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Analysis of the risk of climate hazards to the airport system

Faculty of Engineering and Applied Sciences
PhD in Transport Systems

Doctor of Philosophy
Academic Year: 2025

Supervisor: Dr Thomas Budd
Associate Supervisor: Professor Keith Mason
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This thesis is submitted in partial fulfilment of the requirements for the
degree of Doctor of Philosophy

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Abstract

Climate hazards are increasingly disrupting the normal functioning of airports worldwide, leading to damage, operational disruptions, safety concerns, economic loss and broader business, environmental and social impacts. Climate extremes such as storms, precipitation, and heat waves are increasing in occurrence and magnitude. As the Earth warms, these threats are only set to grow, placing additional stress on airport infrastructure and current operating practices. While airports make efforts to mitigate risks, a critical gap remains in understanding the scale and complexity of climate hazards, especially lower frequency, high-impact events that typically have the highest potential for causing disruption. Current risk analysis practices and tools often fail to account for these complexities.

This research investigates the impact of climate hazards on airports and how current risk management practices address these challenges. In doing so, it introduces a new framework for analysing the risk of climate hazards to airport systems, the Airport Climate Risk Index (ACRI). The ACRI is a composite indicator addressing climate hazards, including flooding (coastal and inland), extreme temperatures, storms, wind, heavy snowfall, and drought/water scarcity. The index, designed as a self-assessment tool, seeks to empower airports to identify, analyse, and assess their risks related to climate hazards. The validation of the tool was carried out at four regional airports in the UK, providing insights into current practices and challenges in managing climate hazards within existing frameworks.

The research findings reveal a need for a change in practices to improve regional airports' preparedness for climate-resilient development. Existing mitigation measures must be evaluated for their effectiveness in addressing the increasing intensity and variety of climate hazards. A more proactive approach is essential for integrating climate-related risks into long-term planning, infrastructure development, and investment decisions. Building more adaptability within the airport elements appears necessary to enable the regional airports to grow sustainably.

Keywords: airports, climate hazards, climate risk, climate adaptation, climate change

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The ancient Greek philosopher Heraclitus once said, "*No man ever steps in the same river twice, for it's not the same river, and he's not the same man*".

This is the end of a long and highly transformative journey. The purpose of the journey has been to shape my way of thinking into that of a researcher and to stimulate my creativity in science. During the process, it pushed me out of my comfort zone, expanding my potential, building my self-confidence, and showing me how to step into the unknown. Without a doubt, it has been a journey marked by constant change and learning; one that showed me how to adapt and bring a better version of myself to the surface.

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List of Publications

Earlier stages and aspects of the research and the developed framework have been published in journals, as well as conference, and seminar proceedings.

Journals:

- Verschuur J., Fernández A., Mühlhofer E., Nirandjan S., Borgomeo E., Becher O., Voskaki A., Oughton E., Stankovski A., Greco S., Koks E., Pant R. and Hall J. (2024). Quantifying climate risks to infrastructure systems: a comparative review of developments across infrastructure sectors, *PLOS Climate*, 3(4): e0000331, DOI: 10.1371/journal.pclm.0000331
- Voskaki A., Budd T. and Mason, K. (2023). The impact of climate hazards to airport systems: a synthesis of the implications and risk mitigation trends, *Transport Reviews*, 43(3), 652-675, DOI: 10.1080/01441647.2022.2163319

Conferences:

- Voskaki, A., Budd, T., and Mason, K. (2024). Climate risk analysis: reflections from a pilot study in UK airports, 27th ATRS World Conference, Lisbon, Portugal 01-04 July 2024
- Voskaki, A., Budd, T., and Mason, K. (2024). Adapting coastal airports to climate change challenges, European Geosciences Union General Assembly 2024, EGU24-6568, <https://doi.org/10.5194/egusphere-egu24-6568>
- Voskaki, A., Budd, T., and Mason, K. (2023). Airports and climate hazards: a framework for analysing risk, 26th ATRS World Conference, Kobe, Japan, 01-04 July 2023
- Voskaki, A., Budd, T., and Mason, K. (2022). Airports and climate change: measuring adaptive capacity, 25th ATRS World Conference, Antwerp, Belgium, 24-27 August 2022
- Voskaki, A., Budd, T., and Mason, K. (2020). An overview of climate hazard impacts on the global airport system, European Geosciences Union General Assembly 2020, EGU2020-6014, <https://doi.org/10.5194/egusphere-egu2020-6014>

Seminars:

- Voskaki, A. (2024). Climate resilient development for aviation, UK Civil Aviation Authority, Safety and Airspace Regulation Group (Airspace, Air Traffic Management and Aerodromes), November 2024 Seminar
- Voskaki, A. (2024). Climate risk and airports, UK Civil Aviation Authority, Safety and Airspace Regulation Group (Airspace, Air Traffic Management and Aerodromes), May 2024 Seminar

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List of Abbreviations

ACI	Airport Council International
ACRI	Airport Climate Risk Index
AR6	6 th Assessment Report
CAA	Civil Aviation Authority
CAEP	Committee on Aviation Environmental Protection
CCC	Climate Change Committee
DfT	Department for Transport (UK)
EASA	European Union Aviation Safety Agency
ECAC	European Civil Aviation Conference
EEA	European Environment Agency
EU	European Union
FAA	Federal Aviation Administration (USA)
GDP	Gross Domestic Product
GHG	Greenhouse Gas Emissions
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change
NASA	National Aeronautics and Space Administration (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
SDGs	Sustainable Development Goals
SSP	Shared Socioeconomic Pathways
RCA	Regional & City Airports
RCP	Representative Concentration Pathways
RO	Research Objective
UK	United Kingdom
UKCP18	UK Climate Projections 2018
UNEP	United Nations Environment Programme
UNISDR	United Nations Office for Disaster Risk Reduction
US(A)	United States (of America)
WEF	World Economic Forum
WHO	World Health Organisation

1 Introduction

Climate hazards are a product of the Earth's complex climatic system, and as natural phenomena, they are part of the planet's history and evolution. While events such as storms, floods, heatwaves, and droughts are not new, the magnitude of their impact on human environments has recently become the focus of the discussion in the domain of natural hazards. Exploring the key factors that shape this complex but dynamic relationship is essential to better understand how these phenomena interact with human activity. This thesis is about climate hazards and airports, and how climate risk can be analysed, supporting decisions on measures to build more adaptability.

1.1 Background and context of the research

Climate change is a term used to describe widespread changes in the atmosphere, ocean, cryosphere and biosphere, primarily driven by human activity through the emissions of greenhouse gases, leading to global warming (IPCC, 2018a; Filonchyk *et al.*, 2024). In the 6th Assessment Report (AR6), the Intergovernmental Panel on Climate Change (IPCC) summarises the knowledge on the current status and trends of the global climate, demonstrating that since the pre-industrial era, the global surface temperature has increased by around 1.1°C (IPCC, 2023a). The increase in the global temperature leads to shifts in weather patterns and intensifies extreme events worldwide.

Changes in the climate disrupt natural cycles, affecting both natural and human systems, with the latter facing the most direct and severe consequences. While climate change affects the entire planet, the most severe impacts are observed where human activity is concentrated; urban development, including physical and social infrastructure, and human, social, natural, and financial capital are the most affected. As the Earth warms, the changes in the climate system are expected to become more significant and, to a greater extent, unpredictable, leading to an increase in the intensity and/or frequency and a likely change in the timing and/or geographic region of the climate hazard occurrences. As a result, more adverse effects are expected, and it is highly likely that multiple and concurrent climate hazards will intensify (IPCC, 2023a).

In the past decades, global temperature records have consistently been surpassed on an annual basis. For example, the World Meteorological Organisation (WMO) confirmed that in 2023, the annual average global temperature reached 1.45 ± 0.12 °C above pre-industrial

levels (WMO, 2024). In the United Kingdom (UK), the Met Office (Kendon *et al.*, 2024) ranks the past decade (2011-2020) as the warmest on record, with the year 2023 the second warmest and the seventh wettest year on record.

In 2024, the National Aeronautics and Space Administration (NASA) reported that the global annual mean surface temperature was 1.285°C higher than the 20th-century average (1951-1980), surpassing the record set in 2023 (NASA, 2025). Figure 1-1 illustrates the global mean surface temperature increase over the past five decades. It is noted that the term anomaly (IPCC, 2018b) is used here to describe the deviation of the annual mean global surface temperature from the average value over the reference period (in this case, 1951-1980).

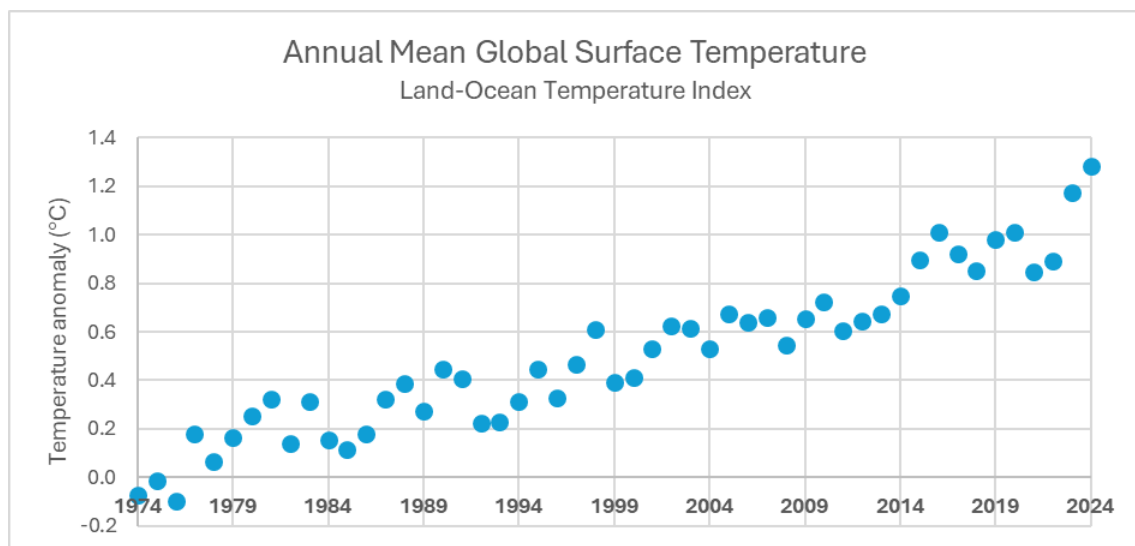


Figure 1-1 Annual mean global surface temperature anomalies vs. 1951-1980 (adapted from NASA GISS Surface Temperature Analysis (GISTEMP v4) (NASA)

This warming of the atmosphere acts as a catalyst, leading to superstorms and extreme rainfall, evidenced by the recent flood events in Spain and the hurricanes on the Eastern coast of the Americas. In Spain, in October 2024, the Valencia region and the surrounding areas experienced the most catastrophic floods in recent history that claimed over 200 lives, displaced thousands and caused extensive damage to infrastructure and livelihoods (Chavda, 2024; Harrigan, 2024). The events revealed failures in preparedness, response and recovery mechanisms and the growing risks of climate change, especially in regions where urban development has occurred in river floodplains. In 2024, in Europe alone, flash floods resulted in 20.3 billion USD in overall losses, leading to the loss of life of 266 people

(Munich Re, 2024). In the Americas, Hurricane Helene alone caused the loss of 227 people and an overall loss of 56 billion USD (Munich Re, 2024).

Although adaptation planning has progressed in recent years, adaptation gaps exist and will continue to grow as the climate changes. Scientific evidence confirms that the adverse effects, already observed worldwide, will further intensify with an additional increase in global temperature (IPCC, 2023a). This intensification of extremes will have implications for urban systems, leading to loss of life, displacement of population and extensive damage to infrastructure, livelihoods and ecosystems (IPCC, 2021b). The demonstrated sensitivity of the urban systems raises concerns about the current level of resilience and whether measures in place are sufficient to address the intensity of the climate extremes.

Without a doubt, the need to take action to address climate change has long been recognised (Stern, 2006). While discussions are ongoing regarding efforts to meet the Paris Agreement targets (United Nations, 2015), the occurrence of climate extremes points out the necessity to balance action and build more adaptability to climate hazards that have the potential to result in severe multi-level consequences. It is evident that mitigation and adaptation should be viewed as interconnected and mutually beneficial, both playing an essential role in enabling sustainable development.

In the latest report (AR6), the IPCC underscored the urgency of undertaking accelerated action, as the observed pace and scale of climate action are insufficient to tackle climate change (IPCC, 2023b). This involves prioritising measures to build more climate resilience in all systems and functions. This task will undoubtedly become more complex and costly as global temperatures continue to rise, requiring more extensive interventions and significant transformational changes. Therefore, decision-making on action planning will be crucial in shaping the future.

However, determining the course of action when it comes to adaptation is a complex and dynamic process. Predicting the scale, nature and location of climate extremes is a difficult task, typically involving high levels of uncertainty. In addition, considering their unique characteristics and interconnections, the relationship between climate hazards and urban systems leads to a series of possible outcomes, with myriad interconnected and complex feedbacks. Exploring the factors that shape these uncertainties and the relationships between climate hazards and urban systems is essential. Effectively navigating the

components that shape the risk profiles is a dynamic process, starting with building an understanding of the patterns of exposure and vulnerability to climate hazards.

1.2 Air transport, climate hazards, risk and adaptation

Like all infrastructure networks, air transport plays a vital role in the urban system, facilitating mobility, economic growth and global connectivity (Air Transport Action Group, 2024). Airports, as hubs within this system, offer essential infrastructure that enables the movement of people and goods while supporting sustainable development goals (Graham, 2014). However, as changes in the climate become more pronounced, the increasing variability and intensity of extreme climate hazard events are likely to pose growing challenges to airport operations and infrastructure resilience, affecting network efficiency and potentially leading to other cascading consequences.

Airports around the world have demonstrated sensitivity to climate hazards like floods, storms, and extreme temperatures, leading to the loss of airport infrastructure, impacts on safety and performance and a series of business, environmental and socio-economic impacts (Burbidge, Paling and Dunk, 2023; Voskaki, Budd and Mason, 2023). The International Civil Aviation Organisation (ICAO) Committee on Aviation Environmental Protection (CAEP) Climate Adaptation survey (ICAO, 2018) provided insights into the type of climate hazards affecting aviation; higher average and extreme temperatures, changing precipitation, increased intensity of storms, sea level rise, changing icing conditions and changes in wind patterns are referenced as climate hazards of concern in terms of impact. Table 1-1 provides examples of extreme climate events causing disruption.

Table 1-1 Selected examples of climate-related asset damage or service disruption in an airport context (adapted/supplemented from the original from Voskaki, Budd and Mason, 2023)

Reference	Location and disruption driver	Climate hazard	Short description
(Makuyana, Nhamo and Dube, 2023)	India (2018)	Flood	Cochin International Airport suspended operations for 3 days, airside was inundated for 4 days, damage to critical equipment
(De Vivo <i>et al.</i> , 2021)	Germany, extreme heat (2018)	Temperature	High temperature (above 36°C) damaged the north runway of Hanover Airport resulting in the cancellation of 41 flights
(Lacoin, 2019)	Japan, typhoon Jebi (2018)	Flood	Kansai International Airport closed for 3 days and resumed full operations after 17 days
(IATA, 2017)	US, Caribbean, hurricanes Irma and Maria (2017)	Flood, wind	Miami, and Orlando airports closed completely, while Atlanta and small airports were affected, airlines lost around USD 75-85m of revenue/day
(Borsky and Unterberger, 2019)	US, extreme heat (2017)	Temperature	Phoenix Sky Harbor International Airport cancelled more than 40 flights due to extreme temperature (49°C)
(Sebastian <i>et al.</i> , 2017)	US, hurricane Harvey (2017)	Flood, wind	Houston George Bush and William P. Hobby Airports closed for 5 days cancelling more than 10,000 flights
(Chen and Wang, 2019)	China, snowstorm (2016)	Snow	42 flights between Beijing and Shanghai experienced a 42 min delay on average
(Makuyana, Nhamo and Dube, 2023)	South Africa, rainfall (2018)	Flood	Inundation of OR Tambo International Airport, flight diversions, surface access disruption
(Commonwealth of Dominica, 2015)	Dominica, storm Erika (2015)	Flood	Douglas-Charles Airport runway and ground-level kept electrical equipment were damaged
(National Academies, 2016)	US, extreme low temperature (2013)	Temperature	Dallas/Fort Worth International Airport cancelled 750 flights due to ice and low temperature
(Mcmillan, 2014)	UK, rainfall (2013)	Flood	London Gatwick Airport cancelled 143 flights, affecting more than 16,000 passengers
(IATA, 2012)	US, hurricane Sandy (2012)	Flood	New York La Guardia Airport closed for 3 days
(Begg <i>et al.</i> , 2011; Merkert and Mangia, 2012)	UK, snowstorm (2010)	Snow	London Heathrow Airport cancelled 4000 flights, estimated cost of disruption around £20m
(Zapata <i>et al.</i> , 2004)	Hurricane Ivan (2004)	Wind	Norman Manley and Donald Sangster airports closed for 3 days, damage to airport facilities

(Zapata *et al.*, 2004; Begg *et al.*, 2011; Merkert and Mangia, 2012; Transportation Research Board, 2012; IATA, 2012; Mcmillan, 2014; Commonwealth of Dominica, 2015; Chatterton *et al.*, 2016; National Academies, 2016; IATA, 2017; Sebastian *et al.*, 2017; Borsky and Unterberger, 2019; Chen and Wang, 2019; ICAO, 2019a; Lacoin, 2019; De Vivo *et al.*, 2021; Makuyana, Nhamo and Dube, 2023)

In Europe, an increasing trend in en-route delays due to the weather has been observed during the past years (Eurocontrol, 2025); storms have been historically responsible for up

to 7.5% of total en-route delays (Eurocontrol, 2021b). While there is uncertainty about how climate change will influence storminess in Europe, there is high confidence that it will lead to a rise in sea levels (IPCC, 2022), potentially putting approximately 178 coastal airports at risk (Eurocontrol, 2021b). In addition, considering the projected increase in temperature and heat extremes (IPCC, 2022), the European air transport system will likely have to deal with infrastructure and performance challenges, as well as shifts in tourism trends in terms of time or location (Eurocontrol, 2021b). In the UK, based on climate change projections (Met Office, 2022b), airports will likely have to deal with flood and extreme heat events, threatening infrastructure and operational capability.

Flooding (coastal or pluvial or fluvial) of critical airport infrastructure is identified as one of the key concerns for many airports, leading to airport closure and asset damage while raising concerns about local biodiversity and travel patterns if the occurrence becomes frequent (Griggs, 2020; Eurocontrol, 2021b; Voskaki, Budd and Mason, 2023). Recent examples demonstrating the scale of impact in the present day include the flash flooding observed in Dubai, causing the closure of Dubai International Airport and the cancellation of around 300 flights (Gritten, Gillett and Comerford, 2024) and the inundation of Barcelona, Valencia (Boyd, 2024; Martin, 2024) and Exeter airports (Sharp, 2023). The economic cost of an airport closure can vary depending on factors like the severity of the flood, including asset damage and the extent of flight disruptions. The impact of the 2013 flood at London Gatwick Airport was estimated to be around £2.6 million to £3.9 million due to flight disruptions, while around £50 million was invested in flood defence, power resilience and recovery efforts (Chatterton *et al.*, 2016).

Besides floods, climate hazards such as storms cause disruption and the cancellation of hundreds of flights; for instance, Storm Eunice caused the cancellation of around 436 flights in the UK due to the extreme intensity of wind (Kendon, 2022a; Timmins, 2022). The economic impact of such events is significant for the air transport sector, as illustrated by recent events. IATA (IATA, 2017) estimated that hurricanes Irma and Maria caused airlines a loss of around USD 75-85 million of revenue a day at the peak of the disruption; the restoration of Puerto Rico airports after Hurricane Maria was estimated to be around USD 80 million (Yesudian and Dawson, 2021).

Extreme heat is also a climate hazard for consideration for airports located in specific geographies, such as Phoenix in the United States; Phoenix Sky Harbour International

Airport often experiences disruptions due to temperatures reaching 49°C (Borsky and Unterberger, 2019). High temperatures can limit the maximum take-off weight of an aircraft, lead to pavement melting, an increased risk of fires, more frequent need for maintenance, heat stress for employees and increased cooling demand (Coffel and Horton, 2015; Arbuthnott and Hajat, 2017; Monioudi *et al.*, 2018). Lately, extreme heat has become a concern in regions that historically did not experience high temperatures exceeding the specifications of pavement materials, such as the UK; a recent example is the closure of London Luton Airport due to damage caused on the runway during the 2022 heatwave (Freed, 2022; Hughes, 2022).

The scale of impact from extreme events on large hub airports can be significant in terms of disruption in air connectivity and the economy. For instance, the closure of Kansai International Airport due to Typhoon Jebi led to losses surpassing USD 500 million for the airport and the regional economy (Takabatake *et al.*, 2018; ICAO, 2019a). However, extreme climate events such as extreme precipitation or storms can also affect smaller airports serving a region. The consequences can be significant, considering the role these airports play. Regional airports play a critical role in facilitating mobility in remote regions (Adler, Ülkü and Yazhensky, 2013), serving as vital socio-economic drivers. They enhance connectivity and regional integration (Olariaga, 2021), enable local and regional economic activity and business growth, attract investments, create employment opportunities, support tourism development and promote trade. Additionally, they bring people together, provide access to better healthcare and education, and, in certain cases, facilitate humanitarian and disaster response to crises and emergencies (Donehue and Baker, 2012; Pauwels, Buyle and Dewulf, 2024).

Despite their importance, regional airports frequently face challenges related to infrastructure, outdated facilities and insufficient financial capacity to invest in upgrading assets or building more resilience. This can become a significant concern when their location is exposed to climate hazards, such as sea level rise and storm surges, as in airports in the Pacific Islands (Kumar and Taylor, 2015; The World Bank, 2024) or the Caribbean (Monioudi *et al.*, 2018; Burbidge, Paling and Dunk, 2025). For example, Douglas Charles Airport in Dominica experienced significant damage from flash flooding and mud deposits triggered by storm Erika in 2015; the cost for repairs was around USD 15 million (Commonwealth of Dominica, 2015).

Numerous examples point out the susceptibility of regional airports to climate hazards. In Spain, the June 2024 storm led to the flooding of Palma Airport's runway, terminal building, car park and access roads, affecting more than 100 flights (Palma Airport, 2024). In Greece, Rhodes Airport was severely affected by the wildfires in 2023, while Skiathos Airport faced disruption to air operations and surface access due to floods that same year (ECAC, 2024). In Italy, Bologna Airport was affected by snowstorms during the winter of 2018, which led to increased operating costs and loss of revenue (Aeroporto di Bologna, 2018). In France, Nice Côte d'Azur Airport often has to deal with surface access disruption due to flooding (French Civil Aviation Authority, 2016). While large airports like Singapore Changi (Dolman and Vorage, 2019) or San Francisco International (Johnson *et al.*, 2018) have initiated large-scale infrastructure works to build climate resilience, financing similar-scale projects remains a challenge for smaller airports, particularly those located in small islands or developing countries.

The intensification of extreme precipitation, temperatures or storminess due to climate change (IPCC, 2021b) will likely place additional stress on airport infrastructure, threatening airports' ability to maintain their functions. Although many aviation stakeholders acknowledge the likely implications of climate hazards (ICAO, 2018), the observed sensitivity suggests a gap in how climate hazards have been addressed due to limited resources, regulatory gaps and insufficient knowledge of how they manifest or their impacts.

The above implies that there is a growing demand for enhanced climate risk assessments and studies to determine how to build more adaptive capacity in the air transport system to achieve long-term sustainable development goals. It also suggests that better protection and preparedness strategies are critical to respond to climate hazard events; airports with higher adaptive capacity are expected to address disruptive events more efficiently.

1.3 UK airports and climate risk

Air transport is crucial for the UK's economic growth and prosperity as it enables the movement of people and drives investments, facilitating international trade. As a sector, it provides employment for 378,400 individuals and generates an economic output of USD 40.2 billion, around 1.2% of the country's GDP. When considering the broader economic impact, the sector contributes a total of USD 160.7 billion to the UK's GDP and supports

1.6 million jobs (IATA, 2023). Besides the economic impact, air travel contributes to connectivity with the rest of the world, enabling economic activity, cultural exchange and leisure. In addition to international travel, domestic air travel plays an important role in enhancing social mobility and regional development, with airports being vital nodes connecting people and businesses throughout the UK.

The UK enjoys high connectivity with the rest of the world, with major airports such as London Heathrow and London Gatwick serving as key global hubs. London Heathrow Airport is the busiest airport in Europe and among the top 10 globally in terms of passenger numbers. Besides the London area airports (Heathrow, Gatwick, London City, Stansted, Luton and Southend) the UK aviation system includes over 50 large, medium and small airports. In 2024, over 292.5 million passengers departed from the UK CAA's reporting airports; approximately 53.7% of the traffic served by the UK airport system travelled through one of the main London airports (Heathrow, Gatwick, Stansted, Luton and London City) (UK CAA, 2024c). Overall, a total number of 2,742,553 movements was recorded in 2024 (UK CAA, 2024a).

Looking at the top 25 airports in terms of passenger numbers (Figure 1-2) it is obvious that many are still operating below the pre-pandemic levels. However, several airports, including London Heathrow, Manchester, London Stansted, Edinburgh, and Belfast International, appear to have surpassed the 2019 levels. Compared to that year, passenger traffic in 2024 reflects a growth ranging from 0.6% at Liverpool Airport to a 35.5% increase at Bournemouth Airport (UK CAA, 2024c).

In recent years, the UK has adopted a proactive approach towards expanding the sector, putting emphasis on infrastructure investments and decisions to enhance global connectivity. Key examples include the decision on a third runway at London Heathrow Airport (DfT, 2025b), approval for the expansion of London Luton Airport to accommodate up to 32 million passengers per annum (Planning Inspectorate, 2025), and London City Airport's plans to reach 9 million passengers per year by 2031 (DfT, 2025a). A forthcoming decision on the development of the northern runway at London Gatwick Airport is also anticipated (DfT, 2025c). Additional investments in airport upgrades at London Stansted (DfT, 2024a), Leeds Bradford (Leeds Bradford Airport, 2025), Newcastle (Newcastle International Airport, 2024), Cardiff International Airport (Welsh Government, 2024), Southampton Airport (Southampton Airport, 2022), and Belfast International Airport

(Belfast International Airport, 2024b), illustrate the momentum in decision making and planning across the sector.

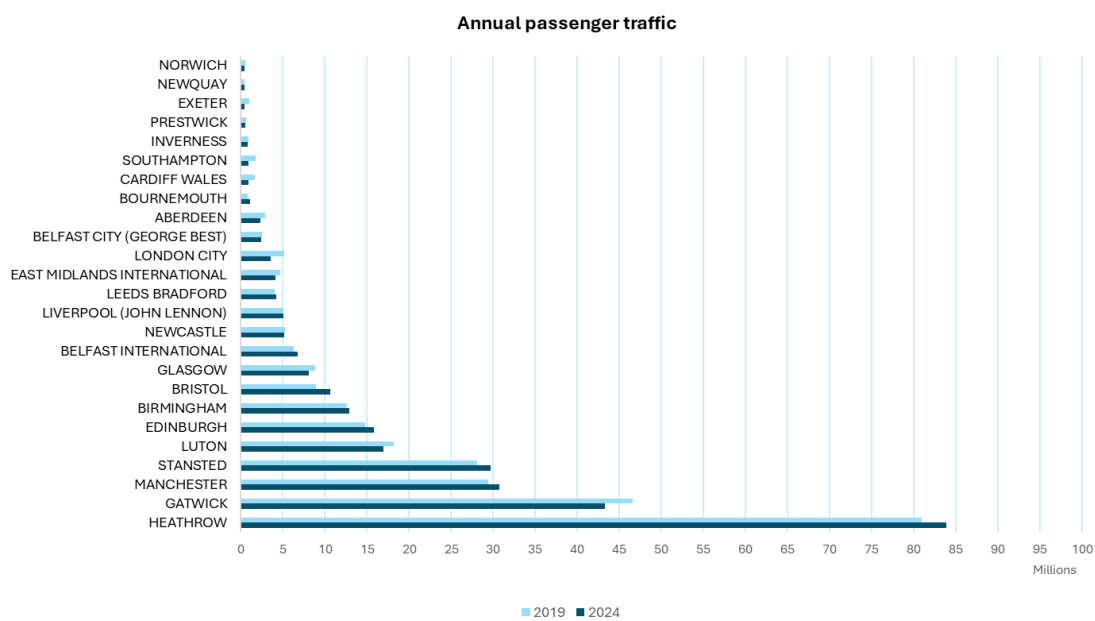


Figure 1-2 Top 25 UK airports in terms of passenger traffic (2024 and 2019) (data source UK CAA)

As aviation continues to recover from the effects of COVID-19, attention has primarily focused on achieving sustainable growth. Thus, efforts have been directed at airspace modernisation, innovations in aircraft technology, sustainable aviation fuels and meeting the ambition of net-zero carbon emissions by 2040 for domestic aviation and by 2050 for all aviation (Jet Zero Strategy). This strategy also calls on airport operators to achieve zero emissions by 2040 while supporting further reductions within the system (DfT, 2022). At the same time, the Climate Change Committee (CCC) (CCC, 2024) emphasises that without adequate adaptation to the physical risks posed by climate change, efforts to deliver the Jet Zero Strategy may become less effective or significantly more expensive. Addressing the growing risk of climate hazards requires a scale of response that goes beyond what is currently reflected in the latest National Adaptation Programme.

Despite ongoing progress toward meeting the goals of the Paris Agreement, the UK has experienced an increase in the frequency and intensity of extreme climate events. The latest UK Climate Projections (UKCP18) indicate that extreme events such as heatwaves and intense rainfall will likely intensify (DfT, 2024c; Kendon *et al.*, 2024). These climate trends pose growing risks to airport infrastructure and operations, increasing the likelihood

of disruption; these factors could ultimately become a challenge for further growth. Climate hazards like extreme heat, storms and flooding have been identified as acute risks in the government's 2025 National Risk Register (HM Government, 2020), requiring an emergency response, reflecting the overall concern.

Disruptions to transport systems, supply chains and utility networks caused by climate hazards could lead to broader social and economic implications; the potential for compound or consecutive hazards may amplify the impact. In recent years, the UK has experienced a series of severe storms causing nationwide air travel disruption, power outages and fatalities. For instance, Storm Eunice in 2022 led to more than 430 flight cancellations across London's airports (Davis, 2022). Similarly, Storm Ciara in 2020 disrupted hundreds of flights across major and regional airports in the UK, including London Heathrow, London Gatwick, Manchester, Birmingham, Leeds Bradford and London City (Calder, 2020). In early 2025, storm Eowyn caused widespread disruption across airports in the north of the UK, especially in Edinburgh, Glasgow, Aberdeen, Prestwick, Inverness and Dundee (Pollock, 2025).

In addition to storm-related disruption, UK airports also demonstrate sensitivity to flooding, extreme heat and snow events. Exeter Airport was temporarily closed in 2023 due to the inundation of its terminal (Exeter Airport, 2023; Sharp, 2023), while Leeds Bradford Airport closed due to a snowstorm in early 2025 (Grealish, 2025). Similarly, in 2018, the 'Beast from the East' snowstorm led to extremely low temperatures, heavy snow, and strong winds, causing airport closures across the UK (Vonberg, 2018). More recently, in 2022, London Luton Airport suspended operations after extreme heat caused a runway surface defect (Freed, 2022). Disruptive events also bring attention to the role of interdependencies. Besides incidents of flooding causing disruption in airport surface access, as in the case of London Luton Airport in 2024 (Raemason, 2024), the recent fire at London Heathrow Airport, originating in an off-site substation (Department for Energy Security and Net Zero, 2025) underscores the need to examine dependencies and how they may influence climate resilience within airport infrastructure and operations.

These incidents not only bring to the surface current challenges posed by climate hazards but also raise questions about the adaptive capacity of the UK airports to cope and respond to the climate hazard occurrences of the future. In the UK context, the focus of the discussion has recently turned towards how the transport sector, including aviation, can

proactively undertake action to adapt to the changing climate. Given the economic implications of extreme climate events arising from damaged infrastructure, operational disruptions, disruptions in supply and distribution networks, or the redirection of capital away from more productive investments (DfT, 2024c), it is deemed necessary to put together a proactive and comprehensive approach to climate risk and resilience. Without a doubt, to prepare for the future, it is essential to consider the scale and complexity of climate hazard-related risks.

The acknowledgement that ‘business as usual’ is not an option to support sustainable development suggests that a more forward-looking, flexible and proactive view into climate risk management should be incorporated. To enable a shift in the existing culture in how climate risks are considered and accounted for in decision-making, there is a compelling need to better understand the complex nature and underlying requirements for climate risk analysis to contribute to policy and practice.

1.4 Structure of the thesis

The remainder of the thesis is structured into five distinct, interrelated chapters.

Chapter 2 – Literature review: climate hazards and the airport system

This chapter explores existing literature on the impacts of climate hazards and existing adaptation strategies within the airport sector. It discusses topics around climate change, climate hazards, climate extremes, climate risk, and adaptation while considering the airport as a system. In addition, it delves into climate risk analysis perspectives and methodologies. The chapter aims to provide an overview of the current knowledge, building an understanding of the trends and priority areas while identifying gaps in the literature that this thesis aims to address.

Chapter 3 – Methodology: the development of a framework for climate risk analysis

The third chapter outlines the methodological approach for creating a framework to analyse climate hazard risk for airports; it provides details on the identification of the research problem, the definition of the research aim and objectives, the steps and methods involved and the overall development process. It discusses the conceptualisation of the research problem, the process of developing the prototype version of the Airport Climate Risk Index

(ACRI) tool, actions to validate the tool, and aspects relevant to data collection and analysis.

Chapter 4 – *Analysis of the case examples*

The fourth chapter provides an analysis of the results of four case examples of regional airports in the UK. Using the ACRI tool, the analysis provides information on the observed levels of climate hazard, exposure, vulnerability and adaptability, pointing out areas for consideration. Also, it highlights climate hazards requiring further attention considering climate change influence.

Chapter 5 – *Climate risk trends and recommendations*

The fifth chapter discusses the main climate risk trends identified from analysing the output of the tool and the main areas of focus for the four regional airports. The discussion focuses on identifying gaps in the applied risk mitigation and adaptation strategies and areas requiring attention due to the level of exposure or vulnerability or the demonstrated effectiveness of applied adaptation measures. The above provides the basis for recommendations for measures to enhance climate hazard intelligence, improve asset resilience, adapt operations, and develop formal adaptation plans to address both short- and long-term risks.

Chapter 6 – *Discussion and conclusions*

The final chapter synthesises the research findings, identifying cross-cutting themes that underpin the key concepts while discussing the climate hazard risk analysis process and related implications. It presents the research's contributions and limitations and suggests directions for future research.

To develop a comprehensive understanding of the impacts of climate hazards on airport systems and to identify prevailing trends in adaptation strategies, it is essential to review existing literature. Chapter 2 will provide an overview of findings from studies looking at the historical sensitivity of airports to climate hazards, offering insights into the broader climate risk landscape.

2 Literature review: Climate hazards and the airport system

As a result of increasing global warming, many changes in the climate system have become more significant, exhibiting an increase in the frequency and intensity of climate extremes (Easterling *et al.*, 2016; IPCC, 2021b), affecting natural and human-made systems. The Global Risks Report (WEF, 2025) underscores the escalating threat of extreme weather, identifying these events as the second most severe global risk for the year 2025. Floods, hurricanes, heatwaves and wildfires leading to substantial socio-economic impact highlight the urgency to act, as existing adaptation efforts seem inadequate to address the scale and intensity of extremes. The increasing susceptibility of airports to climate hazards in the past years and the scale of disruption caused by storms, extreme precipitation or extreme temperatures raise concerns about the existing levels of resilience and how they can maintain their ability to function efficiently in the future (Voskaki, Budd and Mason, 2023; Burbidge, Paling and Dunk, 2025).

This chapter examines the literature on climate hazard implications and adaptation in an airport context. It delves into topics around climate change, climate extremes, climate hazards, climate risk, adaptation, and airport systems. It sets out to build an understanding of existing knowledge, trends, and priority areas and to identify gaps in the literature that this thesis will address. The structure of the chapter is presented in Figure 2-1.

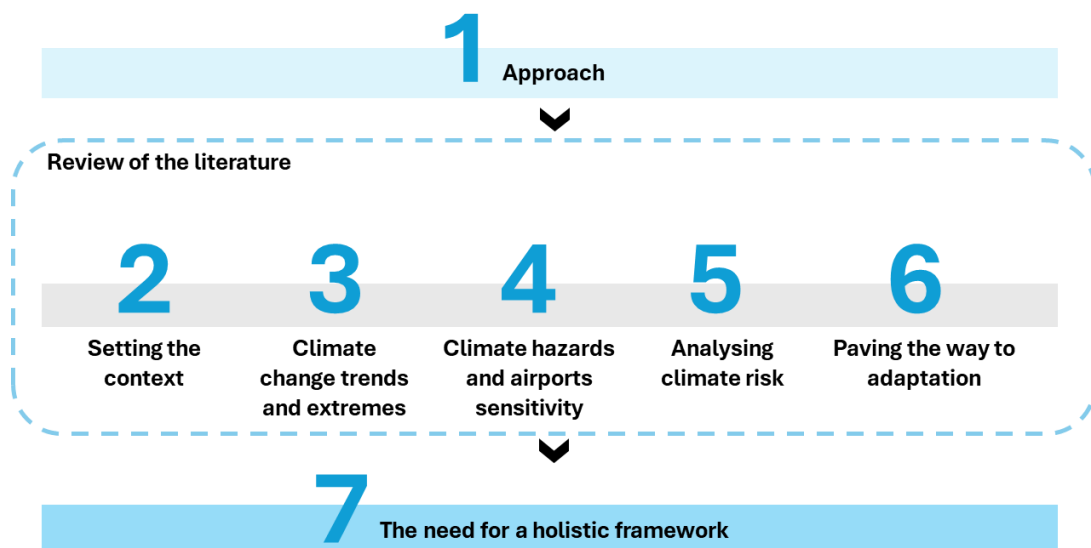


Figure 2-1 Structure of the literature review

Section 2.1 provides an overview of the adopted approach for the analysis of the reviewed literature. This is followed by Section 2.2, which sets the context of the reviewed literature and the topics this chapter will discuss. Section 2.3 offers an overview of the main points for reflection and builds an understanding of the trends that should be considered. The following section (Section 2.4) discusses extreme climate events that have historically affected airports, revealing different implications. Section 2.5 delves into various concepts and elements involved in risk analysis and how different approaches identified in the literature address risk, while the following section (Section 2.6) looks at the current trends on how to build adaptive capacity. The last section of the chapter (Section 2.7) discusses the gap this research will seek to address.

2.1 Approach

The focus of the review of the literature is to provide an analysis of aspects around airport systems and climate hazards and related risks under both current and future climate change scenarios. An analysis of a broad body of peer-reviewed articles, contributions to conferences, government or airport-commissioned studies, and technical reports is conducted to address this goal. The scope of the research is restricted to literature published in English. Initially, searches are performed using academic databases, primarily Scopus and Science Direct. Keywords including combinations of “*airport*” and “*climate hazard*”; “*climate risk*”; “*extreme weather*”; “*climate extremes*”; “*climate adaptation*” as well as phrases including “*impact of climate change on airport*” or “*impact of climate hazards on airport*” or “*airport vulnerability to climate change*” or “*airport sensitivity to natural or climate hazards*” or “*exposure to natural or climate hazards*” or “*airport climate adaptation*” are used to guide the search.

The identified articles are reviewed and refined to eliminate duplicates and ensure they are relevant to the scope of the study. While the search focuses on airport infrastructure, consideration is also given to the impact of climate change on air transport in general. Therefore, “*air transport*” and “*aviation*” are also used as keywords to enrich the search results. Also, aiming to have a more holistic perspective, the search included technical reports issued by aviation organisations like ICAO, EASA, Eurocontrol, ECAC, the Department for Transport and airport operators. Furthermore, post-event technical reports are also considered to analyse examples of climate impact on airports and how airports respond.

Overall, the analysis includes 61 peer-reviewed articles and conference proceedings and 34 technical or industry or institution/government type of reports published between 2005 and 2025 (Figure 2-2). Approximately 43% of the reviewed literature has been published since 2020, reflecting a growing emphasis on this research area. This trend shows a shift from viewing disruptive events as isolated weather-related impacts on operational resilience to recognising them as broader climate change-driven occurrences.

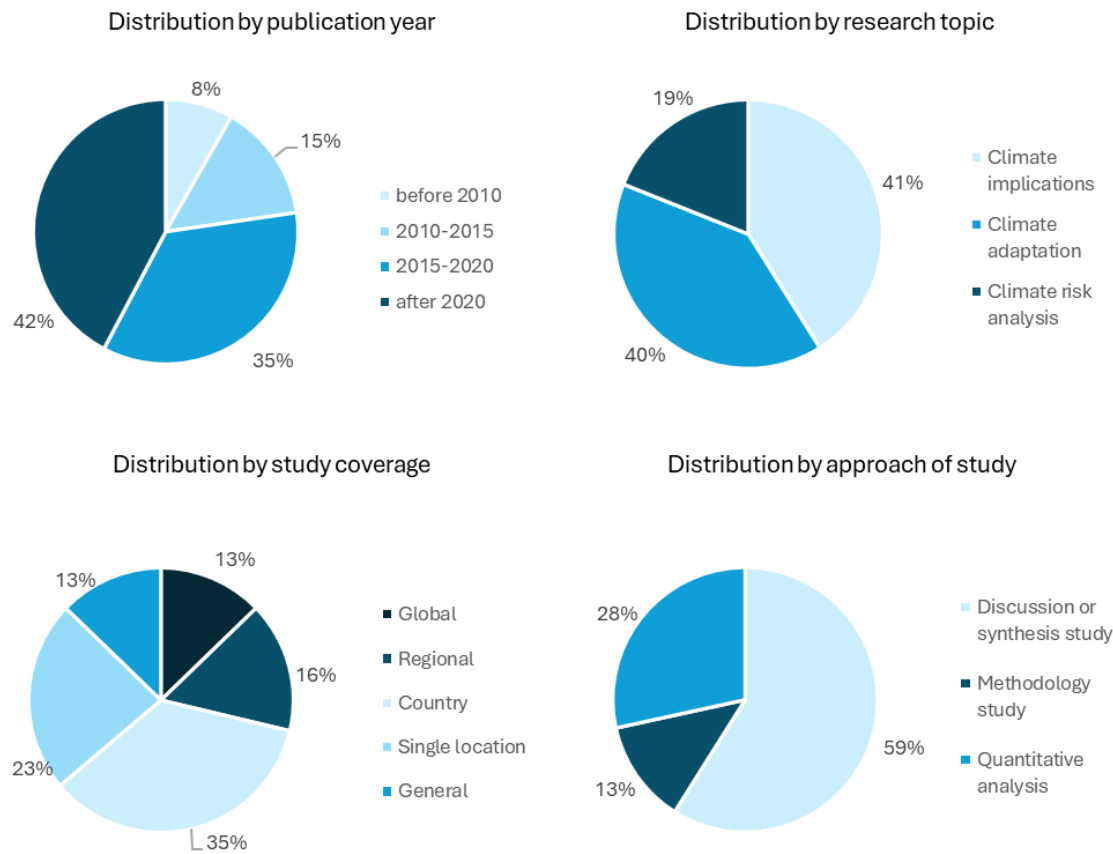


Figure 2-2 Categorisation of the reviewed literature

Regarding the coverage of the study, most reviewed literature (around 58%) refers to a single location (a case study airport) or a specific country. Around 28% of the reviewed studies have a global and/or regional focus.

While many of the reviewed studies cover multiple topics within the scope of this research, the research topics can be categorised as climate implications (around 41%), climate adaptation (around 40%) or climate risk analysis (around 19%). In terms of the approach of the study, most of the reviewed literature (around 59%) refers to a discussion or synthesis

study; the remaining studies revolve around methods to analyse or quantify climate hazard-related risk or risk elements, such as exposure or vulnerability to climate hazards.

2.2 Setting the context

Climate change is considered one of the most significant challenges our world is facing (WEF, 2025). Evidence shows that changing weather patterns and climate extremes will become more pronounced as the Earth continues to warm (European Environment Agency (EEA), 2021; IPCC, 2023a). Insurance and reinsurance records over the past decades indicate a rising trend in economic and insured losses attributed to natural hazards, around 5-7% annually (Swiss Re Institute, 2024). In 2024, the estimated insured losses exceeded USD 135 billion, while economic loss was estimated at around USD 310 billion (Figure 2-3). Significant events include the floods in Europe and the Middle East, leading to an estimated USD 13 billion in insured losses. Furthermore, the aftermath of the hurricanes Helene and Milton in the US resulted in around USD 50 billion in insured losses (Swiss Re Institute, 2024).

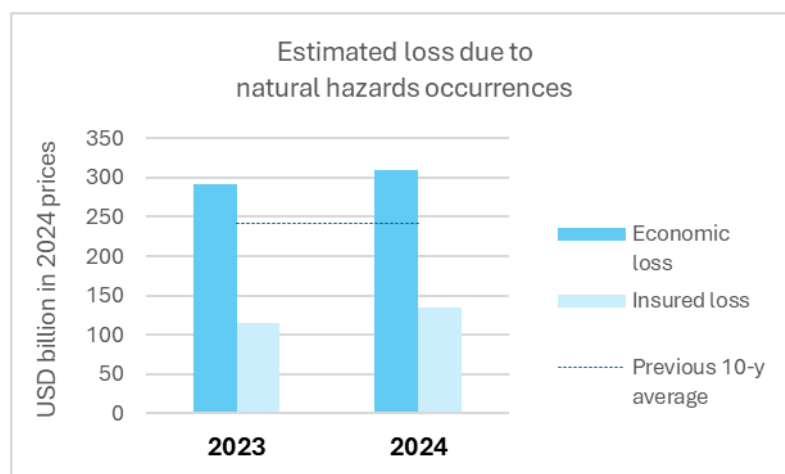


Figure 2-3 Estimated loss due to natural hazards occurrences (adapted from Swiss Re, 2024)

In the case of human-made systems such as urban, transport or infrastructure systems, one of the main concerns is that the extent of climate impacts and the related losses will be amplified in the future as their design was based on different climate parameters (Becker *et al.*, 2018). Focusing on critical infrastructure, there is a general agreement that the variability in climate influences the structural and operational performance, disrupting the services (Dawson *et al.*, 2018; Guest *et al.*, 2019; Verschuur *et al.*, 2024) with significant adverse socio-economic impacts (Chang *et al.*, 2007).

Infrastructure systems provide a critical service to modern society, which has been widely identified in the literature (McEvoy, Ahmed and Mullett, 2012; Dawson *et al.*, 2018; Qiang, 2019). According to EU Directive 2008/114/EC, the term '*critical infrastructure*' is used to define assets or systems essential for maintaining vital societal functions, like health, safety, security, transport, and economic and social well-being of people (European Union, 2008).

The word system is often used to describe a group of elements placed together and organised in a specific way to achieve a purpose (Gass and Fu, 2013). The components of a system may be interrelated with each other and the environment, or they may be interdependent. Hence, a system can be conceptualised as a set of relationships between the system's elements and the environment (Conger and Mason, 2013; Dekkers, 2017). In this context, a transport system can be perceived as a set of relationships between elements like hubs, nodes, links, or corridors and the environment (Rodrigue, 2020). Therefore, the transport system analysis would need to look at the system's purpose, elements, processes, and the internal and external environment (Conger and Mason, 2013; Kiel *et al.*, 2016).

Like all transport systems, air transport is a vital element of modern society, enabling the movement of people and goods from one location to another. As a key driver for global economic prosperity, air transport supports worldwide connectivity essential for business, tourism and trade. In 2023, more than 4.4 billion passengers travelled, and more than 61.4 million tonnes of cargo was transported, contributing around USD 4.1 trillion to the global economy; this corresponds to around 3.9% of the GDP. Besides the contribution to the global economy, air transport supports more than 86.5 million jobs across various sectors, enhances social networks and provides critical services and humanitarian aid relief to remote communities and areas affected by natural hazard events (Zanin and Lillo, 2013; Air Transport Action Group, 2024).

Airports play a crucial role in the air transport system, providing the necessary infrastructure to enable the movement of passengers and freight and supporting economic and social interactions (Graham, 2014; Rodrigue, 2020). Large airports serve as global hubs, handling high volumes of passenger traffic and facilitating international trade, while smaller airports enhance regional connectivity, provide access to remote locations, and support the local economy (Graham and Guyer, 2000). The airport as a system brings

together different elements and activities to achieve its role, which is the movement of people and/or freight and, as a result, can be studied in various ways. The ICAO uses the term aerodrome to describe the area used for aircraft movement. This area can be located on land or water and may include buildings, facilities, installations and equipment required for the arrival, departure and surface movement of an aircraft (ICAO, 2009).

Airports are designed to comply with an extensive set of standards and recommended practices set by national authorities and international aviation organisations (for example, ICAO, EASA, FAA, UK CAA) to ensure required levels of safety (De Neufville *et al.*, 2013). The basic airport infrastructure includes runways for take-off and landing, taxiways to enable connections between the runways and the apron areas and terminal gates; aprons serve as the interface between airside and landside facilities, enabling the park of the aircraft and the access of passengers to the aircraft through the gates and aircraft and airside maintenance and fuelling areas (De Neufville *et al.*, 2013; Edwards, 2005; Graham, 2014).

Besides the basic infrastructure, facilities that support the air and/or ground operations include an air traffic control tower, rescue and firefighting and other emergency response facilities (e.g. winter operation and aircraft de-icing), as well as security and ground handling areas (Schmitt *et al.*, 2016; Wittmer, Bieger, and Muller, 2011). The airport terminals serve as the passenger buildings supporting processes like check-in, baggage handling, security and customs activities, and various commercial activities (De Neufville *et al.*, 2013; National Academies of Sciences Engineering and Medicine, 2024). Furthermore, airports commonly include ground transport interchanges, road connections, and parking areas (Edwards, 2005; Graham, 2014; Schmitt *et al.*, 2016).

As a system, airports do not operate in isolation, as they are part of one or more networks connecting other airports (De Neufville *et al.*, 2013). Also, like all transport systems, airports are interconnected and interact with other systems, like utilities (electricity, water), meteorological facilities, communication, supply chains or even urban, economic and social systems or the environment (Urfer and Weinert, 2011; Rodrigue, 2020; National Academies of Sciences Engineering and Medicine, 2024).

Bearing in mind the primary role of the airport system, which is to facilitate the movement of people and/or freight, the following elements would need to interact to achieve its purpose:

- Airside and landside infrastructure and buildings, like runways, taxiways, aprons, terminal gates, terminals, air traffic control towers, maintenance and other support buildings used by service providers to deliver air and ground operations.
- Air and ground operations and services.
- Passengers and freight and people working at the airport.
- Supply chain, distribution network and supporting systems, like main utility networks (electricity, water), communication, meteorological facilities, logistics, and ground access to/from the airport.
- The environment in which the airport operates.

Figure 2-4 presents the main elements of the airport system, grouping components needed to perform the main functions to deliver its purpose, along with core inputs (resources) and outputs (Bubalo, 2012) that support the airport production process (air transport movements, aeronautical and non-aeronautical revenues, environmental externalities).

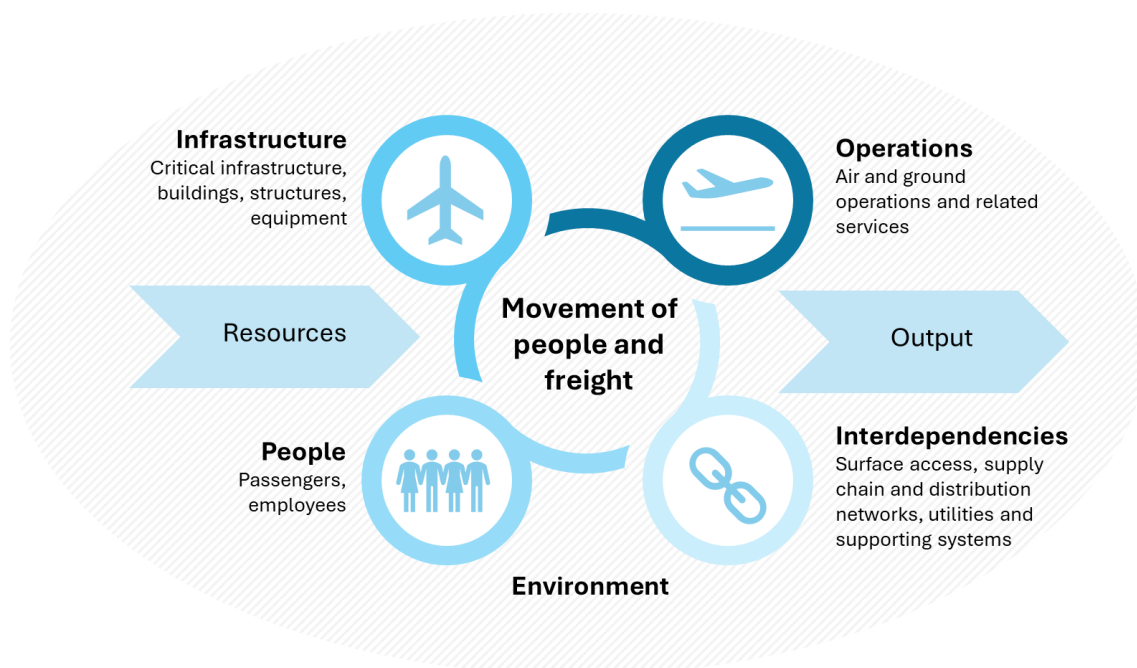


Figure 2-4 Analysis of the airport as a system

Considering that critical infrastructure systems, such as airports, are fundamental to modern society and underpin the Sustainable Development Goals (SDGs), ensuring they will remain resilient to future climate is essential (Verschuur *et al.*, 2024). The above is also highlighted in the latest report by the United Nations Office for Project Services (UNEP, 2021).

Although the impact of climate change indicates the need for investments to strengthen critical infrastructure systems and make them more climate-proof, recent years' events point out that there is still a long way to go to achieve the required level of adaptation (Koetse and Rietveld, 2009; Christodoulou and Demirel, 2017). While the emphasis of scholars has long been on the contribution of air transport to climate change (Lee *et al.*, 2009, 2021) and how the industry could reduce its carbon footprint (Wennberg, 2019; Gössling and Lyle, 2021), recently there has been a growing acknowledgement that there is a balance that the sector needs to meet between mitigating its impact and adapting to the changes of the climate (Burbidge, 2016; Ryley, Baumeister and Coulter, 2020).

The need for maintaining this balance is becoming evident considering the disruptions caused by events, such as the floods in Spain (Boyd, 2024; Martin, 2024), the Middle East (Gambrell, 2024; Gritten, Gillett and Comerford, 2024) and the UK (Chatterton *et al.*, 2016; Sharp, 2023) causing the inundation of runways and terminal buildings. Also, the occurrences of tropical storms like Milton, Helene, Sandy, Irma and Maria that led to the cancellation of thousands of flights and the closure of airports on the eastern coast of the United States and the Caribbean (IATA, 2012, 2017; Kunz *et al.*, 2013; Salisbury, 2024; Wong, 2024). Events such as the above indicate that despite ongoing progress to build resilience, adaptation gaps still exist and will continue to grow (IPCC, 2023a). As a result, further damage and alteration to the normal functioning of critical infrastructure, such as airports, may be likely in the future, especially in cases of airports already demonstrating sensitivity (De Vivo *et al.*, 2021; Burbidge, Paling and Dunk, 2023; Voskaki, Budd and Mason, 2023).

2.3 Climate change trends and extremes

The warming of the Earth since the pre-industrial era is causing changes in the climate, affecting natural and human systems. In 2011-2020, the global surface temperature reached 1.1°C above 1850-1900, and there is clear evidence that global greenhouse gas emissions will continue to rise due to unsustainable energy and land use, consumption patterns and production methods (IPCC, 2023a).

The IPCC, the United Nations body for assessing the science related to climate change, reviews in detail the leading science of global warming and trends in climate change. Through its assessments, the IPCC verifies the extent to which relevant knowledge has

been established. There are many definitions for climate change; the most widely accepted definition is the one provided by the IPCC, according to which "*climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or variability of its properties and that persists for an extended period, typically decades or longer*" (IPCC, 2018a).

The observed changes, as analysed in the latest report (AR6) (IPCC, 2021b), mainly refer to the warming of the atmosphere, ocean and land, changes in the temperature and precipitation patterns, sea-level rise, and the occurrence of weather and climate extremes, such as heatwaves, severe precipitation, droughts, and tropical storms worldwide. For the projection of future changes in the earth's climate, AR6 considers a set of five new emissions scenarios¹, called Shared Socio-economic Pathways (SSP), reflecting the various socio-economic trends and land use, greenhouse gas emissions (GHG) and atmospheric concentrations, solar activity, background forcing from volcanoes and air pollutant emissions. The projected climate scenarios suggest that the global surface temperature will continue to increase, and it is virtually certain that the global mean sea level will continue to rise through 2100, as presented in Table 2-1.

Under the high emissions scenario (SSP5-8.5), the extent of increase for global mean surface temperature and mean sea level is expected to be 3.3 to 5.7°C and 0.63 to 1.01 m, respectively. With the continued global warming, changes are anticipated to occur, like a reduction in Arctic Sea ice, snow cover, and permafrost, and changes in the global water cycle in terms of variability, precipitation, and severity of wet and dry events. Precipitation is expected to likely increase over high latitudes, the Equatorial Pacific, and parts of the monsoon regions, but it will decline over parts of the subtropics and in limited areas of the tropics (IPCC, 2021b).

¹ [SSP1-1.9](#), [SSP1-2.6](#), [SSP2-4.5](#), [SSP3-7.0](#) and [SSP5-8.5](#)

Table 2-1 IPCC climate change scenarios, global surface temperature and sea level change (adapted from IPCC, 2021)

Scenarios and modelled pathways	Global surface temperature change over the long term (2081-2100)	Global sea-level rise up to 2100 relative to 1900
Very low / limit warming to 1.5°C SSP1-1.9	1.4°C (1.0–1.8°C)	0.28–0.55 m
Low / limit warming to 2°C SSP1-2.6	1.8°C (1.3–2.4°C)	0.32–0.62 m
Intermediate / limit warming to 3°C SSP2-4.5	2.7°C (2.1–3.5°C)	0.44–0.76 m
High / limit warming to 4°C SSP3-7.0	3.6°C (2.8–4.6°C)	0.56–0.89 m
Very high / exceed warming of 4°C SSP5-8.5	4.4°C (3.3–5.7°C)	0.63–1.01 m

As a result of the increasing global warming, many changes in the climate system have become more significant, exhibiting an increase in the frequency and intensity of climate extremes. The IPCC defines climate extremes as *"the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable"* (IPCC, 2012). These may include unexpected or severe extreme weather or climate patterns, such as heatwaves, droughts, floods, tropical storms, heavy precipitation, and wildfires (Easterling *et al.*, 2000).

An example showing the extent of change in the occurrence of climate extremes is hot temperature extremes over land. Table 2-2 depicts the increase in frequency and intensity of extreme temperature events considering global warming levels. Extreme heat events that used to occur once in 10 years, on average in a climate without any human influence, nowadays, are likely to occur 2.8 times and are 1.2°C more intense; considering a 4°C increase in global warming, the frequency of these events will likely increase to 9.4 times, and the intensity will likely be 5.1°C.

Table 2-2 Increase in frequency and intensity of extreme temperature events under different global warming levels (adapted from IPCC, 2021)

Scenario	Change in frequency (per 10 years)	Change in intensity
Pre-industrial (1850-1900)	Once	Baseline conditions
Present (1.1°C warming)	2.8 times	+1.2°C hotter
Future global warming levels		
1.5°C warming	4.1 times	+1.9°C hotter
2.0°C warming	5.6 times	+2.6°C hotter
4.0°C warming	9.4 times	+5.1°C hotter

Another example is heavy precipitation over land. Table 2-3 presents the increase in the frequency and intensity of a heavy 1-day precipitation event that occurred once in 10 years on average; global warming leads to a likely increase in the frequency from 1.3 times at present to 2.7 times considering a 4°C increase in global surface temperature; the intensity for the latter is projected to increase by 30.2%.

Table 2-3 Increase in frequency and intensity of extreme precipitation events under different global warming levels (adapted from IPCC, 2021)

Scenario	Change in frequency (per 10 years)	Change in intensity
Pre-industrial (1850-1900)	Once	Baseline conditions
Present (1.1°C warming)	1.3 times	+6.7% wetter
Future global warming levels		
1.5°C warming	1.5 times	+10.5% wetter
2.0°C warming	1.7 times	+14.0% wetter
4.0°C warming	2.7 times	+30.2% wetter

With every increment of global warming, changes will likely become more widespread and pronounced, increasing the level of impact on natural and human systems worldwide (IPCC, 2023a). For example, the intensification of precipitation will likely have implications relating to flooding in many areas of the world, with consequences to exposed and vulnerable assets, social systems, society, and the environment. However, the change may not be the same for all areas of the world; for instance, there is high certainty that some mid-latitude regions are expected to experience the maximum increase in the temperature of the heat extremes (about 1.5 to 2 times the rate of global warming) (IPCC, 2021b).

In the UK, in the past years, record-breaking extremes have been observed; instances of flooding, water scarcity, temperature extremes and extensive storm damage (Dessai *et al.*, 2023). 2023 was recorded as the second warmest and relatively wet year, with 11% more rainfall on average (Met Office, 2023a) and 2024 was provisionally recorded as the fourth warmest year, with a 7% increase in rainfall on average (Met Office, 2025). It is noteworthy that in 2022, for the first time on record, temperatures exceeded 40°C. In terms of temperature from 1961-90 to 2008-17, there are notable changes in extreme heat events, from increases in the average higher maximum temperatures (by 0.8°C) to increases in the duration of warm spells; the average length of warm spells has more than doubled in the recent decades, especially in the southeast England (Met Office, 2021a). Evidence suggests that the chances of experiencing similar or more intense events in the future could be 10 times more likely (Met Office, 2022a). Considering the UK Climate Projections (UKCP18) (Bernie *et al.*, 2018), there is a trend for warmer, wetter winters and hotter, drier summers.

Specifically, by the 2070s, hot summer days could increase by 3.8 °C to 6.8 °C under a high emissions scenario (Met Office, 2022b); hot spells could become more common, with an average increase in hot days and nights between 5 and 39 days per year under a 1.5°C to 4°C of warming, as shown in Table 2-4 (Hanlon *et al.*, 2021; Met Office, 2021a).

Table 2-4 Average summer days with temperatures exceeding 25°C under different scenarios of global warming (adapted from Hanlon *et al.*, 2021, Met Office, 2021)

Scenario	Average days of extreme temperature
Present (2000-2017)	10 days per year
Future global warming levels	
2.0°C warming	18 days per year
3.0°C warming	27 days per year
4.0°C warming	39 days per year

Rainfall is expected to decrease by up to 45% during summer and increase by up to 39% during winter. The seasonality of extremes is likely to change from summer to autumn, with increased intensity in heavy hourly rainfall (Met Office, 2022b). Precipitation extremes and the risk of flooding are expected to increase, as presented in Table 2-5; an increase of 1 to 8 days per year of high impact rainfall is anticipated under a 1.5°C to 4°C of warming (Hanlon *et al.*, 2021; Met Office, 2021b).

Table 2-5 Average days of extreme precipitation for England and Wales under different scenarios of global warming (adapted from Hanlon et al., 2021, Met Office, 2021)

Scenario	Average days of extreme precipitation
Present (2000-2017)	7 days per year
Future global warming levels	
2.0°C warming	9 days per year
3.0°C warming	10 days per year
4.0°C warming	11 days per year

Climate projections also suggest that winter windstorms are likely to increase slightly in frequency and intensity, with a chance of more severe storms in the future. However, considering the difference in the outputs of the climate models and the factors influencing storms, the level of confidence in the above projection is medium (Met Office, 2021c, 2023b). Sea level rise presents variations, being more significant moving from north to south; for London, a rise in the sea level of 0.53 to 1.15 m seems likely under the high emissions scenario (Met Office, 2022b). As a result, coastal flooding due to storms and rising sea levels is anticipated to become a concern, amplifying the impacts of storm surges (Met Office, 2021c; Perks, Howard and Palmer, 2023).

The projected changes in severity, frequency, and spatial patterns of extremes indicate that climate hazards like **flooding**, **extreme wind** and **temperature extremes** will likely further affect transport infrastructure in the following decades (Dessai *et al.*, 2023).

2.4 Climate hazards and airports' sensitivity

Infrastructure systems like airports tend to be impacted by climate hazards and extremes (Verschuur *et al.*, 2024). In the context of this thesis, the term climate hazard describes a weather-, hydrological – or other climate-related phenomenon, such as flood, drought, temperature extreme, storm, and many others that can affect people and the built environment and, in this case, an airport (McBean and Rodgers, 2010; Mora *et al.*, 2018). The IPCC (IPCC, 2018a) uses the term impact to define '*the consequences of realised risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability*'.

ICAO (2021) and ACI (2018) identified key climate stressors affecting airport systems; these can be broadly categorised as either slow onset events, like rising sea levels or

desertification, or rapid onset extreme climate events, like storm surges, more intense storms, temperature changes, changes in precipitation or wind patterns or in icing conditions. Eurocontrol (2021) explored the risks posed by climate change on the European aviation sector, focusing on the link between disruptive weather, changes in storm and wind patterns and delays and the impact of sea level rise. Both slow and rapid onset events can lead to physical risks, such as loss of airport infrastructure and asset damage or operational risks, like service and supply disruptions and impact on safety or performance (ICAO, 2022a). Also, climate hazards can lead to a series of business-related risks (ICAO, 2020) that may also influence social and environmental aspects (Lopez, 2016; Burbidge, Paling and Dunk, 2023; Voskaki, Budd and Mason, 2023). Considering the existing literature, physical risks to airports include inundation or damage to critical infrastructure and assets, while operational risks involve disruptions to air or ground operations or airport surface access, critical supply chains and safety-related concerns (Voskaki, Budd and Mason, 2023). Figure 2-5 depicts the most reported climate-related factors impacting airports and the related impact and risk types identified in the reviewed literature.

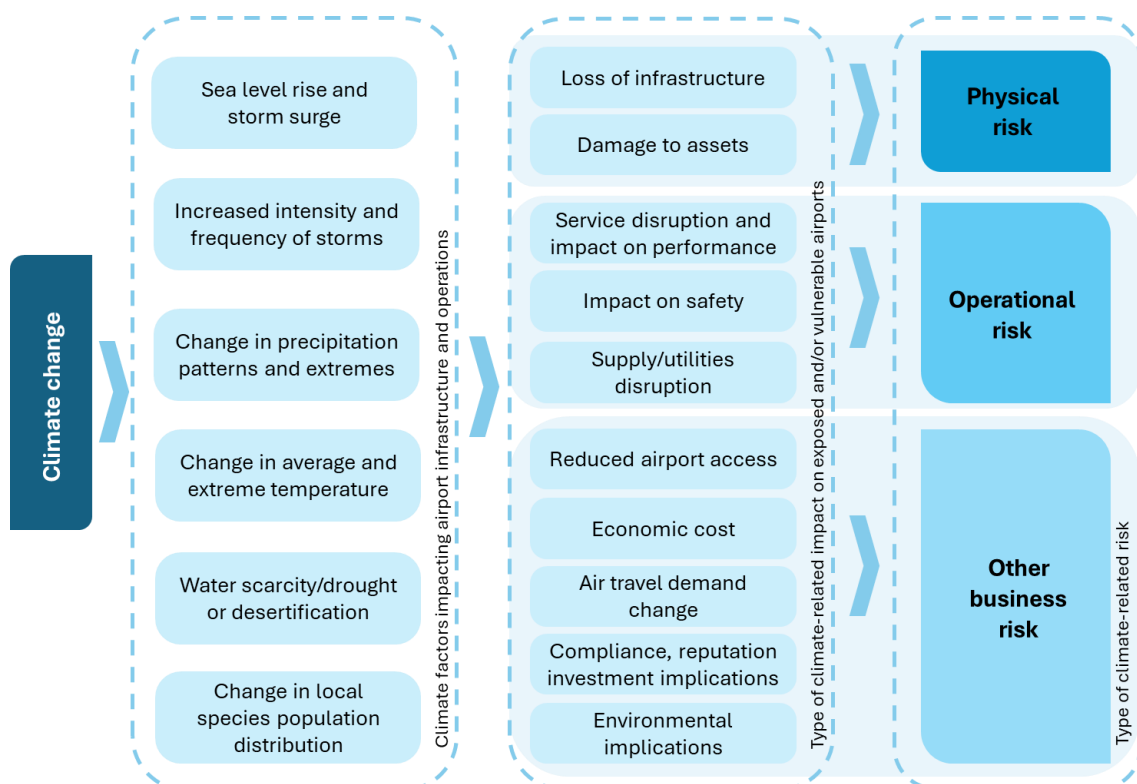


Figure 2-5 Key climate-related factors impacting airports and types of related impact (source author, adapted from Voskaki, Budd and Mason, 2023)

In addition to physical and operational aspects, which are the most obvious and will be analysed in the following paragraphs, climate hazards can lead to business risks. Apart from meeting obligations posed by legislation (for example, the Climate Change Act in the UK) (Kollamthodi, Fordham and Stephens, 2011), and the financial burden due to the loss of landing fees and compensation claims (Merkert and Mangia, 2012), more airports nowadays are called to address climate hazards of concern proactively. In some cases, addressing the business aspects of climate hazard-related implications is driven by investors and other stakeholders who recently have become more interested in the economic impact of climate change (transition and physical climate risk) and how airport operators respond (Pek and Caldecott, 2020; ICAO, 2021; Verschuur *et al.*, 2024).

Also, climate change can influence travel flows, as climate extremes may make some destinations less appealing for travellers, or airlines may change the schedule of operations to avoid disruption at vulnerable airports (Cools *et al.*, 2010; Pek and Caldecott, 2020). Additionally, growing environmental concerns can influence travel demand (Gössling, Humpe and Bausch, 2020) and may shape the choice of future generations towards more sustainable transport modes, especially for short-haul travel (Higham and Cohen, 2011; Grønhøj and Hubert, 2021). This possible shift in social behaviours could put pressure on policymakers to implement stricter carbon mitigation measures, such as taxes or sustainable fuel mandates (Lu, 2018; Valdés *et al.*, 2021). These additional costs will likely be passed on to passengers via an increase in ticket price, potentially reducing air travel demand (Tol, 2007).

Table 2-6 outlines a selection of studies discussing aspects of climate hazards and related risks, providing details on the reference, description of the study, and climate stressors/implications while characterising the type(s) of climate risk involved (physical, operational or other business).

Table 2-6 Selected examples of literature discussing aspects of climate risk and possible impact on airports (adapted/supplemented from the original from Voskaki, Budd and Mason, 2023)

Reference	Brief study description	Climate stressor/climate implication	Type of climate risk									
			Physical			Operational			Other business			
			Loss of infrastructure	Damage to assets	Service disruption	Supply disruption	Impact on safety	Airport accessibility	Economic cost	Change in demand	Reputation/investments	Environmental impact
(Holmes <i>et al.</i> , 2024)	Identifies climate hazards affecting airports and discusses their implications	Sea level rise, increases in temperature, intensity of storms, lightning, changing snow/icing conditions, wind and precipitation patterns, fog, changes in biodiversity	x	x	x		x		x			
(Burbidge, Paling and Dunk, 2023)	Presents an overview of climate change impacts and adaptation in the aviation sector	Sea level rise, changes in storm and wind patterns, changes in temperature, precipitation, turbulence, permafrost thaw	x	x	x		x	x	x	x		x
(Gratton <i>et al.</i> , 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
(Eurocontrol, 2021b)	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
(De Vivo <i>et al.</i> , 2021)	Presents a climate risk assessment framework for Mediterranean airports	Extreme temperature, extreme precipitation and sea-level rise	x	x	x	x						x

Reference	Brief study description	Climate stressor/climate implication	Type of climate risk									
			Physical			Operational			Other business			
			Loss of infrastructure	Damage to assets	Service disruption	Supply disruption	Impact on safety	Airport accessibility	Economic cost	Change in demand	Reputation/investments	Environmental impact
(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 and 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
(ICAO, 2018, 2022a)	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
(Fisk, 2017)	Discusses the implications of climate hazards to coastal infrastructure and provides guidelines for adaptation planning	Sea-level rise, extreme temperature, storms, change to rainfall patterns	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, the local species population distribution, sea-level rise	X	X	X		X		X			
(Pejovic <i>et al.</i> , 2009)	Climate impact on airport performance in the UK	Weather-related extremes (temperature, wind, fog, snow, thunderstorms)	X		X				X			

(Pejovic *et al.*, 2009; Lopez, 2016; Fisk, 2017; ICAO, 2018; Griggs, 2020; Pek and Caldecott, 2020; De Vivo *et al.*, 2021; Eurocontrol, 2021b; ICAO, 2022a; Gratton *et al.*, 2022; Burbidge, Paling and Dunk, 2023; Holmes *et al.*, 2024)

Considering the reviewed studies, coastal or inland flooding (fluvial/pluvial) is identified as a key climate hazard of concern and one of the main implications of extreme precipitation (De Vivo *et al.*, 2021; Eurocontrol, 2021b; Yesudian and Dawson, 2021). Flooding can lead to the inundation of the runway(s) or buildings (ICAO, 2018) and the closure of the airport, the damage of critical assets, for instance, power generation, electrical equipment, navigation and communications, or cause disruption to surface access (Burbidge, 2018; Pek and Caldecott, 2020; Lindbergh, Ju, *et al.*, 2022; De Vivo *et al.*, 2023a). In addition, flooding can result in changes in the local species population distribution, increasing the risk of wildlife strikes (ACI, 2018; ICAO, 2021). Where flooding occurs frequently, it may affect route planning or even a destination's attractiveness (Pek and Caldecott, 2020).

Coastal airports are, without doubt, exposed to sea-level rise and storm surges (Dolman and Vorage, 2019; Griggs, 2020). A study conducted by Yesudian and Dawson (2021) suggests 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 the event of a storm surge, two-thirds of coastal or low-lying airports in Europe are at risk of flooding (Eurocontrol, 2021a). An example of the impact of compound coastal flooding from storm surges (Zscheischler *et al.*, 2020) is Hurricane Sandy in 2012. The storm generated a surge of up to 9ft above normal tide levels, affecting the east coast of the US, including the metropolitan area of New York. The storm flooded the runways at La Guardia and Kennedy airports in New York, leading to the closure of these airports and disruption in Philadelphia and Washington airports (Dulles and Reagan) (National Oceanic and Atmospheric Administration (NOAA), 2013). The above resulted in the cancellation of over 5,000 flights per day (IATA, 2012).

Multivariate events that arise from a mixture of different drivers and/or hazards, like storms that combine extreme winds and precipitation and/or storm surges, depending on the location of occurrence, can cause significant disruption and, as a result, have economic implications. For instance, in 2004, Hurricane Ivan forced the closure of Norman Manley and Donald Sangster airports in Jamaica for three days; the estimated impact due to damage to roofs and lighting systems and loss of revenue was 47.0 and 13.1 million Jamaican dollars, respectively (Zapata *et al.*, 2004). Similarly, severe thunderstorms at Frankfurt Airport in 1997-1998 led to approximately 1000 minutes of delays within four hours (Sasse and Hauf, 2003). Beyond the direct economic consequences of infrastructure

damage, flight delays and cancellation, storms can have wider regional economic repercussions, especially when the airport serves as a key gateway for tourism or business. For example, the closure of Kansai International Airport in Japan due to the flooding caused by Typhoon Jebi that triggered a historic storm surge had an economic impact of more than half a billion USD on the airport and the local economy (Takabatake *et al.*, 2018; ICAO, 2019a).

In some cases, the manifestation of multi-hazards can have a catastrophic outcome. For instance, in 2015, Storm Erika hit Dominica, triggering flash flooding, slope failure and debris generation. Because of the event, both Canefield and Douglas-Charles International airports were flooded. In addition, the flood caused damage to Douglas Charles International due to extensive deposits of mud and debris from the nearby river. The overall damage to the airport infrastructure was estimated at around USD 14.5 million (Commonwealth of Dominica, 2015).

Flooding can also result from changes in the average values and/or rainfall intensity in cases where stormwater infrastructure cannot handle the volume of water (Lopez, 2016; ACI, 2018; Wu, Taniguchi and Tajima, 2021). A recent example is the case of Dubai International Airport; within a day, the area received nearly double the average annual rainfall, causing the inundation of the runways and the surface access to the airport (Gambrell, 2024). Similarly, in 2013, at London Gatwick Airport, the combination of heavy rain and strong winds disrupted travel for more than 16,000 passengers; the consequences were amplified because the event occurred on Christmas Eve, typically one of the busiest days of the year for the UK for air travel (Chatterton *et al.*, 2016). Besides inundation, extreme precipitation may cause pollution control systems to fail, raising pollution concerns for local water resources and/or ecosystems (ICAO, 2018).

Shifts in rainfall patterns can reduce water availability, leading to water scarcity and/or drought conditions and limiting water-intensive activities (Fisk, 2017). Although drought is not often identified as a climate hazard posing risks for airports, there are examples of airports located in water-scarce areas, like Dallas/Fort Worth International Airport in Texas; restrictions on water usage for irrigation and pavement cleaning are imposed during periods with limited water availability (Transportation Research Board, 2012).

Other climate hazards for consideration are extreme temperature, heatwaves and cold and icing conditions, which can cause asset damage and operational disruptions. Considering that, in most cases, buildings and structures are designed for specific thermal conditions, the rising temperatures will likely increase cooling demand and energy consumption (Dolinar *et al.*, 2010). Temperature extremes, especially extreme heat, can lead to cracking and degradation of pavement surfaces, malfunctioning of equipment (e.g. navigation) or, in the case of icing conditions, additional demand for anti-icing and de-icing. Another aspect is that the demand for increased energy consumption (for cooling or heating) (Lopez, 2016; ACI, 2018; ICAO, 2019b) can affect the airport's carbon footprint. De Vivo *et al.* (2021) refer to the example of Hanover Airport in Germany, where the heatwave of July 2018 caused damage to the runway. Also, Borsky and Unterberger (2019) discuss the 2017 extreme heat in the United States, when the temperature reached 49°C, leading to the cancellation of more than 40 flights at Phoenix Sky Harbor International Airport.

Many studies recognise increased temperature and heatwaves as one of the climate hazards for consideration, especially in the case of airports in the Southern Europe (Milanés *et al.*, 2013; Gratton *et al.*, 2020; De Vivo *et al.*, 2021) or other geographies, like the Caribbean, North America and China (Monioudi *et al.*, 2018; Zhao and Sushama, 2020; Yuan *et al.*, 2021). High temperatures can restrict the aircraft's maximum take-off weights because of the reduced lift generated in less dense air (Coffel, Thompson and Horton, 2017); this creates issues for airports with short runways located at higher altitudes (Coffel and Horton, 2015; Monioudi *et al.*, 2018; Y. Zhou *et al.*, 2018; Zhou *et al.*, 2018). Additionally, extreme heat conditions pose health and safety risks for airport staff working outdoors, with studies documenting the impact of extreme heat on human health (Arbuthnott and Hajat, 2017).

Monioudi *et al.* (2018) looked at the direct impacts of changing climate stressors, like extreme heat and sea level, on airport operations in Jamaica airports. Based on the take-off requirements of a Boeing 737-800 aircraft, the analysis concluded that Sangster International Airport and Norman Manley International Airport would, on average, require to address around 65 days of disruption per year due to heat extremes and aircraft weight restrictions by the year 2030. The above implies concerns for the air operator around aircraft performance and economic considerations due to increased fuel consumption

(Coffel, Thompson and Horton, 2017) or the need to change routes to avoid susceptible airports (Pek and Caldecott, 2020).

Depending on the location, the design of airports may consider different thresholds as regards climate extremes. For example, in the case of runway tarmac, the temperature threshold is different in the UK compared to airports in the Middle East (Al-Abdul Wahhab, Ramadhan and Asi, 1994; London Heathrow Airport, 2022). An overview of thresholds considered in the design and operation of airports is provided in Table 2-7.

Table 2-7 Selected examples of operational thresholds for climate extremes for airports in the UK (adapted from the original from Verschuur et al., 2024)

Climate driver	Threshold
High temperature	UK tarmac standards lose integrity when temperatures exceed 32°C (in the shade). The threshold for maximum take-off weight restriction for London airports, such as London Heathrow, is over 35°C, while in other countries ranges from 29-54°C (Pek and Caldecott, 2020; London Luton Airport, 2021; London Heathrow Airport, 2022; De Vivo <i>et al.</i> , 2023a)
Low temperature	The response threshold for de-icing is $T_{\text{mean}} \leq 0^{\circ}\text{C}$, while -7°C suggests that de-icers start becoming less effective (London Luton Airport, 2021; London Heathrow Airport, 2022)
Flooding	Although the inundation level depends on the stormwater infrastructure capacity, a threshold of 25 mm/hr of precipitation has been recorded (London Heathrow Airport, 2022). Water films >3mm can lead to reduced safety standards (aquaplaning) during take-off and landing (Meyboom, 2022)
Extreme wind	Wind speeds 15-20 knots or wind gusts ≥ 28 knots may impact aircraft take-off performance. Impacts on high structures may be possible when wind speed exceeds 30-34 knots or wind gusts ≥ 43 knots (London Luton Airport, 2021; London Heathrow Airport, 2022)
Extreme snowfall	The threshold for lying snow in the UK London airports is ≥ 20 mm for dry snow, 10mm for wet snow and 3mm for slush, while accumulations of snow of more than 1 cm trigger winter operations plan (London Luton Airport, 2021; London Heathrow Airport, 2022). In US airports, such as Seattle, a threshold of 76.2mm of snow is used to trigger a snow alert (National Academies, 2016)

(National Academies, 2016; Pek and Caldecott, 2020; London Luton Airport, 2021; London Heathrow Airport, 2022; Meyboom, 2022; De Vivo *et al.*, 2023a)

Another implication of climate change is the impact on wildlife populations in local ecosystems or bird migratory patterns (for example, spring migration may occur earlier, or species may expand their territory) (Burbidge, 2018; Gratton *et al.*, 2022). While the above

impacts are highly localised and can be managed within a local biodiversity management plan, a shift in bird distribution can pose safety risks or even lead to disruption to airport operations (ICAO, 2022a). On certain occasions, changes in climate parameters may lead to the introduction of new flora species that could change the balance in the local ecosystem attracting new bird species; for instance, 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). Accounting for shifts in local biodiversity has been considered when analysing vulnerability, like in the case of Nice Côte d’Azur Airport (French Civil Aviation Authority, 2016; Lopez, 2016).

A consequence, often overlooked in many studies, relates to the interdependence and interrelation of the different elements of the airport. Infrastructure systems are interconnected by nature; therefore, disruptions or failures in one system may lead to cascading failures in others (DEFRA, 2011; Wilbanks *et al.*, 2020). For instance, in 1998, a severe ice storm in northeastern Canada disrupted electricity networks, triggering failures in the water and transport systems. Due to the failure of the electrical power grid, there was widespread disruption at Montréal-Trudeau International Airport (Chang *et al.*, 2007). Also, in Melbourne, Australia, during the heatwave of 2009, failures in the power grid had ripple effects, leading to multiple failures in communication systems and air, rail and road transport systems (McEvoy, Ahmed and Mullett, 2012).

When climate extreme events occur during periods of high demand for air travel (for example, during the summer holidays, Christmas or Easter period), the level of impact in terms of disruption can be amplified, as in the example of the London Gatwick Airport flood on Christmas Eve (Chatterton *et al.*, 2016). The above suggests that in geographies where winter or summer weather conditions can become extreme, the implications of such events can be severe (Sheehan, 2019; Zhao and Sushama, 2020; De Vivo *et al.*, 2021). However, climate extremes do not always align with seasonal fluctuations in air travel demand.

Despite efforts to mitigate climate change, it is widely acknowledged that a certain level of change has become inevitable (IPCC, 2021b), suggesting that a further increase in global warming will increase the frequency and intensity of the projected changes in extremes. It seems almost certain 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.

2.5 Analysing climate risk

Identifying, analysing, understanding, and assessing risk is significant in any risk reduction strategy. It provides the basis for setting priorities and establishing a tailored action plan to mitigate risk (Burbidge, 2018; ICAO, 2019a; National Academies of Sciences Engineering and Medicine, 2020). There are many definitions for risk; the ICAO (2013) defines risk as *‘the predicted probability and severity of the consequences or outcomes of a hazard’*. According to the United Nations Office for Disaster Risk Reduction (UNISDR, 2015), risk is *‘the combination of the probability of an event and its negative consequences’* while disaster risk is defined as *‘a function of hazard, exposure and vulnerability that provides an estimate of potential disaster losses in physical, social, or environmental assets’*. Bearing in mind the latter, risk includes a combination of the measurable characteristics of the climate hazard that describe its expected impact, the number of assets and people exposed to the hazard and their vulnerability to damage, as depicted in Figure 2-6.



Figure 2-6 Risk definition (developed considering the terminology provided by UNISDR (2015))

By definition (UNISDR, 2015), the term **hazard** is associated with the probability of experiencing a certain intensity of a harmful event, which in our case is a climate hazard, at a specific location; therefore, the key measurable characteristics typically refer to the following (United Nations, 2016):

- A geographic location is a precondition for the occurrence of the hazard as it relates to an area subject to the possibility of a climate hazard event (e.g. airports located by the coastline are subject to flooding due to sea-level rise and/or storm surges).
- Frequency typically refers to the number of times a specific event has occurred within a particular timeframe (Jackson, 2013).
- Intensity is a measurement of the consequence of the hazard in a specific location (Jackson, 2013). Depending on the type of hazard, a wide range of scales and indices are used for the measurement, including loss estimate, state of the damage, and monetary value (Blong, 2003).
- The probability of occurrence shows the extent to which the climate hazard is likely.

In many studies, the hazard analysis and its characteristics use historical scenarios and statistical analyses of observations or different probabilistic hazard assessment methods (Apel *et al.*, 2004; IPCC, 2012; UNISDR, 2015; Stephens and Bledsoe, 2020). Regarding climate change and related hazards, besides the above characteristics, the IPCC (IPCC, 2018b) uses the term confidence to define the robustness of a finding by considering the evidence and degree of agreement.

Exposure, as a term, defines the presence of assets and/or people in a hazard-prone area (IPCC, 2012; UNISDR, 2015; United Nations, 2016) and includes all components that might be exposed to and affected by specific climate hazards (Birkmann, 2013). As a term, scholars often use exposure to describe the nature and extent to which a system is prone to experience climate variability or environmental change (Rowan *et al.*, 2014). Airports may be exposed to climate hazards differently, depending on their geographic location; for example, airports in close proximity to rivers or coastal areas can be exposed to flooding (Dolman and Vorage, 2019). Consequently, the airport's location is one of the main factors contributing to climate hazard exposure. Also, the exposure level may differ depending on the climate change scenarios or the airport characteristics (e.g., parts of the infrastructure exposed to the climate hazard, number of passengers).

Quite often and depending on the focus of the study, exposure has different dimensions, addressing the physical (infrastructure, buildings, other assets), social (people) or economic dimension (economic and business activity) (Peduzzi *et al.*, 2009; Nguyen, Liou

and Terry, 2019). These dimensions are often used as a metric in risk modelling studies; for example, the number of people or buildings in a given area exposed to a specific hazard (Peduzzi *et al.*, 2009) or the value of assets or the service/product produced (Novelo-Casanova and Suárez, 2012). Insurance companies also use the dimensions mentioned above to define how exposed an organisation can become in the event of a natural hazard occurrence (Zurich Risk Engineering, 2022).

Vulnerability is a risk determinant with many definitions, and in general, many scholars use this concept to define the outcome of a series of conditions and processes (Füssel and Klein, 2006). As a term, vulnerability is used to describe the potential for harm or loss (Cutter, 2013) and is often linked to the predisposition to '*be adversely affected*' (IPCC, 2012). Usually, it addresses the expected degree of loss and reflects the hazard consequences to assets or people (Fuchs, Heiss and Hübl, 2007). In transport system studies, vulnerability often reflects the risk posed to society by service disruption (Mattsson and Jenelius, 2015). In contrast to exposure, vulnerability tends to relate to the characteristics of the systems and the specific hazard (IPCC, 2012). For instance, an airport system may be exposed to multiple hazards such as storms, extreme precipitation, and sea-level rise; however, it may be vulnerable to just one (e.g. pluvial flooding).

In many cases, vulnerability is associated with a system's ability to cope with a hazard's impact from the physical, social and economic perspective, reflecting the resistance to damage (Wu, Yarnal and Fisher, 2002; Proag, 2014). In climate change research, vulnerability is often linked to adaptive capacity and sensitivity (Adger, 2006; Füssel and Klein, 2006; Smit and Wandel, 2006). While sensitivity addresses the degree to which an exposed system is affected (Füssel and Klein, 2006) and how it reacts to a change in climate (Rowan *et al.*, 2014), **adaptive capacity** mainly refers to the ability of a system to adapt (Engle, 2011; Rowan *et al.*, 2014).

The concept of adaptation has only recently been identified as one of the blocks to strengthening the global response to climate change (United Nations, 2007, 2015). As a term, it refers to '*the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit opportunities*' (Field *et al.*, 2012). It, therefore, addresses the ability of a system to prepare for or respond to stresses to reduce the negative impacts of climate hazards (Nguyen, Liou and Terry, 2019).

As a result, adaptive capacity influences the existing levels of vulnerability, moderates the exposure and the sensitivity of the overall system (Engle, 2011) and consequently reduces the overall levels of risk. In an airport context, it addresses the capacity of the airports to adjust their functions and characteristics to increase their ability to cope with existing climate variability, anticipate future change, reduce risk, and recover from the consequences in a timely and orderly manner.

Looking at defining risk in a holistic way, the main risk determinants need to reflect the characteristics of the climate hazards, the exposure of the airport system and how vulnerable the exposed elements are to the occurrence of the specific climate hazard and actions undertaken to increase the airport system's capacity to adapt and reduce the risk (Figure 2-7).

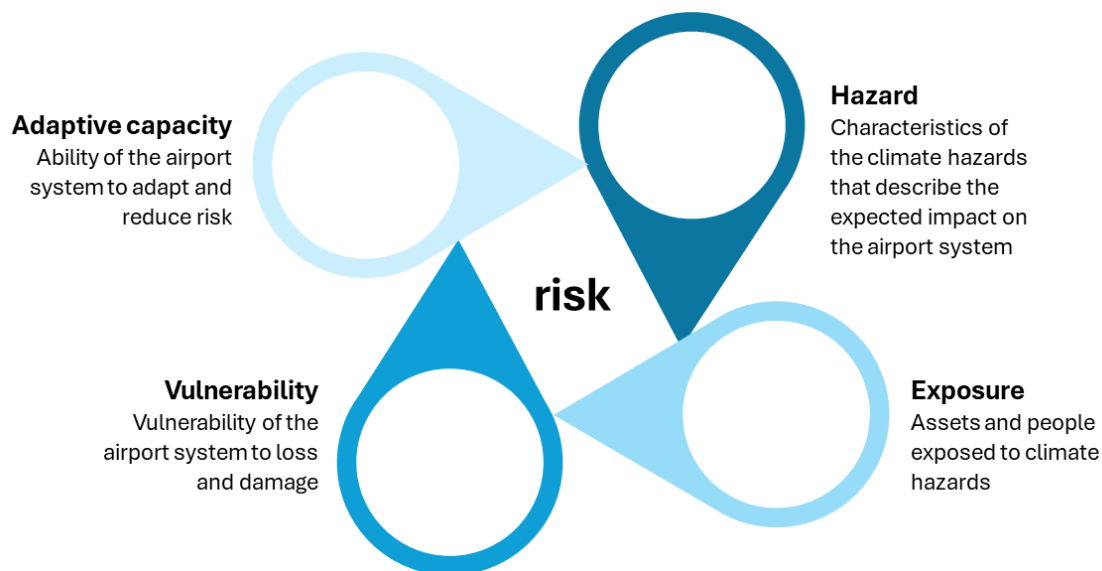


Figure 2-7 Determinants of risk (developed based on the work of Engle, 2011; IPCC, 2012; Nguyen, Liou and Terry, 2019; Proag, 2014; Rowan et al., 2014; Smit and Wandel, 2006)

Analysing climate hazard-related risks in the context of airports has only recently gained attention. This is surprising, considering that risk assessment is integral to aviation safety management. Common applied practices and frameworks for risk assessment typically refer to risk matrices that consider aspects of probability and severity (ICAO, 2013a) or the 'bowtie' methodology (de Ruijter and Guldenmund, 2015).

When it comes to climate risk, the conceptualisation and analysis appear to be influenced by how risk is defined. For instance, Lopez (2016) describes a risk matrix developed by the French Technical Centre for Civil Aviation to assess climate change risks to airport

components; risk is conceptualised as a combination of the probability of climate change occurring and its potential impact on airport operations. Similarly, Norway's primary airport operator employs a risk priority matrix to evaluate climate hazards based on the likelihood of occurrence, severity and potential consequences (Larsen, 2015).

Lately, organisations such as ICAO or the UK Department for Transport (DfT) have provided structured guidance on conducting climate change risk assessments (ICAO, 2022b; DfT, 2024b). ICAO's methodology employs a risk matrix that evaluates risk based on the likelihood of a climate hazard event occurring and its potential consequences, while also factoring in the adaptive capacity to identify residual vulnerabilities. Similarly, the DfT framework determines current risk levels to use as a baseline and compares these with future risks under various climate change scenarios; risk is defined as a combination of likelihood and consequence scores.

While the risk matrix approach addresses the probability of occurrence of a climate hazard and the potential impact on the airport system, it could underestimate the overall climate risk as it tends to prioritise high-probability events. This raises concerns about low-probability events, which have not been given much attention but could have a significant impact, especially considering that the past years have been marked by the occurrence of a series of unprecedented events. For example, in 2022 in the UK, an extreme heatwave was recorded when temperatures exceeded 40°C for the first time (Kendon, 2022b). Also, in the same year, the Met Office issued rare red warnings for storm Eunice, one of the past decade's most severe and damaging storms, with wind gusts exceeding 122mph (Kendon, 2022a). It also draws attention to how risk and its determinants are understood and perceived, and how these shape risk mitigation strategies (Slovic, 1987; Raaijmakers, Krywkow and van der Veen, 2008)

Besides the risk matrix approach, many scholars look at scenario-based approaches (Dolman and Vorage, 2019) or use curves or indicators to quantify risk or vulnerability (Papathoma-Köhle, 2016; De Ruiter *et al.*, 2017). For instance, Li *et al.* (2016) use curves to measure the vulnerability of a civil aviation network considering the hazard-prone area and the overall direct and indirect impact. Lately, the overall risk assessment process has started becoming more systemic, associating the different elements that drive risk aspects (Poo *et al.*, 2018; De Vivo *et al.*, 2023b). The combination of risk elements like exposure, sensitivity and adaptive capacity is often found in indicator-based frameworks developed

to measure vulnerability in transport systems or an urban context (Novelo-Casanova and Suárez, 2012; Rowan *et al.*, 2014; Eidsvig, Kristensen and Vangelsten, 2017; Havko, Titko and Kováčová, 2017).

Building upon the concept found in the IPCC risk analysis (IPCC, 2014), De Vivo *et al.* (2021) present a risk assessment framework for Mediterranean airports that considers a combination of hazard, exposure, and vulnerability. A similar approach is introduced by Debortoli *et al.* (2019) to assess the vulnerability of Arctic aviation. Although the concepts mentioned above tend to offer a more holistic method of risk analysis compared to the typical risk matrix, they tend to address mainly physical and socio-economic aspects without incorporating business elements or considering interdependencies and interactions with other systems that have the potential to influence the operational capacity of the airport if impacted by a climate hazard occurrence. Furthermore, they partially address the airport system's ability to anticipate, prepare, adapt and respond to the adverse effects of the climate hazard.

Valuable examples from the literature of airports conducting climate risk assessments as part of the broader adaptation planning process are the cases of London Heathrow Airport and Athens International Airport (London Heathrow Airport, 2011; Vogiatzis *et al.*, 2021). In 2011, London Heathrow Airport conducted an extensive risk assessment to evaluate climate-related risks affecting direct and indirect operations, aiming to inform climate adaptation strategies. The adopted process revealed 34 short- and medium-term risks, which were prioritised based on the timeline, likelihood, impact, existing control measures, and the understanding of uncertainties and critical thresholds. In addition, a series of adaptation measures were put forward addressing aspects such as action, preparation and monitoring (London Heathrow Airport, 2011). Athens International Airport adopted a similar approach; identifying and prioritising risks allowed quantification based on the likely direct and indirect consequences of climate hazard occurrences to the airport operations. The above allowed for a tailored approach to adaptation, considering the defined severity of the risk (Vogiatzis *et al.*, 2021).

2.6 Paving the way to adaptation

From the risk management perspective, airport operators are expected to undertake action to mitigate climate hazard-related risks. Such action (Figure 2-8) may focus on

strengthening airport critical infrastructure or adjusting operations to cope with the current and future climate stressors. This could involve limiting the exposure of critical assets, operations, and people to climate risks and/or reducing vulnerability to climate hazards in airport locations. It may also involve action to enhance the airports’ ability to anticipate future change and respond effectively or maintain its functions during an extreme climate event, and if a climate-driven disruptive event occurs, actions that enhance the airport’s ability to recover quickly. Finally, it may include transforming the existing business culture to develop and sustain a mechanism to coordinate and deliver the different adaptation actions to prepare for, respond to the changing climate and recover when the change occurs (Berman, Quinn and Paavola, 2012; Brooks and Adger, 2005; Cutter, 2013; Masood et al., 2016).

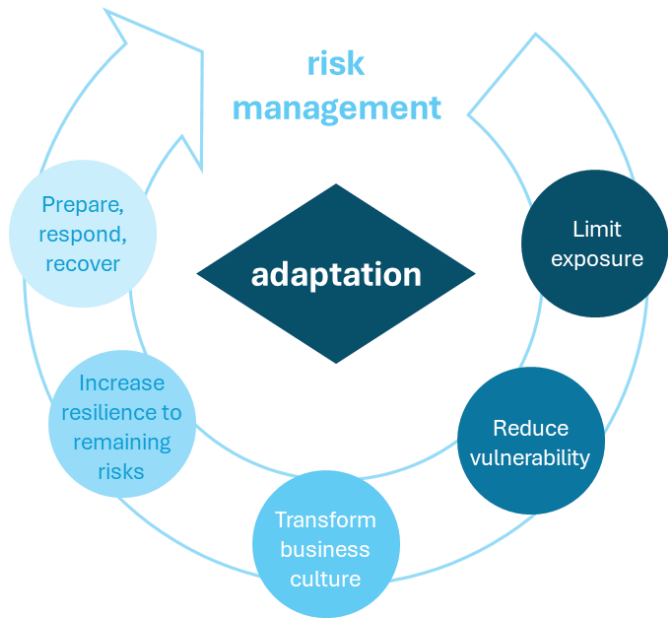


Figure 2-8 Adaptation as part of the risk management approach (based on IPCC, 2012)

There are many drivers for undertaking action to minimise climate hazard-related risks (Figure 2-9).

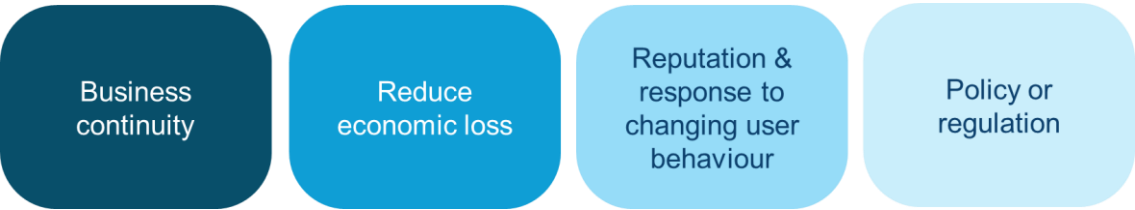


Figure 2-9 Main drivers for undertaking climate risk mitigation action (adapted from Voskaki, Budd and Mason (2023)

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 undertaken actions aim to control potential loss, as failing to implement climate-proofing can result in significant repair/restoration costs for damaged assets (Taylor and Philp, 2010).

Other parameters that drive airports to undertake climate hazard-related risk mitigation action include policy or regulation; without doubt, there is a need for airports to maintain compliance as part of national adaptation planning activities (Transportation Research Board, 2012); for instance, the Climate Change Act in the UK sets out a set of requirements for airport operators and the need to address climate risks (Kollamthodi, Fordham and Stephens, 2011). Lately, there has been an emphasis on changing the 'business as usual' practices and proactively act to build more climate resilience into the system (DfT, 2024c). The latter calls for a qualitative, semi-quantitative or quantitative climate change risk assessment to identify climate hazards affecting airports, define future climate conditions, identify potential impacts, assess the risk and develop an appropriate adaptation plan (DfT, 2024b). Also, lately, in countries like the UK, assessing and undertaking action is mandated by financial institutions and investors to secure financing or insurance premiums (Taylor and Philp, 2010; Pek and Caldecott, 2020). Furthermore, climate risk mitigation action can respond to user behaviour, considering that climate change may shift trends regarding travel flows (Adger, Arnell and Tompkins, 2005; Taylor and Philp, 2010; Burbidge, 2018).

Commonly, decision-making on the choice of risk mitigation measures is shaped by the characteristics of the anticipated consequences, and many parameters shape the choice and prioritisation of measures (Koetse and Rietveld, 2012). The process is iterative with multiple feedbacks (IPCC, 2012). The mechanism of assessing, planning and deciding on the measures typically starts with identifying, analysing and assessing risk, building an understanding of the implications due to one or multiple climate hazard occurrences and analysing areas presenting susceptibility, providing the basis for establishing goals and prioritising action (Rattanachot *et al.*, 2015; European Environment Agency (EEA), 2025). The ultimate goal of the process is to deploy strategies, such as infrastructure upgrades, protection measures, operational interventions, or changes in procedures and policies in

place after evaluating current management, design and planning frameworks (Lindbergh, Reed, *et al.*, 2022).

From a climate risk perspective, adaptation can be seen as an integral part of the risk management process with a forward-looking focus. Adaptation strategies and planning can shape the airport system's vulnerable parts, increasing the capacity to respond to current or future climate challenges (Yang and Ge, 2020). It can take many shapes depending on the individual climate challenges and the airport characteristics, ranging from the initial observation of the climatic stressors affecting airport systems to the planning of action to adjust. For instance, adaptation may include increasing the infrastructure's resistance through flood defences, setting up early warning systems, re-designing vulnerable parts of the infrastructure, and re-adjusting affected operations to address new climatic conditions. It can also involve strengthening technical capacity, developing policies, facilitating financial support, raising awareness and learning to anticipate (Brooks and Adger, 2005; Koetse and Rietveld, 2012; Masood *et al.*, 2016; Orsato, Barakat and De Campos, 2017).

Numerous examples of measures airports undertake to address climate hazard-related risks are presented in the literature. Table 2-8 provides selected examples grouped into four main categories:

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

Table 2-8 Selected examples of literature covering climate risk mitigation types of measures (adapted/supplemented from the original from Voskaki, Budd and Mason, 2023)

Reference	Brief study description	Examples of measures	Key category of action			
			Infrastructure improvement & protection measures	Operational response and preparedness	Knowledge and awareness of the risk	Governance and institutional capacity
(ECAC, 2024)	Presents examples of adaptation measures addressing different approaches for multiple climate hazards	Incorporation of a climate resilience study into the master plan, advanced climate modelling to determine enhancements, knowledge sharing, upgrade drainage systems, regular inspection, maintenance, and cleaning of the drainage system, building water resistance and flood protection, terrain adjustments, coastline protection, green spaces, water recycling	x	x	x	x
(Burbidge, Paling and Dunk, 2023)	Presents examples of adaptation measures addressing different climate hazards	Reinforce infrastructure, update design standards, contingency plans and emergency procedures, awareness raising, forecasting, and monitoring	x	x	x	x
(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 <i>et al.</i> , 2021)	Presents Athens International Airport's framework to assess climate risk and provides a list of existing control measures and targeted actions to increase resilience to climate change	Critical infrastructure improvements, enhance emergency response mechanisms 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

Reference	Brief study description	Examples of measures	Key category of action			
			Infrastructure improvement & protection measures	Operational response and preparedness	Knowledge and awareness of the risk	Governance and institutional capacity
(Dolman and Vorage, 2019)	Presents the example of Changi Airport and measures to build climate resilience to heavier storms and rising sea levels	Flood protection for vulnerable assets, a holistic system of protection around the airport perimeter, and 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
(Fisk, 2017)	Provides a sample of resilience and adaptation options for coastal airports	Upgrade electrical and lighting systems, drainage systems, review emergency procedures, pest fauna controls to control bird strikes, alternative water supplies, improve energy efficiency, relocation of assets, consider the impact on supply chains	x	x	x	
(Ferrulli, 2016)	Discusses climate resilient airport design and provides examples of the likely climate change effects and design solutions	Protection measures, infrastructure improvements (e.g. flood protection, critical infrastructure enhancements, elevation/relocation of critical infrastructure and equipment, climate-proofing assets), climate-resilient infrastructure design, improve operational practices (e.g. water management, vegetation, energy efficiency)	x	x		
(Stewart, Klin and Vigilante, 2011)	Discusses adaptation actions at US airports	Infrastructure improvements, revisiting design standards, climate-proof ground access, improving operational practices, communication and collaboration with stakeholders	x	x		x

(Stewart, Klin and Vigilante, 2011; Ferrulli, 2016; Burbidge, 2017; Fisk, 2017; ACI, 2018; Dolman and Vorage, 2019; ICAO, 2021; Vogiatzis *et al.*, 2021; Burbidge, Paling and Dunk, 2023; ECAC, 2024)

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. This can help inform adaptation planning. Airports already facing the impacts of climate change tend to prioritise action to strengthen critical infrastructure; for instance, airports located in low-lying, flood-prone or coastal areas, like Amsterdam Airport Schiphol (Dolman, 2016; Dolman and Vivekanandhan, 2022). While the design and specifications of infrastructure and assets influence the vulnerability level, new developments can use new design specifications, like elevating the runway, to protect against flooding. A notable example is Brisbane International Airport, which is at risk from coastal flooding due to sea level rise and storm surges (ACI, 2018). To build flood resilience, the new runway has been constructed 1.5 meters above the minimum regulatory requirements; seawalls and upgraded drainage systems with channels to address tidal flooding are also included in the flood-proofing plans (National Climate Change Adaptation Research Facility, 2016). Similarly, Changi International Airport has implemented measures to address coastal erosion, rising sea levels and storm surges. The development of the Changi East site was designed 5.5 meters above the mean sea level, incorporating upgraded drainage systems to reduce flood risk within the airport area (ACI, 2018; Dolman and Vorage, 2019).

Setting new standards for infrastructure design is often observed where airports have had to deal with severe consequences after an event. Following the severe damage caused by Typhoon Jebi in 2018, Kansai International Airport in Japan amended the design criteria and expanded the overall flood protection to account for similar extreme storm surges and sea level rise (ICAO, 2019a). Likewise, the design of Istanbul Grand Airport in Turkey incorporated standards exceeding the national regulations to account for climate change; examples include higher structural load factors for wind and snow and more conservative assumptions for temperature variations (ICAO, 2019a). Other interventions for new infrastructure revolve around water and energy efficiency. For example, new airport developments in Spain are called to consider increasing energy demand for cooling in the terminal design due to extreme temperatures. In addition, planning for longer runways will allow airports to address potential aircraft weight restrictions during heatwaves (Milanés et al., 2013). In terms of water efficiency, water conservation is often taken into account when airports need to deal with water scarcity, including initiatives to control leaks and monitor demand and uses; Carvalho et al. (2013) refer to Sydney Airport and the installation of a

sophisticated real-time water demand monitoring system and the leak detection program at Manchester Airport. Water reuse is also an applied practice; collecting rainwater at Munich Airport allows it to return to the groundwater via a decentralised infiltration system (ECAC, 2024).

Designing new infrastructure may not always be an option. In most cases, airports need to look at different measures to mitigate climate risks, like safeguarding critical assets and making targeted interventions. Strategies to protect the coastline are often seen when coastal airports are threatened by sea level rise and storm surge. San Francisco International Airport in the US is in a flood-prone coastal zone, facing the risk of flooding due to rising sea levels and extreme tidal events, especially during the El Niño season. To address the risk of coastal flooding, a USD 587 million shoreline protection program has been implemented, including installing concrete-capped steel sheet pile walls and steel king pile walls along the 8 miles of the airport's shoreline. This initiative aims to provide flood protection for the airport, considering a 100-year storm surge and future sea level rise (San Francisco International Airport, 2020). Similarly, the risk of coastal flooding at the Thessaloniki Airport in Greece will be addressed through the construction of rip rap walls to stabilise the coastline and provide protection during storm surges and sea level rise (ECAC, 2024). To build more flood resilience, Munich Airport conducted a hazard analysis with flood modelling, considering different precipitation scenarios and identifying vulnerable areas; these were addressed by deploying resilient drainage infrastructure and greening surfaces (ECAC, 2024).

In addition to climate-proofing, measures to build more resilience to operations enhance the airport's preparedness. One of the most widely adopted approaches is having an efficient emergency response mechanism in place, especially in the case of airports frequently dealing with disruptions due to storminess or extreme winter conditions. Dallas-Fort Worth International Airport in the US often faces several extreme winter events that lead to severe disruption and the cancellation of hundreds of flights. In response to extreme winter conditions, the airport has implemented a snow and ice control program, which includes upgrading snow and ice management systems, acquiring snow removal equipment, and ensuring that airport staff remain trained to respond to such events (Sheehan, 2019).

Besides measures that aim to enhance infrastructure and operations, a key focus in the literature is the capacity of airports to adjust to changes driven by climate variability (Rowan *et al.*, 2014; Nguyen *et al.*, 2016; Yang and Ge, 2020); for example, how efficiently the airport can adjust its operations during a climate hazard occurrence and how swiftly it can resume services following a disruption (Hellingrath *et al.*, 2015; Zhou and Chen, 2020). The above highlights the need for decision-making within the airport system that supports timely planning, coordination, and collaboration with stakeholders to ensure an effective response and recovery process. An example is the decision-making at Hong Kong International Airport; the airport authority actively engages with relevant stakeholders to prepare for emergency scenarios. In this context, during Typhoon Hato in 2017, early coordination and thorough planning allowed airport operations to resume the following day (ACI, 2018).

Also, the level of awareness and understanding of the implications of climate hazards and how they manifest is a critical factor. A lack of awareness is widely recognised as a bottleneck when it comes to adaptation (Burbidge, 2018). The sharing of knowledge and best practice has been identified as essential to recognising emerging risks and developing suitable and cost-effective risk mitigation strategies (Transportation Research Board, 2012; ICAO, 2019a). For instance, London Heathrow Airport, following the 2010 snowfall event, conducted a study to review best practices adopted at airports operating in extreme winter weather to develop an approach tailored to the UK conditions (Begg *et al.*, 2011; London Heathrow Airport, 2016). Building knowledge is also essential, and many airports, like Athens International Airport, invest in training airport staff and creating awareness of climate hazards and their implications. For example, to address rising temperatures and heat waves, first aid training and ways to address safety risks were provided to staff working outdoors (Vogiatzis *et al.*, 2021).

Overall, depending on the airport's climate hazard challenges and the level of awareness, climate risk mitigation can be proactive, reactive, or a combination of both. In many cases, undertaken action is shaped by the findings of assessments, such as climate risk or vulnerability assessments, identifying gaps and areas of susceptibility. However, certain key considerations are noted despite the wide range of measures. Integrating climate resilience into broader airport business planning allows for a comprehensive approach that combines critical infrastructure enhancements, improvement in existing operational

practices, and targeted changes in the governance and institutional capacity that further improve the airport's ability to respond (Voskaki, Budd and Mason, 2023).

Looking at applied actions to address climate hazards, the literature indicates that they are often implemented in reaction to climate events that cause significant disruption. Although this demonstrates the airports' ability to react and learn from previous experiences (Brooks and Adger, 2005), it can be a short-sighted approach as it is not part of broader medium or long-term adaptation planning. In many cases, the undertaken measures are focused on either reducing the exposure of the critical infrastructure through hard protection measures (e.g. elevating the runway) or increasing the effectiveness of the emergency response mechanism (e.g. conducting regular drills to prepare to respond quickly and efficiently in the case of an event). In these cases, measures to address climate hazards do not always include all aspects of related risk, compared to the cases of new airport development, where the risk mitigation measures are more holistic and are embedded into the broader planning and design of infrastructure. The above suggests a need to enhance the overall capacity of airports to design and implement effective adaptation strategies.

This reveals one additional challenge for airports to resolve: using their existing capability to cope with climate hazards to build further their adaptability over the long term (Berman, Quinn and Paavola, 2012). This journey requires a holistic and comprehensive understanding of the climate risk dimensions, their interrelation, and how they are translated in terms of impact and broader sustainability implications.

2.7 The need for a holistic framework

In general, how risk is understood and analysed influences the prioritisation of actions and the ability to facilitate targeted initiatives to build adaptability. Although climate hazards suggest a unique type of risk that is dependent on the geographic location and the climate scenario, it can be interpreted into a series of slow-onset or extreme events with varying degrees of predictability that add a level of complexity to the risk analysis process (Shakou *et al.*, 2019).

Another aspect for consideration as regards the risk analysis concepts identified in the literature is how the relationship between risk determinants is perceived. In the approach introduced by Treby, Clark and Priest (2006) to analyse flood insurance, the risk is seen as a triangle with sides the hazard, exposure and vulnerability; if one side of the triangle is

eliminated, the risk can also be eliminated. This implies that even though an airport system may be exposed to a specific climate hazard, the occurrence of an event with different characteristics (for example, different level of intensity) or the implementation of measures to mitigate or cope with the impact of the hazard may reduce the vulnerability, and as a result will probably lead to a different level of risk.

Understanding climate risk is essential in developing a strategy and taking action to tackle the climate change challenge. This requires a holistic climate risk analysis that does not only focus on the characteristics of a climate hazard occurrence, often found in traditional risk matrix approaches, as the magnitude and implications of the impact may not necessarily be a function of the size of this single event only. Climate risk emerges when a triggering climate event affects an exposed airport, whose elements are vulnerable to that specific hazard. Considering the description provided by IPCC (2012) on climate risk reduction, the overall risk can be reduced if measures are implemented to reduce the airport's exposure and/or vulnerability to the specific climate event or to increase the airport's ability to anticipate, prepare, adapt and respond to the adverse impacts. Consequently, the level of climate risk depends on an airport's decisions on planning and operational matters to reduce vulnerability and exposure and build adaptive capacity, assuming that climate events cannot be avoided. The above brings to the surface the importance of having appropriate tools that analyse and bring the different dimensions of climate risk together and support informed decision-making.

Evidence suggests that scholars have only recently started analysing the implications of specific climate hazards to the airport system. Lately, more comprehensive climate risk frameworks have been developed, incorporating indicators and considering regional climate change projections. Still, they fail to address all related aspects, such as network failures or interdependencies, resulting in disruption or any other business impact. Also, although adaptation is an integral part of the risk management process and a requirement for airports, many risk analysis frameworks mainly focus on quantifying specific risk determinants like hazard, exposure, or vulnerability. Only in some instances, risk analysis addresses factors reflecting the adaptive capacity of the airport system. When this happens, the included factors primarily reflect a reduction in loss and potential disruption without including attributes relating to anticipation, adjustment, learning, preparedness, or recovery (Proag, 2014; Shakou *et al.*, 2019). Furthermore, there is limited focus on the

process needed to create the environment to facilitate action to respond to current climate hazards while at the same time building capacity to adapt to the projected change (Masood *et al.*, 2016). Practically, while these dimensions of adaptability are acknowledged as necessary by scholars or aviation organisations (Burbidge, 2018; Yang and Ge, 2020; ICAO, 2021), risk analysis only on certain occasions includes the dimension of adaptation in a holistic way.

Taking into account how airport operators currently address the changing risk profile, the availability of tools to support a more comprehensive way of looking at climate hazard aspects will enable the design of more sophisticated risk management strategies to address future climate challenges. This requirement is also reflected by changes in the investment environment, demanding airport operators to present comprehensive climate risk assessments and risk management strategies to address climate-related risks (Pek and Caldecott, 2020). The need to address the changing risk profile is becoming more apparent for regional airports as they frequently encounter distinct operational challenges in contrast to larger ones, such as constrained resources and infrastructure limitations, which can hinder their capacity to respond effectively to climate change.

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. Reliance on existing climate risk assessment approaches raises concerns about the ability of available tools to account for the complexity and nature of climate hazards, climate change influence, and adaptation planning. A holistic approach would identify weaknesses in existing strategies and enable building adaptability further.

In summary, **understanding and analysing climate risk is essential for prioritising action** to build adaptability. Acknowledging the aspects that influence how climate hazards can be manifested and influenced by climate change adds a layer of complexity to the risk analysis process, making the existing frameworks inadequate for **comprehensively addressing risk**. With climate change intensifying climate extremes, the demonstrated sensitivity is only set to grow, placing additional stress on airport infrastructure and the current way of operating. This underlines a growing need for comprehensive climate risk tools that consider the risk **holistically**, from **risk determinants** and elements that reflect **network failures** and **interdependencies** to

elements that reflect the **airport's ability to drive adaptation** action. Addressing this gap is the key focus of this thesis, which aims to advance methodological approaches for analysing climate hazard-related risk within airport systems. The development of such tools would enable the design of more sophisticated risk management strategies to address future climate challenges and **meet the demands of the changing investment environment**. The methodological approach for addressing this research gap will be the focus of the next chapter (*Methodology*).

3 Methodology: The development of a framework for climate risk analysis

To address the research gap identified in Chapter 2, this research will introduce the development of a framework to support airports in identifying, analysing, and assessing potential risks resulting from climate-related hazards. This framework, hereafter referred to as the Airport's Climate Risk Index (ACRI), will aim to provide a holistic approach to understanding and analysing climate hazard risks within airport systems. This chapter outlines the methodology for developing ACRI; it describes the approach, detailing the steps and the methods used. The development of the framework includes six main stages.

Stage 1 (Section 3.1) identifies the nature of the research problem. This is followed by Stage 2 (Section 3.2), which includes a definition of the research approach, aim and objectives. The conceptualisation of the research problem is presented in Stage 3 (Section 3.3). The adopted approach for developing the prototype version is described in detail in Stage 4 (Section 3.4). Stage 5 (Section 3.5) includes information on the test and validation of the working prototype version of the tool, while the next stage (Section 3.6) describes the steps taken to develop the final version of the tool. The final stage (Section 3.7) describes the next level of validation, data collection and analysis process. Figure 3-1 graphically presents the main stages of the research process.

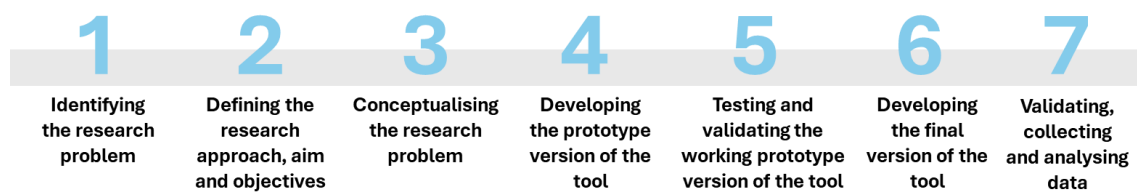


Figure 3-1 Key stages of the research process

3.1 Stage 1 – Identifying the research problem

As described in Chapter 2 (*Literature review*), a literature review was undertaken to investigate the research problem. The review focused on identifying the primary climate hazards affecting the global airport system, their impact and the broader implications, methodologies used to assess climate hazard-related risk and elements affecting climate risk, including concepts such as exposure, sensitivity, vulnerability, and adaptive capacity

in an airport or critical infrastructure context. The main topics used in the literature review are presented in Figure 3-2. Three main topic areas are used in the search: (a) climate factors impacting airports, (b) climate hazard implications and (c) elements affecting climate risk.

Climate factors impacting airports	Climate hazard implications	Elements affecting climate risk
Extreme precipitation Sea-level rise Flooding Storminess Changing wind intensity Changing wind patterns Extreme snowfall Cold waves Heatwaves Drought	Airport infrastructure damage Airport critical equipment damage Service disruption Performance implications Economic impacts Environmental impacts Impact on safety margins Health and safety considerations Supply disruption Reduced airport access Impact on reputation, investments Air travel demand change	Climate hazards Hazard exposure and analysis Vulnerability analysis Sensitivity assessment Adaptive capacity Coping capacity Climate change adaptation Protection measures Risk management Safety management Meteorological forecasting Contingency plans Emergency response

Figure 3-2 Literature review concept mapping

The review of the literature included a broad body of peer-reviewed articles using academic databases, including Scopus and Science Direct, contributions to conferences, government or airport-commissioned studies, technical reports, and research studies (Table 3-1). The articles and reports were reviewed and analysed to determine the work that has already been conducted and identify gaps in the literature this research could address. More information on the literature review process and outcomes are included in Section 2.1.

Table 3-1 Literature review sources

Literature category	No of sources
Peer-reviewed articles	57
Conference proceedings	4
Aviation industry and other technical/scientific reports	34

The review of the literature (Chapter 2) revealed a notable research gap in the availability of risk tools that comprehensively address all dimensions of climate hazard-related risks. This research seeks to bridge that gap by developing a framework that integrates critical yet often overlooked aspects of climate hazard risk analysis for airports. The following sections describe the roadmap for developing this framework.

3.2 Stage 2 – Defining the research approach, aim and objectives

The overall **aim** of the thesis is to develop a framework to analyse the risk of climate hazards to the airport system under current and future climate change projections.

A practical tool, the Airport Climate Risk Index (ACRI), will be developed to accomplish this aim. ACRI will be a composite indicator tool airports can use to analyse the overall risk due to climate-related hazard trends and variability changes. The tool will consider the applicable climate hazards in the airport location, climate change influences, the airport's exposure and sensitivity and the current adaptability level.

Four research objectives (RO) are used to deliver the research aim:

RO1 To identify the key climate hazards and their impact on the airport system and analyse their implications.

RO2 To define the exposure and vulnerability of the airport system to climate hazards.

RO3 To assess the operational and compliance risk of climate hazards to the airport system.

RO4 To recommend measures to increase airport climate resilience.

The research objectives will be addressed using four research questions that guide the literature review and the overall approach to constructing the climate risk analysis framework, as shown in the research design in Figure 3-3.

RESEARCH AIM:
to develop a framework to analyse the risk of climate hazards to the airport system under current and future climate change projections

- OBJECTIVE 1:**
To identify the key climate hazards and their impact on the airport system and analyse their implications
- OBJECTIVE 2:**
To define the exposure and vulnerability of the airport system to climate hazards
- OBJECTIVE 3:**
To assess the operational and compliance risk of climate hazards to the airport system
- OBJECTIVE 4:**
To recommend measures to increase airport climate resilience

Research questions	Data source	Method	Chapter
Literature			
What are the key climate hazards affecting airports, their impacts, and how can we analyse the climate implications in an airport context?	Literature	Critical review of the literature	Chapter 2: Literature review
Development of the tool and application to UK airports			
How can we measure the exposure and vulnerability of airports to climate hazards, and how can we measure climate risk in an airport context?	Literature Data from the UK airports participating in the pilot study	Critical review of the literature Conceptualisation of the research problem Construction of the risk analysis model Test and validation of the risk analysis model	Chapter 2: Literature review Chapter 3: Methodology Chapter 4: Analysis
What approach should be adopted to climate risk in an airport context, what indicators should be included in a model, and how can they be measured?	Data from the UK airports participating in the data collection phase	Risk analysis model application to UK airports Data collection and analysis	Chapter 3: Methodology Chapter 4: Analysis
Recommendations			
How can the airport system build adaptability and resilience to climate hazards?	Literature Output of the model	Critical review of the results of the data collection	Chapter 4: Analysis Chapter 5: Recommendations

Figure 3-3 Research design

To address RO1 and RO2, a systematic analysis was conducted to identify literature discussing climate change and related implications for airports and best practices to respond to airports' current challenges, as presented in Chapter 2. This analysis built an understanding of the existing sensitivity to climate hazards and climate-related trends and approaches to analyse risk-related concepts in this context. This process, in turn, will support the conceptualisation of the research problem, using an approach combining fundamental elements adopted in various frameworks supported by theoretical perspectives in the fields of natural hazards, adaptive change, and risk perception.

RO3 addresses the development of the model, the composite indicator tool. The development of the tool will combine a literature review and case studies. Its construction will be hierarchical; each stage will be more complex than the one before it, bringing together elements of the preceding stages. The reasoning behind this approach is the level of complexity found in the main risk components requiring analysis at different levels of detail for their measurement, at least on a relative scale. For instance, the analysis will address concepts like the historical sensitivity to applicable climate hazards, prevention, response, and preparedness aspects, as well as other elements valuable in measuring airports' level of exposure to specific climate hazards, vulnerability, and ongoing efforts to build adaptive capacity. The quantification of these concepts is essential to conclude on existing weaknesses and qualities influencing the airport's ability to control climate hazard-related impacts and ensure business continuity. However, the measurement of these concepts is simultaneously a complicated task considering the complexity of the airport system and the different aspects that need to be accounted for.

To address RO4, an analysis will be conducted to identify literature discussing best-applied practices to mitigate climate-related implications and build climate resilience. The results of the analysis will support the recommendation of measures to increase the airports' adaptability to specific climate hazards.

More details on the conceptualisation, the methods used, the framework development and the data collection and analysis process followed are provided in Sections 3.3 to 3.7:

- 3.3 Stage 3 – *Conceptualising the research problem*
- 3.4 Stage 4 – *Development of the prototype version of the tool*
- 3.5 Stage 5 – *Test and validation of the working prototype version of the tool*

- 3.6 Stage 6 – Development of the final version of the tool
- 3.7 Stage 7 – Collecting and analysing data

3.3 Stage 3 – Conceptualising the research problem

While RO1 was addressed in the literature review (Chapter 2), addressing RO2 and RO3 and responding to the research questions concerning defining and measuring concepts such as exposure, vulnerability, and climate risk in an airport context requires conceptualising the research problem.

As discussed in Chapter 2, various frameworks in the literature analyse climate or natural hazard-related risk using various methodologies. Examples include the use of probabilistic risk assessment approaches, such as risk priority matrices (Larsen, 2015; Becker *et al.*, 2018; Vogiatzis *et al.*, 2021), indicator frameworks focused on specific climate hazards or geography (De Vivo *et al.*, 2021, 2025) and tools that measure the susceptibility of physical assets to hazards (Lopez, 2016; Debortoli *et al.*, 2019).

The conceptualisation of the ACRI tool is based on the theory used by the IPCC (IPCC, 2012), according to which exposure and vulnerability to climate events determine the impacts and the likelihood of disasters. This concept has been adopted in many studies in the field of risk, vulnerability and climate change adaptation using different variations depending on the context (Peduzzi *et al.*, 2009; Welle and Birkmann, 2015; De Almeida, Welle and Birkmann, 2016b; Weis *et al.*, 2016).

Developing a climate hazard risk analysis tool appropriate for an airport requires the combination of different elements. On the one hand, airports constitute complex systems with many interdependent elements; on the other hand, climate risk can be influenced by many factors, from the topography and how well-protected the airport's critical assets are to the supply chain's resilience. Also, considering all the interconnected and interdependent elements and factors, how climate risk is perceived and addressed can be a complex concept on its own. Therefore, a tailored approach is required to address all aspects that determine and influence climate risk, combining different building blocks identified in the literature. This approach is guided by the theoretical perspectives adopted in this research and how risk and its outcomes are perceived and analysed.

The key concepts used for the conceptualisation process are presented and discussed below (Figure 3-4).

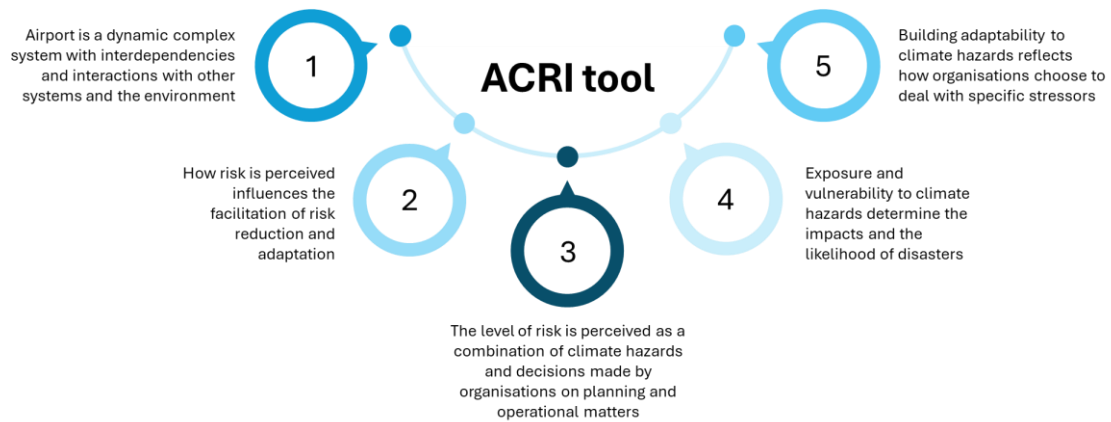


Figure 3-4 Key concepts used to address the research problem

1 The airport is considered a dynamic and complex system.

One of the main building blocks is considering the airport system as complex and dynamic rather than simple and static. Besides being part of a broader air transport network, the airport, as a system, consists of several sub-systems and interrelated components; changes in one of them can trigger events affecting parts of the airport or even its capability to maintain its functions. The conceptualisation of the airport as a system includes not only the physical components, like the critical infrastructure and critical assets, but also aspects relating to the airport capacity, interrelated elements that support the overall airport function, like, for example, ground operations, ground access, energy supply, the socio-economic aspect, and the physical environment in which the airport operates.

2 Risk perception influences risk reduction.

How risk is perceived influences the airport's adaptive behaviour as it drives action to facilitate efficient and targeted risk reduction initiatives. Therefore, an essential building block relates to the perceived level of risk and how the airport understands the severity of climate hazard, the exposure and overall vulnerability, and the efficiency of measures and costs related to climate risk.

3 Risk is a combination of climate hazards and decisions on matters.

Considering that a climate hazard occurrence cannot be eliminated, implementing measures to reduce the airport's exposure and vulnerability or building adaptability to the

specific climate hazard can support the overall risk reduction (IPCC, 2012). Consequently, risk can be perceived as a combination of climate hazard, exposure, vulnerability, and decisions made by the airport on various planning and operational matters that can shape its adaptability and, subsequently, its level of resilience.

4 Exposure and vulnerability to climate hazards determine the impacts.

An important concept adopted in the process considers that the character and the severity of impacts caused by a climate hazard depend not only on the hazard characteristics but also on aspects relating to exposure and vulnerability (IPCC, 2012). Therefore, climate risk emerges when there is an overlap of the following: (a) a triggering climate event affecting the airport system, (b) airport assets, operations and people being exposed to this climate event, and (c) airport elements being vulnerable to the specific triggering event. This also implies that the climate risk can be reduced or eliminated if one of the above parameters is reduced or eliminated (Treby, Clark and Priest, 2006).

5 Adaptability reflects a response to climate stressors.

Elements that reflect qualities that lead to increased adaptability are considered an essential risk reduction dimension. The airport's capacity to adjust to potential damage or disruption involves reinforcing crucial structures and functions. In addition, it requires taking advantage of opportunities to implement a comprehensive preparation and response mechanism, which determines how the airport will respond to the applicable climate stressors and their consequences. Another attribute that is considered necessary is the airport's overall ability to transform to ensure business continuity, minimise loss, and support quick recovery after a disruptive event. All of the above imply that the airport can understand risk, learn, and accordingly shape its strategy.

Considering the above concepts, the development of the framework is composed of the following key risk determinants (Figure 3-5):

- **Climate hazard profile**, including current and future climate hazard levels considering climate change influence. Climate hazard is a risk-increasing factor; its occurrence may impact an exposed and/or vulnerable airport.
- **Exposure analysis**. Exposure is a risk-increasing factor; it depicts a range of airport elements that can be affected by a climate hazard occurrence.

- **Vulnerability analysis.** Vulnerability is a risk-increasing factor; it reflects the tendency of the exposed airport elements to experience negative consequences in the event of a climate hazard occurrence.
- **Adaptability analysis.** Adaptability is a risk-reducing factor; it reflects the ability of the airport to adjust and take advantage of opportunities to anticipate, prepare and respond to a climate hazard occurrence.

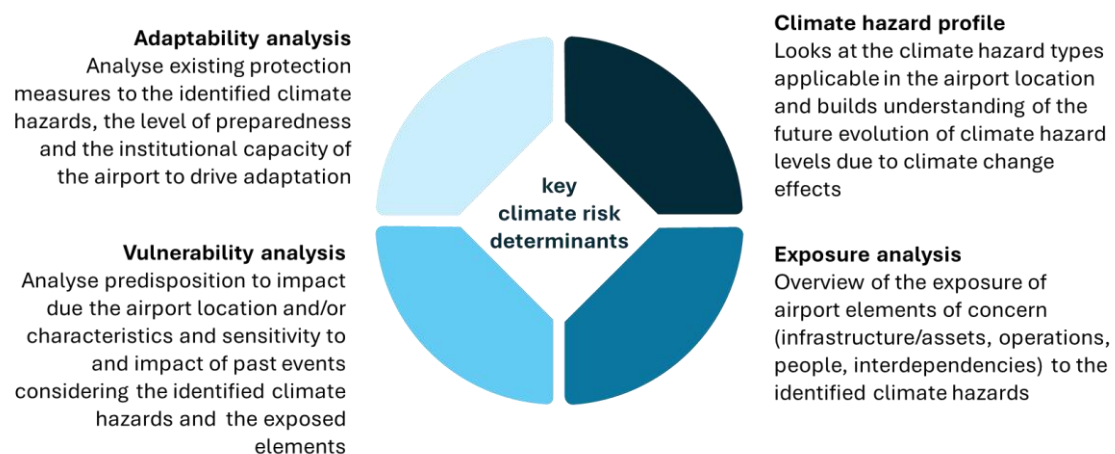


Figure 3-5 Main climate risk determinants considered in the conceptualisation of the research problem

The following section will detail the adopted process for developing the framework and how the tool is constructed and validated.

3.4 Stage 4 – Developing the prototype version of the tool

The conceptualisation of the research problem supports the development of a framework that constitutes the basis for the development of the ACRI tool, addressing RO3 and how to assess the operational and compliance risk of climate hazards to the airport system. The development follows a hierarchical top-down approach as it makes it easier to define the distinct parts that influence climate risk and the main risk determinants. The analysis of the elements that can contribute to determining the concepts and subsequently measuring the risk determinants and the risk itself uses four levels (Figure 3-6), moving from level 1, the index level, to level 4, the variable level, which constitutes the basis of the analysis and the overall measurement process.

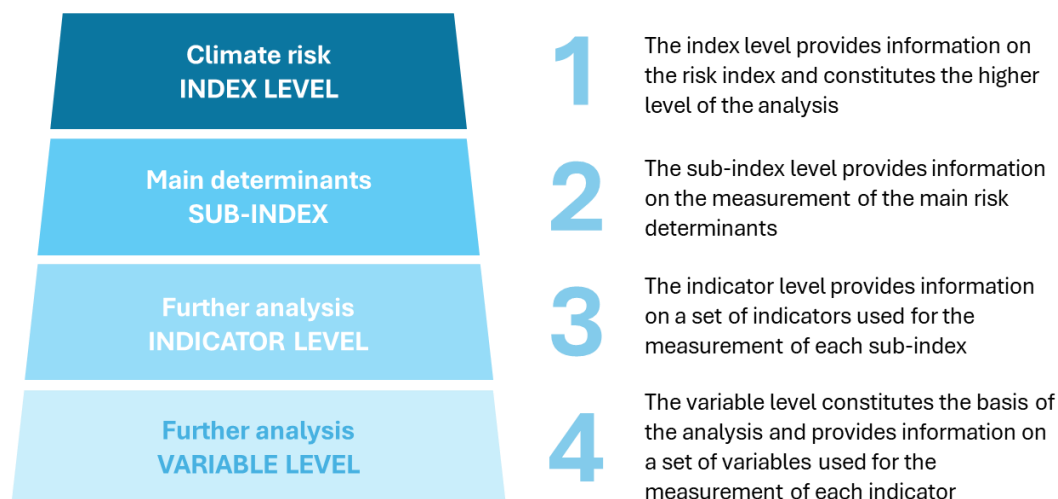


Figure 3-6 Hierarchy of the analysis for the development of the framework

ACRI represents a composite index, and its development follows an indicator-based approach. Indicator-based approaches are used in the literature, especially in the fields of sustainability and natural hazards (for instance, Eidsvig, Kristensen and Vangelsten, 2017; Kappes, Papathoma-Köhle and Keiler, 2012; Rowan et al., 2014) to combine and simplify information into measurable metrics, making the analysis of complex phenomena and the communication of the outcome of the analysis easier, supporting decision-making. The measurement of the index considers approaches in the literature, such as the approach of Welle and Birkmann (2015) to develop a World Risk Index. As mentioned, and shown in Figure 3-6, the measurement of ACRI uses a combination of sub-indices, indicators and variables. The construction of these elements uses building blocks identified in the literature and specifically in indicator-based approaches used to measure climate risk or other types of natural hazard risk, vulnerability, climate resilience or adaptive capacity (for example, Cutter et al., 2003; De Vivo et al., 2021; Eidsvig et al., 2017a; Weis et al., 2016).

The reasoning behind this approach is that the sub-indices (i.e. the main climate risk determinants) are complex concepts on their own, and their measurement requires further analysis. Thus, they are further analysed into sets of indicators and variables to allow measurement, at least on a relative scale. Similar reasoning is followed by Weis et al. (2016) to map exposure, sensitivity and adaptive capacity and by De Vivo et al. (2021) to assess extreme temperature and precipitation risk. In many cases, the selected indicators and variables are used without any modification; in other cases, the variables or their measurement scale are tailored to address the scope of the research (for example,

indicators that are initially developed for urban or other types of infrastructure are tailored to be relevant to an airport context).

Figure 3-7 provides the graphical representation of the ACRI structure.

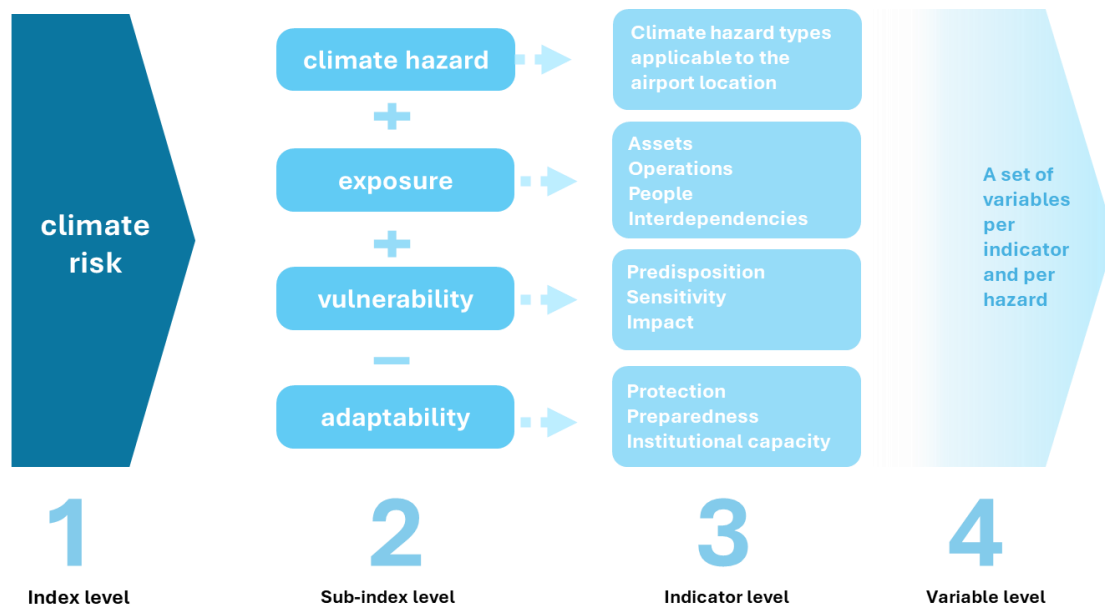


Figure 3-7 ACRI structure

As a general rule, variables contribute equally to their indicator; an average of each set of variables per indicator is considered. Variables are scored based on a 1 to 5 or 1 to 3 scale; the justification for the choice of the variables and their scoring is provided in the relevant paragraphs below. The scores are standardised using min-max normalisation, scaling them from 0 to 1 (OECD, 2008). This approach is found in composite index studies, like the one adopted by Kotzee and Reyers (2016) to measure flood resilience. Similarly, each indicator contributes equally to the relevant sub-index; an average of the set of indicators per sub-index is considered.

The calculation of ACRI uses the formula below (Equation 1), where H represents climate hazard, E exposure, V vulnerability, and A adaptability.

$$ACRI = H + E + V - A \quad \text{(Equation 1)}$$

The development of the formula (Equation 1) considers approaches found in the literature to construct a comparative risk or vulnerability index (for example, Calil et al., 2017; De Vivo et al., 2021; Debortoli et al., 2019; Welle & Birkmann, 2015).

The value of the ACRI is defined with a 5-point scale (Table 3-2), ranging from 0 to 1, where zero (0) refers to the insignificant risk and one (1) to catastrophic risk. A similar approach has been adopted for many years to define the severity of risk in aviation safety (Transport Canada, 2016; UK CAA, 2014).

Table 3-2 Climate risk rating scale

Climate risk rating	Value
Catastrophic risk	0.76 – 1.00
Major risk	0.51 – 0.75
Moderate risk	0.26 – 0.50
Minor risk	0.01 – 0.25
Insignificant risk	0.00

Information on how the sub-indices and incorporated indicators and variables are measured and the rationale for their selection is provided in the following paragraphs:

- *Sub-index climate hazard*
- *Sub-index exposure*
- *Sub-index vulnerability*
- *Sub-index adaptability*

3.4.1 Sub-index climate hazard

Climate hazard, as a term, is widely used in the literature to describe hydrometeorological hazards of atmospheric, hydrological or oceanographic origin, such as storms, storm surges, floods, temperature extremes, droughts and other weather- or climate-related phenomena that impact people and the built environment (McBean and Rodgers, 2010; Mora *et al.*, 2018). As a sub-index and risk determinant, the role of climate hazard is to describe the climate hazard profile of the airport, namely the climate hazards that could occur in the airport location and changes in the frequency or intensity of occurrence due to climate change influence.

Climate hazards are location-specific; they occur at different geographical scales. As a result, depending on their location, airports experience different climate hazards or hazards with different characteristics, like different intensities in terms of probability or return period. Another consideration is climate change and how it affects ocean circulation, weather patterns and climate extremes in different regions across the globe

(IPCC, 2021b). Different geographies also imply different regulatory frameworks and, therefore, different requirements for infrastructure development, operations, safety, and environmental management. Developing a tool that addresses, from the climate hazard perspective, all climate hazards occurring on all spatial scales and their evolution due to the influence of climate change constitutes a significant challenge in terms of the size of the research project. To address this challenge, the study focuses on explicit geography; specifically, the UK is chosen as a basis for the study. The selection of the geography is based on the following reasons:

- Due to the geographic location and diverse landscape, the UK experiences a wide range of climate hazards, such as storms, flooding, snowfall, heatwaves, and others, which provide the ideal spatial scale to investigate climate hazard-related challenges for airports. For instance, according to the UK Met Office, the 2021/22 season included six named storms, a rare red warning for wind for coastal areas east of Scotland and northeast of England and a milestone with 40°C being recorded for the first time in the UK.
- Climate extremes in the UK pose significant risks to airports, as demonstrated by events that occurred in the past few years. For example, in 2013, at London Gatwick Airport, heavy rain and strong winds combined to severely disrupt travel for more than 16,000 passengers (McMillan, 2014). In 2010, London Heathrow Airport cancelled 4,000 flights due to a snowstorm, with an estimated cost of disruption of around £20 million (Begg et. al, 2011; Merkert and Mangia, 2012). Every year, due to storminess (for example, Storm Eunice, Storm Ciara), hundreds of flights are disrupted.
- The UK presents a robust regulatory framework for aviation risk management to manage safety-related risks effectively. This suggests that airports have safety management systems and contingency plans to identify and address extreme climate hazard-related risks. Also, regulated airports, like London Heathrow and London Gatwick, are required to develop operational resilience plans to comply with the licence conditions (Dawson et. al, 2016). As a result, the UK provides different case studies to investigate how airports use existing risk management to address climate hazard challenges.

- Under the Climate Change Act 2008 (HM Government, 2008), organisations with functions of a public nature and statutory undertakers are required to produce reports on undertaken action to adapt to climate change. UK airports are therefore invited to report in line with the strategy for climate adaptation reporting; the third round of reporting includes 11 strategic airport operators in England, Scotland and Wales (DEFRA, 2021). In addition, the UK Government made the Task Force on Climate-related Financial Disclosures (TCFD) aligned disclosure mandatory across the economy by 2025, with some requirements in place from 2023 (HM Treasury, 2024).
- The airport infrastructure in the UK is widespread and therefore provides a plethora of case studies to investigate how different climate hazards affect airports, but also how the same type of climate hazard affects airports of varying sizes and characteristics, and how the climate hazard-related implications are managed by airports presenting differences in the management or institutional framework.

Considering that ACRI uses airports in the UK as a basis for the study, the sub-index reflects climate hazard types applicable in the chosen geographical area. The choice of climate hazards considers the following conditions:

- climate hazard types occurring in the UK;
- climate hazard types that can impact an airport system;
- climate hazard types that are influenced by climate change.

Taking into account the reviewed literature on climate hazards typically occurring in the UK, climate hazards that meet the above conditions and are included in the sub-index are:

- coastal flooding and storm surge
- fluvial/pluvial flooding
- storminess and extreme wind
- extreme heat
- cold and icing conditions
- snowstorm and extreme snowfall
- drought/water scarcity

The measurement of the sub-index considers the climate hazards applicable to the airport location. The quantification considers current and future climate hazard levels and the

confidence in the direction of change to account for the influence of climate change. The variables used and the rationale for their choice and measurement are included in Appendix B Table 1.

- **Current climate hazard level:** it reflects the level of the climate hazard as observed today (for example, 30-year averages for the nearest climate station to the chosen location). The measurement considers a set of climate variables produced by organisations such as the Met Office, the Environment Agency, the National Tidal and Sea Level Facility, the World Resources Institute and the Water Risk Atlas.
- **Future climate hazard level:** it reflects the level of climate hazard considering climate change projections. The measurement considers a set of climate variables derived from the climate change projections, considering organisations such as the Met Office (UKCP18), the World Resources Institute and the World Bank. Climate variables consider the intermediate scenario, with a very likely range of warming of between 2.1°C–3.5°C (Representative Concentration Pathway (RCP4.5)) (IPCC, 2023a). This scenario, designated as SSP2-4.5 or RCP 4.5, is selected as it represents the situation where countries apply ambitious emissions reduction measures but still fall short of the 2°C upper limit defined by the Paris Agreement (IPCC, 2021b). In addition, it aligns with the UK Net Zero Strategy (DfT, 2022). The year 2050 is chosen as the time horizon to align with the broader climate target plan in the UK. It is noted that the tool incorporates the latest climate change projections for the UK (UKCP18). Should the projections be updated, the information included in the tool should also be updated to reflect the most updated information. This update refers only to the variables used to define the future climate hazard level.
- **Confidence in the direction of change:** it reflects the confidence level for the projected change per climate hazard for the specific geographic region. The information is retrieved from the IPCC (IPCC Working Group I (WGI): Sixth Assessment Report). The IPCC confidence levels are defined considering the quality of evidence and scientific agreement and show the likelihood of the different climate variables (Kause *et al.*, 2022). It is noted that if the IPCC confidence levels change an update in the relevant variables is required to reflect the most recent information.

The measurement of the climate hazard sub-index considers the indicators' average value. The scoring of each indicator considers the average value of a set of climate variables (Appendix B Table 1).

Acknowledging that each climate variable uses a different scale for its measurement (for example, the temperature is measured in degrees Celsius, while precipitation is in millimetres) to integrate the different hazards in the tool, their value is calibrated using a 5- or a 3-point scale, adopted from the literature in the initial form (for example, flood hazard measurement adopts the ratings used by the Environment Agency in England and the equivalent agencies in Scotland, Wales and Northern Ireland) or modified to meet the objectives of the study following a simplified rationale (for instance, considering thresholds based on increments). The 5-point scale uses a one (1) to five (5) measurement, with one (1) representing the lowest point in the scale. The 3-point scale uses a one (1) to five (5) measurement, with one (1) representing the lowest, three (3) the average and five (5) the highest point in the scale. The reason for choosing 1, 3 and 5 as measurement points (instead of 1, 2 and 3) is to maintain the same highest and lowest points in all variables.

Appendix B Table 1 provides information on the indicators and variables that set up the sub-index of climate hazards. It presents the variables used to measure each indicator, the measurement scale, the rationale for their choice and information on the literature used for their development.

3.4.2 Sub-index exposure

Exposure, as a term, defines the presence of infrastructure, assets or people in a hazard-prone area (IPCC, 2012; UNISDR, 2015; United Nations, 2016). As a sub-index and risk determinant, the role of exposure is to reflect the elements, activities and subjects of the airport system that may be exposed to climate hazards occurring at the airport location (Birkmann, 2013).

Considering the definition of the term, in the airport context, the exposure sub-index considers the presence of critical assets, operations (air and ground) and other business-related activity and social aspects (airport employees and passengers) that could be exposed and subsequently affected by the climate hazard.

The quantification of these elements follows approaches used in the literature and specifically in risk modelling studies; the most commonly used metrics reflect the different

dimensions, namely physical (infrastructure, buildings, other assets), social (people) or economic (economic and business activity) (Nguyen et al., 2019; Peduzzi et al., 2009). One of the most typical metrics used in such studies is the number of buildings or the number of people in a given area exposed to a specific hazard (Peduzzi *et al.*, 2009; Weis *et al.*, 2016).

Four (4) indicators are used for the quantification of the exposure sub-index:

- **Critical assets:** addresses the extent to which critical assets, such as critical infrastructure and equipment, are exposed to climate hazards. Quantifying the extent of the exposure of critical assets within the airport system provides a proxy for understanding the degree of potential damage. The exposure of assets to climate hazards has been considered one of the risk-determining factors by the IPCC (IPCC, 2012). Also, many studies in the literature in the field of climate change, vulnerability and adaptation refer to the physical impact of a climate or natural hazard on the built environment, critical assets and facilities (Hallegatte *et al.*, 2011; Balica, Wright and van der Meulen, 2012; Novelo-Casanova and Suárez, 2012; Weis *et al.*, 2016; Paprotny *et al.*, 2020).
- **Operations:** addresses the extent to which air and ground operations are exposed to climate hazards. Quantifying the extent of the exposure of airport operations provides a proxy for understanding the degree of the potential disruption and the business-related consequences. Although many studies focus mainly on the physical aspect of exposure, the business and economic aspect is also essential as it links to the potential for economic loss or other business impacts (e.g. reputational impact). For example, when assessing exposure, risk engineers look at the total insured value or proportion of operations potentially affected by a climate hazard (Zurich Resilience Solutions, 2022). Considering the IPCC definition (IPCC, 2012), the presence of services in places that could be negatively affected by climate hazards is an integral part of the exposure. Also, many studies in the literature include the exposure of services when discussing climate change impact, vulnerability and disaster risk (Chang et al., 2018; Demertzidis et al., 2015; Nguyen et al., 2016; Shah et al., 2020).

- **People:** addresses the extent to which airport staff and passengers are exposed to climate hazards. Quantifying the extent of people's exposure provides a proxy for understanding the degree of the social-related consequences. The social aspect of exposure is included in many studies in the field of climate change and disaster risk reduction, reflecting the presence of people in places that could be negatively affected by climatic change or natural hazards (Peduzzi *et al.*, 2009; De Almeida, Welle and Birkmann, 2016a; Weis *et al.*, 2016; Shah *et al.*, 2020). Also, natural hazard risk assessment frameworks often look at the population (Hanson *et al.*, 2011; Welle and Birkmann, 2015) or, in the case of risk engineers assessing the potential exposure of an organisation to climate hazard occurrences, the number of employees (Zurich Resilience Solutions, 2022).
- **Interdependencies:** addresses the extent to which interdependent systems critical for airport functions, such as utilities, fuel supply, and airport surface access, are exposed to climate hazards. Quantifying the extent of exposure to interdependent systems provides a proxy for understanding the degree of indirect operational and business-related consequences. Although many approaches in the literature include only the airside and landside components (De Vivo *et al.*, 2021) or limit the analysis to the spatial coverage (Nguyen *et al.*, 2019), some studies address the necessity to integrate connected sectors or functions (Gallina *et al.*, 2016) and reflect the complexities of the interdependencies and the related business impacts (Surminski *et al.*, 2018).

The measurement of each indicator considers a set of variables (Appendix B Table 2). In many cases, the selected variables were initially developed for other types of systems (e.g., urban systems) and were modified to address the airport context. In other cases, there was a need to develop a new variable to address specific elements of the airport system. The measurement of the sub-index of exposure considers the average value of the indicators and the measurement of the indicators the average value of their variables.

The scoring of each variable uses a 1 to 5 scale, which is developed considering examples in the literature. An example is the work of Novelo-Casanova and Suárez (2012) regarding the measurement of the level of exposure of main critical facilities to natural hazards in Grand Cayman; they used a 0 to 5 scale where zero (0) represents no exposure and five (5) very high exposure considering specific thresholds relating to the hazards (e.g. the level of

exposure is very high when facilities are located in a zone where there is coastal flooding or wave action during a hurricane of categories 1 or 2 and above). Following a similar logic, the scoring of Exposure variables (Appendix B Table 2) considers certain thresholds based on 25% increments; score one (1) corresponds to 0% exposure and score five (5) to >75% exposure.

Appendix B Table 2 provides information on the indicators and variables that set up the sub-index of exposure. It presents the variables used to measure each indicator, the measurement scale, the rationale for their choice and information on the literature used for their development.

3.4.3 Sub-index vulnerability

Vulnerability, as a term, addresses the potential for harm or loss due to climate hazards (Cutter, 2013) and the tendency to '*be adversely affected*' (IPCC, 2012). It also addresses the expected degree of loss (Fuchs, Heiss and Hübl, 2007), including quantifiable consequences of past climate hazard occurrences and the societal (Mattsson and Jenelius, 2015) and environmental impact.

Considering the definition of the term, the sub-index of vulnerability reflects the tendency of the exposed airport elements, operations, subjects, or interdependencies to experience negative consequences when a climate hazard event occurs. The quantification of vulnerability focuses on the key elements that influence this tendency, identifying interactions of different components and interdependent elements by looking at how the airport system responded to previous hazard occurrences. The overall method adopted is a mixture of approaches used in the literature to assess vulnerability in the field of climatic change or natural hazards (Balica, Wright and van der Meulen, 2012; Lopez, 2016; Eidsvig, Kristensen and Vangelsten, 2017)

As in exposure, the vulnerability sub-index uses metrics to reflect the different dimensions, namely physical (infrastructure, buildings, other assets), social (people) or economic (economic and business activity). The sub-index considers the airport's physical and geographical characteristics that influence its predisposition to experience loss or disruption. It also considers the historical sensitivity and maps the level of impact (physical damage, business-related loss, social impact) based on significant past occurrences.

Three (3) indicators are used for the quantification of vulnerability sub-index:

- **Predisposition:** the airport's physical and geographic characteristics may influence its sensitivity to experience loss or disruption due to a climate hazard event. For example, an airport in the coastal zone, on a river floodplain or in low-lying areas may be prone to flooding due to a storm/storm surge or extreme precipitation. Quantifying the predisposition provides a greater understanding of the airport's tendency to experience a negative impact. The predisposition of elements at risk is acknowledged as a core element of vulnerability in the MOVE Framework (Birkmann et al., 2013). Also, many studies discussing vulnerability refer to the physical components relevant to predisposition and how these influence the probability of being harmed when an event occurs (Balica et al., 2012; Kappes et al., 2012; Rowan et al., 2014).
- **Sensitivity:** quantifying the historical sensitivity of the airport to disruption or damage due to a climate hazard event can indicate the airport's robustness towards climate hazard occurrences. The IPCC considers sensitivity a key vulnerability component (IPCC, 2012). In the literature, the sensitivity of assets to climate extremes or other natural hazard types is a core element of vulnerability (Weis et al., 2016; Debortoli et al., 2019) and is often linked to the degree to which an exposed system is affected (Füssel and Klein, 2006), capturing how it reacts to a change in climate (Rowan et al., 2014).
- **Impact:** addresses the level of physical damage and business-related impact, considering the airport's past performance to a significant climate hazard event. While the sensitivity indicator addresses the overall level of disruption in the past 10 years, the impact indicator offers quantifiable consequences of the most significant disruptive event, reflecting the potential expected degree of loss. The IPCC points out that the severity of the impacts of climate hazard events depends on the vulnerability (IPCC, 2012). Therefore, looking at how the airport system responded to past events indicates how severe the impacts may be in the future. In the literature, the level of impact is considered when analysing the vulnerability or risk posed by climate change or natural hazards (Lopez, 2016; Eidsvig, Kristensen and Vangelsten, 2017; Dawson et al., 2018).

The measurement of each indicator considers a set of variables (Appendix B Table 3). As mentioned above, in many cases, the selected variables were initially developed for other

types of systems and were modified to address the airport context. In other cases, there was a need to develop a new variable to address specific elements of the airport system.

The measurement of the sub-index of vulnerability considers the average value of the indicators and the measurement of the indicators the average value of their variables.

The measurement of each variable uses a 3- or 5-point scale. The 5-point scale uses a 1 to 5 measurement, with one (1) representing the lowest point in the scale. The 3-point scale uses a 1 to 5 measurement, with one (1) representing the lowest, three (3) the average and five (5) the highest point in the scale. The reason for choosing 1, 3 and 5 as measurement points instead of 1, 2 and 3 is to maintain the same highest and lowest points in all variables. Considering the broad and diverse focus of the variables, the scale is often adopted from the literature, adapted to reflect the airport's environment and characteristics regarding assets, operations, and interdependencies. Where a suitable metric is not identified, the measurement scale is developed following common logic (for example, thresholds based on 25% increments).

Appendix B Table 3 provides information on the indicators and variables that set up the sub-index of vulnerability. It presents the variables used to measure each indicator, the measurement scale, the rationale for their choice and information on the literature used for their development.

3.4.4 Sub-index adaptability

Adaptive capacity, or adaptability, refers to '*the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences*' (IPCC, 2018a). It addresses the ability of a system to prepare for or respond to stresses to reduce the negative impacts of climate hazards (Nguyen et al., 2019). The definition of the term suggests that adaptability can influence the existing levels of exposure or sensitivity (Engle, 2011), leading to reduced levels of risk.

For example, adaptability addresses the capacity of airports to adjust their functions and characteristics to increase their ability to cope in the event of a climate hazard occurrence, anticipate future change, reduce risk and recover from the consequences in a timely and orderly manner (Yang and Ge, 2020). Accordingly, the sub-index of adaptability reflects the actions of the airport to adjust, be better prepared, anticipate, and manage a climate hazard occurrence, as well as the attributes the airport has that support an effective

response and efficient recovery. Thus, adaptability can take many shapes depending on the climate hazard and the airport's characteristics. It can involve measures aiming to increase the resistance of infrastructure, setting up early warning systems, re-designing vulnerable parts, developing policies, raising awareness, and learning to anticipate impact (Brooks and Adger, 2005; Koetse and Rietveld, 2012; Masood *et al.*, 2016; Orsato, Barakat and De Campos, 2017).

The quantification of adaptability focuses on the key elements; it addresses the ability of the airport to understand climate hazard-related risks, prepare for an event, respond effectively and efficiently, plan to control potential loss and prevent future disruption. The overall method adopted is a mixture of approaches used in the literature to assess adaptive capacity in the field of climatic change or natural hazards (Berkhout *et al.*, 2004; De Vivo *et al.*, 2021; Koetse & Rietveld, 2012; Rowan *et al.*, 2014). The most typical metrics used in such studies include the level of protection to reduce infrastructure exposure, the efficiency of emergency response and elements reflecting redundancy (Eidsvig *et al.*, 2017).

Three (3) indicators are used for the quantification of the adaptability sub-index:

- **Protection:** protection measures for critical infrastructure, assets, and equipment are vital in reducing exposure to climate hazards. It, therefore, determines the airport's ability to resist. For example, in the case of a coastal airport, a seawall can protect against rising sea levels and storm surges. The quantification of the level of protection builds an understanding of the existing capacity to resist and anticipate damage or disruption. In the literature, protection measures, such as flood barriers, sea walls, vegetation, wind-resistant structures, and resilient pavements, are considered essential to prevent loss and ensure business continuity (Dolman and Vorage, 2019; Yesudian and Dawson, 2021; Burbidge, Paling and Dunk, 2023).
- **Preparedness:** Emergency response and preparedness mechanisms are significant in reducing business impacts due to natural hazard event occurrences. For example, having an early warning system in place allows for assessing the potential impact and preparing contingency measures, like flight rescheduling. The quantification of the level of preparedness reflects the airport's ability to control potential disruption and loss and take action to maintain its functioning during or

right after the event occurrence. In the literature, preparedness focuses on measures like forecasting, early warning systems, monitoring systems, coordination and communication protocols (De Vivo *et al.*, 2021; Burbidge, Paling and Dunk, 2023; Voskaki, Budd and Mason, 2023).

- **Institutional capacity:** The ability of the airport to understand the climate hazard-related implications and the existing capacity to plan for adaptation is essential to reducing risk. Quantifying the institutional capability to drive adaptation supports the organisation in building awareness, proactively planning and securing the necessary resources to deliver action (Burbidge, 2018; Vogiatzis *et al.*, 2021).

The measurement of the adaptability sub-index considers the indicators' average value. Each indicator considers a set of variables (Appendix B Table 4); the measurement of the indicators considers the average value of their variables.

The scoring of each variable uses a 1 to 5 scale, which is developed considering examples in the literature, like the one used by Dymnicki *et al.* (2021); they use a 5-point rating scale to address dimensions of capacity ranging from insufficient information to continuously improving. Also, Pescaroli *et al.* (2020) use a 5-point scale to rate resilience levels, ranging from no implemented measures to fully developed strategies in place and applying good practices and established mechanisms of continual improvement.

Appendix B Table 4 provides information on the indicators and variables that set up the sub-index of adaptability. It presents the variables used to measure each indicator, the measurement scale, the rationale for their choice and information on the literature used for their development.

The next section will provide details on the prototype version, its development and structure and how it will be tested and validated.

3.5 Stage 5 – Testing and validating the working prototype version of the tool

Following the process described in Section 3.4, a pilot version of the tool is developed in MS Excel to address the RO3 and how to assess the operational and compliance risk of climate hazards to the airport system. The tool is developed in a way that combines and connects data collection (Part A) with data analysis and results (Part B) (Figure 3-8).

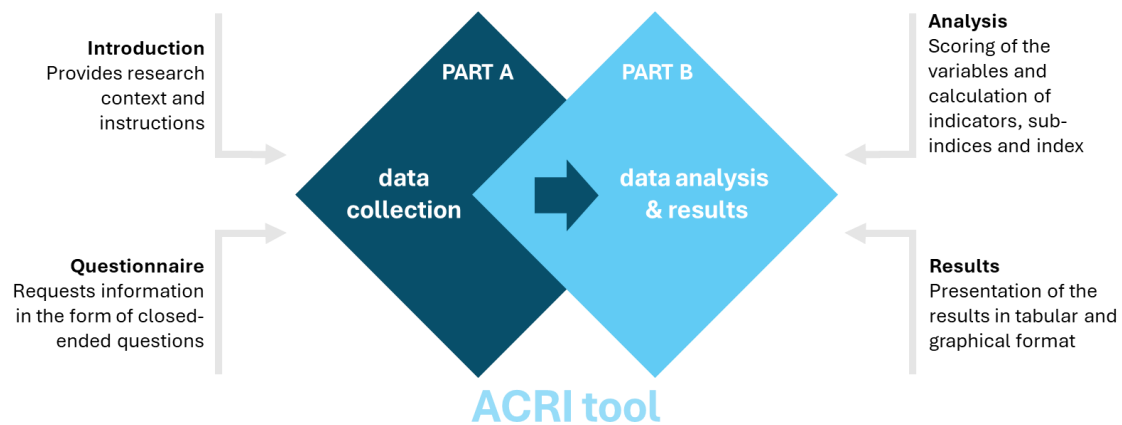


Figure 3-8 Structure of the prototype version of the ACRI tool

Part A is developed as a questionnaire to support data collection. The data collection is conducted in sections; different tabs include questions the users are asked to respond to. Each question corresponds to a variable. Almost all questions are closed-ended, offering the user a fixed set of choices to select from through a drop-down menu. Each choice corresponds to a score based on the variable measurement scale presented in Section 3.4. Besides the questionnaire, Part A provides information on the research context and instructions for the user.

Part B conducts the analysis of the data collected in Part A. This part includes tabs connected with the tabs included in Part A to enable the scoring and standardisation of the variables and the subsequent calculation of the indicators, sub-indices and index. Part B also includes tabs for the presentation of the results in the form of tables and graphs, providing different perspectives and allowing conclusions on climate hazards, exposure, vulnerability, and adaptability levels to be drawn, identifying areas for consideration.

3.5.1 Test and validation of the prototype version

A pilot study is conducted to test and validate the prototype version of the ACRI tool. While the tool is developed to apply **to all UK airports**, regardless of size or operational or management model, a decision has been made to use **regional airports** for the test and validation. The rationale for this choice is based on the following:

- Regional airports play an important role in the UK's aviation system, facilitating domestic and international connectivity and supporting local and regional

economic development while at the same time serving as transport hubs for less densely populated areas.

- While regional airports play an important role in the UK air transport network, they may operate with fewer financial and operational resources compared to larger hub airports. As a result, they may be less able to invest in comprehensive climate risk studies and tools or have dedicated in-house specialists to plan and lead such efforts. These possible constraints could place regional airports in a relatively less advantageous position, potentially limiting their ability to keep pace with building more adaptability to address evolving climate hazard-related risks.
- As regional airports may have fewer resources to invest in climate resilience, they can be more receptive to using new tools and participating in pilot studies, particularly when there is a benefit to their operation and planning. This suggests they may offer more constructive, practical feedback, as they may likely seek to shape a tool they can eventually use in day-to-day business/operations.
- Regional airports may be likely to operate with limited resources, and therefore, airport staff may have multiple responsibilities. As a result, a single airport professional may often contribute to different roles and activities. This allows for more efficient discussions around climate hazard implications and existing risk mitigation measures. This arrangement enhances the overall process of testing and validation as there is a need to engage with fewer people to gain a comprehensive perspective. At the same time, the exchange of knowledge becomes more meaningful, allowing airport personnel to gain insights into climate risk perspectives they may not have previously considered. The above suggests a motivated and engaged team willing to support the tool's development and validation.
- Thus far, climate risk research in an airport context has focused on larger airports, which tend to attract attention due to the scale of disruption and economic impact climate extremes can have. However, regional airports are also susceptible to climate hazard-related loss and disruption. Despite their exposure and vulnerability to climate extremes, regional airports have received limited attention, suggesting a

knowledge gap in how they conceptualise, assess, and respond to climate hazard occurrences.

In this context, a pilot study is conducted with Regional and City Airports (RCA) to test and validate the prototype version of the ACRI tool. Three (3) regional airports participate in the study:

- Exeter Airport
- Norwich Airport
- Bournemouth Airport

The study's goal is to test practical aspects and collect feedback regarding the tool's applicability, usefulness, completeness, practicality, and ease of use. The objective of the study is not only to collect data and the views of participants but also to enable discussions and explore in-depth aspects related to the tool development. Therefore, different engagement methods, such as one-to-one interviews, questionnaires, focus groups, workshops, and case study approaches, are initially considered.

While one-to-one interviews would allow meaningful discussions on climate hazard implications and adaptation measures enabling obtaining valuable qualitative insights, to collect the information required at an airport level, multiple interviews with different airport professionals would need to be accommodated, making the process time-consuming, especially considering the airport staff availability. Also, it is not easy to have comprehensive responses for elements requiring input from more than one individual. The use of questionnaires offers an efficient way to collect data and gather feedback, as airport professionals can complete those independently. However, they may restrict the insights as they are not interactive.

Conversely, focus groups allow for capturing diverse views, encouraging discussions on climate hazards, existing practices and future planning, and exploring airport professionals' opinions and how they address challenges. However, while they allow gaining the current level of understanding of climate hazard aspects, they do not allow easy testing of the tool as they are typically not structured, making it challenging to incorporate practical applications. Workshops, on the other hand, are more interactive, allowing the practical testing of the tool and enabling diverse discussions during the process. Nevertheless, they can be time and resource-intensive and challenging to schedule and facilitate as they

require several hours of participation. Finally, a case study approach is initially explored as it allows for a more in-depth analysis of climate hazard implications at a single airport; nevertheless, it will only provide outputs for the studied airport, and it will be difficult to conclude the tool's applicability across different settings.

Given the objective of the pilot study and the need to gain insights while obtaining practical feedback, a combination of the above methods is decided. These include the use of questionnaires and discussion groups in the form of workshops with embedded open-ended interviews:

- **Questionnaire:** The use of questionnaires at different stages of the pilot study allows for data collection and feedback. Questionnaires are used during the test phase of the prototype version (Part A of the ACRI tool) and during the last phase of the study to collect feedback in a structured way.
- **Workshop/discussion group:** Discussion groups in the form of workshops (face-to-face and online) are used to allow the testing and validation of the tool and enable discussion on aspects relevant to the tool's applicability, usefulness, completeness, practicality, and ease of use. The workshops are also used as a mechanism to explore aspects relevant to the airports' challenges regarding climate hazards of concern, how they address those currently, and what tools they use to capture the analysis of risk and their overall progress in building adaptability. Furthermore, the workshops are utilised to collect insights and the views of the participants.

Details on the type of interaction with each airport as part of the pilot study and the composition of the airport teams are presented in Table 3-3.

The focus of the workshop is to collect insights on the current level of understanding, challenges regarding climate hazards, and current practices to analyse climate hazard-related risks. During the workshops, the prototype version of the tool is presented to the airport teams. The composition of the teams included staff from airport operations, business continuity, safety, engineering, and environment/sustainability departments.

The main topics for discussion revolve around the main elements of the tool, the type of information required for the analysis, how information is captured and how results are

presented. At the end of the workshop, the participants receive a copy of the tool and are asked to complete the questionnaire, a necessary step to conduct the analysis. To ensure that the airport teams understand the questions and what they need to consider responding, time is spent reviewing each question for one or two climate hazard types with the teams.

Table 3-3 Details on the pilot study with Regional and City Airports

Airport	Details on the type of interaction	Composition of the airport team
Exeter	Face-to-face workshop at Exeter airport (22/06/2023) - Duration: half a day (am) Online feedback session via Teams (31/08/2023) - Duration: 1 hour	Safety, Airfield & Compliance Manager, Fire Service Manager, Energy & Environment Manager, Estates & Facilities Manager, Managing Director
Norwich	Face-to-face workshop at Norwich airport (26/06/2023) - Duration: half a day (pm) Online feedback session via Teams (28/07/2023) - Duration: 1 hour	Operations Director, Airside Services Manager, Airfield Manager, Air Traffic Engineering Manager, Airfield Manager, Fuel Services Manager, Managing Director
Bournemouth	Online introductory call to determine requirements and discuss the process (16/06/2023) – Duration: 1 hour Face-to-face workshop at Bournemouth airport (25/07/2023) – Duration: half a day (pm) Online feedback session via Teams to collect feedback (29/08/2023) - Duration: 1 hour	Fire Service and Business Continuity Manager, Environmental and Sustainability Officer

The next step is an online session to collect feedback on practical aspects, missing elements, and the tool's usefulness, applicability, ease of use, clarity of the questions and response options. Feedback is collected through discussion and supported by a questionnaire developed for this purpose. The online sessions are attended by representatives of the airport teams participating in the workshops. Although the workshops are attended by 14 people, a representation of the teams participated in the online sessions; in total, seven (7) responses are received, yet responses reflected the views of the full airport teams.

Feedback discussions focused on key aspects, such as usability, completeness, clarity, and the role of ACRI in decision-making regarding climate hazard risk management. The key points of the feedback discussions are summarised in the following paragraphs.

The participants generally recognise the tool as a valuable resource for developing their adaptation plans and making long-term strategic decisions on climate risk mitigation. Most of the respondents agree that the tool can support decision-making on climate hazard risk mitigation and adaptation aspects; very few participants remained neutral in their assessment (Figure 3-9).

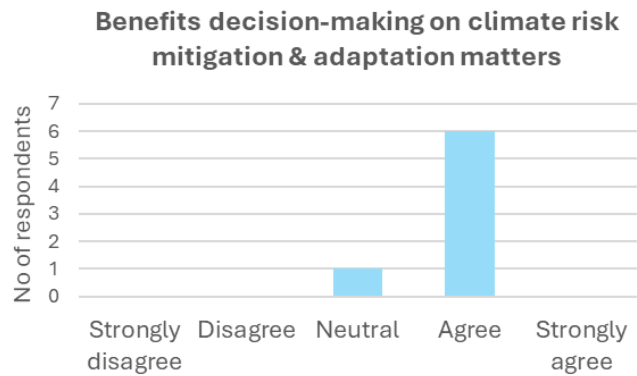


Figure 3-9 Feedback on decision-making

Most participants found it helpful or relatively useful as a self-assessment tool (Figure 3-10), supporting discussions on climate hazards and decision-making. A small number considered it only slightly helpful, with none rating it as not useful at all. The teams acknowledged that the overall process facilitated meaningful discussions among cross-functional airport teams. The overall activity allowed them to look at aspects previously overlooked, contributing to a more comprehensive risk profile. Responding to the questions introduced a new way of thinking about emerging climate hazards, climate hazard trends and their potential implications on the airports' operations.

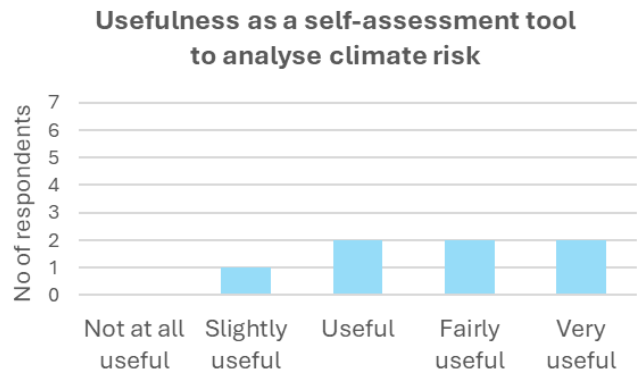


Figure 3-10 Feedback on usefulness as a self-assessment tool

Therefore, the tool is seen as a support tool to their existing risk management framework, allowing the team to expand current assessments and enrich their risk response mechanisms. While some participants agreed or strongly agreed that the tool meets their expectations, a small part remained neutral, offering their views on how the tool can be enhanced and expanded.

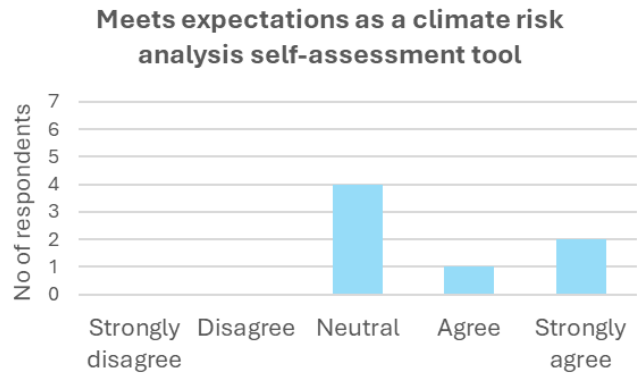


Figure 3-11 Feedback on expectations as a self-assessment tool

When it comes to how complete the tool is, most of the respondents stated that most elements are included (Figure 3-12). They pointed out that while the tool effectively identifies climate hazard levels, it does not differentiate between current and future ones, making it challenging to identify areas for consideration over the short and long term that would increase its applicability. Additionally, some participants pointed out that the tool could include elements relevant to business loss due to disruption for the analysed climate hazard occurrences.

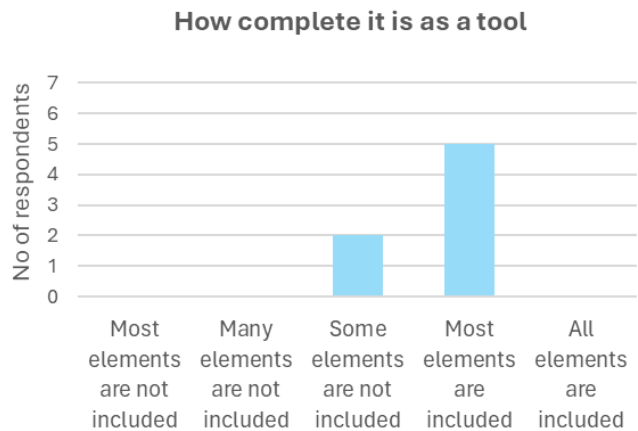


Figure 3-12 Feedback on the completeness of the tool

Furthermore, although the tool addresses climate hazards typically observed, providing information on the hazard levels, it does not include weather events that could cause disruption, such as low visibility due to fog. Expanding the scope by including other climate hazards would make it more complete.

All participants found all the questions clear (Figure 3-13).

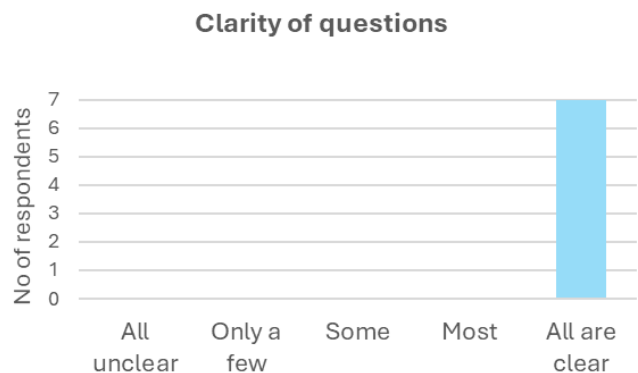


Figure 3-13 Feedback on the clarity of the questions

Nevertheless, a few noted that some categories of response could be slightly reworded for better understanding (Figure 3-14).

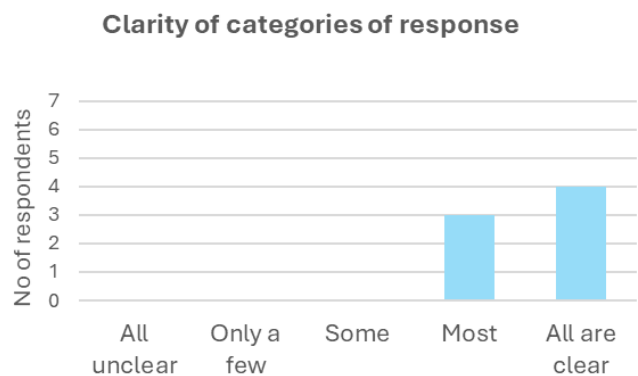


Figure 3-14 Feedback on the clarity of response categories

When it comes to user-friendliness, responses are mixed (Figure 3-15). Some participants rated the tool as fairly user-friendly, while others found it useful but slightly difficult to navigate. A small number found it not user-friendly at all.

The provided feedback highlights a need for structural improvements to enhance its user-friendliness. Considering how the tool is structured, many elements are repeated, making

it less user-friendly and requiring much time to complete. Suggestions include making the tool more concise, grouping questions for different climate hazards, avoiding repetition, and streamlining how the information is captured.

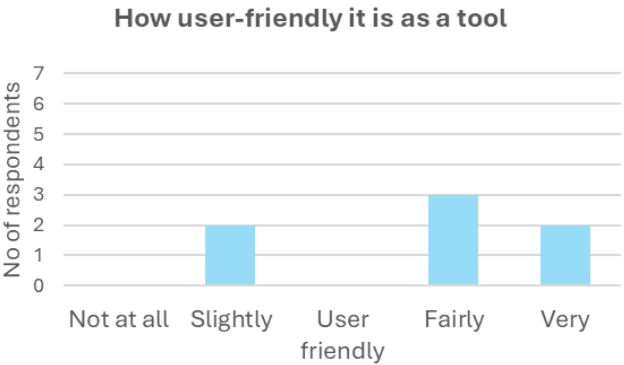


Figure 3-15 Feedback on the user-friendliness

Some participants also focused on the tool's intended use; if the tool is to be used as a replacement of ongoing risk monitoring, it should incorporate aspects that will allow tracking mitigation measures and controls for all types of risk (not only climate hazard-related).

To summarise the key takeaways, the tool is generally considered useful and helpful for the regional airport teams; however, some improvements are required to fulfil its aim better. In this context, the tool will be refined to better address some concerns from the airport user's perspective, improving user-friendliness.

The next stage will focus on the refinement and development of the final version of the tool.

3.6 Stage 6 – Development of the final version of the tool

After the workshops and feedback sessions, the collected information is further analysed to identify the points that add value to determine the required changes to make the tool more valuable and user-friendly. The changes mainly focus on the tool's structure, ways to improve the clarity of the response categories, differentiation of the climate hazard levels, and how the results are presented.

In its final version, the ACRI tool includes 13 tabs; Part A includes seven and Part B consists of six tabs (Figure 3-16):

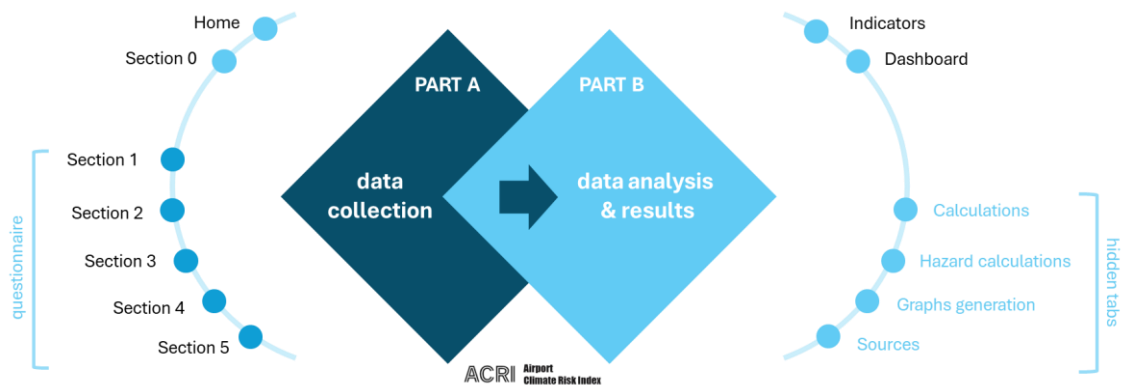


Figure 3-16 Final structure of the ACRI tool

- **Home:** the start page of the tool.
- **Section 0:** provides information on the research context, instructions for the user on how to complete Sections 1 to 5 and terminology used.
- **Section 1:** includes questions on airport and airport location characteristics that influence aspects of vulnerability considering the different climate hazards.
- **Section 2:** includes questions relevant to the airport exposure and sensitivity to climate hazards. Figure 3-17 provides a snapshot of Section 2 of the tool.
- **Section 3:** includes questions on historical incidents that affected the airport. Figure 3-18 provides a snapshot of Section 3 of the tool.
- **Section 4:** includes questions relevant to the implemented measures to reduce the level of exposure or vulnerability to the applicable climate hazards.
- **Section 5:** includes questions on the climate hazards and is used to generate the climate hazard profile of the airport. The section is automated, eliminating the need for the user to identify the climate hazards that apply to the airport location, the climate variables, and their values. To this end, the UK was split into 21 regions considering the geography and the largest airports in terms of passenger traffic. For each location category, climate variables are used to measure the current and future hazard levels. Each variable is assigned a score considering the region and the representative airport. To complete this section, the user chooses the region that best represents the airport location, and the hazard level is assigned automatically.

- **Indicators:** presents the indicators, sub-indices, and index results.
- **Dashboard:** presents the results in a series of graphs, allowing different views of the level of risk determinants and supporting a greater understanding of the outcome. A snapshot of the Dashboard is presented in Figure 3-19.
- **Calculations:** links the responses (Part A) to the scoring and standardisation of the variables and the subsequent calculation of the indicators, sub-indices, and index (Part B).
- **Hazard calculations:** includes the climate hazard variables values for the 21 UK regions.
- **Graph generation:** includes calculations used to generate the graphs in the Dashboard.
- **Sources:** includes links with information on climate hazard variables for the user to access.

The development of the final version of the tool allows moving to the next stage of the validation process, which involves presenting the tool to airport professionals and specialists for collecting insights and further evaluating its usefulness and effectiveness. The validation process will also include using the tool in case studies to see how it performs in practice, ensuring it fulfils its intended purpose.

Airport exposure and sensitivity to climate hazards

SECTION 2

ACRI Airport Climate Risk Index

Questions/variables	Airport response								Rationale for giving this response (not mandatory)
1 Considering the design standards/ technical specifications, is the integrity of airport critical infrastructure (e.g. runway, taxiway, apron, pavement material etc.) potentially affected by the mentioned climate hazards?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
2 What proportion of critical infrastructure/assets (e.g. runway, taxiway, apron etc.) is potentially affected by the mentioned climate hazards?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
3 Considering the design standards/ technical specifications, is the integrity of airport critical equipment (e.g. Navigational Aids, IT, comms etc.) potentially affected by the mentioned climate hazards?	Coastal flooding/storm surge	Fluvial/pluvial flooding	<div> <div>>75%</div> <div>50-75%</div> <div>25-50%</div> <div>0-25%</div> <div>0%</div> </div>	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
4 What proportion of airport critical equipment (e.g. Navigational Aids, IT, comms etc.) is potentially affected by the mentioned climate hazards?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		

Drop-down menus offering options

Figure 3-17 Snapshot of Section 2 of the ACRI tool (the tool can be made available upon request)

Historical incidents affecting the airport

SECTION 3

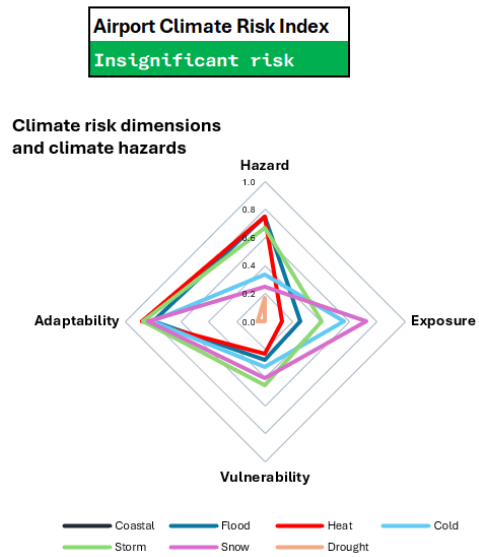
ACRI Airport Climate Risk Index

Questions/variables	Airport response								Rationale for giving this response (not mandatory)
1 What was the most significant event affecting the airport in the past 20 years? <small>Please provide information on the event in the yellow-shaded cell (e.g. name of the storm or year of occurrence)</small>	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
2 Was the above mentioned event in a peak day?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
3 If the event caused the airport closure, what best describes the time the airport was out of service?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
4 What best describes the number of ATMs disrupted (cancelled, diverted or delayed) due to the event?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
5 What best describes the financial impact/business loss due to the disruption caused by the event?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		
6 What best describes the cost for restoration or repairs or replacement due to the event considering the annual maintenance cost?	Coastal flooding/storm surge	Fluvial/pluvial flooding	Extreme heat	Cold and icing conditions	Storminess and extreme wind	Snowstorm and extreme snowfall	Drought/water scarcity		

Drop-down menus offering options

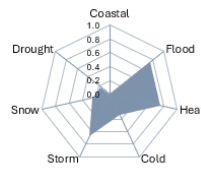
The airport was out of service for the whole duration of the event and after the event
 The airport was out of service for the whole duration of the event
 The airport was out of service for a period of time 25-50% of the overall duration of the event
 The airport was out of service for a short period of time - duration of the disruption <25% of the overall duration of the event
 The airport remained operational during the event

Figure 3-18 Snapshot of Section 3 of the ACRI tool (the tool can be made available upon request)

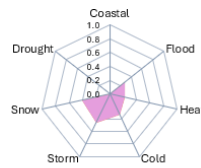


Climate risk determinants

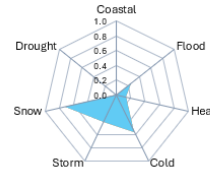
Climate hazard



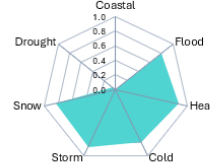
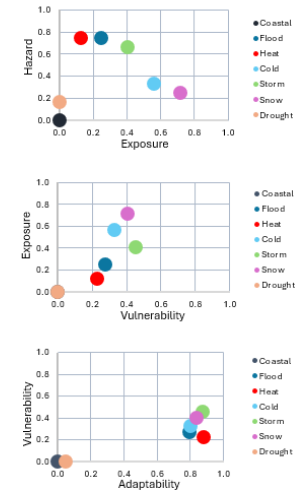
Vulnerability



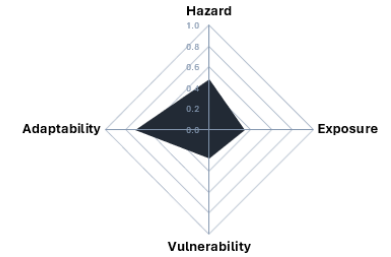
Exposure



Adaptability



Climate risk



Climate hazard levels

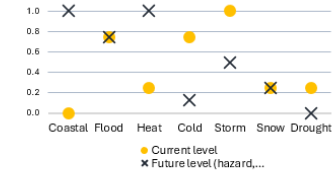


Figure 3-19 Snapshot of the Dashboard of the ACRI tool (the tool can be made available upon request)

3.7 Stage 7 –Validating, collecting and analysing data

The last stage of the methodology includes a two-phase validation process.

Phase one focuses on engaging with aviation and sustainability specialists to gather their views on the index's usefulness and applicability and to discuss key considerations that will shape the selection of the case examples.

As a first step, a dedicated call is held with Airports UK, offering an opportunity to present the tool to their Airport Regulation, Safety and Operations Manager and Senior Policy Manager. Airports UK is a trade association representing the interests of UK airports. During the discussion, Airports UK offered positive feedback regarding the value of the index, especially for regional airports. They pointed out that while larger airports tend to outsource comprehensive climate risk assessments, regional airports often lack the resources to do so. Therefore, using the tool can have a more significant impact on those airports. The above feedback and insights support the initial rationale for focusing the pilot study on regional airports.

As a second step, the research and the tool are presented to the UK Civil Aviation Authority (CAA) during a seminar for the Airspace, Aerodromes and Air Traffic Management teams within the Safety and Regulation Group. The CAA is the UK's aviation regulatory body. The presentation enabled discussion with regulators on how the tool can support (complement) existing risk management mechanisms. It is acknowledged that a tool like this is needed to assist airports in identifying gaps in their current risk management plans.

In the third step, a meeting with Eurocontrol offered the opportunity to present the tool to the Aviation Sustainability Unit and discuss its applicability and how it can be expanded to address airports within the wider Eurocontrol's remit. Eurocontrol is a pan-European, civil-military organisation supporting European aviation by coordinating and managing air traffic control across member states. Eurocontrol provided positive feedback on the tool's usability and suggested further discussions about the possibility of inclusion as a tool for airports under the Flying Green Platform.

Phase two involves selecting case example airports and conducting the data collection and analysis.

Following the specialist discussions and the pilot study outcomes, a decision is made to continue focusing on UK regional airports. Since the pilot study had already involved regional airports, including them as case examples is a logical next step. Therefore, their input will be used to respond to the Part A questionnaire of the ACRI tool; additional information will be requested as necessary (for instance, to address newly added questions).

Besides the three regional airports, further efforts are undertaken to recruit more airports for the validation study. In this context, an outreach campaign is planned, including:

- Direct outreach via email to several regional airports across the UK, inviting them to participate in the study and test the tool.
- A blog post on Cranfield University's website² describing the research, its objectives, and the benefits to participating airports, while including an invitation to participate in the study.
- Engagement through Airports UK; a summary of the tool, including its intended use and benefits, is shared with their member airports to encourage participation.

As a result of this campaign, one additional regional airport; Belfast International Airport, has joined the study. With four regional airports representing varied sizes, characteristics, and geographies within the UK, the number of case examples is considered sufficient for the validation process.

Overall, these four case examples, Belfast International, Bournemouth, Exeter and Norwich, enable the practical validation of the ACRI tool within the context of UK regional airports.

A separate copy of the tool is used for each airport to collect data, with airport input added into Part A. This allows the generation of the results in Part B automatically, as described in earlier sections of this chapter. The analysis of the results (Chapter 4) will focus on interpreting the tool's output. It will look at the variables and indicators and their combinations to identify gaps, analyse the risk and propose recommendations on how to build more adaptability (Chapter 5). The above process uses simple calculations, enabling the graph generation.

² [Is your airport ready for climate change? - Cranfield University Blogs](#)

3.8 Conclusions

This chapter outlined the steps and the adopted methodology to conceptualise the framework and develop the ACRI tool. It included information on the selection and development of variables, their measurement and how they are combined into indicators and sub-indices. In addition, it described the pilot study, the overall validation process, and the rationale behind the selection of airports.

Four regional airports have been selected as case examples for the validation of the tool. The next chapter will focus on these examples. It will present an overview of the results produced by the ACRI tool and discuss how these outputs can be interpreted to identify issues for further consideration regarding climate hazard risk mitigation.

4 Analysis of the case examples

This chapter analyses the results of case examples of airports in the UK, addressing RO3 – 'To assess the operational and compliance risk of climate hazards to the airport system'. The analysis uses the ACRI tool described in the Methodology chapter; it seeks to build an understanding of the existing practices that will allow the identification of gaps in existing risk mitigation and the climate hazard types for which additional action is needed to reduce exposure or vulnerability levels and build further adaptive capacity to increase resilience.

Four (4) UK regional airports are used as case examples (Figure 4-1). These are selected to represent a diverse geographic sample and a range of size and traffic mix.



Figure 4-1 Location of case study airports (source: Google Maps)

Key information for the selected airports is provided in Table 4-1, and a short description of each is provided below. Considering the annual passenger numbers and ACI Europe categorisation of regional airports (ACI Europe, 2022), the case study examples include Group 3 (between 5 and 10 million passengers per year) and Group 4 (less than 5 million passengers per year) airports.

Table 4-1 Airport case examples

Airports	Location	Airport management	Annual pax (2024) ³
Belfast International Airport (BFS)	Belfast, N. Ireland	Vinci Airports	6,750,440
Bournemouth Airport (BIA)	Dorset, England	Regional & City Airports (RCA)	1,088,370
Exeter Airport (EXT)	East Devon, England	Regional & City Airports (RCA)	449,722
Norwich Airport (NWI)	Norfolk, England	Regional & City Airports (RCA)	415,099

Belfast International Airport (BFS) is an international airport in Northern Ireland, 12 miles northwest of Belfast. The airport has two runways, one terminal, and cargo facilities, and it serves approximately 7 million passengers annually (2023) (UK CAA, 2024b). Besides providing air links to domestic and international destinations, the airport also serves as a regional air freight centre in the UK (Belfast International Airport, 2024a). Belfast International Airport is the largest airport in the sample in terms of annual passenger numbers.

Bournemouth Airport (BIA) is an international airport in Dorset, 4 miles north of Bournemouth. The airport has one runway and one terminal building and serves more than 1 million passengers annually (2023) (UK CAA, 2024b). In addition to providing connectivity to domestic and European destinations, the airport also serves air freight operations (Regional & City Airports, 2024).

Exeter Airport (EXT) is an international airport in East Devon, 4 miles east of Exeter. The airport has one runway and one terminal building and serves approximately 500,000 passengers annually (2023) (UK CAA, 2024b). Besides providing air links to domestic and international destinations, it also serves as a Royal Mail hub (Regional & City Airports, 2024).

Norwich Airport (NWI) is an international airport in Norfolk, 2.5 miles north of Norwich. The airport has one runway and one terminal building and serves more than 400,000 people annually (2023) (UK CAA, 2024b). Apart from providing connectivity to domestic and European destinations, the airport is a transport hub for the Southern North Sea offshore industry in the oil and gas and windfarm technology sectors (Norwich Airport, 2019). Norwich Airport is the smallest airport in the sample in terms of annual passenger numbers.

³ UK CAA Annual airport data 2024

The structure of this chapter is as follows: first, an analysis of the climate hazard risk is provided in Section 4.1, with details on the climate hazard levels and trends. This is followed by the analysis of the levels of exposure (Section 4.2), vulnerability (Section 4.3) and adaptability (Section 4.4). The last section (Section 4.5) provides the main conclusions of the analysis.

4.1 Climate hazards and airports

To analyse climate risk, it is important to understand the climate hazard challenges each of the airports faces, considering its geographic location. Therefore, an analysis of the climate hazard profile of the airport is essential. The climate profile will include information on the applicable climate hazards for each airport location and how these are influenced by climate change. Therefore, the climate profile considers:

- the climate hazards in the present day, reflecting the hazards observed today;
- the future climate hazards, considering the impact of the SSP2-4.5 scenario, based on UKCP18 and IPCC's climate change scenarios, and the mid-term horizon (up to 2050);
- the confidence in the direction of change, showing the likelihood of change of the different climate variables (Kause *et al.*, 2022).

These three elements provide a holistic view of the climate hazard levels, from their current manifestation to their projected future characteristics. This approach allows for a more comprehensive, forward-looking analysis that integrates observations, climate change projections and associated uncertainties. Detailed information on the variables used for establishing the indicators and sub-index of climate hazard is included in Section 3.4.1 and Appendix B Table 1.

The ACRI output for the sub-index of climate hazard is presented in figures and tables. It is noted that the term 'hazard level' is used here to define the tool's output, considering the climate metrics that are used as variables. Hazard level is defined as the average value of the selected variables, using a 5-point scale, moving from very low to very high (Table 4-2).

Table 4-2 Rating scale used for climate hazard metrics

Hazard levels	Value in ACRI
Very high	0.76 – 1.00
High	0.51 – 0.75
Moderate	0.26 – 0.50
Low	0.01 – 0.25
Very low	0.00

An example is provided below to aid in understanding the analysis of the tool's output.

In the case of Exeter, the current climate hazard level (Table 4-3) is determined considering the values of the following variables/climate metrics:

- Flood hazard rating – river, as defined in Appendix B Table 1. Based on the Environment Agency's flood risk maps, the location of Exeter Airport is within the 30-year flood zone. Considering the definition of the ACRI variable, this corresponds to a value of 4 and a score of 0.75 in the tool, suggesting a 'High' level of climate hazard.
- Flood hazard rating – surface, as defined in Appendix B Table 1. Similarly, the airport's location is within the 30-year flood zone, which suggests a 'High' level of climate hazard.

To assign the overall rating for flood–current level, the maximum of the two ratings (i.e. for either river or surface) is adopted. In this case, the overall hazard level for Exeter Airport is determined as 'High'.

The results for the hazard indicators are provided in the following paragraphs.

4.1.1 Current climate hazard level

Storm, cold and flood are the most significant hazards in the present day for the airport sample. Out of the four airports, Norwich and Bournemouth present the highest scores, with average scores of 0.54 and 0.50, respectively, as illustrated in Table 4-3. The main climate hazards of concern for both airports are storm, cold and flood.

Table 4-3 Scores for the indicator 'Current climate hazard'

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.50	0.00	0.75	0.50	0.25	0.00	0.33
Bournemouth	0.75	0.25	0.75	0.75	0.00	0.50	0.50
Exeter	0.75	0.00	0.50	0.50	0.00	0.00	0.29
Norwich	0.75	0.25	0.75	1.00	0.25	0.25	0.54

Belfast International demonstrates higher scores for cold and then storm and flood. Exeter shows the lower scores, with flood as the main climate hazard for consideration.

4.1.2 Future climate hazard level

When it comes to the future climate hazard level, heat emerges as the most significant concern across all airports, with snow and drought presenting the lowest scores. Flood is also noted as a significant hazard for almost all airports (Table 4-4).

Table 4-4 Scores for the indicator 'Future climate hazard'

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.75	1.00	0.50	0.50	0.00	0.00	0.46
Bournemouth	0.75	1.00	0.50	0.50	0.00	0.25	0.50
Exeter	0.75	1.00	0.50	0.50	0.00	0.00	0.46
Norwich	0.50	1.00	0.50	0.50	0.00	0.25	0.46

Bournemouth presents the highest score of the airport sample; the airport location demonstrates high scores for heat and flood. Flood appears to be also a concern for Belfast International and Exeter, while heat a concern for all airports .

4.1.3 Confidence in the direction of change

The confidence in the direction of change for the hazards included in ACRI is presented in Table 4-5.

Table 4-5 Scores for the indicator 'Confidence in the direction of change'

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	1.00	1.00	1.00	0.50	0.00	0.00	0.58
Bournemouth	1.00	1.00	1.00	0.50	0.00	0.00	0.58
Exeter	1.00	1.00	1.00	0.50	0.00	0.00	0.58
Norwich	1.00	1.00	1.00	0.50	0.00	0.00	0.58

The values for this indicator are the same for all airports. This is due to the level of detail expressed in the IPCC AR6, covering all the Northern Europe region (IPCC, 2021a). Overall, flood and heat are the hazards with the most substantial projected change – high confidence of an increase. Cold shows a high confidence of a decrease.

Storm shows a medium confidence of an increase. In the case of snow and drought, there is low confidence in the direction of change.

4.1.4 Climate hazard trends

From the change point of view, there are some notable trends. While in some airport locations, there are clear trends regarding the direction of change of climate hazard levels (for example, moving from low to high), in other cases, there is no apparent change. This suggests that airport locations are not necessarily expected to experience a rapid change in the future (considering the incorporated time horizon), especially when there is a low or medium level of confidence in the direction of change.

To illustrate the observed change, based on the output of ACRI, three types of arrows are used. An upward arrow illustrates an increasing trend in the level of climate hazard (output of the tool); for example, if the current level is low and the future level is high. A downward arrow shows a decreasing trend, for instance, moving from a high to a low level. A flat arrow demonstrates no change in the climate hazard level or uncertainty in the direction of change. Table 4-6 illustrates the combinations and decision-making on the choice of the arrows.

Table 4-6 Illustration of climate hazard trends

Climate hazard levels	Trend
The future climate hazard level is higher than the current level (e.g., the current level is low, and the future is high), or there is high confidence in the increase if the current level is very high.	↗
The future climate hazard level is lower than the current level (e.g., the current level is high, and the future is moderate), or there is high confidence in a decrease if the current level is very low.	↘
The current and the future climate hazard levels are the same (e.g. moderate to moderate), or there is low confidence in the direction of change.	→

The observed trends are depicted in Figure 4-2.

	VERY LOW	LOW	MODERATE	HIGH	VERY HIGH
Belfast International	Water scarcity → Extreme heat ↗	Snowstorm ↘	Storminess/wind → Inland flood ↗	Cold/icing ↘	
Bournemouth	Snowstorm →	Extreme heat ↗	Water scarcity ↘	Inland flood → Storminess/wind ↘ Cold/icing ↘	
Exeter	Extreme heat ↗ Snowstorm → Water scarcity →		Cold/icing → Storminess/wind →	Inland flood →	
Norwich		Extreme heat ↗ Snowstorm ↘ Water scarcity →		Inland flood ↘ Cold/icing ↘	Storminess/wind ↘

Figure 4-2 Climate hazard trends

Considering the analysis of climate hazards, the main identified trends are given below.

Coastal flooding/storm surge: The hazard type is not included in the analysis, considering the location of the case study airports and distance from the coastal zone (more than 25km).

Inland (fluvial/pluvial) flooding: This climate hazard is rated as high for all airports except for Belfast International, where a moderate hazard level is observed, although showing an increasing trend. In most cases, observed trends indicate an increase in the hazard level or no significant trend. Considering the confidence in the direction of change, as expressed in the IPCC AR6 and the Interactive Atlas (IPCC, 2021a), there is a high confidence level regarding fluvial/pluvial flooding in the UK.

Extreme heat: Extreme heat is rated low and very low for all airports. In all airports, trends indicate a high level of confidence in an increase, as future climate hazard levels in all cases are rated as very high.

Cold and icing conditions: The level of the climate hazard ranges from moderate for Exeter to high for all other airports. In most cases, trends indicate a moderate decrease or no change in the hazard level.

Storminess and wind: The level of the climate hazard ranges from moderate in the case of Belfast International and Exeter to high for Bournemouth and very high for Norwich. For most airports, trends reflect uncertainty regarding the direction of change. Based on the IPCC AR6 (Seneviratne *et al.*, 2023), climate models consistently project environmental changes that would support an increase in the frequency and intensity of severe

thunderstorms and windstorms in the UK by the middle of the century and beyond and for global warming levels of 2°C or more; however, there is not a high level of confidence in the details of the projected increase.

Snowstorm and extreme snowfall: The level of snowstorm is rated as low and very low for all airports, showing a moderate decline in the hazard level, depending on the location. However, there is low confidence in the observed trend.

Drought and water scarcity: The level of water scarcity is rated as moderate for Bournemouth, while all other airports present low and very low levels. In most cases, trends indicate uncertainty and low confidence in the direction of change.

It is important to note that the climate hazard level presented Figure 4-2 strictly refers to the climate hazard in the airport location and not the climate hazard-related risk. For instance, it does not consider any defences or other measures that may be in place to address a potential flood risk. In addition, it does not consider whether airport elements demonstrate exposure, predisposition or susceptibility to flooding or other climate hazards and, therefore, the overall risk. These elements will be discussed in the following sections.

For simplicity, the rest of the chapter will use the following abbreviations when referring to the different climate hazards:

- **Flood**, to reflect inland (fluvial/pluvial) flooding
- **Heat**, to reflect extreme heat
- **Cold**, to reflect cold and icing conditions
- **Storm**, to reflect storminess and wind
- **Snow**, to reflect snowstorm and extreme snowfall
- **Drought**, to reflect drought and water scarcity

Additionally, for simplicity, the term *hazard* throughout the remainder of this chapter and in the following chapters will refer specifically to *climate hazard* unless otherwise stated.

4.1.5 Overall climate hazard

The ACRI output for the sub-index of climate hazard is presented in Table 4-7. Overall, Bournemouth shows the highest level of hazard (average value of 0.53), followed by Norwich (average value of 0.51). Belfast International and Exeter present slightly lower average scores (0.43 and 0.44, respectively).

Table 4-7 Sub-index of climate hazard

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.75	0.67	0.75	0.50	0.08	0.00	0.46
Bournemouth	0.83	0.75	0.75	0.58	0.00	0.25	0.53
Exeter	0.83	0.67	0.67	0.50	0.00	0.00	0.44
Norwich	0.75	0.75	0.75	0.67	0.08	0.17	0.53

Flood is identified as the main climate hazard of concern across all airports in the present day and future. Bournemouth and Exeter demonstrate the highest levels of hazard in the airport sample. The observed climate hazard levels suggest that the airports are either located within a flood zone, and/or climate metrics associated with precipitation extremes show increasing trends related to surface flooding.

Heat is a growing concern across all airports; while extreme heat occurrences are recorded as low in the present day, they will likely increase in the future, based on the climate change projections. This intensification of extreme heat events may create conditions that the airports may not be ready to address effectively, and therefore, they may lead to potential operational challenges. Cold shows high levels in all airport locations; nevertheless, projections show a decline in the number of frost days, potentially reducing the cold-related impacts in the future.

Storms could become a critical climate hazard, especially for Norwich and Bournemouth. However, although projections may suggest intensification there is a medium confidence in the direction of change. The hazard level for snow appears to be very low or low across all airports. The average days of snow lying in the present day, especially in the case of Norwich and Belfast International, indicate that the airport location has already dealt with snow conditions recently. Nevertheless, projections indicate a declining trend, and therefore, this hazard type is unlikely to introduce conditions that are not consistent with past or present-day circumstances.

Finally, all airports present a low hazard level for drought. The location of Bournemouth and Norwich indicates that the airports' region already deals with incidents of water stress that may become a concern in the future.

4.1.6 Climate hazard focus

In conclusion, the climate hazard analysis identifies flood, storm, heat and cold as significant hazards due to the way they manifest in the present day, or their projected increasing intensity over time, requiring a shift in attention over the medium to long-term (Figure 4-3).

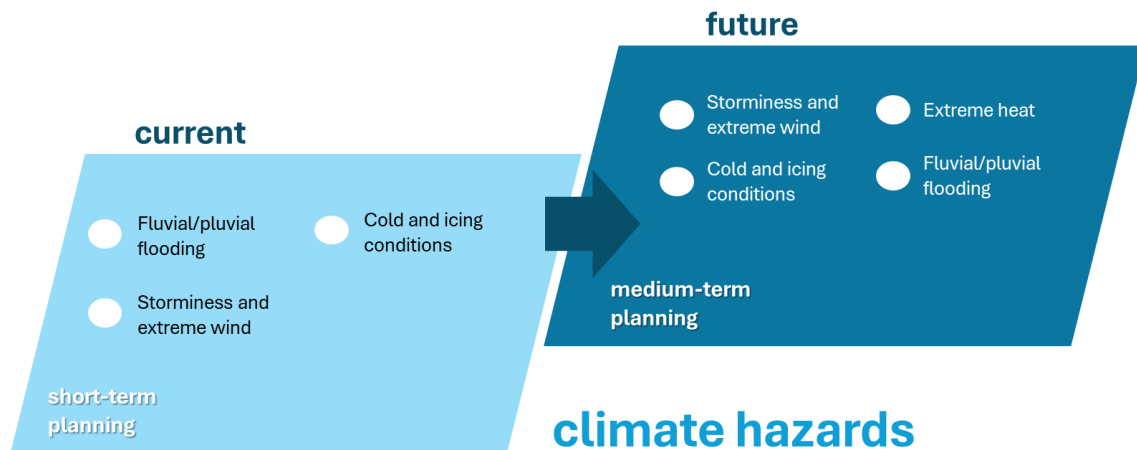


Figure 4-3 Current and future climate hazard focus for the studied airports

Acknowledging the current and future climate hazard focus, the following paragraphs will analyse the airports' exposure, vulnerability, and adaptability.

4.2 Exposed elements

The exposure analysis looks at the airport elements within a hazard-prone area (for example, within a flood zone) or elements that might be exposed to and affected by the hazards of concern. The level of exposure is determined in the ACRI tool, considering the variables and indicators that constitute the sub-index. Detailed information on the variables used for establishing the indicators and sub-index of exposure is included in Section 3.4.2, and Appendix B Table 2.

As with climate hazards, the ACRI output for the sub-index of exposure is presented in tables. It is noted that the term 'exposure level' is used here to define the tool's output, considering the airport responses in the exposure variables; it shows the proportion of the airport elements that are likely to be exposed to the analysed climate hazards.

As described in the Methodology chapter, exposure levels are defined as the average value of the selected variables, using a 5-point scale, moving from no exposure (value of 0.00) to very high exposure (value of 1.00) (Table 4-8 Rating scale used for exposure elements).

Table 4-8 Rating scale used for exposure elements

Exposure levels	Value in ACRI
Very high exposure	0.76 – 1.00
High exposure	0.51 – 0.75
Moderate exposure	0.26 – 0.50
Low exposure	0.01 – 0.25
No exposure	0.00

To assist in the understanding of the tool's output, an example is provided below.

The exposure level of critical assets to cold for Belfast International (Table 4-9) is the average value of the following variables in the tool:

- The proportion of *critical infrastructure/assets* (e.g. runway, taxiway, apron, etc.) that can be affected by cold; details on the variable and its measurement are provided in Appendix B Table 1. Based on the ACRI input/output, more than 75% of critical infrastructure is exposed to cold; therefore, considering the measurement of the variable, this corresponds to a value of 5 and a score of 1.00 in the tool, suggesting a 'Very high' level of exposure.
- The proportion of *critical equipment* (e.g. navigational aids, IT, comms, etc.) that can be affected by cold; details on the variable and its measurement are provided in Appendix B Table 1. Similarly, considering the ACRI input/output, more than 75% of critical equipment is exposed to cold, suggesting a 'Very high' level of exposure.

The results for the exposure indicators (i.e. critical assets, operations, people and interdependencies) are provided in the following paragraphs.

4.2.1 Critical assets

Out of the four airports, and as regards all hazards, Bournemouth and then Belfast International present the highest exposure of critical assets, with average scores of 0.77 and 0.58, respectively, as shown in Table 4-9.

Table 4-9 Exposure levels for the indicator 'Critical Assets'

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.50	0.50	1.00	0.50	1.00	0.00	0.58
Bournemouth	0.25	0.38	1.00	1.00	1.00	1.00	0.77
Exeter	0.25	0.50	0.38	0.13	0.63	0.13	0.34
Norwich	0.38	0.25	0.63	0.63	0.75	0.00	0.44

The highest values of exposure (value of 1.00), indicating that 100% of the assets are likely to be exposed to the hazard, are observed at Bournemouth (cold, storm, snow and drought) and Belfast International (cold and snow). As regards the climate hazard type, snow and cold are the hazards presenting the highest exposure in the sample; approximately 85% and 75% of the assets on average are likely to be exposed to those hazards.

4.2.2 Operations

Air and ground operations across the studied airports show varying levels of exposure to climate hazards. Overall, Bournemouth presents the highest exposure of operations; 100% of air and ground operations are likely to be exposed to cold, storm and snow (value of 1.00), as shown in Table 4-10.

Table 4-10 Exposure levels for the indicator 'Operations'

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	1.00	0.13	0.38	0.25	0.25	0.00	0.34
Bournemouth	0.00	0.00	1.00	1.00	1.00	0.50	0.58
Exeter	0.25	0.25	0.25	0.25	1.00	0.00	0.33
Norwich	0.13	0.00	0.75	0.50	0.75	0.00	0.36

Operations are more exposed to snow and then cold; on average, around 75% and 60% respectively of operations are likely to be exposed. In general, operations appear to be more exposed to winter conditions, especially at Bournemouth and Norwich; 100% of the operations are likely to be exposed to flood in the case of Belfast International.

4.2.3 People

Airport staff and passengers are mainly exposed to winter conditions; snow, cold, and storm are the climate hazards driving the exposure levels. Considering all four airports and all hazards, Bournemouth and Norwich show the highest exposure of people, with scores of 0.50 and 0.33, respectively, as shown in Table 4-11.

Table 4-11 Exposure levels for the indicator 'People'

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.25	0.13	0.25	0.25	0.25	0.00	0.19
Bournemouth	0.00	0.00	1.00	1.00	1.00	0.00	0.50
Exeter	0.25	0.25	0.13	0.25	0.88	0.00	0.29
Norwich	0.25	0.25	0.50	0.25	0.75	0.00	0.33

Belfast International presents the lowest exposure, with around 25% of people exposed to flood, cold, storm and snow. Snow, cold and storm are the primary climate hazards of concern in terms of average exposure across the four airports.

4.2.4 Interdependencies

Within the group of four airports, Bournemouth and Belfast International show the highest overall exposure of interdependencies (utilities and surface access), with average scores of 0.44 and 0.29, respectively, as presented in Table 4-12.

Table 4-12 Exposure levels for the indicator 'Interdependencies'

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.25	0.13	0.50	0.38	0.50	0.00	0.29
Bournemouth	0.25	0.00	0.75	0.63	0.75	0.25	0.44
Exeter	0.13	0.13	0.13	0.00	0.25	0.00	0.11
Norwich	0.25	0.00	0.38	0.25	0.63	0.00	0.25

Exeter demonstrates the lowest overall exposure among the sample, with approximately 25% of its interdependencies (utilities and surface access) being exposed to snow. Across the four regional airports, interdependencies are most commonly exposed to snow and cold, with average exposure levels of around 53% and 44%, respectively.

4.2.5 Overall exposure

Bournemouth shows the highest level of exposure (value of 0.57), followed by Belfast International (value of 0.35) and Norwich (value of 0.35), as presented in Table 4-13. In contrast, Exeter demonstrates the lowest level of exposure, with a high value only to snow (value of 0.69).

Table 4-13 Sub-index of exposure

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.50	0.22	0.53	0.35	0.50	0.00	0.35
Bournemouth	0.13	0.10	0.94	0.91	0.94	0.44	0.57
Exeter	0.22	0.28	0.22	0.16	0.69	0.03	0.27
Norwich	0.25	0.13	0.57	0.41	0.72	0.00	0.35

Overall, snow and cold emerge as the most significant climate hazards, followed by storm. In cases where more than 50% of the airport elements are exposed to a particular hazard, it becomes essential to understand the overall susceptibility to impact. For instance, 72% of the airport elements at Norwich (value of 0.72) are potentially exposed to snow. Analysing the susceptibility of these elements will support the identification of gaps in the current level of resilience.

4.2.6 Hazard – exposure analysis

Following the analysis of climate hazards and trends (Section 4.1) and the exposed elements in this section, it is essential to explore the relationship between these two sub-indices and climate risk determinants (hazard and exposure).

The exposure levels in the tool reflect the present-day scenario and the airport elements that can be potentially affected due to their presence in areas subject to these hazards (for instance, critical infrastructure located within a floodplain). The above implies that, without any protection measures, elements that are currently exposed will also likely remain exposed in the future. Where climate projections indicate that the climate hazard level will be intensified (for example, more extreme precipitation potentially leading to an increase in flood events), the level of exposure will likely increase over time.

To investigate these dynamics, hazard-exposure mapping is conducted per hazard type, with a focus on the climate hazard trends (illustrated with the use of light blue arrows in Figure 4-4, Figure 4-5 and Figure 4-6). It is noted that the input for the mapping is strictly based on the tool's output (scores for indicators and sub-indices).

Flood hazard and exposure levels (Figure 4-4) are currently moderate⁴ at Belfast International with an exposure value of 0.50, suggesting that around 50% of airport elements may become exposed to flood. Given that climate projections indicate a likely intensification in the hazard level (moving to 0.75), additional elements could become exposed in the future. In contrast, Norwich exhibits lower exposure, with around 25% of the airport elements likely to become exposed, and a declining trend in the hazard level. Bournemouth and Exeter show no projected change in the hazard level; however, both locations currently present high hazard values (value of 0.75). The exposure levels for both airports are low, 0.13 and 0.22, respectively.

Notably, Exeter completed the questionnaire in August 2023. One month later (17 September 2023), a heavy rainfall event led to the terminal's flooding, causing the airport's closure. This incident raises questions regarding potentially under-identified elements exposed to flood or whether the intensity of the hazard led to the exposure of elements that were not previously recognised as such.

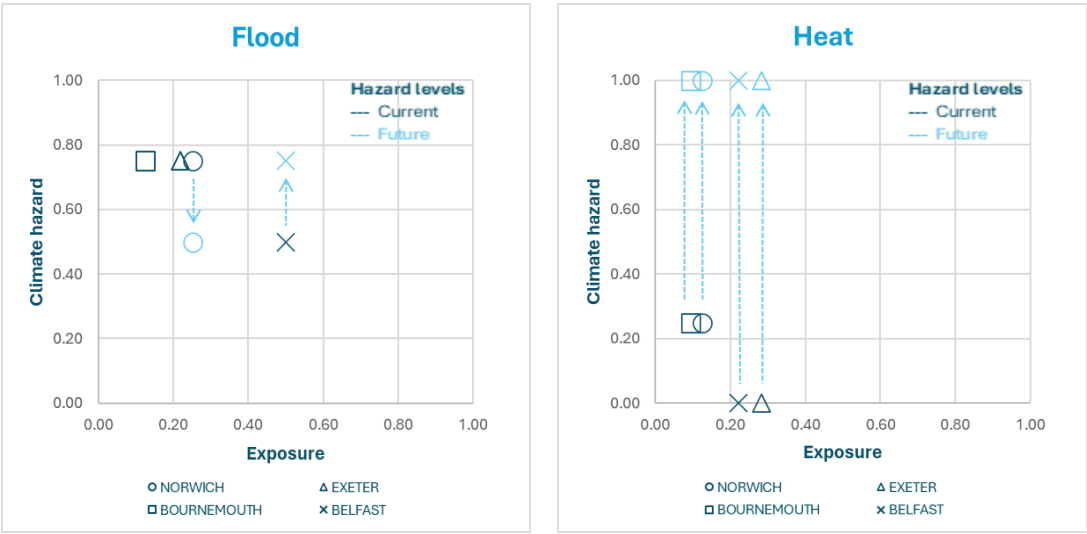


Figure 4-4 Flood (left) and heat (right) hazard trends and exposure mapping (The dark blue colour depicts the current, and the light blue colour represents the future climate hazard levels. The arrows show the identified climate hazard trends; where no arrow is shown, there is no observed change in the current and future climate hazard levels, considering the climate metrics included in the tool)

⁴ As mentioned in Table 4-2 and Table 4-8, the levels have been defined as follows: Very low (0.00), Low (0.01-0.25), Moderate (0.26-0.50), High (0.51-0.75), Very high (0.76-1.00)

The heat-exposure mapping (Figure 4-4) highlights notable trends in the hazard level. Currently, Belfast International and Exeter demonstrate a very low hazard level (value of 0.00), which is projected to increase significantly (value of 1.00). In the present-day, around 22% and 28% of airport elements at these airports are likely to be exposed to heat; considering the intensification of the hazard, more elements can become exposed to heat in the future. Bournemouth and Norwich show lower exposure levels, yet their geographic location suggests that extreme heat conditions are already observed. Considering the trends (hazard value moving from 0.25 to 1.00), extreme heat conditions may expose more elements in the future.

The cold-exposure mapping (Figure 4-5) illustrates that Bournemouth presents high exposure to cold, with around 94% of elements likely affected. Although the current hazard level is high, climate projections indicate a warming trend, suggesting a future decrease in cold conditions and hazard levels (from 0.75 to 0.50). Belfast International and Norwich demonstrate moderate exposure (value of 0.53 and 0.57, respectively) and a declining hazard trend. No observed trends in terms of hazard are noted for Exeter; yet, the currently observed hazard level is moderate (value of 0.50).

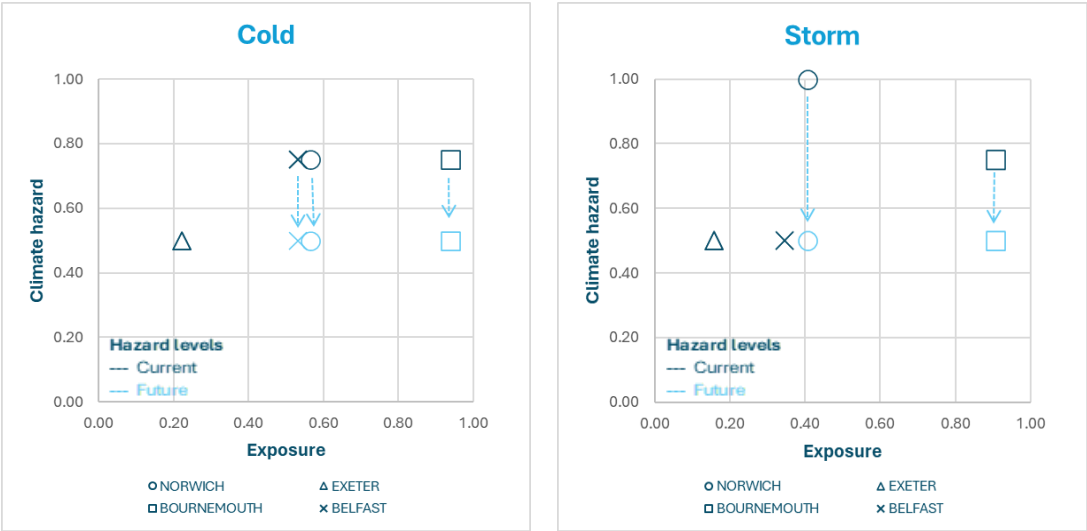


Figure 4-5 Cold (left) and storm (right) hazard trends and exposure mapping (The dark blue colour depicts the current, and the light blue colour represents the future climate hazard levels. The arrows show the identified climate hazard trends; where no arrow is shown, there is no observed change in the current and future climate hazard levels, considering the climate metrics included in the tool)

Storm (Figure 4-5) is noted as a concern for Bournemouth, with over 90% of airport elements likely to become exposed (value of 0.91) to a high hazard level (0.75) in the present

day. Norwich shows lower levels of exposure (value of 0.41), but its location implies a very high hazard level in the present day (value of 1.00). Although climate projections indicate a decline in the hazard level for both locations, there is an uncertainty in the confidence level, suggesting that existing exposure should be further investigated. No significant trends are observed for Exeter and Belfast International; nevertheless, the model's output shows that both locations are characterised by a moderate hazard level (value of 0.50).

The hazard-exposure mapping for snow (Figure 4-6) indicates low hazard levels for Norwich and Belfast International in the present day (value of 0.25), with a projected declining trend. However, a substantial proportion of airport elements, approximately 72% at Norwich and 50% at Belfast International, are likely to become exposed. Bournemouth and Exeter locations present a very low hazard level; nevertheless, 94% and 69% of the airport elements, respectively, could potentially become exposed in the event of a snowstorm.

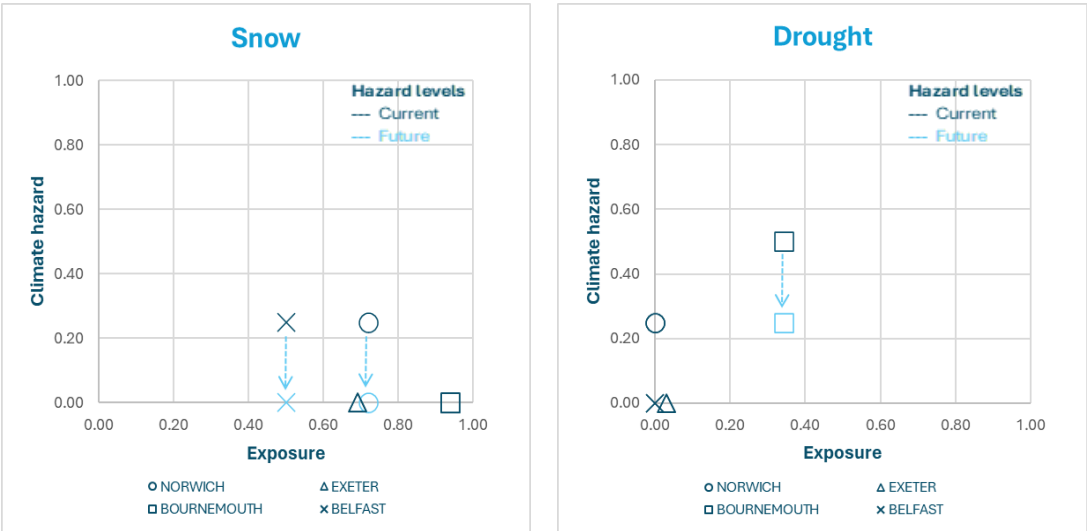


Figure 4-6 Snow (left) and drought (right) hazard trends and exposure mapping (The dark blue colour depicts the current, and the light blue colour represents the future climate hazard levels. The arrows show the identified climate hazard trends; where no arrow is shown, there is no observed change in the current and future climate hazard levels, considering the climate metrics included in the tool)

Drought (Figure 4-6) does not present a notable concern in terms of hazard and exposure levels for most airports. However, in the case of Bournemouth, approximately 44% of the airport elements could become exposed if drought conditions occur in the airport region.

4.2.7 Climate hazard focus in terms of exposure

In conclusion, short-term planning efforts to reduce the exposure of assets, operations, people, and interdependencies should focus on snow, cold, storm and flood. For medium-term planning, it is essential to consider both existing exposure levels and projected hazard trends. Therefore, planning should also address the growing implications of heat alongside storm, cold and flood hazards (Figure 4-7).

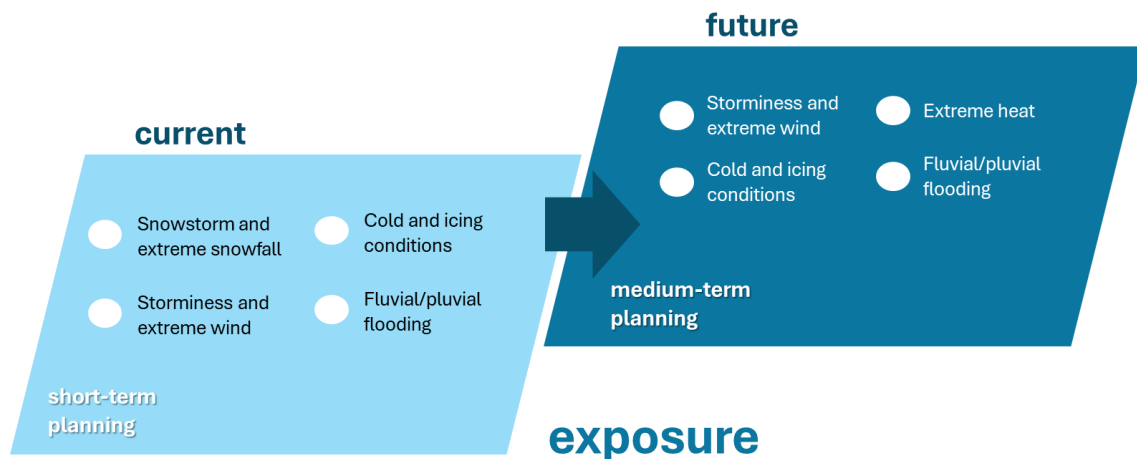


Figure 4-7 Focus of action to reduce exposure to climate hazards for the studied airports

It is underlined that the fact that airport elements present high levels of exposure does not necessarily mean they are also vulnerable to a specific hazard. The following sections (4.3 and 4.4) will provide more insights into existing vulnerabilities and risk mitigation practices; Section 4.3 will present an analysis of the levels of vulnerability, while Section 4.4 will focus on adaptability.

4.3 Vulnerability aspects

The vulnerability analysis looks at the airport elements that exhibit susceptibility to impact in the case of a climate hazard occurrence. The measurement of vulnerability in the ACRI tool considers a set of variables and indicators; detailed information on the variables used for establishing the sub-index is included in Section 3.4.3 and Appendix B Table 3.

The vulnerability analysis looks at the airport elements that are susceptible to impact due to a climate hazard occurrence, either due to their sensitivity as demonstrated by past events or their predisposition. The results are summarised in tabular format. It is noted that

the term ‘vulnerability level’ is used here to define the tool's output, considering the airport responses in the vulnerability variables. As explained in the Methodology chapter, vulnerability levels are defined as the average value of the variables, using a 5-point scale, moving from no vulnerability (value of 0.00) to very high vulnerability (value of 1.00) (Table 4-14).

Table 4-14 Rating scale used for vulnerability elements

Vulnerability levels	Value in ACRI
Very high vulnerability	0.76 – 1.00
High vulnerability	0.51 – 0.75
Moderate vulnerability	0.26 – 0.50
Low vulnerability	0.01 – 0.25
No vulnerability	0.00

An example is provided below to assist in understanding the tool’s output.

The sensitivity level of critical assets to heat for Belfast International (Figure 4-8, Figure 4-9, Appendix B Table 3) is the average value of the following variables in the tool:

- The *frequency of critical infrastructure/asset damage* due to extreme heat in the past 10 years; details on the variable and its measurement are provided in Section 3.4.3 and Appendix B Table 3. Based on the ACRI input/output, extreme heat events affecting critical infrastructure occur more than once every year; this frequency corresponds to a value of 5 in the defined 5-point scale of measurement and a score of 1.00 in the tool, suggesting a 'Very high' level of sensitivity.
- The *frequency of critical equipment damage* due to extreme heat in the past 10 years; similarly, details on the variable and its measurement are provided in Section 3.4.3 and Appendix B Table 3. Based on the ACRI input/output, extreme heat events affecting critical equipment, such as Navigational Aids, IT, comms, etc., occur once every 10 years; this frequency corresponds to a value of 2 and a score of 0.25 in the tool, suggesting a 'Low' level of sensitivity.

4.3.1 Sensitivity

Examining the sensitivity of airport elements to climate hazards offers insights into the ones most sensitive to a climate hazard occurrence, based on recent past events. The sensitivity

indicator incorporates elements relevant to critical assets, operations, people, interdependencies, safety, and environmental considerations. Table 4-15 presents the overall sensitivity of the airport sample.

Overall, the airport sample exhibits higher sensitivity to cold and storm, followed by snow. On the other hand, drought is the hazard with the lowest level of sensitivity.

Table 4-15 Sensitivity levels to the applicable climate hazards

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.32	0.27	0.61	0.50	0.25	0.00	0.33
Bournemouth	0.16	0.02	0.34	0.16	0.34	0.14	0.19
Exeter	0.32	0.09	0.27	0.39	0.30	0.00	0.23
Norwich	0.23	0.18	0.27	0.34	0.32	0.00	0.22

Belfast International presents the highest overall sensitivity among the airports, with an average score of 0.33. This represents a moderate sensitivity level, suggesting that, on average, the airport experiences damage or disruption once every 5 years. Sensitivity to cold is higher, with incidents occurring at least once a year.

Conversely, Bournemouth shows the lowest sensitivity (score of 0.19), with disruptive incidents occurring once every 10 years. Cold and snow are the primary hazards causing disruption. Exeter also shows a low average sensitivity score (score of 0.23), implying disruptions once every 10 years. In this airport example, storm, flood, and snow are the hazards that result in the most disruption. Similarly, Norwich exhibits a low overall sensitivity with an average score of 0.22, with storm and snow being the most frequent causes of disruption.

Across all airports, the most sensitive elements are operations, people, safety and assets (Figure 4-8). Interdependencies and environmental aspects exhibit lower sensitivity, falling below the overall average across all airports. At Belfast International and Bournemouth, assets show the highest sensitivity, whereas Exeter presents the lowest sensitivity (assets) among the airport elements. At Exeter, operations, safety and people demonstrate the highest sensitivity levels. In the case of Norwich, the sensitivity levels are relatively even across most elements, except for interdependencies and the environment; notably, safety emerges as the most sensitive element in this regional airport.

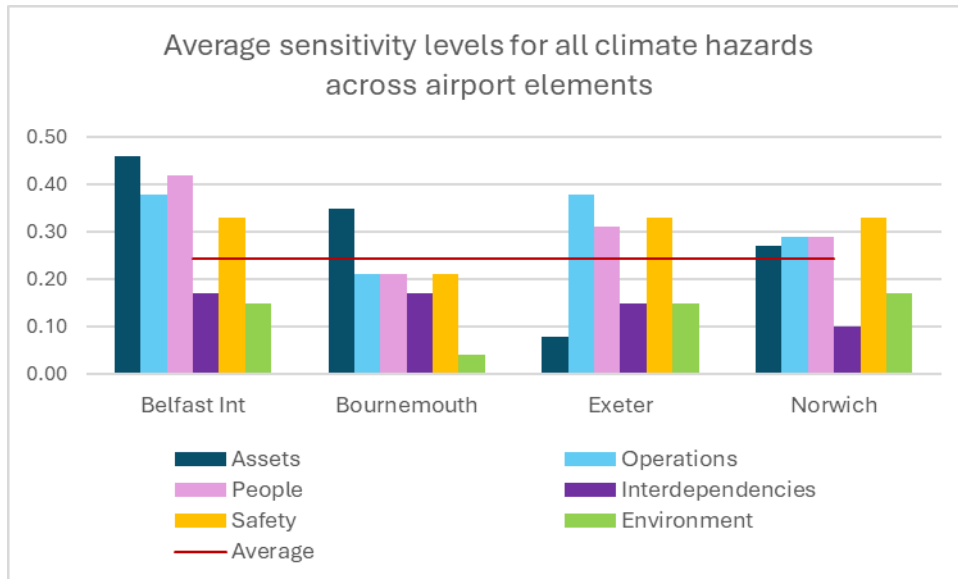


Figure 4-8 Average sensitivity levels for all climate hazards across airport elements

Appendix B Table 5 includes the output of the tool for the indicator of sensitivity, presenting information on the main elements for each case example airport. Figure 4-9 illustrates the average sensitivity levels of different airport elements to the climate hazards.

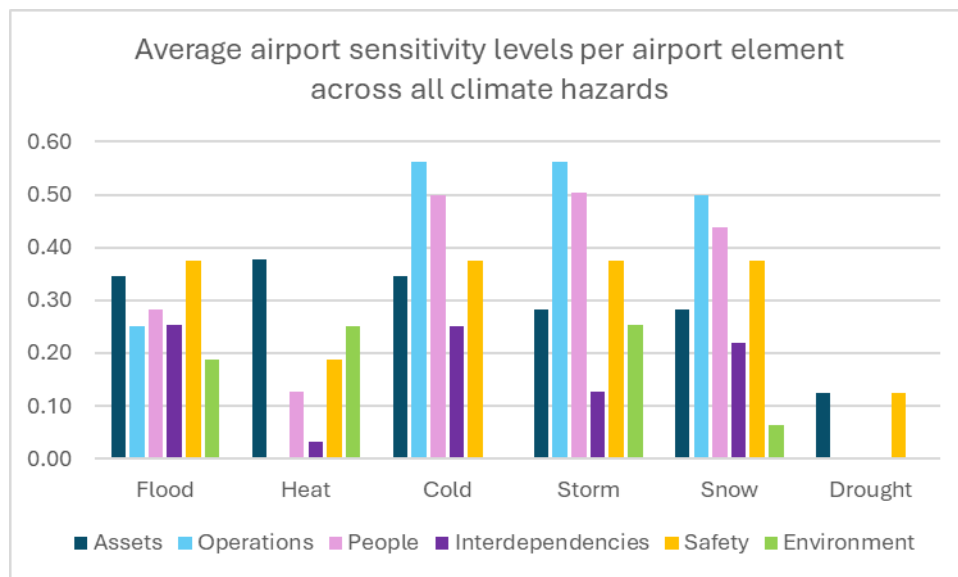


Figure 4-9 Average airport sensitivity levels per airport element across all climate hazards

Overall, as previously identified, operations and people emerge as the most sensitive elements, particularly in relation to cold, storm, and snow. Critical assets demonstrate a moderate sensitivity level to almost all hazards (except drought), with flood, heat and cold showing the highest scores. This suggests that climate hazards may lead to damage or

disruption approximately once every 5 years. More detailed information on critical assets is provided in Section 4.3.2.

Air and ground operations across all airports are more sensitive to cold, storm and snow. Belfast International and Exeter show the highest levels of the airport sample, with storms and cold being the main disruptive hazards. In terms of airport staff and passengers, moderate sensitivity levels are observed for most hazards, with cold, storm and snow being the key concerns. Belfast International shows the highest sensitivity levels in this regard. Interdependencies, such as surface access and utilities, generally exhibit low sensitivity across all hazards, though they show slightly higher values in the case of flood, cold and snow. Among the airports, Norwich demonstrates the lowest sensitivity across these areas.

Bournemouth shows the lowest average sensitivity levels for safety across all climate hazards. The climate hazards of concern for the case example airports include flood, cold, storm and snow. Further insights into safety aspects are included in Section 4.3.4.

The sensitivity of the environmental factors addressed in the tool is consistent across all hazards, with storm, heat and flood the main climate hazards for consideration. Norwich presents the highest sensitivity among the airports, followed by Exeter and Belfast International. Based on the tool's output, the local environment at these airports is affected once every 10 years on average due to a hazard occurrence. Additional information on the environment is included in Section 4.3.5.

4.3.2 Insights on critical assets

As mentioned previously, critical assets broadly show higher sensitivity to extreme temperatures (heat and cold) and flood (Appendix B Table 5, Figure 4-8). At Belfast International, assets demonstrate very high sensitivity to cold (score of 0.88), suggesting disruptions occur more than once a year and high sensitivity to heat (score of 0.63), with damaging events occurring at least annually. Norwich also experiences heat-related incidents, with critical assets being affected every 5 years. Flood is a concern for critical assets at Norwich and Belfast International (score of 0.50), with incidents occurring at least once every 5 years. Critical assets at Bournemouth show moderate sensitivity (score of 0.50) to cold, snow and drought, while Exeter exhibits the lowest sensitivity levels among the airports in the sample.

To better understand the sensitivity of critical assets, it is essential to understand the existing levels of predisposition to experience impact. This includes factors such as their geographic location and asset characteristics, such as the number, length or orientation of the runways, and technical specifications and standards. The variables that contribute to predisposition are included in Section 3.4.3 and Appendix B Table 3. Critical assets generally show at least moderate predisposition to multiple climate hazards (e.g., flood, heat, storm), suggesting that their location, characteristics, or design standards increase their sensitivity. For instance, Belfast International’s location within the 100-year flood zone and proximity to inland water bodies heighten its predisposition to flooding during extreme precipitation events, assuming no mitigation measures are in place.

Overall (Table 4-16), critical assets at Belfast International exhibit higher average predisposition levels, with a very high level for flood (score of 0.86), and cold (score of 1.00) and a high level for snow (score of 0.67). Bournemouth shows a very high predisposition to snow (score of 0.83). Exeter demonstrates a moderate predisposition to most hazards, with cold being the highest (score of 0.50). At Norwich, critical assets are highly predisposed to storm (score of 0.83).

Table 4-16 Predisposition of critical assets to experience impact

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.86	0.35	1.00	0.50	0.67	0.17	0.59
Bournemouth	0.39	0.35	0.50	0.42	0.83	0.67	0.53
Exeter	0.32	0.35	0.50	0.33	0.17	0.33	0.33
Norwich	0.54	0.45	0.17	0.83	0.50	0.00	0.41

Combining the tool’s output on sensitivity and predisposition offers insights into critical asset-related issues that can be further investigated and effectively addressed in the risk management strategies.

Flood (Figure 4-10) emerges as a major concern for Belfast International, with critical assets showing high predisposition and moderate sensitivity. This indicates that most critical assets present a tendency to experience impact once every 5 years, based on the past decade. Given that 25–50% of assets are already exposed and with climate projections indicating an increase in flood intensity, these assets may become more susceptible in the future, leading to more frequent damage. A similar pattern is observed at Norwich, although the level of predisposition is relatively lower. Exeter and Bournemouth exhibit moderate

levels of predisposition, and the past incidents suggest that exposed critical assets have experienced damage around once every 10 years.

The heat mapping (Figure 4-10) indicates that Norwich and Belfast International present moderate levels of both predisposition and sensitivity. Conversely, Exeter and Bournemouth, despite moderate predisposition, exhibit low sensitivity, implying that existing mitigation measures are effective under present-day conditions. At Belfast International, around 22% of critical assets are exposed to heat. These assets may become more susceptible given the projected intensification of extreme heat events. Currently, heat-related impacts on critical assets occur more than once a year, suggesting a potentially insufficient level of mitigation. Norwich demonstrates moderate levels of predisposition and sensitivity, with impacts occurring once every 5 years. Nonetheless, considering the climate hazard trends, this may increase in the future.

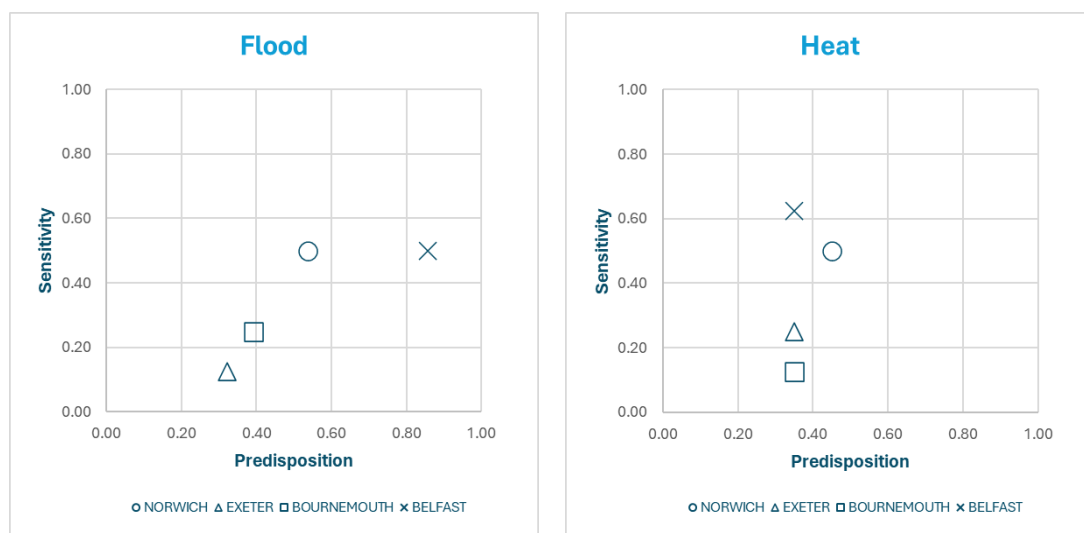


Figure 4-10 Mapping the relationships between predisposition and sensitivity of critical assets for flood (left) and heat (right)

Very high predisposition and sensitivity, as in the case of Belfast International in relation to cold (Figure 4-11), indicates high vulnerability of critical assets and, subsequently, suggests that existing measures do not address the hazard effectively. Bournemouth shows moderate sensitivity to cold, with cold and icing conditions affecting critical assets once every 5 years. Exeter, despite showing moderate levels of predisposition to cold, reports no sensitivity, indicating that current mitigation is adequate for the present-day conditions.

Regarding storm (Figure 4-11), critical assets at Norwich demonstrate a high predisposition and are affected at least once every 5 years. At Belfast International, both predisposition and sensitivity levels are moderate, highlighting the need for enhanced adaptation measures to address trends and uncertainty in the future.

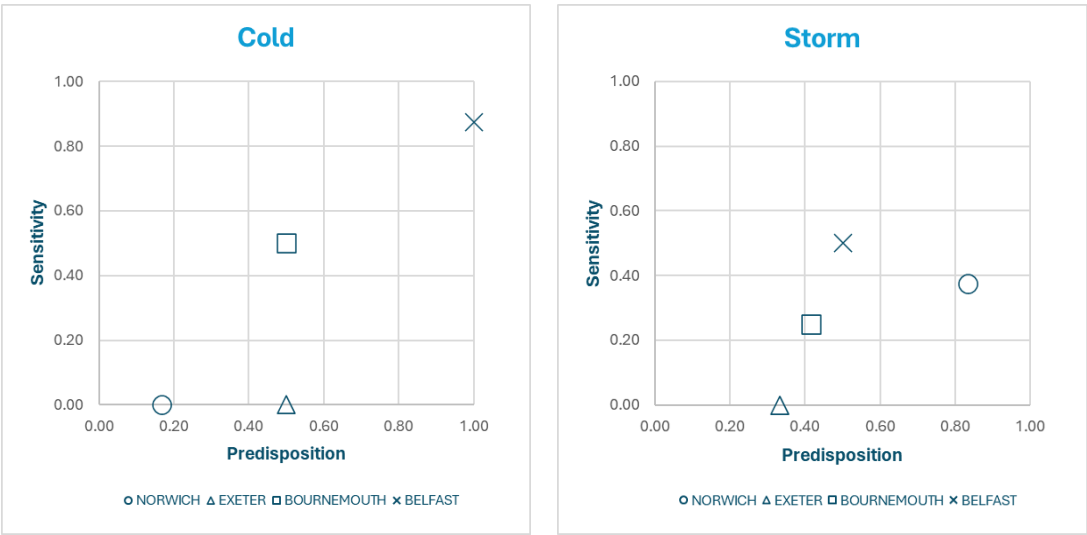


Figure 4-11 Mapping the relationships between predisposition and sensitivity of critical assets for cold (left) and storm (right)

At Bournemouth, critical assets demonstrate very high predisposition and moderate sensitivity to snow (Figure 4-12), indicating a notable vulnerability. In the case of Belfast International, while predisposition to snow is high, sensitivity levels remain low, with critical assets being affected once every 10 years. Norwich presents a similar pattern, although the level of predisposition is moderate.

Drought (Figure 4-12) appears to be a concern only for critical assets at Bournemouth; they exhibit high levels of predisposition and marginally moderate sensitivity levels.

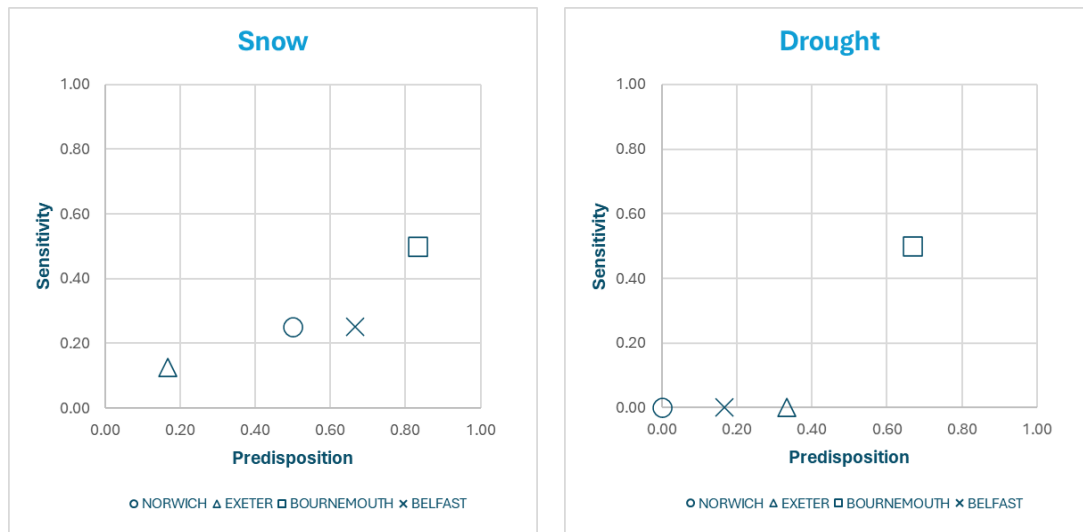


Figure 4-12 Mapping the relationships between predisposition and sensitivity of critical assets for snow (left) and drought (right)

4.3.3 Insights on surface access

Besides critical assets, surface access emerges as an airport element demonstrating sensitivity to flood, cold, snow and storm. Across the case example airports, surface access modes show a tendency to experience disruption due to snow and cold (Figure 4-13). In addition, flood and storm are also identified as hazards for consideration.

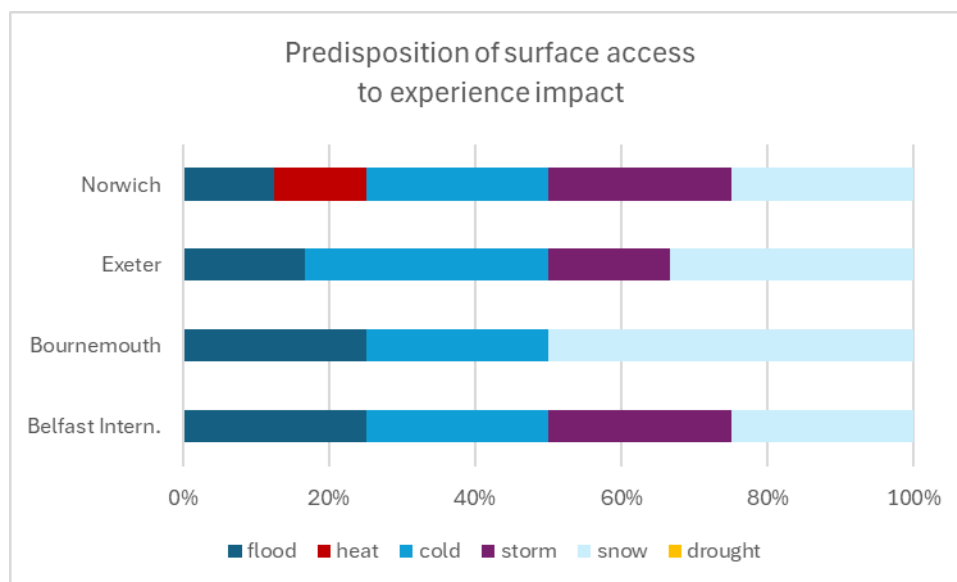


Figure 4-13 Predisposition of surface access

Based on the ACRI output (Appendix B Table 6) Belfast International, Bournemouth and Exeter demonstrate a very high predisposition to snow (value of 1.00), suggesting that

surface access may be significantly disrupted during a snowstorm. In Bournemouth and Exeter, disruption has historically occurred approximately once every 5 years, considering past events. The frequency of disruption in the case of Belfast International is lower (once every 10 years). Similarly, cold can become a concern for Belfast International and Bournemouth (value of 1.00); disruptive incidents in these airports have occurred once every 5 years.

Surface access modes demonstrate a moderate predisposition to flood across all airports (value of 0.50). Despite the moderate level, disruption has historically occurred at least once yearly in Bournemouth and Exeter over the past decade. The above observations highlight that even though airports can maintain their functions during an extreme flood event, the lack of reliable access links may result in, amongst others, operational challenges and passenger inconvenience.

4.3.4 Insights on safety

Exploring the variables that influence the likely effect on safety reveals the hazards most likely to reduce safety margins. Information on the variables considered for measuring the indicator of impact is provided in Section 3.4.3, and Appendix B Table 3.

The ACRI output (Table 4-17) shows that snow and, secondly, cold are the primary hazards affecting safety margins across airports. Storm and flood are also recognised as potential concerns; however, the level of likely effect is presented as lower.

Table 4-17 Likely effect of climate hazards on safety

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.25	0.25	0.38	0.25	0.38	0.00	0.25
Bournemouth	0.00	0.00	0.13	0.13	0.13	0.00	0.07
Exeter	0.13	0.00	0.25	0.25	0.38	0.00	0.17
Norwich	0.25	0.25	0.38	0.38	0.38	0.00	0.27

At Exeter, a combination of a high sensitivity level to flood (Appendix B Table 5) with a low likely effect (Table 4-17) suggests that, while a flood event may not significantly reduce safety margins, safety-related incidents occur at least once a year. At Belfast International, a moderate level of sensitivity to heat (Appendix B Table 5) is combined with a slight reduction in safety (Table 4-17). This indicates that heat-related safety challenges may arise once every 5 years under current climate conditions.

In the case of cold (Belfast International and Norwich) and storm (Norwich), moderate sensitivity levels (Appendix B Table 5) are combined with moderate effects on safety (Table 4-17). This implies that although cold can potentially reduce safety margins, this occurs around once every 5 years. The observed moderate impact levels suggest the existence of mitigating measures addressing the intensity of the climate hazard occurrence under the present-day scenario.

4.3.5 Insights on environmental issues

Based on the ACRI output, and specifically the frequency of events resulting in incidents of pollution in water bodies or increased noise complaints (Appendix B Table 5), along with the likely effect (Table 4-18), flood, cold and snow are identified as the climate hazards having an overall effect on the environment.

Table 4-18 Likely effect⁵ of climate hazards on the environment

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.63	0.00	1.00	0.19	1.00	0.00	0.47
Bournemouth	0.63	0.00	0.25	0.00	0.25	0.50	0.27
Exeter	0.38	0.38	0.75	0.19	0.00	0.00	0.28
Norwich	0.38	0.38	0.00	0.31	0.00	0.00	0.18

Flood is identified as the hazard with the most significant effect on water resources, especially at Belfast International and Bournemouth (Table 4-18); where incidents have approximately occurred once every 5 years (Appendix B Table 5). Heat is a hazard of concern for Norwich and Exeter, presenting moderate levels of sensitivity (Appendix B Table 5) and a moderate effect on noise complaints (Table 4-18). Although heat-related incidents have occurred once every 5 years in the past decade, the potential for environment-related impact is only considered substantial in Exeter and Norwich. A high effect on water resources is also noted for cold in the case of Exeter. At Belfast International, although cold is identified as a climate hazard with very high potential for water resources pollution (Table 4-18), no incident has been recorded in the past 10 years (Appendix B Table 5). A similar pattern is observed for snow; a very high potential for effect on water resources is noted in

⁵ Information on the variables considered for measuring the indicator of impact is provided in Section 3.4.3, and Appendix B Table 3.

the case of Belfast International (Table 4-18), but with a lower frequency of incidents, once every 10 years (Appendix B Table 5).

4.3.6 Impact

Examining the most impactful event of the past 20 years reveals key insights into the existing vulnerability of the airports. For example, in the case of Norwich, the most impactful snowfall was the occurrence of 2018 (the so-called the 'Beast from the East'). The significance of this event in terms of the level of impact is determined by considering the average value of the following variables in the tool. Section 3.4.3 and Appendix B Table 3 provides details on the indicator and its measurement.

- The *time the airport was out of service*. Based on ACRI input/output, the airport was out of service for the whole duration of the event and after the event. The measurement of the variable corresponds to a value of 5 and a score of 1.00 in the tool, suggesting a 'Very high' level of impact.
- The *number of ATMs disrupted*. More than 75% of the movements were cancelled due to this occurrence. Similarly, the measurement of the variable corresponds to a value of 5 and a score of 1.00 in the tool, suggesting a 'Very high' level of impact.
- The *financial impact/business loss*. Based on ACRI input/output, the business loss was high and considering the measurement of the variable, it corresponds to a value of 4 and a score of 0.75 in the tool, suggesting a 'High' level of impact.
- The *cost for restoration, repairs, or replacement*. Considering the ACRI input/output, the maintenance/repair cost was low. Based on the measurement of the variable, it corresponds to a value of 2 and a score of 0.25 in the tool, suggesting a 'Low' level of impact.

Looking at the recorded events in the ACRI (Table 4-19), cold and snow have caused the most significant disruptions in the past 20 years, especially at Norwich and Bournemouth. Both airports were severely impacted by the 'Beast from the East' in 2018; due to snow, both airports remained out of service for the whole event and after the event. Cold conditions also forced Norwich to remain closed for the whole duration of the event, while Bournemouth experienced more extended disruption. At Belfast International, the level of impact of cold, storm and snow has been moderate. Although the recorded events

occurred on a peak day, the airport remained out of service for a short period of time, with the disruption lasting less than 25% of the overall duration of the event.

Table 4-19 The most impactful event of the past 20 years in terms of the level of impact

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.25	0.22	0.38	0.35	0.38	0.00	0.26
Bournemouth	0.06	0.03	0.44	0.24	0.44	0.03	0.21
Exeter	0.13	0.00	0.25	0.20	0.31	0.00	0.15
Norwich	0.13	0.19	0.53	0.29	0.56	0.00	0.28

Flood incidents have generally caused low operational impact at Belfast, Bournemouth and Exeter; all airports maintained their functions during the recorded events. However, it is worth mentioning that Exeter airport completed the questionnaire in the summer of 2023, prior to the terminal flooding incident on the 17th of September 2023, which caused the airport's closure. Therefore, this event is not captured in the tool's output.

Where the events caused high disruption (for instance, cold and snow events) (Figure 4-14), financial impact and/or business loss are observed to be high. Norwich and Bournemouth experienced high business impact due to the disruption caused by the 'Beast from the East' in 2018. Focusing on snow, while Exeter and Belfast demonstrate low disruption in ATMs; the observed business impact is noted as moderate.

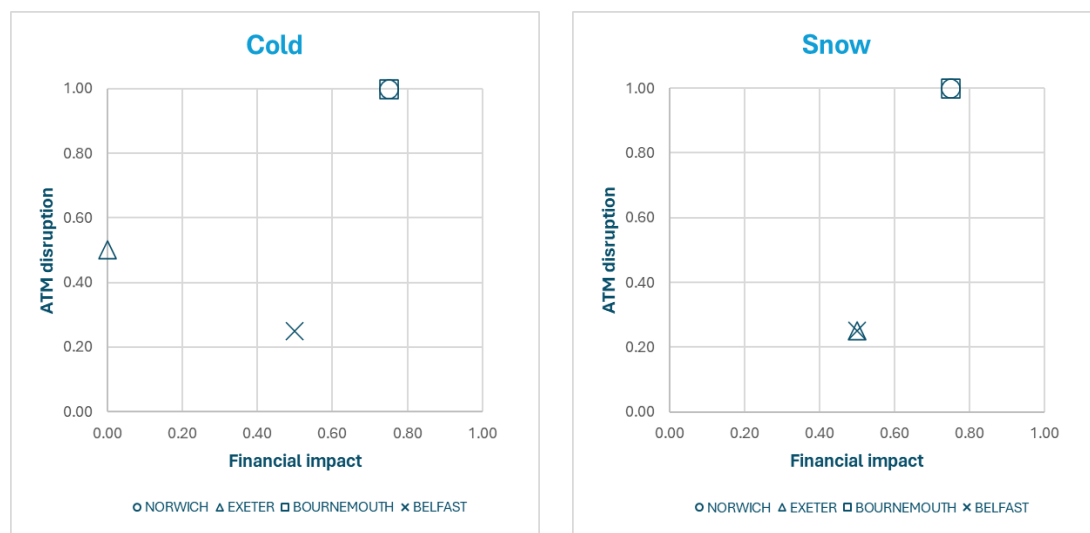


Figure 4-14 Mapping the most impactful cold (left) and snow (right) event of the past 20 years in terms of the level of ATM disruption and financial impact/business loss

4.3.7 Overall vulnerability

Looking at the overall vulnerability, the case study airports are more vulnerable to snow, cold, storm and flood (Table 4-20).

Table 4-20 Sub-index of vulnerability

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.46	0.26	0.59	0.48	0.45	0.02	0.30
Bournemouth	0.16	0.07	0.52	0.33	0.56	0.17	0.25
Exeter	0.27	0.16	0.34	0.31	0.39	0.04	0.30
Norwich	0.28	0.21	0.40	0.46	0.48	0.00	0.38

Cold emerges as the most significant concern for Belfast International, followed by storm; similar values are observed in the case of flood and snow. For Bournemouth, snow and cold are the primary hazards of concern, while in the case of Exeter, vulnerability is also higher to these hazards. Norwich shows higher vulnerability to snow, storm, and cold.

4.3.8 Exposure-vulnerability analysis

Exposure-vulnerability analysis reveals airport elements that are both exposed and vulnerable to a climate hazard.

Regarding flood (Figure 4-15) Belfast International demonstrates moderate levels of both exposure and vulnerability, while Norwich and Exeter present a similar picture, but at lower levels.

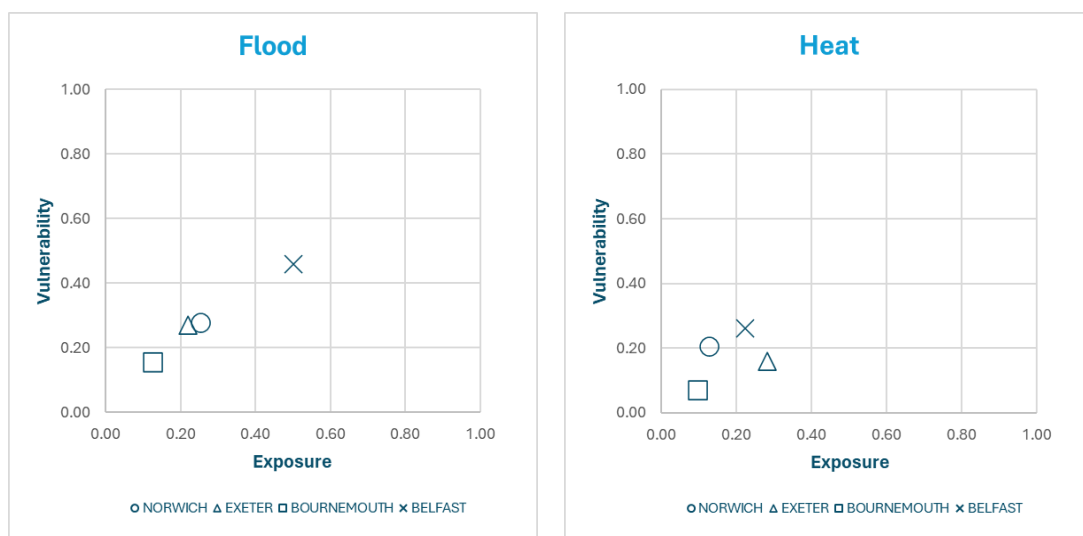


Figure 4-15 Mapping the average levels of exposure and vulnerability to flood (left) and heat (right)

When considering heat (Figure 4-15), both exposure and vulnerability remain low to moderate across all airports. However, considering climate change trends, an increase is likely in the future.

Cold (Figure 4-16) can have significant consequences for Bournemouth; the airport demonstrates very high exposure and high vulnerability, suggesting that exposed airport elements are also likely to be vulnerable and therefore susceptible to impact. Similarly, Belfast International shows high levels of vulnerability and exposure, indicating that a cold occurrence can have significant consequences without effective adaptation measures. Cold can also become a concern for Norwich, as high levels of exposure are combined with moderate levels of vulnerability.

As in cold, storm (Figure 4-16) is a hazard of interest for Bournemouth, presenting very high exposure and moderate vulnerability. Belfast International and Norwich demonstrate moderate levels of exposure and vulnerability, indicating a notable susceptibility to damage or disruption.

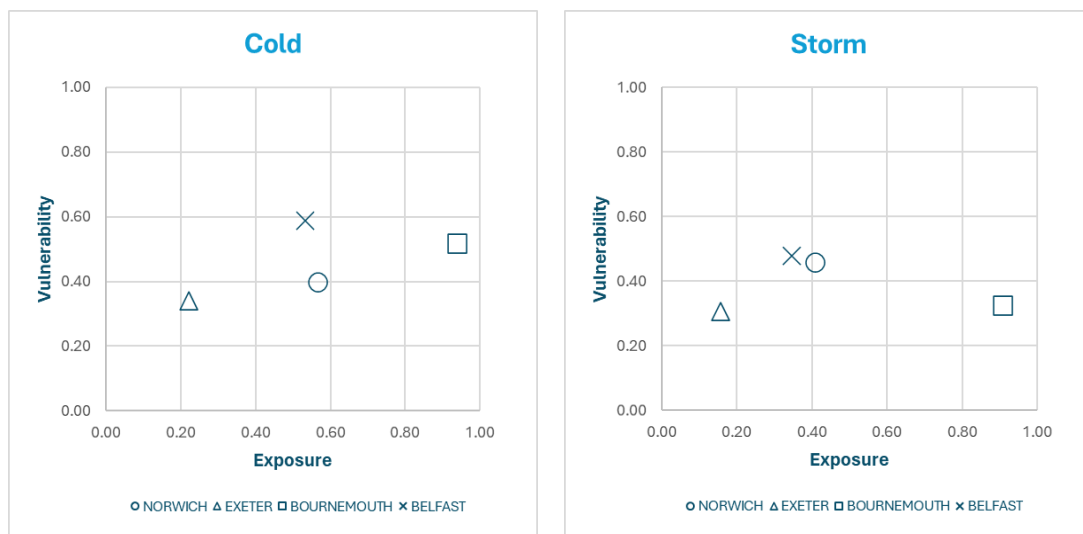


Figure 4-16 Mapping the average levels of exposure and vulnerability to cold (left) and storm (right)

Very high levels of exposure and vulnerability to snow (Figure 4-17), as in the case of Bournemouth, indicate that the airport may experience significant damage/disruption under current climate conditions. A similar pattern is observed in the case of Norwich and Exeter, although at slightly lower levels.

Drought does not appear to be a concern for the case study airports (Figure 4-17). Bournemouth is the only airport presenting a moderate level of exposure; however, the low

level of vulnerability suggests that it is unlikely to experience significant damage/disruption under the current climate conditions.

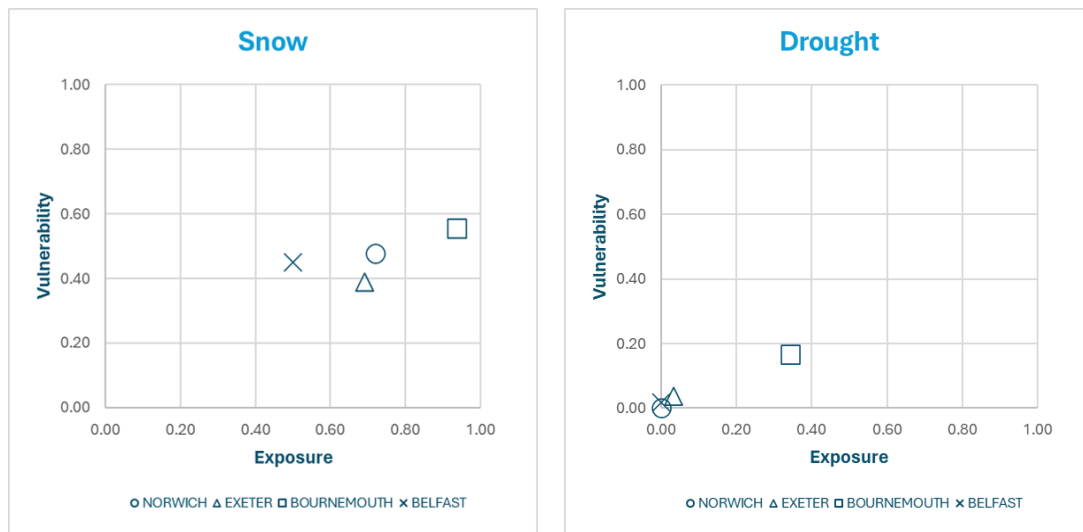


Figure 4-17 Mapping the average levels of exposure and vulnerability to snow (left) and drought (right)

It is noted that airport elements currently vulnerable are expected to continue being vulnerable if measures to reduce the vulnerability are not implemented. In some instances, vulnerability may even increase over time if, for example, there is no appropriate maintenance or if the technical specifications/design standards become inadequate to address climate hazard-related challenges.

4.3.9 Climate hazard focus in terms of vulnerability

Concluding the vulnerability analysis, short-term planning should prioritise action to address reducing predisposition, sensitivity and the potential for impact of climate hazards such as cold, storm, flood and snow.

Medium-term planning must also consider climate hazard trends, and therefore, planning should also focus on heat (Figure 4-18).

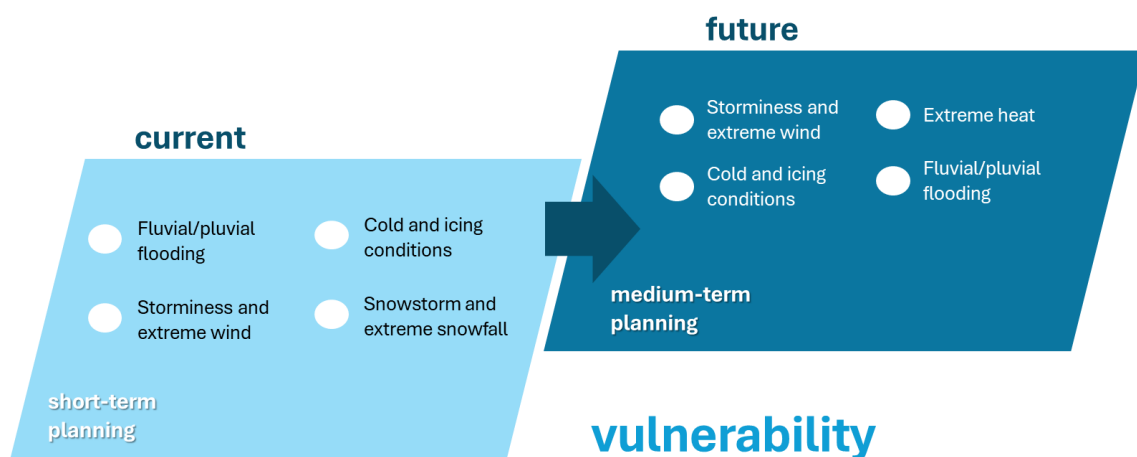


Figure 4-18 Focus of action to reduce vulnerability to climate hazards for the studied airports

Considering the climate hazards of concern (Section 4.1), the exposed (Section 4.2) and the vulnerable elements of the airport system (Section 4.2), the following section (4.4) will analyse the airports' adaptability.

4.4 The road to adaptation

The analysis of adaptability looks at the measures in place aiming to reduce exposure and/or vulnerability to climate hazards and build more adaptive capacity to the system. The measurement of adaptability in the ACRI tool considers a set of variables and indicators; detailed information on the variables used for establishing the sub-index is included in Section 3.4.4 and Appendix B Table 4.

The analysis looks at measures to protect critical assets and other airport elements, enhance the preparedness mechanisms and build more institutional capacity. The results are mainly summarised in tabular format. It is noted that the term 'adaptability level' is used here to define the output of the ACRI tool, considering the airport responses in the adaptability variables. As analysed in the Methodology chapter, adaptability levels are defined as the average value of the variables, using a 5-point scale, moving from no adaptability (value of 0.00) to very high adaptability (value of 1.00) (Table 4-21).

Table 4-21 Rating scale used for adaptability elements

Adaptability levels	Value in ACRI
Very high adaptability	0.76 – 1.00
High adaptability	0.51 – 0.75
Moderate adaptability	0.26 – 0.50
Low adaptability	0.01 – 0.25
No adaptability	0.00

To support the interpretation of the tool's output, an example is provided below.

The flood protection for Bournemouth (Table 4-22) is the average value of the following variables in the tool:

- The existence of flood defences is reported as in progress (not fully integrated), corresponding to a value of 4 in the defined 5-point scale of measurement and a score of 0.75 in the tool, indicating a 'High' level of protection.
- Whether critical infrastructure/buildings in low-lying areas are elevated to address inundation risk. This measure is not in place and hasn't been considered, and therefore, indicates a value of 1 and a score of 0.00 in the tool, suggesting a 'Very low' level of protection.
- Whether critical equipment at risk is relocated to address inundation risk. Similarly, this measure is not in place and hasn't been considered, suggesting a 'Very low' level of protection.
- Whether drainage systems are upgraded to handle greater peak flows. This measure is in progress (not fully integrated), corresponding to a value of 4 and a score of 0.75 in the tool, suggesting a 'High' level of protection.
- The existence of backup power sources. This measure is in place (fully integrated) and therefore corresponds to a value of 5 and a score of 1.00 in the tool, suggesting a 'Very high' level of protection.
- Relocation of critical equipment. This measure is not in place and hasn't been considered, suggesting a 'Very low' level of protection.

The following paragraphs will analyse protection, preparedness and institutional capacity.

4.4.1 Protection

The level of protection reflects the efforts undertaken to reduce the exposure of the airport elements to the different hazards, building its ability to resist. Overall, among the studied airports (Table 4-22) Norwich, Bournemouth, and Belfast International present higher levels of protection. Airports appear to primarily address hazards such as storm and snow, followed by extreme temperatures (heat and cold).

Table 4-22 Protection levels for the applicable climate hazards

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.50	0.61	0.64	0.57	0.71	0.60	0.61
Bournemouth	0.50	0.75	0.64	0.79	0.57	0.40	0.61
Exeter	0.65	0.46	0.36	0.96	0.54	0.30	0.55
Norwich	0.75	0.71	0.67	0.75	0.64	0.15	0.61

Flood is a key hazard of concern for assets at Belfast International, given the moderate sensitivity and exposure levels analysed in Sections 4.2 and 4.3. This highlights the need to evaluate existing measures considering projected changes in climate. While Exeter shows low sensitivity (Appendix B Table 5) and high protection levels (Table 4-22), the September 2023 flood event (occurring after the engagement) raises questions about the effectiveness of existing measures. At the same time, it highlights the need to reassess them, considering future changes in hazard intensity and/or frequency.

Norwich presents high protection levels for heat (Table 4-22); while aspects like runway length, upgraded equipment, and backup power contribute to heat adaptability, the fact that critical infrastructure has been damaged at least once every five years indicates gaps in existing adaptation. Since climate projections suggest more frequent and severe heat events, further evaluation of existing measures is needed to address potential gaps in adaptation strategies. Although Belfast International shows a high level of protection against cold (Table 4-22), airport assets have experienced incidents more than once every year over the past decade (Appendix B Table 5). This indicates that current measures may not be sufficient for the current hazard intensity.

All regional airports show at least a moderate level of protection against storms (Table 4-22). In the case of Belfast International, the demonstrated sensitivity of critical assets (Appendix B Table 5) implies that existing protection measures (Table 4-22) should be further expanded. Similarly, although Bournemouth presents a high level of protection,

existing sensitivity levels (Appendix B Table 5) suggest a need to evaluate the effectiveness of existing mitigation. Protection measures for drought present the lowest levels among the hazards (Table 4-22); nevertheless, most of the case example airports demonstrate low levels of sensitivity (Appendix B Table 5).

It is important to note that the presence of more measures does not necessarily suggest that the airport is better protected against an event. Aspects such as the level of preparedness, whether measures address the specific vulnerabilities, and the intensity of the hazard occurrence influence the likely impact and the level of damage or disruption.

4.4.2 Preparedness

The level of preparedness reflects the ability of the airport to control potential loss or disruption and maintain its operational capabilities during extreme events. It presents the extent to which an airport has a response and preparedness mechanism to reduce business impacts due to an event. Details on the variables used to define preparedness and their measurement are provided in Section 3.4.4 and Appendix B Table 4.

Essentially, the case study airports exhibit very high levels of preparedness across most cases (Table 4-23); Belfast International presents the highest (score of 0.91) and Exeter the lowest level (score of 0.59). Existing preparedness mechanisms appear to primarily address cold and snow, followed by storm and flood. It is worth mentioning that all airports demonstrate a very high level of preparedness in the case of snow. Drought is the least addressed hazard, especially for Norwich and Exeter (scores of 0.00 and 0.08, respectively).

Table 4-23 Level of preparedness to the applicable climate hazards

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.91	0.91	0.91	0.92	0.91	0.90	0.91
Bournemouth	0.57	0.86	0.91	0.90	0.91	0.60	0.79
Exeter	0.80	0.43	0.79	0.65	0.79	0.08	0.59
Norwich	0.80	0.93	0.79	0.87	0.91	0.00	0.72

Some commonly implemented measures across all airports include an aviation meteorological forecasting mechanism and/or early warning systems. In addition, airports present emergency response plans; however, they are not fully implemented in all cases. Other adopted practices include established communication protocols with stakeholders,

plans for inspections and maintenance, and climate-hazard-specific health and safety procedures.

4.4.3 Institutional capacity

In terms of institutional capacity, and the extent to which airports have undertaken action to build awareness and proactively plan for the future, storm, cold and snow are the hazards primarily addressed (Table 4-24). Drought is the least addressed hazard, particularly in Norwich and Exeter.

Table 4-24 Level of institutional capacity to the applicable climate hazards

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Bournemouth	0.71	0.75	0.83	0.79	0.79	0.79	0.78
Exeter	0.54	0.33	0.33	0.46	0.50	0.00	0.36
Norwich	0.83	1.00	0.96	1.00	0.96	0.00	0.79

Norwich demonstrates the highest level of institutional capacity, while Exeter presents the lowest in the sample. Belfast International shows moderate and consistent scores across all hazards, indicating a uniform approach.

Common applied measures include insurance coverage, formal organisational structures, risk awareness efforts, and resource allocation. However, these measures are not fully implemented at all airports.

4.4.4 Overall adaptability

The overall level of the sub-index, as determined in the tool, is presented in Table 4-25.

Table 4-25 Sub-index of adaptability

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.62	0.66	0.67	0.65	0.69	0.65	0.66
Bournemouth	0.59	0.79	0.79	0.83	0.76	0.60	0.73
Exeter	0.67	0.41	0.49	0.69	0.61	0.13	0.50
Norwich	0.80	0.88	0.80	0.87	0.84	0.05	0.71

Overall, drought and flood exhibit the lowest adaptability levels across all case example airports. For instance, while Norwich airport demonstrates a very high level of adaptability to most climate hazards, no measures seem to be in place to address a potential drought

incident. On the contrary, storm and snow are associated with high and very high adaptability levels in all airports. Belfast International shows high adaptability across all hazards. Bournemouth demonstrates a very high level of adaptability to heat, cold, storm and snow and a high level of adaptability to flood and drought. Exeter focuses its efforts on flood, storm and snow, yet it only shows a moderate adaptability level to extreme temperatures.

4.4.5 Vulnerability-adaptability analysis

Considering the analysis of the risk determinants, building adaptability can address the likely consequences associated with exposure and/or vulnerability (Sections 4.2 and 4.3). Therefore, airports demonstrating high adaptive capacity will likely be in a better position to address climate hazard-related implications. Identifying gaps in the current adaptation strategies allows for a deeper understanding of the opportunities for improvement. By mapping the average levels of adaptability and vulnerability to relevant climate hazards, it becomes possible to highlight areas where adjustments are required.

The case study airports demonstrate low to moderate levels of vulnerability to flood, while adaptability is noted as high or very high in the case of Norwich (Figure 4-19). Belfast International presents the highest vulnerability among the airport sample. Although some preparedness measures are in place, the ACRI output indicates a lack of focus on protection and institutional capacity aspects. Despite the measures in place, the level of sensitivity is moderate, suggesting that current measures are insufficient to address the high predisposition of the airport and the typical observed intensity of the hazard. An increase in the intensity of extreme precipitation events is likely to exacerbate the existing vulnerability level, potentially leading to a more severe impact.

Norwich and Exeter both demonstrate moderate levels of vulnerability but also exhibit high levels of adaptability. While Norwich has not reported an incident in the past 10 years, Exeter experienced disruption due to the 2023 flood event, which led to the airport's closure. The above incident suggests that the applied measures do not effectively address the dimensions of hazard, exposure, and vulnerability. Therefore, they should be expanded further to build more flood resilience.

Regarding heat, all case example airports demonstrate low to levels of vulnerability under current climate, while adaptability levels in almost all airports appear to be high. Exeter is

the only airport presenting a moderate level; measures to build adaptive capacity focus primarily on protection and preparedness. Considering that the frequency and intensity of extreme heat events will likely increase, the airport should focus on taking advantage of opportunities to build more adaptability to address future challenges.

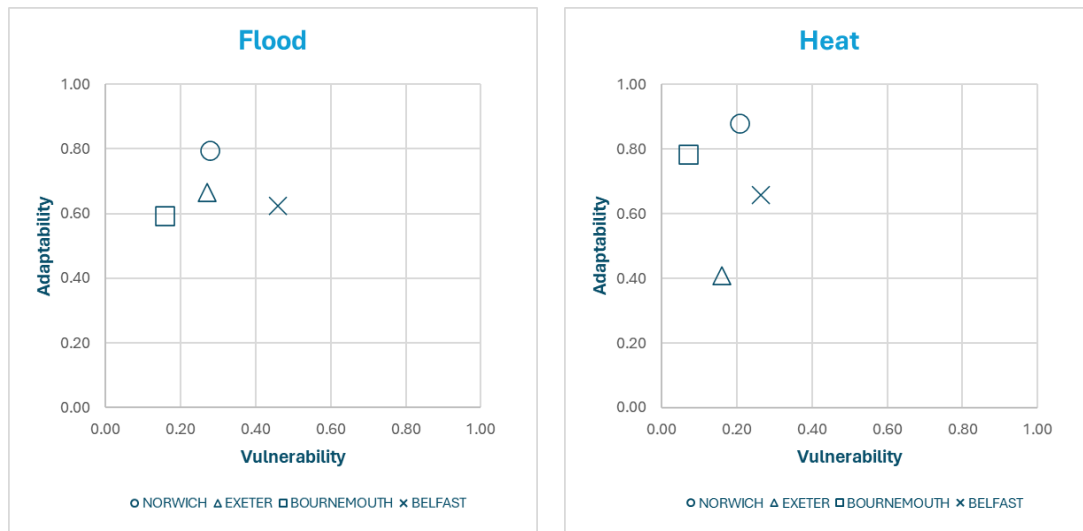


Figure 4-19 Mapping the relationships between adaptability and vulnerability for flood (left) and heat (right)

Cold emerges as a hazard of interest for most airports (Figure 4-20). Belfast International presents both high levels of vulnerability and adaptability, suggesting that although the airport is particularly susceptible to cold, it has implemented a range of measures addressing different issues. While mitigation actions primarily focus on enhancing the preparedness mechanism, measures such as de-icing operations, backup power systems, and the condition of pavements imply awareness of the existing vulnerabilities and the potential consequences of an extreme cold and icing event. Considering the frequency of disruptive events (at least once every year), further investigation of the existing adaptation measures is deemed necessary to determine the focus of action in the future.

Bournemouth demonstrates a high level of both vulnerability and adaptability to cold. Vulnerability is mainly driven by the airport's predisposition of the exposed critical assets, with impactful events occurring once every 5 years. Measures in place primarily focus on enhancing preparedness and building institutional capacity, while measures targeting protection refer to meeting de-icing requirements, energy efficiency and system resilience. Given the level of predisposition of assets, further analysis of adaptation options will determine the focus of action. A similar picture is depicted for Norwich; the main difference

lies in the airport’s focus on building institutional capacity. Exeter shows moderate levels of vulnerability and adaptability, suggesting that there are aspects that require further investigation to enable targeted improvements.

Regarding storm, the adaptability levels across all airports (Figure 4-20) are at least high, with Bournemouth and Norwich presenting very high levels. Belfast International and Norwich demonstrate the higher levels of vulnerability in the airport sample. While the existence of measures in both airports indicates awareness of the current vulnerability, the frequency of disruption, especially in the case of Belfast International, suggests that the applied measures may not be very effective, or their planning has not considered the intensity of the climate hazard occurrence. Looking at the applied measures, Belfast International mainly focuses on enhancing the preparedness mechanism, while Exeter focuses on building more protection. The approach of Norwich includes actions to strengthen preparedness and institutional capacity. Bournemouth presents a similar distribution of effort on all three adaptability aspects.

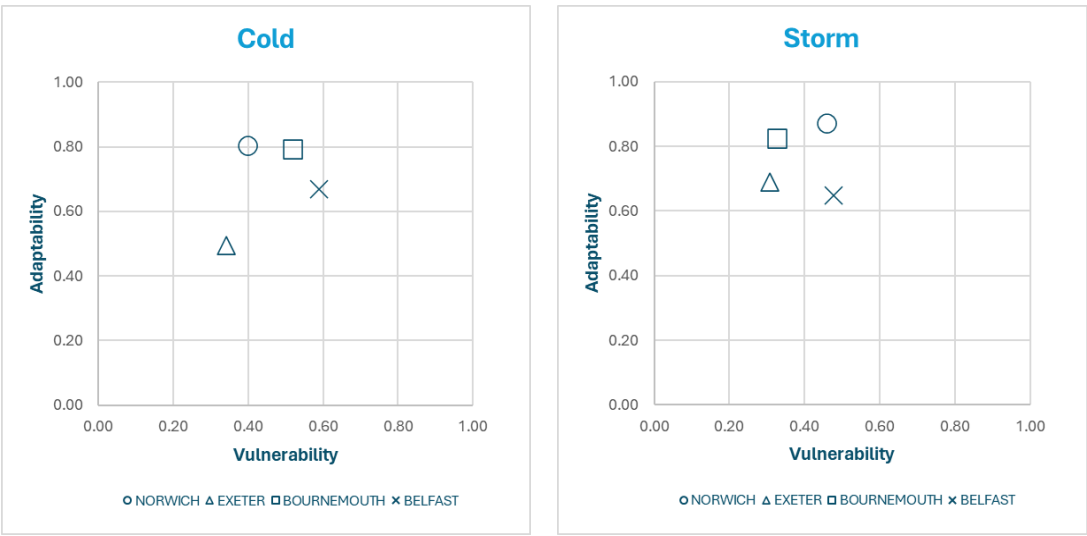


Figure 4-20 Mapping the relationships between adaptability and vulnerability for cold (left) and storm (right)

The adaptability level to snow (Figure 4-21) is at least high across all airports, with Bournemouth and Norwich presenting a very high level. From a vulnerability perspective, Bournemouth, Norwich, and Belfast International show comparatively higher levels. As in the case of cold, airports demonstrate susceptibility to snow conditions despite implemented measures, such as snow and ice removal equipment. The observed susceptibility suggests that existing measures may not adequately account for the intensity

of the hazard occurrence. Bournemouth and Norwich demonstrate high and moderate vulnerability to snow, respectively, mainly due to the airports' level of predisposition, with critical infrastructure experiencing damage once every 5 years on average.

Drought does not currently present a significant concern in terms of vulnerability for most airports (Figure 4-21). Despite the low vulnerability levels, high adaptability is observed in the case of Belfast International and Bournemouth. At Bournemouth, adaptation efforts focus on building institutional capacity, whereas at Belfast, International action is focused on enhancing the preparedness mechanism.

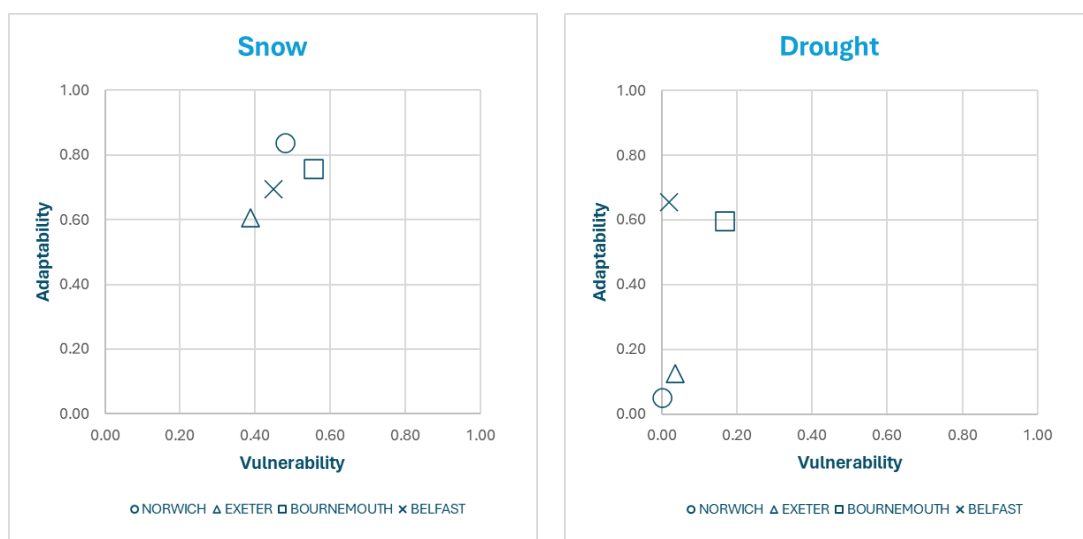


Figure 4-21 Mapping the relationships between adaptability and vulnerability for snow (left) and drought (right)

Largely, adaptability levels across the studied airports generally align with or exceed the corresponding vulnerability levels. While the existence of measures implies awareness of the existing vulnerabilities, the observed level of sensitivity of critical assets suggests that the applied measures may not be very effective, or their planning has not considered the climate hazard intensity. Where climate trends indicate that hazard occurrences may become more frequent and/or more severe, airport elements already demonstrating vulnerability will likely be affected to a greater extent without more robust adaptation measures.

For example, in the case of Bournemouth, snow has emerged as a hazard of interest in terms of exposure and vulnerability. The airport demonstrates a very high level of adaptability, particularly through preparedness. Fully implemented measures refer to

sufficient de-icer storage facilities, backup power sources, forecasting capabilities, an emergency response plan, the existence of decision-making mechanisms and communication protocols, health and safety procedures, regular inspections and maintenance checks, building capacity to respond, organisational structure and accountability, knowledge of the risk and insurance policy. Additional measures are in the planning or implementation process. Nevertheless, the question remains whether those measures sufficiently mitigate the existing vulnerabilities. Past occurrences indicate that around 75% of air and ground operations can be affected once every 5 years. Investigating the extent to which the applied measures effectively address the anticipated level of operational disruption will lead to specific recommendations to build more adaptive capacity.

Another example is Belfast International; the analysis identified flood as an issue of attention, mainly due to the observed vulnerability level. Therefore, risk mitigation efforts should focus on minimising the airport's susceptibility to experiencing impact and ensuring business continuity. The adaptability analysis revealed that the airport has implemented several measures addressing aspects of protection, preparedness, and institutional capacity. Fully implemented measures refer to flood defences, backup power systems, forecasting capability, emergency response planning and experience, the existence of decision-making and communication protocols, health and safety procedures, maintenance procedures, monitoring mechanisms for water pollutants and insurance policy. Furthermore, some additional measures are underway in the planning or implementation stage. While preparedness is addressed more efficiently, actions focused on strengthening protection and institutional capacity have not been implemented fully. For instance, while a flood can damage 25-50% of the critical equipment, relocating critical equipment at risk has not yet been considered an option. Similarly, even though the drainage systems are identified as vulnerable, they have yet to be upgraded to handle more significant peak flows, although the airport is actively pursuing improvements.

4.4.6 Climate hazard focus in terms of adaptability

In conclusion, short-term planning efforts to build adaptability should also consider the hazards currently associated with lower levels, like drought, flood, heat and cold. For medium-term planning, accounting for projected climate-related trends and uncertainties

is essential. Therefore, emphasis should also be placed on building more adaptability to hazards like storms (Figure 4-22).

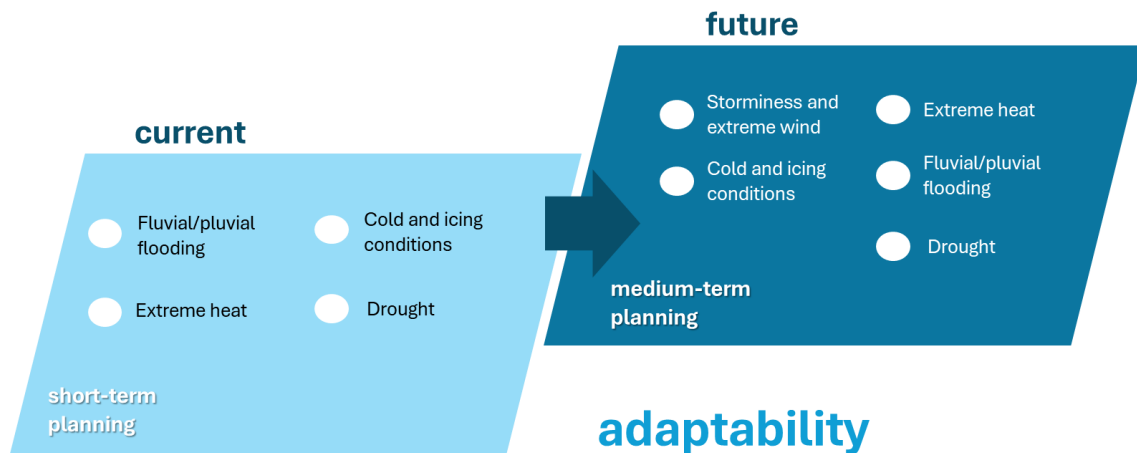


Figure 4-22 Focus of action to build adaptability to climate hazards for the studied airports

The next section of the chapter will summarise the conclusions of the analysis based on the output of the tool.

4.5 Conclusions

The analysis of the output of the ACRI tool provided insights on the levels of climate hazard, exposure, vulnerability and adaptability, pointing out areas for further consideration. While the output of the tool can be used in many ways, this analysis was specifically framed to establish a baseline by considering present-day conditions and recent past events and looking at risk identification and mitigation using a forward-looking perspective. The main reason for following this approach is to align with the concept used in the development of the index; using the present-day and the recent past to understand the opportunities for improvement, while at the same time account for evolving trends in the climate hazard occurrences.

Looking at the case example airports, there are similarities and differences, and despite the different geographic locations, there are common challenges. The airports present high levels of preparedness, primarily addressing cold and snow, followed by storm and flood. The extent of undertaken measures appears to be driven by the observed hazard intensity or the technical specifications of assets, which may often be based on outdated climate hazard characteristics. Therefore, existing risk mitigation planning primarily considers how

climate hazards have manifested recently. Based on the demonstrated levels of adaptability and future climate hazard trends, there are opportunities for improvement in all airports.

Flood is a consideration for all airports, and in the case of Belfast International, a climate hazard, pointing out the airport's predisposition and sensitivity. Heat is not currently a significant concern for most airports; however, in the case of Exeter, it is a hazard that indicates a marginally moderate level of exposure, suggesting a need for action. Cold is a concern across nearly all airports, although different levels of exposure and vulnerability are observed. Snow is a noteworthy hazard for all airports in the present day, with all airports experiencing disruptive events. In most cases, the extent of the applied measures aligns with the level of the hazard in the present day and the frequency of the disruptive occurrences. Storm can become a challenge for all regional airports. Although they present strong levels of preparedness, the inherent uncertainty as regards the intensity of future events suggests an evaluation of the effectiveness of existing risk mitigation measures. Finally, drought is currently the least concern; despite the lack of incidents of disruption/damage, airports present action (or are in the planning process) to build adaptability to water scarcity conditions.

The next chapter will discuss the main climate risk trends based on the output of the tool and the areas of focus in terms of climate hazards and airport elements. It will also show the identified gaps and provide specific recommendations on measures that would enable airports to build more adaptive capacity.

5 Climate risk trends and recommendations

This chapter discusses the main climate risk trends (Section 5.1) from analysing the tool output, as presented in Chapter 4 and the areas of focus in terms of climate hazards (Section 5.2). It also provides specific recommendations (Section 5.3), addressing RO4 – ‘*To recommend measures to increase airport climate resilience*’. The last section of the chapter (Section 5.4) offers conclusions on climate risk and the focus of the proposed climate risk mitigation action.

5.1 Climate risk trends

The climate risk analysis, conducted using the ACRI tool, identified climate hazard trends and exposure, vulnerability, and adaptability levels to the applicable hazards. The definition of risk follows the approach described in Section 3.4 in the methodology chapter and uses a 5-point scale, moving from insignificant to catastrophic risk (Table 5-1):

Table 5-1 Rating scale used for climate risk

Risk rating	Value
Catastrophic risk	0.76 – 1.00
Major risk	0.51 – 0.75
Moderate risk	0.26 – 0.50
Minor risk	0.01 – 0.25
Insignificant risk	0.00

For example, in the case of Belfast International, climate risk for flood is determined considering the average value of the main risk determinants (i.e. climate hazard, exposure, vulnerability and adaptability) and the formula:

$$\text{Flood risk} = \text{Flood} + \text{Exposure} + \text{Vulnerability} - \text{Adaptability}$$

The score for the flood hazard, considering the measurement of the sub-index, is calculated as 0.75, while the scores for exposure and vulnerability to flood are 0.50 and 0.46, respectively. The score for adaptability to flood is 0.62. After applying the formula, the flood risk score is standardised, scaling the result from 0 to 1; the flood risk is calculated as 0.54, corresponding to ‘Major risk’ in the defined 5-point rating scale. The results for the airport sample are presented in Figure 5-1.

Based on the climate risk rating, cold, flood, snow, and storm emerge as the top hazards of concern in terms of risk level. Flood is the hazard that draws attention, with risk levels ranging from minor (Norwich) to major (Belfast International). Storm presents a moderate risk level for all airports except Exeter (minor risk level). Snow presents a minor risk for all airports besides Bournemouth (moderate risk). The risk level for cold ranges from moderate (Exeter and Norwich) to major (Belfast International and Bournemouth). Heat generally presents a lower concern, rated as minor for all airports except Exeter, where it is rated moderate. Finally, the drought risk appears insignificant (Belfast International and Exeter) to minor (Bournemouth and Norwich).

Bournemouth exhibits a higher overall level of climate risk. Despite demonstrating high adaptability, the levels of the other risk determinants indicate that there are issues the airport should address in the applied action plan. On the other hand, Norwich presents a lower overall climate risk.

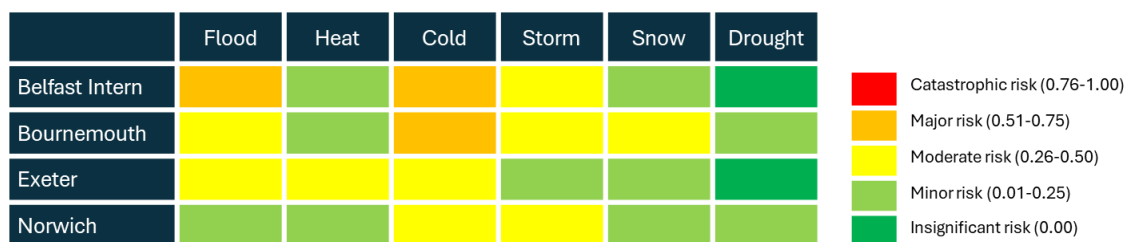


Figure 5-1 Mapping the level of climate risk to the applicable climate hazards

The following figures illustrate the climate risk dimensions in a graphical format. Each figure depicts the climate risk determinants per hazard type, allowing for easy identification of areas of concern in terms of their respective levels.

Norwich (Figure 5-2) demonstrates an overall climate risk index of 0.23, suggesting a minor risk level (based on the ACRI definition, minor risk corresponds to a score of 0.01 to 0.25). Cold and storm are identified as the main hazards of concern, with climate risk scores of 0.45 and 0.33, respectively, indicating a moderate level of risk. Flood and snow present minor climate risk levels, with scores of 0.24 and 0.22, respectively. The lowest levels of climate risk are observed in the case of drought (score of 0.06) and heat (score of 0.10).

The hazard level is high in the case of flood, cold and heat (score of 0.75); storm also presents a high hazard level. The exposure level is high in snow (score of 0.72) and cold (score of 0.56). Storm is the most significant concern in terms of vulnerability, showing a

high level (score of 0.53), followed by snow (moderate level, score of 0.45). Heat shows the higher level of adaptability (score of 0.88), while drought shows the lowest level (score of 0.05).

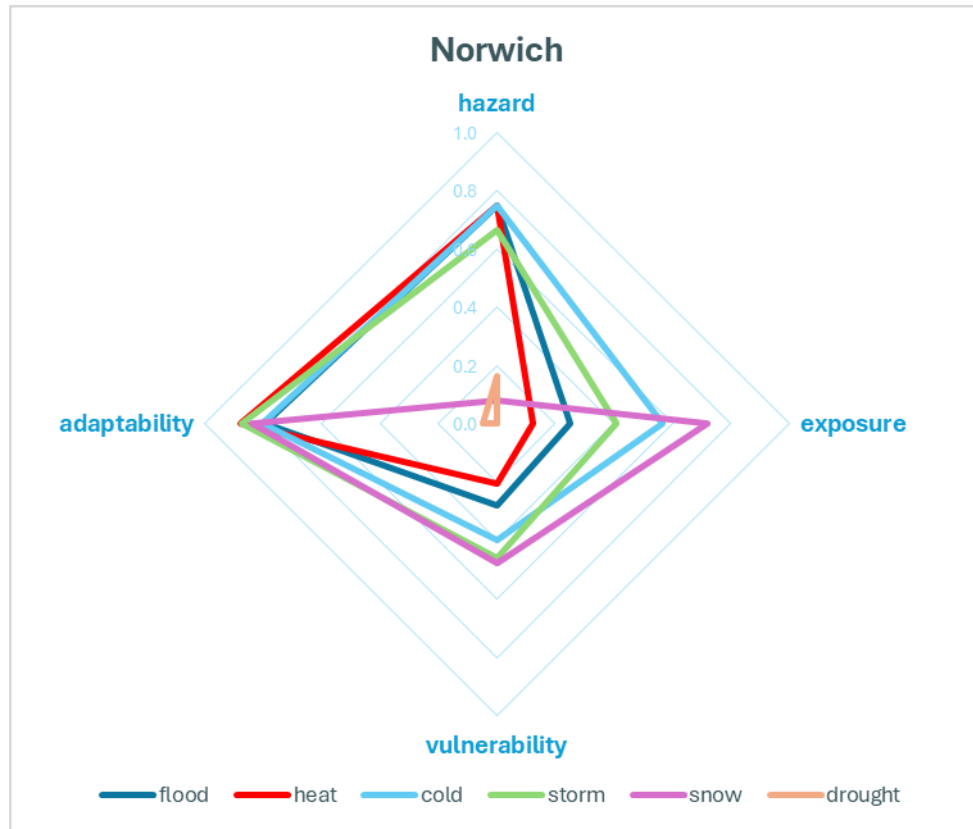


Figure 5-2 Climate risk dimensions for Norwich (source: ACRI tool)

Exeter (Figure 5-3) presents an overall climate risk index of 0.23, suggesting a minor climate risk level (based on the ACRI definition, minor risk corresponds to a score of 0.01 to 0.25). The primary hazards of concern are heat, cold and flood, with overall climate risk scores of 0.35, 0.37 and 0.33, respectively, reflecting moderate risk levels. Snow presents a minor risk with a score of 0.24. The lowest levels of climate risk are observed in the case of drought (score of 0.00) and storm (score of 0.14).

Flood is the primary hazard of interest, presenting a very high level (score of 0.83), followed by heat and cold (high level, score of 0.67). Exposure is notably high in the case of snow (score of 0.69), which also represents the most significant concern in terms of vulnerability, with a moderate level (score of 0.39). Cold follows with a moderate level (score of 0.34). Storm presents the highest level of adaptability (score of 0.69), and drought has the lowest level (score of 0.13).

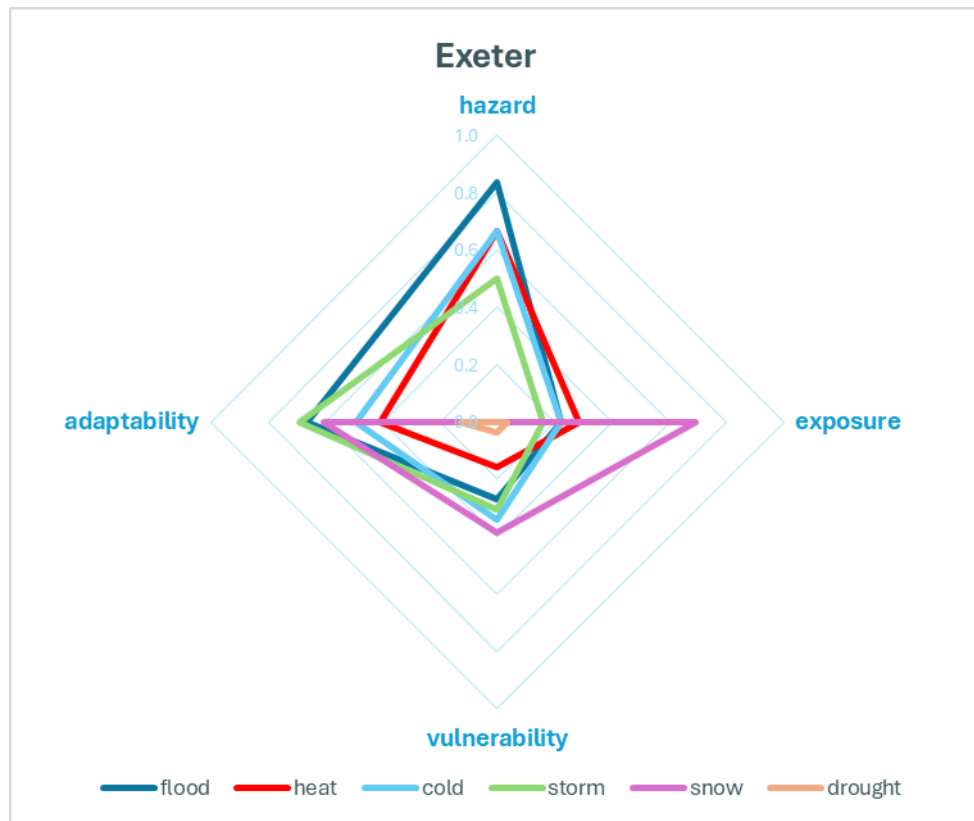


Figure 5-3 Climate risk dimensions for Exeter (source: ACRI tool)

Bournemouth (Figure 5-4) shows an overall climate risk index of 0.33, indicating a moderate climate risk level (based on the ACRI definition, minor risk corresponds to a score of 0.26 to 0.50). The main hazards of concern are cold and storm, with overall climate risk scores of 0.71 and 0.50, respectively, reflecting major and moderate levels. Snow presents a moderate level of climate risk with a score of 0.37. The lowest levels of climate risk are observed in the case of heat (score of 0.07) and drought (score of 0.08).

Hazards of interest include flood (very high level, score of 0.83) and heat and cold (high level, score of 0.75). Exposure level appears to be very high in the case of snow (score of 0.94) and storm (score of 0.91). Snow is also the most significant concern in terms of vulnerability, showing a high level (score of 0.56), followed by cold (high level, score of 0.52). Storm presents the highest level of adaptability (score of 0.83), and flood presents the lowest level (score of 0.59).

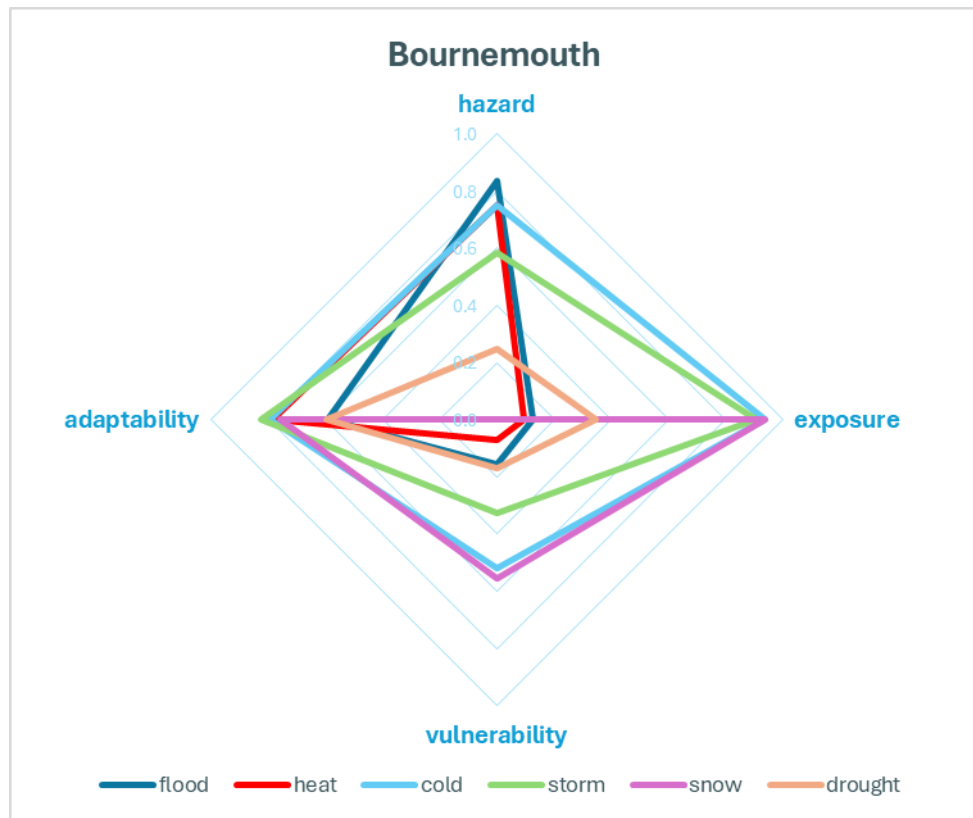


Figure 5-4 Climate risk dimensions for Bournemouth (source: ACRI tool)

Belfast International (Figure 5-5) demonstrates an overall climate risk index of 0.26, suggesting a moderate climate risk level (based on the ACRI definition, moderate risk corresponds to a score of 0.26 to 0.50). Among the analysed hazards, cold and flood are identified as the main hazards for consideration (presenting risk scores of 0.60 and 0.54, respectively, corresponding to a high level), followed by storm (moderate level).

The hazard level is high for flood and cold (score of 0.75). Exposure levels are presented as high in the case of cold (score of 0.53, corresponding to a high level) and moderate for both flood and snow (score of 0.50). Cold represents the most significant hazard in terms of vulnerability, demonstrating a high level (score of 0.59). Flood and storm are also a concern, each demonstrating moderate vulnerability levels (scores of 0.46 and 0.48, respectively). The adaptability scores for all hazards range from 0.62 (flood) to 0.69 (snow), indicating a consistently high level.

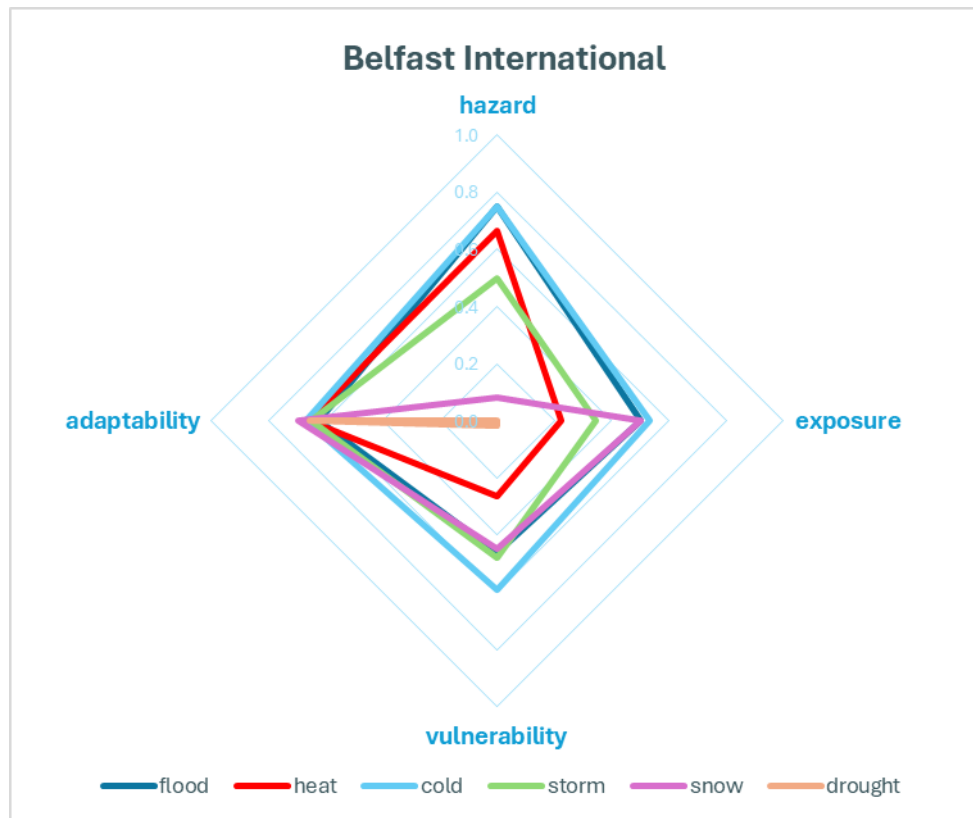


Figure 5-5 Climate risk dimensions for Belfast International (source: ACRI tool)

The following sections will discuss the areas of focus based on the analysis of climate risk, providing recommendations on measures to address issues of concern.

5.2 Areas for focus

Considering the analysis of the risk determinants, based on the output of the ACRI tool, certain areas in the existing strategies require more attention. This is due to the level of exposure and vulnerability, or because the existing adaptation measures may not effectively address the issue, as evidenced by the frequency of events causing damage/disruption in the past 10 years.

The identification of the main areas for focus, which will form the basis for the recommendations, considers the following observations:

- A major climate risk (score above 0.51) for specific climate hazards;
 - Flood (Belfast International)
 - Cold (Bournemouth and Belfast International)

- An at least moderate climate risk (score above 0.25) combined with observed increasing trends in the level of hazard;
 - Flood (Belfast International)
 - Heat (Exeter)
- A very high or high hazard level (score above 0.50) combined with a high or very high exposure of critical assets (score above 0.50):
 - Storm (Norwich, Bournemouth)
- An at least high exposure (score above 0.50) combined with an at least moderate vulnerability (score above 0.25):
 - Cold (Norwich, Bournemouth, Belfast International)
 - Storm (Bournemouth)
 - Snow (Norwich, Exeter, Bournemouth)
- A very high and high sensitivity of critical assets in the past 10 years (score above 0.50):
 - Cold (Belfast International)
 - Heat (Belfast International)
- An at least high predisposition of critical assets combined with an at least high sensitivity (score above 0.50):
 - Cold (Belfast International)
- A very high and high sensitivity of airport operations in the past 10 years (score above 0.50):
 - Cold (Belfast International)
 - Storm (Belfast International, Exeter)
- A very high and high sensitivity of people in the past 10 years (score above 0.50):
 - Cold (Belfast International)
 - Storm (Belfast International, Exeter)
- A very high and high sensitivity of airport surface access in the past 10 years (score above 0.50):
 - Flood (Bournemouth, Exeter)

- A very high and high sensitivity of safety (score above 0.50):
 - Flood (Exeter)
- An at least moderate sensitivity of safety combined with at least moderate effect (score above 0.25):
 - Cold (Norwich, Belfast International)
 - Storm (Norwich)
 - Snow (Norwich, Exeter)
- A very high and high likely effect of hazards on the environment (score above 0.50):
 - Flood (Belfast International, Bournemouth)
 - Cold (Belfast International, Exeter)
 - Snow (Belfast International)
- Low levels of adaptability (score below or equal to 0.25):
 - Drought (Norwich)
- A low level of protection of critical assets (score 0.25 or below):
 - Cold (Bournemouth, Exeter)
 - Drought (Bournemouth, Exeter, Norwich)
- An at least moderate level of sensitivity of critical assets (score above 0.25) combined with an at least moderate level of protection (score below or equal to 0.50):
 - Flood (Belfast International)
 - Cold (Bournemouth)
 - Storm (Norwich, Belfast International)
 - Snow (Exeter, Bournemouth)
 - Drought (Bournemouth)
- Moderate or below levels of preparedness (score below or equal to 0.50):
 - Heat (Exeter)
 - Drought (Exeter, Norwich)

Considering the above observations, the following paragraphs will provide recommendations on how to build more adaptive capacity.

5.3 Recommendations

The analysis of the output of the ACRI tool pointed out issues that the case study airports should address to build more adaptability. Overall, adaptation measures can become part of the risk management process, aiming to reduce the airport's exposure and vulnerability to different climate hazards. Depending on the specific challenges the airport must address, the measures can include various types of action, such as strengthening preparedness and implementing particular protection measures to increase the resistance of critical assets. Thus, the development of recommendations for the regional airports in scope looks at elements aiming to improve the airport infrastructure and assets in general and build more protection, actions to enhance operational response and the overall preparedness mechanism and aspects that can build stronger governance frameworks and institutional capacity to support adaptation actions, while at the same time increasing knowledge and awareness of climate risks.

The structure and focus of the recommendations will build upon the menu of adaptation options provided by ICAO (ICAO, 2022c) and ACI (ACI, 2018). ICAO provides options for aviation organisations to address vulnerabilities from climate change. Options are based on lessons learned and best practices and are organised as either operational or infrastructure-focused. ACI looks at the type of initiative, and based on the focus, it mainly classifies options as assessment, study, infrastructure upgrade, coordination, strategy, and design guideline. Broadening the focus, the IPCC (Noble *et al.*, 2014) suggests that considering the different sectors and stakeholders, there is no universal categorisation of adaptation options, and therefore, depending on the sector and the focus, different categories can exist. A general categorisation refers to structural, institutional and social options. Other classifications in the literature look at “grey” measures focused on asset upgrade and/or protection systems, “soft” measures including strategic or managerial actions to address a climate stressor and “green” when the focus is on green infrastructure, or bioclimatic features and nature-based solutions (Climate ADAPT, 2016). Studies focused on transport infrastructure suggest categories such as infrastructure, operational practices, extreme event response and miscellaneous activities (Picketts *et al.*, 2016).

The categorisation used in the context of this research moves beyond binary approaches (for example, operational vs. infrastructure) and considers the overall conceptualisation in the development of the ACRI tool, as presented in the Methodology chapter. This approach

enables the integration of broader climate hazard risk, resilience, sustainability, and governance-focused behavioural elements.

The following paragraphs discuss the selected categories and the recommendations for the case study airports.

5.3.1 Categorisation of options to build adaptability

In the context of the ACRI framework, the conceptualisation of adaptability and subsequently measures to enhance the existing levels reflect different qualities airports should demonstrate to reduce climate hazard-related risk. Attributes considered reflect the following:

- Enhancing the airport's capacity to understand the cause and effect of the impact of a hazard occurrence, how an event may impact the airport functions, and what aspects allow hazard occurrences to interact with vulnerable airport elements.
- Allowing the airport to adjust to the changes and climate extremes, having the ability to modify operations and strategies in response to the changing climate.
- Shaping decision-making on planning and operational matters influences how airports prepare and respond to an extreme event.
- Shaping the learning ability of the airport on how to transform to cope effectively with a disruptive event.
- Considering the interdependencies of the airport system since changes in climate or the occurrence of an extreme event may trigger a domino of changes, affecting not only airport assets but also interactions with internal and/or external components or sub-systems and the environment.
- Shaping the airport's ability to understand the severity of the implications of the hazard occurrence and the willingness to act to facilitate efficient and targeted actions.

Building on the above and considering the categorisation of adaptation options identified in the literature, the following categories are used:

1. Climate hazard risk intelligence

This category includes measures to enhance the airport's ability to comprehend the cause-and-effect relationships of the impact of a climate hazard occurrence and how they interact with the vulnerable airport elements and make decisions. Typical initiatives focus on the identification and assessment of hazard-related risks and their associated implications for the airport system. Examples of measures include conducting climate hazard analysis, exposure analysis, identification of high-risk areas, vulnerability analysis, climate risk assessments, evaluating long-term impacts of climate hazards, mapping interdependencies and impact of a climate hazard occurrence, or mapping climate risk awareness within the airport system.

2. Climate-proofing assets

Options under this category aim to make infrastructure and assets more robust by adjusting design parameters or standards, or by making enhancements to existing assets. Measures under this category include both hard and soft adaptation options, focusing on airside (runways, taxiways, apron), terminal(s) and landside (building, roads, parking), support facilities (maintenance, cargo, firefighting facilities, wastewater treatment, other facilities), fuel farms, or navigational aids. Examples involve using resistant materials/structures, reinforced systems, backup systems, retrofitting buildings, and actions to build more efficiency (for instance, energy or water efficiency). In addition, options incorporate protection measures that decrease the exposure of assets or the probability of damage/disruption, allowing the airport to adjust to climate extremes (for example, flood protection systems).

3. Flexible and adaptable operations

This category reflects actions to make airport operations more flexible and adaptable to climate extremes, acknowledging the interdependencies with other systems and networks. Measures include frameworks for adapting operational strategies, flight rescheduling and rerouting to avoid disruptions, diversified suppliers and robust supply chain and distribution network, climate-proofing procurement strategies, backup systems (power, water, communication etc.), training of staff to enable effective decision-making and emergency management, adapting maintenance and checks, and the integration of new technologies.

4. Emergency response and preparedness

Options in this category reflect the ability of the airport to learn from past events and cope effectively with disruptive and damaging climate hazard occurrences. Typical initiatives put emphasis on establishing formal climate hazard response and management plans and frameworks for coordination. Examples of measures include multi-stakeholder crisis coordination, emergency response plans, regular climate hazard-focused simulations and response drills, weather and climate forecasting and early warning systems, and access to temporary protection (for instance, mobile flood barriers, emergency power backup systems).

5. Sustainable interactions

This category incorporates measures focused on environmental sustainability and addresses the interdependency and interaction of the airport system with the environment. Representative actions refer to strategic land use planning, wildlife hazard management plans, bio-architecture, green infrastructure (for instance, nature-based solutions for flood mitigation, tree planting for heat reduction), sustainable resource management, energy and water efficiency, and carbon-neutrality. In addition, actions in this category look at protecting the environment, such as water resources, from discharges of chemicals during a climate hazard event (for instance, de-icers) and/or issues focused on noise pollution.

6. Passenger and workforce adaptability

Measures in this category focus on adapting workforce practices and passenger experience to climate hazards and related risks. Common initiatives concentrate on shaping the ability of the airport to recognise the severity of hazard occurrences and take action efficiently to address the potential impact on people. Examples of measures include accessibility during disruption, communication protocols, behavioural awareness, training programs for staff, and climate hazard-specific health and safety-focused initiatives.

7. Climate-embedded governance

This category addresses the airport's actionability and aspects related to the overall long-term climate risk awareness and capacity to plan and respond. Examples of options include developing climate risk governance frameworks, enabling dedicated teams, initiatives to enhance stakeholder collaboration and engagement, adaptable finance and

insurance mechanisms adjusted to reflect climate hazard risks, compliance with climate adaptation frameworks and climate risk reporting demonstrating climate risk mitigation activities and overall adaptation progress.

Building on the measures already in place, as captured in the airport responses in the ACRI questionnaire, the recommendations below aim to allow for a more holistic approach to climate risk management.

5.3.2 Recommendations for all regional airports

Considering the output of the tool for the regional airports, there are recommendations applicable to all airports and all types of climate hazards. These cross-sectoral options can enhance the airports' ability to adapt to multiple hazards, which are presented in Table 5-2.

Effective adaptation planning requires having knowledge of the climate hazard types that may affect the airport, how these hazards may evolve in the future, considering climate change influences, and their broader implications at a system level. Conducting focused studies will allow a thorough climate hazard, exposure and vulnerability analysis to support planning for targeted adaptation action. For example, undertaking climate hazard mapping (for instance, flood mapping) will help identify critical and susceptible elements that require specific attention.

Building awareness and knowledge sharing will enable leveraging hazard-related intelligence to inform decision-making across airport teams and management levels. One important aspect that is often overlooked is the depth of knowledge airport staff have on climate hazard risk and the importance of aligning day-to-day activities and responses to events. Educating airport staff on climate hazards, related implications, and best practices to address risks will shape the airport's ability to recognise the severity of climate hazards and direct and indirect implications and act efficiently.

Table 5-2 Cross-sectoral options for building adaptability applicable to all regional airports

Recommendations	Main categories
Conduct focused studies on climate hazards, trends and implications to identify exposed and vulnerable elements.	Climate hazard risk intelligence
Building awareness and knowledge sharing across teams and stakeholders	Climate hazard risk intelligence Climate-embedded governance
Educating airport staff on climate hazards and related implications and prevention	Climate-embedded governance Flexible and adaptable operations Emergency response and preparedness
Promote stakeholder engagement	Climate-embedded governance Emergency response and preparedness
Enhancing communication protocols with passengers and transport authorities	Emergency response and preparedness
Use of forecasting and early warning systems	Emergency response and preparedness
Flexible maintenance checks to align with climate hazard occurrences	Emergency response and preparedness Flexible and adaptable operations
Backup systems for critical elements	Flexible and adaptable operations Passenger and workforce adaptability
Sustainability-focused initiatives that will enhance multiple areas	Flexible and adaptable operations Sustainable interactions
Alignment of climate change mitigation action to climate change adaptation action	Sustainable interactions Climate proofing assets
Incorporating climate hazard risk and adaptation into the overall risk, safety, and environmental management	Climate-embedded governance
Clear roles and responsibilities to deal with adaptation matters	Climate-embedded governance
Climate adaptation study based on climate risk assessments	Climate-embedded governance
Allocation of economic resources to climate hazard risk mitigation	Climate-embedded governance

Having a coordinated response requires engaging with stakeholders before, during and after an event. Stakeholder engagement will allow the effective implementation of climate hazard-related policies and measures to address risks. Although there are communication protocols in place with service providers, enhancing the existing protocols with passengers and transport authorities will mitigate the impact of anticipating climate hazard extreme

events (for example, when there is an early warning for extreme precipitation that would result in a likely disruption).

Forecasting and early warning systems for all applicable hazards should be used to allow time for preparedness and coordination. Maintenance schedules should be amended to ensure they are conducted before and after an event to enable quick action and effective preparedness before an anticipated climate hazard occurrence. This is important in the case of assets showing sensitivity to specific hazards, such as critical equipment that may malfunction during an extreme heat event. To build more adaptability, it is recommended to have backup systems for critical elements, such as energy, water, and communications, but also elements that indirectly influence aspects of ground operations (for instance, backup de-icer materials or equipment) or even people (for example, backup systems for cooling, heating).

It is also recommended to identify options that can have multiple benefits; sustainability-focused initiatives that will enhance multiple areas are generally preferred, especially regarding energy or water efficiency. For example, choosing nature-based solutions to address extreme heat within buildings, such as vegetated areas, green roofs or walls, can also reduce cooling requirements, leading to more energy and carbon efficiency. Overall, aligning climate change mitigation to climate change adaptation action will enable a more holistic and forward-looking approach to planning (for instance, ensuring the climate hazard resilience of energy transition infrastructure, considering the use of nature-based solutions or sustainable design).

Incorporating climate hazard risk and adaptation into the overall risk, safety, and environmental management will allow a more proactive approach and the prioritisation of action, as well as the integration of organisational structure and accountability procedures. Clear roles and responsibilities will ensure that all areas of climate hazard risk mitigation efforts are coordinated and consistent. Currently, the airports do not present an adaptation action plan; conducting detailed and focused climate hazard risk assessments to inform future adaptation plans with short- and long-term actions is recommended. The above can allow the allocation of economic resources while at the same time ensuring sufficient capacity of airport staff to deliver action to build more climate hazard adaptability. A proactive approach will allow continuous improvement over the longer term, considering the evolving climate hazard profiles.

The following paragraphs provide additional recommendations regarding airports and climate hazards of concern.

5.3.3 Recommendations for Belfast International Airport

Considering the tool's output and the focus areas, the recommendations below address aspects relevant to flood, heat, cold, storm, and snow.

Flood is a significant climate hazard of concern based on the tool's output, showing a major climate risk level. Opportunities to build more adaptability mainly focus on protection aspects and are presented in Table 5-3.

Table 5-3 Recommendations for Belfast International to build flood adaptability

Recommendations	Main categories
Flood risk mapping	Climate hazard risk intelligence
Elevation of critical infrastructure or buildings	Climate-proofing assets
Relocation of critical equipment	Climate-proofing assets
Upgrading drainage systems	Climate-proofing assets
Permeable flooring	Climate-proofing assets Sustainable interactions
Regular checks and maintenance of exposed and/or vulnerable assets	Flexible and adaptable operations Emergency response and preparedness
Monitoring local biodiversity	Sustainable interactions

A dedicated flood exposure analysis and climate change-informed flood risk mapping at an asset level will allow the identification of exposed and vulnerable assets. Identifying airport areas prone to flooding can allow a more flood-resilient airport development with opportunities to build more protection. Furthermore, identifying exposed assets will enable action to decrease the exposure and build more flood resilience to the airport system. Measures to consider may include elevating critical infrastructure or buildings in low-lying areas or areas affected by surface flooding when redeveloping airport assets and/or relocating critical equipment. Knowing the likely flood depth in areas where critical assets are located can allow for identifying priority areas and developing a plan for permanent or temporary relocation if permanent relocation is not an option to consider (for example, when there is a warning for extreme rainfall). An example of intervention includes the protection of electric wiring (elevation above expected flood depth) or the relocation of electric generators or IT systems from the basement to a higher level.

Based on the provided input, the airport is pursuing improvements regarding upgrading drainage systems to handle more significant peak flows. Incorporating climate change projections in the flood modelling will allow the design criteria for drainage systems to become more forward-looking and able to address stormwater efficiently. To further enhance the level of preparedness, regular checks to ensure drainage networks are functioning, especially when extreme rainfall is anticipated, will ensure they maintain sufficient capacity during the event. Even though less than 25% of the airport surface is impervious, surface flooding can become an issue in the event of extreme precipitation. Although a significant intervention, using highly permeable flooring in airside components combined with an underground drainage system can allow the rainwater to infiltrate, be collected and disposed of appropriately; this measure has been considered in Bergamo airport (De Vivo *et al.*, 2023b). Considering the likely effect on the environment, establishing a mechanism to monitor local biodiversity, combined with the existing water quality monitoring, will decrease the environmental impact of a future flood event.

Heat emerges as a hazard of interest based on the tool's output, considering the observed high sensitivity of critical assets in the past 10 years and the climate hazard trends. The recommended measures are presented in Table 5-4.

Table 5-4 Recommendations for Belfast International to build heat adaptability

Recommendations	Main categories
Heat risk mapping	Climate hazard risk intelligence
Reinforcement of critical assets	Climate-proofing assets
Heat-resistant coatings for runways	Climate-proofing assets
Protection/relocation of critical equipment	Climate-proofing assets
Protection of fuel storage facilities	Climate-proofing assets
Increase cooling capacity in buildings	Climate-proofing assets
Increase green (e.g. green roofs, green walls) and vegetated areas	Climate-proofing assets Sustainable interactions
Retrofit buildings to improve thermal efficiency and natural ventilation	Climate-proofing assets Passenger and workforce adaptability
Increase shaded outdoor areas	Passenger and workforce adaptability
Heat-adaptive work schedule	Passenger and workforce adaptability
Update the wildlife management and monitoring plan	Sustainable interactions

A heat exposure analysis will identify criticalities that the airport needs to address, such as critical assets with high levels of sensitivity to extreme heat conditions. Considering the frequency of infrastructure damage, protection measures already in place should be expanded. For instance, critical assets can be reinforced/protected to cope with extreme heat events. Examples include pavements suitable for higher temperatures, applying heat-resistant coatings to runways, and cooling runways with water. Also, ensuring that critical equipment (for instance, IT systems) or facilities (for example, fuel storage) remain protected from extreme heat (for example, maintaining temperature within their technical specifications using A/C systems) will reduce the exposure and minimise the consequences. Relocating critical equipment in such conditions, if a permanent option is not feasible, is recommended during extreme heat events (for instance, installing climate-controlled cabins for equipment and systems such as substations and IT systems).

Increasing the cooling capacity in buildings and ensuring that cooling systems can withstand the projected temperature extremes can mitigate the consequences for people. Implementing bio-architecture interventions such as green roofs, walls, or other vegetated areas can reduce heat stress within terminal buildings and surrounding areas. At the same time, these interventions can reduce the cooling requirements and support the airport's efforts to build energy efficiency. In this context, any future development or renovation should consider retrofitting existing buildings to improve thermal efficiency (for instance, insulation, glazing, shading) and improve natural ventilation, creating better conditions for passengers and airport staff while addressing energy efficiency efforts. In addition, the increase in shaded outdoor areas will provide protection for people during extreme heat events. The heat-adaptive work schedule for airport staff working outdoors will further support existing health and safety measures. Extreme heat can also impact local wildlife; therefore, updating the wildlife management plan and establishing a monitoring mechanism will ensure that changes in local biodiversity do not threaten operational safety.

Cold is one of the climate hazards for consideration due to the very high sensitivity of critical assets in the past 10 years and the high hazard level. The recommendations for the airport are presented in Table 5-5.

Table 5-5 Recommendations for Belfast International to build cold adaptability

Recommendations	Main categories
Cold risk mapping	Climate hazard risk intelligence
Reinforcement of critical assets	Climate-proofing assets
Protection/relocation of critical equipment	Climate-proofing assets
Increase sustainable heating capacity in buildings	Climate-proofing assets

A cold exposure analysis will allow the identification of high priority areas that the airport needs to address, such as critical assets exposed or susceptible to impact during cold and icing conditions and/or assets already demonstrating sensitivity to cold extremes. Those identified assets can be strengthened; for instance, use of coatings to prevent pavement structures from deteriorating. Also, critical equipment identified as sensitive to cold extremes can be protected or relocated to areas where suitable conditions apply based on their technical specifications. Considering the heating requirements, interventions aiming to build more sustainable heating capacity in buildings can address consequences to people and energy requirements. Plans to retrofit existing buildings should consider improving energy, thermal efficiency, insulation, and options to sustainably create better conditions for passengers and airport staff.

Storm is a climate hazard of interest due to the sensitivity of operations, people and critical assets, although at a lower level for the latter. Considering the compound nature of a storm event, typically combining heavy rainfall leading to flooding, strong winds, and potentially lightning⁶, there are opportunities to build more adaptability and address all hazards (Table 5-6). To avoid repetition, flood-specific recommendations that are included in Table 5-3 are not analysed in the below paragraphs, as have already been mentioned under flood.

A storm exposure analysis will identify important elements the airport needs to address, such as assets exposed to flood and/or extreme wind. Critical assets (for instance, the control tower) identified as vulnerable due to their design standards will need to be reinforced to cope with a likely increase in wind loads. Based on the ACRI response, a study is being undertaken to determine whether the control tower is designed to withstand extreme wind loads. The study's results should be considered in future action to build adaptability. Also, ensuring that critical equipment remains protected from extreme wind

⁶ Storms can also involve storm surges but due to the location of the airports this aspect is not considered.

occurrences is highly recommended. Examples of initiatives include securing or relocating assets prior to storm events. Furthermore, maintaining additional supplies will ensure that equipment and infrastructure can quickly get back online after a lightning strike (National Academies, 2016). Nature-based interventions in landscaping, such as an increase in vegetation, can support addressing wind gusts.

Table 5-6 Recommendations for Belfast International to build storm adaptability

Recommendations	Main categories
Storm risk mapping (flood and wind)	Climate hazard risk intelligence
Reinforcing structures to withstand extreme wind	Climate-proofing assets
Elevation of critical infrastructure or buildings	Climate-proofing assets
Relocation of critical equipment	Climate-proofing assets
Upgrading drainage systems	Climate-proofing assets
Permeable flooring	Climate-proofing assets Sustainable interactions
Regular checks and maintenance of exposed and/or vulnerable assets and lightning protection systems	Flexible and adaptable operations Emergency response and preparedness
Maintain additional supplies	Flexible and adaptable operations Emergency response and preparedness
Monitoring local biodiversity	Sustainable interactions
Increase vegetated areas	Climate-proofing assets Sustainable interactions

Snow is a climate hazard that attracts attention due to its likely effect on the environment. Based on the airport's responses, the local water resources are likely impacted during snowfall events, and most water pollution incidents are associated with snowfall events. Table 5-7 shows the recommended measures.

Overall, discharges of de-icers, such as glycol-based, typically used on runways or aircraft, can pollute the local aquifer or surface water in the vicinity of the airport. Using alternative agents, such as biodegradable de-icers or anti-icing agents, before snowstorms will prevent excessive pollutants from entering the stormwater management system. Other interventions include the use of designated areas for de-icing operations. These areas can be fitted with a separate runoff collection system leading to detention basins or other water storage units that temporarily hold the contaminated water until it is driven to a wastewater

management facility. In other cases, an advanced filtration system can help prevent de-icer chemicals from entering the airport drainage system. In areas where discharges may escape and infiltrate the groundwater, installing impermeable linings can prevent the intrusion of pollutants into the local aquifer or water courses. Regarding wastewater management, biological treatment ponds are considered an option to treat wastewater before it is released further into the runoff network, reducing the risk of water contamination that may also threaten local biodiversity.

Table 5-7 Recommendations for Belfast International to build snow adaptability

Recommendations	Main categories
Use of biodegradable de-icer agents	Sustainable interactions
Use of designated areas for de-icing operations	Sustainable interactions
Use of advanced filtration systems and linings	Sustainable interactions
Enhance the wastewater management system	Sustainable interactions

Overall, the airport is currently conducting studies to plan for adaptation; conducting a climate-hazard-specific risk assessment (i.e. flood, heat, cold, storm, snow) to inform the adaptation plan with short- and long-term actions is recommended. Building more knowledge of climate hazard risk, causes and prevention through training will allow airport staff to make more data-driven, informed decisions. Considering the evolving climate hazards, this proactive approach will allow for continuous improvement over the longer term.

5.3.4 Recommendations for Bournemouth Airport

Considering the tool's output and focus areas, the recommendations below address flood, cold, storm, snow and drought aspects.

Flood is a climate hazard of concern based on the tool's output, showing high sensitivity of airport surface access and a significant effect on the environment. The following options for building more adaptability (Table 5-8) focus on these aspects.

Identifying exposed elements in the surface access network will allow seeking options to build flood protection. Further enhancing engagement and communication with the local transport authorities will allow exploring options for alternative surface access routes, developing detour plans, and priority lanes for airport staff and passengers. Exploring options for permanent or deployable flood defences along susceptible parts of the road

network should also be considered. Based on the airport's responses, establishing a monitoring mechanism for water quality is in progress. The airport is enhancing its drainage system to accommodate higher peak flows better. Integrating climate change projections into flood modelling and using filtration for runoffs will lead to improved stormwater and wastewater management. Conducting routine inspections of drainage networks, mainly when there is a warning for extreme rainfall, will help maintain their capacity and effectiveness during the event. Also, establishing a biodiversity monitoring system alongside the water quality initiatives will help mitigate the likely environmental impacts of potential flooding.

Table 5-8 Recommendations for Bournemouth to build flood adaptability

Recommendations	Main categories
Flood risk mapping	Climate hazard risk intelligence
Alternative surface access routes	Emergency response and preparedness
Permanent or deployable flood defences	Climate-proofing assets Emergency response and preparedness
Enhance the stormwater management system	Climate-proofing assets
Enhance the wastewater management system	Sustainable interactions
Regular checks and maintenance of exposed and/or vulnerable assets	Flexible and adaptable operations Emergency response and preparedness
Monitoring local biodiversity	Sustainable interactions

Cold represents a notable hazard in the tool's output, showing a major climate risk level. Opportunities to build more adaptability mainly focus on protection aspects and are presented in Table 5-9.

A cold exposure mapping will enable pointing out the issues the airport must address. It will identify critical assets that are either directly exposed or prone to damage under cold and icing conditions, and critical parts of the infrastructure and/or equipment that already demonstrate sensitivity to cold extremes. Assets identified at risk can be protected or relocated to areas with more suitable environmental conditions as per their technical requirements. Pavements considered susceptible to cold conditions can be hardened/reinforced to withstand extreme conditions. Considering that using chemical agents for icing prevention on runways and taxiways may raise water quality concerns, the use of biodegradable alternatives should be considered. The enhancement of the wastewater management system (as mentioned in the flood paragraph above) will allow

pollutants to be processed before being released into the overall runoff system. To better manage heating demands, the airport should consider building retrofits focusing on insulation, thermal efficiency and overall sustainability, creating better conditions for passengers and airport staff while reducing energy consumption.

Table 5-9 Recommendations for Bournemouth to build cold adaptability

Recommendations	Main categories
Cold risk mapping	Climate hazard risk intelligence
Protection/relocation of critical equipment	Climate-proofing assets
Reinforcement of critical assets	Climate-proofing assets
Use of biodegradable anti-icer agents	Sustainable interactions
Enhance the wastewater management system	Sustainable interactions
Increase sustainable heating capacity in buildings	Climate-proofing assets

Storm is among the climate hazards of concern due to the observed levels of exposure and vulnerability. Opportunities to build more adaptability to storm address heavy rainfall, strong winds and lightning⁷. Aiming to avoid repetition, certain flood-specific measures already mentioned under flood and presented in Table 5-10 will not be included in the rationale in the paragraphs below.

A storm exposure analysis will help identify key vulnerabilities the airport must address, particularly critical elements susceptible to flooding and/or extreme wind. Ensuring that critical elements are adequately protected is essential; for instance, measures such as securing or temporarily relocating assets ahead of a storm, regular checks and maintenance of critical systems are examples of measures that can help mitigate the likely impact. In addition, keeping essential backup equipment and supplies can facilitate quicker recovery in the event of a lightning strike or storm-induced disruptions and incidents (National Academies, 2016). Other interventions that have the potential to address extreme wind include the integration of strategic tree planting to mitigate wind gusts, managing runoffs, and further strengthening the airport's ability to withstand the effects of storminess and wind.

⁷ Storms can also involve storm surges but due to the location of the airports this aspect is not considered.

Table 5-10 Recommendations for Bournemouth to build storm adaptability

Recommendations	Main categories
Storm risk mapping (flood and wind)	Climate hazard risk intelligence
Protection/relocation of critical equipment	Climate-proofing assets
Regular checks and maintenance of exposed and/or vulnerable assets and lightning protection systems	Flexible and adaptable operations Emergency response and preparedness
Maintain additional supplies/essential backup equipment	Flexible and adaptable operations Emergency response and preparedness
Increase vegetated areas	Climate-proofing assets Sustainable interactions
Permanent or deployable flood defences	Climate-proofing assets Emergency response and preparedness
Enhance the stormwater management system	Climate-proofing assets
Enhance the wastewater management system	Sustainable interactions
Monitoring local biodiversity	Sustainable interactions

Snow has been identified as a climate hazard of interest mainly due to the levels of exposure and vulnerability. Options to build adaptability address elements such as climate-proofing assets and operations while protecting the environment. Recommendations that have already been mentioned for other climate hazards (for example, cold) are included in Table 5-11 but are not further analysed to avoid repetition.

Table 5-11 Recommendations for Bournemouth to build snow adaptability

Recommendations	Main categories
Reinforcement of critical assets	Climate-proofing assets
Use of biodegradable anti-icer agents	Sustainable interactions
Use of designated areas for de-icing operations	Sustainable interactions
Use of advanced filtration systems	Sustainable interactions
Enhance the wastewater management system	Sustainable interactions
Maintain additional supplies/essential backup equipment	Flexible and adaptable operations Emergency response and preparedness

Besides using alternative agents for de-icing and anti-icing procedures, as mentioned under cold, having designated areas for de-icing operations will allow effective wastewater management by collecting runoffs and driving them to a water storage unit before receiving treatment. In addition, the use of advanced filtration will further enhance the levels of

protection of local water resources. To build further preparedness, maintaining additional supplies of de-icers/anti-icers will ensure that snow resilience operations can be executed.

Drought is a climate hazard of interest due to the sensitivity of critical assets and the low level of protection. Table 5-12 shows the proposed measures.

Table 5-12 Recommendations for Bournemouth to build drought adaptability

Recommendations	Main categories
Alternate water supply sources	Flexible and adaptable operations Emergency response and preparedness
Water efficiency in airport operations	Flexible and adaptable operations
Communication protocols with the water authority	Emergency response and preparedness Sustainable interactions
Reinforcement of critical assets	Climate-proofing assets
Regular monitoring of critical assets	Flexible and adaptable operations Emergency response and preparedness
Monitoring local biodiversity	Sustainable interactions

Drought can limit the airport's capacity to use water for operations or maintenance. Having alternative water supply sources, such as rainwater harvesting or greywater recycling, will allow the use of non-potable water where appropriate. A contingency plan for alternate water use during extended periods with water use restrictions is recommended. Also, the use of low-water-demand vegetation in landscaping will reduce the quantity of water used for irrigation. Establishing communication protocols with the local water authority will help align the airport's water management with regional drought response strategies. Furthermore, as prolonged drought conditions may lead to material degradation and/or cracks in paved surfaces, regular monitoring of critical surfaces and reinforcing surfaces where possible to withstand drought conditions is recommended.

Overall, the airport has not presented an adaptation plan. It is recommended that a climate hazard risk assessment addressing the main climate hazards of concern is conducted to shape an adaptation action plan. Besides addressing critical issues over the short and long term, the plan should include action to build a better understanding of the risk and drive decision-making.

5.3.5 Recommendations for Exeter Airport

Based on the tool's output and the key focus areas, the following recommendations target different aspects related to flood, heat, cold, storm, snow and drought.

Flood is a hazard of concern based on the tool's output, due to the demonstrated high levels of sensitivity regarding the airport's surface access and safety matters. In September 2023, a surface flooding event occurred that led to the inundation of the terminal building. This event happened after the airport provided data for the ACRI tool; therefore, the incident was not considered in the responses and the analysis. Although the recommendations focus on the tool's output, suggestions on how the airport can build more flood resilience are also provided. Table 5-13 presents recommendations to build more adaptability.

Table 5-13 Recommendations for Exeter to build flood adaptability

Recommendations	Main categories
Flood risk mapping	Climate hazard risk intelligence
Elevation of critical infrastructure or buildings	Climate-proofing assets
Relocation of critical equipment	Climate-proofing assets
Upgrading drainage systems	Climate-proofing assets
Permeable pavements	Climate-proofing assets Sustainable interactions
Nature-based solutions or detention basins	Climate-proofing assets Sustainable interactions
Regular checks and maintenance of exposed and/or vulnerable assets	Flexible and adaptable operations Emergency response and preparedness
Alternative surface access routes	Emergency response and preparedness
Permanent or deployable flood defences	Climate-proofing assets Emergency response and preparedness
Monitoring local biodiversity	Sustainable interactions

A dedicated and climate change-informed flood risk mapping will enable the airport to identify exposed and vulnerable assets and areas within the airport boundaries prone to flooding, supporting further action to build flood protection. The mapping of the exposed assets will allow targeted action, such as elevating critical infrastructure or buildings in low-lying areas or areas affected by surface flooding when redeveloping airport assets and/or relocating critical equipment. Where permanent relocation is not an option, temporary relocation or protection when there is a warning for extreme rainfall are options

to consider, especially for critical systems, such as electric generators. Also, identifying exposed elements within the surface access network in collaboration with the local transport authority will facilitate the development of alternative routes or detour plans for airport staff and passengers in case of disruption. In this context, exploring the feasibility of permanent or deployable flood defences along critical sections of the network will ensure accessibility during flooding events.

A study to determine the capacity of the existing stormwater management infrastructure is recommended. Climate change projections regarding precipitation need to be incorporated into any plan for enhancement. The airport's response regarding upgrading the drainage system suggests that work may be undertaken focused on improvements. Ensuring that the enhanced system manages future peak flows is highly recommended. Enhanced stormwater management systems for consideration may include smart drainage systems that can monitor water levels and adjust flow rate, highly permeable pavements that allow water to infiltrate, reducing the surface runoffs, nature-based solutions that absorb excess water or a system of detention basins to allow storing excess water controlling its release into the drainage system. Although there is an established process for inspections and checks, as regards the efficiency of protection and/or prevention measures, these would need to be conducted before and after an extreme precipitation event and, when possible, during the event to determine the efficiency. Given the potential for a surface flooding event to impact local water resources and biodiversity, introducing a biodiversity monitoring system alongside the ongoing water quality assessments will help address the adverse effects.

Heat represents a notable hazard, considering the observed trends. The recommended measures (Table 5-14) mainly look at enhancing the current level of preparedness, which was analysed as marginally below the moderate level (score of 0.43). In addition, recommendations include options to build more protection.

Incorporating heat as a hazard into existing emergency response plans will allow identifying critical airport assets (for instance, IT systems, substations, fuel storage) that demonstrate sensitivity to extreme heat conditions. For example, IT systems can be protected from extreme heat conditions by ensuring they are in a suitable environment, considering their technical specifications. Their relocation to a climate-controlled location will ensure their normal functioning during a heatwave. Similarly, fuel storage facilities should ensure that

temperature is regulated, for example, by ventilation, insulation or reflective coatings. In addition, ensuring that fire prevention measures are in place in those areas is recommended. High-temperature resistant materials, such as heat-reflective coatings, can build more heat resilience to critical assets. When necessary, the runway temperature can be regulated with water. Regular inspections before, during, and after a heatwave will allow for the identification of malfunctions or failures in existing protection measures.

Table 5-14 Recommendations for Exeter to build heat adaptability

Recommendations	Main categories
Heat risk mapping	Climate hazard risk intelligence
Incorporate heat as a hazard into emergency response and decision mechanisms	Emergency response and preparedness Climate hazard risk intelligence
Protection/relocation of critical equipment	Climate-proofing assets
Protection of fuel storage facilities	Climate-proofing assets
Reinforcement of critical assets	Climate-proofing assets
Regular checks and maintenance of exposed and/or vulnerable assets	Flexible and adaptable operations Emergency response and preparedness
Increase shaded outdoor areas	Passenger and workforce adaptability
Heat adaptive work schedule	Passenger and workforce adaptability
Increase green (e.g. green roofs, green walls) and vegetated areas	Climate-proofing assets Sustainable interactions
Retrofit buildings to improve thermal efficiency and improve natural ventilation	Climate-proofing assets Passenger and workforce adaptability
Update wildlife management and monitoring plan	Sustainable interactions
Adaptive noise mitigation action	Sustainable interactions

Conducting heat stress risk assessments for airport staff working outdoors, amending work schedules and increasing shaded outdoor areas and hydration stations during heatwaves will protect the workforce. Having vegetated areas will improve local conditions; for example, green roofs or green walls can alleviate heat stress in buildings and surrounding spaces while at the same time reducing cooling demand. Also, improving natural ventilation can create better conditions for airport staff and passengers. As extreme heat conditions can also affect local wildlife, monitoring biodiversity changes will ensure that they do not pose any risk to airport operations. Furthermore, during extreme heat events, there may be an increase in noise complaints; having a mechanism to adapt noise mitigation action can minimise community disturbance.

Cold is identified as a hazard of concern due to the low level of protection of critical assets and the potential environmental effects. Table 5-15 includes key recommendations for the airport.

Table 5-15 Recommendations for Exeter to build cold adaptability

Recommendations	Main categories
Cold risk mapping	Climate hazard risk intelligence
Protection/relocation of critical equipment	Climate-proofing assets
Reinforcement of critical assets	Climate-proofing assets
Retrofit buildings to improve thermal efficiency	Climate-proofing assets Passenger and workforce adaptability
Use of biodegradable anti-icer agents	Sustainable interactions
Enhance the wastewater management system	Sustainable interactions

Cold risk mapping will help identify critical assets susceptible to damage or malfunction during cold and icing conditions. Assets identified at risk should be reinforced or relocated to areas with suitable environmental conditions in accordance with their technical specifications. Pavements considered susceptible to cold conditions can be hardened/reinforced to withstand extreme conditions. Retrofitting and/or energy-efficiency upgrades will address inefficiencies in terminal design, such as insulation and inadequate thermal efficiency, creating better conditions for passengers and airport staff while reducing overall energy consumption. During anti-icing procedures, eco-friendly agents will minimise the risk of local water resources degradation. Enhancing the wastewater management system will also ensure that pollutants are treated before being discharged into the runoff system.

Storm is among the hazards of interest due to the observed sensitivity levels. Opportunities to build adaptability address heavy rainfall, strong winds and lightning⁸; nevertheless, while Table 5-16 captures all recommendations for the airport the recommendations below focus on elements not mentioned under other climate hazards.

⁸ Storms can also involve storm surges but due to the location of the airports this aspect is not considered.

Table 5-16 Recommendations for Exeter to build storm adaptability

Recommendations	Main categories
Storm risk mapping (flood and wind)	Climate hazard risk intelligence
Storm response plan	Emergency response and preparedness Flexible and adaptable operations Passenger and workforce adaptability
Elevation of critical infrastructure or buildings	Climate-proofing assets
Protection/relocation of critical equipment	Climate-proofing assets
Upgrading drainage systems	Climate-proofing assets
Permeable pavements	Climate-proofing assets Sustainable interactions
Nature-based solutions or detention basins	Climate-proofing assets Sustainable interactions
Regular checks and maintenance of exposed and/or vulnerable assets and lightning protection systems	Flexible and adaptable operations Emergency response and preparedness
Maintain additional supplies/essential backup equipment	Flexible and adaptable operations Emergency response and preparedness
Increase vegetated areas	Climate-proofing assets Sustainable interactions
Permanent or deployable flood defences	Climate-proofing assets Emergency response and preparedness
Enhance the wastewater management system	Sustainable interactions
Monitoring local biodiversity	Sustainable interactions

A storm mapping and incorporating storm in the existing emergency response plan will assist the airport in identifying and addressing susceptibilities, especially regarding elements at risk due to flooding and extreme wind. The plan will also enable the proper levels of coordination with service providers and internal and external stakeholders to ensure efficient action when needed. Enhancing protection for susceptible assets is essential; for instance, securing or relocating assets before a storm, conducting routine inspections, but also inspections before and after a storm, adapting maintenance schedules to ensure their functionality during the event, and having backup supplies to address disruptions. A study will allow the identification of nature-based options that could provide multiple benefits for the airport. Vegetated areas can assist in managing surface runoffs, and strategically planted trees can act as windbreaks, reducing the intensity of strong winds.

Snow is recognised as a hazard of interest due to the levels of exposure and sensitivity of critical assets. Table 5-17 presents recommendations for building snow adaptability. It is noted that measures already recommended in the context of other hazards, such as cold, flood, and storm, are included in the table but they are not further analysed.

Table 5-17 Recommendations for Exeter to build snow adaptability

Recommendations	Main categories
Reinforcement of critical assets	Climate-proofing assets
Use of biodegradable anti-icer/de-icer agents	Sustainable interactions
Use of designated areas for de-icing operations	Sustainable interactions
Use of advanced filtration systems	Sustainable interactions
Upgrading drainage systems	Climate-proofing assets
Enhance the wastewater management system	Sustainable interactions
Regular checks and maintenance of exposed and/or vulnerable assets	Flexible and adaptable operations Emergency response and preparedness
Maintain additional supplies/essential backup equipment	Flexible and adaptable operations Emergency response and preparedness
Monitoring local biodiversity	Sustainable interactions

To further enhance preparedness for a snowstorm or extreme snowfall event, it is recommended to maintain additional supplies of de-icers/anti-icers to ensure snow operations can be implemented. Furthermore, having alternatives regarding the snow and ice removal equipment is an option to consider. Besides using biodegradable agents, as mentioned under cold, the use of designated areas for de-icing operations is proposed as they will allow more effective wastewater management. Incorporating an advanced filtration system will further enhance the protection of local water resources.

Drought emerges as an issue due to the low levels of preparedness. Table 5-18 shows the proposed measures to build further drought adaptability.

As drought can impact the airport's ability to use water for operations and maintenance, it is recommended to explore the feasibility of using alternative water sources, such as rainwater harvesting or greywater recycling, where possible. Putting in place a response plan for periods with prolonged water restrictions will allow for essential functions. Establishing communication protocols with the water authority will enable the airport to align the water management actions with regional drought response plans. Considering

that prolonged drought conditions may cause cracks in paved surfaces, having a regular schedule of inspections is recommended.

Table 5-18 Recommendations for Exeter to build drought adaptability

Recommendations	Main categories
Alternate water supply sources	Flexible and adaptable operations Emergency response and preparedness
Communication protocols with the water authority	Emergency response and preparedness Sustainable interactions
Regular inspections of critical assets	Flexible and adaptable operations Emergency response and preparedness

Currently, the airport does not present an adaptation plan; however, actions to reduce the overall climate risk are being implemented. To further enhance the airport's adaptability, a comprehensive climate hazard risk assessment is recommended. This assessment can shape forward-looking action to build more climate resilience.

5.3.6 Recommendations for Norwich Airport

Considering the output of the tool and the identified areas of focus, the following recommendations address aspects relevant to cold, storm, snow and drought.

Cold is one of the climate hazards that is considered due to the level of exposure and vulnerability. Table 5-19 shows the proposed measures to build further cold adaptability.

Table 5-19 Recommendations for Norwich to build cold adaptability

Recommendations	Main categories
Cold risk mapping	Climate hazard risk intelligence
Reinforcement of critical assets	Climate-proofing assets
Protection/relocation of critical equipment	Climate-proofing assets
Increase sustainable heating capacity in buildings	Climate-proofing assets
Maintain additional supplies	Flexible and adaptable operations Emergency response and preparedness
Water quality monitoring	Sustainable interactions
Use of biodegradable de-icer agents	Sustainable interactions

Analysing exposure to cold and icing conditions is essential for identifying elements that may become susceptible to impact. The process should primarily focus on those elements

that have been recorded as sensitive over the past 10 years. Assets such as pavements can be hardened to withstand cold and icing conditions. Sensitive equipment can be relocated to areas where temperatures are within the threshold mentioned in their technical specifications. Addressing heating needs is also important, and investing in sustainable heating solutions can deliver the necessary heating capacity while optimising energy efficiency. Retrofitting buildings to improve insulation and energy performance is recommended. Also, ensuring the availability of additional supplies, such as anti-icers and de-icers, will enhance preparedness. Given the potential for de-icing agents to contaminate water resources, a regular water quality system is advisable. Considering the airport input, this measure is not yet fully integrated. Also, to address potential water quality issues, using biodegradable alternatives is recommended.

Storm attracts attention due to the observed levels of hazard, exposure, sensitivity of critical assets and safety. Table 5-20 outlines recommendations to enhance adaptability. As in other cases, measures already addressed under different climate hazard categories will not be repeated here.

Table 5-20 Recommendations for Norwich to build storm adaptability

Recommendations	Main categories
Storm risk mapping (flood and wind)	Climate hazard risk intelligence
Reinforcing structures to withstand extreme wind	Climate-proofing assets
Storm response plan	Emergency response and preparedness Flexible and adaptable operations Passenger and workforce adaptability
Relocation of critical equipment	Climate-proofing assets
Upgrading drainage systems	Climate-proofing assets
Regular checks and maintenance of exposed and/or vulnerable assets and lightning protection systems	Flexible and adaptable operations Emergency response and preparedness
Maintain additional supplies	Flexible and adaptable operations Emergency response and preparedness
Increase vegetated areas	Climate-proofing assets Sustainable interactions
Monitoring local biodiversity	Sustainable interactions

A storm risk mapping will identify essential elements the airport needs to address, such as critical assets exposed to flood and/or extreme wind. Should critical assets (for instance,

control tower, drainage systems) be identified as vulnerable due to their design standards, they would to be reinforced to cope with a likely increase in the wind loads or peak flows. To address extreme precipitation and the potential risk of inundation, a study is recommended to determine the capacity of the existing drainage system. Climate change projections regarding the change in precipitation levels must be considered. Examples of initiatives to build preparedness and protection include securing or relocating assets ahead of a storm, performing regular inspections pre- and post-storm, adjusting maintenance schedules to ensure critical equipment maintains functionality during the event, and ensuring backup supplies are available. Other options to consider is the relocation or protection of critical equipment to address inundation. If permanent relocation is not feasible, temporarily moving or safeguarding critical systems, such as electric generators, should be considered in response to extreme rainfall warnings.

Exploring nature-based options, for example increased vegetation, can support addressing issues such as managing runoffs and wind gusts. Given the potential for a surface flooding event to impact local water resources and biodiversity, introducing a biodiversity monitoring system alongside the ongoing water quality assessments will help address the adverse effects on the environment. Updating existing emergency response plans to address storm-related aspects will help facilitate effective coordination with service providers and internal and external stakeholders to ensure timely and efficient action when required.

Snow has been identified as a hazard of concern mainly due to the levels of exposure and vulnerability. Table 5-21 provides recommendations for the airport.

Table 5-21 Recommendations for Norwich to build snow adaptability

Recommendations	Main categories
Use of biodegradable anti-icer agents	Sustainable interactions
Use of designated areas for de-icing operations	Sustainable interactions
Use of advanced filtration systems	Sustainable interactions
Maintain additional supplies/essential backup equipment	Flexible and adaptable operations Emergency response and preparedness
Alternative surface access routes	Emergency response and preparedness
Snow alert rating system	Emergency response and preparedness Flexible and adaptable operations

Building on the recommendations for the airport to build adaptability to cold and icing conditions, besides using biodegradable agents for de-icing and anti-icing procedures, having designated areas for de-icing operations will allow effective wastewater management by collecting runoffs and driving them to a water storage unit before receiving treatment. In addition, using advanced filtration will further enhance the protection of local water resources. To build further preparedness, maintaining additional supplies of de-icers/anti-icers and backup options for equipment will ensure that snow resilience operations can be executed. To address disruption in surface access, collaborating with the local transport authority will allow the identification of vulnerable elements within the surface access network that will support developing alternative routes or detour plans for airport staff and passengers during disruptions. Developing a snow alert rating system that determines appropriate staffing levels for specific amounts of snowfall will allow the quick mobilisation of resources when needed.

Drought is considered a hazard of interest as the output of the tool shows low levels of preparedness. Table 5-22 shows the proposed measures.

Table 5-22 Recommendations for Norwich to build drought adaptability

Recommendations	Main categories
Alternate water supply sources	Flexible and adaptable operations Emergency response and preparedness
Communication protocols with the water authority	Emergency response and preparedness Sustainable interactions
Regular inspections of critical assets	Flexible and adaptable operations Emergency response and preparedness

Aiming to enhance the level of preparedness for drought-related water shortages, it is recommended that alternative water sources, such as rainwater harvesting or greywater recycling, be explored for suitable uses. Establishing communication protocols with the water authority will allow aligning water management and drought response plans with regional drought response measures. Incorporating regular inspections during prolonged drought periods in the response plan will allow the prompt identification of conditions that need to be addressed, such as cracks in paved surfaces.

Although the airport does not present an adaptation plan, steps are being taken to mitigate climate hazard-related risks. To strengthen its adaptability, it is recommended that a

thorough climate hazard risk assessment be conducted to allow the airport to be more proactive and develop options to enhance its adaptability over time.

5.4 Conclusions

Using the ACRI tool, the analysis of the climate hazard risk identified key hazards affecting the case study regional airports, with flood, cold, storm and snow, presenting the most significant risks. While some airports demonstrate high levels of adaptability, the results show opportunities to address issues that currently contribute to aspects of exposure or vulnerability. The key focus areas include strengthening flood and storm resilience and improving cold weather and snow preparedness. Additionally, heat and drought were identified as emerging risks, pointing out further opportunities for proactive planning for the regional airports.

Despite the different geographic locations, the case example regional airports present similarities in the challenges they must address. Undertaken measures appear to align with the typically observed hazard intensity or with existing specifications that may be based on outdated climate hazard characteristics. Therefore, existing risk mitigation planning seems to consider how climate hazards have manifested in the recent past. When an extreme event occurs with varied intensity compared to past occurrences, applied risk mitigation measures are likely to become inadequate to address the risk efficiently. Therefore, there is a need for proactive measures that will enable regional airports to manage climate hazard risks better while adapting to evolving climate challenges over time.

A categorisation of options is developed to provide recommendations to build adaptability. Key recommendations focus on strengthening climate hazard risk intelligence, improving asset climate hazard resilience, adapting operational aspects to address the nature of climate extremes, having backup options and flexibility, and integrating sustainability-focused initiatives. While all airports are undertaking measures to respond to climate hazard occurrences, none presents a formal adaptation plan. Therefore, a comprehensive and detailed climate hazard risk assessment is also recommended, focused on the critical issues identified using the ACRI tool to shape an action plan to address short- and long-term risks.

The following chapter will discuss the main findings of the research in the context of the tool and the overall climate hazard risk analysis process. Furthermore, it will present the

main conclusions, the research's contribution and, limitations and ideas to be explored in future research.

6 Discussion and conclusions

While Chapters 4 and 5 demonstrated the applicability and validation of the tool through its use in four case study regional airports, the objective of this chapter is to look at the main findings of the research in the context of its contribution to the overall climate hazard risk analysis process and the broader literature (Section 6.1). The chapter also identifies cross-cutting themes that underpin the key concepts described throughout the thesis and presents the main conclusions and contributions of the study (Section 6.2). Limitations of the research (Section 6.3) and directions for future research in the context of climate hazard risk and adaptability are also discussed (Section 6.4).

6.1 Summary of research findings: climate hazard risk analysis and the ACRI tool

Four (4) research objectives were used to deliver the aim of the thesis, *“to develop a framework to analyse the risk of climate hazards to the airport system under current and future climate change projections”*.

RO1 – *To identify the key climate hazards and their impact on the airport system and analyse their implications.*

To address RO1, a literature review was conducted in **Chapter 2**. The literature review was used to identify key climate hazards affecting the global airport system and to examine their broader implications. The review explored the types of climate hazards, their impact on airport infrastructure and operations and how they are addressed within the applied risk management mechanism.

Airports are exposed to different types of climate hazards, from slow-onset events, like sea-level rise, drought and long-term changes to weather patterns, to rapid-onset extreme events, like heatwaves, storms, storm surges, and flash floods. The analysis built an understanding of the nature and complexity of climate hazards and how their characteristics and effects are often interconnected with other systems. Climate hazards do not act in isolation. The way they materialise and impact the airport system is influenced by multiple factors, many of which are driven by the geographic location and characteristics of the airport system, the global climate system, climate change, and the implementation of policies or decisions focused on risk mitigation aspects.

Climate hazards can lead to physical, operational or other business risks, such as asset damage, disruption in operations, and other safety, socio-economic, or environmental implications. Despite the aviation sector's proactive approach to hazard identification and safety management, climate hazards are not always identified as threats or included in the airport's overall risk management process. They are often addressed as weather phenomena without fully acknowledging their complexity, implications, or inherent uncertainty. Even when climate hazards are considered threats, they are only likely to be assessed concerning their probability of occurrence, a process that is likely to fail in capturing low-probability events with the potential for significant implications. When such events occur, they are classified as unprecedented. Therefore, existing practices limit the integration of climate hazard-related risk into long-term resilience strategies.

With climate change intensifying extremes, such as storms, floods and heatwaves, climate hazard occurrences are expected to become more frequent and intense, placing additional stress on airport infrastructure and operations. The above illustrates the need for airports to have better protection and preparedness strategies to address associated damage and disruption. Treating climate hazard events as just operational challenges rather than medium and/or long-term risks impacting the overall airport resilience will likely lead to inadequate risk management. Thus, as a system, the airport will find it difficult to navigate future challenges and adapt to the evolving risk and investment landscape. For a complex system such as an airport, employing appropriate climate risk mitigation strategies implies understanding what drives the risk, how it can be manifested at a system level and how proactively it can be addressed.

The literature review addressed RO1 and led to the above findings, raising several topics regarding the types of climate hazards affecting airports, the factors driving the impact and ways they can affect them, the drivers for undertaking action to adapt, and the effectiveness of the applied practices in responding to climate hazard events. These insights underline the need to explore further the elements that shape the overall climate risk. Understanding what drives climate hazard risk and how it can be defined and analysed is essential, and the second research objective focused on this aspect.

RO2 – *To define the exposure and vulnerability of the airport system to climate hazards.*

To address RO2, a review of the literature was conducted in **Chapter 2** on the concepts of climate risk and how it is defined in terms of risk determinants. The review explored how the concepts of exposure, vulnerability and adaptability are analysed and how they contribute to the overall risk. In addition, the analysis focused on identifying the existing methodological approaches for analysing these concepts, particularly in the context of airports or other infrastructure or urban systems.

Based on the findings, there is a growing body of research investigating climate hazard-related implications for airports; however, limited studies provide comprehensive climate hazard risk analysis frameworks developed explicitly for airports. While various approaches exist for analysing risk-related concepts, current frameworks do not fully address the complexity and nature of climate hazards and their manifestation and implications in the context of airport systems. Moreover, existing climate risk analysis frameworks tailored specifically for airports do not adequately capture aspects around what drives the climate hazard occurrence, how it impacts the different airport elements and interconnected aspects, and the airport's capacity to comprehend, plan and deliver action to implement risk reduction measures. In addition, they do not account for the increasing severity or unpredictability of extreme events driven by climate change. Even the most recently developed tools (for example, De Vivo et al., 2021; Vogiatzis et al., 2021) either follow the typical probability and severity approach to address specific climate hazards or limit the vulnerability analysis within particular boundaries in the airport system (for instance, infrastructure-related aspects). Thus, the review revealed that addressing climate hazard-related challenges requires a new set of tools that can support airports in building an understanding of the nature of the risk while at the same time acting as a guide to the overall process of identifying how to build further their capacity to adapt.

Considering the characteristics of climate hazards and how they are manifested, the climate hazard risk determinants are defined in **Chapter 3** using a tailored approach. The definition of the concepts of climate hazard, exposure, vulnerability, and adaptability in an airport context combined fundamental elements adopted in various frameworks, and it was supported by theoretical perspectives in the fields of natural hazards, adaptive change and risk perception. Airports are conceptualised as complex and dynamic systems with interrelated elements supporting their overall functions and the physical environment in

which they operate. Climate hazard risk emerges when a climate hazard occurrence affects exposed and/or vulnerable airport elements. Actions to address the implications and to build more adaptive capacity contribute to overall risk reduction.

The process of analysing the climate hazard risk determinants investigated the airport systems to identify what drives the risk. A climate hazard event cannot be controlled in terms of timing, location or intensity of occurrence; nevertheless, how the event will affect the airport system can be moderated by eliminating the elements that are exposed to the climate hazard or reducing their sensitivity or likelihood to experience damage or lead to disruption. This process is highly complex and dynamic, requiring a holistic perspective that considers different types of capacity (physical, operational, institutional, human, financial and simultaneously, coping, adaptive and transformative) and interdependencies within the airport system. Traditional risk management approaches may fail to incorporate the needed level of complexity.

The analysis also addressed how climate hazard risk is analysed and understood, and how this understanding influences the prioritisation of adaptation action. Many airports assess climate hazards partially (for example, as part of the environmental management system) or in isolation (as an operational matter driven by a meteorological occurrence that caused disruption) rather than embedding them within the overall risk management framework. Therefore, the conceptualisation of risk is essential, especially in the case of small regional airports, as they often operate with limited resources and may not always consider medium- or long-term adaptation action a concern. Nevertheless, low adaptability levels may imply a low capacity to recover quickly after an extreme event.

The overall conceptualisation process of the climate hazard risk and the activities undertaken to address RO2 raised some important questions on how to quantify the main risk components and how they can be brought together in a framework developed for airports. Also, how this framework can be used to draw conclusions on characteristics that influence the airport's ability to control climate hazard-related impacts and ensure business continuity. These topics highlighted the need for an approach that analyses the risk determinants and provides the means to guide decision-making on adaptation action. These findings lead to the next objective, which focuses on developing and validating the climate hazard risk analysis framework.

RO3 – *To assess the operational and compliance risk of climate hazards to the airport system.*

After developing the conceptual framework, the Airport Climate Risk Index (ACRI) tool was introduced, addressing RO3; the adopted methodological approach for the tool development was described in **Chapter 3**. Climate hazard risk analysis is seen as a multi-level process, moving from defining the climate hazard profile to analysing the risk determinants. Climate risk determinants include the airport's exposure to the identified climate hazards, the predisposition to experience impact, the demonstrated sensitivity to damage or disruption, the observed effects, and the airport's ability to adapt to extreme occurrences.

ACRI was constructed as a composite indicator-based framework that enables UK airports (regardless of size or location) to self-analyse their climate hazard risk profile and identify gaps in current adaptation strategies. Incorporating a multi-level approach allows airports to better understand the issues that should be included in climate hazard risk and resilience discussions. Composite indicators such as the ACRI tool offer a multi-level perspective. They can address complexity by combining multiple variables into a single index, such as the factors shaping the airport's risk profile, making it easy to interpret data from different sources. As a result, it can help decision-makers identify trends, revealing elements more susceptible to climate stressors, which need to be strengthened. They provide insights into existing practices and allow the identification of gaps that need to be addressed.

One of the major challenges in climate risk management is the inherent uncertainty associated with predicting extreme events and their consequences. To address this, the tool utilises the IPCC and the UK climate change projections that provide probabilistic climate change scenarios under different greenhouse gas emission pathways. This integration allows location-specific aspects to be incorporated into the tool, facilitating a more forward-looking climate risk view. In addition, the tool incorporates climate hazard metrics as indicators that can be updated if new data becomes available, making it more dynamic.

Following the development of the tool, the validation process used four (4) case study regional airports. The research focused on regional airports as they represent an under-

researched area in the literature. In addition, regional airports are the ones that would primarily gain benefit as limited resources often constrain them and, therefore, cannot apply comprehensive climate hazard risk management strategies. The analysis in **Chapter 4** used the ACRI tool and pointed out issues the regional airports should address to build more adaptability. Although the regional airports involved in the validation process are in different geographic locations in the UK, they present some similar climate hazard-related challenges.

The analysis revealed that flood is gradually becoming a key concern for almost all regional airports, with Belfast International presenting higher levels of susceptibility. Snow was identified as a disruptor, especially for Bournemouth and Norwich, requiring the implementation of mitigation measures addressing protection and preparedness elements. While cold and storm occurrences can lead to significant disruption, regional airports generally demonstrate preparedness and experience in responding to such events. However, considering the unpredictability driven by climate change when it comes to the intensity and/or frequency of storms, the existing business continuity strategies call for a reassessment. While heat was not identified as a major issue in the present day, considering the climate change projections, it is anticipated to impact regional airports in the future. The above suggests that airports need to be more proactive in their adaptation strategies and plan for extreme events that have the potential to cause disruption in the near future. Drought was identified as the least concerning hazard, with no major implications.

Overall, the adaptation action of the regional airports mainly focuses on preparedness, especially for climate hazards that have long been recognised as highly disruptive, such as storms, cold and snow events. However, the existing measures primarily address the characteristics of past climate hazard patterns, which may not fully reflect the evolving climate hazard risk. As climate change projections suggest a likely increase in the frequency and/or intensity of climate extremes, the absence of effective adaptation measures could lead to increased levels of vulnerability. The above calls for a more forward-looking and proactive approach to enhance the current levels of adaptability.

A better understanding of climate hazards and related implications can support integrating climate-hazard-focused considerations into airport resilience planning. While the regional airports may need to conduct detailed climate hazard risk assessments (for instance, flood

risk assessment) for specific high-risk scenarios, ACRI provided the basis for identifying vulnerabilities and ways to build more capacity for the airport system. The above can support the prioritisation of risk mitigation action, considering the level of sensitivity of exposed elements and the potential for impact.

The above findings raised critical questions about the effectiveness and forward-looking nature of existing adaptation measures in UK regional airports. They also brought the topic of climate hazard risk awareness and anticipation to the surface, influenced by the overall climate hazard risk perception. These topics indicate that the prioritisation of action to build adaptability is likely shaped by how airports perceive risk and related implications of climate hazard occurrences. Given the observed gaps in existing action to address climate hazards, the following research objective focused on key recommendations to mitigate climate hazard-related risks.

RO4 – *To recommend measures to increase airport climate resilience.*

While research objectives 1 to 3 enabled the development and validation of the framework, to address RO4, specific recommendations were provided to the regional airports to mitigate the identified risks. Thus, **Chapter 5** focused on identifying opportunities to strengthen the regional airports' resilience to climate hazards.

The recommendation of measures considered a levelled approach. **Chapter 2** provided an analysis of applied practices to address climate-related implications. In **Chapter 3**, the conceptualisation of adaptability revealed certain qualities airports should demonstrate to address climate hazard-related risks. The analysis outcome in **Chapter 4** identified opportunities to reduce exposure and vulnerability. The categorisation of recommendations in **Chapter 5** incorporated these findings and explored how certain qualities can be integrated into existing strategies, such as risk, resilience and sustainability-focused strategies.

When exploring adaptability options, the recommendations considered how airports understand the impacts of climate hazards and their system-wide implications. This analysis examined whether existing practices allow the airport to adjust to climate extremes and improve decision-making for planning and operations. Also, the analysis identified elements that shape the learning ability and the overall transformation process to better cope with disruptions at a system level. The categorisation of recommendations

addressed climate hazard risk intelligence to allow assessing risks and vulnerabilities to inform decision-making, strengthening assets through design enhancements, resilient materials and protection measures, and adjusting operations to become more flexible. Additionally, it reflected actions to enhance the emergency response and preparedness mechanism, environmental sustainability, and people's adaptability, as well as actions that would allow the integration of climate risk into strategic planning and compliance.

Research findings for all regional airports revealed the need for effective adaptation planning. Although all regional airports implement measures to address climate hazards, they do not present a formal adaptation plan. Therefore, developing an adaptation plan with short- and long-term measures would enable airports to act proactively, allowing continuous improvement over the longer term, considering the evolving climate hazard profiles. Decision-making regarding these actions can be supported by a comprehensive climate hazard risk assessment focused on critical issues identified in this research.

Integrating climate risk into the broader risk management will ensure accountability and prioritisation of action, allowing risks to be systematically addressed. Building adaptability to climate hazards of concern should be incorporated into the decision-making process to allow the prioritisation of action to address vulnerabilities and enhance response and business continuity mechanisms proactively, the allocation of resources, ensuring sufficient capacity of airport staff to deliver action, and the coordination among departments. The above would lead to a more forward-looking approach to climate resilience planning.

Regional airports should pursue improvements to existing critical infrastructure and assets to ensure they remain resilient to the evolving climate hazard profiles. It is essential to acknowledge that many of the airports' assets were initially designed based on historical climate parameters and patterns. Therefore, enhancements should account for observed or projected extremes, such as increased precipitation, heat, or wind resistance. A proactive approach that allows the integration of future climate scenarios into the asset design and maintenance will ensure these assets maintain their functionality under extreme climate conditions.

In addition, airports should consider the interactions with the environment in which they operate and integrate environmental considerations into the broader climate hazard

management and adaptation strategies. The choice of nature-based solutions, like sustainable drainage systems, bio-architectural interventions, or green infrastructure, can build more resilience while reducing the overall environmental impact. Also, having dedicated water and wildlife management plans can further contribute to long-term environmental sustainability.

The research also revealed the need for regional airports to build climate risk awareness among airport staff and stakeholders while strengthening communication and coordination elements. Having targeted training programs and knowledge-sharing initiatives will enhance the current level of knowledge, building a better understanding of the implications of climate hazards at the system level. The above will enable shaping the perception of climate hazard-related risk, recognising vulnerability and anticipating potential damage and disruption. In addition, greater climate risk awareness can enable informed decision-making, which is associated with prioritising action and allocating resources, strengthening the overall capacity to address climate hazard challenges. Also, strengthening existing communication and coordination mechanisms, both internally and externally, will allow for a more effective response and preparedness.

The findings raised several questions regarding the importance of enhancing climate resilience in regional airports through strategic adaptation planning, climate hazard risk assessment and proactive infrastructure improvements. In addition, they highlight the need to integrate climate risk into broader risk management, build climate hazard awareness, strengthen emergency response and preparedness, and consider environmental sustainability. Although these topics emerge from researching four airports and may not fully capture the diverse context of all UK regional airports, the research offers several valuable contributions presented in the following sections.

6.2 Research contributions

The development of the ACRI tool and the research undertaken in this thesis represent significant contributions to policy and practice and the broader research landscape. These original contributions are detailed below.

6.2.1 Enhancing the Airport Climate Risk Assessment Process

As highlighted in the literature review in Chapter 2, while airports are often aware of the issues they face concerning climate hazards and risk, they often face challenges in terms of the hazard and risk assessment process. These challenges typically relate to issues of accuracy, data requirements, or often complex or unwieldy models that can be costly to operate. By developing an accurate yet accessible tool for practitioners, the ACRI represents a fundamental contribution to airports' climate and hazard risk assessment process. The contribution is even more important for regional airports, which typically rely on solutions that lack specialised tools that address climate hazard-related considerations or do not have specialists to use them.

The development of the ACRI tool, designed for UK airports as an easy-to-use self-assessment tool, supports airports in identifying, analysing, and assessing potential risks resulting from climate-related hazards. Using sets of indicators, the tool enables the development of the airport's climate hazard profile, the analysis of its exposure and vulnerability to the identified climate hazards and the analysis of its ability to adapt to climate extremes.

One of the characteristics of the tool is the novelty of its design. While it uses regional airports for its validation, it is designed to be applicable to all UK airports, regardless of size or geographic location. This broad applicability ensures that a wide range of airports can use the tool, from small to larger ones. The tool allows airports to self-analyse the climate hazard-related risks relevant to their site, drawing conclusions and identifying areas for consideration. Additionally, the tool has user-friendly elements; it has been developed in MS Excel, making it easily accessible for airport teams without needing specialised software. Crucially, manipulating the tool does not require significant prior knowledge or training in climate hazard risk or climate sciences, increasing the accessibility and usefulness of the tool. This is important in the case of regional airports, which often lack resources with climate hazard science knowledge.

The overall research highlights the need for airports to analyse climate hazard-related risks. The research findings contribute to understanding the implications while pointing out issues that should be included in climate risk and resilience discussions. The conceptualisation of the framework and the development of the tool offer a guide for the airports to follow to identify elements they need to address to build more adaptability.

ACRI has been developed to become an easy-to-use self-assessment tool for airports to better understand the issues that should be included in the discussions around climate hazard risk and resilience. It allows the identification of gaps in the existing level of adaptability, which in turn supports informed decision-making on the prioritisation of risk mitigation action over the short and long term. This analysis can be used to develop a more robust adaptation plan. In the case of regional airports, the tool's contribution is even more significant as it allows airports with limited resources to conduct meaningful assessments that allow decision-making on proactive adaptation action.

The way it is structured and how it addresses the climate risk-related issues supports greater engagement between the teams and allows methodically looking at relevant topics, identifying areas that are not typically considered in current risk management practices, especially in the case of climate hazard events that historically only caused minimum impact and are not given attention. In addition, ACRI can be used as a communication and awareness tool to inform internal (including management teams) and external stakeholders of the potential risk and related implications, as well as of undertaken or planned initiatives to address the different aspects. Additionally, it can support airports in addressing current and future requirements related to climate hazards, as lately, financial institutions and regulatory authorities have put emphasis on developing adaptation plans.

The value and contributions of the research were further validated through its presentation to senior practitioners at Eurocontrol, the UK CAA, Airports UK, and the regional airports participating in the pilot study. This validation process allowed for critical feedback from experts, who confirmed that ACRI is a valuable contribution to the industry. It is a tool that enables airports to identify opportunities to build more adaptability, supporting prioritisation of action and informed decision-making.

6.2.2 Contribution to knowledge

The process of developing the ACRI tool covered a range of topics linked to climate hazards, implications to the airport system, exposure of airport elements, sensitivity or predisposition of critical elements, adaptability of the airport as a system and climate risk analysis. The main themes and important contributions to knowledge are discussed in the following paragraphs.

1 Furthering knowledge on the impacts of climate change on airports and their assessment.

As identified in the literature review, while there is a general awareness and recognition that there will be increasing impacts on aviation from climate change, scientific research is needed to focus specifically on these impacts at the airport level. Fundamentally, this thesis contributes to an important growing area of research; by building on the existing literature on climate hazards, risk and adaptation, it provides insights into the primary climate factors affecting airports' infrastructure and operations and related physical, operational or business risks. Using the demonstrated sensitivity of airports around the world, the conducted analysis identified different types of impact on exposed and/or vulnerable airports, ranging from the loss of airport infrastructure and damage of assets to service disruption, economic cost, impact on performance, safety, access, environment but also on reputation and investments and air travel demand. The overall process brought issues that should be considered under a constantly changing climate. Furthermore, it pointed out elements that influence the airports' ability to address climate hazard effects efficiently.

2 How climate risk is analysed and assessed for airports.

A key driver to better understanding and mitigating climate hazards and risks for airports is the risk assessment and analysis process. As discussed in Chapter 2, there is a great diversity in how risks are assessed and acted upon for airports. This work seeks to address these challenges by presenting an accurate but parsimonious tool for practitioners to self-assess their levels of climate hazard risk and its determinants.

An important contribution to knowledge emerges from the conceptualisation of the research problem and the development of the tool. The development of the ACRI tool looks at the concept of climate risk from a different perspective, rebalancing the focus from the physical vulnerability of assets to the broader business and operational aspects and attributes that shape the airport's adaptability to climate hazards. As a composite index, the tool integrates a set of indicators and variables tailored to the airport context, quantifying the airport's capacity to advance climate adaptation. Using the developed set of indicators and variables provides a way to enable consistent and comparable evaluations across different airport contexts.

The conceptualisation of the tool demonstrated that climate risk can be analysed by looking at the following four main risk determinants: (a) climate hazard profile, including the influence of climate change; (b) the range of airport elements that can be affected by a climate hazard event; (c) the tendency of exposed airport elements to be adversely affected by a climate hazard event; and (d) the ability of the airport to adjust its functions, learn to anticipate, prepare and respond to a climate hazard event.

The adopted methodological approach incorporates concepts that reflect the complex and systemic character of the airport, with a series of interdependencies and interrelationships, elements that drive the risk, including elements that influence the risk perception, as well as organisational culture elements that shape how decisions are made on climate hazard-related matters. Besides offering a new perspective on climate hazard risk analysis, the overall approach can be used as a decision-making point of reference for climate adaptation and risk reduction plans, providing insights into qualities that airports need to demonstrate to strengthen their capacity and shift towards a more informed risk management culture.

3 Exploring climate hazard risks and adaptation strategies for regional airports

An important contribution of this research is its focus on regional airports, a topic that is relatively underexplored in existing literature, particularly in the context of climate hazards. Regional airports play a critical part in the UK's air transport system, supporting regional development, enhancing accessibility and improving connectivity. Despite their importance, they face unique challenges due to their limited resources and infrastructure. This research provides a deeper understanding of the regional airports' vulnerabilities to the addressed climate hazards, offering valuable insight into the gaps within existing protection and preparedness mechanisms, how regional airports perceive climate hazard risk and how the overall risk management can be shaped to address climate hazard-related risks.

4 How the risk determinants can be defined.

Given the complexity of the climate hazard risk determinants, the research introduced various sets of variables for measurement. In many instances, the selection of these variables and their measurement were adapted or inspired from studies across different

contexts (for example, urban or other infrastructure systems) after adjustment to fit the airport context.

Climate hazards are quantified by considering both current and future climate hazard levels and confidence in the direction of change. The novelty of this approach lies in integrating multiple climate metrics from sources such as the IPCC and the UKCP18, which provide a dynamic and forward-looking analysis. The adaptation of the varying climate variables to a unified 5- or 3-point scale adds to its originality, while at the same time, the calibration process supports a standardised framework.

Exposure uses four key indicators (critical assets, operations, people and interdependencies), each one measured using variables adapted from urban systems yet modified to reflect the airport context. The integrated variables address physical, business, economic and social dimensions of exposure while incorporating interdependencies between essential systems, such as surface transport and utilities. The approach is innovative as it combines established risk modelling concepts with customised variables and scales specific to the airport environment.

The measurement of vulnerability introduces a novel perspective by integrating and adapting a mixture of methods from climatic change or natural hazard research to the unique context of airports. This approach looks at key factors that influence the airport's predisposition to loss or disruption, incorporates historical data to analyse the airport's sensitivity to climate hazards, and indicates the magnitude of the potential impact by mapping significant past occurrences. Unlike existing approaches that primarily focus on physical or social vulnerability, the variables used in the framework also address business and economic aspects, further enhancing its originality.

The measurement of adaptability introduces a novel perspective by integrating and customising variables used in climatic change or natural hazard research to the specific context of airports. The adopted approach looks at the airport's efforts to adapt, enhance preparedness, anticipate, and manage climate hazard events, along with the qualities that enable an effective response and efficient recovery. Unlike conventional approaches that mainly focus on protection and preparedness measures, the way adaptability is perceived incorporates elements to reflect the airport's understanding of the climate hazard

implications, level of awareness and proactiveness in implementation, further demonstrating its originality.

5 How adaptation measures can be categorised.

The research supported a greater understanding of how airports are currently addressing existing climate stressors and the main actions to adjust to a changing climate. Considering the category of action undertaken by airports, climate risk mitigation measures can be categorised as infrastructure improvement and protection measures, operational response and preparedness, knowledge and awareness of the risk and governance and institutional capacity (Voskaki, Budd and Mason, 2023)

In addition, the research introduced a structured categorisation of options to build more adaptability. Options to build adaptability have been considered in the context of seven categories, reflecting the different qualities airports should demonstrate to reduce climate hazard-related risk: (a) climate hazard intelligence, (b) climate-proofing assets, (c) flexible and adaptable operations, (d) emergency response and preparedness, (e) sustainable interactions, (f) passenger and workforce adaptability and (g) climate-embedded governance. The above categorisation provides a structured and systematic approach to analysing actions to mitigate climate hazard-related risks. Even though this approach has been developed to be applied in the airport context, it can be easily adapted to other types of infrastructure.

6.2.3 Implications for policy

The observed shift in how airports approach climate hazard-related disruptions underlines the significance of having appropriate tools for analysing climate risk to support decision-making. Nowadays, many airports are called to present climate risk mitigation strategies to communicate actions, demonstrate compliance or address financial requirements. In the UK context, the Climate Change Act 2008 puts emphasis on the climate change adaptation of critical sectors and calls for sectors to undertake climate change risk assessments every 5 years. However, despite aviation's critical role, there is currently no mandated and standardised approach to climate risk assessment specific to airports. Introducing such a mandate would ensure that climate risks are systematically identified and addressed across the sector.

Conducting a climate risk assessment can provide the basis for understanding the potential implications, allowing the prioritisation of adaptation action. In this context, the development of the ACRI tool can support the enhancement and standardisation of the climate risk assessment process, serving as a framework for airports to analyse climate hazard-related risks consistently across the different UK regions. From the airport management perspective, standardisation can enable decision-making and efficient resource allocation where it is most needed, optimising adaptation efforts across different airport areas. From the policymaker's perspective, its application can ensure consistency, enabling the comparison of different climate hazard risk mitigation efforts regardless of each airport's geographic location, size, or type of management.

6.3 Research limitations

While the research presents several contributions, some considerations must be acknowledged, particularly around the sample size and focus. While the case study airports validate the tool, they are limited in number and geographic coverage. Expanding the application to a broader range of airports across diverse geographies and of varying sizes would further enhance the generalisability of the findings. Nevertheless, the selected case study airports are located in different parts of the UK, and as a result, they are exposed to distinct climate hazards or varying frequency or intensity of the same climate hazard type. Therefore, they offer diversity in terms of challenges they must address, requiring tailored risk mitigation strategies. Examining how airports respond to climate hazards allowed the research to generate valuable insights into how regional airports perceive climate hazard risk, prioritise adaptation action and implement mitigation measures.

Although the tool is developed for and can be used by all airports, the validation of the tool focused on regional airports handling less than 7 million passengers per annum. Overall, regional medium-sized and small airports seem to gain significant benefits from this research, considering the limited resources available for dedicated studies. The overall validation process allowed meaningful discussions, interaction and valuable feedback during the development phase, from the topics it addresses to the overall usefulness and practicality.

Validation was conducted at different stages; data collection was carried out through face-to-face workshops and in-depth discussions with airport specialists. The participating

teams represented a range of specialisations, including business continuity, safety, compliance, fire service, fuel service, airfield management, energy, environment, sustainability and other management-focused functions. The airport teams worked closely and collaboratively to provide the necessary data for their airport, engaging in discussions on how information is captured, how the indicators are calculated and how the results are interpreted. The above approach resulted in accuracy in the responses, with high-quality input data enabling meaningful results. Without a doubt, as with any assessment tool, its effectiveness inherently depends on the data's reliability and accuracy.

Although the sample size of four regional airports is limited, their validation of the tool's concept, usability, and usefulness remains valuable. Given the limited number of regional airports in the UK, this sample size is considered adequate for the purpose of validating the tool. The above is supported by the direct engagement with the airport teams, which allowed for obtaining high-quality input data. The discussions offered valuable insights, allowing for a thorough validation of both the tool's output and the adopted methodological approach for its development, reinforcing its relevance in the overall process of analysis of climate hazard-related risks.

Therefore, the research remains valuable despite the sample size, airport size, and geographical coverage. It highlights similarities and differences in applied climate hazard risk mitigation strategies and investigates the challenges airport teams are called to address in the face of climate change. Moreover, it explores how climate hazard risk is perceived and how existing risk management frameworks can be shaped to be suitable for the future. The above findings offer a solid foundation for validating the tool and contribute to a broader understanding of the airport management culture driving climate adaptation.

The data collection process using the incorporated questionnaire reflects the current scenario and the airport's responses to climate hazard risks, demonstrating the existing levels of exposure and vulnerability. However, due to the dynamic nature of these concepts, the results are subject to change after significant events affecting the airports. For example, Exeter completed the questionnaire one month before the September 2023 flood caused the airport's closure. As a result, the analysis did not capture this specific incident when measuring vulnerability aspects. The flood risk level would have been different if the airport had completed the questionnaire after the flood event. Nevertheless, this is not a significant limitation, considering the dynamic nature of the tool, which is

designed to accommodate change easily. Airports can easily update the relevant sections to reflect changes in exposure, vulnerability or adaptability after the occurrence of significant events. The ease of adjustment allows a dynamic view of risk, enabling airports to monitor their analysis continuously and adjust their actions to reflect real-time conditions.

The incorporation of only one climate scenario and time horizon in the measurement of future climate hazard levels can be viewed as a limitation of the tool, as it could restrict airports from considering the full range of potential impacts or climate variability. ACRI incorporates climate variables that consider only the intermediate climate scenario (RCP4.5) and 2050 as the time horizon. Nevertheless, by using just one climate scenario and a one-time horizon aligned with the broader climate target plan in the UK, the tool simplifies the analysis while allowing meaningful insights into the climate hazard risk aspects. In addition, considering the dynamic nature of the tool, a different climate scenario can easily be incorporated if needed. Users can easily choose a different climate scenario and update the tool with the new data. In fact, users can even add multiple scenarios, increasing the complexity of the analysis as needed.

The tool is developed in MS Excel; therefore, certain limitations need to be acknowledged regarding how data is captured, analysed and presented. The questionnaire uses drop-down menus to provide the options for the user to choose from, and calculations require the use of many tabs. A specialised data analysis software could have provided a more efficient way to manage data and complex functions. Also, the results are presented in a tabular and graphical format without allowing customised views, as other software might do. Furthermore, it requires manual updates and changes to data. Nevertheless, Excel is a widely accessible and user-friendly platform; due to its accessibility and familiarity to users it is considered a practical choice. Future enhancements of the tool could benefit from exploring other platforms offering more enhanced capabilities.

Another consideration is the dependency of the quality of the results on the quality and accuracy of the input data. The tool relies on the user's input through the questionnaire; therefore, any errors or inconsistencies in the provided data could affect the reliability of the results. Furthermore, subjective judgements when selecting from the available options could potentially introduce variability in the results. Nevertheless, this limitation is not significant as the tool is designed with the understanding that the results are reliant on the

user's responses to the questionnaire. Additionally, the dynamic nature of the tool allows users to amend their responses and refine the input data as needed to ensure it reflects current-day conditions.

6.4 Directions for future research

While this research conceptualised and developed a framework and a composite indicator-based tool for analysing climate hazard-related risks at UK airports, it identified areas for research beyond the scope of this study. Future research can build on the existing framework, enhancing and expanding the tool's applicability.

1 Incorporating additional climate hazards

In its current state, the tool addresses seven (7) climate hazard types, namely, coastal flood, inland (fluvial/pluvial) flood, extreme heat, cold and icing conditions, storminess and wind, snowstorm and extreme snowfall and drought/water scarcity. In a UK context, as climate changes, other climate hazards can become a concern and, therefore, can be incorporated into the tool. For example, although wildfires are not considered relevant in a UK context, extreme heat and drought can create conditions that give rise to wildfires, posing risks to airport operations. The tool can be easily adapted to incorporate more climate hazards in the analysis.

2 Transferability to other geographies

Considering that climate hazards are location-specific, the development of the index focused on explicit geography. The UK was selected, and the framework considered climate hazards applicable to the UK context. Future research can shape the tool to include other countries. This can be done by amending the set of variables included in the climate hazard indicators to reflect the conditions in the new geography. Discussions with Eurocontrol around the expansion of the tool beyond the UK highlighted an opportunity to expand its applicability to a broader European context or even beyond Europe. This could involve analysing climate hazards affecting airports beyond the UK borders, such as wildfires, looking at the climate hazard-related metrics and climate change projections and shaping the climate hazard variables to address additional locations.

3 Expand to incorporate innovation and new developments

Considering that aviation is rapidly evolving, emphasis has been placed on sustainability and the transition towards alternative energy sources (for instance, hydrogen). As airports prepare to accommodate these changes, it is essential to ensure that future assets are designed to be resilient to climate hazards. Future research can shape the tool to address these challenges by including specific variables to quantify exposure, vulnerability, and adaptability aspects that are currently not within the scope of this research.

4 Assign weights to reflect the level of significance

In its current state, the tool incorporates variables and indicators equally, and no weighting has been assigned to reflect the level of importance of different elements or different climate hazards. A future iteration of the tool can consider the level of importance airport practitioners or airport specialists give to the different airport elements or the level of importance different climate hazards have in terms of disruption.

5 Incorporating multi-hazards

Currently, the tool addresses individual hazards and does not account for a series of single hazards affecting an airport, causing ripple effects and cascading impacts, typically called multi-hazards. Multi-hazard occurrences can generally lead to more significant impacts compared to individual hazards (Hochrainer-Stigler *et al.*, 2023), and their conceptualisation has received lots of attention in recent years. Future research can shape the tool to address multi-hazard occurrences and how they can influence the climate hazard risk.

6 Transferability to other sectors

While the tool was initially developed for airports, it has the potential to be adapted for use in other sectors of infrastructure as part of future research. The conceptualisation and how it addresses climate hazards, exposure, vulnerability and adaptability can be tailored to apply to a wide range of infrastructure types and urban systems. The tool can be customised by adjusting the variables, indicators and certain elements to incorporate specific characteristics and requirements of each sector, allowing for a broader application across different sectors.

6.5 Conclusions

Climate hazards impact airports worldwide, leading to infrastructure damage, operational and safety challenges, financial losses, and broader environmental and social impacts. Climate extremes are expected to escalate as climate changes, placing additional pressure on airport infrastructure and operations. In recent years, UK airports have dealt with the implications of record-breaking temperatures, severe storms, snowstorms, and even drought events. Implementing effective climate risk reduction measures is important to address these emerging challenges, and airports with greater adaptive capacity are generally presented as more qualified to respond to and recover from a disruptive event quickly and efficiently.

The research provided insights into how climate hazards are perceived and how this perception influences the overall risk management process. Climate hazards are often treated as short-term operational challenges rather than long-term risks with potential for system-wide implications. This shapes the culture of risk management, including what is perceived as a threat, how it can be assessed and how it can be mitigated. Therefore, the way climate hazard risk is analysed eventually affects the prioritisation of action. Thus, having the right approach when analysing climate hazard risk is crucial to ensure that threats will be identified and appropriately addressed.

The research also brought to the surface the topic of the effectiveness of existing risk mitigation measures and whether they have been designed to address the intensity and characteristics of the observed climate hazard events. While regional airports appear to have measures in place to address climate hazards of concern, the demonstrated level of sensitivity in the past decade suggests that the implemented measures need to be enhanced to address the level of extreme of the future. This observation highlights the need for a monitoring mechanism to evaluate the effectiveness of existing or planned measures considering the climate hazard trends and the anticipated nature of extremes.

Addressing climate hazard risks effectively demands an in-depth understanding of their complexities and evolving nature and a willingness to drive the necessary transformations in existing airport risk management practices. A more proactive approach is essential to allow the integration of climate hazard-related risk into long-term planning, infrastructure

development and investment decisions. Building more adaptability within the airport elements appears necessary to enable the regional airports to grow sustainably.

The PhD research met the set aim, as demonstrated by this thesis, by developing a framework to analyse the risk of climate hazards to the airport system under current and future climate change projections. To achieve this, the key climate hazards, their impact and implications on the airport system were investigated, and the gap in the current capabilities of climate hazard risk analysis frameworks was identified in Chapter 2. Elements around the definition of climate hazard risk, focused on aspects of exposure and vulnerability of the airport system to climate hazards, were explored in Chapters 2 and 3. The conceptualisation and methodological approach and the ACRI tool were developed in Chapter 3, where the key elements defining the main risk determinants and addressing operational and compliance aspects were discussed. The framework was applied to four (4) case study regional airports, validating the tool, and an analysis of the outcome for the main climate hazard risk determinants was included in Chapter 4. Discussion on the climate hazard risk levels and recommendations of measures the regional airports can undertake to increase their climate resilience were provided in Chapter 5.

As a closing remark, this thesis offers perspectives, interpretations, and practical contributions, and it aims to support airports in better understanding and managing climate hazard-related risks. Without a doubt, constant change is part of all natural processes, and the ability to transform and adapt is part of human nature. Finding ways to shape our environment and systems to be flexible, enabling change, is key. This work supports that progress.

References

- ACI (2018) *Airports' resilience and adaptation to a changing climate*. Available at: www.aci.aero.
- ACI Europe (2022) *Airport industry connectivity report 2022*. Available at: <https://www.aci-europe.org/downloads/resources/CONNECTIVITY%20REPORT%202022.pdf>.
- Adger, W.N. (2006) 'Vulnerability', *Global Environmental Change*, 16, pp. 268–281.
- Adger, W.N., Arnell, N.W. and Tompkins, E.L. (2005) 'Successful adaptation to climate change across scales', *Global Environmental Change*, 15(2), pp. 77–86.
- Adler, N., Ülkü, T. and Yazhensky, E. (2013) 'Small regional airport sustainability: Lessons from benchmarking', *Journal of Air Transport Management*, 33, pp. 22–31.
- Aeroporto di Bologna (2018) *Q1 2018 Results*. Available at: <https://www.bologna-airport.it/>.
- Air Transport Action Group (2024) *Aviation benefits beyond borders – Global summary*. Available at: <https://aviationbenefits.org/downloads/aviation-benefits-beyond-borders-2024/>.
- Al-Abdul Wahhab, H.I., Ramadhan, R.H. and Asi, I.M. (1994) 'Temperature impact on pavement structures in hot arid environment', *Journal of Materials in Civil Engineering*, 6(1), pp. 1–15.
- De Almeida, L.Q., Welle, T. and Birkmann, J. (2016a) 'Climate risk and response: Physical hazards and socioeconomic impacts', in *Proceedings of the International ISCRAM Conference. Information Systems for Crisis Response and Management (ISCRAM)*.
- De Almeida, L.Q., Welle, T. and Birkmann, J. (2016b) 'Disaster risk indicators in Brazil: A proposal based on the world risk index', *International Journal of Disaster Risk Reduction*, 17, pp. 251–272.
- Apel, H. et al. (2004) 'Flood risk assessment and associated uncertainty', *Natural Hazards and Earth System Science*, 4(2), pp. 295–308.
- Arbuthnott, K.G. and Hajat, S. (2017) 'The health effects of hotter summers and heat waves in the population of the United Kingdom: A review of the evidence', *Environmental Health: A Global Access Science Source*, 16(1), pp. 1–13.

Balica, S.F., Wright, N.G. and van der Meulen, F. (2012) 'A flood vulnerability index for coastal cities and its use in assessing climate change impacts', *Natural Hazards*, 64(1), pp. 73–105.

Becker, A. et al. (2018) 'Implications of climate change for shipping: Ports and supply chains', *WIREs Climate Change*, 9(2), p. e508.

Begg, I. et al. (2011) *Report of the Heathrow Winter Resilience Enquiry*. Available at: https://www.icax.co.uk/pdf/BeggReport220311_BAA.pdf.

Belfast International Airport (2024a) *Belfast International Airport*. Available at: <https://www.belfastairport.com/>.

Belfast International Airport (2024b) 'Terminal Extension', *Belfast International Airport*. Available at: <https://www.belfastairport.com/more/airport-info/terminal-extension>.

Berkhout, F., Hertin, J. and Arnell, N. (2004) *Business and climate change: Measuring and enhancing adaptive capacity*. Technical Report 11. Norwich: Tyndall Centre for Climate Change Research. Available at: https://tyndall.ac.uk/wp-content/uploads/2021/11/it1_23-1.pdf.

Berman, R., Quinn, C. and Paavola, J. (2012) 'The role of institutions in the transformation of coping capacity to sustainable adaptive capacity', *Environmental Development*, 2(1), pp. 86–100.

Bernie, D. et al. (2018) *UKCP18 Applied Projections of Future Climate over the UK*. Available at: <https://www.metoffice.gov.uk>.

Birkmann, J. (2013) 'Exposure to natural hazards', in Bobrowsky, P.T. (ed.) *Encyclopedia of Natural Hazards*. Dordrecht: Springer Netherlands, pp. 305–306.

Birkmann, J. et al. (2013) 'Framing vulnerability, risk and societal responses: The MOVE framework', *Natural Hazards*, 67(2), pp. 193–211.

Blong, R. (2003) 'A review of damage intensity scales', *Natural Hazards*, 29, pp. 57–76.

Borsky, S. and Unterberger, C. (2019) 'Bad weather and flight delays: The impact of sudden and slow onset weather events', *Economics of Transportation*, 18, pp. 10–26.

Boyd, M. (2024) 'Barcelona Airport on "Red Alert" as severe flooding cancels 50 flights', *Mirror*, 4 November. Available at: <https://www.mirror.co.uk/travel/europe/breaking-flights-cancelled-amid-red-34030928>.

Brooks, N. and Adger, N. (2005) 'Assessing and enhancing adaptive capacity', in Lim, B. and Spanger-Siegfried, E. (eds.) *Adaptation policy frameworks for climate change: Developing strategies, policies and measures*. Cambridge: Cambridge University Press, pp. 165–181.

Bubalo, B. (2012) 'Benchmarking European airports based on a profitability envelope', in *Proceedings of the Third International Conference on Computational Logistics*, pp. 171–189.

Burbidge, R. (2016) 'Adapting European airports to a changing climate', *Transportation Research Procedia*, 14, pp. 14–23.

Burbidge, R. (2017) 'Climate-proofing the airport of the future', *Journal of Airport Management*, 11(2), pp. 114–128.

Burbidge, R. (2018) 'Adapting aviation to a changing climate: Key priorities for action', *Journal of Air Transport Management*, 71, pp. 167–174.

Burbidge, R., Paling, C. and Dunk, R.M. (2023) 'A systematic review of adaption to climate change impacts in the aviation sector', *Transport Reviews*, 44(1), pp. 8–33.

Burbidge, R., Paling, C. and Dunk, R.M. (2025) 'Adapting Latin American and Caribbean airports to a changing climate: Impacts, challenges and solutions', *Climate Risk Management*, 47, p. 100684.

Calder, S. (2020) 'Storm Ciara: Travel chaos as hundreds of flights cancelled due to gale-force winds', *Independent*, 10 February. Available at: <https://www.independent.co.uk/travel/news-and-advice/storm-ciara-travel-flights-trains-cancelled-uk-weather-latest-british-airways-easyjet-a9325456.html>.

Calil, J. et al. (2017) 'Comparative Coastal Risk Index (CCRI): A multidisciplinary risk index for Latin America and the Caribbean', *PLoS ONE*, 12(11).

de Castro Carvalho, I. et al. (2013) 'Sustainable airport environments: A review of water conservation practices in airports', *Resources, Conservation & Recycling*, 74, pp. 27–36.

CCC (2024) *2024 Progress Report to Parliament*. Committee on Climate Change. Available at: <https://www.theccc.org.uk/publication/progress-in-reducing-emissions-2024-report-to-parliament/#publication-downloads>.

Chang, S.E. et al. (2007) 'Infrastructure failure interdependencies in extreme events: Power outage consequences in the 1998 Ice Storm', *Natural Hazards*, 41(2), pp. 337–358.

Chang, S.E. et al. (2018) 'Community vulnerability to coastal hazards: Developing a typology for disaster risk reduction', *Applied Geography*, 91, pp. 81–88.

Chatterton, J. et al. (2016) *The costs and impacts of the winter 2013 to 2014 floods*. Environment Agency. Available at: <https://www.gov.uk/government/publications>.

Chavda, S. (2024) 'The 2024 Spain Floods: Failures in Early Warning, Action, Coordination, and Localisation', *Global Network of Civil Society Organisations for Disaster Reduction*, December. Available at: <https://www.gndr.org/2024-spain-floods-early-warning-action-coordination-and-localisation/>.

Chen, Z. and Wang, Y. (2019) 'Impacts of severe weather events on high-speed rail and aviation delays', *Transportation Research Part D: Transport and Environment*, 69, pp. 168–183.

Christodoulou, A. and Demirel, H. (2017) *Impacts of climate change on transport: A focus on airports, seaports and inland waterways*. Available at: <https://ec.europa.eu/jrc>.

Climate ADAPT (2016) '3.1 Creating a catalogue of relevant adaptation options', in *Urban Adaptation Support Tool*. Available at: <https://climate-adapt.eea.europa.eu/en/knowledge/tools/urban-ast/step-3-1>.

Coffel, E. and Horton, R. (2015) 'Climate change and the impact of extreme temperatures on aviation', *Weather, Climate, and Society*, 7(1), pp. 94–102.

Coffel, E., Thompson, T. and Horton, R. (2017) 'The impacts of rising temperatures on aircraft take-off performance', *Climatic Change*, 144, pp. 381–388.

Commonwealth of Dominica (2015) *Rapid Damage and Impact Assessment Tropical Storm Erika - August 27, 2015*. Available at: <https://reliefweb.int/report/dominica/rapid-damage-and-impact-assessment-tropical-storm-erika-august-27-2015>.

Conger, S.A. and Mason, R.O. (2013) 'Systems Analysis', in *Encyclopedia of Operations Research and Management Science*. Boston, MA: Springer US, pp. 1523–1536.

Cools, M. et al. (2010) 'Changes in travel behavior in response to weather conditions. Do type of weather and trip purpose matter?', *Journal of the Transportation Research Board*, 2157, pp. 22–28.

Cutter, S.L. (2013) 'Vulnerability', in *Encyclopedia of Earth Sciences Series*. Springer Netherlands, pp. 1088–1090.

Cutter, S.L., Boruff, B.J. and Shirley, W.L. (2003) 'Social vulnerability to environmental hazards', *Social Science Quarterly*, 84(2), pp. 242–261.

Davis, B. (2022) 'Storm Eunice: All the London cancellations caused by red warning as hundreds of flights are hit', *The Standard*, 19 February. Available at: <https://www.standard.co.uk>.

Dawson, R. et al. (2016) *UK Climate Change Risk Assessment Evidence Report: Chapter 4, Infrastructure*. London. Available at: <https://www.theccc.org.uk/wp-content/uploads/2016/07/UK-CCRA-2017-Chapter-4-Infrastructure.pdf>.

Dawson, R.J. et al. (2018) 'A systems framework for national assessment of climate risks to infrastructure', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2121).

Debortoli, N.S. et al. (2019) 'An integrative climate change vulnerability index for Arctic aviation and marine transportation', *Nature Communications*, 10, p. 2596.

DEFRA (2011) *Climate Resilient Infrastructure: Preparing for a Changing Climate*. Available at: <https://www.defra.gov.uk>.

DEFRA (2021) *List of organisations reporting under adaptation reporting power: third round*. Available at: <https://www.gov.uk/government/publications/climate-change-adaptation-reporting-third-round/list-of-organisations-reporting-under-adaptation-reporting-power-third-round>.

Dekkers, R. (2017) *Applied Systems Theory*. 2nd edn. Edited by R. Dekkers. Springer International Publishing AG.

Demertzidis, N. et al. (2015) 'A benchmarking framework to evaluate business climate change risks: A practical tool suitable for investors decision-making process', *Climate Risk Management*, 10, pp. 95–105.

Department for Energy Security and Net Zero (2025) 'NESO review into the North Hyde Substation outage: terms of reference'. *Department for Energy Security and Net Zero*. Available at: <https://www.gov.uk/government/publications/review-into-the-north-hyde-substation-outage-terms-of-reference/neso-review-into-the-north-hyde-substation-outage-terms-of-reference>.

Dessai, S., Surminski, S., Watkiss, P. and Scobie, M. (eds) (2023) *Quantifying Climate Risk and Building Resilience in the UK*. Cham: Palgrave Macmillan

DfT (2022) *Jet Zero Strategy: Delivering net zero aviation by 2050*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1095952/jet-zero-strategy.pdf.

DfT (2024a) '£1.1 billion investment to expand Stansted Airport welcomed by ministers'. *Department for Transport*. Available at: <https://www.gov.uk/government/news/11-billion-investment-to-expand-stansted-airport-welcomed-by-ministers>.

DfT (2024b) *Climate Risk Assessment Guidance for the Transport Sector*. Available at: <https://assets.publishing.service.gov.uk/media/67d94416975fce529e32f459/dft-climate-risk-assessment-guidance.pdf>.

DfT (2024c) *Fit for a changing climate? Adapting the UK's transport system*. Available at: <https://assets.publishing.service.gov.uk/media/66152059c4c84de468346aea/dft-transport-adaptation-strategy-consultation.pdf>.

DfT (2025a) *Government update on airport expansion*. Available at: <https://www.gov.uk/government/publications/airport-capacity-and-expansion-a-government-update/government-update-on-airport-expansion>.

DfT (2025b) 'Securing the future of aviation'. *Department for Transport*. Available at: <https://www.gov.uk/government/speeches/securing-the-future-of-aviation>.

DfT (2025c) 'Transport planning: Gatwick Airport'. *Department for Transport*. Available at: <https://www.gov.uk/government/speeches/transport-planning-gatwick-airport>.

Dolinar, M. et al. (2010) 'Predicted changes in energy demands for heating and cooling due to climate change', *Physics and Chemistry of the Earth*, 35(1–2), pp. 100–106.

Dolman, N. (2016) 'Creating water sensitive airports in times of climate change', in *Singapore International Water Week 2016*. Singapore.

Dolman, N. and Vivekanandhan, S. (2022) 'Climate change impacts on airports and measures — case of Schiphol Airport', in *ICAO Environmental Report*. ICAO.

Dolman, N. and Vorage, P. (2019) 'Preparing Singapore Changi Airport for the effects of climate change', *Journal of Airport Management*, 14(1), pp. 54–66.

Donehue, P. and Baker, D. C. (2012) 'Remote, rural, and regional airports in Australia', *Transport Policy*, 24, pp. 232–239.

Dymnicki, A. et al. (2021) 'Development and validation of a measure of organizational capacity for implementing youth development programs', *Evaluation and Program Planning*, 86, p. 101916.

Easterling, D. R. et al. (2000) 'Climate extremes: Observations, modeling, and impacts', *Science*, American Association for the Advancement of Science, pp. 2068–2074.

Easterling, D. R. et al. (2016) 'Detection and attribution of climate extremes in the observed record', *Weather and Climate Extremes*, 11, pp. 17–27.

ECAC (2024) 'Adapting to climate change: Building a resilient future for aviation', *ECAC News*. Available at: https://www.ecac-ceac.org/images/news/ecac-news/ECAC_News_79_Environment.pdf

Edwards, B. (2005) *The modern airport terminal: New approaches to airport architecture*. 2nd ed. London and New York: Taylor & Francis Group.

Eidsvig, U., Kristensen, K. and Vangelsten, B. (2017) 'Assessing the risk posed by natural hazards to infrastructures', *Natural Hazards and Earth System Sciences*, 17(3), pp. 481–504.

Engle, N. L. (2011) 'Adaptive capacity and its assessment', *Global Environmental Change*, 21, pp. 647–656.

Eurocontrol (2021a) ‘Annex 3: Impact of sea level rise on European airport operations’, in *Climate Change Risks for European Aviation 2021*. Available at: www.eurocontrol.int

Eurocontrol (2021b) *Climate Change Risks for European Aviation*. Available at: www.eurocontrol.int

Eurocontrol (2021c) *Climate Change Risks for European Aviation 2021*. Annex 2: Impact of changes in storm patterns and intensity on flight operations. Available at: www.eurocontrol.int

Eurocontrol (2025) *Balanced Scorecard*. Available at: <https://www.eurocontrol.int/Economics/BalancedScorecard.html>

European Environment Agency (EEA) (2021) *Europe’s changing climate hazards - an index-based interactive EEA report*. Available at: <https://www.eea.europa.eu/publications/europes-changing-climate-hazards-1>

European Environment Agency (EEA) (2025) ‘The Adaptation Support Tool’, in *Climate Adapt*. Available at: <https://climate-adapt.eea.europa.eu/en/knowledge/tools/adaptation-support-tool>

European Union (2008) Council Directive 2008/114/EC of 8 December 2008 on the identification and designation of European critical infrastructures and the assessment of the need to improve their protection. *European Union*.

Exeter Airport (2023) *Airport reopens after flash flood shuts terminal*. Exeter Airport. Available at: <https://exeter-airport.co.uk/airport-reopens-after-flash-flood-shuts-terminal>.

Ferrulli, P. (2016) ‘Chapter 23: Resilient Architectural Design: Considerations in the Design of Airports to Withstand Climate Change Effects’, in W.L. Filho et al. (ed.) *Climate Change Adaptation, Resilience and Hazards*. Springer International Publishing, pp. 381–393. Available at: www.aci-na.org.

Field, C. B. et al. (2012) *Managing the risks of extreme events and disasters to advance climate change adaptation: Special report of the intergovernmental panel on climate change*. Available at: <https://www.ipcc.ch/>

Filonchyk, M. et al. (2024) 'Greenhouse gases emissions and global climate change: Examining the influence of CO₂, CH₄, and N₂O', *Science of the Total Environment*, 935.

Fisk, G. (2017) *Climate risks and adaptation pathways for coastal transport infrastructure. Guidelines for planning and adaptive responses*. Available at: https://coastadapt.com.au/sites/default/files/factsheets/RR7_Guidelines_Climate_Risks_Coastal_Transport.pdf

Freed, J. (2022) 'Luton Airport Runway Meltdown Shows That Airports Are Vulnerable to Climate Change', *Insurance Journal*, July. Available at: <https://www.insurancejournal.com>.

French Civil Aviation Authority (2016) *Airport Vulnerability to Climate Change*. Available at: www.stac.aviation-civile.gouv.fr.

Fuchs, S., Heiss, K. and Hübl, J. (2007) 'Towards an empirical vulnerability function for use in debris flow risk assessment', *Natural Hazards and Earth System Science*, European Geosciences Union, 7(5), pp. 495–506.

Füssel, H. M. and Klein, R. J. T. (2006) 'Climate change vulnerability assessments: An evolution of conceptual thinking', *Climatic Change*, pp. 301–329.

Gallina, V. et al. (2016) 'A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment', *Journal of Environmental Management*, Academic Press, 168, pp. 123–132.

Gambrell, J. (2024) 'Storm dumps heaviest rain ever recorded in desert nation of UAE, flooding roads and Dubai's airport', *Associated Press*. Available at: <https://apnews.com/article/uae-oman-rains-flooding-fatalities-7bf3881efbea998dfa4c1ed8d538217c>.

Gass, S. and Fu, M. (2013) 'System', in Gass, S. I. and Fu, M. C. (eds) *Encyclopedia of Operations Research and Management Science*. Boston, MA: Springer US, p. 1519.

Gössling, S., Humpe, A. and Bausch, T. (2020) 'Does “flight shame” affect social norms? Changing perspectives on the desirability of air travel in Germany', *Journal of Cleaner Production*, 266.

Gössling, S. and Lyle, C. (2021) 'Transition policies for climatically sustainable aviation', *Transport Reviews*, 41(5), pp. 643–658.

Graham, A. (2014) *Managing airports. An international perspective*. Fourth, Managing Airports. Fourth. Edited by Routledge. New York: Taylor & Francis Group.

Graham, B. and Guyer, C. (2000) 'The role of regional airports and air services in the United Kingdom', *Journal of Transport Geography*, 8(4), pp. 249–262.

Gratton, G. et al. (2020) 'The impacts of climate change on Greek airports', *Climatic Change*, 160(2), pp. 219–231.

Gratton, G. et al. (2022) 'Reviewing the impacts of climate change on air transport operations', *The Aeronautical Journal*, 126, pp. 209–221.

Grealish, R. (2025) 'Leeds Bradford Airport: Flights cancelled and runway closed as Yorkshire snow causes disruptions', *The Yorkshire Post*, 5 January. Available at: <https://www.yorkshirepost.co.uk>.

Griggs, G. (2020) 'Coastal Airports and Rising Sea Levels', *Journal of Coastal Research*, 36(5), pp. 1079–1092.

Gritten, D., Gillett, F. and Comerford, R. (2024) 'Dubai airport chaos as UAE and Oman reel from deadly storms', *BBC News*, 18 April. Available at: <https://www.bbc.co.uk/news/world-middle-east-68831408>.

Grønhøj, A. and Hubert, M. (2021) 'Are we a growing a green generation? Exploring young people's pro-environmental orientation over time'. Available at: <https://www.tandfonline.com/action/journalInformation?journalCode=rjmm20>.

Guest, G. et al. (2019) 'Incorporating the impacts of climate change into infrastructure life cycle assessments: A case study of pavement service life performance', *Journal of Industrial Ecology*, pp. 1–13.

Hallegatte, S. et al. (2011) 'Assessing climate change impacts, sea level rise and storm surge risk in port cities: a case study on Copenhagen', *Climatic Change*, 104, pp. 113–137.

Hanlon, H. M. et al. (2021) 'Future changes to high impact weather in the UK', *Climatic Change*, 166(3–4), pp. 1–23.

Hanson, S. et al. (2011) 'A global ranking of port cities with high exposure to climate extremes', *Climatic Change*, 104(1), pp. 89–111.

Harley, G., Timmis, A. and Budd, L. (2020) 'Factors affecting environmental practice adoption at small European airports: An investigation', *Transportation Research. Part D, Transport and Environment*, 88, p. 102572.

Harrigan, E. (2024) 'Lessons on (un)preparedness and (in)action from Spain', *PreventionWeb*, November. Available at: <https://www.preventionweb.net/news/lessons-unpreparedness-and-inaction-spain>.

Havko, J., Titko, M. and Kováčová, J. (2017) 'Vulnerability of the City Infrastructure as a Part of the Resilient City Concept', *Procedia Engineering*, 192, pp. 307–312.

Hellingrath, B. et al. (2015) 'Disaster Management Capacity Building at Airports and Seaports', in M. Klumpp et al. (eds.) *Humanitarian Logistics and Sustainability*. Switzerland: Springer International Publishing, pp. 87–112.

Higham, J. E. S. and Cohen, S. A. (2011) 'Canary in the coalmine: Norwegian attitudes towards climate change and extreme long-haul air travel to Aotearoa/New Zealand', *Tourism Management*, 32(1), pp. 98–105.

HM Government (2008) *Climate Change Act*. Available at: <https://www.legislation.gov.uk/ukpga/2008/27/introduction?view=plain>.

HM Government (2020) *National Risk Register: 2025 edition*. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/952959/6.6920_CO_CCS_s_National_Risk_Register_2020_11-1-21-FINAL.pdf.

HM Treasury (2024) *Task Force on Climate-related Financial Disclosure (TCFD) -aligned disclosure application guidance - Phase 1 and Phase 2*. Available at: <https://www.gov.uk/government/publications/tcfd-aligned-disclosure-application-guidance/task-force-on-climate-related-financial-disclosure-tcfd-aligned-disclosure-application-guidance>.

Hochrainer-Stigler, S. et al. (2023) 'Toward a framework for systemic multi-hazard and multi-risk assessment and management', *iScience*, 26(5), p. 106736.

Holmes, M. E. et al. (2024) 'Journal of Air Transport Management Australasian aviation climate change hazards: A systematic review', *Journal of Air Transport Management*, 121(April), p. 102670.

Hughes, L. (2022) 'Luton airport: Runway forced to close due to heatwave damage', *Luton Today*, 18 July. Available at: <https://www.lutontoday.co.uk/news/people/luton-airport-runway-forced-to-close-due-to-heatwave-damage-3772750>.

IATA (2012) *The impact of hurricane Sandy*. Available at: <https://www.iata.org/en/iata-repository/publications/economic-reports/impact-of-hurricane-sandy/>.

IATA (2017) *Assessing the impact of hurricanes Irma and Maria on aviation*. Available at: <https://www.iata.org/en/iata-repository/publications/economic-reports/assessing-the-impact-of-hurricanes-irma-and-maria-on-aviation/>.

IATA (2023) *The value of air transport to the United Kingdom*. Available at: <https://www.iata.org/en/iata-repository/publications/economic-reports/the-value-of-air-transport-to-united-kingdom/>

ICAO (2009) *Annex 14 to the Convention on International Civil Aviation International Civil Aviation - Aerodromes*. International Civil Aviation Organisation (ICAO). Available at: <https://www.icao.int/>.

ICAO (2013a) *Annex 19 to the Convention on International Civil Aviation - Safety Management*. Available at: <https://www.icao.int/>.

ICAO (2013b) *Doc 9859 Safety Management Manual (SMM)*. Available at: <https://www.icao.int/>.

ICAO (2018) *Climate Adaptation Synthesis 2018*. Available at: <https://www.icao.int>.

ICAO (2019a) *Destination Green: The Next Chapter - 2019 Environmental Report*. Available at: <https://www.icao.int/>.

ICAO (2019b) *Waste Management at Airports ECO AIRPORT TOOLKIT*. Available at: <https://www.icao.int/>.

ICAO (2020) *Effects of Climate Change on Aviation Business and Economics*. Available at: <https://www.icao.int/>.

ICAO (2021) *Climate Resilient Airports*. Available at: <https://www.icao.int/>.

ICAO (2022a) *Climate Change: Climate Risk Assessment, Adaptation and Resilience. Key Climate Change Vulnerabilities for Aviation Organisations*. <https://www.icao.int/>.

ICAO (2022b) *Climate Change: Climate Risk Assessment, Adaptation and Resilience. Key steps in Aviation Organisation Climate Change Risk Assessment and Adaptation Planning*. <https://www.icao.int/>.

ICAO (2022c) *Climate Change: Climate Risk Assessment, Adaptation and Resilience. Menu of Adaptation Options*. <https://www.icao.int/>.

IPCC (2012) *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*. Edited by S.T.F. Field C.B., Barros V., A.S.K. Qin D., Dokken D.J., Ebi K.L., Mastrandrea M.D., Mach K.J., Plattner G.-K., and M.P.M. (eds.). Cambridge, UK and New York, NY, USA: Cambridge University Press. Available at: <https://www.ipcc.ch/>.

IPCC (2014) *Climate Change 2014 Impacts, Adaptation and Vulnerability. Summary for Policymakers*. Cambridge: Cambridge University Press. Available at: <https://www.ipcc.ch/>.

IPCC (2018a) ‘Annex I: Glossary’, in Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.) *Global Warming of 1.5°C*. IPCC, pp. 541–562. Available at: <https://www.ipcc.ch/>.

IPCC (2018b) *Glossary IPCC SR1.5, IPCC Special Report on the impacts of global warming of 1.5°C*. Available at: <https://www.ipcc.ch/>.

IPCC (2021a) ‘*IPCC Interactive Atlas (Sixth Assessment Report)*’. Available at: <https://interactive-atlas.ipcc.ch/>.

IPCC (2021b) ‘*Summary for Policymakers*’, in Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.) *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, p. 41. Available at: <https://www.ipcc.ch/>.

IPCC (2022) ‘*Fact sheet - Europe Climate*’, in *Sixth Assessment Report*. Available at: <https://www.ipcc.ch/>.

IPCC (2023a) *Climate Change Synthesis Report*. Available at: <https://www.ipcc.ch/>.

IPCC (2023b) *Urgent climate action can secure a liveable future for all*. Available at: <https://www.ipcc.ch/>.

Jackson, L.E. (2013) ‘Frequency and Magnitude of Events’, in Bobrowsky, P.T. (ed.) *Encyclopedia of Natural Hazards*. Dordrecht: Springer Netherlands, pp. 359–363.

Johnson, A. et al. (2018) ‘Protecting the Shoreline of the San Francisco International Airport From Sea Level Rise’, in *36th International Conference on Coastal Engineering*, p. 42.

Kappes, M.S., Papathoma-Köhle, M. and Keiler, M. (2012) ‘Assessing physical vulnerability for multi-hazards using an indicator-based methodology’, *Applied Geography*, 32, pp. 577–590.

Kause, A. et al. (2022) ‘Confidence levels and likelihood terms in IPCC reports: a survey of experts from different scientific disciplines’, *Climatic Change*. Springer Netherlands, 173(1–2), pp. 1–18.

Kendon, E. et al. (2021) *Update to UKCP Local (2.2km) projections*. Available at: www.metoffice.gov.uk.

Kendon, M. (2022a) *Storm Dudley, Eunice & Franklin*. Available at: <https://www.metoffice.gov.uk>.

Kendon, M. (2022b) *Unprecedented extreme heatwave, July 2022, Met Office*. Available at: <https://www.metoffice.gov.uk>.

Kendon, M. et al. (2024) ‘State of the UK Climate 2023’, *International Journal of Climatology*, 44(S1), pp. 1–117.

Kiel, J. et al. (2016) ‘A Decision Support System for the Resilience of Critical Transport Infrastructure to Extreme Weather Events’, *Transportation Research Procedia*, 14, pp. 68–77.

Koetse, M.J. and Rietveld, P. (2009) 'The impact of climate change and weather on transport: An overview of empirical findings', *Transportation Research Part D*, 14, pp. 205–221.

Koetse, M.J. and Rietveld, P. (2012) 'Adaptation to Climate Change in the Transport Sector', *Transport Reviews*, 32(3), pp. 267–286.

Kollamthodi, S., Fordham, D. and Stephens, M. (2011) 'United Kingdom's Experience with Climate Change Adaptation and Transportation', *Transportation Research CIRCULAR*, E-C152, pp. 19–26.

Kotzee, I. and Reyers, B. (2016) 'Piloting a social-ecological index for measuring flood resilience: A composite index approach', *Ecological Indicators*. Elsevier, 60, pp. 45–53.

Kumar, L. and Taylor, S. (2015) 'Exposure of coastal built assets in the South Pacific to climate risks', *Nature Climate Change*. Nature Publishing Group, 5(11), pp. 992–996.

Kunz, M. et al. (2013) 'Investigation of superstorm Sandy 2012 in a multi-disciplinary approach', *Hazards Earth Syst. Sci. Discuss*, 1, pp. 625–679.

Lacoin, S., 2019. 'Climate Change Resilience Strategy-Redefining Flood Protection at Kansai International Airport', in ICAO Environmental Report. ICAO, pp. 263–267. Available at: <https://www.icao.int/>.

Larsen, O. M., 2015. 'Climate change is here to stay: Reviewing the impact of climate change on airport infrastructure', *Journal of Airport Management*, 9(3), pp. 264–269.

Lee, D. S. et al., 2009. 'Aviation and global climate change in the 21st century', *Atmospheric Environment*. Pergamon, 43(22–23), pp. 3520–3537.

Lee, D. S. et al., 2021. 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018', *Atmospheric Environment*, 244(July 2020).

Leeds Bradford Airport, 2025. 'FIRST LOOK: LEEDS BRADFORD AIRPORT UNVEILS FIRST ANIMATION OF TERMINAL EXPANSION'. Leeds Bradford Airport. Available at: <https://www.leedsbradfordairport.co.uk/the-latest/first-look-leeds-bradford-airport-unveils-first-animation-of-terminal-expansion>.

Li, H. et al., 2016. 'A New Quantitative Method for Studying the Vulnerability of Civil Aviation Network System to Spatially Localized Hazards', *International Journal of Disaster Risk Science*. Beijing Normal University Press, 7(3), pp. 245–256.

Lindbergh, S., Ju, Y., et al., 2022. 'Cross-sectoral and multiscalar exposure assessment to advance climate adaptation policy: The case of future coastal flooding of California's airports', *Climate Risk Management*. Elsevier, 38, p. 100462.

Lindbergh, S., Reed, J., et al., 2022. 'Decoding climate adaptation governance: A sociotechnical perspective of U.S. airports', *Journal of Cleaner Production*. Elsevier Ltd, 334, p. 130118.

London Heathrow Airport, 2011. *Heathrow Airport Climate Change Adaptation*. Available at: <https://www.heathrow.com>.

London Heathrow Airport, 2016. *Climate Change Adaptation and Resilience Progress Report*. Available at: <https://www.heathrow.com>.

London Heathrow Airport, 2022. *Climate Change Adaptation Report*. Available at: <https://www.heathrow.com>.

London Luton Airport, 2021. *Climate Change Adaptation Report (CCAR)*. Available at: <https://www.gov.uk/government/publications/climate-adaption-reporting-third-round-luton-airport>.

Lopez, A., 2016. 'Vulnerability of airports on climate change: an assessment methodology', *Transportation Research Procedia*, 14, pp. 24–31.

Lu, C., 2018. 'When will biofuels be economically feasible for commercial flights? Considering the difference between environmental benefits and fuel purchase costs', *Journal of Cleaner Production*. Elsevier Ltd, 181, pp. 365–373.

Makuyana, T., Nhamo, G. and Dube, K., 2023. 'The Great O.R. Tambo International Airport Flood: Dealing with the Harsh Realities of Climate-induced Extreme Weather Events', *African Journal of Hospitality, Tourism and Leisure*, 12(5SE), pp. 1765–1772.

Martin, J., 2024. 'Valencia floods: Shocking video shows airport runway submerged in flood water as 62 dead and travel disrupted', *Manchester World*, 30 October.

Masood, T. et al., 2016. 'Towards the future-proofing of UK infrastructure', *Infrastructure Asset Management*. Thomas Telford Ltd., 3(1), pp. 28–41.

Mattsson, L.-G. and Jenelius, E., 2015. 'Vulnerability and resilience of transport systems – A discussion of recent research', *Transportation Research Part A: Policy and Practice*, 81, pp. 16–34.

McBean, G. and Rodgers, C., 2010. 'Climate hazards and disasters: The need for capacity building', *Wiley Interdisciplinary Reviews: Climate Change*, 1(6), pp. 871–884.

McEvoy, D., Ahmed, I. and Mullett, J., 2012. 'The impact of the 2009 heat wave on Melbourne's critical infrastructure', *Local Environment*. Routledge, 17(8), pp. 783–796.

McMillan, D., 2014. *Disruption at Gatwick Airport*. Available at: <https://www.scribd.com/document/211635894/The-McMillan-Report-Gatwick-Airport>.

Merkert, R. and Mangia, L., 2012. 'Management of airports in extreme winter conditions- some lessons from analysing the efficiency of Norwegian airports', *RTBM*, 4, pp. 53–60.

Met Office, 2021a. *UK and Global extreme events – Heatwaves*. Available at: <https://www.metoffice.gov.uk>.

Met Office, 2021b. *UK and Global extreme events – Heavy rainfall and floods*. Available at: www.metoffice.gov.uk.

Met Office, 2021c. *UK and Global extreme events – Wind storms*. Available at: www.metoffice.gov.uk.

Met Office, 2021d. *UKCP18 Factsheet: Snow*. Available at: www.metoffice.gov.uk.

Met Office, 2022a. *Record breaking temperatures for the UK*. Available at: www.metoffice.gov.uk.

Met Office, 2022b. *UK Climate Projections: Headline Findings*, Met Office. Available at: www.metoffice.gov.uk.

Met Office, 2023a. "Quantifying Climate Risk and Building Resilience in the UK". Available at: www.metoffice.gov.uk.

Met Office, 2023b. *UKCP18 Factsheet: Storms*. Available at: www.metoffice.gov.uk.

Met Office, 2025. *2024: provisionally the fourth warmest year on record for the UK*. Available at: www.metoffice.gov.uk.

Met Office, no date. *UK climate averages*. Available at: www.metoffice.gov.uk.

Met Office Hadley Centre, 2018. 'UKCP18 Probabilistic Climate Projections'. Available at: <https://www.metoffice.gov.uk>.

Meyboom, P., 2022. 'More common than expected: How standing water impacts airport safety and operations', *ACI World Insights*. Available at: <https://blog.aci.aero/more-common-than-expected-how-standing-water-impacts-airport-safety-and-operations/>.

Milanés et al., 2013. *Climate change adaptation needs of the core network of transport infrastructure in Spain*. Available at: <http://www.cedex.es/NR/rdonlyres/872032C9-00FB-4DF4-BFA3-63C00B3E8DF1/122814/ACCITFinalreportSeptember2013.pdf>.

Monioudi, I. N. et al., 2018. 'Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia', *Regional Environmental Change*, 18, pp. 2211–2225.

Mora, C. et al., 2018. 'Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions', *Nature Climate Change*. Springer US, 8(12), pp. 1062–1071.

Munich Re, 2024. *Natural disasters in 2024*. Available at: <https://www.munichre.com>.

NASA, 2025. *Temperatures Rising: NASA Confirms 2024 Warmest Year on Record*. Available at: <https://www.nasa.gov/news-release/temperatures-rising-nasa-confirms-2024-warmest-year-on-record/>.

NASA, no date. 'GISS Surface Temperature Analysis (v4)'. Available at: https://data.giss.nasa.gov/gistemp/graphs_v4/#.

National Academies, 2016. 'Airport Case Studies', in *Addressing Significant Weather Impacts on Airports: Quick Start Guide and Toolkit Useful*. Available at: <https://www.trb.org/ACRP/ACRPReport160.aspx>.

National Academies of Sciences Engineering and Medicine, 2020. *Airport Environmental Research Roadmap Narrative Report*, National Academies of Sciences, Engineering and Medicine. Washington DC: The National Academies Press.

National Academies of Sciences Engineering and Medicine, 2024. *Assessing Climate Change Vulnerability at Airports: A Primer*, Assessing Climate Change Vulnerability at Airports. Washington D.C.

National Climate Change Adaptation Research Facility, 2016. *Planning for Brisbane Airport's new runway: accounting for climate change*. Available at: www.nccarf.edu.au/localgov/case-study/.

National Oceanic and Atmospheric Administration (NOAA), 2013. *Hurricane/Post-Tropical Cyclone Sandy*. Maryland, USA. Available at: <https://www.weather.gov/media/publications/assessments/Sandy13.pdf>.

National Tidal and Sea Level Facility, no date. *Skew surges*. Available at: <https://ntslf.org/storm-surges/skew-surges>.

De Neufville, R., Odoni, A., Belobaba, P. and Reynolds, T. , 2013. *Airport Systems. Planning, design and management*. 2nd edition, McGraw-Hill Publishing.

Newcastle International Airport, 2024. 'Newcastle Airport set to commence work on major £17m runway resurfacing project'. Newcastle International Airport. Available at: <https://www.newcastleairport.com/news-and-reporting/latest-news/newcastle-airport-set-to-commence-work-on-major-17m-runway-resurfacing-project/>.

Nguyen, K., Liou, Y. and Terry, J. P., 2019. 'Vulnerability of Vietnam to typhoons: A spatial assessment based on hazards, exposure and adaptive capacity', *Science of the Total Environment*. Elsevier B.V., 682, pp. 31–46.

Nguyen, T. T. X. et al., 2016. 'Indicator-based assessment of climate-change impacts on coasts: A review of concepts, methodological approaches and vulnerability indices', *Ocean & Coastal Management*. Elsevier, 123, pp. 18–43.

Noble, I. R. et al., 2014. 'Adaptation needs and options', in *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.

Norwich Airport, 2019. *Norwich-Airport-Masterplan 2019*. Available at: <https://www.norwichairport.co.uk/wp-content/uploads/Norwich-Airport-Masterplan.pdf>.

Novelo-Casanova, D. A. and Suárez, G., 2012. 'Exposure of main critical facilities to natural and man-made hazards in Grand Cayman, Cayman Islands', *Natural Hazards*, 61(3), pp. 1277–1292.

OECD (2008) *Handbook on constructing composite indicators: methodology and user guide*. OECD Publishing. Available at: https://www.oecd.org/en/publications/handbook-on-constructing-composite-indicators-methodology-and-user-guide_9789264043466-en.html

Olariaga, O.D. (2021) 'The role of regional airports in connectivity and regional development', *Periodica Polytechnica Transportation Engineering*, 49(4), pp. 394–406.

Orsato, R.J., Barakat, S.R. and De Campos, G.J. (2017) 'Organizational adaptation to climate change: learning to anticipate energy disruptions', *International Journal of Climate Change Strategies and Management*, 9(5), pp. 1756–8692.

Palma Airport (2024) *Severe storm causes major disruptions at Palma Airport*. Available at: <https://www.palmaairport.info>

Papathoma-Köhle, M. (2016) 'Vulnerability curves vs. vulnerability indicators: application of an indicator-based methodology for debris-flow hazards', *Natural Hazards and Earth System Sciences*, 16, pp. 1771–1790.

Paprotny, D. et al. (2020) 'Estimating exposure of residential assets to natural hazards in Europe using open data', *Natural Hazards and Earth System Sciences*, 20(1), pp. 323–343.

Pauwels, J., Buyle, S. and Dewulf, W. (2024) 'Regional airports revisited: unveiling pressing research gaps and proposing a uniform definition', *Journal of the Air Transport Research Society*, 2, p. 100008.

Peduzzi, P. et al. (2009) 'Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index', *Natural Hazards and Earth System Sciences*, 9, pp. 1149–1159.

Pejovic, T. et al. (2009) 'Factors affecting the frequency and severity of airport weather delays and the implications of climate change for future delays', *Transportation Research Record: Journal of the Transportation Research Board*, 2139, pp. 97–106.

Pek, S. and Caldecott, B. (2020) *Physical climate-related risks facing airports: an assessment of the world's largest 100 airports*. Oxford. Available at: <https://www.smithschool.ox.ac.uk/research/sustainable-finance>

Perks, R., Howard, T. and Palmer, M. (2023) *UKCP18 Factsheet: Sea-level rise and storm surge - supplementary data*. Available at: <https://www.metoffice.gov.uk>

Pescaroli, G. et al. (2020) 'A Likert scale-based model for benchmarking operational capacity, organizational resilience, and disaster risk reduction', *International Journal of Disaster Risk Science*, 11(3), pp. 404–409.

Picketts, I.M. et al. (2016) 'Climate change adaptation strategies for transportation infrastructure in Prince George, Canada', *Regional Environmental Change*, 16, pp. 1109–1120.

Planning Inspectorate (2025) 'London Luton Airport expansion development consent decision announced'. Available at: <https://www.gov.uk/government/news/london-luton-airport-expansion-development-consent-decision-announced>

Pollock, L. (2025) 'Storm Eowyn: all the latest updates from airports across Scotland', *The National*, 24 January. Available at: <https://www.thenational.scot/news/24881827.storm-eowyn-latest-updates-airports-across-scotland/>

Poo, M. et al. (2018) 'Review on seaport and airport adaptation to climate change: a case on sea level rise and flooding', *Marine Technology Society Journal*, 52(2), pp. 23–33.

Poo, M. et al. (2021) 'An advanced climate resilience indicator framework for airports: a UK case study', *Transportation Research Part D: Transport and Environment*, 101, p. 103099.

Proag, V. (2014) 'The concept of vulnerability and resilience', *Procedia Economics and Finance*, 18, pp. 369–376.

Qiang, Y. (2019) 'Flood exposure of critical infrastructures in the United States', *International Journal of Disaster Risk Reduction*, 39, p. 101240.

Raaijmakers, R., Krywkow, J. and van der Veen, A. (2008) 'Flood risk perceptions and spatial multi-criteria analysis: an exploratory research for hazard mitigation', *Natural Hazards*, 46(3), pp. 307–322.

Raemason, S. (2024) 'Travel chaos as floods at major UK airport leave it "totally inaccessible" with roads "jammed for miles" after downpours', *The Sun*, 23 September. Available at: <https://www.thesun.co.uk/travel/30597601/travel-chaos-flooding-luton-airport/>

Rattanachot, W. et al. (2015) 'Adaptation strategies of transport infrastructures to global climate change', *Transport Policy*, 41, pp. 159–166.

Regional & City Airports (2024) *Our airports*. Available at: <https://www.rca.aero/expertise/our-airports>.

Rodrigue, J.-P. (2020) *Chapter 5: Air transport*. In: *The Geography of Transport Systems*. Available at: <https://transportgeography.org/contents/chapter5/air-transport/>

Rowan, E. et al. (2013) 'Assessing the sensitivity of transportation assets to extreme weather events and climate change', *Transportation Research Record: Journal of the Transportation Research Board*, 2326, pp. 16–23.

Rowan, E. et al. (2014) 'Indicator approach for assessing climate change vulnerability in transportation infrastructure', *Transportation Research Record: Journal of the Transportation Research Board*, 2459, pp. 18–28.

de Ruijter, A. and Guldenmund, F. (2015) 'The bowtie method: a review', *Safety Science*, 88, pp. 211–218.

De Ruiter, M.C. et al. (2017) 'Review article: a comparison of flood and earthquake vulnerability assessment indicators', *Natural Hazards and Earth System Sciences*, 17, pp. 1231–1251.

Ryley, T., Baumeister, S. and Coulter, L. (2020) 'Climate change influences on aviation: a literature review', *Transport Policy*, 92, pp. 55–64.

Salisbury, J. (2024) 'Hurricane Milton: UK flights to Florida axed as US state braces for "worst storm in a century"', *The Standard*, 9 October. Available at: <https://www.standard.co.uk/news/world/hurricane-milton-uk-flights-florida-axed-storm-british-airways-virgin-atlantic-b1186723.html>

San Francisco International Airport (2020) *Shoreline protection program*. San Francisco. Available at: <https://www.flysfo.com/about-sfo/environmental>

Sasse, M. and Hauf, T. (2003) 'A study of thunderstorm-induced delays at Frankfurt Airport, Germany', *Meteorological Applications*, 10(1), pp. 21–30.

Schmitt, D. et al. (2016) 'Airport and infrastructure', in *Air Transport System*. Vienna: Springer-Verlag, pp. 225–269.

Sebastian, A. et al. (2017) *Hurricane Harvey report: A fact-finding effort in the direct aftermath of Hurricane Harvey in the Greater Houston Region*. Delft: Delft University Publishers. Available at: <http://repository.tudelft.nl/>

Seneviratne, S.I. et al. (2023) *Weather and climate extreme events in a changing climate*. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*.

Shah, M.A.R. et al. (2020) 'A review of hydro-meteorological hazard, vulnerability, and risk assessment frameworks and indicators in the context of nature-based solutions', *International Journal of Disaster Risk Reduction*, 50, p. 101728.

Shakou, L.M. et al. (2019) 'Developing an innovative framework for enhancing the resilience of critical infrastructure to climate change', *Safety Science*, 118, pp. 364–378.

Sharp, J. (2023) 'Exeter Airport closes after being hit by flooding', *BBC News*, 17 September. Available at: <https://www.bbc.co.uk/news/uk-england-devon-66838536>

Sheehan, R. (2019) 'Climate change and winter weather impacts', *Journal of Airport Management*, 13(4), pp. 345–353.

Slovic, P. (1987) 'Perception of risk', *Science*, 236, pp. 280–285.

Smit, B. and Wandel, J. (2006) 'Adaptation, adaptive capacity and vulnerability', *Global Environmental Change*, 16, pp. 282–292.

Solecki, W. and Rosenzweig, C. (2020) 'Indicators and monitoring systems for urban climate resiliency', *Climatic Change*, 163(4), pp. 1815–1837. Available at: <https://doi.org/10.1007/s10584-020-02947-4>

Southampton Airport (2022) *Our approved runway plans*. Available at: <https://www.southamptonairport.com/planning/runway/our-approved-runway-plans/>

Stephens, T.A. and Bledsoe, B.P. (2020) 'Probabilistic mapping of flood hazards: depicting uncertainty in streamflow, land use, and geomorphic adjustment', *Anthropocene*, 29, p. 100231.

Stern, N. (2006) 'The Stern Review on the economic effects of climate change', *Population and Development Review*, 32(4), pp. 605–805.

Stewart, B., Klin, T. and Vigilante, M. (2011) 'Climate change adaptation and preparedness planning for airports', *Transportation Research Circular*. Washington, D.C.: The National Academy of Sciences, E-C152, pp. 37–44.

Surminski, S. et al. (2018) 'Assessing climate risks across different business sectors and industries: an investigation of methodological challenges at national scale for the UK', *Philosophical Transactions of the Royal Society A*, 376, p. 20170307.

Swiss Re Institute (2024) *Hurricanes, severe thunderstorms and floods drive insured losses above USD 100 billion for 5th consecutive year*. Available at: www.swissre.com/media

Takabatake, T., Ishikawa, Y., Matsukawa, H., Hayashi, S., Hatayama, M., Ooka, R. and Fukuda, T. (2018) 'Field Survey of 2018 Typhoon Jebi in Japan: Lessons for Disaster Risk Management', *Geosciences*, 8(11), p. 412.

Taylor, M.A.P. and Philp, M. (2010) 'Adapting to climate change - Implications for transport infrastructure, transport systems and travel behaviour', *Road and Transport Research*, 19(4), pp. 69–82.

The World Bank (2024) *Keeping Communities Connected in Small Island Developing States*. Available at: <https://www.worldbank.org/en/who-we-are/news/campaigns/2023/building-beyond-tomorrow>

The World Bank (2023) *Climate Change Knowledge Portal*. Available at: <https://climateknowledgeportal.worldbank.org/>

Timmins, B. (2022) 'Storm Eunice: Flights and train services cancelled', *BBC News*, 18 February. Available at: <https://www.bbc.co.uk/news/business-60430197>

Tol, R.S.J. (2007) 'The impact of a carbon tax on international tourism', *Transportation Research Part D: Transport and Environment*, 12(2), pp. 129–142.

Transport Canada (2016) *Advisory Circular: Safety Management System Development Guide for Smaller Aviation Organizations*. Available at: <https://tc.canada.ca/en/aviation/reference-centre/advisory-circulars/advisory-circular-ac-no-107-002>

Transportation Research Board (2012) *Airport Climate Adaptation and Resilience, A Synthesis of Airport Practice*. Washington D.C.: The National Academy of Sciences. Available at: <http://www.national-academies.org/trb/bookstore>

Treby, E.J., Clark, M.J. and Priest, S.J. (2006) 'Confronting flood risk: Implications for insurance and risk transfer', *Journal of Environmental Management*, 81(4), pp. 351–359.

UK CAA (2014) *Safety Management Systems (SMS) guidance for organisations (CAP 795)*. Available at: <https://www.caa.co.uk>

UK CAA (2024a) *Aircraft Movements 2024*. Available at: <https://www.caa.co.uk>

UK CAA (2024b) *Size of Reporting Airports 2023*. Available at: <https://www.caa.co.uk>

UK CAA (2024c) *Size of Reporting Airports 2024*. Available at: <https://www.caa.co.uk>

UNEP (2021) *Infrastructure for Climate Action*. Available at: <http://www.farmersforclimateaction.org.au/>

UNISDR (2015) *Global Assessment Report on Disaster Risk Reduction. Annex 1: GAR Global Risk Assessment: Data, Methodology, Sources and Usage*. Available at: <https://www.preventionweb.net>.

United Nations (2007) *Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December 2007*. Available at: <https://unfccc.int/resource/docs/2007/cop13/eng/06a01.pdf>

United Nations (2015) *Paris Agreement*. Paris. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

United Nations (2016) *Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction*. Available at: <https://www.undrr.org/publication/report-open-ended-intergovernmental-expert-working-group-indicators-and-terminology>

Urfer, B. and Weinert, R. (2011) 'Managing Airport Infrastructure', in Wittmer, A., Bieger, T. and Müller, R. (eds.) *Aviation Systems*. Springer-Verlag Berlin Heidelberg, pp. 103–131.

Valdés, A.R.M., Abdelalim, A., de León, D.L., Fernandez, J.F. and Kharina, A. (2021) 'How Much Can Carbon Taxes Contribute to Aviation Decarbonization by 2050', *Sustainability*, 13(3), p. 1086.

Verschuur, J., Fernández-Pérez, A., Mühlhofer, E., Nirandjan, S., Borgomeo, E., Becher, O., Voskaki, A., Oughton, E.J., Stankovski, A., Greco, S.F., Koks, E.E., Pant, R. and Hall, J.W. (2024) 'Quantifying climate risks to infrastructure systems: A comparative review of developments across infrastructure sectors', *PLOS Climate*, 3(4), p. e0000331.

De Vivo, C., Mannarini, G., Cartenì, A., D'Alessandro, M. and Iodice, A. (2021) 'Risk assessment framework for Mediterranean airports: a focus on extreme temperatures and precipitations and sea level rise', *Natural Hazards*.

De Vivo, C., Mannarini, G., Russo, F., D'Alessandro, M. and Iodice, A. (2023a) 'Application of climate risk assessment framework for selected Italian airports: A focus on extreme temperature events', *Climate Services*, 30, p. 100390.

De Vivo, C., Russo, F., Mannarini, G., D'Alessandro, M. and Iodice, A. (2023b) 'Climate-Risk Assessment Framework for Airports under Extreme Precipitation Events: Application to Selected Italian Case Studies', *Sustainability*, 15(9), p. 7300.

De Vivo, C., Russo, F., Mannarini, G., D'Alessandro, M. and Iodice, A. (2025) 'A co-design matrix-based approach to evaluate the climate risks for airports: A case study of Bologna airport', *Climate Services*, 37, p. 100536.

Vogiatzis, K., Efthymiou, C., Zannos, S. and Paschalidou, A.K. (2021) 'Climate change adaptation studies as a tool to ensure airport's sustainability: The case of Athens International Airport (A.I.A.)', *Science of the Total Environment*, 754, p. 142153.

Vonberg, J. (2018) 'Snow disrupts travel in UK, Europe as "Beast from the East" meets Storm Emma', *CNN*, 2 March. Available at: <https://edition.cnn.com/2018/03/01/europe/beast-from-east-storm-emma-europe-intl/index.html>

Voskaki, A., Budd, T. and Mason, K. (2023) 'The impact of climate hazards to airport systems: a synthesis of the implications and risk mitigation trends', *Transport Reviews*, 43(4), 652–675.

WEF (2025) *The Global Risks Report 2025*. Available at: https://reports.weforum.org/docs/WEF_Global_Risks_Report_2025.pdf

Weis, S.W.M., Agostini, V.N., Roth, L.C., Gilmer, B. and Schill, S.R. (2016) 'Assessing vulnerability: an integrated approach for mapping adaptive capacity, sensitivity, and exposure', *Climatic Change*, 136, pp. 615–629.

Welle, T. and Birkmann, J. (2015) 'The World Risk Index – An Approach to Assess Risk and Vulnerability on a Global Scale', *J Extreme Events*, 2(1), p. 1550003.

Welsh Government (2024) 'Written Statement: Cardiff Wales Airport – long term strategy', *Welsh Government*. Available at: <https://www.gov.wales/written-statement-cardiff-wales-airport-long-term-strategy>

Wennberg, L. (2019) 'Our ambition is high: Running the most climate-smart airport in the world', *Journal of Airport Management*, 13(2), pp. 167–173.

WMO (2024) 'WMO confirms that 2023 smashes global temperature record', *Press Release*. Available at: <https://wmo.int/news/media-centre/wmo-confirms-2023-smashes-global-temperature-record>

Wilbanks, T.J., Fernandez, S.J., Allen, M.R., Backus, G.A., Bauer, D., Bull, S.R. and Lane, L. (2020) 'Toward indicators of the performance of US infrastructures under climate change risks', *Climatic Change*, 163(4), pp. 1795–1813.

Wittmer, A., Bieger, T. and Muller, R. (eds) (2011) *Aviation Systems. Management of the Integrated Aviation Value Chain*. London: Springer Heidelberg Dordrecht.

Wong, K. (2024) 'Airlines begin canceling flights, offering rebooking ahead of Hurricane Helene', *USA Today*, 24 September. Available at: <https://eu.usatoday.com/story/travel/airline-news/2024/09/24/tropical-storm-helene-airline-waivers-what-to-know/75366880007/>

World Resources Institute (2021) 'Aqueduct Water Risk Atlas – Basin Maps'. Available at: <https://www.wri.org>

- Wu, L., Taniguchi, K. and Tajima, Y. (2021) 'Impact of climate change on flood hazard at airports on pacific islands: A case study of Faleolo International Airport, Samoa', *Journal of Disaster Research*, 16(3), pp. 351–362.
- Wu, S.Y., Yarnal, B. and Fisher, A. (2002) 'Vulnerability of coastal communities to sea-level rise: A case study of Cape May County, New Jersey, USA', *Climate Research*, 22(3), pp. 255–270.
- Yang, Y. and Ge, Y. (2020) 'Adaptation strategies for port infrastructure and facilities under climate change at the Kaohsiung port', *Transport Policy*, 97, pp. 232–244.
- Yesudian, A.N. and Dawson, R.J. (2021) 'Global analysis of sea level rise risk to airports', *Climate Risk Management*, 31(100266), pp. 1–12.
- Yuan, W., Liu, D., Wang, X., Huang, Y. and Liu, Y. (2021) 'Estimating the Impact of Global Warming on Aircraft Takeoff Performance in China', *Atmosphere*, 12(1472).
- Zanin, M. and Lillo, F. (2013) 'Modelling the air transport with complex networks: A short review', *European Physical Journal Special Topics*, 215, pp. 5–21.
- Zapata, M., Medinaceli, A., Del Riego, M. and Alleng, G. (2004) *Assessment of the socioeconomic and environmental impact of Hurricane Ivan on Jamaica*. Available at: <https://www.cepal.org/en/publications/25725-assessment-socioeconomic-and-environmental-impact-hurricane-ivan-jamaica>
- Zeľeňáková, M. and Zvijáková, L. (2017) 'Risk analysis within environmental impact assessment of proposed construction activity', *Environmental Impact Assessment Review*, 62, pp. 76–89.
- Zhao, Y. and Sushama, L. (2020) 'Aircraft Takeoff Performance in a Changing Climate for Canadian Airports', *Atmosphere*, 11(418).
- Zhou, C., Zhang, X., Zhang, S. and Lu, C. (2018) 'Impact of 1.5 °C and 2.0 °C global warming on aircraft takeoff performance in China', *Science Bulletin*, 63(11), pp. 700–707.
- Zhou, L. and Chen, Z. (2020) 'Measuring the performance of airport resilience to severe weather events', *Transportation Research Part D*, 83, p. 102362.

Zhou, Y., Wang, M., Yang, G. and Li, Y. (2018) 'Decreased takeoff performance of aircraft due to climate change', *Climatic Change*, 151, pp. 463–472.

Zscheischler, J., Westra, S., van den Hurk, B., Seneviratne, S.I., Ward, P.J., Pitman, A., AghaKouchak, A. et al. (2020) 'A typology of compound weather and climate events', *Nature Reviews Earth & Environment*, 1(7), pp. 333–347.

Zurich Resilience Solutions (2022) *Climate resilience*. Available at: <https://www.zurich.com/en/commercial-insurance/services/climate-resilience>

Zurich Risk Engineering (2022) *Property - Natural Hazards and Additional Perils Assessment*.

Appendix A Ethics approval letter



16 January 2024

Dear Ms Voskaki ,

Reference: CURES/21083/2024

Project ID: 24116

Title: Analysis of the risk of climate hazards to the airport system

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/21083/2024 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B ACRI variables and outputs

Appendix B Table 1 Indicators and variables that set up the sub-index of climate hazards

Indicator	Variable	Measurement	Rationale	Adapted/inspired from
Current climate hazard level	Flood hazard rating - coastal	1 Within the 1000-year flood zone	Contributes to coastal flooding and storm surge climate hazard. The variable adopts the rating the UK Government departments use for flood policy and strategic flood risk management. The measurement scale adopts and combines the scales considered within the different departments and reflects the flood risk for the specific location considering existing coastal flood defences.	UK Government departments (England, Scotland, Wales and Northern Ireland) for policy on flood and strategic flood risk management, Nguyen et al. (2016), Rowan et al. (2014), insurance companies' natural hazard assessment guidelines
		2 Within the 500-year flood zone		
		3 Within the 100-year flood zone		
		4 Within the 30-year flood zone		
		5 Within the 10-year flood zone		
	Flood hazard rating - river	1 Within the 1000-year flood zone	Contributes to fluvial/pluvial flooding climate hazard. The variable adopts the rating the UK Government departments use for flood policy and strategic flood risk management. The measurement scale adopts and combines the scales considered within the different departments and reflects the flood risk for the specific location considering existing flood defences.	UK Government departments (England, Scotland, Wales and Northern Ireland) for policy on flood and strategic flood risk management, Nguyen et al. (2016), Rowan et al. (2014), insurance companies' natural hazard assessment guidelines
		2 Within the 500-year flood zone		
		3 Within the 100-year flood zone		
		4 Within the 30-year flood zone		
		5 Within the 10-year flood zone		
	Flood hazard rating - surface	1 Within the 1000-year flood zone	Contributes to fluvial/pluvial flooding climate hazard. The variable adopts the rating the UK Government departments use for flood policy and strategic flood risk management. The measurement scale adopts and combines the scales considered within the different departments and reflects the flood risk for the specific location considering existing flood defences.	UK Government departments (England, Scotland, Wales and Northern Ireland) for policy on flood and strategic flood risk management, Nguyen et al. (2016), Rowan et al. (2014), insurance companies' natural hazard assessment guidelines
		2 Within the 500-year flood zone		
		3 Within the 100-year flood zone		
		4 Within the 30-year flood zone		
		5 Within the 10-year flood zone		
	Skew surge history in the airport area	1 < 0.5 m	Contributes to coastal flooding and storm surge climate hazard. It reflects the difference between the maximum observed sea level and the maximum predicted tide and provides an indication of the elevation of the sea level that can rise due to storm surge events. The variable considers the average value of the maximum recorded difference for each region. The scale considers thresholds based on increments of 0.5m.	National Tidal and Sea Level Facility, Poo et al. (2018, 2021), Rowan et al. (2013)
		2 0.5 to 1.0 m		
		3 1.0 to 1.5 m		
		4 1.5 to 2.0 m		
		5 > 2.0 m		
	Wind velocity zone	1 Zone I (up to 21m/s)	Contributes to storminess and extreme wind climate hazard. The variable considers the maximum mean hourly wind speed to reflect local wind conditions. The scale adopts the zones used in UK wind speed maps developed	Met Office, UK wind zones as developed and used for construction purposes and energy generation, Poo et al. (2021), Vogiatzis et al. (2021)
		2 Zone II (21 to 23m/s)		
		3 Zone III (23 to 25m/s)		
		4 Zone IV (25 to 27m/s)		
		5 Zone V (above 27m/s)		

Indicator	Variable	Measurement	Rationale	Adapted/inspired from
			for different purposes (for example, construction and energy generation).	
Average days of thunder	1	<6	Contributes to storminess and extreme wind climate hazard. The variable depicts the thunderstorm occurrence (annual average 1971-2000) and is used to reflect the manifestation of compound events such as storms. The scale is adapted from the thresholds used by the Met Office.	Met Office, Eurocontrol (2021), Poo et al. (2021), Vogiatzis et al. (2021), insurance companies' natural hazard assessment guidelines
	2	6 to 8		
	3	8 to 10		
	4	10 to 12		
	5	>12		
Average days of snow lying	1	<10	Contributes to snowstorm and extreme snowfall climate hazard. The variable is used to reflect the frequency of snowfall occurrence. The scale is adapted from the thresholds used by the Met Office.	Met Office, Poo et al. (2021), Vogiatzis et al. (2021)
	2	10 to 20		
	3	20 to 30		
	4	30 to 40		
	5	>40		
Days of ground frost	1	<60	Contributes to cold and icing conditions climate hazard. The variable is used to reflect the frequency of occurrence of conditions that result in ground frost. The scale is adapted from the thresholds used by the Met Office.	Met Office, Poo et al. (2021), Vogiatzis et al. (2021)
	2	60 to 80		
	3	80 to 100		
	4	100 to 125		
	5	>125		
Days of air frost	1	<20	Contributes to cold and icing conditions climate hazard. The variable is used to reflect the frequency of occurrence of conditions that result in air frost. The scale is adapted from the thresholds used by the Met Office.	Met Office, Poo et al. (2021), Vogiatzis et al. (2021)
	2	20 to 40		
	3	40 to 60		
	4	60 to 80		
	5	>80		
Heating degree days	1	<2000	Contributes to cold and icing conditions climate hazard. The variable is used to reflect the frequency of occurrence of conditions that result in the need for heating. The scale is adapted from the thresholds used by the Met Office.	Met Office, Vogiatzis et al. (2021), Monioudi et al. (2018)
	2	2000 to 2400		
	3	2400 to 2600		
	4	2600 to 2800		
	5	>2800		
Cooling degree days	1	<20	Contributes to extreme heat climate hazard. The variable is used to reflect the frequency of occurrence of conditions that result in the need for cooling. The scale is adapted from the thresholds used by the Met Office.	Met Office, Vogiatzis et al. (2021)
	2	20 to 40		
	3	40 to 60		
	4	60 to 80		
	5	>80		
Water stress	1	Low	Contributes to drought/water scarcity climate hazard. The variable and the measurement are adopted from the Water Risk Atlas and depict the ratio of total water demand to available renewable surface and groundwater supplies.	World Resources Institute (Aqueduct Water Risk Atlas), (Lopez, 2016), insurance companies' climate risk assessment guidelines
	2	Low to medium		
	3	Medium to high		
	4	High		
	5	Extremely high		
	1	< 0.35 m		

Indicator	Variable	Measurement	Rationale	Adapted/inspired from
Future climate hazard level	Change in the mean sea-level in the airport area	2 0.35 to 0.45 m	Contributes to coastal flooding and storm surge climate hazard. An increase in the sea level increases the frequency of flooding in coastal areas in the absence of sufficient coastal protection. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	Perks et al. (2023), Poo et al. (2021), De Vivo et al. (2021), Debortoli et al. (2019), (Lopez, 2016), Rowan et al. (2013), Monioudi et al. (2018), Rowan et al. (2014)
		3 0.45 to 0.55 m		
		4 0.55 to 0.65 m		
		5 > 0.65 m		
	Mean winter precipitation change	1 0 to 10 %	Contributes to fluvial/pluvial flooding climate hazard. Changes in the precipitation patterns suggest a change in the frequency of flooding events during the winter period. When the ground is already saturated (as typically in winter), waterways tend to rise, and therefore, an increase in the precipitation may likely lead to different rainfall levels and potential flooding events. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	Met Office Hadley Centre (2018), Poo et al. (2021), De Vivo et al. (2021), Rowan et al. (2013)
		2 10 to 20 %		
		3 20 to 30 %		
		4 30 to 40 %		
		5 > 40 %		
	Mean summer precipitation change	1 0 to 10 %	Contributes to fluvial/pluvial flooding climate hazard. Changes in the precipitation patterns suggest a change in the frequency of flooding events during the summer period. Without regular rainfall (typically in summer), the ground has difficulty absorbing water, leading to an increased risk of flooding when it rains. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	Met Office Hadley Centre (2018), Poo et al. (2021), De Vivo et al. (2021), Debortoli et al. (2019), (Lopez, 2016), Rowan et al. (2013), Monioudi et al. (2018)
		2 10 to 20 %		
		3 20 to 30 %		
		4 30 to 40 %		
		5 > 40 %		
	Future changes in heavy daily rainfall events in winter	1 < 0 %	Contributes to fluvial/pluvial flooding climate hazard. An increase in the heavy daily rainfall increases the likelihood of flooding during winter. When the ground is already saturated (as typically in winter), waterways tend to rise, and a heavy rainfall event can increase the risk of flooding. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	Kendon et al. (2021), De Vivo et al. (2021), Vogiatzis et al. (2021), Monioudi et al. (2018), Solecki & Rosenzweig (2020)
		2 0 to 15 %		
		3 15 to 30 %		
		4 30 to 45 %		
		5 > 45 %		
	Future change in heavy daily rainfall events in summer	1 < 0 %	Contributes to fluvial/pluvial flooding climate hazard. An increase in the heavy daily rainfall events increases the likelihood of flooding during summer. Without regular rainfall (as typically in summer), the ground has difficulty absorbing water, leading to an increased risk of flash flooding, especially in the case of heavy rainfall. The variable is adopted from the Met Office climate change	Kendon et al. (2021), De Vivo et al. (2021), Vogiatzis et al. (2021), Monioudi et al. (2018), Solecki & Rosenzweig (2020)
		2 0 to 15 %		
		3 15 to 30 %		
		4 30 to 45 %		
		5 > 45 %		

Indicator	Variable	Measurement	Rationale	Adapted/inspired from
			projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	
Winter mean snowfall change	1	> 40 %	Contributes to snowstorm and extreme snowfall climate hazard. A change in the winter mean snowfall (in the case of UK climate projections, suggesting a reduction) implies a change in the parameters that can generate hazardous conditions. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	Met Office (2018, 2021), Debortoli et al. (2019), (Lopez, 2016)
	2	30 to 40 %		
	3	20 to 30 %		
	4	10 to 20 %		
	5	0 to 10 %		
Future change in surface winds in winter	1	< 0 m/s	Contributes to storminess and extreme wind climate hazard. A change in the winter surface wind speed suggests a likely change in the wind intensity. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	Kendon et al. (2021), Poo et al. (2021), (Lopez, 2016), Solecki & Rosenzweig (2020)
	2	0 to 0.3 m/s		
	3	0.3 to 0.6 m/s		
	4	0.6 to 0.8 m/s		
	5	> 0.8 m/s		
The trend in skew surge extremes	1	< 0.2 mm/yr	Contributes to coastal flooding and storm surge climate hazard. Based on the UK climate projections, the variable considers the 21st-century trend in skew surge extremes. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	Poo et al. (2018, 2021), De Vivo et al. (2021), (Lopez, 2016), Solecki & Rosenzweig (2020), Rowan et al. (2014)
	2	0.2 to 0.5 mm/yr		
	3	0.5 to 0.7 mm/yr		
	4	0.7 to 1.0 mm/yr		
	5	> 1.0 mm/yr		
Change in the no of frost days (Tmin<0oC)	1	> 12	Contributes to cold and icing conditions climate hazard. The variable is used to reflect the change in the cold and icing conditions and considers the number of days with minimum temperature below zero. The variable is adopted from the World Bank Climate Change Knowledge Portal; the scale is adapted from the thresholds used by the World Bank.	Poo et al. (2021), Vogiatzis et al. (2021), The World Bank
	2	9 to 12		
	3	6 to 9		
	4	3 to 6		
	5	0 to 3		
Annual mean temperature change	1	0 to 1 °C	Contributes to extreme heat climate hazard. The variable is used to reflect the trends in temperature rise because of climate change. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	De Vivo et al. (2021), Rowan et al. (2013), Monioudi et al. (2018)
	2	1 to 2 °C		
	3	2 to 3 °C		
	4	3 to 4 °C		
	5	> 4 °C		
Mean summer temperature change	1	0 to 1 °C	Contributes to extreme heat climate hazard. The variable is used to reflect the trends in extreme temperature events. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	De Vivo et al. (2021), Debortoli et al. (2019), Vogiatzis et al. (2021), Rowan et al. (2013), Monioudi et al. (2018)
	2	1 to 2 °C		
	3	2 to 3 °C		
	4	3 to 4 °C		
	5	> 4 °C		
	1	> 4 °C		

Indicator	Variable	Measurement		Rationale	Adapted/inspired from	
	Mean winter temperature change	2	3 to 4 °C	Contributes to cold and icing conditions climate hazard. The variable is used to reflect the trends in temperature change because of climate change and its impact on cold and icing conditions. The variable is adopted from the Met Office climate change projections (UKCP18); the scale is adopted from the thresholds used by the Met Office.	De Vivo et al. (2021), Debortoli et al. (2019), Vogiatzis et al. (2021), Rowan et al. (2013), Monioudi et al. (2018)	
		3	2 to 3 °C			
		4	1 to 2 °C			
		5	0 to 1 °C			
	Increase in storminess	1	No	Contributes to storminess and extreme wind climate hazard. The variable is used to reflect the trends in storminess because of climate change. The measurement of the variable is based on whether the projected change is consistent or not across the climate models, as described in the Met Office climate change projections (UKCP18); the scale is developed to reflect this.	Met Office (2023), Eurocontrol (2021), Solecki & Rosenzweig (2020), insurance companies' climate risk assessment guidelines	
		3	Not consistent change			
		5	Yes			
	Water stress	1	Low	Contributes to drought/water scarcity climate hazard. The variable and the measurement are adopted from the Water Risk Atlas and depict the ratio of total water demand to available renewable surface and groundwater supplies under a business-as-usual scenario with 2050 as the timeframe.	World Resources Institute (Aqueduct Water Risk Atlas), (Lopez, 2016), insurance companies' climate risk assessment guidelines	
		2	Low to medium			
		3	Medium to high			
		4	High			
		5	Extremely high			
	Confidence in the direction of change	Confidence for change in the climate hazard levels	1	Low confidence in the direction of change	The variable reflects the level of confidence for the change in climate hazard levels. The variable and the measurement are adopted from the IPCC Interactive Atlas (Sixth Assessment Report) for the Northern Europe (NEU) region, which includes the UK. Metrics considered include coastal flood, heavy precipitation, hydrological drought, severe windstorm, cold spell, extreme heat and heavy snowfall and ice storm. Insurance risk engineering studies use the level of confidence as an indicator of the anticipated change when assessing the influence of climate change on natural hazard occurrences.	(IPCC, 2021a) (WGI Interactive Atlas), insurance companies' climate risk assessment guidelines
			3	Medium confidence of increase or decrease		
			5	High confidence of increase or decrease		

Appendix B Table 2 Indicators and variables that set up the sub-index of exposure

Indicator	Variable	Measurement		Rationale	Adopted/adapted/ inspired from
Critical assets	The proportion of critical infrastructure/assets (e.g. runway, taxiway, apron, etc.) potentially affected by the climate hazard	5	>75%	Identifying critical infrastructure that can be affected by a climate hazard occurrence can provide a measure of the extent to which the airport functions could potentially be affected.	Koetse & Rietveld (2012), Novelo-Casanova & Suárez, (2012), Paprotny et al. (2020), Rowan et al. (2013), Debortoli et al. (2019), De Vivo et al. (2021), Shah et al. (2020), Birkmann et al. (2013), Rowan et al. (2014), Weis et al. (2016), insurance companies' natural hazard assessment guidelines
		4	50-75%		
		3	25-50%		
		2	0-25%		
		1	0%		
	The proportion of airport critical equipment (e.g. Navigational Aids, IT, comms, etc.) potentially affected by the climate hazard	5	>75%	Identifying critical equipment supporting airport operations that can be affected by a climate hazard occurrence can provide a measure of the extent to which the airport functions could potentially be affected.	Koetse & Rietveld (2012), Novelo-Casanova & Suárez, (2012), Paprotny et al. (2020), Rowan et al. (2013), De Vivo et al. (2021), insurance companies' natural hazard assessment guidelines
		4	50-75%		
		3	25-50%		
		2	0-25%		
		1	0%		
Operations	The proportion of air operations potentially affected by the climate hazard	5	>75%	Identifying air operations that can be affected by a climate hazard occurrence can indicate the potential business impact.	Shah et al. (2020), Monioudi et al. (2018), Solecki & Rosenzweig, (2020), Vogiatzis et al. (2021)
		4	50-75%		
		3	25-50%		
		2	0-25%		
		1	0%		
	The proportion of ground operations potentially affected by the climate hazard	5	>75%	Identifying ground operations that can be affected by a climate hazard occurrence can indicate the potential disruption of the normal functioning of the airport.	Solecki & Rosenzweig, (2020), Vogiatzis et al. (2021), Lopez (2016)
		4	50-75%		
		3	25-50%		
		2	0-25%		
		1	0%		
People	The proportion of airport staff potentially affected by the climate hazard	5	>75%	Identifying airport staff that can be affected by a climate hazard occurrence can indicate the potential impact on resources, productivity, and business performance.	Paprotny et al. (2020), Balica et al. (2012), Debortoli et al. (2019), De Vivo et al. (2021), Shah et al. (2020)
		4	50-75%		
		3	25-50%		
		2	0-25%		
		1	0%		
	The proportion of passengers potentially affected by climate hazard	5	>75%	Identifying passengers that can be affected by a climate hazard occurrence can indicate the potential business impact.	Paprotny et al. (2020), Balica et al. (2012), Debortoli et al. (2019), De Vivo et al. (2021), Shah et al. (2020)
		4	50-75%		
		3	25-50%		
		2	0-25%		
		1	0%		
Interdependencies	The proportion of surface access potentially affected by the climate hazard	5	>75%	Identifying surface access modes that can be affected by a climate hazard	De Vivo et al. (2021), Solecki & Rosenzweig, (2020), Eidsvig et al. (2017)
		4	50-75%		
		3	25-50%		

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
		2 0-25%	occurrence can indicate the potential	
		1 0%	business impact.	
	The proportion of utilities (e.g. electricity, water, waste management, etc.) or supplies (e.g. fuel) potentially affected by the climate hazard	5 >75%	Identifying supply and utility networks that	De Vivo et al. (2021), Solecki & Rosenzweig, (2020), Eidsvig et al. (2017)
		4 50-75%	can be affected by a climate hazard	
		3 25-50%	occurrence can indicate the potential	
		2 0-25%	disruption of the normal functioning of the	
		1 0%	airport.	

Appendix B Table 3 Indicators and variables that set up the sub-index of vulnerability

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
Predisposition	Number of airport runways and orientation	5 There is only one runway	The number and orientation of airport runways can play a role in the airport's performance in the event of a storm.	De Vivo et al. (2021)
		3 There are more than one runways with the same orientation		
		1 There are more than one runways with varied orientation		
	Runway length	5 Runways are currently short, and there is no possibility for an extension	Runway length can impact the airport performance in the event of extreme heat due to aircraft restrictions.	De Vivo et al. (2021), Monioudi et al. (2018), Stewart, Klin and Vigilante (2011)
		4 Runways are currently short for many aircraft types, and there are restrictions in place depending on weather conditions and cannot be extended		
		3 Runways are currently short for some aircraft types under typical weather conditions but can be extended		
		2 Runways have sufficient length for all aircraft types under typical weather conditions but cannot be extended		
		1 Runways have sufficient length for all aircraft types under typical weather conditions and can be extended if needed		
	How runways are affected by wind and change in wind patterns	5 There is only one runway, and it is affected	The number and orientation of airport runways can play a role in the airport's performance in the event of extreme wind or changing wind patterns.	Debortoli et al. (2019)
		4 There are more than one runways with same orientation, and are all affected		
		3 There are more than one runways with varied orientation, and most of them are affected		
		2 There are more than one runways with varied orientation, and not all are affected		
		1 Runways are not affected		
	Existence of permanent frozen ground	5 The airport ground is permanently frozen	Permafrost can affect airport critical assets in the case of temperature rise.	Debortoli et al. (2019)
		3 The airport ground is partially frozen		
		1 No permafrost		
	Airport altitude above sea level	5 <10m	In the case of coastal airports, the lower the elevation above sea level, the higher the risk of a flood event, such as a sea level rise or storm surge.	Debortoli et al. (2019), Birkmann et al. (2013), Kappes et al. (2012), Rowan et al. (2014), Nguyen et al. (2016)
		4 10-50m		
		3 50-80m		
		2 80-150m		
		1 >150m		
		5 0-50m		

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	Airport distance from the sea or local water bodies	4 50-100m	The airport's distance from the sea or local water bodies, such as rivers, influences the risk of a flood event in the case of extreme precipitation or storm surge.	Debortoli et al. (2019), Birkmann et al. (2013), Kappes et al. (2012), Rowan et al. (2014), Zeleňáková & Zvijáková (2017)
		3 100-200m		
		2 200-500m		
		1 >500m		
	Proportion of the airport's impervious surface	5 All airport surface is impervious	The proportion of impervious surface plays a role in rainwater accumulation and surface flooding in the case of extreme precipitation.	Rowan et al. (2013), Kappes et al. (2012), Rowan et al. (2014)
		4 More than 75% of the airport surface is impervious		
		3 More than 50% of the airport surface is impervious		
		2 Less than 25% of the airport surface is impervious		
		1 All airport surface is permeable		
	Airport located within a 100-year flood zone	5 Yes	The 100-year flood is a flood event with a 1% probability of occurring or being exceeded in any given year and indicates the risk of flooding in the airport area.	Solecki & Rosenzweig, (2020), Birkmann et al. (2013), Kappes et al. (2012), Rowan et al. (2014), Zeleňáková & Zvijáková (2017)
		3 Partially		
		1 No		
	Airport runways within a 100-year flood zone	5 Yes	The 100-year flood is a flood event with a 1% probability of occurring or being exceeded in any given year and indicates the risk of flooding of the runway and, subsequently, the potential disruption.	Birkmann et al. (2013), Kappes et al. (2012), Rowan et al. (2014), Zeleňáková & Zvijáková (2017)
		3 Partially		
		1 No		
	Airport location affected by climate hazard(s)	5 Yes	If the airport location is affected by climate hazards, the airport can also be affected.	De Vivo et al. (2021), Vogiatzis et al. (2021), Birkmann et al. (2013), Rowan et al. (2014)
		3 Occasionally		
		1 No		
	Considering design standards and technical specifications, whether the integrity of critical assets (runway, taxiway, apron, pavement material etc.) can be affected by climate hazard(s)	5 Yes	If critical infrastructure or assets have been designed considering design standards that do not correspond to current or future climatic conditions, they can become susceptible to damage.	Vogiatzis et al. (2021), Rowan et al. (2013), Kappes et al. (2012), Stewart, Klin and Vigilante (2011)
		3 Occasionally		
		1 No		

Indicator	Variable	Measurement		Rationale	Adopted/adapted/ inspired from
	Considering design standards and technical specifications, whether the integrity of critical equipment (Navigational aids, IT, comms etc.) can be affected by climate hazard(s)	5	Yes	If the technical specifications of critical equipment are not aligned with the current or future climatic conditions, they can become susceptible to damage or malfunction.	Vogiatzis et al. (2021), Rowan et al. (2013)
		3	Occasionally		
		1	No		
	Considering the airport's location and standards of critical infrastructure/ assets, whether air operations are potentially affected (cancelled, delayed or diverted) by climate hazard(s)	5	Yes	If the airport gets exposed to climate hazards, air operations can become susceptible to disruption due to the airport's location or the characteristics of its critical infrastructure.	Vogiatzis et al. (2021), Monioudi et al. (2018), Birkmann et al. (2013)
		3	Partially/Occasionally		
		1	No		
	Considering the airport's location and standards of critical infrastructure/ assets, whether ground operations are potentially affected by climate hazard(s)	5	Yes	If the airport gets exposed to climate hazards, ground operations can become susceptible to disruption due to the airport's location or the characteristics of its critical infrastructure.	Vogiatzis et al. (2021), Monioudi et al. (2018)
		3	Partially/Occasionally		
		1	No		
	Impact of climate hazard(s) on airport staff	5	Yes	If the airport gets exposed to climate hazards, airport staff can be affected (e.g. people working in ground handling cannot perform their duties due to health, safety, or other concerns).	De Vivo et al. (2021), Vogiatzis et al. (2021), Monioudi et al. (2018), Birkmann et al. (2013), Weis et al. (2016)
		3	Partially/Occasionally		
		1	No		
	Impact of climate hazard(s) on passengers	5	Yes	If the airport gets exposed to climate hazards, passengers can be affected.	De Vivo et al. (2021), Vogiatzis et al. (2021), Birkmann et al. (2013), Weis et al. (2016)
		3	Partially/Occasionally		
		1	No		
	Considering the airport's location and resilience of access links and transport modes, whether surface access is potentially disrupted by climate hazard(s)	5	Yes	If the airport location gets exposed to climate hazards, surface access links can become susceptible to disruption due to their characteristics and state of resilience.	De Vivo et al. (2021), Eidsvig et al. (2017), Weis et al. (2016), Dawson et al. (2018)
		3	Partially/Occasionally		
		1	No		
	Considering the airport's location and resilience of utilities and distribution networks, whether supply is	5	Yes	If the airport location gets exposed to climate hazards, utilities and supply and distribution networks can become susceptible to disruption due to their characteristics and resilience.	Vogiatzis et al. (2021), Monioudi et al. (2018), Eidsvig et al. (2017), Weis et al. (2016), Dawson et al. (2018)
		3	Partially/Occasionally		
		1	No		

Indicator	Variable	Measurement		Rationale	Adopted/adapted/ inspired from
	potentially disrupted by climate hazard(s)				
Sensitivity	Frequency of critical infrastructure/asset damage in the past 10 years due to climate hazard	5	Occurs more than once every year	The frequency of critical infrastructure damage due to a climate hazard indicates its robustness and the degree to which it can be harmed by exposure to climate hazards.	Debortoli et al. (2019), Solecki & Rosenzweig, (2020), Rowan et al. (2014)
		4	Occurs at least once every year		
		3	Occurs once every 5 years		
		2	Occurs once every 10 years		
		1	No incident		
	Frequency of critical equipment damage in the past 10 years due to climate hazard	5	Occurs more than once every year	The frequency of critical equipment damage due to a climate hazard indicates its robustness and the degree to which it can be harmed by exposure to climate hazards.	Debortoli et al. (2019), Rowan et al. (2014)
		4	Occurs at least once every year		
		3	Occurs once every 5 years		
		2	Occurs once every 10 years		
		1	No incident		
	Frequency of air operations disruption (cancelled, delayed or diverted) in the past 10 years due to the climate hazard	5	Occurs more than once every year	The frequency of air operations disruption due to a climate hazard occurrence indicates the degree to which they can be affected by exposure to climate hazards.	Vogiatzis et al. (2021), Monioudi et al. (2018), Eidsvig et al. (2017), Stewart, Klin and Vigilante (2011)
		4	Occurs at least once every year		
		3	Occurs once every 5 years		
		2	Occurs once every 10 years		
		1	No incident		
	Frequency of ground operations disruption in the past 10 years due to the climate hazard	5	Occurs more than once every year	The frequency of ground operations disruption due to a climate hazard occurrence indicates the degree to which they can be affected by exposure to climate hazards.	Debortoli et al. (2019), Vogiatzis et al. (2021), Monioudi et al. (2018)
		4	Occurs at least once every year		
		3	Occurs once every 5 years		
		2	Occurs once every 10 years		
		1	No incident		
	Frequency of incidents impacting airport staff in the past 10 years due to the climate hazard	5	Occurs more than once every year	The frequency of incidents indicates the degree to which airport staff can be affected by exposure to climate hazards and links to the impact on resources, productivity and business performance.	Solecki & Rosenzweig, (2020), Monioudi et al. (2018), Birkmann et al. (2013)
		4	Occurs at least once every year		
		3	Occurs once every 5 years		
		2	Occurs once every 10 years		
		1	No incident		
	Frequency of incidents impacting passengers in the past 10 years due to the climate hazard	5	Occurs more than once every year	The frequency of incidents indicates the degree to which passengers can be affected by exposure to climate hazards.	Solecki & Rosenzweig, (2020), Monioudi et al. (2018), Eidsvig et al. (2017), Birkmann et al. (2013)
		4	Occurs at least once every year		
		3	Occurs once every 5 years		
		2	Occurs once every 10 years		
		1	No incident		
	Frequency of incidents impacting airport surface access in the past 10 years due to the climate hazard	5	Occurs more than once every year	The frequency of incidents indicates the degree to which airport access can be disrupted by exposure to climate hazards.	Solecki & Rosenzweig, (2020), Eidsvig et al. (2017)
		4	Occurs at least once every year		
		3	Occurs once every 5 years		
		2	Occurs once every 10 years		
		1	No incident		

Indicator	Variable		Measurement	Rationale	Adopted/adapted/ inspired from			
	Frequency of outages (utilities or supply) in the past 10 years due to the climate hazard	5	Occurs more than once every year	The frequency of outages of supply or utilities networks indicates how exposure to climate hazards can affect the airport's normal functioning.	Debortoli et al. (2019), Solecki & Rosenzweig, (2020), Eidsvig et al. (2017)			
		4	Occurs at least once every year					
		3	Occurs once every 5 years					
		2	Occurs once every 10 years					
		1	No incident					
	Frequency of safety incidents in the past 10 years due to climate hazard	5	Occurs more than once every year	The frequency of incidents indicates the degree to which the airport can maintain safety margins when exposed to climate hazards.	Birkmann et al. (2013)			
		4	Occurs at least once every year					
		3	Occurs once every 5 years					
		2	Occurs once every 10 years					
		1	No incident					
	Frequency of incidents of pollutants exceeding limits in water bodies in the past 10 years due to the climate hazard	5	Occurs more than once every year	The frequency of incidents indicates the degree to which the airport can sustain environmentally friendly operations when exposed to climate hazards.	Birkmann et al. (2013), Stewart, Klin and Vigilante (2011)			
		4	Occurs at least once every year					
		3	Occurs once every 5 years					
		2	Occurs once every 10 years					
		1	No incident					
	Frequency of increased noise complaints in the past 10 years due to climate hazard	5	Occurs more than once every year	The frequency of incidents indicates the degree to which the airport can manage changing conditions when exposed to climate hazards.	Birkmann et al. (2013)			
		4	Occurs at least once every year					
		3	Occurs once every 5 years					
		2	Occurs once every 10 years					
		1	No incident					
Impact	Impact of climate hazard(s) on the safety of airport operations considering past performance	5	Most severe effect on airport operations safety	Climate hazards affecting the airport location may create conditions impacting the safety of operations (e.g. abnormal runway or landing surface, collisions with wildlife, etc.).	Debortoli et al. (2019), Vogiatzis et al. (2021)			
		4	Large reduction in safety margins					
		3	Significant reduction in safety margins					
		2	Slight reduction in safety margins					
		1	No effect on operational capabilities or safety					
	Share of climate hazard(s) related safety incidents	5	>75%	The share of climate hazard-related incidents compromising the safety of airport operations reflects the significance of the potential impact if the airport is exposed.	Debortoli et al. (2019), Vogiatzis et al. (2021)			
		4	50-75%					
		3	25-50%					
		2	0-25%					
		1	0%					
	Impact of climate hazard(s) on local water resources considering past performance	5	Yes	If not appropriately managed, climate hazards affecting the airport location may impact the quality of local water resources (e.g. low quality due to spills, de-icers or other chemicals, saltwater intrusion etc.).	Vogiatzis et al. (2021), Birkmann et al. (2013)			
		3	Occasionally					
		1	No					
			5			>75%	The share of climate hazard-related incidents compromising the quality of	Vogiatzis et al. (2021), Birkmann et al. (2013)
			4			50-75%		

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	Share of climate hazard(s) related water pollution incidents	3 25-50%	local water resources reflects the significance of the potential impact if the airport is exposed.	
		2 0-25%		
		1 0%		
	Impact of climate hazard(s) on noise complaints considering past performance	5 Large increase	Climate hazards may increase noise complaints (for example, in the case of a heatwave, local residents sleep with open windows and may be easily disturbed by aircraft take-off and landing).	Demertzidis et al. (2015), Birkmann et al. (2013)
		3 Moderate increase		
		1 No increase		
	Share of climate hazard(s) related noise complaints	5 >75%	The share of climate hazard-related noise complaints reflects the significance of the potential impact if the airport is exposed.	Demertzidis et al. (2015), Birkmann et al. (2013)
		4 50-75%		
		3 25-50%		
		2 0-25%		
		1 0%		
	Occurrence of the most significant climate hazard event of the past 20 years on a peak day	5 Yes	If a climate hazard event causing disruption occurs on a peak day, the expected impact will be more significant.	Demertzidis et al. (2015)
		1 No		
	The time the airport was out of service if the most significant climate hazard event of the past 20 years caused the airport closure	5 The airport was out of service for the whole duration of the event and after the event	In the event of airport closure, the time needed to resume operations reflects the impact of the climate hazard occurrence and suggests a lack of resilience.	Debortoli et al. (2019), Rowan et al. (2014)
		4 The airport was out of service for the whole duration of the event		
		3 The airport was out of service for a period of time 25-50% of the overall duration of the event		
		2 The airport was out of service for a short period of time - duration of the disruption <25% of the overall duration of the event		
		1 The airport remained operational during the event		
	Number of ATMs disrupted (cancelled, diverted, or delayed) due to the most significant climate hazard event of the past 20 years	5 >75%	The share of ATMs disrupted by climate hazard occurrence indicates the potential impact if the airport is exposed to an event of similar intensity.	Demertzidis et al. (2015)
		4 50-75%		
		3 25-50%		
		2 0-25%		
		1 No disruption in ATMs		
	Financial impact/business loss due to the disruption caused by the most significant	5 Very high	The loss due to the occurrence of the climate hazard indicates the potential financial impact if the airport is exposed to an event of similar intensity.	Demertzidis et al. (2015), Solecki & Rosenzweig, (2020), Monioudi et al.
		4 High		
		3 Moderate		
		2 Low		

Indicator	Variable		Measurement	Rationale	Adopted/adapted/ inspired from
	climate hazard event of the past 20 years	1	Very low or no financial impact/business loss		(2018), Birkmann et al. (2013)
	Cost for restoration, repairs, or replacement because of the most significant climate hazard event of the past 20 years, considering the annual maintenance cost	5	Very high	The economic cost due to the occurrence of the climate hazard indicates the potential financial impact if the airport is exposed to an event of similar intensity.	Demertzidis et al. (2015), Solecki & Rosenzweig, (2020), Birkmann et al. (2013)
		4	High		
		3	Moderate		
		2	Low		
		1	Very low or no cost		

Appendix B Table 4 Indicators and variables that set up the sub-index of adaptability

Indicator	Variable		Measurement	Rationale	Adopted/adapted/ inspired from
Protection	Sea defences and other protective measures (e.g. barriers) are installed to protect the airport's critical infrastructure from coastal flooding	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	A commonly applied practice to manage coastal floods is building structures such as sea walls and flood barriers, raising the coastline, or using natural processes that utilise natural features to reduce flood risk.	Lopez (2016), Solecki & Rosenzweig, (2020), De Vivo et al. (2021), Yesudian & Dawson (2021), Burbidge et al. (2023)
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
	Flood defences and other protective measures (e.g. barriers, retaining reservoirs) are installed to protect the airport's critical infrastructure from river or surface flooding	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	A commonly applied practice to manage fluvial or pluvial floods is constructing barriers (levees, floodwalls, etc.) or using flood control structures such as retaining reservoirs or nature-based solutions.	Solecki & Rosenzweig, (2020), De Vivo et al. (2021), Balica et al. (2012), Burbidge et al. (2023), ACI (2018)
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
	Critical infrastructure/ buildings in low-lying areas are elevated to address inundation risk	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Elevating floor levels of critical structures or raising water-sensitive equipment above ground are commonly applied flood risk mitigation measures, limiting the exposure.	De Vivo et al. (2021), Solecki & Rosenzweig, (2020), Stewart, Klin and Vigilante (2011), Yesudian & Dawson (2021), Burbidge et al. (2023)
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Relocation of critical, water-sensitive equipment to	Solecki & Rosenzweig, (2020), Stewart, Klin

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	Critical equipment at risk are relocated to address inundation risk	4 In progress - applied across some functions/areas but not fully integrated	protected areas reduces their exposure to inundation.	and Vigilante (2011), Demertzidis et al. (2015), Burbidge et al. (2023), Mcmillan (2014)
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	Critical assets are designed considering wind speed thresholds	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Critical assets designed according to the wind design code considering climate change influence reduce their susceptibility to damage.	Stewart, Klin and Vigilante (2011), Transportation Research Board (2012)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	The airport has an energy-efficient terminal design	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	An energy-efficient terminal design reduces the energy demand during energy-intensive climate hazards events, such as heatwaves and cold waves, reducing stress on electricity systems and helping avoid power outages.	De Vivo et al. (2021), Ferrulli (2016)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	The airport has a water-efficient terminal design	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	A water-efficient terminal design reduces the water demand during water scarcity events, minimising the related business impacts.	Ferrulli (2016), Harley et al. (2020), Carvalho et al. (2013)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	Critical equipment is upgraded or protected, or relocated to withstand climate extremes, considering design standards or technical specifications	2	Not in place, but studies are being conducted to identify approach to pursue improvements	De Vivo et al. (2021), Burbidge (2018)
		1	Measure is not in place and has not been considered	
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	
		4	In progress - applied across some functions/areas but not fully integrated	
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements	
		2	Not in place, but studies are being conducted to identify approach to pursue improvements	
	Terminals are equipped with cooling/heating facilities	1	Measure is not in place and has not been considered	Vogiatzis et al. (2021), Burbidge et al. (2023), Ferrulli (2016)
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	
		4	In progress - applied across some functions/areas but not fully integrated	
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements	
		2	Not in place, but studies are being conducted to identify approach to pursue improvements	
		1	Measure is not in place and has not been considered	
	Drainage systems are upgraded to handle greater peak flows	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	De Vivo et al. (2021), Solecki & Rosenzweig, (2020), Stewart, Klin and Vigilante (2011), Burbidge (2018), ACI (2018)
		4	In progress - applied across some functions/areas but not fully integrated	
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements	
		2	Not in place, but studies are being conducted to identify approach to pursue improvements	
		1	Measure is not in place and has not been considered	
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Vogiatzis et al. (2021), Eidsvig et al. (2017)
			Having alternate or backup power sources ensures that a	

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	There are alternate/ backup power sources in place	4 In progress - applied across some functions/areas but not fully integrated	high degree of redundancy is built into the system in the event of a power outage due to a climate hazard occurrence.	
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There are alternate/backup water supply sources in place	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Having alternate or backup water sources ensures that a high degree of redundancy is built into the system in the event of water supply restrictions due to water scarcity events.	Eidsvig et al. (2017), Harley et al. (2020), Carvalho et al. (2013)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	Alternate/backup power sources are in place for cooling/ heating terminals, facilities, etc.	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Having alternate or backup power sources for cooling/heating functions ensures that a high degree of redundancy is built into the system in case of a power outage due to a climate hazard.	Vogiatzis et al. (2021), Eidsvig et al. (2017)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	The runway(s) length is sufficient to operate under extreme heat	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Sufficient runway length ensures that aircraft will operate without restrictions during heat waves.	De Vivo et al. (2021), Stewart, Klin and Vigilante (2011), Burbidge et al. (2023)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	The orientation of the runways has considered trends in the wind patterns	2 Not in place, but studies are being conducted to identify approach to pursue improvements	Runways designed according to the wind pattern trends improve the resilience of air operations and sustain the airport's performance.	Stewart, Klin and Vigilante (2011), Burbidge et al. (2023)
		1 Measure is not in place and has not been considered		
		5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant		
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
	The control tower is designed to withstand extreme wind loads	1 Measure is not in place and has not been considered	A control tower designed to withstand extreme wind loads reduces the susceptibility to damage and builds resilience.	Stewart, Klin and Vigilante (2011), Burbidge et al. (2023)
		5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant		
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	Operating procedures are in place to ensure safe operations during compound or extreme events such as storms/ snowstorms, low visibility, extreme wind conditions, etc.	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Operating procedures supported by time-based separation technology, instrument landing system, etc., ensure the safety and continuation of operations during extreme weather events.	Vogiatzis et al. (2021), London Heathrow Airport (2016)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There are established procedures to ensure	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Having a plan and procedures to address a water scarcity event	

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	water-efficient operations during a drought/water scarcity event	4 In progress - applied across some functions/areas but not fully integrated	reduces operational and business risk.	Lopez (2016), London Heathrow Airport (2016), ICAO (2021)
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There are adequate snow and ice removal equipment	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Having adequate snow and ice removal equipment allows the airport to remain operational during extreme snowfall or icing events.	Burbidge et al. (2023), London Heathrow Airport (2016)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There are sufficient de-icer storage facilities to address the operational needs during an extreme event	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Sufficient de-icer supplies allow the airport to remain operational during extreme snowfall or icing events.	Burbidge et al. (2023), London Heathrow Airport (2016)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There is an off-site de-icer capacity	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Sufficient de-icer supplies and backup storage allow the airport to remain operational during extreme snowfall or icing events.	London Heathrow Airport (2016)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		

Indicator	Variable		Measurement	Rationale	Adopted/adapted/ inspired from
Preparedness	Pavements in runway(s), taxiway(s) and access roads are hardened to withstand extreme conditions	2	Not in place, but studies are being conducted to identify approach to pursue improvements	Using material that is more resilient and tolerant (e.g. heat-tolerant) reduces the propensity to experience damage during extreme climate events.	De Vivo et al. (2021), Lopez (2016), Burbidge et al. (2023), Ferrulli (2016)
		1	Measure is not in place and has not been considered		
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant		
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
	A monitoring mechanism for water pollutants/ water quality is established	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Monitoring ensures that airport operations during extreme climate events do not compromise the quality of local water resources.	Vogiatzis et al. (2021), De Vivo et al. (2021)
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
	A monitoring mechanism for local biodiversity is established	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Monitoring ensures that changes in local biodiversity due to climate hazards and climate change trends are captured and addressed to mitigate potential safety risks.	Lopez (2016), Vogiatzis et al. (2021), Burbidge et al. (2023)
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
	A mechanism to adapt noise mitigation action	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Adapting noise management during extreme climate events	Burbidge et al. (2023)

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	during extreme events (e.g. extreme heat, extreme/changing wind etc.) is established	4 In progress - applied across some functions/areas but not fully integrated 3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements 2 Not in place, but studies are being conducted to identify approach to pursue improvements 1 Measure is not in place and has not been considered	or due to climate change trends addresses noise levels/ propagation changes and related disturbance.	
	There is an accurate aviation meteorological forecasting mechanism/early warning system in place	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant 4 In progress - applied across some functions/areas but not fully integrated 3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements 2 Not in place, but studies are being conducted to identify approach to pursue improvements 1 Measure is not in place and has not been considered	Early warning systems and meteorological forecasting provide advanced notice of potential climate hazards, allowing the timely deployment of contingency plans.	Eidsvig et al. (2017), Burbidge et al. (2023)
	There is experience in responding to the mentioned climate hazard incidents (recorded past events)	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant 4 In progress - applied across some functions/areas but not fully integrated 3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements 2 Not in place, but studies are being conducted to identify approach to pursue improvements 1 Measure is not in place and has not been considered	Experience in responding to climate hazard occurrences builds the capability to develop a suitable emergency response plan, coordinate the implementation, and support a quicker and more effective recovery.	Shah et al. (2020), Eidsvig et al. (2017), Birkmann et al. (2013)
	The existing emergency response plan addresses climate hazards relevant to the airport location	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant 4 In progress - applied across some functions/areas but not fully integrated 3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements	An emergency response plan addressing all climate hazards in the airport location supports effective response and recovery.	Vogiatzis et al. (2021), De Vivo et al. (2021), Balica et al. (2012), Eidsvig et al. (2017), Birkmann et al. (2013), Burbidge et al. (2023), Mcmillan (2014)

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from	
	There is a decision-making mechanism in place to cancel operations before a climate hazard event occurrence to reduce business impact	2	Not in place, but studies are being conducted to identify approach to pursue improvements	Amending the flight schedule before the climate hazard event to manage expected disruption in an orderly manner minimises business risk.	Vogiatzis et al. (2021), ACI (2018), London Heathrow Airport (2016)
		1	Measure is not in place and has not been considered		
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant		
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
	There are established communication protocols with airlines and other service providers in the event of climate hazard incidents	1	Measure is not in place and has not been considered	When a climate hazard occurs, quick and accurate communication is essential; therefore, establishing communication protocols ensures that all parties have the information they need to manage the disruption efficiently.	De Vivo et al. (2021), Burbidge et al. (2023), ACI (2018), London Heathrow Airport (2016), ICAO (2021), Mcmillan (2014)
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant		
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
	There are established communication protocols with passengers in the event of climate hazard incidents	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	When a climate hazard occurs, quick and accurate communication is essential; therefore, establishing communication protocols ensures that all parties have the information they need to manage the disruption efficiently.	Vogiatzis et al. (2021), Burbidge et al. (2023), London Heathrow Airport (2016), ICAO (2021), Mcmillan (2014)
		4	In progress - applied across some functions/areas but not fully integrated		
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2	Not in place, but studies are being conducted to identify approach to pursue improvements		
		1	Measure is not in place and has not been considered		
	There are established communication	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	When a climate hazard occurs, quick and accurate	Burbidge (2017), Mcmillan (2014)

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	protocols with local transport authorities in the event of climate hazard incidents	4 In progress - applied across some functions/areas but not fully integrated	communication is essential; therefore, establishing communication protocols ensures that all parties have the information they need to manage the disruption efficiently.	
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	The established health and safety procedures address climate hazards in the airport location	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	When health and safety procedures consider the relevant implications of climate hazards, they minimise the risk to people.	Vogiatzis et al. (2021), Arbuthnott & Hajat (2017)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	Regular reviews of the efficiency of existing climate hazard protection/prevention measures are scheduled	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Regular reviews are needed to determine how efficient existing measures can lead to improvements that minimise risk.	Vogiatzis et al. (2021), Mcmillan (2014)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There is a process in place to ensure inspections are conducted before/ during/after a climate hazard event	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Inspections before, during and after a climate hazard event ensure the proper implementation of the contingency and emergency response plan and help identify issues for improvement.	Vogiatzis et al. (2021), Mcmillan (2014)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		

Indicator	Variable		Measurement	Rationale	Adopted/adapted/ inspired from	
	The schedule of maintenance checks is adapted to address climate hazards relevant to the airport location	2	Not in place, but studies are being conducted to identify approach to pursue improvements	Adapting the schedule of maintenance checks ensures that issues are identified and addressed before a climate hazard occurrence.	Vogiatzis et al. (2021). Eidsvig et al. (2017)	
		1	Measure is not in place and has not been considered			
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant			
		4	In progress - applied across some functions/areas but not fully integrated			
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements			
		2	Not in place, but studies are being conducted to identify approach to pursue improvements			
	There is evidence of a coordination mechanism to support climate resilience activities	1	Measure is not in place and has not been considered	Coordination among internal and external stakeholders is critical to ensure the correct management of resources and the implementation of the contingency and emergency response plan.	ACI (2018), London Heathrow Airport (2016), Mcmillan (2014)	
		5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant			
		4	In progress - applied across some functions/areas but not fully integrated			
		3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements			
		2	Not in place, but studies are being conducted to identify approach to pursue improvements			
	Institutional capacity	There is a climate adaptation action plan in place with specific adaptation options and targets for all climate hazards occurring in the airport location	1	Measure is not in place and has not been considered	Adaptation action plan supports the planning and delivery of targeted action to risk-proof infrastructure and operations.	De Vivo et al. (2021), Demertzidis et al. (2015), Burbidge (2017), ACI (2018), ICAO (2021)
			5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant		
			4	In progress - applied across some functions/areas but not fully integrated		
			3	Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
2			Not in place, but studies are being conducted to identify approach to pursue improvements			
Organisation structure and accountability	1	Measure is not in place and has not been considered	Building adaptability requires a successful strategy and	Burbidge (2018), London Heathrow		
	5	In place - fully integrated and well established across airport-relevant functions/areas OR not relevant				

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
	procedures address risk and adaptation for all climate hazards	4 In progress - applied across some functions/areas but not fully integrated	willingness to adapt and, therefore, commitment to take action, suggesting accountability and acceptance of the risk linked to climate hazards.	Airport (2016), Mcmillan (2014)
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There is capacity of airport staff to respond or deliver actions to increase climate resilience	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Having secured resources to plan action and respond to an event ensures business continuity and minimises risk.	London Heathrow Airport (2016)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	There is knowledge of the risk, causes and prevention for climate hazards relevant to the airport location	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Understanding the implications of climate hazards and ways to mitigate adverse impacts facilitates the necessary organisational and cultural change to design and implement effective risk mitigation strategies.	Debortoli et al. (2019), De Vivo et al. (2021), Balica et al. (2012), Demertzidis et al. (2015), Shah et al. (2020), Eidsvig et al. (2017)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	Economic resources for climate resilience are allocated	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Having secured economic resources to deliver adaptation and risk mitigation action reduces risk.	Solecki & Rosenzweig, (2020), Burbidge (2018)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		

Indicator	Variable	Measurement	Rationale	Adopted/adapted/ inspired from
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		
	The insurance policy in place covers loss and business interruption due to all climate hazards in the airport location	5 In place - fully integrated and well established across airport-relevant functions/areas OR not relevant	Risk transfer helps mitigate the impact of climate hazard occurrences.	De Vivo et al. (2021), Demertzidis et al. (2015), Birkmann et al. (2013), Burbidge et al. (2023)
		4 In progress - applied across some functions/areas but not fully integrated		
		3 Not in place, but an action plan is being developed to support the implementation - actively pursuing improvements		
		2 Not in place, but studies are being conducted to identify approach to pursue improvements		
		1 Measure is not in place and has not been considered		

Appendix B Table 5 Sensitivity levels of the airport elements to the applicable climate hazards

Airports	Flood	Heat	Cold	Storm	Snow	Drought	Average
Belfast International	0.32	0.27	0.61	0.50	0.25	0.00	0.33
Assets	0.50	0.63	0.88	0.50	0.25	0.00	0.46
Operations	0.25	0.00	0.75	0.75	0.50	0.00	0.38
People	0.50	0.38	0.75	0.63	0.25	0.00	0.42
Interdependencies	0.25	0.13	0.25	0.25	0.13	0.00	0.17
Safety	0.25	0.50	0.50	0.50	0.25	0.00	0.33
Environment	0.25	0.00	0.00	0.38	0.25	0.00	0.15
Bournemouth	0.16	0.02	0.34	0.16	0.34	0.14	0.19
Assets	0.25	0.13	0.50	0.25	0.50	0.50	0.35
Operations	0.00	0.00	0.50	0.25	0.50	0.00	0.21
People	0.00	0.00	0.50	0.25	0.50	0.00	0.21
Interdependencies	0.38	0.00	0.25	0.13	0.25	0.00	0.17
Safety	0.25	0.00	0.25	0.00	0.25	0.50	0.21
Environment	0.25	0.00	0.00	0.00	0.00	0.00	0.04
Exeter	0.32	0.09	0.27	0.39	0.30	0.00	0.23
Assets	0.13	0.25	0.00	0.00	0.13	0.00	0.08
Operations	0.50	0.00	0.50	0.75	0.50	0.00	0.38
People	0.38	0.00	0.25	0.75	0.50	0.00	0.31
Interdependencies	0.38	0.00	0.25	0.00	0.25	0.00	0.15
Safety	0.75	0.00	0.25	0.50	0.50	0.00	0.33
Environment	0.00	0.50	0.00	0.38	0.00	0.00	0.15
Norwich	0.23	0.18	0.27	0.34	0.32	0.00	0.22
Assets	0.50	0.50	0.00	0.38	0.25	0.00	0.27
Operations	0.25	0.00	0.50	0.50	0.50	0.00	0.29
People	0.25	0.13	0.50	0.38	0.50	0.00	0.29
Interdependencies	0.00	0.00	0.25	0.13	0.25	0.00	0.10
Safety	0.25	0.25	0.50	0.50	0.50	0.00	0.33
Environment	0.25	0.50	0.00	0.25	0.00	0.00	0.17

Appendix B Table 6 Predisposition and sensitivity of surface access

Airports	Flood		Heat		Cold		Storm		Snow		Drought		Average	
	P*	S**	P*	S**	P*	S**	P*	S**	P*	S**	P*	S**	P*	S**
Belfast International	0.50	0.50	0.50	0.25	1.00	0.50	1.00	0.50	1.00	0.25	0.00	0.00	0.67	0.33
Bournemouth	0.50	0.75	0.00	0.00	1.00	0.50	0.50	0.25	1.00	0.50	0.00	0.00	0.50	0.33
Exeter	0.50	0.75	0.00	0.00	0.50	0.50	0.00	0.00	1.00	0.50	0.00	0.00	0.33	0.29
Norwich	0.50	0.00	0.00	0.00	0.50	0.50	0.50	0.25	0.50	0.50	0.00	0.00	0.33	0.21

P*: Predisposition of surface access, S**: Sensitivity of surface access