policymakers and the industry. Adaptation measures include the development of risk-assessment frameworks and action plans for the major stakeholders, technology advancements to deal with gas emissions and oil depletion, long-range infrastructure planning and investment, the introduction of climate-related regulations, as well as raising awareness and fostering cooperation as an important step to build resilience to climate change in the global aviation sector.

Initiatives have been taken at national and international levels to build resilience to climate change. In 2016, the United Nations in Paris brokered an international agreement to limit greenhouse gas emissions. The Paris Agreement recognizes the inevitable consequences of climate change and places an important and significant focus on adaptation and climate resilience [21]. The Intergovernmental Panel on Climate Change, the United Nations agency responsible for assessing the science of climate change, regularly assesses the science behind climate change, its impacts and future risks, and options for adaptation and mitigation [1]. European Union has developed the Climate Adaptation Strategy by the Sustainable and Smart Mobility Strategy [23, 24].

Aviation organizations have developed strategic plans focusing on air transport. ICAO in cooperation with Eurocontrol and the Federal Aviation Administration (FAA) has released a Synthesis and Guidance on Climate Change Risk Assessment and Adaptation Planning at the international level [25]. The Airport Council International has released a Policy Brief on Airport Resilience and Climate Change Adaptation, which provides an overview of the potential impacts of extreme and slow-onset climate stressors on airport operations and infrastructure and urges airport operators to conduct risk analysis for robust adaptation planning [26]. ACI has also published the Handbook on Airport Business Continuity Management to assist its members in enhancing their business continuity management [27]. Important initiatives have been also taken by the Federal Aviation Administration in the USA which developed the FAA Aviation

Weather Research Program (AWRP) to relieve weather impacts on National Airspace System safety, capacity, and efficiency [14]. Under the Airport Cooperative Research Program (ACRP) several publications have been made. ACPR Synthesis 33 provides airport executives and their technical managers with a document reviewing the extent of risks to airports from projected climate change and emerging approaches to addressing them [28]. ACRP Research Report 188 incorporates current and anticipated climate change hazards into airport management systems and planning. The manual identifies methods for reducing airport vulnerability to current and projected climate change impacts, such as extreme weather events. It also investigates methods to minimize airport facilities and operations' long-term costs [29]. ACRP Research Report 199 describes how to employ benefit-cost analysis tools and techniques to improve airport infrastructure project decision-making in response to potential long-term climate change and extreme weather impacts [30].

Industry stakeholders, also develop policies and strategic plans to deal with the risks of climate change. Aircraft manufacturers and airlines are working towards a net-zero carbo emissions goal by utilizing Sustainable Aviation Fuel (SAF), exploring hydrogen and biofuels' efficiency, creating better engines, modeling more aerodynamic planes, or even testing electric aircraft [31]. Airports that are particularly affected by climate change, are developing several responses, mainly of technical character. First, they need to re-assess their surface drainage capacity taking into account future precipitation forecasts. For example, Ottawa International Airport in Canada, added grooves to one of its main runways to enhance traction and drainage during heavy precipitation [32]. To avoid flooding, relocation of electrical infrastructure may also be needed and consideration should also be given to maintaining access to ground transportation [8]. Additional measures include flood levees and culverts; water storage; sewage works; improved drainage; seashore nourishment; flood and cyclone shelters; sea walls and coastal protection structures [1]. On the other head, in regions where a decrease in precipitation, drought, and diminished water availability may pose a challenge to airport operations, measures to reduce water consumption or increase supply, such as reusing water or collecting rainwater, must be considered [8].

In regions where significant temperature increases are anticipated, it may be necessary to lengthen airport runways and/or resurface runways and taxiways with materials that can withstand higher temperatures [9, 11]. In regions where higher temperatures may pose a problem for aircraft take-offs, moving heavier long-haul traffic to earlier or later in the day could be considered, despite the impact on schedules and decibel levels at both the airport and departure point [8]. Changes in technology, including engine performance and airframe enhancements will mitigate the effects of rising temperatures to some degree [11].

Changes in wind patterns are more difficult to deal with because modifications to the current runway position/orientation and length can be very challenging. However, a crosswind runway could be added to allow aircraft that cannot operate in strong crosswinds to do so [8].

2. Conclusions

This article presents a conceptual framework of three broad pathways through which climate change will impact the future development of international aviation and tourism. Both ground and air aviation operations are likely to be disrupted by altered climate conditions, affecting all aviation and tourism stakeholders.

Climate changes will affect the competitiveness of tourism destinations and the viability of key tourism market segments (such as maritime and ski tourism). Regional disparities are possible with small islands and developing states being at higher risks due to demand shifts in favor of high-latitude countries, significant impacts on natural tourism resources, increased security risks, relatively low adaptability, and longer distances from major markets [6].

While the aviation industry has long been cited as a contributor to the causes of climate change, the need for the industry to adapt to the effects of climate change has not received as much attention or research [4]. Furthermore, all tourism destinations need to adapt and reduce risks to climate change or take advantage of new opportunities related to local climate change impacts, impacts on competing destinations, and impacts on the wider tourism system. Several major obstacles to adaptation can be identified, some of which are shared with other sectors. Some industry stakeholders are extremely concerned about the scientific uncertainty surrounding climate change, and there is low confidence in the current comprehension of how climate change will impact tourism. The very long timescales of climate change impacts are seen as inconsistent with corporate planning, relegating adaptation to a low priority. All studies cite a lack of technical, human, and financial capacity as the main obstacles to adaptation to climate change. Small and medium enterprises, which make up the majority of tourism businesses, are more vulnerable to climate change due to their limited ability to invest in infrastructure and incorporate climate risks into business planning. Most stakeholders point to a clear need for government leadership on climate change, including early adaptation funding.

However, there is still ground for optimism. The dynamic character of the tourism industry and its ability to withstand a variety of shocks, such as terrorist attacks, the 2009 global financial crisis, and the covid-19 pandemic suggest that the tourism sector as a whole has a relatively high adaptive capacity [21]. Nonetheless, available data suggest that the level of preparedness in the sector remains low. Governments, the tourism industry, and supranational tourism organizations need to collaborate on research and capacity building to advance adaptation mainstreaming and increase the sector's potential to contribute to a green economy and poverty reduction [3].

Funding Details
This work was not supported by any Funding Agency.

Disclosure Statement
The author has no relevant financial or non-financial interests to disclose.

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