SUSTAINABLE FINANCE PROGRAMME

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Physical climate-related risks facing airports: an assessment of the world's largest 100 airports

Briefing Paper

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Executive Summary

Climate change will cause extreme weather events to become more frequent and severe over the 21st century. This will have significant impacts on the aviation industry, which is highly sensitive to weather, and airports in particular.

Two major climate-related adaptation risks facing airports are temporary inundation due to storm surge and restrictions on airplane take-off weight due to high temperatures. The frequency and severity of both are likely to increase due to climate change.

This study applies generalised extreme value and normal distributions to extrapolate historical sea level and temperature data from each airport to the end of the 21st century, using mean values of sea level and temperature rise under three emissions scenarios used by the IPCC (RCPs 2.6, 4.5 and 8.5).

Of the world's top 100 airports by passenger traffic, 13 are projected to experience increased inundation risk by 2100, such that an extreme sea level event inundating the airport is expected to occur at least once in 100 years under RCPs 2.6 and 4.5. 15 airports are projected to experience this level of inundation risk under RCP 8.5.

- Airports exposed to inundation risk under RCP 2.6 and RCP 4.5 are Amsterdam Schiphol, Bangkok Suvarnabhumi, Bangkok Don Mueang, Shanghai Hongqiao, Vancouver, Seoul Incheon, Miami International, San Francisco International, Shanghai Pudong, New York John F. Kennedy, Kansai, New York LaGuardia, and Boston Logan.

- Airports exposed to inundation risk under RCP 8.5 are all of the above, as well as Shenzhen Bao'an and Newark Liberty.

- Under RCP 8.5, 11 of these airports are projected to experience inundation risk at least once every year.

- Inundation is projected to become a significant risk for some airports that do not experience this risk in the present day. For example, the return period for an inundation event at Boston Logan Airport decreases from over 100 years in the present day to just 1.1 years under RCP 8.5.

Of the world's top 100 airports by passenger traffic, 19 airports are already exposed to high take-off weight restriction risk due to at least one of three factors: high maximum daily temperatures, high elevation, or short runways. All of these airports are projected to experience an increase in the number of days when take-off weight restrictions are required, as well as an increase in the weight of required restrictions.

- These 19 airports are Bogotá El Dorado, Mexico City Benito Juarez, Kunming Changshui, Denver International, Salt Lake City, New York LaGuardia, Bengaluru Kempegowda, Riyadh King Khalid, Phoenix Sky Harbor, Las Vegas McCarran, Dubai International, Delhi Indira Gandhi, Xi'an Xianyang, Doha Hamad, Charlotte Douglas, Madrid Barajas, Chongqing Jiangbei, Jeddah King Abdulaziz, and Antalya.

- Under RCP 8.5, all 19 airports are projected to experience days requiring take-off weight restrictions of at least 4,536 kg (10,000 lb) at least once every year.

Of the remaining 81 airports not already exposed to take-off weight restrictions, 10 airports are projected to experience days requiring take-off weight restrictions at least once every 100 years by 2100 under RCP 2.6. This increases to 30 airports under RCP 4.5, and 67 airports under RCP 8.5.

- Under RCP 8.5, 5 airports are projected to experience weight restriction days at least once a year. These airports are Melbourne International, Chengdu Shuangliu, Dallas Fort Worth, Zhengzhou Xinzheng, and Fort Lauderdale-Hollywood.

- Weight restriction days are projected to become significantly more common for some airports that do not experience them in the present day. For 10 airports, the return period for such days decreases from over 100 years to less than 2 years under RCP 8.5. These airports are Baltimore-Washington, Changsha Huanghua, Mumbai Chhatrapati Shivaji, Boston Logan, Bangkok Don Mueang, Hangzhou Xiaoshan, Zurich, Houston George Bush, Dusseldorf, and Hanoi Noi Bai.

Certain cities and countries have a particularly high concentration of climate-vulnerable airports.

- Examples of such cities include New York City, Bangkok, and Shanghai, while examples of such countries include China and the USA.

Both inundation and take-off weight restrictions due to high temperatures create material financial costs for airports.

- Past inundation events suggest that airports could be shut down for several days as a result, resulting in millions of dollars in losses due to foregone revenue and infrastructural damage.

- Take-off weight restrictions result in significant losses due to the inability to carry additional cargo and passengers.

- The 100 airports studied handle 60 percent of passenger traffic. Disruptions at any of these airports are likely to propagate to other airports, causing delays and indirect financial losses, even for airports that are not directly exposed to climate-related risk.

Governments are more exposed to climate-vulnerable airports than commercial institutions. However, some non-state companies and financial institutions also have high exposures.

- Of the 15 airports vulnerable to inundation, 13 have higher than 80% government ownership.

- Of the 19 airports exposed to high take-off weight restriction risk, 13 have higher than 80% government ownership.

- Examples of commercial institutions with ownership in multiple climate-vulnerable airports include Vanguard Group (11 airports), BlackRock (9 airports), Capital Research & Management (6 airports), and Lazard (6 airports).

- Examples of governments with ownership in multiple climate-vulnerable airports include Singapore (6 airports), Frankfurt (5 airports), and Norway (5 airports).

Increasing climate-related risk is likely to reduce credit ratings and increase cost of capital for airports. This will make it increasingly difficult for airports to secure the financing required to implement climate adaptation measures.

Lack of information and understanding of climate-related risks are preventing airport owners from implementing climate adaptation measures at sufficient speed and scale.

- Accounting for climate-related risks in long-term plans is likely to reduce costs for airports, as compared to having to climate-proof infrastructure later.

- The longer airports delay the creation of climate adaptation plans, the more costly and unpredictable climate impacts are likely to become.

For airports exposed to inundation risk, viable climate adaptation strategies may include a combination of elevating low-lying assets such as runways, constructing flood defences and local flood management systems.

For airports exposed to take-off weight restrictions, viable climate adaptation strategies may include extending runways, improving aircraft technology, and changing flight schedules. Different airports may need to combine these solutions to suit their needs.

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1. Introduction

The global aviation industry is intimately tied to anthropogenic climate change. Commercial aviation currently accounts for 2 percent of global anthropogenic carbon dioxide emissions,[1] and direct carbon emissions from aviation are projected to increase 2.5 to 5 times by 2050.[2] Under some projections, aviation will consume up to 27 percent of the remaining carbon budget for keeping the mean global temperature increase below 1.5°C by 2050.[3] This makes aviation one of the most important and fastest growing drivers of worldwide carbon emissions.

On the other hand, the aviation industry is also severely threatened by the impacts of climate change. Over the course of the 21st century, climate change will lead to increased acute risks (event-driven risks, e.g. the probability of extreme weather events) as well as chronic risks (long-term shifts in climate patterns, e.g. sustained higher temperatures).[4] Both these types of risk will have material impacts on commercial aviation operations, with the majority of physical climate impacts on the aviation sector centring on airports.[5]

To date, many major airports have yet to make systematic and robust plans to improve their resilience to climate-related adaptation risks.[6] [7] This leaves these airports exposed to extreme climate events, such as storm surges and high temperatures, that can disrupt airport operations or shut them down completely. Such disruptions would create significant financial losses for airlines and airport operators, as well as for a wide spectrum of stakeholders whose operations are reliant on air transport.[8]

As climate-related disruptions become more frequent and severe, vulnerable airports will incur increasing damages, especially if they fail to implement robust climate resilience strategies. These airports may face increasing difficulty in raising capital and maintaining their credit ratings and reputation.[9] In extreme cases, some or all of an airport's infrastructure may be compromised to the extent of incurring premature write-downs, becoming stranded assets.[10]

The position of the aviation industry with regards to climate change is further complicated by the difficulty of decarbonising air transport. It is unlikely that efficiency improvements in aircraft design and operations will be able to offset greenhouse gas emissions growth due to rising passenger demand.[11] While replacing traditional jet fuels with biofuels is an option, this requires a suite of coordinated policies and may negatively affect the decarbonisation of sectors such as agriculture and land use.[12] This means that a robust climate strategy for commercial aviation will likely require a strong focus on adaptation measures.

In order to design a robust climate adaptation plan, it is crucial for airport operators to have information about the projected impacts their airports are likely to face and the costs of various options for minimising them. The potential impacts and costs of climate change have been studied for different types of infrastructure, including seaports,[13] [14] roads,[15] and railways.[16] However, few studies have done so for airports; the studies that exist have been geographically limited,[17] [18] and have lacked a comparative analysis of the risks facing different airports,[19] possible strategies for mitigating these risks,[20] and the effects of different emissions scenarios.[21] This paper is one of the first that attempts to address these limitations.

The objective of this paper is to investigate how the degree of physical climate-related risk faced by the world's most important airports will change between the present day and the end of the 21st century due to climate change under various emissions scenarios.

The paper contains 7 sections. Section 1 introduces the issue of airport climate-related adaptation risk, while Section 2 describes the types of climate-related adaptation risks faced by airports that are discussed in the academic literature, focusing on two types: inundation risk and risk of take-off weight restrictions caused by high temperatures. Section 3 explains the methodology of calculating and projecting these risks for the end of the 21st century under different emissions scenarios, as well as the data sources used to make these calculations. Section 4 presents how these risks will change for different categories of airports, identifies the airports and geographies that are most at risk, and discusses limitations of the methodology used to produce these results. Section 5 discusses and quantifies the financial, operational, and secondary impacts of increasing climate-related adaptation risk for airports. It also examines the ownership of vulnerable airports and how this may affect their climate adaptation efforts. Section 6 presents the options available to airports for adapting to increased climate-related risk and the trade-offs required for each option. Section 7 concludes.

2. Literature Review

2.1 Overview of Climate-Related Adaptation Risks Faced by Airports

Commercial aviation is a major global industry. It is estimated that in 2019, the global commercial aviation industry will generate US$919 billion, or 1 percent of world GDP.[22] The industry is also expected to continue growing rapidly in the near future, supported by increasing passenger demand and a quickly expanding middle class in developing markets. The International Air Transport Association (IATA) forecasts that passenger numbers will double to 8.2 billion from 2018 to 2037,[23] with annual growth rates in countries such as India and China reaching as high as 11 percent.[24] On top of their economic value, airports and aviation also play a critical role in the infrastructural network of many countries, as they catalyse regional and international commerce, the transport of people and goods, and general economic development.[25]

However, the continued functioning of many airports is materially threatened by operational and financial risks resulting from climate change. Aviation is highly sensitive to weather,[26] with 75 percent of passenger aviation delays being weather-related.[27] As climate change exacerbates over the course of the 21st century, weather-related disruptions to airport operations are likely to grow more frequent, diverse, and severe.[28]

The direct physical impacts on airports due to climate change include both chronic impacts, such as mean sea level and temperature rise, and acute impacts, due to the increased likelihood and intensity of extreme weather events.[29] While these extreme events are likely to be more disruptive for airports, they are also harder to predict and protect against, due to the uncertainties inherent to long-term climate projections.[30] Depending on the airport's location, extreme weather events that could disrupt operations include inundation due to storm surges; inability of airplanes to take off due to high temperatures; and infrastructure damage due to storms, snow, and frost.[31]

On top of these direct impacts, climate change may also result in numerous indirect impacts that are hard to quantify. Examples include changes in tourism traffic due to altered weather patterns, increasing use of airport facilities as shelter or transport hubs after weather-related disasters, and increasing risk of communicable diseases and epidemics.[32]

Table 1 presents a non-exhaustive summary of the climate-related physical adaptation risks for airports that are discussed in the academic literature.

Table 1: Examples of Climate-Related Physical Adaptation Risks for Airports[33] [34] [35] [36] [37]

Direct		**Indirect**
Gradual	Sudden	
Mean sea level rise • Permanent inundation of low-lying infrastructure	Increased frequency and intensity of storm surge and other extreme sea level events	Changes in passenger travel patterns • May result in either

	• Flooding of runways and other airport infrastructure • Flooding of transport and logistical links critical to airport functioning • Flight delays and cancellations • Damage to electrical equipment	increases or decreases in passenger traffic at different times of year
Increased mean temperatures • Reduced aircraft performance • Cruise altitude changes • Effects on navigational signals and satellite coverage • Increased energy consumption for cooling • Increased fire risk	Increased frequency and intensity of extreme high temperature events • Aircraft take-off weight restrictions • Flight delays and cancellations • Infrastructural damage	Increased frequency of extreme weather events in general • Increased demand on airport logistical services for transport, shelter, and rescue • Increased risk of communicable diseases and epidemics
Thawing permafrost • Airport embankment failures • Increased maintenance costs • Infrastructural damage	Increased frequency and intensity of extreme winds • Flight delays and cancellations • Infrastructural damage	Knock-on effects due to climate-related delays at other airports • Flight delays and cancellations
Increased precipitation • Decreased visibility, greater distances between aircraft • Flooding of runways and other airport infrastructure • Flight delays and cancellations	Increased frequency of extreme snow and frost events • Flight delays and cancellations	Desertification in airport environs • Reduced water supply to airport • Reduced air quality
Changes in wind direction • Increased crosswinds reduce operability of certain aircraft and runways • Potential procedural changes		Changes in flora and fauna near airport • Increased propagation and migration of invasive species
		Litigation from customers/ other stakeholders due to climate-related damages • Legal costs • Reputational costs

The remainder of this paper will largely focus on two direct physical risks resulting from climate change: inundation and high temperatures. These risks are chosen for several reasons. Firstly, average sea levels and daily maximum temperatures have already begun increasing across the world, and there is high confidence that they will continue to do so.[38] [39] [40] Secondly, these two impacts are likely to affect a large proportion of the world's airports, unlike other weather phenomena (such as snowstorms or fog), which are restricted to certain regions. Thirdly, for a given emissions pathway, these risks are likely to create impacts with similar directionality and degree across different airports.[41] [42] This allows for the airports that are most vulnerable to these two risks globally to be identified and compared.

2.2 Risk of Inundation

Low-lying coastal areas have often been chosen as locations for airports, due to the availability of cheap land and a lack of aerial obstructions.[43] [44] Many airports are also located in coastal areas because they serve regions of high population density, which are often located close to the sea: it is estimated that 27 percent of the world's population lives within 100 km of a coastline at an elevation below 100 m.[45] This means that rising sea levels due to climate change put many airports at risk of temporary or permanent inundation.

Gradual rises in mean sea level due to climate change may eventually cause low-lying coastal airports to become permanently inundated.[46] For example, Sorokin & Mondello find that a 2 metre sea level rise threatens 11 major European airports with permanent inundation and a further 17 with flood risk, although they do not specifically identify which. [47]

On the other hand, the key threat for a much larger number of airports is not permanent inundation, but increases in the intensity of storm surge events caused by higher mean sea levels.[48] A storm surge is a temporary rise in sea level during an intense storm, such as a hurricane or cyclone, due to atmospheric-pressure differences and wind-induced stresses on the sea surface.[49] [50] Storm surges can increase sea levels by as much as 13 metres,[51] and even a gradual rise in mean sea level may greatly increase the frequency and severity of storm surges.[52] At airports, storm surges may cause flooding of runways and taxiways, damage to underground infrastructure such as electrical equipment, inundation of ground transport links, and damage to parked planes (see Figure 1).[53] [54] All of these would materially disrupt the ability of airports to operate normally.

Figure 1: New York LaGuardia Airport Flooded Due to Hurricane Sandy in 2012[55]

Some studies have previously been conducted to assess the inundation risk of airports. In a study of China's infrastructure system, Hu found that under a moderate emissions pathway, 41 more Chinese airports are at increased risk of flooding by the mid-21st century than at present.[56] According to a report by EUROCONTROL, 34 major European airports are at risk of inundation due to sea level rise, storm surges, and tidal lock, a phenomenon where high tides coincide with high river flows.[57] Governments have also led some work examining airport inundation risk in their respective jurisdictions. For example, the US Global Change Research Programme, commissioned by the United States government, has found that 13 of the USA's 47 largest airports have at least one runway vulnerable to moderate to high storm surge.[58]

However, the scope of these studies has been largely restricted to airports in certain regions, rather than looking at the threats to airports on a global scale. These studies have also only included at most a limited set of emissions pathway scenarios. This leaves an important informational gap for airport administrators and other stakeholders interested in improving the climate resilience of airports.

It should be noted that even airports located at a significant distance from the coast can be exposed to flooding, for example due to heavy rains[59] or the overflowing of nearby rivers.[60] While climate change is expected to increase global net rainfall, this impact will likely be highly heterogenous, with some climates experiencing more rainfall and other climates less;[61] as a result, the relationship between climate change and changes in river flood risk remains uncertain.[62] Therefore, we restrict this study to storm surges, which are projected to increase in magnitude across all locations with a high degree of confidence.[63]

2.3 Risk of High Temperature-Induced Take-off Weight Restrictions

The ability of an aircraft to take off depends on the ambient air temperature. At any given pressure, warmer air is less dense and produces less lift. Higher temperatures therefore require airplanes to attain higher speed before they can take off.[64] However, as attaining higher speeds requires a longer runway, each airplane model requires a certain minimum runway length to take off at a given temperature. If the airport where the airplane is attempting to take off does not have a runway meeting this length requirement, the weight of the airplane must be reduced by removing either passengers or cargo. In other words, for each airplane model, every airport has an upper temperature limit beyond which the airplane will need to reduce its weight below its maximum possible carrying capacity in order to take off.[65]

Take-off weight restrictions are an important issue for airports that regularly experience high temperatures (such as those located in deserts), that are located at high elevations (where lower air pressure creates less lift, causing an effect similar to that of high temperatures), or that have short runways (limiting the maximum take-off speed attainable). In this paper, we collectively refer to these airports as "hot/high/short runway" ("HHS") airports. Prevailing weather conditions at these airports can limit the ability of certain aircraft, especially larger models, to use them safely.[66] High temperatures at these airports have been implicated in major airplane crashes with hundreds of fatalities (see Figure 2).[67] [68] As climate change is projected to increase global mean temperatures, as well as the frequency and magnitude of extreme high temperature events,[69] the issue of take-off weight restrictions will likely become increasingly material for these "HHS" airports.

The impact of climate change on aircraft take-off performance has previously been studied in the literature. Zhou, et al. found that by the middle of the 21st century, increases in average temperature will reduce aircraft take-off performance and increase take-off distance at 30 international airports, although some will be more affected than others due to variations in pressure altitude across different airports.[70] Coffel, Thompson, & Horton studied the impacts of increasing temperature on 5 aircraft models and 19 airports (10 within and 9 outside the USA), finding that 10 to 30 percent of flights at these airports may requre take-off weight restrictions during daily maximum temperatures by 2060-2080.[71]

Figure 2: Crash Site of Spanair Flight 5022

Failure to account for "hot and high" conditions are believed to have contributed to the crash of Spanair Flight 5022 in 2008, which killed 154 people.[72]

However, previous to this paper, there had not yet been a systematic study of climate-related take-off performance risk for the airports most critical to global passenger aviation. In addition, as temperatures increase, other airports that do not currently experience take-off weight restrictions as a material risk ("non-HHS" airports) may also need to begin taking this issue into consideration. No previous study has attempted to separate and compare climate-related impacts on take-off weight restrictions between "HHS" and "non-HHS" airports.

It should be noted that take-off weight restrictions are not the only impact that high temperatures may have on airports. Other, possibly equally material impacts on airports due to high temperatures include heat damage to infrastructure, such as melting runway tarmac; increased energy demand due to greater cooling requirements; and health and safety concerns.[73] However, a detailed investigation of these impacts lies outside the scope of this paper.

3. Methodology and Data

3.1 Selection of Airports and Time Period for Study

In order to capture the impact of climate-related risks on airports key to global aviation, we restrict my study to the world's top 100 airports by passenger volume in 2018, as obtained from AirportProfiles.com.[74] In total, these 100 airports handled 4.5 billion passengers in 2018, or 55 percent of the 8.3 billion passengers handled by the world's airports each year.[75] Finally, an additional airport, Beijing Daxing, was added to the list, bringing the total to 101. This is because Beijing Daxing Airport, which opened in September 2019, is expected to eventually serve 72 to 100 million passengers annually, placing it within the world's 10 busiest airports.[76] [77] A full list of these airports, their locations, and passenger statistics is provided in Appendix 1.

Airports are long-lived assets, with an average operational lifespan of 50 to 70 years.[78] The design life of terminal buildings is around 50 years, while runways are typically designed to exceed 100 years of use.[79] Some major international airports, such as Bangkok Don Mueang Airport (opened 1914) and Amsterdam Schiphol Airport (opened 1916), have been operational for over 100 years.[80] [81] Therefore, it is reasonable to assume that airports operating today will still be in operation at the end of the 21st century, barring major events such as geopolitical changes, catastrophic infrastructural damage, or significant shifts in passenger demand.

Following estimated projections for average global sea level and temperature rise given in the 5th Assessment Report of the Intergovernmental Panel on Climate Change, we define "present day" as the period between 1986 and 2005, and "end of the 21st century" as the period between 2081 and 2100.[82] [83] To reflect different possible pathways for emissions and radiative forcing over the course of the 21st century, three scenarios for the end of the 21st century are investigated. These scenarios are aligned with the Representative Concentration Pathways (RCPs), which are scenarios developed by the academic climate research community to be representative of the full range of trajectories for greenhouse gas emissions, concentrations, and land use discussed in the literature.[84] we refer to the three scenarios used in this paper, in order of least to most warming, as the "low case" (the lower bound of RCP 2.6, representing approximately 490 ppm CO_2e), the "mid case" (the median of RCP 4.5, representing approximately 650 ppm CO_2e), and the "high case" (the upper bound of RCP 8.5, representing approximately 1370 ppm CO_2e).

3.2 Using Generalised Extreme Value (GEV) Distributions for Projecting Extreme Climate Events

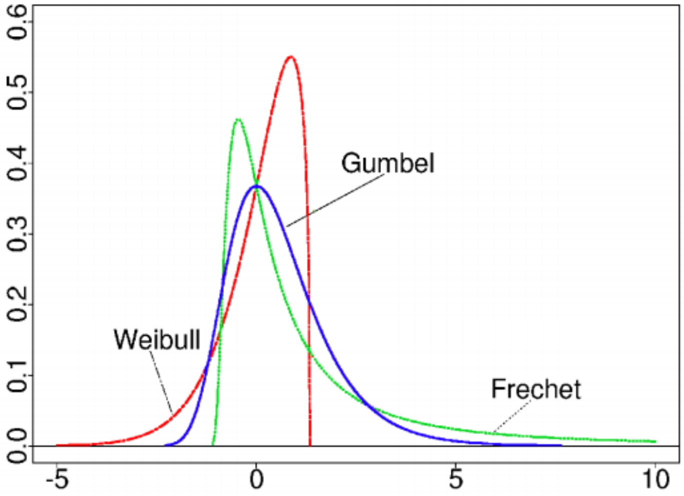
Extreme value theory is the field of study that aims to describe the stochastic behaviour of processes when they approach extreme (very large or small) values.[85] Under extreme value theory, the external types theorem states that for a variable F, as the number of observations of F approach infinity and the sample distribution of F approaches the normal distribution (by the central limit theorem), and the distribution of the extreme values of F observed over n time units (for example, the maximum value of F observed each year) approaches the generalised extreme value (GEV) distribution.[86] The GEV probability distribution function takes the form:

$$f(x) = \left\{ \begin{array}{c} e^{-\left(1+\xi\frac{x-\mu}{\beta}\right)^{-\frac{1}{\xi}}} \; for\ \xi < 0\ (Fréchet\ distribution) \\ e^{-e^{-\frac{x-\mu}{\beta}}} \; for\ \xi = 0\ (Gumbel\ distribution) \\ e^{-\left(1+\xi\frac{x-\mu}{\beta}\right)^{-\frac{1}{\xi}}} \; for\ \xi > 0\ (Weibull\ distribution) \end{array} \right\},$$

where *f(x)* is the probability that the maximum value of the observed variable during each time period is x, μ is the *location parameter* (the value of x with the highest probability within the distribution), β is the *scale parameter* (a measure of the distribution's statistical dispersion), and ξ is the *shape parameter* (a variable that governs the behaviour of the distribution's tails) (see Figure 3).

The use of the GEV distribution to project extreme weather events is well-documented in the literature. As the GEV distribution has been shown to be a good fit for the empirical distribution of many extreme weather events,[87] it has been used to project the probability of extreme values for phenomena such as coastal flooding,[88] rainfall,[89] temperatures,[90] and wind speeds.[91] In this study, we use a similar theoretical basis to project the exposure of airports to two types of risk: inundation due to extreme sea level events and high temperatures.

Figure 3: Sample Distribution Shapes of Fréchet, Gumbel and Weibull Distributions[92]



3.3 Projecting Inundation Due to Extreme Sea Level Events

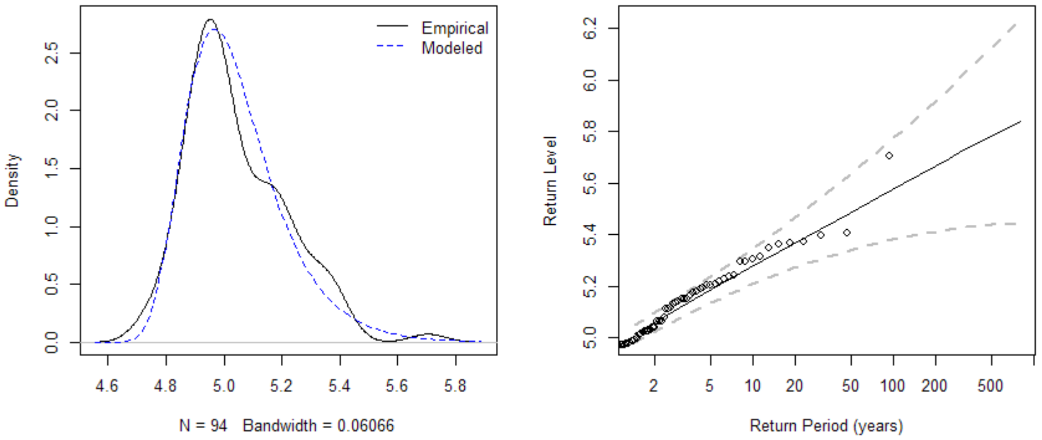
To project the exposure of airports to inundation due to extreme sea level events, we apply a method based on those described by Hunter[93] and Méndez & Menéndez.[94] First, from the total set of 101 airports, we create a subset of airports at risk of extreme sea level events, i.e. those located in coastal areas. As there is no single definition of what constitutes a "coastal area", we follow definitions commonly cited in the literature[95] [96] and define these airports as those with a boundary located within 100 km of a coastline, as determined using Google Earth Pro measurements, as well as at an elevation of 10m or less, according to data from SkyVector.[97] [98] This results in a set of 26 airports.

We then map each coastal airport to the nearest tide gauge within the most comprehensive datasets available for global historical sea levels recorded on at least an hourly basis. These are the Global Extreme Sea Level Analysis (GESLA) Project[99] and the University of Hawaii's Sea Level Centre (UHSLC) datasets.[100] A maximum distance cutoff of 250 km is used when matching airports to tide gauges, as waves within this distance have been found to behave in a temporally consistent manner.[101] We use only those tide gauges with comprehensive readings, which we define as at least 19 years of data with readings for at least 70 percent of the hours in each year, and we only use data from those years. When necessary, data from multiple tide gauges within 250 km of the airport is combined to obtain the requisite number of observations. Where tide gauges with more comprehensive readings are available from national hydrological agencies, this data is used instead. Where no tide gauge with comprehensive readings is available, hourly climate reanalysis data for the period of 1986 to 2005 from ERA5, the latest reanalysis available from the European Centre for Medium-Range Weather Forecasts (ECMWF), is used.[102] A full list of coastal airports and their matching tide gauge stations or data sources is provided in Appendix 2.

Next, we inspect the observed sea level time series for nonstationarity using a linear regression. If the data exhibits significant nonstationarity (p-value < 0.05), we detrend the observed sea levels using a linear regression with origin t = 00:00 hours 1st January 1996, the midpoint of the time period considered as "present day" in this study.

Following this, we use the statistical software R, specifically the "extRemes" software package by Gilleland & Katz,[103] to fit the maximum annual sea levels observed for each tide gauge to the GEV cumulative distribution function (see Figure 4). This produces unique location, scale, and shape parameters for each station. A chi-square test is used to check the goodness of fit of the observations to the GEV distribution. (A full list of chi-square statistics and p-values for each station is presented in Appendix 4.)

Figure 4: Fitting Process of Observed Sea Level Data to GEV Distribution



Note:

Station shown is Boston Logan Airport.

We define a "return period" as the expected time interval at which an event of a given magnitude is first exceeded.[104] To calculate inundation risk, we calculate return periods for which sea level will at least equal the elevation of each airport in the present day, and by increasing the location parameter by likely values for global mean sea level rise for the period 2081-2100 under various RCPs, as given by Church, et al.,[105] we also project these return periods at the end of the 21st century under each of the three scenarios considered. (The likely values of sea level rise for each scenario are given in Table 2.) This method captures extreme sea level events due to both tides and storm surges.[106]

Table 2: End-21st Century Global Mean Sea Level Rise for the Three Scenarios Investigated

Scenario	"Low case" (lower bound of RCP 2.6)	"Mid case" (median of RCP 4.5)	"High case" (upper bound of RCP 8.5)
Sea level rise (m)	0.28	0.53	0.98

3.4 Projecting High Temperatures

To project the exposure of airports to extreme high temperatures, we follow a similar method to that used to project inundation risk. First, we obtain data on the elevation and longest runway of each airport in the set from SkyVector.[107] Runway data is cross-checked against latest news reports to capture recently completed and announced runway extensions and constructions.

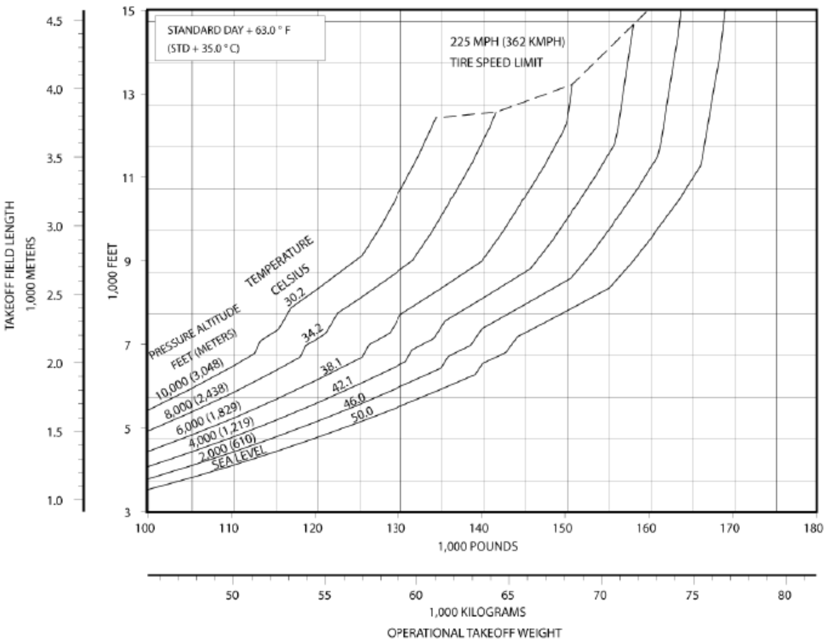
We then map each airport to the nearest weather station within the most comprehensive dataset available for historical daily maximum temperatures, the Global Historical Climatology Network-Daily (GHCN-D) database.[108] A maximum distance cutoff of 200 km is used when matching airports to weather stations, as this is the maximum resolution generally used in global climate models.[109] We use only weather stations with comprehensive temperature readings, which we define as at least 17 years of data with readings for at least 85 percent of the days in each year, and we only use data from those years. When necessary, data from multiple stations within 200 km of the airport is combined to obtain the requisite number of observations. A full list of airports and their matching weather stations is provided in Appendix 3.

Next, we inspect the observed temperature time series for nonstationarity using a linear regression. If the data exhibits significant nonstationarity (p-value < 0.05), we detrend the observed sea levels using a linear regression with origin t = 1st January 1996, the midpoint of the time period considered as "present day" in this study.

Following this, we determine the maximum temperature thresholds beyond which aircraft will be unable to take off at each airport, building on the method used by Coffel & Horton.[110] As each aircraft model has different maximum thresholds, we use the Boeing 737-800, the most widely-used narrowbody jet airliner currently in operation,[111] as a proxy for commercial aircraft in general.

Charts relating minimum runway length, elevation, temperature, and maximum take-off weight for the Boeing 737-800 are available from Boeing (see Figure 5).[112] We combine these charts with information on elevation and maximum runway length for each airport to calculate the maximum temperature thresholds beyond which the Boeing 737-800's weight must be reduced below its maximum possible take-off weight for the aircraft to take off, using 3 levels of weight restriction: 0 kg (i.e. any weight restriction), 4,536 kg (10,000 lbs), and 6,804 kg (15,000 lbs). Where values fall outside of available charts, we apply linear extrapolation to the values available to calculate maximum temperature thresholds. Further, we define weight restriction days as days on which maximum daily temperature will at least equal each of the three take-off weight restriction thresholds (therefore requiring weight restrictions for the Boeing 737-800 to take off).

Figure 5: Sample Take-off Performance Chart for Boeing 737-800[113]



By observing the maximum annual temperature readings and maximum temperature thresholds for each airport, we separate the airports into two categories, "hot/high/short runway" ("HHS") airports and "non-HHS" airports. A "HHS" airport is one that has already experienced weight restriction days in at least 40 percent of the years observed, due to high temperatures, high altitude, or short maximum runway length. Weight restrictions are therefore likely to already be a material concern in the present day for "HHS" airports. (The 40 percent cutoff was chosen because there is a large gap between two clusters in the set of airports studied. The first cluster of airports has experienced weight restriction days in 44 to 100 percent of the years observed, but the second cluster of airports has only experienced such days in 0 to 19 percent of the years observed.) Out of the 101 airports, 19 "HHS" airports were identified (see Table 3). One additional airport, São Paulo Guarulhos, would likely also fall into this category; however, it is excluded from the present study due to inadequate historical temperature data.

Table 3: "Hot/High/Short Runway" ("HHS") Airports

No.	Airport Name	Average Annual Max Temperature[114]	Elevation (m)	Length of Longest Runway (m)

		(^{o}C)		
1	Antalya	42.2	53.9	3400
2	Bengaluru Kempegowda	37.2	915.0	4000
3	Bogotá El Dorado	23.2	2548.1	3800
4	Charlotte Douglas	36.9	227.7	3048
5	Chongqing Jiangbei	39.3	416.1	3800
6	Delhi Indira Gandhi	44.8	237.1	4430
7	Denver International	38.1	1656.0	4877
8	Doha Hamad	47.6	4.0	4850
9	Dubai International	46.5	18.9	4850
10	Jeddah King Abdulaziz	46.3	14.9	4000
11	Kunming Changshui	29.9	2104.0	4500
12	Las Vegas McCarran	45.3	664.8	4423
13	Madrid Barajas	39.4	609.0	4179
14	Mexico City Benito Juarez	32.0	2229.9	3985
15	New York LaGuardia	35.0	6.1	2135
16	Phoenix Sky Harbor	46.3	345.6	3502
17	Riyadh King Khalid	46.5	625.4	4200
18	Salt Lake City	39.1	1289.3	3658
19	Xi'an Xianyang	39.5	479.1	3801

To produce more meaningful results, we project temperature rise at the end of the 21st century using different methods for "HHS" and "non-HHS" airports. For "HHS" airports, we use the statistical software R, specifically the "fitdistrplus" software package by Delignette-Muller & Dutang,[115] to fit the daily maximum temperatures observed for each station to the normal distribution, producing unique mean and standard deviation parameters for each station. A Kolmogorov-Smirnov test is used to check the goodness of fit of the observations to the normal distribution. (A full list of Kolmogorov-Smirnov statistics and p-values for each station is presented in Appendix 4.) While there is disagreement in the literature about whether the normal distribution provides a good fit for daily maximum temperatures,[116] [117] it is chosen here on the basis of its flexibility and theoretical relationship with the GEV distribution. We then calculate return periods (in days) for weight restriction days in the present day. By increasing the mean by likely values for global mean temperature rise for the period 2081-2100 under various RCPs, as given by Collins, et al.,[118] we also project return periods for weight restriction days at the end of the 21st century under each of the three scenarios considered. The values of temperature rise for each scenario are given in Table 4.

Table 4: End-21st Century Global Mean Temperature Rise for the Three Scenarios Investigated

Scenario	"Low case" (lower bound of RCP 2.6)	"Mid case" (median of RCP 4.5)	"High case" (upper bound of RCP 8.5)
Temperature rise (^{o}C)	0.6^{o}C	2.4^{o}C	5.7^{o}C

For “non-HHS” airports, we use R and the “extRemes” software package to fit the maximum annual temperatures observed for each station to the GEV cumulative distribution function. This produces unique location, scale, and shape parameters for each station. A chi-square test is used to check the goodness of fit of the observations to the GEV distribution. (A full list of chi-square statistics and p-values for each station is presented in Appendix 4.) We then repeat the process described in the previous paragraph for the location parameter of the GEV distribution to calculate return periods (in years) for weight restriction days for each of the three take-off weight restriction thresholds, in both the present day and at the end of the 21st century for the three scenarios considered.

4. Results and Discussion

4.1 Airports Vulnerable to Inundation

We define an airport as having inundation risk if it has a return period of 100 years or less for an extreme sea level event at least equal to the airport's elevation. A 100-year return period is often used by government agencies and insurers as a benchmark for adequate resilience to extreme sea level events, as 100 years is the typical lifespan of flood defence infrastructure.[119] [120]

Of the 26 coastal airports, we find that 12 airports are already exposed to inundation risk. This increases to 13 airports in the "low" and "mid" cases, and to 15 airports in the "high case".

Of the 15 airports facing inundation risk in the "high case", 7 are in North America (with 6 in the USA alone), 7 are in Asia (including 3 in China and 2 in Thailand), and 1 is in Europe. Together, these airports accounted for approximately 9 percent of global aviation passenger movements in 2018.

The full set of return periods for inundation is presented in Table 5. Only return periods of 100 years or less are presented.

Table 5: Return Periods of Inundation for Coastal Airports, Ranked from Highest to Lowest Inundation Risk in Present Day

No.	Airport Name	Elev-ation (m)	Return Period of Inundation (years)				Increase in Inundation Frequency Compared to Present Day		
			Present day	"Low case"	"Mid case"	"High case"	"Low case"	"Mid case"	"High case"
1	Amsterdam Schiphol	-3.4	1.0	1.0	1.0	1.0	1.0x	1.0x	1.0x
2	Bangkok Suvarnabhumi	1.5	1.0	1.0	1.0	1.0	1.0x	1.0x	1.0x
3	Bangkok Don Mueang	2.7	1.0	1.0	1.0	1.0	1.0x	1.0x	1.0x
4	Shanghai Hongqiao	3.0	1.0	1.0	1.0	1.0	1.0x	1.0x	1.0x
5	Vancouver	4.0	1.0	1.0	1.0	1.0	1.0x	1.0x	1.0x
6	Seoul Incheon	7.0	1.0	1.0	1.0	1.0	1.0x	1.0x	1.0x
7	Miami International	2.7	1.1	1.0	1.0	1.0	1.1x	1.1x	1.1x
8	San Francisco International	4.0	1.9	1.0	1.0	1.0	1.9x	1.9x	1.9x
9	Shanghai Pudong	4.0	2.5	1.3	1.0	1.0	1.9x	2.5x	2.5x
10	New York John F. Kennedy	3.7	11.4	3.7	1.3	1.0	3.1x	8.8x	11.4x
11	Kansai	5.2	12.8	4.0	1.6	1.0	3.2x	8.0x	12.8x
12	New York LaGuardia	6.1	70.3	30.6	11.2	2.9	2.3x	6.3x	24.2x
13	Boston Logan	5.8	N/A	65.4	10.1	1.1	>1.5x	>9.9x	>91.0x
14	Shenzhen Bao'an	4.0	N/A	N/A	N/A	12.8	N/A	N/A	>7.8x

15	Newark Liberty	5.2	N/A	N/A	N/A	54.6	N/A	N/A	>1.8x

Notably, there are 3 airports that do not face inundation risk in the present day but will do so by the end of the 21st century, especially in the "high case". These airports are Boston Logan, Shenzhen Bao'an, and Newark Liberty. Among these airports, the most drastic change is expected to occur at Boston Logan Airport. There, return periods for inundation are expected to decrease from in excess of 100 years in the present day to only 1.1 year in the "high case" – an over 90-fold increase in frequency.

For airports that already face inundation risk in the present day, the degree of risk increases significantly by the end of the 21st century, sometimes in excess of an order of magnitude. For example, New York LaGuardia Airport currently has an inundation return period of 70.3 years, but in the "high case", this becomes as few as 2.9 years. In other words, inundation is expected to occur more than 24 times as frequently.

As mean sea level rises, the inundation risk of different airports increases at different rates. This is due to differences in how the maximum annual sea levels at each airport are distributed. For example, in the present day, Boston Logan Airport experiences insignificant inundation risk, as compared to New York LaGuardia Airport, which has an inundation return period of 70.3 years. However, in the "mid case" and "high case", the situation is reversed: Boston Logan Airport now has higher inundation risk (return period of 10.1 years under the "mid case" and 1.1 year under the "high case") than New York LaGuardia Airport (return period of 11.2 years under the "mid case" and 2.9 years under the "high case").

There is also no direct correlation between elevation and inundation risk. For example, despite being one of the airports with the highest elevation in the set (7.0m), Seoul Incheon Airport experiences much smaller inundation return periods than airports located at lower elevations, such as New York John F. Kennedy and Shenzhen Bao'an. This is likely to be because of the significant role played by local geographical characteristics in determining storm surge height.[121]

It is important to note that several coastal airports already have very short inundation return periods, which may be as brief as 1 year or less. These airports are reliant on infrastructure such as seawalls, flood gates and drainage basins to prevent flooding. The effectiveness of these strategies is discussed in detail in Section 6.2.1.

4.2 Airports Vulnerable to High Temperatures

4.2.1 "HHS" Airports

As mentioned above, 19 airports in the set of 101 are identified as "HHS" airports. Of the 19 airports, 7 are in North America (with 6 in the USA alone), 10 are in Asia (including 3 in China, 2 in India, and 2 in Saudi Arabia), and 1 each is in Europe and South America. Together, these airports accounted for approximately 10.4 percent of global aviation passenger movements in 2018.

The full set of temperatures at which take-off weight restrictions are required, as well as return periods for weight restriction days in the present day and under each of the 3 scenarios studied, is presented in Table 6. Only return periods of 100 years (36,500 days) or less are shown.

Table 6: Temperatures Requiring Take-off Weight Restrictions and Return Periods (in days) for "HHS" Airports, from Highest to Lowest Risk in Present Day[122]

No.	Airport Name	Temp. threshold for take-off weight restriction (ºC)			Return period for take-off weight restriction (days)											
					Present day			"Low case"			"Mid case"			"High case"		
		>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg
1	Bogotá El Dorado	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL
2	Mexico City Benito Juarez	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL
3	Kunming Changshui	ALL	ALL	20.4	ALL	ALL	1.7	ALL	ALL	1.6	ALL	ALL	1.3	ALL	ALL	1.1
4	Denver International	ALL	29.0	34.3	ALL	5.8	13.0	ALL	5.4	11.7	ALL	4.3	8.8	ALL	3.0	5.5
5	Salt Lake City	ALL	32.6	37.8	ALL	9.3	21.5	ALL	8.5	19.3	ALL	6.6	14.3	ALL	4.4	8.6
6	New York LaGuardia	ALL	30.6	35.2	ALL	14.6	38.0	ALL	13.1	33.2	ALL	9.5	22.6	ALL	5.7	11.9
7	Bengaluru Kempegowda	30.5	40.1	44.7	2.5	4097.6	-	2.1	1965.6	-	1.4	272.4	-	1.1	17.3	1097.1
8	Riyadh King Khalid	36.2	44.8	47.3	2.6	9.8	16.5	2.5	8.7	14.5	2.1	6.3	10.0	1.6	3.8	5.6
9	Phoenix Sky Harbor	38.5	47.7	52.6	5.4	37.5	153.4	4.9	32.2	127.3	3.8	20.8	74.4	2.5	10.2	30.6
10	Las Vegas McCarran	36.4	44.7	47.6	5.6	23.9	45.3	5.2	21.1	39.4	4.1	14.9	26.6	2.8	8.3	13.8
11	Dubai International	44.5	52.1	55.9	19.5	339.1	2175.7	16.3	259.6	1591.0	9.9	121.7	650.0	4.7	35.8	149.3
12	Delhi Indira Gandhi	42.7	50.3	54.2	20.5	367.2	2527.4	17.1	280.4	1840.8	10.4	130.5	743.4	4.8	37.9	167.2
13	Xi'an Xianyang	37.4	45.9	50.2	20.5	141.4	467.5	18.3	121.1	392.1	13.1	77.4	235.5	7.6	36.4	98.9
14	Doha Hamad	46.2	53.6	57.3	20.6	224.8	1015.5	17.6	179.6	783.8	11.3	94.6	372.7	5.6	33.1	108.6
15	Charlotte Douglas	36.8	43.3	48.7	21.3	125.2	789.7	18.5	104.2	632.7	12.5	61.6	333.8	6.6	25.8	114.1
16	Madrid Barajas	36.2	45.0	49.3	22.7	286.0	1366.2	19.7	233.9	1084.1	13.2	132.3	555.6	7.0	50.1	180.1
17	Chongqing Jiangbei	38.4	46.8	51.0	29.0	351.0	1660.3	25.0	285.9	1312.9	16.4	158.5	666.0	8.4	59.2	211.8
18	Jeddah King Abdulaziz	44.6	52.1	55.9	90.0	36313.6	-	62.9	20221.2	-	23.8	3902.3	-	5.9	293.4	6061.0
19	Antalya	42.6	50.6	54.1	97.5	2405.0	13304.1	79.7	1828.2	9789.7	45.0	830.2	4033.7	17.8	222.0	904.1

We find that for all "HHS" airports, return periods for weight restriction days decrease between the present day and the end of the 21st century. (The two exceptions are Bogotá El Dorado Airport and Mexico City Benito Juarez Airport, where weight restrictions are already required on all days, due to these airports' high elevation.) While the average return period for weight restriction days (of any amount) across the 19 airports in the present day is 19.1 days (or 19.1 weight restriction days per year), this decreases to 15.6 days (23.4 weight restriction days per year) in the "low case", 9.1 days (40.1 weight restriction days per year) in the "mid case", and 4.3 days (84.9 weight restriction days per year) in the "high case". The most drastic change in the number of weight restriction days per year occurs at Jeddah King Abdulaziz Airport, where 4.1 such days are currently expected per year. In the "high case", this increases to 61.9 days by the end of the 21st century – an over 15-fold increase.

In particular, days requiring large weight restrictions, which we define as weight restrictions of at least 4,536 kg, are projected to become significantly more common under all 3 scenarios studied. In the present day, the number of airports experiencing a return period of less than 1 year for weight restriction days of 4,536 kg and 6,804 kg is 15 and 9, respectively. In the "low case", the number of airports increases to 16 and 9, while in the "mid case", the number increases to 17 and 11, respectively. Finally, in the "high case", almost all airports will be affected by large weight restrictions: all 19 airports will have a return period of less than 1 year for 4,536 kg weight restriction days, while 16 airports will have a return period of less than 1 year for 6,804 kg weight restriction days.

A particularly striking example is provided by Bengaluru Kempegowda Airport, which both experiences high temperatures and is located at a high elevation of 915 m. While weight restriction days are already relatively common at Bengaluru Kempegowda Airport, with a weight restriction day occurring every 2.5 days on average, large weight restrictions are not: a 4,536 kg restriction is required only every 11 years, and a 6,804 kg restriction in excess of once every 100 years. However, in the "high case", a 4,536 kg restriction will be required every 17.3 days, and a 6,804 kg restriction will be required every 3 years by the end of the 21st century. This translates to an almost 237-fold increase in the frequency of large weight restriction days.

4.2.2 "Non-HHS" Airports

Of the 81 "non-HHS" airports, we find that 67 airports will experience a return period for weight restriction days of 100 years or less by the end of the 21st century in at least one of the 3 scenarios studied. These 67 airports cover a wide geographical range, with 28 in Asia, 19 in Europe, 18 in North America, and 2 in Oceania. Together, they accounted for 36.6 percent of global aviation passenger movements in 2018.

The full set of temperatures at which take-off weight restrictions are required, as well as return periods for weight restriction days in the present day and under each of the 3 scenarios studied, is presented in Table 7. Only return periods of 100 years (36,500 days) or less are presented.

For the vast majority of "non-HHS" airports, weight restrictions are not a material concern in the present day. Only 9 of the 67 "non-HHS" airports currently experience return periods for weight restriction days of 100 years or less, and only 2 airports, Melbourne International and Dallas Fort Worth, experience return periods of 10 years or less.

Table 7: Temperatures Requiring Take-off Weight Restrictions and Return Periods for “Non-HHS” Airports, Ranked from Highest to Lowest Risk for 0 kg Restriction in “High Case”[123]

No.	Airport Name	Temp. threshold for take-off weight restriction (°C)			Return period for take-off weight restriction (years)											
					Present day			“Low case”			“Mid case”			“High case”		
		>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg
1	Melbourne International	42.4	50.0	53.6	5.3	-	-	3.7	-	-	1.7	-	-	1.0	20.0	-
2	Chengdu Shuangliu	36.2	44.9	50.5	12.6	-	-	5.5	-	-	1.2	-	-	1.0	-	-
3	Dallas Fort Worth	42.5	50.3	54.2	8.3	-	-	5.0	-	-	1.7	-	-	1.0	-	-
4	Zhengzhou Xinzheng	42.0	49.9	53.6	20.8	-	-	10.6	-	-	2.5	-	-	1.0	-	-
5	Fort Lauderdale-Hollywood	37.3	44.9	48.7	65.4	-	-	30.2	-	-	2.6	-	-	1.0	-	-
6	Minneapolis St Paul	39.5	50.3	53.3	26.5	-	-	12.9	-	-	3.0	-	-	1.1	-	-
7	Atlanta Hartsfield-Jackson	40.0	47.5	52.1	32.5	-	-	15.7	-	-	4.5	-	-	1.1	-	-
8	Baltimore-Washington	41.3	48.9	52.6	-	-	-	64.1	-	-	6.3	-	-	1.2	-	-
9	Changsha Huanghua	43.5	51.0	54.7	-	-	-	-	-	-	36.4	-	-	1.2	-	-
10	Mumbai Chhatrapati Shivaji	44.0	51.2	54.8	-	-	-	-	-	-	-	-	-	1.3	-	-
11	Sydney Kingsford Smith	44.6	52.1	55.9	29.4	-	-	15.7	-	-	4.4	-	-	1.4	-	-
12	Boston Logan	40.7	48.1	51.8	-	-	-	-	-	-	15.3	-	-	1.4	-	-
13	Bangkok Don Mueang	44.2	51.4	55.0	-	-	-	-	-	-	-	-	-	1.8	-	-
14	Hangzhou Xiaoshan	43.9	51.1	54.7	-	-	-	-	-	-	-	-	-	1.8	-	-
15	Zurich	37.9	46.4	50.7	-	-	-	-	-	-	16.2	-	-	1.9	-	-
16	Houston George Bush	43.8	51.0	54.6	-	-	-	-	-	-	20.7	-	-	1.9	-	-
17	Dusseldorf	39.4	46.9	50.7	-	-	-	-	-	-	21.0	-	-	1.9	-	-

18	Hanoi Noi Bai	44.2	51.6	55.3	-	-	-	-	-	-	-	-	-	1.9	-	-
19	Athens Eleftherios Venizelos	43.5	51.2	55.1	-	-	-	-	-	-	18.5	-	-	2.0	-	-
20	Lisbon	42.9	50.5	54.3	-	-	-	-	-	-	22.5	-	-	2.0	-	-
21	Munich	38.4	46.7	50.8	-	-	-	-	-	-	26.0	-	-	2.0	-	-
22	Wuhan Tianhe	43.5	50.9	54.5	-	-	-	-	-	-	-	-	-	2.2	-	-
23	Newark Liberty	43.1	50.6	54.2	-	-	-	-	-	-	32.1	-	-	2.4	-	-
24	Milan Malpensa	41.5	49.4	53.3	-	-	-	-	-	-	39.2	-	-	2.4	-	-
25	Toronto Pearson	40.9	50.3	53.5	-	-	-	-	-	-	56.0	-	-	2.5	-	-
26	Shanghai Hongqiao	43.3	50.7	54.3	-	-	-	-	-	-	-	-	-	2.5	-	-
27	Chicago O'Hare	41.9	49.8	53.7	-	-	-	-	-	-	32.9	-	-	2.6	-	-
28	Jeju International	41.2	48.8	52.5	39.4	-	-	31.4	-	-	14.9	-	-	2.8	75.7	-
29	Beijing Capital	43.9	51.3	55.0	-	-	-	-	-	-	52.5	-	-	2.8	-	-
30	Manila Ninoy Aquino	43.1	50.7	54.3	-	-	-	-	-	-	57.0	-	-	2.8	-	-
31	Beijing Daxing	44.0	51.4	55.1	-	-	-	-	-	-	59.9	-	-	2.9	-	-
32	Detroit Metropolitan	41.5	49.2	53.1	-	-	-	-	-	-	40.0	-	-	3.0	-	-
33	Cancun	43.6	50.9	54.5	-	-	-	-	-	-	-	-	-	3.0	-	-
34	Nanjing Lukou	43.8	51.0	54.6	-	-	-	-	-	-	86.0	-	-	3.6	-	-
35	Istanbul Sabiha Gokcen	41.9	50.5	53.8	-	-	-	-	-	-	33.3	-	-	4.0	-	-
36	Haikou Meilan	43.7	51.0	54.6	-	-	-	-	-	-	-	-	-	4.1	-	-
37	Xiamen Gaoqi	43.1	50.7	54.3	-	-	-	-	-	-	-	-	-	4.6	-	-
38	Los Angeles	44.2	51.7	55.5	-	-	-	-	-	-	32.5	-	-	4.8	-	-
39	Tokyo Haneda	43.2	50.6	54.3	-	-	-	-	-	-	-	-	-	5.3	-	-
40	Ho Chi Minh City Tan Son Nhat	44.3	51.6	55.3	-	-	-	-	-	-	-	-	-	5.3	-	-
41	Bangkok Suvarnabhumi	44.8	52.3	56.0	-	-	-	-	-	-	-	-	-	5.7	-	-
42	Seattle Tacoma	42.3	50.0	53.7	-	-	-	-	-	-	-	-	-	7.0	-	-
43	Philadelphia International	44.0	51.2	54.8	-	-	-	-	-	-	-	-	-	7.2	-	-
44	Paris Orly	43.0	50.4	54.1	-	-	-	-	-	-	-	-	-	8.8	-	-

45	Palma de Mallorca	42.4	49.8	53.5	-	-	-	-	-	-	-	-	-	10.0	-	-
46	Istanbul	43.7	51.4	55.2	-	-	-	-	-	-	-	-	-	12.2	-	-
47	Dublin	32.8	42.1	46.2	-	-	-	-	-	-	31.7	-	-	12.7	-	-
48	Paris Charles de Gaulle	43.7	51.4	55.2	-	-	-	-	-	-	-	-	-	14.1	-	-
49	Shanghai Pudong	44.7	52.3	56.0	-	-	-	-	-	-	-	-	-	14.4	-	-
50	London Stansted	38.9	46.6	50.3	-	-	-	-	-	-	-	-	-	16.6	-	-
51	Rome Fiumicino	44.5	52.0	55.7	-	-	-	-	-	-	-	-	-	16.8	-	-
52	Jakarta Soekarno-Hatta	44.0	51.2	54.8	-	-	-	-	-	-	-	-	-	19.1	-	-
53	Kansai	44.7	52.2	56.0	-	-	-	-	-	-	-	-	-	19.6	-	-
54	Guangzhou Baiyun	44.2	51.5	55.2	-	-	-	-	-	-	-	-	-	21.1	-	-
55	Seoul Gimpo	43.7	51.1	54.6	-	-	-	-	-	-	-	-	-	23.2	-	-
56	San Francisco International	44.0	51.2	54.8	-	-	-	-	-	-	-	-	-	23.5	-	-
57	Frankfurt	43.3	51.0	54.9	-	-	-	-	-	-	-	-	-	23.7	-	-
58	Kuala Lumpur International	44.5	52.1	55.9	-	-	-	-	-	-	-	-	-	24.5	-	-
59	Vienna Schwechat	41.5	49.6	53.3	-	-	-	-	-	-	-	-	-	25.1	-	-
60	Orlando International	43.8	51.0	54.6	-	-	-	-	-	-	-	-	-	28.2	-	-
61	Manchester	39.3	46.9	50.7	-	-	-	-	-	-	-	-	-	32.5	-	-
62	London Gatwick	42.0	50.1	53.6	-	-	-	-	-	-	-	-	-	32.6	-	-
63	Moscow Sheremetyevo	41.7	49.4	53.3	-	-	-	-	-	-	-	-	-	43.7	-	-
64	New York John F. Kennedy	45.4	53.0	56.7	-	-	-	-	-	-	-	-	-	51.3	-	-
65	Qingdao Liuting	43.2	50.7	54.3	-	-	-	-	-	-	-	-	-	55.2	-	-
66	Moscow Domodedovo	42.0	49.7	53.6	-	-	-	-	-	-	-	-	-	57.6	-	-
67	Brussels	43.4	50.7	54.4	-	-	-	-	-	-	-	-	-	92.3	-	-

However, by the end of the 21st century, weight restriction days become significantly more common for "non-HHS" airports under all 3 scenarios. In the "low", "mid", and "high" cases, 10, 30, and 67 airports will experience return periods for weight restriction days of 100 years or less, respectively. In other words, weight restrictions will begin to become a material risk for a significantly larger group of airports beyond "HHS" airports, which have traditionally been regarded as the key group of airports exposed to this risk.

Notably, for a significant number of airports, weight restriction days will change from a non-material risk to a near-annual occurrence. For 5 airports, the return period for weight restriction days by the end of the 21st century decreases to 1 year or less. These airports are Melbourne International, Chengdu Shuangliu, Dallas Fort Worth, Zhengzhou Xinzheng, and Fort Lauderdale-Hollywood. For 10 airports, the return period for weight restriction days in the present day exceeds 100 years, but reduces dramatically to less than 2 years by the end of the 21st century in the "high case". These airports are Baltimore-Washington, Changsha Huanghua, Mumbai Chhatrapati Shivaji, Boston Logan, Bangkok Don Mueang, Hangzhou Xiaoshan, Zurich, Houston George Bush, Dusseldorf, and Hanoi Noi Bai.

Across the 67 airports, the average return period for >0 kg weight restriction days (counting only return periods of 100 years or less) in the present day is 26.7 years. This decreases to 19.5 years, 25.8 years, and 11.8 years for the "low", "mid", and "high" cases, respectively. (The smaller change observed for the "mid case" as compared to the "low case" is due to a large increase in the number of affected airports, but with relatively long return periods.)

On the other hand, large weight restrictions are unlikely to become common enough to pose a material concern for the vast majority of "non-HHS" airports. Even in the "high" case, only 2 airports, Melbourne International and Jeju International, had return periods of 100 years or less for a weight restriction day of 4,536 kg, and no airports had a return period of 100 years or less for a weight restriction day of 6,804 kg.

4.3 Airports Most Exposed to Climate-Related Risk

Among the 101 airports studied, New York LaGuardia is the airport most vulnerable to climate-related risk. It is the only "HHS" airport that is also exposed to inundation risk. This is a function of both its low-lying coastal location (at an elevation of 6.1 m bordering New York City's Flushing Bay) and its exceptionally short runways (its longest runway is only 2,135 m).

In 2012, New York LaGuardia Airport was closed for 3 days due to flooding caused by Hurricane Sandy.[124] (CBS, 2013) Using this as a benchmark, in the present day, New York LaGuardia Airport is expected to experience 9.6 days of 6,804 kg weight restrictions and an average of 0.04 day of complete shutdown due to flooding every year. In the "high case", LaGuardia Airport is projected to experience 30.7 days of 6,804 kg weight restrictions (a 3.2x increase), as well as 1.03 day of complete shutdown due to flooding every year (a 24.2x increase).

In addition, 10 airports with inundation risk are also exposed to high temperature risk as "non-HHS" airports. These are Bangkok Don Mueang, Bangkok Suvarnabhumi, Boston Logan, Kansai, Miami International, Newark Liberty, New York John F. Kennedy, San Francisco International, Shanghai Hongqiao, and Shanghai Pudong. Boston Logan Airport is projected to experience the largest change in risk exposure. In the present day, inundation and weight restriction days both have a return period in excess of 100 years at Boston Logan Airport. However, in the "high case", the airport is projected to experience an inundation event every 1.1 year (an over 90-fold increase) and a weight restriction day every 1.4 year (an over 71-fold increase) by the end of the 21st century.

4.4 Geographies Most Exposed to Climate-Related Risk

In this section, we use a simple points-based system to measure the exposure of airports in specific geographical regions to climate-related risk. Each airport receives three points for exposure to inundation risk, two points for being a “HHS” airport, and one point for exposure to high temperature risk as a “non-HHS” airport. These points are then totalled to calculate the region’s “risk factor”.

Using this metric, New York City is the city whose airports are most exposed to climate-related risk, with a risk factor of 13. Aside from LaGuardia, New York City’s two other major airports, New York John F. Kennedy and Newark Liberty, are both exposed to inundation risk as well as high temperature risk, albeit as “non-HHS” airports. Bangkok and Shanghai both have a risk factor of 8, with multiple airports exposed to both inundation and high temperature risk. Other cities with two or more major airports exposed to climate-related risk are Beijing, Istanbul, London, Miami, Moscow, Paris, and Seoul. The risks that the airports of these cities are exposed to are presented in Table 8.

Table 8: Cities with Two or More Airports Exposed to Climate-Related Risk

City	**Affected Airport**	**Risks Exposed To**			**Risk Factor**
		Inundation Risk (3 points)	High Temperature Risk (“HHS”) (2 points)	High Temperature Risk (“Non-HHS”) (1 point)	
Bangkok	Don Mueang	Yes	-	Yes	8
	Suvarnabhumi	Yes	-	Yes	
Beijing	Capital	-	-	Yes	2
	Daxing	-	-	Yes	
Istanbul	Istanbul	-	-	Yes	2
	Sabiha Gokcen	-	-	Yes	
London	Gatwick	-	-	Yes	2
	Stansted	-	-	Yes	
Miami	Fort Lauderdale-Hollywood	-	-	Yes	4
	Miami International	Yes	-	-	
Moscow	Domodedovo	-	-	Yes	2
	Sheremetyevo	-	-	Yes	
New York City	John F. Kennedy	Yes	-	Yes	13
	LaGuardia	Yes	Yes	-	
	Newark Liberty	Yes	-	Yes	
Paris	Charles de Gaulle	-	-	Yes	2
	Orly	-	-	Yes	
Seoul	Gimpo	-	-	Yes	4

	Incheon	Yes	-	-	
Shanghai	Hongqiao	Yes	-	Yes	8
	Pudong	Yes	-	Yes	

At the country level, two countries stand out as having a particularly large number of airports exposed to climate-related risk: the USA and China. The USA has a risk factor of 46 and China a risk factor of 29; both are far ahead of Thailand, which is in third place with a risk factor of 8. A full list of countries with two or more airports exposed to climate-related risk, as well as the risk factors of these countries, is presented in Table 9.

Table 9: Countries with Two or More Airports Exposed to Climate-Related Risk

Country	No. of Airports Exposed To			Risk Factor
	Inundation Risk (3 points)	High Temperature Risk ("HHS") (2 points)	High Temperature Risk ("Non-HHS") (1 point)	
Australia	-	-	2	2
Canada	1	-	1	4
China	3	3	14	29
France	-	-	2	2
Germany	-	-	3	3
India	-	1	2	4
Italy	-	-	2	2
Japan	1	-	2	5
Mexico	-	1	1	3
Russia	-	-	2	2
Saudi Arabia	-	2	-	4
South Korea	1	-	2	5
Spain	-	1	1	3
Thailand	2	-	2	8
Turkey	-	1	2	4
United Kingdom	-	-	3	3
USA	6	6	16	46
Vietnam	-	-	2	2

The risk exposure of the USA's and China's airports can be attributed to two factors. Firstly, the two countries have a large number of airports in the top 100 busiest airports by passenger traffic: the USA has 23 while China has 19 (including Beijing Daxing Airport). This is due to the two countries' dominant positions in the commercial aviation market. The USA and China are the world's two largest domestic aviation markets, at 14.1 percent and 9.5 percent of revenue-passenger-kilometres, respectively, in 2018.[125] If international flights are included, these percentages would be even higher.

Secondly, both countries also have a large number of airports located in coastal areas, which are exposed to inundation risk, and at high elevations, which are exposed to "HHS" high temperature risk. Of the 23 American airports studied in this paper, 6 are located in coastal areas, while 5 are "HHS" airports. Similarly, of the 19 Chinese airports studied, 5 are located in coastal areas, while 4 are "HHS" airports.

This means that climate mitigation and adaptation measures for airports will be particularly critical for the USA and China, especially to safeguard the rapid growth in passenger aviation traffic that is projected for these two markets until at least the mid-21st century.[126]

4.5 Limitations of Methodology and Results

While we apply methods in this study that are well-supported by the academic literature, there are notable methodological and data limitations that may affect the interpretation and accuracy of the results.

Firstly, limited data availability affects how accurately the fitted distributions reflect actual conditions at the airports studied. For example, a dataset of 30 years or longer is considered ideal for use with a GEV distribution.[127] [128] However, only 17 of the 26 coastal airports studied for extreme sea levels and 71 out of the 81 "non-HHS" airports studied for extreme temperatures in my dataset met this requirement. A statistically significant fit (p-value of chi-square test for GEV distribution and Kolmogorov-Smirnov test for normal distribution of less than 0.05) was obtained for 3 out of 26 stations for sea level, 19 out of 19 stations for temperature at "HHS" airports, and 33 out of 81 stations for temperature at "non-HHS" airports. If a p-value of 0.1 is used, this increases to 5 out of 26 stations for sea level and 47 out of 81 stations for temperature at "non-HHS" airports. Across the stations observed, longer data sets are associated with better fit (lower p-value for chi-square and Kolmogorov-Smirnov tests), presenting an opportunity for further research if more comprehensive datasets can be obtained.

Secondly, while this study applies a single value for increases in sea level and temperature to all airports, actual increases are likely to be more region-specific. However, numerical projections of sea level rise at regional scales are often inconsistent with empirical observations and between different projections, and also fail to take into account the possibility of global-level changes, such as the possibility of large-scale ice sheet melting and collapse.[129] With regards to temperature rise, while there is good agreement between climate models on how much mean temperatures are expected to increase in broadly-defined geographical regions, the validity of these projections is limited at more local scales and at higher levels of warming.[130] In light of these limitations, we have decided to apply a single value across all airports in this analysis.

Thirdly, the methodology of this paper assumes that extreme sea level and high temperature events are only affected by changes in mean sea level and temperature. However, there is evidence that the frequency and magnitude of such extreme events do not scale linearly with increases in the mean, due to changes in the dispersion and distribution shape of the underlying variable.[131] For example, increases in extreme temperature values are likely to exceed average global temperature increases, even at moderate average warming levels of less than 2.5°C.[132] Similarly, while mean sea level is the primary determinant of storm surge levels,[133] increase in storm surge height may be higher or lower than mean sea level rise due to local environmental conditions and dynamic interactions between the two variables.[134] Due to the difficulty of applying these heterogeneous interactions across the stations studied, these effects are ignored in the present analysis.

Fourthly, climate change is also expected to increase the risk of inundation by increasing the frequency of stormy weather in certain regions.[135] This is not captured by the method used in this paper, which assumes that the probability and intensity of extreme sea level events relative to mean sea levels at the end of the 21st century will be similar to those in the present day. However, as the directionality and magnitude of this effect is not consistent across geographical regions, and there is low confidence in the accuracy of region-specific projections for changes in storminess,[136] this effect is ignored in the present analysis.

Fifthly, we use the Boeing 737-800 in this study as a proxy for all types of commercial aircraft. Different aircraft will have different temperature thresholds for weight restrictions. The effect of temperatures on take-off weight restrictions for different aircraft models has been investigated elsewhere in the literature, for example by Coffel, Thompson, & Horton.[137] Broadly speaking, in response to growing passenger demand, there has been a historical trend in the aviation industry to produce increasingly larger aircraft,[138] which are generally heavier and require longer runways to take off.[139] Take-off weight restrictons will therefore likely have a greater impact on the carrying capacity of larger aircraft than smaller ones.[140] This means that the results in this paper are likely to present a conservative view of the risks faced by airports due to high temperature-related take-off weight restrictions.

While we do not believe that the above limitations detract from the paper's overall findings, they do present opportunities for future research to more accurately quantify the risks discussed.

5. Operational and Financial Impacts of Climate-Related Risks for Airports

5.1 Impacts of Inundation

Inundation is among the most serious climate-related risks threatening airports, due to its ability to force the complete shutdown of an airport. Recent examples of prolonged airport closures due to weather-related inundation include:

1. Kansai Airport (2018), which shut down completely for 3 days and reduced operations for a further 14 days due to flooding caused by Typhoon Jebi;[141] [142]

2. Houston George Bush and William P. Hobby Airports (2017), which shut down completely for 3 and 6 days respectively due to flooding caused by Hurricane Harvey, with an additional week of service disruptions;[143] [144]

3. New York John F. Kennedy, Newark Liberty, and New York LaGuardia Airports (2012), which shut down completely for 2, 2, and 3 days respectively due to flooding caused by Hurricane Sandy.[145] [146]

Inundation typically causes airport shutdowns because of flooded runways. Runways are typically the essential airport infrastructure lying at the lowest elevation, and flooded runways prevent some or all scheduled flights from taking off or landing. However, runways are not the only critical airport infrastructure vulnerable to inundation. Other critical low-lying airport infrastructure includes electrical equipment; inter-terminal transport routes and access roads to the airport; and communications equipment such as landing lights, radar, and navigation instruments.[147] Extreme flooding may also breach infrastructure at higher elevations such as terminals, resulting in longer and more expensive shutdowns.[148] [149]

The disruptions to airport operations caused by climate-related inundation are often magnified by the characteristics of extreme weather events. Such events tend to affect multiple airports in close proximity at the same time, reducing the options available for airports to divert operations.[150] In addition, even after initial re-opening, operational capacity is often reduced for several days due to the widespread infrastructural damage caused by flooding.[151]

Estimates vary with regards to the financial impact that a prolonged shutdown due to inundation may inflict on airport operations, but are generally high. Pejovic, et al., modelled the cost of closure for London Heathrow airport, producing an estimate of over US$1 million an hour due to traffic disruptions alone.[152] The shutdown of 3 New York City-area airports due to Hurricane Sandy in 2012 was estimated to have cost US$700 million to $1 billion due to lost revenue from flight cancellations and expenses involved in restarting operations;[153] dividing this by 3 airports and 7 days of complete shutdown produces a cost estimate of US$1.4 million to US$2.0 million per hour per airport. While these costs accrue to airlines rather than the airport operator, major airports derive 50 to 60 percent of their revenue from aeronautical revenues paid by airlines,[154] meaning that the profits of airport operators are likely to also be materially affected by these airline disruptions. The same holds true for the financial impacts described in the following sections.

With regards to the cost of inundation-related damages to the airport itself, a multi-day shutdown of Kochi International Airport due to flooding in 2018 is estimated to have cost Rs 2 to 2.5 billion (US$27.9 to 34.9 million).[155] Inundation would likely result in even higher costs for the airports studied in this paper, as they are generally significantly larger and busier than Kochi International.

5.2 Impacts of Take-off Weight Restrictions Due to High Temperatures

Take-off weight restrictions due to high temperatures can exert financial impacts on airlines in several ways. Firstly and most directly, take-off weight restrictions due to high temperatures mean that less cargo and fewer passengers can be carried. Given an average weight per adult passenger (including checked and carry-on luggage) of 100.5 kg,[156] the 4,536 kg (10,000 lbs), and 6,804 kg (15,000 lbs) weight restrictions investigated in this paper respectively represent 45 and 68 passengers that cannot be carried. Given that in a typical two-class configuration, the Boeing 737-800 has a seating capacity of 160 passengers,[157] these weight restrictions translate to 28.1 percent and 42.5 percent of passenger capacity, respectively.

Where weight restrictions are not anticipated and accounted for in advance – for example, when unexpectedly high temperatures disrupt normal operations at an airport where weight restrictions are not commonly experienced – airlines face an additional set of costs. The process of reseating passengers and removing cargo from aircraft is likely to create delays. For U.S. passenger airlines, it is estimated that each minute a flight is delayed costs an airline US$74.20.[158] Using similar figures, Carpenter (2018) estimates that the cost of 52 delayed flights at Phoenix Sky Harbor Airport on a single weight restriction day in 2016 was US$125,600, excluding knock-on delays at other airports. On the same day, 40-50 flights were eventually cancelled at Phoenix Sky Harbour Airport due to extreme high temperatures. With an estimated cost of US$1,050 per cancelled flight segment, these cancellations inflicted an additional estimated US$26,250 in costs.[159]

Weight restrictions are likely to affect certain flight services more than others. Busy routes with high load factors, which airplanes often fly at or close to the maximum take-off weight, are likely to face greater and more frequent weight restrictions, adding up to significant losses in revenue.

5.3 Secondary and Indirect Impacts of Climate-Related Risks for Airports

While this paper has focused on the direct climate-related risks faced by airports, climate change may also materially affect the operations of airports that do not face direct risks due to inundation and high temperatures. Global airports form a highly interdependent network, with operations concentrated at a small number of large hubs. According to Airports Council International, there are 17,678 commercial airports currently in operation,[160] yet 60 percent of passenger traffic is handled by just 100 airports. Disruptions at any of these major hub airports can easily propagate and magnify to affect a significant part of the global airport network.[161] For example, it is estimated that one-third of air traffic delays in the USA are caused by delays at the three New York City-area airports.[162]

Given the low profit margins at which many airlines operate – the average historical profit margin of commercial airlines is less than 1 percent[163] – take-off weight restrictions and flight cancellations due to extreme weather events represent a severe financial burden.[164] Repeated climate-related disruptions at specific airports may force affected airlines to reduce or reroute traffic. For example, in response to regular temperature-related take-off weight restrictions, airlines may cancel long routes, which can carry fewer passengers because of higher fuel requirements,[165] [166] or suspend service to susceptible airports in the summer months.[167] As the frequency and intensity of such disruptions increases over the 21st century, airlines may respond by shifting their operations to avoid susceptible airports altogether.[168]

More broadly, airport disruptions, especially if they become regular occurrences, can have material impacts on the wider economy and even national resilience.[169] Multiple industries depend critically on air transport to function; most of these industry stakeholders will experience negative financial impacts as a result of airport service disruptions. The sum of these financial impacts across the economy may exceed direct financial impacts on the airport itself.[170] [171]

5.4 Ownership of Climate-Threatened Airports

As demonstrated in the preceding section, climate change is projected to create material additional financial costs for owners of vulnerable airports. Depending on their ownership and shareholding structure, some airports may find it more difficult to withstand the financial impacts imposed by these costs. In addition, investors that hold many such airports in their portfolios are likely to be disproportionately exposed to such financial impacts.

The following tables summarise the ownership structures of vulnerable airports. Table 10 details the ownership of the 15 airports vulnerable to inundation, while Table 11 details the ownership of the 19 "HHS" airports, which are exposed to high take-off weight restriction risk. Finally, Table 12 details the ownership of the 67 "non-HHS" airports, which are exposed to take-off weight restriction risk to a smaller extent. The tables also state the total percentage of each airport's shares owned by government agencies and the percentage owned by commercial companies (both private and publicly traded). In cases where the airport is government-owned but commercially operated, the airport is denoted with an asterisk (*) and the ownership structure of the commercial operator is shown. Only the top three shareholders by percentage in each category are listed.

Table 10: Ownership Structure of Airports Vulnerable to Inundation

No.	Airport Name	% Govt Owned	Government Shareholders	% Comm Owned	Commercial Shareholders
1	Amsterdam Schiphol	92%	• 69.8% Dutch government • 20.0% Municipality of Amsterdam • 2.2% Municipality of Rotterdam	8%	• 8% Groupe ADP
2	Bangkok Suvarnabhumi	75.7%	• 70.0% Ministry of Finance, Thailand • 4.5% Thai NDVR Company Ltd (fully	24.3%	• 2.8% South East Asia UK (Type C) Nominees Ltd • 1.7% State Street Europe Ltd

			owned subsidiary of Stock Exchange of Thailand) • 1.2% Social Security Office of Thailand		• 0.5% South East Asia UK (Type A) Nominees Ltd • 0.5% The Bank of New York Mellon
3	Bangkok Don Mueang	100%	• 100% Royal Thai Air Force	0%	-
4	Shanghai Hongqiao	100%	• 100% Government of China	0%	-
5	Vancouver	100%	• 100% Transport Canada	0%	-
6	Seoul Incheon	100%	• 100% Government of South Korea	0%	-
7	Miami International	100%	• 100% Government of Miami-Dade County	0%	-
8	San Francisco International	100%	• 100% City and County of San Francisco	0%	-
9	Shanghai Pudong	100%	• 100% Government of China	0%	-
10	New York John F. Kennedy	100%	• 100% City of New York	0%	-
11	Kansai	0%	-	100%	• 40% ORIX Corp • 40% Vinci Airports • 20% Other
12	New York LaGuardia	100%	• 100% City of New York	0%	-
13	Boston Logan	100%	• 100% Massachusetts Port Authority	0%	-
14	Shenzhen Bao'an	100%	• 100% Shenzhen Airport Authority	0%	-
15	Newark Liberty	100%	• 100% City of New York	0%	-

Table 11: Ownership Structure of "HHS" Airports

No.	Airport Name	% Govt Owned	Government Shareholders	% Comm Owned	Commercial Shareholders
1	Bogotá El Dorado*[172]	0%	-	100%	• 65% Grupo Argos • 23% CSS Constructores • 12% Other
2	Mexico City Benito Juarez	100%	• 100% Grupo Aeroportuario de la Ciudad de México	0%	
3	Kunming Changshui	86%	• 60% Yunnan Provincial Government • 26% Kunming Provincial Government	14%	• 14% Yunnan-based investment group
4	Denver International	100%	• 100% City and County of Denver	0%	-
5	Salt Lake City	100%	• 100% Salt Lake City Corporation	0%	-
6	New York LaGuardia	100%	• 100% City of New York	0%	-
7	Bengaluru	26%	• 13% Karnataka State	74%	• 54% Fairfax Financial

	Kempegowda		Industrial & Infrastructure Development Corporation • 13% Airports Authority of India		Holdings • 20% Siemens Projects Ventures
8	Riyadh King Khalid*[173]	51.5%	• 31.3% State of Hesse • 20.2% Stadtwerke Frankfurt am Main Holding GmbH	48.5%	• 8.4% Deutsche Lufthansa AG • 5.0% Lazard Asset Management • 35.1% Other
9	Phoenix Sky Harbor	100%	• 100% City of Phoenix	0%	-
10	Las Vegas McCarran	100%	• 100% Clark County, Nevada	0%	-
11	Dubai International	100%	• 100% Dubai Airports	0%	-
12	Delhi Indira Gandhi	36.3%	• 26% Airports Authority of India • 3.3% Khazanah Nasional Bhd (through Eraman) • 3.1% State of Hesse (through Fraport)	63.7%	• 50.1% GMR Group • 3.9% IDF • 0.8% Deutsche Lufthansa AG (through Fraport)
13	Xi'an Xianyang	88.1%	• 51.0% Xi'an Airport Logistics Co. • 24.5% China National Aviation Holding Company • 7.7% State of Hesse (through Fraport)	11.9%	• 2.1% Deutsche Lufthansa AG (through Fraport) • 1.2% Lazard Asset Management (through Fraport) • 8.6% Other
14	Doha Hamad	100%	• 100% Qatar Civil Aviation Authority	0%	-
15	Charlotte Douglas	100%	• 100% City of Charlotte	0%	-
16	Madrid Barajas	51%	• 51% ENAIRE	49%	• 4.7% TCI Fund Management • 3.1% Capital Research & Management • 1.7% Norges Bank
17	Chongqing Jiangbei	100%	• 51% Chongqing Airports Group • 49% Changi Airports International	0%	-
18	Jeddah King Abdulaziz	100%	• 100% General Authority for Civil Aviation of Saudi Arabia	0%	-
19	Antalya*[174]	37.7%	• 16.0% State of Hesse (through Fraport) • 11.4% Government of France (through TAV Airports) • 10.3% Stadtwerke Frankfurt am Main Holding GmbH (through	62.3%	• 4.3% Deutsche Lufthansa AG (through Fraport) • 2.6% Lazard Asset Management (through Fraport) • 2.5% Crédit Agricole Assurances/Predica (through TAV Airports)

			Fraport)		

Table 12: Ownership Structure of Non-"HHS" Airports Facing Take-off Weight Restrictions

No.	Airport Name	% Govt Owned	Government Shareholders	% Comm Owned	Commercial Shareholders
1	Melbourne International	47.5%	• 20.3% Future Fund • 18.5% SAS Trustee Corporation • 8.7% Utilities of Australia	52.5%	• 27.3% AMP • 25.2% IFM Investors
2	Chengdu Shuangliu	100%	• 100% Sichuan Province Airport Group	0%	-
3	Dallas Fort Worth	100%	• 100% Cities of Dallas and Fort Worth	0%	-
4	Zhengzhou Xinzheng	100%	• 100% Henan Airport Group	0%	-
5	Fort Lauderdale-Hollywood	100%	• 100% Broward County Aviation Department	0%	-
6	Minneapolis St Paul	100%	• 100% Minneapolis-St Paul Metropolitan Airports Commission	0%	-
7	Atlanta Hartsfield-Jackson	100%	• 100% City of Atlanta Department of Aviation	0%	-
8	Baltimore-Washington	100%	• 100% Maryland Aviation Administration	0%	-
9	Changsha Huanghua	100%	• 100% Hunan Airport Authority	0%	-
10	Mumbai Chhatrapati Shivaji	26%	• 26% Airports Authority of India	74%	• GVK • Airports Company South Africa • Bidvest
11	Sydney Kingsford Smith	0%	-	100%	• 17.4% UniSuper • 3.0% Capital Research & Management • 2.1% Fidelity
12	Boston Logan	100%	• 100% Massachusetts Port Authority	0%	-
13	Bangkok Don Mueang	100%	• 100% Royal Thai Air Force	0%	-
14	Hangzhou Xiaoshan	<100%	• <65% Zhejiang Province Administrative Company and Hang Zhou Xiaoshan State Owned Capital Management Company • 35% Airport Authority Hong Kong	>0%	• Hang Zhou Investment Holding Co
15	Zurich	38.4%	• 33.3% Canton of Zurich • 5.1% City of Zurich	61.6%	• 3.0% USS Investment Management • 2.5% UBS Asset

					Management • 1.8% Vanguard Group
16	Houston George Bush	100%	• 100% Houston Airport System	0%	-
17	Dusseldorf	80%	• 50% City of Dusseldorf • 20% Aer Rianta International (through Airport Partners GmbH) • 10% AviC GmbH (through Airport Partners GmbH)	20%	• 20% AviAlliance GmbH (through Airport Partners GmbH)
18	Hanoi Noi Bai	95.4%	• 95.4% Government of Vietnam	4.6%	• 4.6% Other
19	Athens Eleftherios Venizelos	55%	• 55% Government of Greece	45%	• 36.1% Hochtief Airport GmbH (through AviAlliance GmbH) • 5% ABB Group
20	Lisbon*[175]	3.7%	• 3.7% Qatar Holding LLC	100%	• 8.9% Vinci SA Employee Stock Ownership Plan • 7.1% Vinci SA • 2.2% Vanguard Group
21	Munich	100%	• 51% Free State of Bavaria • 26% Government of Germany • 23% State Capital of Munich	0%	-
22	Wuhan Tianhe	70%	• 70% Capital Airports Holding Co	30%	• 30% Other
23	Newark Liberty[176]	100%	• 100% City of New York	0%	-
24	Milan Malpensa	54.8%	• 54.8% Municipality of Milan	45.2%	• 36.4% 2i Aeroporti SpA • 8.6% F2i Sgr SpA • 0.2% Other
25	Toronto Pearson	100%	• 100% Greater Toronto Airports Authority	0%	-
26	Shanghai Hongqiao	100%	• 100% Government of China	0%	-
27	Chicago O'Hare	100%	• 100% Chicago Department of Aviation	0%	-
28	Jeju International	100%	• 100% Korea Airports Corporation	0%	-
29	Beijing Capital	61.9%	• 56.8% Capital Airport Holding • 5.1% GIC	42.2%	• 18.8% Horizon Kinetics Asset Management • 8.0% Aberdeen Asset Management • 6.0% Matthews International Capital Management
30	Manila Ninoy Aquino	100%	• 100% Manila International Airport Authority	0%	-
31	Beijing Daxing	100%	• 100% Government of	0%	-

			China		
32	Detroit Metropolitan	100%	• 100% Wayne County Airport Authority	0%	-
33	Cancun	0%	-	100%	• 24.7% Aberdeen Asset Management • 16.5% Fernando Chico Pardo • 16.1% Grupo ADD
34	Nanjing Lukou	100%	• 100% Eastern Airport Group	0%	-
35	Istanbul Sabiha Gokcen	52.5%	• 33.2% Khazanah • 12.7% Employees Provident Fund • 3.2% Permodalan Nasional	47.5%	• 1.9% Vanguard Group • 1.9% BlackRock Asset Management North Asia • 1.7% Citigroup Global Markets Investment Management
36	Haikou Meilan	50.2%	• 50.2% Haikou Meilan International Airport Co	49.8%	• 19.9% Oriental Patron • 10.5% UBS Group AG • 6.9% ARC Capital
37	Xiamen Gaoqi	68%	• 68% Government of Xiamen	32%	• 3.6% China Pacific Insurance Group • 2.5% China Asset Management • 2.4% Invesco Great Wall Fund Management
38	Los Angeles	100%	• 100% Los Angeles World Airports	0%	-
39	Tokyo Haneda	0%	-	100%	• 5.3% Keikyu Pension Fund • 5.2% ANA Holdings • 5.2% Japan Airlines
40	Ho Chi Minh City Tan Son Nhat	95.4%	• 95.4% Government of Vietnam	4.6%	• 4.6% Other
41	Bangkok Suvarnabhumi	75.7%	• 70.0% Ministry of Finance, Thailand • 4.5% Thai NDVR Company Ltd (fully owned subsidiary of Stock Exchange of Thailand) • 1.2% Social Security Office of Thailand	24.3%	• 2.8% South East Asia UK (Type C) Nominees Ltd • 1.7% State Street Europe Ltd • 0.5% South East Asia UK (Type A) Nominees Ltd • 0.5% The Bank of New York Mellon
42	Seattle Tacoma	100%	• 100% Port of Seattle	0%	-
43	Philadelphia International	100%	• 100% City of Philadelphia	0%	-
44	Paris Orly	58.6%	• 50.6% Government of France • 8% Royal Schiphol Group	41.4%	• 8% Vinci Airports • 5.1% Crédit Agricole • 28.3% Other
45	Palma de Mallorca	51%	• 51% ENAIRE	49%	• 4.7% TCI Fund Management • 3.1% Capital Research & Management

					• 1.7% Norges Bank
46	Istanbul	100%	• 100% General Directorate of State Airports of Turkey	0%	-
47	Dublin	100%	• 100% Dublin Airport Authority	0%	-
48	Paris Charles de Gaulle	58.6%	• 50.6% Government of France • 8% Royal Schiphol Group	41.4%	• 8% Vinci Airports • 5.1% Crédit Agricole • 28.3% Other
49	Shanghai Pudong	100%	• 100% Government of China	0%	-
50	London Stansted	64.5%	• 35.5% Manchester City Council • 29% 9 Greater Manchester Councils	35.5%	• 35.5% IFM Investors
51	Rome Fiumicino	8.5%	• 8.1% GIC • 0.3% City of Rome • 0.1% Commune of Fiumicino	91.5%	• 30.1% Sintonia • 5.0% Lazard Asset Management • 5.0% HSBC
52	Jakarta Soekarno-Hatta	100%	• 100% Angkasapura II	0%	-
53	Kansai	0%	-	100%	• 40% ORIX Corp • 40% Vinci Airports • 20% Other
54	Guangzhou Baiyun	100%	• 100% Guangdong Airport Authority	0%	-
55	Seoul Gimpo	100%	• 100% Korea Airports Corporation	0%	-
56	San Francisco International	100%	• 100% City and County of San Francisco	0%	-
57	Frankfurt	51.5%	• 31.3% State of Hesse • 20.2% Stadtwerke Frankfurt am Main Holding GmbH	48.5%	• 8.4% Deutsche Lufthansa AG • 5.0% Lazard Asset Management • 35.0% Other
58	Kuala Lumpur International	52.5%	• 33.2% Khazanah • 12.7% Employees Provident Fund • 3.2% Permodalan Nasional	47.5%	• 2.0% Vanguard Group • 1.9% BlackRock Asset Management North Asia • 1.7% Citigroup Global Markets Investment Management
59	Vienna Schwechat	40%	• 20% Province of Lower Austria • 20% City of Vienna	60%	• 39.2% IFM Investors • 10.0% Private employees • 10.2% Other
60	Orlando International	100%	• 100% Greater Orlando Aviation Authority	0%	-
61	Manchester	64.5%	• 35.5% Manchester City Council • 29% 9 Greater Manchester Councils	35.5%	• 35.5% IFM Investors

62	London Gatwick	1.8%	• 1.9% Qatar Holding LLC (through Vinci Airports)	98.2%	• 50% Global Infrastructure Partners • 4.4% Vinci SA Employee Stock Ownership Plan (through Vinci Airports) • 3.5% Vinci SA (through Vinci Airports)
63	Moscow Sheremetyevo	30.4%	• 30.4% Federal Property Management Agency	69.6%	• 66% TPS Avia • 3.6% Other
64	New York John F. Kennedy	100%	• 100% City of New York	0%	-
65	Qingdao Liuting	100%	• 100% Qingdao International Airport Group	0%	-
66	Moscow Domodedovo	0%	-	100%	• 100% Dimitry Kamenshchik
67	Brussels	25%	• 25% State of Belgium	75%	• 39% Ontario Teachers‘ Pension Plan • 36% Macquarie European Infrastructure Fund

Most of airports in the two highest risk categories are fully or majority government-owned. Of the 15 airports vulnerable to inundation, 13 have higher than 80% government ownership, and 12 are fully state-owned. Of the 19 "HHS" airports vulnerable to high temperatures, 13 have higher than 80% government ownership, and 11 are fully government-owned. Notable exceptions in these two categories are Kansai Airport (fully owned by a private consortium led by ORIX and Vinci Airports) and Bogotá El Dorado Airport (fully owned by a private consortium led by Grupo Argos).

Non-"HHS" airports that are vulnerable to high temperatures are more diverse in terms of ownership. Out of these 67 airports, 38 have higher than 80% government ownership, and 34 are fully government-owned. The list of commercial owners is internationally diverse and includes large institutional investors, sovereign wealth funds, pension funds, and private equity firms.

A significant number of these commercial owners are exposed to multiple climate-threatened airports, either through direct ownership or through ownership of airport management and investment holding companies. The most exposed of these investors include Vanguard (11 airports), BlackRock (9 airports), Lazard (6 airports), and Capital Research & Management (6 airports).
Table 13 shows the list of commercial institutions most exposed to climate-threatened airports.

Table 13: Commercial Owners Most Exposed to Climate-Threatened Airports

No.	**Commercial Owner**	**No. of Airports Owned**	**Airports Owned**
1	Vanguard Group	11	Beijing Capital, Bengaluru Kempegowda, Delhi Indira Gandhi, Istanbul Sabiha Gokcen, Kuala Lumpur International, Lisbon, London Gatwick, Madrid Barajas, Palma de Mallorca, Sydney Kingsford Smith, Zurich
2	BlackRock	9	Beijing Capital, Bengaluru Kempegowda, Delhi Indira

			Gandhi, Istanbul Sabiha Gokcen, Kuala Lumpur International, Madrid Barajas, Palma de Mallorca, Sydney Kingsford Smith, Zurich
3	Capital Research & Management	6	Bengaluru Kempegowda, Lisbon, London Gatwick, Madrid Barajas, Palma de Mallorca, Sydney Kingsford Smith
4	Lazard	6	Antalya, Delhi Indira Gandhi, Frankfurt, Riyadh King Khalid, Rome Fiumicino, Xi'an Xianyang
5	Crédit Agricole/Predica	5	Antalya, Lisbon, London Gatwick, Paris Charles de Gaulle, Paris Orly
6	Lufthansa	5	Antalya, Delhi Indira Gandhi, Frankfurt, Riyadh King Khalid, Xi'an Xianyang
7	Amundi	4	Lisbon, London Gatwick, Madrid Barajas, Palma de Mallorca
8	DWS	4	Lisbon, Madrid Barajas, Palma de Mallorca, Zurich
9	IFM	4	London Stansted, Manchester, Melbourne, Vienna Schwechat
10	Citigroup	3	Delhi Indira Gandhi, Istanbul Sabiha Gokcen, Kuala Lumpur International
11	Invesco	3	Beijing Capital, Sydney Kingsford Smith, Xiamen Gaoqi
12	UBS	2	Haikou Meilan, Zurich
13	Wellington Management	2	Lisbon, London Gatwick

Some governments are also particularly exposed through their state-owned investments and airport operating companies, such as Singapore (6 airports), Norway (5 airports), and Frankfurt (5 airports). Table 14 shows the list of governments most exposed to climate-threatened airports through their investments and airport operating companies.

Table 14: Governments Most Exposed to Climate-Threatened Airports

No.	Government	No. of Airports Exposed	Airports Exposed	Investment/Airport Operating Companies
1	Singapore	6	Beijing Capital, Chongqing Jiangbei, Delhi Indira Gandhi, Istanbul Sabiha Gokcen, Kuala Lumpur International, Rome Fiumicino	GIC, Changi Airport Group
2	Frankfurt	5	Antalya, Delhi Indira Gandhi, Frankfurt, Riyadh King Khalid, Xi'an Xianyang	Fraport
3	Norway	5	Lisbon, London Gatwick, Madrid Barajas, Palma de Mallorca, Zurich	Norges Bank
4	Qatar	4	Doha Hamad, Kansai, Lisbon, London Gatwick	Qatari Holding LLC

5	The Netherlands	4	Amsterdam Schiphol, Antalya, Paris Charles de Gaulle, Paris Orly	Royal Schiphol Group
6	France	3	Amsterdam Schiphol, Paris Charles de Gaulle, Paris Orly	Groupe ADP
7	Malaysia	3	Delhi Indira Gandhi, Istanbul Sabiha Gokcen, Kuala Lumpur International	Eraman, Malaysia Airports Holdings

Increasing climate-related financial costs have different implications for majority state-owned and commercially-owned airports. State-owned airports may face increasing pressure to sell all or part of their shares to commercial entities in order to raise funds for climate resilience works or to reduce risk exposure. Commercially-owned airports face impacts such as erosion of asset value, increased cost of capital, and loss of cash flow. Institutions that are exposed to multiple climate-threatened airports will find it more challenging to diversify their climate-related risk.

5.5 Impacts of Climate-Related Risks on Investment Valuation of Airports

Currently, major airport operators enjoy generally high credit ratings, supported by consistent profits, positive cash flow, and strong passenger growth projections.[177] [178] A review of the credit ratings of major airport operating companies shows that most of them fall into the A1-A3 range, which is investment-grade. However, other companies in the commercial aviation industry, particularly airlines, are given a less positive outlook by ratings agencies, with a median rating of Ba1-Ba2 (borderline non-investment grade). One reason commonly cited by ratings agencies for this rating is the perceived long-term fragility of the aviation industry, due in part to its continued reliance on fossil fuels and its impact on climate change.[179] (For a list of credit ratings of selected major airport operating companies and airlines, see Table 15.)

Table 15: Credit Ratings of Selected Major Airport Operating Companies and Airlines[180]

Company	**Major Airports Majority Owned and/or Operated**	**Moody's Rating**
Airport Operating Companies		
AENA	Barcelona El Prat, Madrid Barajas	A3/Negative
Delhi International Airport Ltd	Delhi Indira Gandhi	Ba3/Negative
Malaysia Airports Holdings	Kuala Lumpur International	A3/Negative
Royal Schiphol Group	Amsterdam Schiphol	A1/Negative
Vinci Airports	Lisbon, London Gatwick	A3/Stable
Airlines/Airline Holding Groups		
American Airlines	-	B2/Negative
British Airways	-	Ba1/Negative
Delta Air Lines	-	Baa3/Negative
easyJet	-	Baa3/Negative
IAG	-	Ba1/Negative

Lufthansa Group	-	Ba2/Negative
Southwest Airlines	-	Baa1/Negative
United Airlines	-	Ba2/Stable

As climate-related disruptions to airport operations become more common, these risks will increasingly be seen as material not just for airlines, but for airport operators as well. Some airport operators have already begun experiencing a change in their investment environment, driven by the increasing adoption of the Task Force on Climate-related Financial Disclosures (TCFD) recommendations and sustainability reporting frameworks.[181] [182] [183] To secure financing, airport operators are increasingly being asked by investors to demonstrate comprehensive risk management strategies for ensuring continued operational ability and profitability in the face of increasing climate-related risk.[184] However, many airports do not yet have such strategies (see Section 6.1).

The credit ratings of airports are particularly relevant to climate adaptation because major airport infrastructural works, such as those that will be required to climate-proof airports, tend to be financed through external capital raise, consisting largely of debt.[185] [186] This creates a pernicious cycle for airport operators, where those airports that most require climate-proofing works face the greatest difficulty in financing them. Through a similar mechanic, vulnerable airports may experience lower profitability due to higher expenditure on climate adaptation, be forced to pay higher insurance premiums, and receive lower valuations.[187] [188] In severe cases, for example where the costs of adequately protecting airport infrastructure against climate-related risks exceeds investors' required return (see Section 6.2), some or all of an airport's infrastructure may become stranded assets – assets that have incurred unexpected or premature write-downs, devaluations or conversions to liabilities.[189] In addition, airports with frequent climate-related disruptions are also likely to suffer damage to their brand and service ratings.[190]

6. Strategies and Costs of Improving Climate Resilience for Airports

6.1 The Changing Climate-Related Risk Environment for Airports

As discussed in the preceding sections, airports are significantly exposed to climate-related risks. In addition, due to their nature as land-intensive, capital-intensive and immobile investments with specific siting requirements, airport infrastructure is not easily relocated or rebuilt. Climate adaptation is therefore particularly important for airports in order to protect vital infrastructure and ensure future service continuity. Such adaptation will require substantial planning and investment,[191] and should include not only operational considerations on safety and security, but also legal, environmental, financial and business effects on airport operations.[192]

However, surveys of airport administrators have found that lack of information and an inadequate understanding of the climate-related risks faced by airports are posing barriers to action. According to a 2013 survey of 35 European airport operators and air navigation service providers, over 80 percent of respondents believed that measures to make airports resilient to climate change would be necessary either now or in the future, but less than half had begun planning these measures, and only 4 had successfully completed such a plan.[193] Similarly, a 2012 survey of 16 airports in North America found that while most airport administrators were aware that climate-related risks are likely to become more frequent and severe, many do not yet have any form of climate-related risk management system, believing that existing emergency procedures are sufficient for addressing these risks.

Instead of comprehensive adaptation plans robust to multiple eventualities, some airports are also choosing an iterative risk management strategy, involving the high-level identification of risks and the revisiting of earlier decisions based on new information.[194] However, as climate change progresses, critical assumptions used to construct these risk management plans may no longer be valid.[195] [196] One example is Japan's Kansai Airport, which was built on a reclaimed island in Osaka Bay and expected to gradually sink towards a stable elevation over a period of 50 years. However, faster-than-expected subsidence rates and rising sea levels due to climate change have forced the airport to implement measures such as adding seawalls on the airport's perimeter, using large pumps to drain runways after heavy rain, and raising the columns on which the airport rests. It is estimated that such repairs and modifications have cost at least US$12 billion.[197] [198] In a similar vein, increased exposure to extreme weather events may cause faster rates of structural deterioration than originally anticipated, forcing airports to increase the frequency, scale, and cost of refurbishment projects.[199] The trend of rising passenger traffic across the global aviation market will exacerbate this impact by placing greater stress on infrastructure, as well as by increasing the size of disruptions and economic damages in the event of a climate-related shutdown.

In addition, while climate modelling indicates the need for protective measures to be implemented by the end of the 21st century, it is possible that impacts due to unpredictable extreme events may occur much earlier.[200] For example, the flooding of Kansai Airport by Typhoon Jebi in 2018 triggered Japan's Land, Infrastructure, Transport and Tourism Ministry to initiate the airport's first large-scale overhaul since its construction, including raising runways, building seawalls, and waterproofing electrical equipment. The project is expected to cost the airport's operator (Kansai Airports) and owner (New Kansai International Airport Co.) at least 54 billion yen (US$508 million).[201] [202]

On the other hand, while climate-related risks are unpredictable, many such risks have a long onset period, allowing airport administrators time to engage in adaptive long-term planning.[203] In general, planning for future climate change effects when undertaking new infrastructure projects is likely to significantly reduce costs for airports, as compared to having to climate-proof infrastructure later.[204] This is especially relevant for countries that are rapidly constructing and expanding airports in response to increasing demand for passenger aviation, such as China, where an average of 8 new civil airports are built every year.[205] Even existing airports require a significant terminal construction or refurbishment project about every 25 years to remain current with latest aircraft models, security policies, and operational processes.[206] This necessary ongoing rebuilding provides an opportunity for these airports to simultaneously build climate resilience into their infrastructure.

The interconnected nature of the global aviation industry presents a special challenge to climate resilience. Even if one airport has adequately protected itself against localised climate impacts, it may still be severely affected by impacts on another airport that has not.[207] This makes it critical for airports, especially the major ones discussed in this paper, to undertake climate resilience efforts in a coordinated manner. The following sections will discuss the options for climate adaptation available to these airports, the gaps between need and current implementation, and possible steps that the aviation industry can take to mitigate climate-related risk.

6.2 Climate Adaptation Strategies for Airports

6.2.1 Improving Resilience to Extreme Sea Level Events

As flooding can force significant or total disruption to airport operations, it is valuable for airports to invest in protection against even extreme sea level events with relatively low probability.[208] However, given the fat-tailed behaviour of extreme climate events,[209] it is generally accepted in the aviation industry that it would be prohibitively expensive to completely protect airports against inundation.[210] Hence, in deciding the optimal level of protection against extreme sea level events, airports face a tradeoff between higher risk and higher cost; in this process, protection against 100-year extreme storm surge events is widely used as a benchmark of optimality.[211]

Table 16 shows the levels of 100-year extreme storm surge events at the 15 airports vulnerable to inundation in the present day, as well as at the end of the 21st century under the three scenarios studied. In other words, to be resilient against a 100-year storm surge event, the airports need to be able to cope with a storm surge of at least this level.

Table 16: Return Period for 100-Year Storm Surge Event at Airports with Inundation Risk

No.	**Airport Name**	**Elevation (m)**	**100-Year Sea Surge Event (m)**			
			Present day	"Low case"	"Mid case"	"High case"
1	Amsterdam Schiphol	-3.4	3.0	3.3	3.5	4.0
2	Bangkok Suvarnabhumi	1.5	4.3	4.6	4.8	5.3

3	Bangkok Don Mueang	2.7	4.3	4.6	4.8	5.3
4	Shanghai Hongqiao	3.0	4.8	5.1	5.4	5.8
5	Vancouver	4.0	5.6	5.9	6.1	6.6
6	Seoul Incheon	7.0	11.3	11.6	11.9	12.3
7	Miami International	2.7	5.1	5.3	5.6	6.0
8	San Francisco International	4.0	4.4	4.7	4.9	5.4
9	Shanghai Pudong	4.0	4.8	5.1	5.4	5.8
10	New York John F. Kennedy	3.7	4.5	4.8	5.0	5.5
11	Kansai	5.2	5.7	6.0	6.2	6.7
12	New York LaGuardia	6.1	6.2	6.5	6.8	7.2
13	Boston Logan	5.8	5.6	5.9	6.1	6.6
14	Shenzhen Bao'an	4.0	3.3	3.6	3.9	4.3
15	Newark Liberty	5.2	4.5	4.8	5.0	5.5

Table 16 shows that the required level of fortification against inundation risk ranges widely between airports. For a 100-year inundation event in the "high case", Shenzhen Bao'an and Newark Liberty airports will both need to cope with only 0.3 m of storm surge in excess of their elevation. At the other end of the spectrum, Amsterdam Schiphol Airport, which already sits below sea level, will need to cope with a storm surge 7.4 m higher than its elevation.

A variety of methods exist for flood-proofing buildings and other built infrastructure. A 2012 review by FloodProBE, a research programme of the European Commission, organised these methods into six categories: wet flood-proofing, dry flood-proofing, elevating structures, floating or amphibious structures, temporary or demountable flood defences, and permanent flood defences.[212] A brief summary of each of these methods is presented in Table 17.

Table 17: Methods for Flood-Proofing Buildings[213]

Method	Description	Appropriate for
Wet flood-proofing	• Allow temporary flooding of lower parts of building • Use water-resistant building materials to prevent water damage • Use catwalks to access higher floors during flood	• Floods between 1 metre and 1 floor with short duration • Buildings where lower floors are non-essential for function
Dry flood-proofing	• Prevent water from entering building by using waterproof coatings on facade or water-impermeable building materials • Stronger construction methods used to withstand water pressure on walls	• Floods lower than 1 metre • Buildings with small footprint/circumference

Floating or amphibious structures	- <u>Floating structures</u>: Construct building on floating structure permanently located in water - <u>Amphibious structures:</u> Construct building with traditional foundation and additional floating foundation that allows building to float if flood occurs	- New buildings (difficult to retrofit existing building structures) - <u>Floating structures</u>: Building situated on permanent body of water - <u>Amphibious structures</u>: Small/light buildings with high buoyancy, located in areas of frequent tlooding
Elevation	- <u>Stilts</u>: Elevate building above ground using stilts - <u>Mounds</u>: Construct buildings on artificial hills (mounds)	- New buildings (difficult to retrofit existing building structures) - Floods higher than 2 metres with long or permanent duration - <u>Stilts</u>: Small and light buildings - <u>Mounds</u>: Smaller buildings that do not require large mounds to be constructed
Temporary or demountable flood defences	- <u>Temporary flood defences</u>: Install temporary flood barriers that are removed once flood is over - <u>Demountable flood defences</u>: Flood barriers that are partially temporary and partially permanent	- <u>Temporary flood defences:</u> Non-permeable ground surface with ample space - <u>Demountable flood defences</u>: Usually used to supplement permanent flood defences
Permanent flood defences	- Various permanent structures, including dykes, levees, embankments, walls, and gates	- Ample space for siting of barrier - Appropriate for either permanent protection or protection against occasional extreme events

From Table 17, it is clear that many existing methods for flood-proofing buildings are inappropriate for airports. Wet flood-proofing is unfeasible as lower levels of airports are essential to their function, and airport buildings are likely too large to implement dry flood-proofing. Floating structures are inappropriate as airports are not situated on permanent water bodies, while amphibious structures are expensive and require relatively small, buoyant buildings.

Elevation does present a viable option for airports, but the applicability of this method is limited. While it is conceivable that an entire airport terminal building could be elevated, this would have to be carried out in stages and would likely entail significant disruptions to airport operations.[214] Elevating buildings on such a large scale is also likely to be prohibitively expensive. For example, Brisbane Airport previously investigated the construction of a new building complex on raised ground, but abandoned the idea as doing so would cause the construction budget to more than double to AU$125 million (US$84.4 million).[215]

Rather, it is more feasible for airports to elevate only the most vulnerable low-lying assets, such as runways. This option is currently being pursued by some airports, such as Kansai Airport.[216] For relatively small increases in height, the cost of raising runways may be low enough to be feasible. For example, resilience against a 100-year inundation event at Shenzhen Bao'an Airport would require raising the two runways, measuring 3,800 m x 60 m and 3,400 m x 45 m,[217] by 0.3 m. Using latest available cost estimates for concrete in the Guangzhou area by infrastructure consultancy Turner & Townsend,[218] this would cost an estimated US$10.2 million, excluding labour costs. In addition, runways typically require repaving every 8 to 10 years, providing an opportunity for such works to be conducted simultaneously.[219]

However, the strategy of elevating runways also has several drawbacks. Airports that require fortification against higher storm surges would likely find the cost prohibitive, especially those in developed markets with higher labour costs. In addition, at busy airports operating at near-capacity, construction works on a runway would have a significant effect on revenue and operations. Some countries, such as Norway, have introduced minimum heights for newly-built runway,[220] but this does not solve the problem of flood-proofing existing ones.

The most cost-effective option for many airports is likely to construct flood defences, such as seawalls and flood barriers. This appears to be one of the most common options chosen by airports facing inundation risk, having been implemented by airports such as Boston Logan, San Francisco International, and Hong Kong.[221] [222]

A key advantage of this strategy is that flood defences are flexible and adaptable to an airport's specific needs. Seawalls may be constructed in various forms out of a variety of materials, ranging from earth berms to concrete dykes.[223] Other infrastructure assets like roads can also double as seawalls, a strategy that has been implemented by Singapore Changi Airport (see Figure 6).[224] Airports may also be able to save costs by constructing demountable barriers consisting of permanent sections that are supplemented by temporary, modular barriers when extreme storm surges are expected; this strategy has been adopted by Minneapolis-St. Paul Airport, among others.[225]

Figure 6: Road Doubling as Seawall at Singapore Changi Airport[226]

On the other hand, while building barriers are cheaper than elevating infrastructure, it is often still an expensive undertaking. For example, Kansai Airport has spent more than US$150 million to date on raising its seawall.[227] Runways may also need to be raised together with flood barriers so that airplanes can continue to safely land and take off, potentially adding tens of millions of dollars to the cost.[228] Finally, the location of certain airports may also mean that flood defences require integration into broader city-

wide flood resilience measures to be effective, which may cause costs to increase dramatically. After conducting a study of the city's vulnerability to climate change-induced flooding, the City of Boston concluded that the recommended proposal for protecting Boston Logan Airport would involve constructing a barrier across the Boston Harbour, at an estimated cost of US$10 billion.[229] [230]
In practice, the "hard" defence infrastructure described above is often most effectively used by airports in combination with local flood management systems, such as drainage systems, pumping stations, and retention ponds. Examples of airports that have implemented local flood management systems to complement "hard" flood defence infrastructure include Amsterdam Schiphol, Bangkok Don Mueang and Suvarnabhumi, New York LaGuardia, and Singapore Changi (see Figure 7).[231] [232] [233] [234]

Figure 7: Expansion Works on Flood Retention Basin at Chicago O'Hare Airport[235]

This strategy has multiple advantages. Firstly, local flood management systems may be significantly cheaper than flood defences offering similar protection.[236] Secondly, given that flood defence infrastructure has been known to fail in the past due to engineering oversights[237] or greater-than-expected flooding,[238] local flood management systems provide an additional margin of safety.[239] Thirdly, such systems also serve the dual purpose of protecting airports against other impacts of climate change, such as increased precipitation and reduced soil absorption capacity due to rising groundwater tables. As such, they can be seen as "no-regret" interventions that provide net benefits to airports, no matter the incidence of extreme sea level events.[240] [241]

In summary, while flood defence infrastructure is the most practical option for protecting airports against extreme sea level events, their cost is highly dependent on the individual characteristics of the airport in question. In choosing between flood defence infrastructure options, airports face a tradeoff between safety and cost, a decision which is made more difficult by the uncertain nature of future climate impacts. To mitigate against this uncertainty, airports will likely find it most feasible to adopt local flood management systems alongside flood defence infrastructure.

6.2.2 Improving Resilience to High Temperatures for "HHS" Airports

For "HHS" airports, options for improving resilience to extreme temperature risk are more limited than those available to mitigate inundation risk. Of the three "HHS" risk factors, two – high temperature and high elevation – are inherent characteristics of the airport's surrounding climate and cannot be modified. Hence, the only viable infrastructural intervention for a "HHS" airport is to extend its runways. Indeed, many "hot and high" airports already have longer-than-average runways to deal with the restrictions imposed by their surrounding climate.[242]

Table 18: Temperatures Requiring Take-off Weight Restrictions and Return Periods (in days) for "HHS" Airports, with Current Runways and with Theoretical 4,500m Runway[243]

	Airport Name	Longest Runway (m)	Temp. threshold for take-off weight restriction (^{o}C)						Return period for take-off weight restriction (days), "high case"					
			With current runways			With 4,500m runway			With current runways			With 4,500m runway		
			>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg	>0 kg	4,536 kg	6,804 kg
1	Bogotá El Dorado[244]	3800	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL
2	Mexico City Benito Juarez[5]	3985	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL	ALL
3	Kunming Changshui[245]	4500	ALL	ALL	20.4	N/A	N/A	N/A	ALL	ALL	1.1	N/A	N/A	N/A
4	Denver International[6]	4877	ALL	29.0	34.3	N/A	N/A	N/A	ALL	3.0	5.5	N/A	N/A	N/A
5	Salt Lake City	3658	ALL	32.6	37.8	22.6	34.8	39.9	ALL	4.4	8.6	4.4	5.8	11.8
6	New York LaGuardia	2135	ALL	30.6	35.2	45.4	53.1	56.8	ALL	5.7	11.9	115.1	1153.2	4211.0
7	Bengaluru Kempegowda	4000	30.5	40.1	44.7	32.4	41.4	45.9	1.1	17.3	1097.1	1.2	44.9	4648.5
8	Riyadh King Khalid	4200	36.2	44.8	47.3	37.3	45.5	48.5	1.6	3.8	5.6	1.7	4.2	6.8
9	Phoenix Sky Harbor	3502	38.5	47.7	52.6	41.7	49.1	53.0	2.5	10.2	30.6	3.7	13.4	33.0
10	Las Vegas McCarran	4423	36.4	44.7	47.6	36.7	45.0	48.2	2.8	8.3	13.8	2.9	8.7	15.4
11	Dubai International	4000	44.5	52.1	55.9	45.2	52.9	56.6	4.7	35.8	149.3	5.4	47.2	200.3
12	Delhi Indira Gandhi	4430	42.7	50.3	54.2	42.9	50.4	54.2	4.8	37.9	167.2	5.0	38.9	167.2
13	Xi'an Xianyang	3801	37.4	45.9	50.2	40.3	47.4	51.4	7.6	36.4	98.9	12.2	50.7	134.3
14	Doha Hamad[6]	4850	46.2	53.6	57.3	N/A	N/A	N/A	5.6	33.1	108.6	N/A	N/A	N/A
15	Charlotte Douglas	3048	36.8	43.3	48.7	43.0	50.5	54.4	6.6	25.8	114.1	24.0	201.8	789.6
16	Madrid Barajas	4179	36.2	45.0	49.3	38.2	45.8	49.8	7.0	50.1	180.1	10.1	62.6	211.9
17	Chongqing Jiangbei	3800	38.4	46.8	51.0	41.0	48.2	52.2	8.4	59.2	211.8	14.1	88.5	316.6
18	Jeddah King Abdulaziz	4000	44.6	52.1	55.9	45.3	53.0	56.7	5.9	293.4	6061.0	7.6	562.8	12591.7
19	Antalya	3400	42.6	50.6	54.1	44.8	52.5	56.3	17.8	222.0	904.1	32.4	464.9	2405.0

Table 18 shows how extending runways to 4,500 m changes the temperature thresholds for take-off weight restrictions, and in turn the return periods of weight restriction days, for “HHS” airports in the “high case”. A theoretical runway length of 4,500 m was chosen as this is the maximum runway length that the Boeing 737-800 can use at most “HHS” airports without exceeding its tyre speed limit.

Runway extensions have the greatest potential benefit for airports with short runways located at lower elevations. For example, for Charlotte Douglas, an airport located at a relatively low elevation of 227.7 m and with a relatively short runway of 3,048 m, extending the runway to 4,500 m increases the return period of weight restriction days by 3.6 times. This effect tends to be more pronounced for larger weight restriction days: returning to the example of Charlotte Douglas Airport, extending the runway increases the return period of 4,536 kg weight restriction days from 25.8 days to 201.8 days (a 7.8x increase), and the return period of 6,804 kg weight restriction days from 114.1 days to 789.6 days (a 6.9x increase).

However, this solution will not be effective for all “HHS” airports. Airports located at a very high elevation, such as Bogotá El Dorado and Mexico City Benito Juarez, experience no change from extending runways because taking off at a longer runway at these airports would cause the Boeing 737-800 to exceed its tyre speed limit. In addition, 3 “HHS” airports – Kunming Changshui, Denver International, and Doha Hamad – already have at least one very long runway of at least 4,500 m. These airports, too, will be unable to extend their runways much farther without encountering airplane tyre speed limits.

In addition, there are geographical limitations preventing certain airports from extending their runways. A notable example is New York LaGuardia Airport, whose runways are surrounded by Flushing Bay; hence, it is impossible for the airport to extend its existing runways without resorting to land reclamation (see **Error! Not a valid bookmark self-reference.**), which is unlikely given the very high cost. For example, it is estimated that Wellington International Airport’s proposed extension of its runway by 355 m into Lyall Bay will cost NZ$300 million (US$192 million), or approximately US$541,000 per metre.[246]

Figure 8: Satellite View of New York LaGuardia Airport[247]

A satellite view of New York LaGuardia Airport shows that its runways are surrounded by Flushing Bay and existing roads and buildings, restricting room for expansion.

Even when such geographical restrictions do not apply, extending runways can still be very expensive. For example, extending the longest runway at Charlotte Douglas Airport from 3,048 m to 4,500 m will require laying concrete an estimated 0.5 m thick and 46 m wide,[248] [249] or an additional 33,396 m^3 of concrete. At an estimated US$156 per cubic metre,[250] this will cost US$5.2 million, excluding labour costs and the cost of airport service disruptions.

The available area for runway expansion is also limited by a wide array of legal and geographical restrictions. To extend runways, an airport must first purchase the necessary land, which may mean negotiating with the owners of existing buildings or the government. Airports also have to contend with government planning permissions, noise regulations, no-fly zone regulations, and other laws.[251] Besides accommodating airplane take-off movements, the runway must usually also include a runway safety area, which increases the width of necessary construction by about 150 m and the length by about 300 m.[252] All of these will increase costs and reduce the feasibility of extending runways for airports.

Technological change – including lighter airplanes, improvements in engine performance, and new wing designs for better lift – may help ameliorate this problem to some extent in the future. However, any possible improvements are limited by the tradeoff between better lift generation when taking off at low speeds and better efficiency when flying at high speeds; these can generally not be increased together.[253] Introducing new models will likely also have to wait for the existing airplane stock to be depreciated, which takes on average 25 to 30 years.[254] [255]

One final solution is for "HHS" airports to shift flights to cooler parts of the day. This strategy is already being employed by some airports in desert climates.[256] However, this option is not feasible at busy airports that are already operating at close to capacity limits.[257]

In summary, the only feasible infrastructural solution to increasing high temperature risk for "HHS" airports is to extend their runways. However, this solution may not be effective for airports at a high elevation or those that already have long runways. In addition, legal barriers, operational hurdles, and the need to acquire land may further drive up costs. While improved aircraft technology and flight scheduling may help reduce the problem, they both entail tradeoffs that may not be appropriate for all airports.

6.2.3 Improving Resilience to High Temperatures for "Non-HHS" Airports

This study has found that over the course of the 21st century, disruptions due to take-off weight restrictions will become more common, even at "non-HHS" airports. However, for 62 of the 67 "non-HHS" airports exposed to this risk, the return period of weight restriction days will remain greater than 1 year, even in the "high case". The direct costs of such infrequent disruptions to airports, amounting to several hundred thousand US dollars per year, is unlikely to be high enough to justify expensive infrastructural projects such as runway extensions, which may cost upwards of several million US dollars.

Rather, these airports will likely have to rely on improved systems for managing weather-related disruptions. One airport that has invested in doing so is Hong Kong. Hong Kong Airport's approach relies on two key elements. Firstly, the airport operator, Airport Authority Hong Kong, communicates closely with the Hong Kong Observatory and Air Traffic Control to assess the impact of prospective extreme weather events. Secondly, when necessary, the airport is able to trigger dedicated contingency management systems, such as its Flight Rescheduling Control System, which handles rescheduling requests from airlines, and its Airport Emergency Centre, which functions as a temporary hub for coordinating aircraft ground holding, passenger evacuation, and other services.[258] Aside from its relatively lower cost as compared to building new infrastructure, this strategy also has the advantage of being applicable to any kind of weather-related disruption, not just extreme temperatures.

A final key element of a robust climate mitigation strategy is participatory planning with airport stakeholders and surrounding communities. Such a systematic approach will help to prevent knock-on disruptions to other systems, as well as help airports to better collect information, assess risks, and reduce costs.[259]

7. Conclusion

This study has attempted to provide a broad insight into two major physical climate-related risks facing global airports, inundation risk and take-off weight restriction risk, and the issues that airport operators should consider when addressing them. It has found that as the effects of global warming intensify over the 21st century, a much larger proportion of the world's major airports will become materially affected by physical climate-related risks. Airports that are already exposed to these risks will see the incidence of extreme weather events increase further, threatening their profitability and asset quality.

In addition, as only two types of climate-related risk are considered, the true spectrum of climate-related risks that airports are exposed to is likely to be much greater, underscoring the need for airports to take urgent and thorough action.

By including a large number of key airports internationally, it has been necessary to sacrifice a degree of granularity. More work can and should be done, by both airport operators and the research community, to better measure and understand the risks facing each airport and identify the best strategies for managing them. The earlier this work is undertaken, the more cheaply and effectively an airport will be able to execute successful climate adaptation measures.

Owners of airports and their investors have an important role to play in drawing attention to the issue of climate-related physical risk, as well as supporting airports to implement the necessary measures to adapt to this risk. Widely used frameworks such as the TCFD provide comparable methods for benchmarking the performance of airports on climate-related risk and disclosure, and provide a useful starting point for an airport to develop an adaptation strategy that is suited to its particular needs. Conversely, failure to seriously consider climate-related risk and demonstrate robust adaptation strategies will increasingly cause airports to lose investor confidence, especially as the costs of extreme weather events become more apparent.

Adopting measures that are robust under multiple climate scenarios can help airports manage the uncertainties inherent to projecting climate-related risk. Airports that have already begun this process can also share their learnings with other airports, thereby helping to build greater resilience across the deeply interconnected web of global aviation.

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[172] Bogotá El Dorado Airport is owned by the government of Colombia, but operated by a commercial concession OPAIN. The table shows the ownership of OPAIN.

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[173] Riyadh King Khalid Airport is owned by the General Authority for Civil Aviation of Saudi Arabia, but is operated by commercial airport operator Fraport (except Terminal 5, which is operated by the Dublin Airport Authority, owned by the government of Ireland.) The table shows the ownership of Fraport.

[174] Antalya Airport is owned by the General Directorate of State Airports, but is operated by commercial consortium Fraport TAV Antalya Airport Terminal AS. The table shows the ownership of Fraport TAV Antalya Airport Terminal AS.

[175] Lisbon Airport is owned by ANA Aeroportos de Portugal, but is operated by commercial operator Vinci Airports. The table shows the ownership of Vinci Airports.

[176] Terminal One of Newark Liberty Airport is operated by Flughafen Munchen GmbH, which is owned by the government of Germany.

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[245] "N/A" is because airport already has a runway of 4,500m or longer.

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