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The impact of climate hazards to airport systems: a synthesis of the implications and risk mitigation trends

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ABSTRACT

Climate hazards have only fairly recently been acknowledged as key risk factors for airports. While there is a growing body of research examining specific climate change impacts, there is only limited work that combines this literature with overall climate risk. This paper seeks to address this gap in the literature by investigating and synthesising findings from studies relating to historical airport sensitivity to climate hazards and offering insights on the overall climate risk for the global airport system. With airports increasingly needing to become more "climate-resilient" due to projected changes in global climate, airport planners and decision-makers face challenges in terms of identifying key priority areas for resilience planning and investment. The findings of the paper provide insights into these challenges by examining best-applied practices and current levels of vulnerability. The paper supports the wider inclusion of climate risks as a key factor in airports' planning and operational processes. This will require transforming current management cultures to enhance an airport's operational ability to respond to climate events efficiently and recover quickly in the event of a disruption.

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1. Introduction

Worldwide, climate change has increasingly impacted natural and human-made systems in various ways. While the process of climate change is well understood by climate scientists, predicting the nature, scale, and location of potentially damaging climate-related events is complex and uncertain. Insurance and reinsurance records of the past 15 years provide evidence that insured losses due to climate hazards are increasing; in the United States alone, insured losses due to tropical cyclones and hurricanes correspond to around USD 450 billion (Swiss Re Institute, 2019). Evidence shows that changing weather patterns and climate extremes will likely become increasingly prominent as the earth continues to warm (European Environment Agency (EEA), 2021; IPCC, 2021). Consequently, climate risk-related economic loss is anticipated to rise in many parts of the world (World Economic Forum, 2021).

As demonstrated at the recent United Nations Climate Change Conference of the Parties in Glasgow (COP26) (United Nations, 2021), further damage and alteration to

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the normal functioning of critical infrastructure systems are expected as a result of a changing climate, especially for infrastructure already demonstrating sensitivity to climate extremes. For example, in 2017, hurricane Harvey caused severe disruption in the greater Houston region and the closure of major airports in Texas, USA, with nearly 10,000 flights cancelled as a result (Sebastian et al., 2017). The level of disruption caused by these events, combined with the projected changes in their expected frequency of occurrence, underlines the urgency to analyse how climate change will affect airport assets and to identify effective response measures (ACI, 2018; Burbidge, 2018; ICAO, 2021).

A recent focus on the reciprocal impacts of climate change on air travel (as opposed to the other way around) signals a noteworthy shift in contemporary debates around aviation and the environment. Although climate change is anticipated to result in widespread implications for airports and air transport networks all around the world (United Nations Economic Commission for Europe (ECE), 2020), until recently, much of the focus and research concerned how the industry can effectively mitigate the impact of aviation on the global climate (Gössling & Lyle, 2021; Wennberg, 2019). It is now understood that aviation both affects and is affected by climate change (Poo et al., 2018).

Although there are different interpretations of "risk" as a term, climate risk is considered here as a combination of a climate-related hazard event and its probable impact on exposed and vulnerable assets and people (UNISDR, 2015). While climate refers to long-term weather conditions in an area, the term "climate hazard" is widely used in the literature to describe weather-, hydrological – or other climate-related phenomena, such as floods, drought, temperature extremes, storms, and many others that can affect people and the built environment (McBean & Rodgers, 2010; Mora et al., 2018). Also, in the context of this paper, climate risk mitigation refers to actions aiming to reduce the exposure or vulnerability of assets and people to climate hazards. The concept of adaptation has only recently been identified as one of the building blocks to strengthening the global response to climate change (United Nations, 2007). Actions to mitigate climate risks have also only recently become part of an airport's broader strategic and planning regime. An example includes mitigation actions adopted by Kansai International Airport in response to the wider implications linked to typhoon Jebi in 2018 (ICAO, 2019).

To date, research in this area has tended to focus either on a specific impact or climate stressor and the related implications for aviation (for example, Coffel & Horton, 2015; Yesudian & Dawson, 2021) or has used a case study approach to analyse the impact of climate change at airports in specific geographic regions (for example, Debortoli et al., 2019; Gratton et al., 2020; Poo et al., 2021). By comparison, only limited research provides a synthesis of the main climate impact drivers *and* the related implications for airports at a broader level (for example, Burbidge, 2018; Lopez, 2016; Ryley et al., 2020). Equally, few studies have sought to approach this issue holistically, incorporating both climatic impact drivers, interrelated implications and risks for airports, but also, crucially, how risk can be analysed and what enables (or inhibits) an adequate response.

This review paper seeks to build on the growing body of literature on climate risk and adaptation research. By providing a synthesis of the literature on climate change implications in an airport context, it sets out to address existing knowledge gaps relating to risk, building an understanding of existing trends, priority areas, and best practices to respond to the climate-related challenges airports currently face. The paper also discusses the adequacy of existing tools to support informed decision-making and identifies areas for further research. The study's findings provide insights into current sensitivity levels and determine aspects that can assist airports in becoming more climate-resilient. This includes the need to transform current management cultures to enhance an airport's operational ability to respond to climate events efficiently and recover quickly in the event of a disruption.

The remainder of the paper is organised as follows. The following section outlines the concept of the study and the approach used (Section 2). In turn, this is followed by a discussion of climate hazards and airport sensitivities (Section 3) and the results of the analysis (Section 4). The paper proceeds by outlining topics warranting further research (Section 5) and closes with some concluding remarks (Section 6).

2. Approach

This study is based on a broad body of peer-reviewed articles, contributions to conferences, government or airport-commissioned studies, and technical reports. A systematic analysis was conducted to identify literature addressing the scope of the study. The scope was restricted to academic articles published in English. Initially, searches were conducted using academic databases, including Scopus and Web of Science, using search keywords including "airport"; "transport infrastructure"; "climate risk"; "climate adaptation" as well as phrases including "impact of climate change on airport" or "airport vulnerability to climate change".

The identified articles were then reviewed and refined to eliminate duplicates and ensure relevance to the scope of the study. While the search focused on airport infrastructure, consideration was given to the impact of climate change on air transport in general. Also, aiming to have a broader perspective on the topic, technical reports issued by aviation organisations like ICAO, Eurocontrol, and airport operators were also included. Furthermore, post-event technical reports were also considered to present examples of climate impact on airports and how airports respond.

Overall, the analysis included 48 peer-reviewed articles, conference proceedings and book chapters, and 21 technical or industry reports published between 2005–2022 (Figure 1). Around 49% of the reviewed literature was published in the past five years, demonstrating a gradually increasing focus on this research topic and a shift in classifying disruptive events from weather occurrences to climate change-driven events.

Considering the coverage of the study, the majority of the reviewed literature (around 59%) focuses on a single location (case study) or a specific country. Although many of the researched studies address more than one research topic relevant to the scope, most of the studies discuss the impact of climate change on air transport, transport in general, or the implications for airports or adaptation to climate change. The remaining articles revolved around methods to analyse climate risk, exposure, or vulnerability to climate change.

Looking at the research methods used, most of the reviewed work offered a discussion on the topic area (59%); with the remaining studies presenting a methodology framework (9%) or quantitative analysis (32%) on a specific topic or case study.

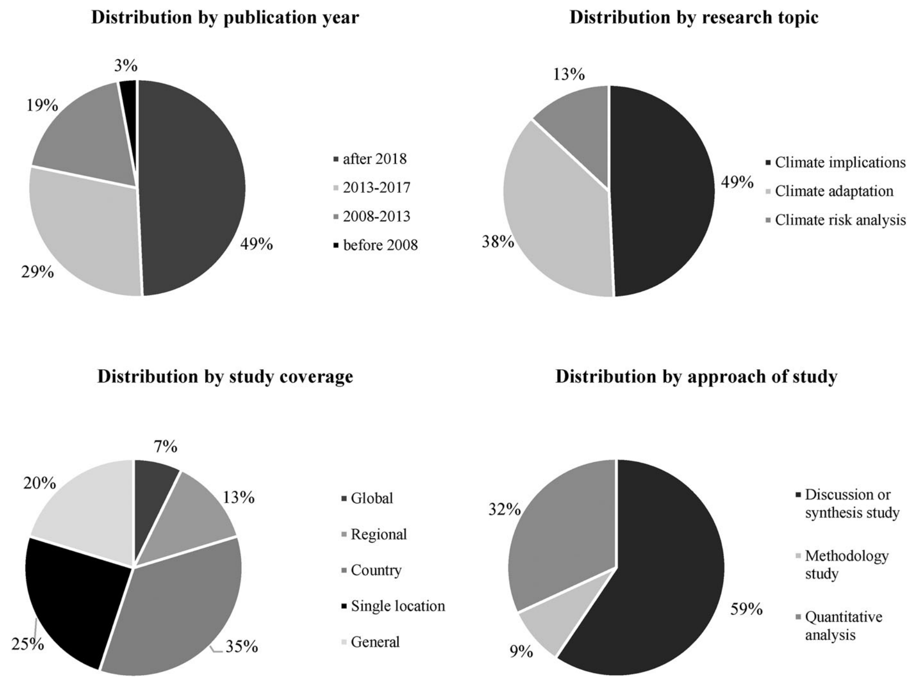

Figure 1. Categorisation of the reviewed literature (authors' own).

Papers presenting methodological approaches using quantitative methods or modelling tools, like the work of Wu et al. (2021) on the flood hazard at airports in the Pacific Islands, use satellite observation data and experimental models to estimate future rainfall variations and the possible inundation risk. Studies that provide a global or regional analysis of climate risk, (for instance, Yesudian & Dawson, 2021) use a combination of datasets collected from different sources (for example, meteorological stations, OpenFlights, Coastal Dataset for the Evaluation of Climate Impact and others). It was also common for studies to combine primary and secondary datasets, as exemplified by studies like Debortoli et al. (2019).

The conceptual approach of the present study is depicted in Figure 2. Initially, the paper investigates the primary climate factors impacting airport infrastructure and operations and discusses these via examples identified in the literature, focusing on physical, operational, and other business aspects. This process identifies cases of airport historical sensitivity in different parts of the world and provides insights into the existing exposure and vulnerability and the level of impact. Then, the study examines the main response drivers for a risk-mitigating response and evaluates best practices and adaptation trends in terms of risk mitigation actions in different parts of the world. While no two airports are identical, examining historical sensitivity and mitigation actions across different settings and geographies provides important insights into the challenges airports face and how they prioritise climate risk-mitigating action. This is followed by a discussion around effective response strategies and the efficacy of existing tools to support informed decision-making on climate resilience, as well as gaps in the research.

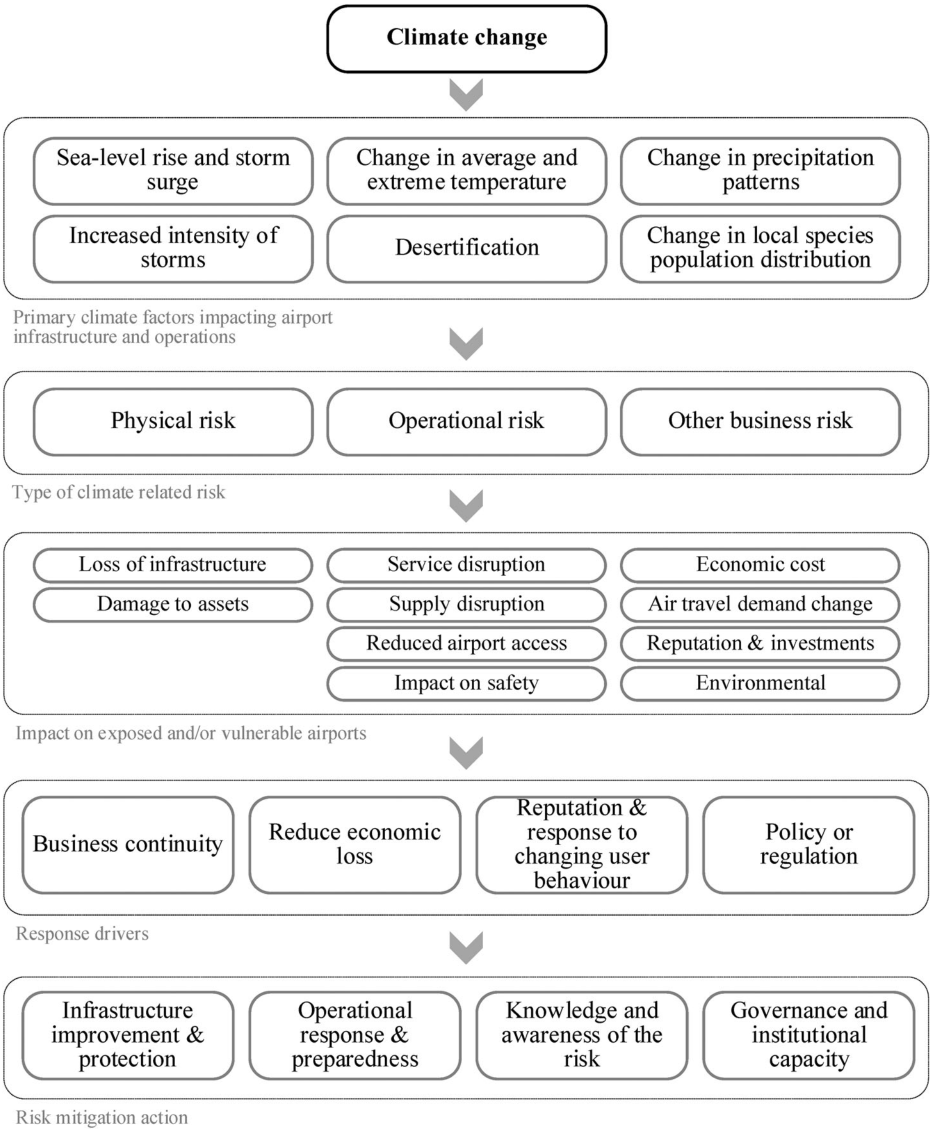

Figure 2. Conceptual approach of the study (authors' own).

3. Climate hazards and airports' sensitivity

The earth's climate is changing, and considering current climate projections, the Intergovernmental Panel on Climate Change (IPCC) forecasts that global mean surface temperature and sea level will likely increase, leading to more frequent and intense extreme climate events in many world regions (IPCC, 2021). The projected changes in global climate will likely amplify existing risks or create different types of risks, increasing the exposure of the built environment and economic assets to climate hazards and the associated economic losses (IPCC, 2012). In the case of infrastructure systems, the variability in climate and the occurrence of climate extremes influence the structural and operational performance of infrastructure (Burbidge, 2018; Hayes et al., 2019; Lopez, 2016), leading to service disruption (Dawson et al., 2018; Guest et al., 2019) and broader socioeconomic consequences (Chang et al., 2007; Eurocontrol, 2021).

In 2019, the International Civil Aviation Organisation (ICAO) carried out a survey to identify its member states' current level of awareness regarding how climate change will affect international aviation infrastructure and operations. Based on the key findings, 74% of the states had already experienced climate change-related impacts, and a further 17% are expected to be impacted by 2030 (ICAO, 2019).

ICAO (2021) and ACI (2018) identified the primary climate factors affecting airport infrastructure and operations. These mainly refer to sea-level rise, storm surge, increased intensity of storms, changes in average and extreme temperatures, changing precipitation, changing icing conditions, changing wind, desertification, and changes in the local species population distribution. These factors, in turn, can lead to physical or operational risks for the airport. In line with the existing literature, inundation or damage to airport assets or airport surfaces are classified as physical risks, while air or ground operations disruption, surface access or critical supply disruption and safety-related risks are considered operational risks.

It is observed that climate change can also lead to changes in travel flows as some destinations become less attractive due to extreme climate events or the shift of airline operations to avoid disruption in susceptible airports (Cools et al., 2010; Pek & Caldecott, 2020). Changes in travel demand can also be influenced by environmental attitudes (Gössling et al., 2020), and there is growing evidence suggesting that future generations may select different transport modes on environmental grounds, especially for short-haul travel (Grønhøj & Hubert, 2022; Higham & Cohen, 2011). This potential change in the social norms may add further pressure to policymakers to implement more stringent carbon mitigation measures (for instance, carbon taxes or requirements for more sustainable fuel use), the costs of which will likely be passed onto passengers via higher ticket prices and may negatively affect demand further (Arnaldo Valdés et al., 2021; Lu, 2018; Tol, 2007). Furthermore, there may also be additional business risks, as investors and other stakeholders are becoming more interested in the economic impact of climate change and how airport operators respond (ICAO, 2021; Pek & Caldecott, 2020).

Table 1 presents selected examples of literature addressing various aspects of climate risk used in this review. Besides the reference and a brief description, a summary of the relevant climate stressor/climate implication is provided, as well as an assessment of the type(s) of climate risk (i.e. physical, operational, or other) covered.

As can be seen in Table 1, flooding of airport critical infrastructure is recognised as one of the main implications of climate change (for example; Eurocontrol, 2021; Griggs, 2020; Koetse & Rietveld, 2009). Flooding can cause airport closure in the case of flooded runways or other critical infrastructure (e.g. electrical equipment, navigation and communications equipment) or impact surface access (Burbidge, 2018; Pek & Caldecott, 2020). Flooding can also severely damage airport pavements, equipment, or buildings (ICAO, 2018) or lead to changes in the local species population distribution, increasing the risk for wildlife strikes (ACI, 2018; ICAO, 2021). In cases where disruption occurs frequently, it may lead to changes in route planning or impact the destination's attractiveness (Pek & Caldecott, 2020).

Table 1. Selected examples of literature discussing aspects of climate risk and possible impact on airports.

			Type of climate risk									
			Physical			Operational			Other business			
Reference	Brief study description	Climate stressor/climate implication	Loss of infrastructure	Damage to assets	Service disruption	Supply disruption	Reduced airport accessibility	Impact on safety	Economic cost	Change in air travel demand	Reputation & investments	Environmental impact
(Gratton et al., 2022)	Discusses the characteristics of climate change that can impact air transport	Increased storminess or changing wind conditions, reduced rainfall leading to drought, changing in the local species population distribution	x	x	x			x		x		x
(De Vivo et al., 2022)	Presents a climate risk assessment framework for Mediterranean airports	Extreme temperature, extreme precipitation and sea-level rise	x	x	x	x						x
(Eurocontrol, 2021)	The study discusses the climate change impacts on the European aviation	Changes in storm patterns and intensity, mean sea-level rise and/or storm surge leading to flooding, changes in wind patterns, impact on tourism demand	x	x	x				x	x		x
(Griggs, 2020)	Climate implications for coastal airports around the world due to rising sea-level and storm surge	Extreme flood events due to hurricanes, typhoons, large storms, high tides and sea-level rise	x	x	x	x			x			
(Pek & Caldecott, 2020)	Discusses the main physical climate-related risks facing large airports around the world	Sea-level rise, extreme temperature	x	x	x			x	x		x	x
(Burbidge, 2018)	Discusses climate change impacts on European airports	Precipitation change, temperature change,	x	x	x	x	x	x	x	x		x

(*Continued*)

Table 1. Continued.

			Type of climate risk									
			Physical			Operational			Other business			
Reference	Brief study description	Climate stressor/climate implication	Loss of infrastructure	Damage to assets	Service disruption	Supply disruption	Reduced airport accessibility	Impact on safety	Economic cost	Change in air travel demand	Reputation & investments	Environmental impact
		sea-level rise, wind change, extreme events										
(ICAO, 2018)	Discusses the impacts of climate change on aviation, addressing specific infrastructure and operational impacts and associated business implications	Sea-level rise, increased intensity of storms, change in temperature, precipitation, icing conditions, wind, in the local species population distribution, desertification, impact on business	x	x	x	x	x	x	x	x	x	x
(Lopez, 2016)	Presents a methodology to measure airports' vulnerability to climate change and discusses climate changes and their impact on airports	Changes in temperature, precipitation, wind, in the local species population distribution, sea-level rise	x	x	x			x	x			
(Koetse & Rietveld, 2009)	Discusses the impact of climate change and weather on transport	Sea-level rise, storm surge and flooding implications change in temperature and precipitation	x	x	x	x		x	x	x		
(Pejovic et al., 2009)	Climate impact on airport performance in the United Kingdom	Weather-related extremes (temperature, wind, fog, snow, thunderstorms)	x		x				x			

Airports located in coastal areas or on smaller islands are inevitably more exposed to sea-level rise and storm surges. A recent study conducted by Yesudian & Dawson (2021) identified that sea-level rise linked to a 2°C temperature rise would place 100 coastal or low-lying airports below the mean sea level and 364 airports at risk of flooding. In Europe, two-thirds of coastal or low-lying airports are at risk of flooding in the event of a storm surge (Eurocontrol, 2021). There are illustrative examples of studies investigating the implications of climate change for coastal airports, including Griggs (2020), who presents examples of coastal airports at risk, or the work of Dolman & Vorage (2019), focussing on risks at Singapore's Changi Airport.

Although the sea-level rise is a slow onset event, inundation due to a storm surge can cause rapid and significant damage to airports. An example is Hurricane Sandy in 2012, which generated a storm surge of up to 9 ft above normal tide levels. The resulting storm surge severely affected the east coast of the United States, from Georgia to Maine and in the metropolitan area of New York. As a result, the runways at both La Guardia and Kennedy airports in New York were flooded (National Oceanic and Atmospheric Administration (NOAA), 2013). The closure of the New York airports and the disruption in Philadelphia and Washington airports (Dulles and Reagan) resulted in the cancellation of over 5,000 flights per day (IATA, 2012).

In some cases, where there is a combination of hazardous events, the result can be catastrophic. For example, in 2015, storm Erika hit Dominica and triggered flash flooding, slope failure and debris generation. As a result, both Canefield and Douglas-Charles International airports were flooded, with the latter also receiving significant damage due to extensive deposits of mud and debris from the river. The overall damage to the airport infrastructure was estimated at around USD 14.5 million (Commonwealth of Dominica, 2015).

Flooding can also occur due to changes in the mean values and/or intensity of precipitation, especially where storm drainage systems cannot handle the increased volumes of water (ACI, 2018; Lopez, 2016; Wu et al., 2021). In 2013, at London Gatwick Airport, heavy rain and strong winds combined to severely disrupt travel for more than 16,000 passengers. The consequences here were magnified by the fact that the events occurred on Christmas Eve, which is usually one of the busiest days for air travel in the UK (Chatterton et al., 2016). Also, in cases where drainage systems fail, pollution control systems may also fail, raising pollution concerns (ICAO, 2018).

Besides flooding, changing precipitation patterns can lead to drought conditions in specific locations, resulting in reduced water availability and restrictions on activities requiring large quantities of water. For example, Dallas/Fort Worth International Airport in Texas is located in a water-scarce area with restrictions on water consumption for uses such as irrigation and pavement washing (Transportation Research Board, 2012).

Selected examples of literature showing the level of disruption due to past hydrological or other extreme climate events, such as hurricanes, extreme wind, or extreme temperature, are presented in Table 2. Here, as well as the reference and a short description of the relevant event(s), the location and disruption driver of the event are identified, as well as the specific hazard(s) that caused disruption (flood, snow, wind, temperature).

As demonstrated by past occurrences (Table 2), the level of disruption and economic loss due to extreme climate events can be significant. A single event can cause the airport's closure for days, as illustrated in the reviewed literature (for example, IATA, 2012;

Table 2. Selected examples of climate-related asset damage or service disruption in an airport context.

Reference	Location and disruption driver	Identified climate hazards causing disruption/damage (historically)				Short description
		Flood	Snow	Wind	Temperature	
(De Vivo et al., 2022)	Germany, extreme heat (2018)				x	High temperature (above 36°C) caused damage to the north runway of Hanover airport leading to the cancellation of 41 flights
(ICAO, 2019)	Japan, typhoon Jebi (2018)	x				Kansai International Airport remained closed for 3 days and resumed full operations after 17 days
(Borsky & Unterberger, 2019)	US, extreme heat (2017)				x	In Phoenix Sky Harbor International Airport, more than 40 flights were cancelled due to extreme temperature (49∘C)
(Sebastian et al., 2017)	US, hurricane Harvey (2017)	x		x		Houston George Bush and William *P*. Hobby Airports remained closed for 5 days cancelling more than 10,000 flights
(Chen & Wang, 2019)	China, snowstorm (2016)		x			42 flights between Beijing and Shanghai experienced a delay, with an average of 42 min
(Commonwealth of Dominica, 2015)	Dominika, storm Erika (2015)	x				Damage to ground-level kept electrical equipment in Douglas-Charles Airport
(Chen et al., 2017)	US, snowstorm (2015)		x			More than 4700 flights were delayed and around 3900 flights were cancelled on a single day in the north-eastern states
(National Academies of Sciences Engineering and Medicine, 2016)	US, thunderstorm (2014)	x		x		Damage in two of the Phoenix Sky Harbor International Airport terminals
(Mcmillan, 2014)	UK, rainfall (2013)	x				London Gatwick Airport cancelled 143 flights, affecting more than 16,000 passengers
(National Academies of Sciences Engineering and Medicine, 2016)	US, extreme low temperature (2013)				x	Dallas/Fort Worth International Airport cancelled 750 flights due to ice and low temperature
(IATA, 2012)	US, hurricane Sandy (2012)	x				New York La Guardia Airport remained closed for 3 days
(Begg et. al, 2011; Merkert & Mangia, 2012)	UK, snowstorm (2010)		x			London Heathrow Airport cancelled 4000 flights with estimated cost of disruption around £20m
(Zapata et al., 2004)	Jamaica, hurricane Ivan (2004)			x		Norman Manley and Donald Sangster airports closed for 3 days; significant damage to airport facilities
(National Academies of Sciences Engineering and Medicine, 2016)	US, strong wind (2003)			x		Ted Stevens Anchorage International Airport experienced damage to terminal, cargo, and GA facilities

ICAO, 2019). Besides tropical storms, extreme temperatures (heatwaves and extreme low temperatures) can also lead to damage and disruption. As buildings were usually designed for different (lower) thermal conditions, under projected climate scenarios, there will be an additional need for cooling and thus increased energy demand (Dolinar et al., 2010). Also, temperature extremes can lead to cracking and degradation of pavement surfaces, equipment (e.g. navigation) or additional demand for de-icing or energy consumption (for cooling or heating) (ACI, 2018; Lopez, 2016) that will likely impact the airport's carbon footprint. De Vivo et al. (2022) refer to the example of Hanover Airport in Germany, where the runway was damaged due to extreme temperature in July 2018.

Many studies identify extreme temperature as one of the main climate risks for airports in Southern Europe (De Vivo et al., 2022; Gratton et al., 2020; Milanés et al., 2013) or other geographies, like the Caribbean, North America and China (Monioudi et al., 2018; Yuan et al., 2021; Zhao & Sushama, 2020). Extreme temperatures can cause restrictions on the aircraft's maximum take-off weights because of the reduced lift generated in less dense air. This is especially relevant for airports located at higher altitudes and especially where the airport has a short runway (Coffel & Horton, 2015; Monioudi et al., 2018; Zhou et al., 2018). Another potential impact of the increased temperature and heat waves relates to the health and safety of people working outdoors, and many researchers have documented the effects of extreme heat on human health (Arbuthnott & Hajat, 2017).

Monioudi et al. (2018), considering Boeing 737–800 aircraft take-off length requirements, projected that in 2030 Sangster International Airport and Norman Manley International Airport in Jamaica would, on average, need to deal with around 65 days of disruption of air operations per year due to heat extremes and aircraft weight restrictions. The above restrictions may negatively affect aircraft performance with adverse economic effects on the air operator; for example, there may be the need for increased fuel consumption due to the additional thrust needed to operate safely (Coffel et al., 2017) or altering routes to avoid vulnerable airports (Pek & Caldecott, 2020).

Additionally, climate change may lead to changes in the local species population distribution or bird migratory patterns (for instance, spring migration may occur earlier or species may expand their territory) (Burbidge, 2018; Gratton et al., 2022). The modification in bird population distribution, although localised, may lead to safety and service disruption implications, and has been considered in airport climate change vulnerability assessments; including at Nice Côte d'Azur Airport (French Civil Aviation Authority, 2016; Lopez, 2016). Also, in some instances, climate change may lead to the introduction of alien species of plants to new areas. For example, in the Dallas/Fort Worth International Airport area, the introduction of a species of pea plant attracted pigeons leading to an increase in bird strikes (ICAO, 2018).

The interdependence and interrelation of the different elements of the airport is another parameter to consider; although it is seemingly disregarded by many studies. Due to the interconnected nature of infrastructure systems (such as energy and water supply, information and communication technologies), there may be ripple effects (Wilbanks et al., 2020); where a failure in one infrastructure system may trigger failures in other, interconnected parts (Defra, 2011). For example, in Melbourne (Australia) in 2009, extreme heat affecting the electricity system led to failures in communications, air, rail and road transport systems (McEvoy et al., 2012). In 1998, in the north-eastern region of Canada, an ice storm resulted in disruption to the electricity supply, which triggered disruptions to water and transport systems. As a result of the loss of the electrical power network supply in Montréal-Trudeau International Airport, many flights were cancelled or delayed (Chang et al., 2007).

When climate extremes are combined with high demand for air travel, such as during the Christmas or summer holidays, disruption can be magnified even further. This is becoming more obvious in geographies where winter weather conditions or extreme heat can pose severe challenges to airport operations (De Vivo et al., 2021; Sheehan, 2019; Zhao & Sushama, 2020). Nevertheless, extreme climate events do not necessarily align with the seasonality of air transport demand. Despite efforts to mitigate climate change, it is widely acknowledged that a certain level of change has become inevitable (IPCC, 2021), suggesting that a further increase in global warming will increase the frequency and intensity of the projected changes in extremes. It seems almost inevitable that airports that have previously experienced climate-related impacts will likely continue to experience more significant consequences if they do not undertake action to mitigate the risk.

The above also reveals how airport operators view climate risk and how existing risk management is adjusted to address the changing risk profile. Over time, climate change and related risks have changed from having operational procedures to address extreme weather phenomena to designing comprehensive risk management strategies to prepare for the future climate. This is reflected by changes in the investment environment, demanding airport operators to present comprehensive risk management strategies to address climate-related risks (Pek & Caldecott, 2020). To this end, an existing understanding of sensitivity and potential predisposition to future impact can become the basis for setting priorities and establishing a tailored plan of action to mitigate risk (Burbidge, 2018; ICAO, 2019; National Academies of Sciences Engineering and Medicine, 2020).

4. Analysing and mitigating climate risk

Although assessing risk has long been a requirement under applied safety risk management processes in aviation, climate-related risk conceptualisation and analysis have only recently made their way into the airport management agenda.

It is common in the aviation safety field to adopt an appropriate framework to conceptualise risk and develop a risk evaluation process. Typical examples are the risk matrices that consider aspects of probability and severity (ICAO, 2013). However, when it comes to climate risk, there is no single approach; the overall analysis is often determined by the definition of risk itself and the aspects it covers. For example, Lopez (2016) presents a risk matrix adopted by the French technical centre for civil aviation to evaluate the risk that climate change poses to the different airport components; risk is comprehended as a combination of the probability of occurrence of the given climate change and the impact that this change poses to the airport. A risk priority matrix combining the likelihood and severity of the climate hazards and the potential consequences is also used in the approach followed by the Norway's main airport operator to assess existing and new airport infrastructure, navigation systems and surface access (Larsen, 2015).

Useful examples from the literature of airports conducting climate risk assessments and in this way and how these are used in the broader adaptation planning process are provided by the cases of London Heathrow Airport and Athens International Airport (London Heathrow Airport, 2011; Vogiatzis et al., 2021). In 2011, London Heathrow Airport conducted a comprehensive risk assessment of climate-related risks to direct or indirect operations to guide climate adaptation action. The assessment identified 34 risks in the short and medium to longer-term, which were prioritised considering the timescale, the likelihood and consequence of the event, the adequacy of the control measures already in place, and the understanding of the uncertainties and critical thresholds. From the perspective of risk prioritisation, a series of adaptation responses were proposed, grouped into three categories: action, preparation and monitoring (London Heathrow Airport, 2011). Athens International Airport adopted a similar approach; risk identification and quantification of the likely consequences to direct and indirect operations allowed the prioritisation of risks and the choice of suitable adaptation response considering the severity of the risk and the urgency of action (Vogiatzis et al., 2021).

Having in place a comprehensive plan of action to mitigate climate risk requires a deep understanding of current and future climate and associated potential hazards and how they affect the individual airport considering its unique characteristics (ACI, 2018; Burbidge, 2018; ICAO, 2019). From an airport's perspective, reducing climate risk tends to be driven by ensuring business continuity or reducing economic loss. The primary type of measures adopted by airports aim to enhance the airport's ability to prepare for and respond effectively or maintain its functioning during or after an extreme climate event (Burbidge, 2017; Debortoli et al., 2019; ICAO, 2021). In some cases, the applied actions focus on controlling potential loss, as the absence of climate-proofing or protection measures can lead to a high cost for repairs or rebuilding the damaged parts of the infrastructure (Taylor & Philp, 2010).

Climate risk-mitigating action can also be driven by policy or regulation, the need to maintain compliance to secure financing, reduce insurance premiums (Pek & Caldecott, 2020; Taylor & Philp, 2010), or participate in national adaptation planning activities (Transportation Research Board, 2012). For example, in the United Kingdom, the Climate Change Act sets out the requirements for airports and the need to assess and address the potential risks linked to climate change (Kollamthodi et al., 2011).

Besides the above, and considering that climate change may shift trends relating to travel flows, climate risk mitigation actions can be a form of response to user behaviour (Adger et al., 2005; Burbidge, 2018; Taylor & Philp, 2010). In general, the choice of climate mitigation action relates to the anticipated localised impact, intensity, probability and frequency of occurrence in association with the existing vulnerability and the characteristics and lifecycle of the airport infrastructure (Burbidge, 2016; Christodoulou & Demirel, 2017; Koetse & Rietveld, 2012). Based on case studies identified in the literature, the analysis of how airports respond to existing climate stressors provides a greater understanding of current actions to adjust and mitigate changes in the climate. In turn, this can help inform the assessment of climate-related risks and adaptation planning. Selected examples of literature covering climate mitigation action are presented in Table 3. Here, as well as a brief description of the study in question, example mitigation actions are presented along with an evaluation of the key area of action, identified here as being;

Table 3. Selected examples of literature covering climate risk mitigation types of measures.

			Key category of action			
Reference	Brief study description	Examples of measures	Infrastructure improvement and protection measures	Operational response and preparedness	Knowledge and awareness of the risk	Governance and institutional capacity
(ICAO, 2021)	Presents examples of airports taking action to improve critical infrastructure and become more climate-resilient	Protection measures, climate-proofing assets, climate risk embedded into organisational decision-making, coordination with stakeholders, emergency communication systems	x	x	x	x
(Vogiatzis et al., 2021)	Presents a framework to assess climate risk for Athens International Airport and provides a list of existing control measures and targeted adaptation action to increase resilience to climate change	Critical infrastructure improvements, enhance emergency response mechanism and disruption contingency plans, improve operational practices (e.g. water management, energy efficiency, back-up for safety critical systems), coordination with stakeholders, training	x	x	x	x
(Dolman & Vorage, 2019)	Presents the example of Changi Airport and the approach adopted to increase climate resilience to heavier storms and rising sea levels	Flood protection for vulnerable assets, holistic system of protection around the airport perimeter, water conservation measures	x	x		
(ACI, 2018)	Provides a list of climate adaptation initiatives undertaken by airports in different parts of the world	Protection for vulnerable assets, critical infrastructure enhancements, design guidelines for climate resilience, integration of climate change issues into strategic planning and operational activities, forecasting and early warning systems, coordination with stakeholders	x	x		x
(Burbidge, 2017)	Discusses airport climate adaptation and key priorities for action	Protection measures and measures to ensure that ground transport access can be climate-resilient, coordination and cooperation with stakeholders, communication protocols for passengers, allocation of resources for climate resilience, awareness raising	x	x	x	x
(Ferrulli, 2016)	Discusses climate resilient airport design and provides examples of the likely climate change effects and design solutions	Protection measures and/or critical infrastructure improvements (e.g. flood protection, critical infrastructure enhancements, elevation/relocation of critical infrastructure and equipment,	x	x		

		climate-proofing assets), climate-resilient infrastructure design, improve operational practices (e.g. water management, vegetation, energy efficiency)				
(London Heathrow Airport, 2016)	Presents the climate adaptation report and risk assessment conducted by London Heathrow Airport	Climate risk embedded into planning and organisational decision-making, coordination with stakeholders, business continuity & contingency plan, forecasting and early warning systems, climate-proof ground access and ground handling, improve operational practices, climate-resilient design standards for new buildings	x	x	x	x
(Stewart et al., 2011)	Discusses adaptation actions that airport operators in the US taking to adapt to climate change	Infrastructure improvements, revisit design standards, climate-proof ground access, improve operational practices, communicate and collaboration with stakeholders	x	x		x

- Infrastructure improvement and protection measures
- Operational responses and preparedness
- Knowledge and awareness of the risk
- Governance and institutional capacity

As indicated in Table 3, one of the most important aspects addressed in the literature is the ability of critical infrastructure, like airports, to accommodate the change linked to climate variation (Nguyen et al., 2016; Rowan et al., 2014; Yang & Ge, 2020). This aspect suggests that in the event of a disruption, airports must have the capacity to adjust their functions to resume operations as quickly as possible in an organised and efficient way (Hellingrath et al., 2015; Zhou & Chen, 2020). The above highlights the need for an organisation's decision-making mechanism, allowing timely planning and coordination with the stakeholders to enable proper response and timely recovery. For instance, climate risk-related considerations have been embedded into decision-making in Hong Kong, and the airport authority works closely with the relevant stakeholders to prepare for critical contingency measures as they did in 2017 when Typhoon Hato hit the city–state; the early planning and collaborative effort allowed the airport operations to return to normal the following day (ACI, 2018).

Considering the identified case studies, building robust and sustainable infrastructure is usually a priority for airports already experiencing the implications of climate change, such as airports located in low-lying, flood-prone or coastal areas, like Amsterdam Airport Schiphol (Dolman, 2016). Although infrastructure design is one of the main factors determining the level of impact, setting new design specifications, like the elevation of the runway, can only be applied to the construction of new infrastructure. A typical example is the Brisbane International Airport, a low-lying airport in Australia threatened by storm surges and sea-level rise (ACI, 2018). The construction of the new runway is designed 1.5 m above the minimum regulatory requirements. Better drainage systems with channels to reduce tidal flooding and the construction of a seawall are also part of the adopted adaptation measures (National Climate Change Adaptation Research Facility, 2016). A similar approach is followed by Changi International Airport, aiming at protecting vulnerable assets from coastal erosion and inundation due to sea-level rise and storm surge; Changi East site has been designed 5.5 m above the mean sea level with new drains to prevent flood occurrence within the airport site (ACI, 2018; Dolman & Vorage, 2019).

Also, setting new design standards is common in cases where extreme events have caused a significant impact. After the damage caused by typhoon Jebi in 2018 in the Kansai region in Japan, Kansai International Airport revised the design parameters and expanded its flood protection mechanism to address the likely climate change-related impact of the sea-level rise and the frequency and intensity of extreme events (ICAO, 2019). Another example is Istanbul Grand Airport in Turkey; the design parameters used were higher than the national regulatory standards to address the possible climate change implications. The airport design considered higher loads of structural elements for wind and snow and more conservative temperature variance (ICAO, 2019). In other cases, airports aim to become more water or energy-efficient, such as the new airport infrastructure in Spain; new terminal buildings will consider the rise in energy demand for A/C systems. Also, the construction of longer runways to address potential aircraft weight restrictions due to high temperature will be part of the design parameters for new airports (Milanés et al., 2013).

When designing new infrastructure is not an option, protecting the existing infrastructure is the primary approach, especially in airports located on the coastline, like San Francisco International Airport, in the United States of America. As the airport is located in an area prone to flooding due to sea-level rise and extreme tidal events, especially during the El Nino season, a $587 million shoreline protection program is in place. The program aims to protect the airport's assets, airport operations, as well as travellers and workers from flooding from a 100-year storm surge and future sea-level rise and includes the installation of a system of concrete-capped steel sheet pile walls and steel king pile walls along the 8 miles of the airport's shoreline (San Francisco International Airport, 2020).

Besides the climate-proofing interventions, other means to mitigate climate risk include operational measures. The most applied measure regards improving the level of preparedness and the efficiency of the emergency response mechanism. This measure is frequently seen at airports often dealing with disruptions due to storms and extreme winter events, like Dallas-Fort Worth International Airport in the United States of America or London Heathrow Airport in the United Kingdom.

Dallas-Fort Worth International Airport in North Texas has increasingly experienced extreme winter events, which have increased from occasional snowstorms every few years to multiple snowstorms every winter. These events often cause significant disruption and the cancellation of hundreds of flights. The airport has since invested in implementing a snow and ice control program to adapt to the new conditions. The new program focused on improving their snow and ice mechanism, purchasing new snow removal equipment, and training airport employees to improve the airport's ability to manage extreme events in winter (Sheehan, 2019).

Another critical factor concerns the level of awareness and the ability of the airport to understand the climate-related risks. Lack of awareness of climate risk has been identified as one of the key barriers to adaptation (Burbidge, 2018) and according to ICAO (2019), sharing of knowledge and applied best practices at a global level is essential to identify applicable new risks and to propose appropriate risk mitigation strategies (Transportation Research Board, 2012). Following the 2010 disruptive snowfall event, London Heathrow Airport conducted a study to identify best practices applied to airports operating in extreme winter weather to determine a model suitable for the United Kingdom (London Heathrow Airport, 2016). At the airport level, a focus on training and raising awareness activities is presented in airports experiencing the impacts of higher temperature and extreme heat events, like Athens International Airport in Greece. The airport's response to health and safety risks includes first aid training for outdoors workers and information on dealing with heat during shifts (Vogiatzis et al., 2021).

As demonstrated in the reviewed studies, climate risk mitigation action can be proactive or reactive or both, and it mostly depends on the individual challenges the airport is called to overcome and the current level of awareness. Often, action is determined as a climate risk or vulnerability assessment outcome. Nevertheless, there are some notable aspects despite the broad range of identified measures. Climate resilience can be part of the broader airport business planning, and as such, it can include a combination of critical infrastructure enhancements, operational processes and changes in the governance and institutional capacity that further improve the airport's ability to respond.

5. Research agenda and outlook

Examining how airports respond to existing climate challenges and evaluating the effectiveness of their response constitute essential aspects in identifying weaknesses in an airport's adaptive capacity. A holistic approach to increasing climate resilience requires focused research on how climate change will likely impact airports already demonstrating vulnerability and new potential risks. Considering the underlying uncertainties relating to climate change, one significant but often overlooked aspect is how climate risk is understood and analysed, as this will influence the prioritisation of actions and the overall ability to facilitate targeted climate resilience initiatives.

Typically, climate risk emerges when an overlap of a triggering climate event affects an exposed airport vulnerable to the specific event. Airports can control risk with measures that reduce the airport's vulnerability to a particular climate stressor or increase its adaptive capacity; therefore, building climate resilience relies on its formulated policies and decisions on planning and operational matters. This, in turn, depends on how airports globally view climate change events. In many instances, mitigating actions are often implemented in reaction to climate events that caused significant disruption, and they are not part of a broader medium or long-term adaptation planning. The reviewed literature shows a gradual shift in how disruptive events are perceived, moving from weather occurrences managed as part of the airport's standard operational procedures to climate change-driven extreme events requiring a more systematic response. This is more evident in the cases of new airport development, where measures tend to be more holistic and embedded into the broader planning and design of infrastructure.

This highlights the importance of having appropriate tools to analyse risk that support informed decision-making, especially considering the inherent uncertainties associated with climate change projections. Addressing these concerns and uncertainties is becoming increasingly critical for airports, not least because airports are increasingly required to present effective climate risk management strategies to secure financing, reduce insurance premiums or maintain their brand reputation (ICAO, 2021; Pek & Caldecott, 2020).

While straightforward methods like the risk matrices are frequently found in the literature, reliance on such approaches raises concerns about their ability to account for the inherent complexity and multifaceted nature of climate risk and adaptation planning. An additional parameter is that, in most cases, low probability events are often not afforded the same attention as higher frequency events, and there may be an underestimation of the risk of these climate hazards (Raaijmakers et al., 2008). It could be argued that existing approaches to climate risk can exacerbate these issues.

In contrast to other types of risks, climate risk analysis should be a dynamic process, including interrelated aspects arising from various physical, operational or business factors that may change over time. The latter will depend on the different climate scenarios and how they influence the primary climate factors impacting airport infrastructure and operations and the airport's future ability to absorb change and maintain its function or quickly recover when the event occurs.

The development of conceptual approaches, like the one used in this study (Figure 2), can guide airports in understanding the essential risk determinants, considering the individual airport characteristics, their interrelation, how they are translated in terms of impact considering historical events and the broader sustainability implications. Also, it can support the identification of the existing attributes relating to protection, preparedness, learning, anticipation, or recovery. This, in turn, can support creating the environment to prioritise and facilitate action to address climate hazards. In addition, the conceptual approach can become the groundwork for developing the measures needed to build a more comprehensive framework to support airports in building further their existing adaptability over the long term.

Finally, although some significant work has been done in explaining ways of mitigating climate risk and how airports respond to specific challenges, much remains unknown about the efficiency of the adopted measures and how to assess the overall airport adaptive capacity. Given that a "business as usual" approach is increasingly no longer an attractive or viable option for many operators, considering the wider expected climate change implications and regulatory and investor demands, future research needs to focus on aiding airports in designing an effective adaptation action plan that covers a comprehensive risk and vulnerability assessment framework to support the identification of options and a performance monitoring mechanism for related adaptive action.

6. Conclusions

As existing airport infrastructure has been designed largely considering outdated climatic parameters, studies indicate that future changes in the climate will likely increase these sites' existing sensitivity and vulnerability. This suggests the need to assess the overall climate risk and invest in effective control measures. Although there are widespread implications relating to airport assets, operational capacity and broader performance, there is limited research on the overall impact and comprehensive adaptation planning.

Building on the existing literature, this study provides insights into the overall climate risk and the airports' ability to respond, considering examples of demonstrated sensitivity and outlining topics that should form part of airport risk reduction strategies. From the aspect of risk mitigation, the paper reviewed actions commonly carried out by airports to reduce the risk, drawing attention to topics around the risk and vulnerability assessment process and implementing action to increase the overall airport adaptive capacity.

The physical robustness of the infrastructure and the broader operational ability to respond and recover quickly significantly influence airports' ability to withstand the likely adverse effects of climate change without losing essential functions. Consequently, any decision-making on risk mitigation options should be holistic and build on a comprehensive analysis and understanding of the overall aspects of risk. Therefore, the analysis of the airport's overall exposure to the applicable climate hazards and the identification of existing and future vulnerabilities over the medium and long term will provide the basis for developing suitable and cost-efficient adaptation options. Having an efficient and sustainable climate risk mitigation process over time implies that the effectiveness of the planned or adopted measures should be evaluated, and this paper acknowledges that existing research on this topic is still at the developing stage.

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