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Rachel Burbidge, Christopher Paling & Rachel M. Dunk

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A systematic review of adaption to climate change impacts in the aviation sector

Rachel Burbidge [a,b], Christopher Paling [a] and Rachel M. Dunk [a]

[a]Department of Natural Sciences, Manchester Metropolitan University, Manchester, United Kingdom; [b]EUROCONTROL, Brussels, Belgium

ABSTRACT

The incremental changes and greater extremes of a changing climate will have operational, infrastructure and economic impacts for aviation. Given the criticality of aviation for global connectivity and mobility, it is vital that the sector understands and adequately adapts to these risks. This article presents a systematic review of the growing but somewhat dispersed academic literature on climate change impacts and adaptation in the aviation sector. Information was synthesised from 131 studies (published between January 2000 and November 2022) on eleven climate change effects and the associated impacts and potential adaptation measures. Six areas for action to address knowledge, awareness and implementation gaps were identified: (i) to broaden geographical coverage, particularly to address the current lack of studies addressing climate risks and responses in Central and South America, Africa and the Middle East; (ii) to extend knowledge of physical impacts; (iii) to address known-unknowns such as the risks associated with unprecedented or compound extreme events; (iv) to extend knowledge of adaptation including cost–benefit analysis and consideration of integrated mitigation and adaptation; (v) to identify and apply other relevant research; and (vi) for sector bodies to support and facilitate collaboration between researchers and practitioners to co-develop accessible user-oriented climate adaptation services.

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1. Introduction

Climate change presents a dual challenge for the aviation sector. First, there is an urgent need to rapidly reduce the sector's climate impact, both carbon dioxide (CO_2) and other greenhouse gas (GHG) emissions, and non-CO_2 effects. Second, and in parallel, there is a growing necessity to adapt to the changing climate. The Intergovernmental Panel on Climate Change (IPCC) has recently warned that the world is on track to exceed 1.5°C of warming above pre-industrial levels (at least temporarily), even under scenarios with

CONTACT Rachel Burbidge rachel.burbidge@eurocontrol.int EUROCONTROL, Rue de la Fusée 96, 1130 Brussels, Belgium

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significantly reduced GHG emissions, and that risks and impacts substantially increase for each additional 0.5°C of warming (IPCC, 2021). While aviation is experienced in managing weather-related disruption (c.f. Borsky & Unterberger, 2019; EUROCONTROL, 2021b; Gultepe et al., 2019; Schultz et al., 2018), the sector is now experiencing the impacts of climate change (EUROCONTROL, 2018; International Civil Aviation Organisation (ICAO), 2020). This will necessitate the management of new norms, such as rising sea levels, higher average temperatures, and more extreme events, and the associated operational disruption, infrastructure damage, and increased safety risks (Budd & Ryley, 2012; Burbidge, 2018; Gratton et al., 2021). The IPCC has identified European aviation as a "key vulnerable economic sector" that is in the early stages of adaptation planning (IPCC, 2022, pp. 13–83), and sector surveys indicate this is likewise the case for other world regions (Airports Council International (ACI) World, 2020; ICAO, 2020). Given the critical role of aviation in the global mobility of people and goods, it is vital that the sector understands and adapts to what is ahead, where the need for effective adaptation is increasingly recognised by investors and insurers (Ambrosio et al., 2020).

Both climate mitigation and adaptation are urgent. However, there is a significant body of literature on mitigation of aviation (c.f. Gössling & Lyle, 2021 and references therein), and the sector has adopted targets for global net-zero carbon emissions by 2050 (Air Transport Action Group (ATAG), 2021; ICAO, 2022). This review therefore focuses on the physical impacts of climate change on the aviation sector and the adaptation measures required.

While knowledge of impacts and adaptation measures has increased steadily over the last decade, it is dispersed across numerous industry works and the academic literature. Within the sector, organisations such as EUROCONTROL (2013, 2018, 2021a), the Airport Cooperative Research Programme (2012, 2014, 2018) and ACI World (2018) have published assessments based on practitioner input, scientific knowledge, and expert analysis. The ICAO Climate Adaptation Synthesis (2020) is, arguably, the most comprehensive consolidation of information to date. However, it is strongly focused on the grey literature with less consideration of academic publications. In the academic literature, some work takes a broad perspective, either analysing impacts across the sector or identifying vulnerabilities for specific stakeholder groups such as airports (Budd & Ryley, 2012; Larsen, 2015; Thompson, 2016). Meanwhile, a growing body of work quantifies more specific impacts such as how changes to the jet stream could affect journey times (Karnauskas et al., 2015) or increase clear air turbulence for en-route traffic (Williams, 2017), and potential risks to aircraft performance from increased temperatures (Coffel et al., 2017). Two reviews have also been published. Gratton et al. (2021) compiled an overview of selected articles addressing physical risks alongside data on stakeholder perceptions from industry publications, but do not address the adaptation response beyond identifying the proportion of organisations and states engaged in adaptation planning. Ryley et al. (2020) conducted a systematic review, identifying 46 articles and discussing climate impacts and industry responses. However, this did not capture a number of key articles published within the search period (see Supplementary Information Appendix 1), with a significant number of articles published since. Thus, an up to date and comprehensive synthesis of academic work is not currently available. This review addresses this gap by systematically identifying relevant academic literature on the physical impacts of climate change and adaptation measures for the aviation sector. This then enables the compilation of a unique overview of knowledge, its critical assessment, and identification of significant knowledge gaps.

The following section describes the systematic review methodology. Section 3 presents a synthesis of the potential impacts and adaptation measures identified. Section 4 then discusses the findings, and Section 5 presents the conclusions and recommendations.

2. Methods

Systematic reviews enable the identification and synthesis of a robust body of knowledge in a specific field which can support evidence-based decision-making (Collins et al., 2019). The Reporting standards for Systematic Evidence Syntheses (ROSES) framework was selected to structure and report on the identification of articles for this review as it is purposefully designed for use in the environmental management field (Haddaway et al., 2018).

Three databases (Scopus, Science Direct, Web of Knowledge) were selected to ensure coverage of both the physical and social science dimensions of adaptation, thereby overcoming potential biases or limitations from the use of a single database.

The search was restricted to articles published in English between January 2000 and November 2022 (the date of the search). A title, abstract and key word search was conducted using the search criteria in Table 1. The combination of an aviation term (Criteria 1), a climate change term (Criteria 2), and an impact or adaptation term (Criteria 3) was designed to capture all potentially relevant literature. The search criteria were tested against the ability to retrieve 20 key articles, where the terms included were expanded until full retrieval was achieved (Supplementary Materials Appendix 1). The final Criteria 2 terms included those effects previously recognised as being of most concern to the sector (EUROCONTROL, 2018; ICAO, 2020).

Figure 1 presents a flow diagram of the down-selection of articles. To be eligible for review an article had to identify potential climate change impacts and/or adaptation actions for the aviation sector. In total, 7204 unique articles were identified through the database search. Title and abstract screening excluded 6715 articles, with a further 18 excluded due to restricted online access or unavailability, and 342 excluded following full-text screening. During the full-text screening it was identified that while some articles did not explicitly refer to climate change impacts or adaptation, they did contain information that could be applied or extrapolated to support the aviation sector in understanding and adapting to potential impacts. Thus, the 131 articles which made direct reference to impacts and adaptation measures (comprising the 129 articles selected after full text screening plus two additional known articles from Climate Law Review, a journal not held by the databases for the publication year) were classed as Tier 1, while

Table 1. Search terms used.

Criteria 1 terms	AND Criteria 2 terms	AND Criteria 3 terms
(Aviation OR airport OR "air transport" OR "air transportation")	(Climate OR turbulence OR "jet stream" OR storm OR hurricane OR typhoon OR cyclone OR temperature OR "sea level" OR precipitation)	(Impact OR impacts OR effect OR effects OR exposure OR vulnerable OR vulnerability OR adapt OR adaptation OR adapting OR adaptive OR resilience OR resilient OR resiliency)

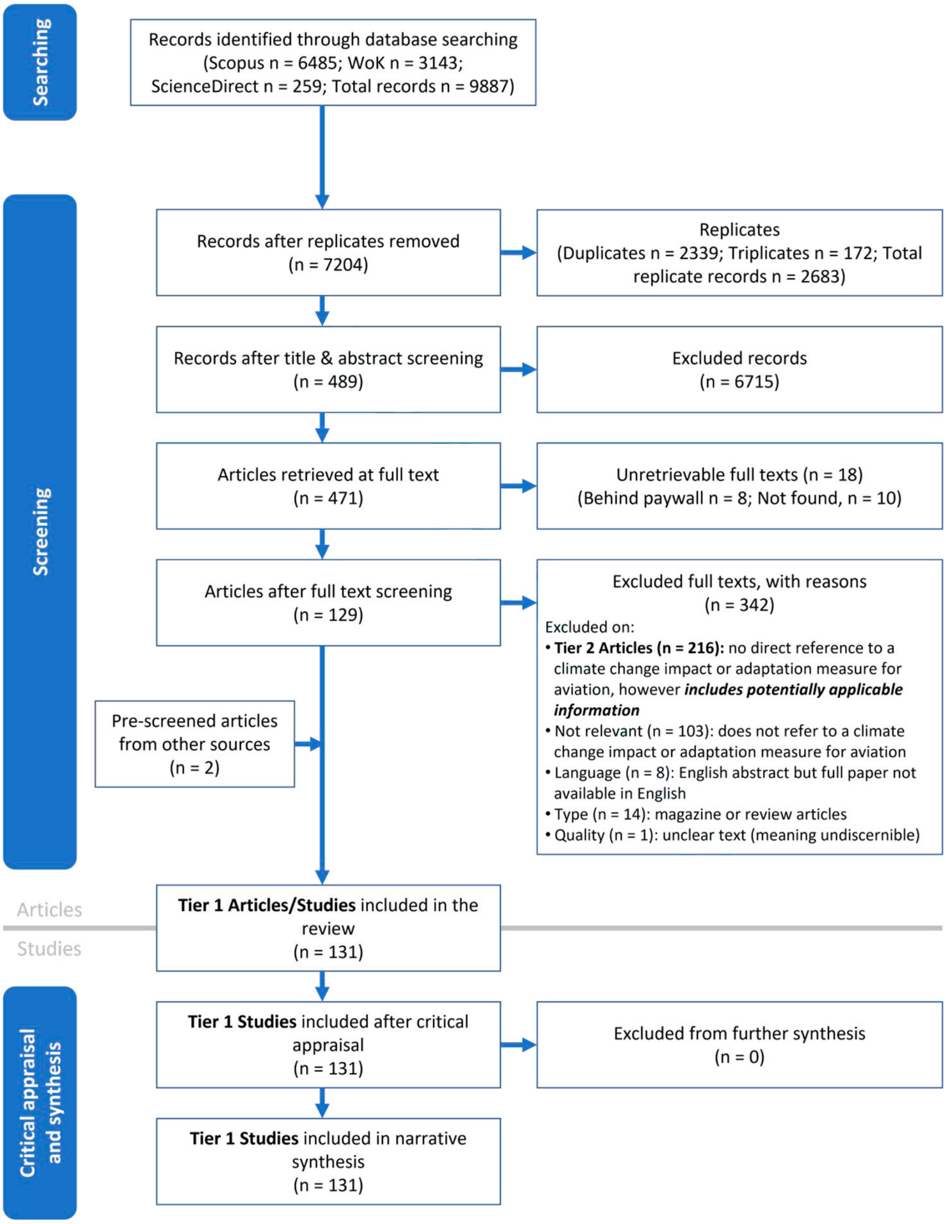

Figure 1. Flow diagram of down-selection of articles (based on Haddaway et al., 2018).

the 216 excluded articles which contained potentially applicable information were classed as Tier 2.

The Tier 1 articles were then critically appraised and synthesised, with a focus on:

(1) Climate change impacts.
(2) Potential adaptation measures.
(3) Identified knowledge gaps and challenges.

Details of the Tier 1 studies are provided in Supplementary Materials Appendix 2. While a full review of the Tier 2 articles is beyond the scope of this study, a list is provided in Supplementary Materials Appendix 3.

3. Results

This section first presents a breakdown of the studies included in the review categorised by geographic scope, stakeholder, and climate effect. For reasons of clarity, the findings are then presented categorised by climate effect with the corresponding adaptation responses identified. Acknowledging that individual climate effects cannot be considered in isolation given the complexity of climate change, Section 4 then takes a cross-sectional view of the results and discusses the implications for effective adaptation in the sector.

3.1. Breakdown of identified articles

Table 2 presents a breakdown of the Tier 1 studies categorised according to geographic scope, whether the focus is on climate impacts and/or the adaptation response, and the stakeholder group(s) considered. The ICAO regions were selected for geographical classification as this is an established grouping in the sector (ICAO, n.d.), although it is recognised that there will be differences in climate and national aviation sector specificities within each region. A clear geographic bias is evident in the results. The North America, Central America and Caribbean (NACC) region has by far the greatest coverage, with a marked focus on the United States and Canada (43 studies), limited coverage of the Caribbean (four studies) and no coverage of Central America. The Asia-Pacific (APAC) and European and North Atlantic (EUR/NAT) regions receive the second highest coverage. However, just one study covers Western and Central Africa, and no studies cover Eastern and Southern Africa, the Middle East, or South America, all regions where significant climate change impacts are projected.

Table 3 presents a breakdown of the Tier 1 studies categorised by climate change effect. The following text summarises the impacts and adaptation responses for each effect, highlighting issues identified for aviation infrastructure, operations, and particular

Table 2. Number of articles identifying climate change impacts, adaptation measures, and the stakeholder groups considered, categorised by region.

			Stakeholder Groups				
Region	Impacts	Adaptation	Airport	Airline	ATM	Regulator	Total
ICAO regions							
N America, C America, & Caribbean	46	38	44	16	4	9	46
Asia Pacific	26	18	24	8	1	2	26
Europe & N Atlantic	26	17	23	16	6	2	26
W & C Africa	1	1	1	1	0	0	1
E & S Africa, Middle East, S America	0	0	0	0	0	0	0
Other							
Global	13	11	10	11	5	2	13
Transatlantic	7	3	0	7	1	0	7
Non-specific	12	10	11	8	6	2	12
Total	131	98	113	67	23	17	131

Note: "Global" articles refer to locations in multiple regions. "Transatlantic" articles cover flights in this airspace. "Non-specific" articles are not geographically situated. "ATM" is Air Traffic Management.

Table 3. Number of articles identifying climate change impacts and adaptation measures, categorised by climate change effect (an article may cover more than one effect).

Climate change effect	Impacts	Adaptation	Total
Storms	60	36	60
Temperature	50	28	50
Sea level rise	46	31	46
Precipitation	41	25	41
Wind	31	13	31
Permafrost thaw	18	13	18
Turbulence	15	9	15
Wildlife patterns	8	4	8
Icing	7	4	7
Desertification & dust	6	4	6
Fog	5	2	5

regions or stakeholder groups. Climate change driven changes in demand and adaptation barriers and drivers are also considered.

3.2. Changes in storm patterns

3.2.1. Impacts from changes in storm patterns

While the term "storm" can be applied to any violent atmospheric disturbance, the usage here aligns with that of the IPCC assessment of climate extremes, including cyclones (hurricanes and typhoons) and severe convective weather (thunderstorms), where climate change is projected to change the frequency, intensity, and location of such extreme events (IPCC, 2021).

Storms can damage infrastructure such as airport terminals, air traffic control (ATC) towers, communication towers, and navigation equipment (Pümpel, 2016; Yair, 2018). The associated heavy precipitation, coupled with storm surges at coastal airports, can overwhelm drainage systems and flood runways, terminal buildings, ATC towers, electricity generators, communications equipment, and fuel stores (Dolman & Vorage, 2020; Fisk et al., 2019; Najafi et al., 2021). Flooding from storm water can also impact ground access to airports (Kim et al., 2018). Increased frequency of lightning increases the risk of lightning strikes, both en-route and at airports, ATC towers and for ground-based navigation equipment (He et al., 2019; Yair, 2018). It also increases fire risk, and could potentially disrupt energy supply (Vogiatzis et al., 2021).

Operational impacts include delays, diversions, capacity reduction, cancellations and impacts to ground operations, with associated economic impacts (Budd & Ryley, 2012; Pejovic et al., 2009a; Zhou & Chen, 2020). There are safety concerns for aircraft operations, airside vehicles and ground personnel (Vogiatzis et al., 2021), where suspension of refuelling may be required (Dolman & Vorage, 2020). Major storms can affect multiple regional airports, reducing diversion options (Burbidge, 2018).

Impacts differ according to location, season, and traffic levels. Summer storms can have greater impacts on delays due to high seasonal traffic, with heavy disruption causing knock-on effects on following days (Burbidge, 2018). Small island states are at particular risk from increased frequency or intensity of storms. They are often international tourism destinations, and their airports provide essential connectivity and facilitate socioeconomic development, thus operational disruption has significant social and economic impacts (Monioudi et al., 2018; Najafi et al., 2021; Pagán-Trinidad et al., 2019). Likewise, the connectivity of remote Canadian communities, which rely on aviation for essential supplies and services, is being threatened by an increase in summer thunderstorms impacting operations (Dimayuga et al., 2022).

For en-route traffic, avoiding convection decreases operational efficiency, increasing flight times, fuel burn, CO_2 emissions, and operating costs (Budd & Ryley, 2012; Thompson, 2016), and may require changes in cruise altitude, potentially causing flow management issues or reducing capacity of an airspace sector (Vogiatzis et al., 2021). In Europe in 2018, 4.8 million minutes of en-route delay were caused by adverse weather, a 124% increase on 2017 (Jardines et al., 2019).

Increased storminess may impact passengers' perceptions of risk. In a survey of passengers at Kaohsiung International Airport, over 70% of respondents agreed that climate change will impact aircraft take-off and landing, whilst greater awareness of climate change caused passengers to be more likely to accept flight disruptions due to weather (Chang, 2017).

3.2.2. Adaptation to changes in storm patterns

Design standards need to be updated and infrastructure reinforced to withstand stronger storms (Vogiatzis et al., 2021). To manage associated heavy precipitation, effective surface drainage is essential, alongside other flood risk adaptation measures such as pumping systems and raising electrical infrastructure (Burbidge, 2018; Fisk et al., 2019; Najafi et al., 2021). To manage increased frequency of lighting, enhanced lightning protection, grounding, binding and shielding (LPGBS) can protect facilities and operations (He et al., 2019), while operational measures such as halting re-fuelling, moving holding stacks, re-routing, and diversions can minimise the risk of lightning strikes (Vogiatzis et al., 2021).

Contingency plans and emergency procedures, supported by awareness raising, training and guidance for personnel, are essential for dealing with extreme events (Suhrbier, 2008; Vogiatzis et al., 2021). Communication with operational stakeholders and passengers is vital to minimise disruption, whilst improved understanding of passengers' attitudes towards weather disruption may assist airlines in managing delays and cancellations (Chang, 2017; Sheehan, 2019). Temporary modal shift, e.g. to rail, can keep passengers moving (Zhou & Chen, 2020).

For regulators it will be a challenge to ensure that aircraft certification requirements are adapted to potential new extremes to ensure they remain structurally intact and controllable (Pümpel, 2016). Air crew require training to avoid extreme weather, and procedures are required to limit risks if there is an encounter (Pümpel, 2016).

Short-term forecasts are vital for storm detection and monitoring. However, the data produced are not always readily useable by operational actors such as pilots and airline planners, where better coordination between forecasters and end-users is essential (Biondi & Corradini, 2020) and a potential quick win. More advanced tools for lightning forecasting and detection are also required (Gultepe et al., 2019). Longer-term forecasts and risk assessments are essential to understand the magnitude of impacts to prepare for, and to ensure that measures taken are sufficient (Shimokawa et al., 2014; Umeyama, 2012). A significant challenge is the development of forecasting tools and guidance for low-probability high-impact extreme events (Kim et al., 2018; Pümpel, 2016). From a disaster prevention perspective, Shimokawa et al. (2014) propose preparing for maximum possible impact, although without noting the finance and resource constraints, while Pümpel (2016) proposes guidance based on probability of event occurrence. Accurate climate projections are required for both approaches.

3.3. Temperature change

3.3.1. Impacts from temperature change

A key operational risk of higher temperatures is deterioration in take-off performance. Hotter air is less dense, therefore more thrust is needed to take-off, increasing distance required and reducing maximum take-off weight (MTOW). As temperatures increase, weight restrictions (i.e. reductions in passengers, cargo and/or fuel) may progressively be required, with obvious economic implications (Coffel & Horton, 2015; Gratton et al., 2020; Zhou et al., 2018). Moreover, changing take-off performance could increase noise impacts and fuel burn, and create challenges for ATC (Burbidge et al., 2011; Németh et al., 2018; Thompson, 2016). In exceptional cases, the certified temperature-altitude envelope of an aircraft may be exceeded, and it would not be allowed to operate (Dolman & Vorage, 2020).

An analysis examining potential impacts at 19 major airports demonstrated that during daily maximum temperatures, 10%–30% of flights may require weight restrictions by mid – to late century (Coffel et al., 2017), while modelling of an airline network suggested that by 2050 daily recovery costs could increase by 25.0%–49.3% on average (relative to 2014) due to fuel burn, aircraft swaps and cancellations, and passenger re-accommodation (Lee et al., 2021). While Hane (2016) noted that aircraft on short-haul flights are rarely loaded to MTOW (providing headroom for future weight restrictions), Yuan et al. (2021) highlighted that current studies do not account for temperature-driven increases in water vapour which further decreases air density. More analysis of potential impacts on MTOW is also needed for at-risk locations such as length limited island airports (Gratton et al., 2020).

Higher temperatures may increase fire risk (the flashpoint of aviation fuel is 38°C), cause damage to runways and taxiways (e.g. buckling, melting), increase the risk of aircraft overheating on stands and cause health risks for ground personnel, potentially restricting working time and affecting aircraft turnaround times (Budd & Ryley, 2012; Qian et al., 2020; Vogiatzis et al., 2021). ATC radar may experience technical problems (De Vivo et al., 2022). High temperatures may cause overheating of equipment and health issues for staff in terminals, and impact ground transport, leading to increased cooling requirements and associated energy costs (Vogiatzis et al., 2021). In some locations reduced winter heating requirements may counter increased summer cooling needs, but overall energy costs are likely to rise (Thompson, 2016).

More variable winter temperatures can cause freeze–thaw damage to infrastructure which can be expensive and time-consuming to repair (Tye & Giovannettone, 2021; Vogiatzis et al., 2021). Colder temperature extremes can also cause delays, predominantly due to icing, where the lower the temperature, the bigger the delay (Borsky & Unterberger, 2019; Kaewunruen et al., 2021).

3.3.2. Adapting to temperature change

Many adaptation measures to reduce impacts on take-off performance have significant financial, operational, or environmental implications. Heavier aircraft can be rescheduled to avoid taking off during the hottest part of the day, as already happens at some locations, although this can shift the timing of noise impacts at both departure and arrival airports (Burbidge, 2018; Coffel & Horton, 2015; Vogiatzis et al., 2021). Depending on available capacity, flights can be redirected to nearby airports (Coffel & Horton, 2015). Alternatively, or additionally, payload can be reduced by carrying fewer passengers, or less freight or fuel, noting the latter would reduce range and may cause safety concerns (Gratton et al., 2020; Jacob et al., 2011; Thompson, 2016). Design changes to decrease aircraft weight to reduce CO_2 emissions present a possible win-win (Hane, 2016), where an improved understanding of how higher temperatures impact aircraft performance is required to inform future designs (Coffel & Horton, 2015; Zhou et al., 2018). An alternative measure is extending or building longer runways, although this may be problematic due to costs, space constraints, community opposition or environmental constraints (Coffel et al., 2017; Thompson, 2016).

To counter the increased fire risk from fuel, measures such as having fire vehicles present or prohibiting passengers from boarding aircraft during refuelling may be needed, which both have scheduling and economic impacts (Budd & Ryley, 2012).

For surfaces such as runways and taxiways, design standards should be regularly reviewed and materials adapted to withstand expected temperatures, whilst fracture risk to underground infrastructure from freeze–thaw damage requires regular inspection and maintenance (Vogiatzis et al., 2021).

To combat heat exposure, air conditioning will be required in airport vehicles, and ground staff could work shorter shifts or take more frequent breaks, although this requires increased staff numbers which has an economic impact (Vogiatzis et al., 2021). Trials at Adelaide airport demonstrated that irrigating the airport buffer reduced runway air temperature up to 1.8°C, which could benefit both operations and ground staff (Qian et al., 2020). However, increased relative humidity, which can be equally dangerous for human health (Raymond et al., 2020), may limit the effectiveness of this measure. Increased air conditioning and better use of natural ventilation can help cool buildings, where this needs to be planned for in new infrastructure and may require redesign or retrofitting in existing infrastructure (Burbidge, 2018; Meng & Chen, 2007). Future research should analyse how heat affects ground staff and improve knowledge of airport cooling techniques (Qian et al., 2020).

3.4. Sea level rise

3.4.1. Impacts from sea level rise

Sea level rise (SLR), exacerbated by high water due to storm surges, increases flood risk for low lying coastal airports, with potential inundation of infrastructure such as terminals, runways, taxiways, car parks, fuel storage and navigation equipment, offsite ATC equipment, and ground transport access (Burbidge, 2016; Fisk et al., 2019; Lindbergh et al., 2022a; Lopez, 2016; Thompson, 2016). In turn, this impacts airport capacity and operations, causing delays, diversions, and cancellations. In extreme cases, airport closures (temporary or permanent) will impact capacity and operations across the network (Burbidge, 2018; Thompson, 2016). A global study calculated that SLR of 0.62 m (consistent with a warming scenario of 2°C by 2100) would place 100 airports below mean sea level, with 364 airports in the coastal floodplain and with over 900 routes at risk of disruption (Yesudian & Dawson, 2021). Under more extreme SLR of 1.8 m, this increases considerably to 572 airports in the coastal floodplain and over 3500 route disruptions (Yesudian & Dawson, 2021). With many hub-airports that serve major cities and handle millions of passengers a year at risk, including Amsterdam Schiphol, Shanghai Pudong International, the New York City airports, Miami International, and San Francisco International, this could significantly impact global connectivity (Griggs, 2020; Jacob et al., 2011; Pan & Liu, 2020; Yesudian & Dawson, 2021). As with storms, small island states are at particular risk from SLR, where loss of connectivity could lead to devastating socio-economic impacts (Monioudi et al., 2018; Terorotua et al., 2020; Yesudian & Dawson, 2021).

3.4.2. Adapting to sea level rise

Adaptation measures vary in scale and costs (reflecting the severity of impact and the size and nature of the airport), ranging from allowing a safe amount of flooding to full relocation of the airport, where pressure to act is increasing (Burbidge, 2018; Griggs, 2020; Yesudian & Dawson, 2021). Measures include protection with nature-based or hard engineered sea defences, reinforcing or raising infrastructure, water removal through drainage and pumping systems, and land reclamation or construction of floating airports (Griggs, 2020; Lopez, 2016; Najafi et al., 2021; Yesudian & Dawson, 2021).

The slower onset of SLR allows time for planning based on future projections and hazard mapping. Extending planning timeframes to the longer-term is a challenge but essential given the long lifespan of airport infrastructure (Blacka et al., 2013; Umeyama, 2012), where airports should be integrated into wider coastal resilience planning (Byravan et al., 2012).

Small island states face particular challenges to adapt to SLR due to the spatial constraints of their terrain (which may prevent relocation), logistical constraints which also increase costs of materials, and potential lack of human and financial resources (Monioudi et al., 2018).

3.5. Precipitation change

3.5.1. Impacts from precipitation change

Types of precipitation include rain, freezing rain, snow, and hail. Climate change will cause a decrease in precipitation in some regions and an increase in others, alongside seasonal changes (IPCC, 2021). Reduced precipitation (and ultimately drought) can instigate water restrictions (Burbidge, 2018) and cause clay shrinkage leading to infrastructure damage (Ambrosio et al., 2020). Conversely, an increase in intensity, duration or frequency of precipitation events can cause flooding of airport infrastructure, including underground infrastructure such as electrical installations, whilst insufficient surface drainage risks runway and taxiway flooding (Burbidge, 2018; Lopez, 2016; Thacker et al., 2018). Heavy precipitation can also flood ground transport, impacting passenger and employee access to the airport (Lopez, 2016). Many Caribbean islands are at particular risk of compound flooding, e.g. from a combination of storm surge, rain, and river flooding, due to their steep geography and river catchments (Zhang & Najafi, 2020).

Both heavy precipitation and surface flooding can decrease operational efficiency due to reduced visibility and increased separation distances, thus causing delays and cancellations (Budd & Ryley, 2012; Burbidge, 2018; Dolman & Vorage, 2020; Thompson, 2016). Analysis of weather and delay data at ten major U.S. airports showed that intense rainfall increased departure delays by 13–23 min, while snowfall increased delays by 11 min (Borsky & Unterberger, 2019). Safety concerns increase as aircraft braking ability is reduced due to snow and ice on runways and taxiways, particularly from heavy rain-on-snow events, whilst icy conditions can be dangerous for ground vehicles and personnel (Budd & Ryley, 2012; Hansen et al., 2014).

Fewer days with snow and reduced de-icing and snow clearing requirements could be a benefit (Burbidge et al., 2011; Lopez, 2016). However, airports may be less prepared for heavy winter weather when it does occur, and there may be unexpected snowfall in new areas which do not have the necessary equipment or procedures in place (Budd & Ryley, 2012; Sheehan, 2019).

3.5.2. Adapting to precipitation change

Good water management practices, such as water recycling and rainwater harvesting, are required when drought is a risk; although this would incur upfront costs, overall operating costs may reduce over time (Ambrosio et al., 2020; Sumaja et al., 2021). For resilience to increased precipitation, sufficient, efficient, and well-maintained surface drainage is essential (Burbidge, 2018; Najafi et al., 2021). Design standards need to be updated to account for future rainfall projections, where adapting legacy infrastructure to conditions that were not envisaged at the time of construction may be challenging (Dolman & Vorage, 2020). Grooved runways and floodwater overspill sites could be considered (Burbidge, 2018). Electrical infrastructure should be relocated if at risk of inundation (Vogiatzis et al., 2021). Green roofs on terminals have win-win benefits, reducing both runoff and energy use (Shi et al., 2015).

Snow and ice management plans provide resilience to winter precipitation. This should include optimised processes for runway clearance, coordination with airlines and ATC and, potentially, seasonal staffing (Pačaiová et al., 2021; Sheehan, 2019). Accurate near-term precipitation forecasts are essential for operational resilience, whilst investigation of future trends is crucial to understand and adapt to potential risks (Borsky & Unterberger, 2019; Hamzah et al., 2019; Pejovic et al., 2009b).

3.6. Changes in wind patterns

3.6.1. Impacts from changes in wind patterns

Climate change may alter the frequency and/or intensity of extreme winds, with increased high winds leading to increased damage to infrastructure and aircraft at terminals, and risks for personnel (Lopez, 2016; Monioudi et al., 2018; Vogiatzis et al., 2021).

Mean wind speeds are projected to increase in some regions and decrease in others (IPCC, 2021). Strong winds can impact airport operations, reducing capacity, causing delays and diversions, and increasing costs (Moomen, 2012; Pejovic et al., 2009b). For example, a 1 knot increase in wind speeds (above a mean of 8 knots) at London Heathrow increased the likelihood of a delay by 8% (Pejovic et al., 2009b), whilst wind speeds exceeding 8.7 knots (compared to a mean of 7.8 knots) at 10 large U.S. airports increased departure delays by 1–3 min (Borsky & Unterberger, 2019). Although the delays are modest when compared to those occurring due to heavy rainfall or snow, strong winds occur more frequently and impacts may accumulate (Borsky & Unterberger, 2019). Reductions in wind speed could impact take-off performance, where wind speed changes should be integrated into analyses of changes to take-off performance due to higher temperatures, and to account for potential impacts on noise and air pollution (Gratton et al., 2020; Martins et al., 2020).

Runways are usually constructed in alignment with the prevailing wind direction as aircraft take-off and land into the wind. As such, uncertainties in local wind projections present a challenge given that deviations in prevailing wind direction and an increase in crosswinds can impact operational procedures, safety, and noise distribution, and lead to delays (Budd & Ryley, 2012; Pejovic et al., 2009b; Thompson, 2016).

Changes to the speed and strength of high-altitude winds, such as the North Atlantic jet stream, will impact flight times, fuel consumption and CO_2 emissions (Burbidge, 2018; Németh et al., 2018). Projected changes to flight times are modest, with small decreases for eastbound and small increases for westbound North Atlantic routes (Irvine et al., 2016; Williams, 2016), and small increases for routes between mainland U.S.A. and Hawaii (Karnauskas et al., 2015). For the latter, Karnauskas et al. (2015) estimated an associated increase of 4.6 million kg CO_2 per annum, where route-specific analysis would be required to determine a global estimate. Moreover, the route that minimises flight time and fuel burn is not necessarily the route with the lowest climate impact as this also depends on the effects of contrails (Williams, 2016). Further work is required to examine these interdependencies.

3.6.2. Adapting to changes in wind patterns

Updating design standards for materials and structures, regular maintenance, and digital design techniques can help develop airport terminals to withstand future wind conditions (Ferrulli, 2016; Kabosova et al., 2019; Vogiatzis et al., 2021). Tackling an increase in crosswinds is more challenging and may require procedural changes, airspace redesign or, in extreme cases, changing runway orientation, all of which can alter noise impact (Burbidge, 2018). To counter longer flight times, more efficient operations and optimised trajectories will be required (Németh et al., 2018). Further research assessing future changes to surface and en-route winds is essential to support decision-making, for example on take-off and landing procedures and route planning (Leung et al., 2022; Martins et al., 2020; Pejovic et al., 2009b).

3.7. Permafrost thaw

3.7.1. Impacts from permafrost thaw

Permafrost is soil which has remained frozen for at least two consecutive years. At airports constructed on permafrost in the Canadian Arctic, Alaska and Siberia, permafrost thaw due to warming air temperatures is already causing instability and subsidence, degrading runways, buildings, and access roads. This increases safety risks, decreases infrastructure life spans, and increases maintenance requirements and costs (Beaulac & Doré, 2007; Brooks et al., 2019; Uzarowski et al., 2018), with significant socioeconomic impacts on local communities who rely on air transport for connectivity, access to medical care, food, and other supplies (Fortier et al., 2011; Melvin et al., 2017).

3.7.2. Adapting to permafrost thaw

Measures to reduce the impact of thawing include heat extraction, settlement plates, better drainage systems, gentle-slope embankments, and preventative stabilisation, where relocation of infrastructure may be required in extreme cases (Beaulac & Doré, 2007; Brooks et al., 2019; Hernandez et al., 2019; Uzarowski et al., 2018).

Monitoring programmes, understanding of creep rates, design support tools, and climate change projections can support identification of appropriate adaptation measures for existing infrastructure and planning of new infrastructure (Bilodeau et al., 2019; Boucher & Guimond, 2012; Brooks et al., 2019).

3.8. Turbulence changes

3.8.1. Impacts from turbulence changes

Climate change will increase the strength and frequency of en-route turbulence, with increased risk of aircraft damage and injuries to passengers and crew (and associated costs of maintenance and compensation claims), and potentially requiring longer flight times and increased fuel burn to avoid turbulence zones (Lee et al., 2019; Thompson, 2016; Williams & Joshi, 2013). The greatest increases are projected in the busiest airspace such as the Atlantic and North Pacific (Storer et al., 2017), with incidences of severe turbulence on transatlantic routes projected to increase by almost 150% for a doubling of atmospheric CO_2 (Williams, 2017). However, existing work has focused on transatlantic routes, where analysis of different flight levels, seasons and geographic regions is required (Williams, 2017).

3.8.2. Adapting to turbulence changes

The World Area Forecast System currently uses deterministic models to forecast turbulence. Expanding this to probabilistic multi-model forecasts could improve accuracy and assist pilot and flight-planner decision-making (Storer et al., 2019, 2020; Williams, 2017). Ultraviolet Light Detection and Ranging (LiDAR) systems could identify clear-air turbulence up to 10–15 km ahead, allowing pilots time to warn crew and passengers or to attempt to avoid the area (Williams, 2017). However, the costs of retrofitting detection systems are currently higher than the avoidance benefits, though this may change as technology costs decrease and the need for avoidance increases (Williams, 2017). More frequent aircraft maintenance to check for turbulence damage and updated aircraft design to better resist turbulence are both required (Pümpel, 2016).

3.9. Other changes

This section summarises the impacts and adaptation measures for those effects for which there was notably less coverage, namely changes to wildlife, icing, desertification and dust storms, and fog.

As climate change increasingly impacts on ecosystems, increased monitoring and management of wildlife may be required (Burbidge, 2018; Vogiatzis et al., 2021), and there may be an increased risk of airports inadvertently facilitating distribution of invasive species (Sung et al., 2018). Changing migration patterns are expected to cause an increase in bird strikes, with safety, operational and economic implications (Blackwell et al., 2009;

Burbidge, 2018; Lopez, 2016). To adapt, bird control or land management practices to discourage wildlife can be implemented, while flight paths may need to be temporarily altered to avoid migrating birds (Blackwell et al., 2009; Burbidge, 2018).

Icing is a significant safety hazard which increases aircraft weight and drag (thereby reducing lift) and can cause instrument error resulting in false altitude and airspeed data (Budd & Ryley, 2012; Gultepe et al., 2019). Ground de-icing requirements will decrease in some regions (a potential benefit), but increase in others, and potentially extend to new areas (Budd & Ryley, 2012; Burbidge et al., 2011). If de-icing requirements increase, higher balancing pond capacity may be required (to avoid pollution from de-icing fluid run-off), or alternative de-icing methods such as infra-red technology could be considered (Budd & Ryley, 2012). Higher air temperatures and moisture contents may increase the possibility of airborne icing, including at high altitudes (e.g. Pümpel & Williams, 2016). Better global and regional tools and systems are needed to predict potential icing and inform planning for ground de-icing and for ATC to assign aircraft flight altitudes, whilst there is a need for further research to improve numerical weather prediction models and reduce operational risk (Gultepe et al., 2019; Moomen, 2012).

Desertification and frequency of dust storms may increase in some regions, although changes are also driven by land-use and land-cover changes and the influence of climate change remains uncertain (IPCC, 2021). Desertification can cause encroachment of sand dunes and erosion around the runway and apron and impact water supplies, where planting drought resistant trees can inhibit dust and water recycling may be required (Burbidge, 2018). Dust storms can impact operations and safety, damage aircraft and even cause engine failure (Gultepe et al., 2019; Pümpel, 2016). Trade-offs may be required between fuel efficiency and safety in engine design, where increasing combustor temperatures to reduce fuel consumption leads to greater safety risks from melting dust particles (Pümpel, 2016).

Fog impacts visibility which reduces airport throughput, can cause delays and cancellations, and impacts safety. Changes to fog are uncertain and will vary geographically, where increased fog occurrence would exacerbate these risks whereas a decrease would reduce them (Leung et al., 2020; Pejovic et al., 2009a; Vogiatzis et al., 2021). Improved forecasting techniques to predict fog occurrence are required to improve operational predictability and reduce safety risks (Gultepe et al., 2019).

3.10. Traffic demand changes

A significant proportion of air passenger traffic is for tourism purposes. However, changes in climatic conditions, such as higher temperatures, more extreme weather, or reduced snowfall, are expected to influence tourist destination favourability. This may reduce traffic at some locations, displace it to different seasons, or shift it to new destinations, whilst more challenging conditions at a destination may reduce its viability (Burbidge, 2016; Dimitriou, 2016; Vogiatzis et al., 2021). Such changes may positively or negatively affect capacity and ATC workload, and influence airline planning and airport infrastructure plans (Burbidge, 2016; Thompson, 2016).

At both current and potential new destinations, medium- to longer-term traffic demand analyses that integrate the potential consequences of climate projections are required to better understand risks and to allow their incorporation into business cases and planning for infrastructure development (Burbidge et al., 2011). However, conducting such assessments may require significant resources (Dimitriou, 2016). Moving school holidays to cooler times of year at popular destinations could support tourism, although this has significant logistical and social challenges (Burbidge, 2018; Dimitriou, 2016).

3.11. Adaptation barriers and drivers

Identified barriers to adaptation included information deficits, a lack of human and financial resources, and governance issues such as lack of commitment or willingness to act, a singular focus on mitigation targets (Burbidge, 2016; Lindbergh et al., 2022b), a need to rethink planning horizons which tend to focus on short-term priorities rather than longer term challenges (Griggs, 2020), and a lack of national legislation mandating action (Budd & Ryley, 2012). Furthermore, as disruption will inevitably lead to knock-on effects through the highly interconnected global aviation network, a lack of adaptation at one location (particularly hub airports) can reduce the effectiveness of action taken elsewhere (Burbidge, 2018; Thompson, 2016).

While the costs of adaptation will vary according to location and expected impacts, they can be substantive (Griggs, 2020). However, changing climate conditions will drive an increase in infrastructure and operating costs, therefore the costs of adaptation need to be weighed against the costs of inaction (Lee et al., 2021; Thompson, 2016; Vogiatzis et al., 2021; Yesudian & Dawson, 2021). For example, well-designed and timely adaptation of runways and airport buildings has been shown to reduce flood risk and potential climate change costs for Alaskan airports (Melvin et al., 2017). Indeed, meeting the needs of insurers and investors were identified as key drivers of adaptation action, where robust analyses of expected impacts will be required to inform insurance policies for new extremes (De Vivo et al., 2022; Kaewunruen et al., 2021), and there is growing pressure to disclose physical climate change risks to investors (Ambrosio et al., 2020; Tsalis et al., 2018). For example, aviation companies may report to the Task Force on Climate-Related Financial Disclosures, a framework intended to provide transparent data to lenders, investors, and insurers (TCFD, 2023). At present, TFCD reporting is voluntary, except for the U.K. where it has recently been made mandatory for large, listed companies (Department for Business, Energy & Industrial Strategy, 2022). However, the number of countries implementing mandatory reporting may reasonably be expected to increase.

4. Discussion

This section presents a cross-sectional synthesis of the findings presented above. Five areas requiring action to address knowledge gaps are discussed in turn: geographical coverage, knowledge of physical impacts, known-unknowns, knowledge of adaptation measures, and utilisation of related research. This is followed by a consideration of how awareness and implementation gaps may be addressed through increased collaboration between researchers and practitioners and the co-development of climate adaptation services to inform climate risk assessment and adaptation investment decisions.

4.1. Geographical coverage

The most concerning anomaly in the knowledge base is the difference in coverage across ICAO regions (Table 2). It is noted that the search covered English-language articles only and searching in additional languages may expand results in some regions. However, for the majority of articles with a wider geographical scope, the observed regional gaps remain. For example, while Coffel et al. (2017) and Zhou et al. (2018) analyse take-off performance at 19 and 30 global airports respectively, both articles focus on Asia, Europe and North America, with just one Middle Eastern airport included. Therefore, whilst further research in the NACC, APAC and EUR/NAT regions is undoubtedly required, it is imperative to instigate research in regions where there is little or no analysis to date, and where significant climate change impacts are projected.

4.2. Knowledge of physical impacts

Eleven climate change effects and their associated impacts were identified, with the extent of coverage varying significantly (Table 3). While to some extent this reflects the search terms employed, the expansion of Criteria 2 terms beyond "climate OR temperature" to include those effects already recognised as of concern to the sector did not substantively change the relative proportion of literature found for each effect (see Supplementary Materials Appendix 1).

Storms featured most frequently, likely because they occur in all regions, and are high-profile events with some of the most significant operational, infrastructure and financial impacts. For example, nearly 17,000 flights were cancelled due to hurricane Sandy in 2012, with revenue losses conservatively estimated at USD 0.5 billion (International Air Transport Association (IATA), 2012). Temperature change, SLR, and changes to precipitation and wind patterns also received significant coverage, likely because they are widely recognised as consequences of climate change, have a broad geographical occurrence, and impact all sector actors. The somewhat limited coverage of icing, dust storms and fog may reflect uncertainties regarding climate related changes to these phenomena (and therefore impact on the sector) but may also be because they are of concern in a smaller number of locations or in those regions where there is a general dearth of literature. For example, the IPCC (2021) reports no accessible literature on projected changes to dust storms in Europe or Central and South America, while future trends in Africa and Asia (where they are of particular concern) remain uncertain. In contrast, although affecting a relatively specific and sparsely populated geographic region, the coverage of permafrost thaw is more extensive, likely because of the well-understood connection between climate change and permafrost thaw and the criticality of maintaining vital air transport connections for isolated populations.

Even where there is reasonable coverage of an effect, more research is needed on specific aspects. For example, in the case of temperature change, research requirements include; assessing how temperature-driven increases in water vapour impact on MTOW, further analysis of potential impacts on MTOW for at-risk locations such as length-limited island airports, understanding how landing speed can be impacted by changes to air temperature and density, and assessing how noise impacts may change due to changes in performance or rescheduling heavy aircraft to cooler times of day (Burbidge, 2018; Gratton et al., 2020, 2021; Yuan et al., 2021). Similar research gaps exist for each effect, and more in-depth local assessments are required. In many cases, the underpinning physical science is known, but what is lacking is the application to expected future (location specific) conditions and consideration of the implications for aviation operations. Moreover, although there is significant qualitative discussion of operational and economic impacts, further quantification is required to support the business case for adaptation by demonstrating the costs of inaction (see for example Lee et al., 2021), where such information is essential to convince decision-makers of the need for action.

4.3. Known unknowns

There are a number of known but poorly defined risks where further research is required both in terms of scientific understanding and the adaptation response. The IPCC 6th Assessment Report (IPCC, 2021) states that low-likelihood, high-impact outcomes (LLHIs) are possible even under moderate greenhouse gas emissions scenarios, where the probability of a LLHI occurring increases as warming increases. As well as the risk of passing abrupt tipping points, LLHIs encompass rare or unprecedented weather extremes and compound extreme events, including multivariate extremes (e.g. heatwaves combined with drought, compound flooding due to heavy precipitation combined with storm surge, or fire conditions combined with high winds), repeated extreme events in short succession at the same location, and concurrent extremes at different locations (IPCC, 2021).

In general, an increase in extremes is a greater risk than a change in average conditions, suggesting that adapting to the projected mean or best estimate may not be sufficient. Consideration of the implications of this when assessing an appropriate level of adaptation (such as whether to focus on high-likelihood, low-impact or LLHI events) is lacking (Kim et al., 2018). There is some limited coverage of aviation-related multivariate compound events in the literature. For example, Hansen et al. (2014) report that extreme high temperatures combined with heavy rainfall in the High Arctic have resulted in ground-ice that closed airports for safety reasons and slush avalanches that damaged infrastructure. Myers et al. (2019) modelled inundation at Santa Barbara airport due to a combination of 1 m SLR with a 100-year storm, and Najafi et al. (2021) emphasised the risk of compound flooding at the international airport in St Lucia due to a combination of fluvial, pluvial and coastal flooding. However, in general articles either focus on one specific impact, or take an impact-by-impact approach, and there is relatively little attention paid to compound events. Therefore, given their projected increase and potentially significant impact, more research is vital.

4.4. Knowledge of adaptation

While around three quarters of the articles included reference to potential adaptation measures, there was limited consideration of the adaptation process and associated challenges. For example, while increasing disclosure requirements can act as a driver for adaptation by requiring organisations to develop an understanding of their climate vulnerabilities and how to reduce them (Ambrosio et al., 2020), to do so is a non-trivial task requiring both knowledge and know-how. Burbidge (2018) identified challenges such as deciding when and how to act and balancing under- and over-adaptation, which necessitates a detailed understanding of risks and evaluation of the costs of adaptation relative to the costs of inaction. Although some risk-specific tools are available, these are currently constrained to a limited number of impacts and locations (e.g. calculating climate change risk for embankment supported infrastructure on permafrost; Brooks et al., 2019), and cost-benefit analyses are likewise limited. It is essential that such evaluations are based on appropriate climate projections to inform policy and planning and ensure infrastructure is designed and built for future conditions (Dolman & Vorage, 2020; Fisk et al., 2019; Vogiatzis et al., 2021). However, airport climate risk assessment methodologies may be difficult (if not impossible) for operators to apply themselves as they require detailed knowledge of localised climate projections (Lopez, 2016). Similarly, while many tools for weather forecasting exist, the information produced is often not readily useable by decision-makers (Biondi & Corradini, 2020). It is also noted that consideration of the interactions between mitigation and adaptation in the sector is somewhat limited, where the IPCC has recently emphasised the need for integrated climate resilient development to harness synergies and reduce trade-offs (IPCC, 2022).

There is thus a clear need for additional work on the practicalities of climate change risk assessment and adaptation planning, where the applied nature of these challenges also suggests there would be value in a systematic review of grey literature focusing on risk assessment and adaptation processes.

4.5. Utilising related research

The review identified 216 Tier 2 articles (Supplementary Materials Appendix 3) that do not refer directly to aviation climate impacts and adaptation but either analyse weather and climate phenomena of relevance to aviation (e.g. projected changes to fog patterns) or address issues that are relevant to adaptation in the sector (e.g. the use of HVAC systems in airports or development of weather forecasting tools). For example, Jia et al. (2022) analyse the physiological responses of passengers walking through a terminal in summer heat, which could be extrapolated to assess responses under future temperature extremes. While not eligible for this review, these articles demonstrate that a potentially significant body of work already exists which can either be applied directly to support climate adaptation in the sector or could be extended to do so.

4.6. Expand collaboration between researchers and practitioners

Notwithstanding the need to address the knowledge gaps identified above, there is an obvious requirement to ensure that academic knowledge is clearly communicated to industry and translated into practice. For example, a large proportion of the body of knowledge identified in this review could be applied in any relevant context, providing stakeholders are aware that it exists, can access it, and have the capacity (expertise and time) to assimilate the information and apply it.

Whilst some regional groups have recently been established to facilitate such knowledge exchange, notably the European Aviation Climate Change Adaptation Working Group and the ACI Asia-Pacific Climate Change Adaptation Working

Group, these are practitioner-specific with no direct connection to the research community and are currently focused on airports. This speaks to a need to establish a more inclusive community of practice that brings together researchers and practitioners from all stakeholder groups and geographic regions to facilitate information sharing (including the timely translation of published research into easy-to-access information) and support the co-identification of research needs and co-development of climate adaptation services, thereby helping to ensure that outputs meet end-user needs (e.g. Boon et al., 2022). This could be enabled through regular workshops and conferences, alongside an online platform. Indeed, the development of a centralised, freely available, user-needs oriented, and regularly updated, sector-specific climate adaptation platform is strongly recommended. This should draw on both academic and industry work and include a database of impacts and adaptation measures, case studies, good practice guidance, and risk assessment tools. With regards to turning these recommendations into reality, facilitating collaboration and hosting adaptation services is a role which should perhaps be considered a priority by a relevant aviation sector body.

5. Conclusions and recommendations

The physical impacts of climate change will disrupt and damage the aviation sector's infrastructure, operations, safety, and finances if insufficient adaptation action is taken. To address this, immediate action is required to expand understanding of risks, increase awareness of the need for adaptation in the sector, augment adaptation responses, and inform investor decision-making.

This systematic review has taken an important step in addressing the information deficit in the sector by presenting a comprehensive synthesis of academic literature on climate change impacts and adaptation measures. However, not only is more research required, in particular to expand geographic scope and better understand known-unknowns, recognising and applying this research requires collaboration between researchers and practitioners. To drive the aviation sector's adaptation response forward, six areas where urgent action is required were identified:

(1) Broadening geographic coverage
(2) Extending knowledge of physical impacts
(3) Improving understanding of known-unknowns
(4) Extending knowledge of adaptation
(5) Identifying and applying related research
(6) Expanding collaboration between researchers and practitioners to raise awareness and develop climate adaptation services

Knowledge and know-how gaps must be rapidly closed to enable the sector to adequately prepare for the future. As demonstrated by the IPCC (2021), some climate change impacts are now unavoidable and climate change is progressing more quickly than previously projected. Therefore, it is essential that researchers and practitioners work together, with the support of sector bodies, to take immediate and substantive action to safeguard this critical sector.

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ORCID

Rachel Burbidge http://orcid.org/0000-0003-1560-5021
Christopher Paling http://orcid.org/0000-0003-2476-3216
Rachel M. Dunk http://orcid.org/0000-0002-8066-6763

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