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Adapting Latin American and Caribbean airports to a changing climate: Impacts, challenges and solutions

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ABSTRACT

In the Latin America and Caribbean (LAC) region climate change effects such as higher temperatures, sea level rise and stronger storms are already threatening critical airport infrastructure and operations, with this exposure increasing as climate change accelerates. Given the social and economic criticality of airports to the region, it is vital that they adapt and build resilience to the resulting impacts. This paper presents the first evaluation of the climate risk assessment and adaptation status of airports in the LAC region. Drawing on a survey of airport professionals from 35 LAC airports and airport groups (representing a total of 54 airports) it finds that although 80% are already experiencing climate change effects, just 14% have carried out a climate change risk assessment to establish what impacts they may face and only 3% (one airport) have developed a climate adaptation plan. This is a significant exposure-adaptation gap which it is essential to address. This urgently requires (i) enhanced awareness raising of climate effects and impacts; (ii) increased provision of data and guidance; and (iii) development and promotion of capacity building mechanisms such as risk assessment tools and training. A crucial role is identified for national governments and sector bodies to continue and augment support for airports in the region to adapt. While this study focuses on the LAC region, the recommendations are likewise applicable for supporting adaptation action by airports in other regions.

1. Introduction

The impacts of climate change are accelerating for all sectors and regions, with critical infrastructure such as airports increasingly at risk (IPCC, 2022). Airport infrastructure and service continuity is vulnerable to both increasingly extreme weather events, such as storms, heavy precipitation and heatwaves, and incremental changes such as higher average temperatures and sea level rise (SLR) (Burbidge, 2016; De Vivo et al., 2022; Yesudian and Dawson, 2021). The potential impacts are numerous and will vary according to factors such as geographical location, the current climate and how it will evolve in the future, the specifics of the individual airport, and any existing adaptive capacity (Burbidge et al., 2023; ICAO, 2020). However, key impacts include disruption to operations or damage to infrastructure from storms, heat damage to runways and taxiways, flooding from intense precipitation, and temporary or permanent loss of airport capacity due to storm surge or SLR (Budd & Ryley, 2012; Burbidge, 2016; De Vivo et al., 2022). The broad range of impacts can also include risks such as increased occurrence of lightning strikes (Yair, 2018), an increase in bird strikes (Blackwell et al., 2009) and health risks to passengers and personnel due to high temperatures (Qian et al., 2020; Vogiatzis et al.,

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2021). Furthermore, changing climatic conditions are expected to drive economic impacts through, for example, changes in passenger demand or an increase in operating costs or insurance premiums (Burbidge et al, 2023). It is thus vital for the global airport sector to adapt and build resilience to climate impacts (Burbidge, 2016; Voskaki et al., 2023).

To better understand and address airport vulnerability to climate change, industry best practice recommends carrying-out a climate change risk assessment and, on the basis of this, developing and implementing a climate adaptation strategy or plan. (ACI, 2018; ACRP, 2014; ICAO, 2020; ICAO, 2022). A climate risk assessment entails a detailed analysis of how climate change effects may impact the airport, the likelihood of this happening and the consequences if it does. It requires climate change projections at a sufficient level of granularity, usually requires the approval of senior management and, when done thoroughly, can be a resource-intensive process (ICAO, 2022). Once climate risks (effects and impacts) are identified, effective adaptation also requires knowledge of potential measures and practical know-how to inform adaptation actions (Burbidge et al., 2023).

While a growing number of airports around the globe have engaged with this process (CDRI 2022; ICAO 2020), many others are yet to do so and thus may not be aware of how they will be impacted by climate change or taking measures to reduce risks and vulnerabilities. Reasons for a lack of engagement include, but are not limited to, lack of awareness, resources, management support, or absence of legislation mandating action (Budd & Ryley, 2012; Burbidge, 2016). A further barrier may be competing priorities for resources such as climate mitigation targets, possibly due to greater focus on reducing airports' contribution to climate change rather than adapting to it (Lindbergh et al., 2022b). There may also be specific local constraints. For example, Monioudi et al. (2018) highlight particular challenges to adaptation for Small Island Developing States (SIDS) due to their geographical constraints, limited human and financial resources and disadvantageous economies of scale. Such barriers can be reduced or overcome. However, it is essential to recognise them so that measures can be identified to address them, such as effort and resource reallocation or re-prioritization (Moser & Ekstrom, 2010).

There is an increasing body of industry work to support airports in identifying and adapting to climate change risks at a generic level (ACI-WORLD, 2018; ICAO, 2022) and a small but growing body of academic work proposing methodologies for and/or reporting the results of airport climate risk assessments (De Vivo et al, 2022; Dolman and Vorage, 2020; Lopez, 2016; Vogiatzis et al, 2021). However, research on climate change impacts and adaptation in the aviation sector has, to date, been strongly focused on the European, Asian, and North American regions, with limited consideration of Latin America, the Caribbean, the Middle East and Africa, a significant information gap given the extent of climate change impacts projected in all four regions (Burbidge et al., 2023; IPCC, 2021a). While many of the climate risks and responses identified in the literature will be applicable to airports in these regions, many climate effects, and the resulting impacts and adaptation measures, will be locally specific according to geographical, climatological, and individual airport factors (Burbidge et al, 2023; Machado Darze et al., 2022). Consequently, there is a clear need for the geographical broadening of aviation climate adaptation research.

This study addresses that research gap for the Latin America and Caribbean (LAC) region. The region is home to major global airports, important regional hubs, and many airports that are critical for local and regional economies and connectivity. In 2018, the LAC aviation sector directly employed an estimated 722,000 people; 29,000 were employed by airport operators and 394,000 worked on-site at airports, for example in retail and catering (ATAG, 2020). Overall, the sector supported 7.6 million jobs and $187 billion in economic activity, with 356 million passengers using the region's airports (ATAG, 2020). Aviation is crucial for tourism in the region, particularly in the Caribbean where over half of tourists arrive by air (IATA, 2016), and is a major contributor to regional GDP (IATA, 2023). Moreover, the LAC aviation sector is growing. In 2023 traffic was already 5.9 % above 2019 pre-pandemic levels and forecast to grow at 4.4 % annually out to 2032 (ACI-LAC, 2024). By 2052, annual passenger traffic is forecast to increase to 1.79 billion

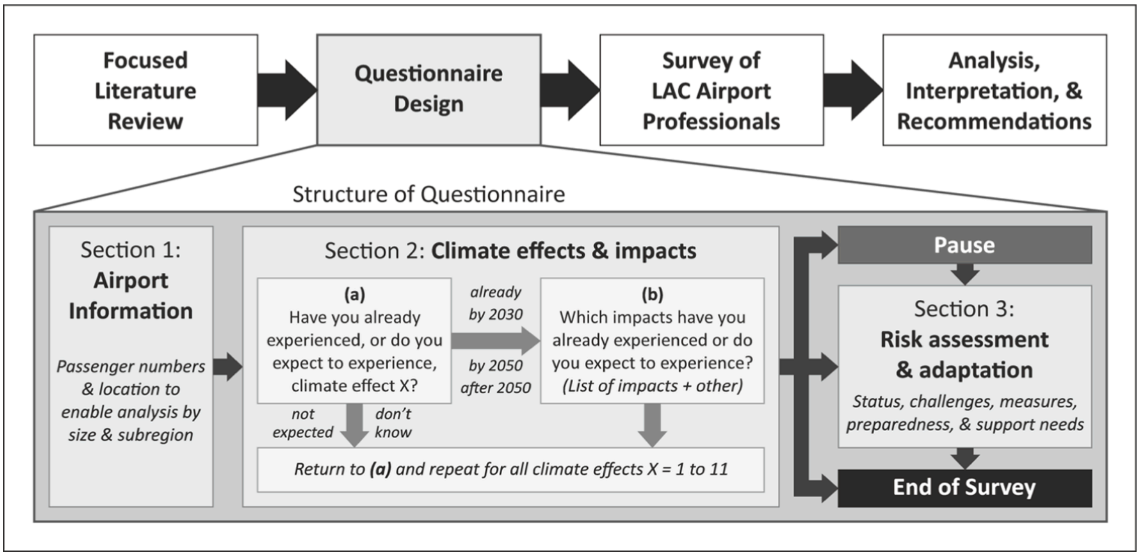

Fig. 1. Overview of study methodology.

passengers, a 2.4-fold increase from 740 million passengers in 2023 (ACI-LAC, 2024). This projected traffic growth increases risk whilst reducing resilience as when traffic levels at an airport are higher the impact of disruption can be greater and recovery times longer (Burbidge, 2018).

This study presents findings from the first regionally focused survey of LAC airport professionals on climate change risks and adaptation planning. It identifies the most significant climate change effects and impacts for airports in the region, to what extent adaptation action is already being implemented, whether survey respondents consider this level to be sufficient, barriers to effective adaptation, and to what extent further information and actions are required to build resilience in the sector. Section 2 describes the survey methodology. Section 3 examines respondents' perceptions of climate effects and impacts for the LAC region, whilst Section 4 explores their engagement with the climate risk assessment and adaptation planning process. Finally, Section 5 discusses the findings and makes recommendations to enhance progress towards achieving airport climate resilience.

2. Methods

A survey of airport professionals was conducted to evaluate engagement with climate risk assessment and adaptation planning in the LAC region. Fig. 1 presents an overview of the study methodology. Further details on the survey development, distribution, analysis, response rate and respondent profile are provided below.

2.1. Survey development, distribution & analysis

The research instrument was an online, self-administered questionnaire created using Survey Monkey. It consisted of three sections with a combination of closed and open questions (Fig. 1; Appendix A). The first section solicited information on the airport such as its location and number of passengers per annum. The second section focused on climate change effects and impacts, and the final section on climate risk assessment and adaptation planning.

A focused literature review was carried out to identify the climate effects and impacts to be included in the second section. First, as an authoritative synthesis of peer-reviewed literature with climate information provided at subregional level, the IPCC Sixth Assessment Report (AR6, 2021a-d) was reviewed to establish current and projected climate changes across the LAC region. Second, the recent reviews of ICAO (2020) and Burbidge et al., (2023), and the responses to four global aviation sector surveys (ICAO; 2020; WMO, 2020; ACI-WORLD; 2021; CDRI, 2023) were appraised to establish climate change effects and impacts of potential relevance for LAC airports (i.e. both LAC specific information and impacts associated with the projected climate changes for the LAC region). In addition, a database search for papers in Spanish and Portuguese was carried out following the search protocol of Burbidge et al., (2023), but did not return any additional literature.

Table 1

Breakdown of respondents by size and subregion. Three letter codes for IPCC AR6 subregions are provided in Fig. 2. The number of airports represented in the risk assessment and adaptation planning section is not provided to preserve the anonymity of respondents.

	Subregion: This Analysis (IPCC AR6)						
	Caribbean (CAR)	Central(NCA SCA)	Eastern(NSA NES SES)	Western(NWS SWS)	**Total (exc. SAM SSA)**	Not included(SAM SSA)	***Total* (inc. SAM SSA)**
Total individual responses							
Small	6	3	4	2	15	0	15
Medium	7	1	2	4	14	0	14
Large	0	0	3	3	6	0	6
Total	13	4	9	9	35	0	35
Airports represented in effects and impacts section							
Small	6	22	4	6	38	0	38
Medium	5	1	2	4	12	0	12
Large	0	0	2	2	4	0	4
Total	11	23	8	12	54	0	54
Airports/groups represented in risk assessment and adaptation planning section							
Small	6	3	4	2	15	0	15
Medium	4	1	2	3	10	0	10
Large	0	0	2	2	4	0	4
Total	10	4	7	7	28	0	28
ACI-LAC members							
Small	84	60	98	28	270	14	284
Medium	8	6	14	6	34	0	34
Large	1	10	10	4	25	0	25
Total	93	76	122	38	329	0	343

For each of the identified climate effects, respondents were first asked whether they were already experiencing the effect or expected to experience it in the future. For those effects that had been (or were expected to be) experienced, respondents were asked a following question on which of the associated identified impacts had been (or were expected to be) experienced. Respondents were also invited to provide their own examples of experienced or expected impacts. After completing the second section, respondents were given the option to exit the survey, pause and continue later, or proceed to the third section. This section covered action the airport had already taken (or expected to take) on climate change risk assessment and adaptation planning, the perceived level of preparedness of the airport to cope with the impacts of climate change, and the information needs and barriers or challenges experienced (or expected) when carrying out a risk assessment and developing an adaptation plan.

The questionnaire was available in both English and Spanish between November 2022 and March 2023 and was disseminated by the Airport Council International Latin America and Caribbean (ACI-LAC), the regional office of ACI-World, the global professional association of airport operators. The invitation to participate was distributed to the members of the ACI-LAC Environment Working Group. At the time of the survey, ACI-LAC represented 86 members, operating more than 340 airports in 41 countries and territories, and handling 95 % of commercial air traffic in the region (ACI-LAC, n.d.).

Survey responses in Spanish were translated into English before analysis. Quantitative data were analysed using Excel. Qualitative data were used to enrich the quantitative findings, highlighting key issues. Finally, a desktop review of the National Adaptation Plans, and other relevant legislation, of survey respondent states was performed to identify whether there were any national adaptation mandates for the respondent states' aviation sectors.

2.2. Response rate and respondent profile

Thirty-five airport professionals from 32 airports and airport groups responded to the survey, collectively representing 54 airports or around 16 % of ACI-LAC member airports. All respondents completed the section on climate change effects and impacts, and thirty respondents from 28 airports answered the section on climate change risk assessment and adaptation planning. This response rate compares favourably with four global aviation sector surveys which received 7–18 individual responses attributable to the LAC region

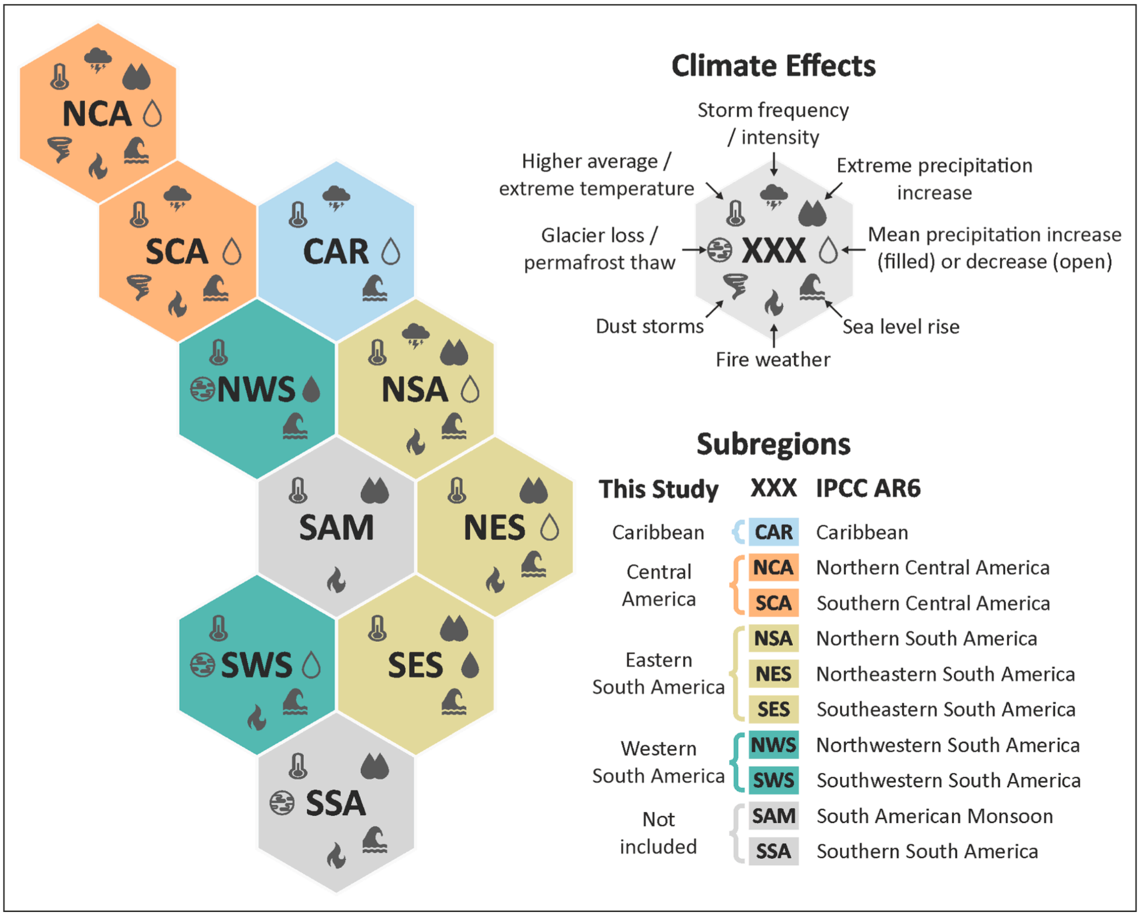

Fig. 2. key climate change effects for IPCC LAC subregions (Based on information provided in IPCC, 2021a, Chapter 12; IPCC, 2021b; IPCC, 2021c; IPCC, 2021d).

(ICAO; 2020; WMO, 2020; ACI-WORLD; 2021; CDRI, 2023).

A breakdown of responses and a comparison to ACI-LAC membership (ACI-LAC Secretariat, personal communication, September 3, 2023) is presented in Table 1, categorised by airport size (based on passengers per annum (ppa)) and LAC subregion. With respect to size, the majority of respondent airports were in the small (under 2 million ppa) or medium (2 to 5 million ppa) categories, with just four respondents in the large category (more than 5 million ppa). This distribution broadly reflects ACI-LAC membership, with the majority of airports in the small category. With respect to location, the largest number of responses were from the Caribbean (CAR), the IPCC AR6 subregion where the greatest number of ACI-LAC members are located. While the majority of the Latin America IPCC AR6 subregions were represented, no responses were received from the South American Monsoon (SAM) and Southern South America (SSA) subregions, thus the following results and analysis exclude these areas. To preserve respondent anonymity, the Latin America IPCC AR6 subregions were grouped into three larger geographical subregions for analytical purposes: Central America, Eastern South America, and Western South America (see Table 1 and Fig. 2).

3. Climate change effects and impacts for LAC airports

This section presents the climate change effects and impacts identified in the literature and incorporated into the survey. Following this, the survey respondents' perceptions of these effects and impacts is considered at both regional and subregional level, mapping the expected progression in effects being experienced out to 2050 and identifying the key impacts facing LAC airports.

Table 2
Climate change effects and impacts identified in the literature. Paper Key: A: Blackwell et al., 2009; B: Borsky & Unterberger, 2019; C: Budd & Ryley, 2012; D: Burbidge, 2016; E: Burbidge, 2018; F: Burbidge et al., 2011; G: Burbidge et al., 2023; H: Coffel, & Horton, 2015; I: Coffel et al., 2017; J: Dimitriou, 2016; K: Dolman & Vorage, 2020; L: Fisk et al., 2019; M: Gratton et al., 2020; N: Gultepe et al., 2019; O: He et al., 2019; P: ICAO, 2020; Q: Kaewunruen et al., 2021; R: Leung et al., 2020; S: Lindbergh et al., 2022a; T: Lopez, 2016; U: Monioudi et al., 2018; V: Najafi et al., 2021; W: Pejovic et al, 2009a; X: Pejovic et al., 2009b; Y: Pümpel, 2016; Z: Qian et al., 2020; AA: Thacker, et al., 2018; AB: Thompson, 2016; AC: Vogiatzis et al., 2021; AD: Yair, 2018; AE: Yesudian & Dawson, 2021; AF: Zhang & Najafi, 2020; AG: Zhou & Chen, 2020; AH: Zhou et al., 2018.

Climate Effects	Impacts
Higher average & extreme temperatures	An increase in cooling demand for infrastructure [Z,AC]
	Heat damage to infrastructure e.g. pavement melting [D,T]
	Increase in fire risk at airport e.g. from fuel [C]
	Health impacts (heat stress) for employees and passengers [Z,AC]
	Increased risk of wildfires [T,AC]
	Impacts to aircraft take-off performance [H,I,M,AH]
	Disruption to ground transport due to overheating [D,AC]
Increased frequency / intensity of precipitation	Flooding of infrastructure such as airport terminals and runways [E,G,T,AA]
	Disruption to operations (delays, diversions, cancellations) [B,C,E,G,K,AB]
	Flooding of ground transport [G,T]
Increased frequency / intensity of storms	Damage to infrastructure such as airport terminals [D,G,Y]
	Flooding of infrastructure from heavy precipitation or storm surge [L,V,AF]
	Disruption to operations (delays, diversions, cancellations) [B,C,X,AG]
	An increase in lightning strikes [O,AD]
Sea level rise	Temporary flooding of infrastructure such as airport terminals and runways [D,L,S,AE]
	Permanent flooding of infrastructure such as airport terminals and runways [D,L,S,AE]
	Disruption to operations (delays, diversions, cancellations) [E,AB]
	Flooding of ground transport [D]
Changes in wildlife patterns and vegetation	Changes in wildlife migration patterns [G,P]
	An increase in bird strikes [A,E]
	Changes to vegetation [P]
Changes to wind patterns	Wind damage to infrastructure [U]
	Disruption to operations due to strong winds (delays, diversions, cancellations) [W]
	Deviations from prevailing wind and/or an increase in crosswinds direction [D]
Decreased frequency / intensity of precipitation	Water shortages and restrictions [E,G]
	Damage to infrastructure due to shrinking of clay [G,T]
Changes to fog patterns / occurrence	A decrease in fog occurrence reducing operational impacts (visibility, delays, cancellations) [R,AC]
	An increase in fog occurrence impacting operations (visibility, delays, cancellations) [R,X]
Desertification	An increase in dust or sand storms impacting operations (visibility, delays, cancellations) [N,Y]
	Increase in dust or sand storms damaging aircraft on stands [P,Y]
	Encroachment of desert sand on airport [E,P]
	Sand erosion of runway and apron [E,P]
Changes to icing occurrence	An increase in de-icing requirements [C,F]
	A decrease in de-icing requirements [C,F]
Business and economic effects	Climate-change driven changes in traffic/tourism demand [E,J]
	An increase in operating costs [G,AB]
	An increase in insurance premiums [G,Q]

3.1. Identified climate change effects and impacts

Observed and projected climate change effects, and thus the resulting impacts for airports, vary across the LAC region. A summary of the key climate change effects identified in AR6 for the 10 IPCC LAC subregions is presented in Fig. 2. The three letter subregional codes (used hereafter), and the larger geographic subregions used in this analysis are also shown. A more extended synopsis of climate effects at subregional level is provided in Appendix B, and the small number of industry and academic studies either focusing on or providing data or information pertaining to LAC airports are briefly summarised below.

The responses to the four global aviation sector surveys (ICAO; 2020; WMO, 2020; ACI-WORLD; 2021; CDRI, 2023) attributable to the LAC region were extracted and are summarised in Appendix C. Although the scope and focus of these industry surveys varied, all identified the impacts of climate change as a growing concern for aviation stakeholders around the globe. However, responses attributable to LAC airports were somewhat limited and only high-level information was available.

An impact assessment of potential vulnerabilities to climate change for four international airports in CAR (specifically, Jamaica and Saint Lucia) identified an increase in disruption and costs due to SLR and higher temperatures if effective adaptation measures were not implemented (Monioudi et al., 2018). Two studies specifically assessed risks for Hewanorra International Airport in St Lucia, identifying it as at risk of flooding from storm surges, high waves and heavy rainfall, with impacts projected to intensify under climate change (Zhang & Najafi, 2020; Najafi et al., 2021). The airport is critical transportation infrastructure, essential to St Lucia's connectivity and economy (Zhang & Najafi, 2020), and due to this criticality, it was deemed essential to model and map potential risks and for flood mitigation plans for the island to prioritize the airport (Najafi et al., 2021).

In Puerto Rico, which has 11 airports within 1 km of the coast, Hurricane Maria in 2017 led to airport closures due to power and communications failures and damage to control towers. When limited traffic resumed it was to bring supplies and aid workers, with commercial flights suspended for weeks (Pagán-Trinidad et al, 2019). It took approximately one year and cost $80 M to return the airport to full capacity (EFE, 2019, as cited in Yesudian & Dawson, 2021). Capacity building to develop resilience was identified as a requirement to limit future impacts (Pagán-Trinidad et al, 2019).

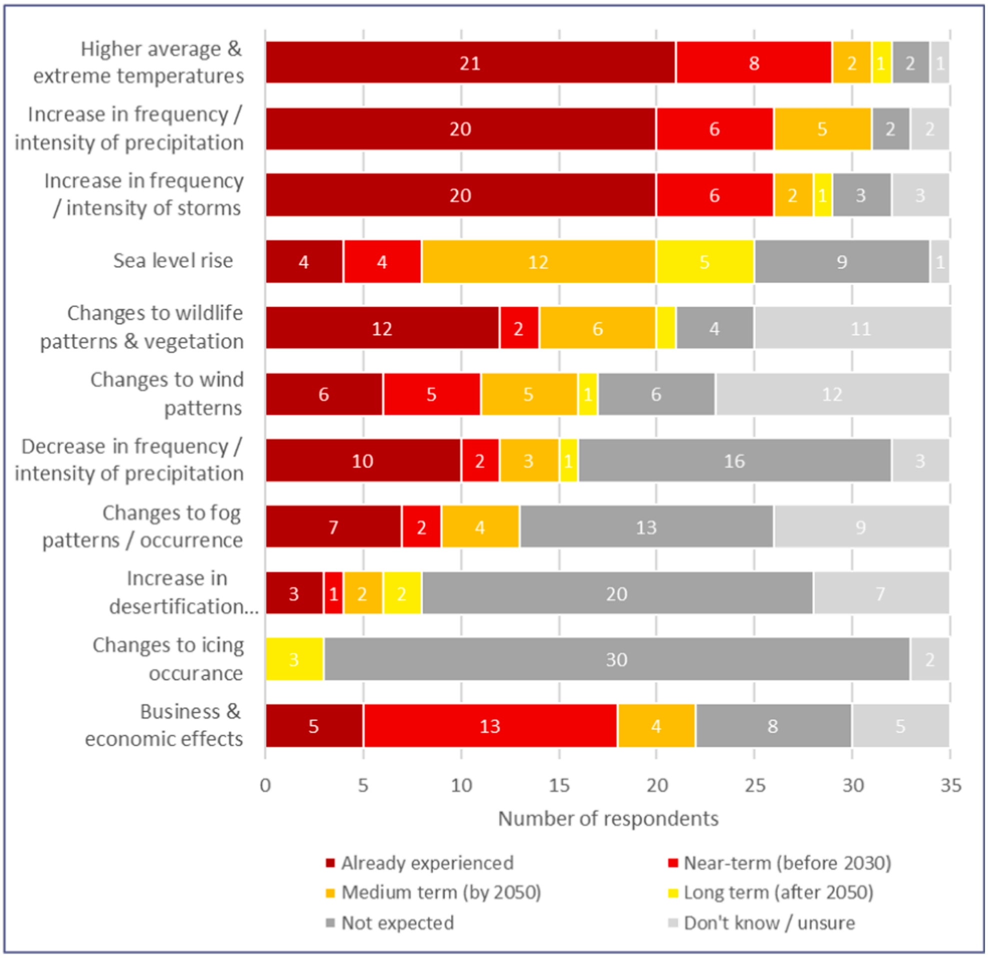

Fig. 3. Climate change effects which respondents had already experienced or expected to experience in the future.

A global analysis identified that the SLR associated with a global mean temperature rise of 2 °C would place 100 airports below mean sea level (Yesudian & Dawson, 2021). Although a large number of those airports are in Europe, North America, Oceania, and Southeast and East Asia, 18 airports in the Caribbean and 26 airports in Central and South America were identified as at risk in a high emissions scenario (RCP8.5) corresponding to warming of 4 °C or more by 2100 (Yesudian & Dawson, 2021).

In addition to the above LAC specific findings, the wider non-LAC specific literature (ICAO (2020), Burbidge et al., (2023) and references therein) was also reviewed with reference to the projected changes in climate to identify other effects and impacts of potential relevance to the LAC region. Overall, 11 climate effects (10 physical climate effects plus economic and business effects) and 37 corresponding impacts were identified and incorporated in the questionnaire (Table 2).

3.2. Climate change effects experienced or expected by LAC airports

In line with IPCC projections for LAC, almost all respondents were already facing or anticipating higher average and extreme temperatures (Fig. 3). The two respondents that did not expect an increase were both in CAR where temperatures are forecast to increase, but by less than the global mean (IPCC, 2021a). The majority of respondents also expected that they would need to prepare for an increase in frequency and/or intensity of both precipitation and storms in the immediate future. For precipitation, this broadly aligns with projections for an increase in mean and/or extreme precipitation in most regions. For storms, projections were more

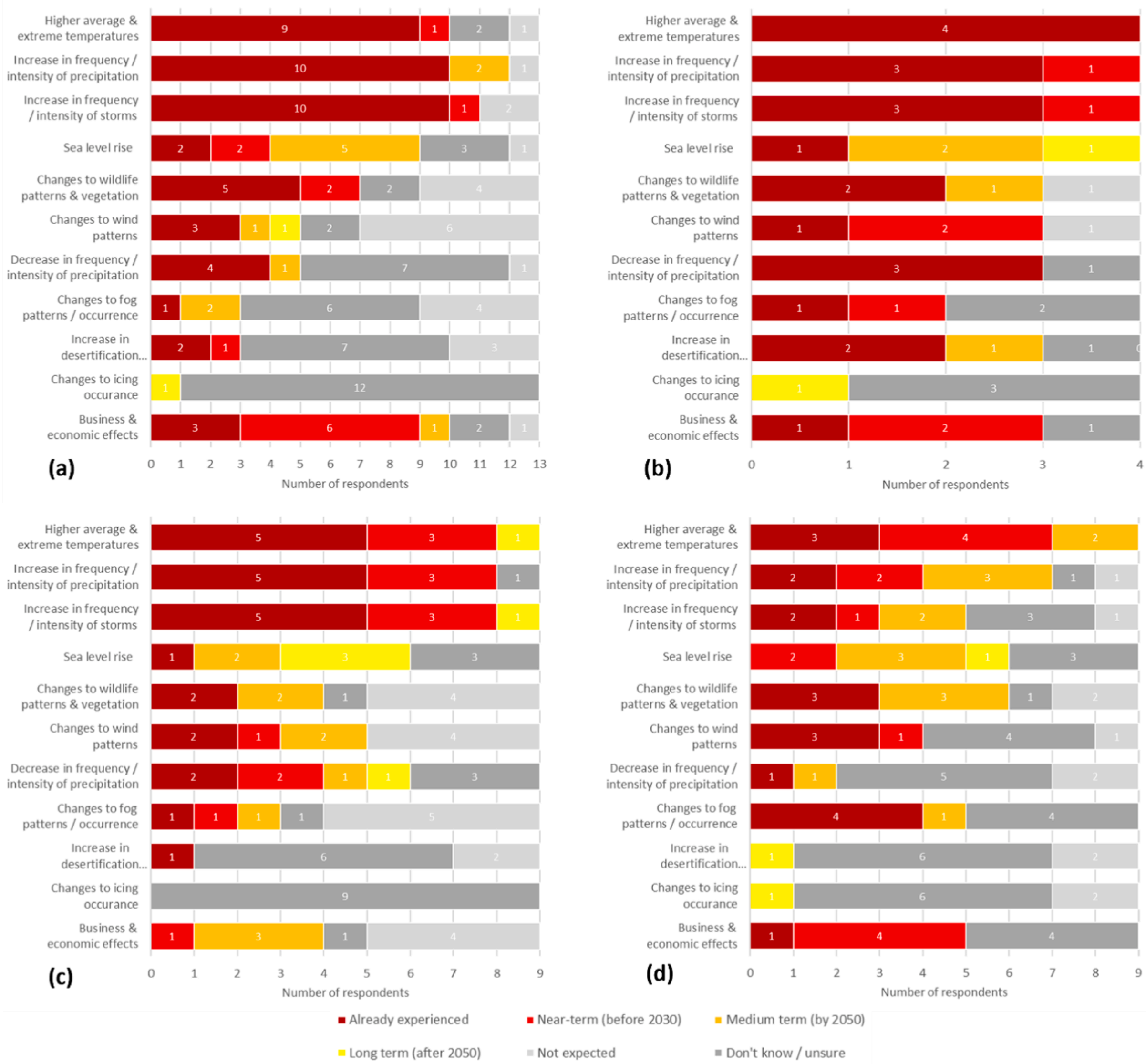

Fig. 4. Regional overview of climate change effects which respondents had already experienced or expected to experience in the future (a) Caribbean; (b) Central America; (c) Eastern South America; (d) Western South America.

geographically specific as reflected in the breakdown of subregional responses below (Fig. 4).

Fewer respondents were expecting to experience changes to wildlife, wind or fog patterns, or an increase in desertification and dust storms. This likely reflects a combination of greater uncertainties (these are the effects with the largest number of "don't know" responses) or that they are more geographically specific, thus a concern for fewer airports.

Sea-level rise will mainly affect low-lying coastal airports. Although the impacts can be significant, the timeframe is longer. Fifteen of the survey respondent airports were located in the low elevation coastal zone (LECZ), a contiguous area along the coastline of less than 10 m above sea level (Yesudian & Dawson, 2021), with most expecting to experience SLR in the medium to longer term.

The majority of respondents reported that they are not yet experiencing business and economic effects. Although not currently a major issue, this was expected to become more significant in the near future, with around half of respondents expecting to experience these effects by 2030.

The only effect that respondents were not yet experiencing, and did not expect to experience before 2050, was changes to icing occurrence.

At subregional level some differences do emerge (Fig. 4). In Central America, Eastern South America, and the Caribbean, the most experienced or anticipated effects reported were higher temperatures, storms and increased precipitation, albeit in different rank orders. In the Caribbean, storms and increased precipitation were already being experienced by around two thirds of respondents, potentially reflecting recent experiences of major hurricanes and the observed increase in heavy precipitation events. Here and Central America, two regions heavily dependent on tourism, were the subregions where business and economic effects were of the most concern. Also in Central America, three out of four respondents reported both an increase and decrease in frequency and/or intensity of precipitation. Respondents' comments indicated this to be an overall decrease but with an increase in extreme precipitation events as well as seasonal changes in rainfall, in line with precipitation projections for the region (IPCC, 2021a). Of note, the one respondent from NES, an IPCC subregion highly susceptible to desertification, did not expect to experience this effect.

In Western South America four respondents were already experiencing changes in fog occurrence (all in NWS). However higher temperatures were the main near-term concern. In general, fewer effects were already being experienced or were anticipated in the near future in this subregion.

3.3. Expected progression in climate effects experienced by LAC airports over time

There was a clear progression in both the number of respondents experiencing or expecting to experience (any number of) climate effects and in the number of effects expected (Fig. 5). While 20 % had not yet experienced any effects at the time of the survey, only 3 % were not expecting to have experienced any effects by 2030, and all airports expected to experience at least one effect by 2050. The median number of effects currently being experienced was three, rising to an expected five in 2030 and six in 2050.

The clear progression in the number of effects respondents expected to experience over time was seen across all subregions, although some differences did emerge (Fig. 6). Of note, in Central America all respondents were already experiencing at least four effects, with a current median of 4.5 effects rising to eight by 2050. However, in Western South America a third of respondents were not yet experiencing any effects and the median number of effects was two, rising to five by 2050.

3.4. Climate change impacts experienced or expected by LAC airports

This section examines the impacts which respondents were already experiencing or expected to experience. Fig. 7 presents climate

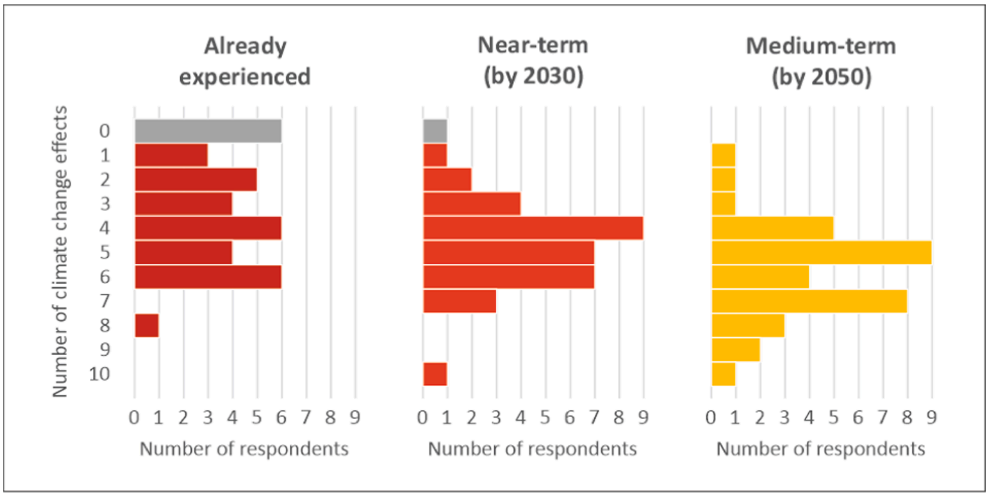

Fig. 5. Number of climate change effects which respondents had already experienced or expected to experience in the near to medium term future. The maximum number of effects reached is 10 as changes in icing occurrence were not expected before 2050 (n = 35).

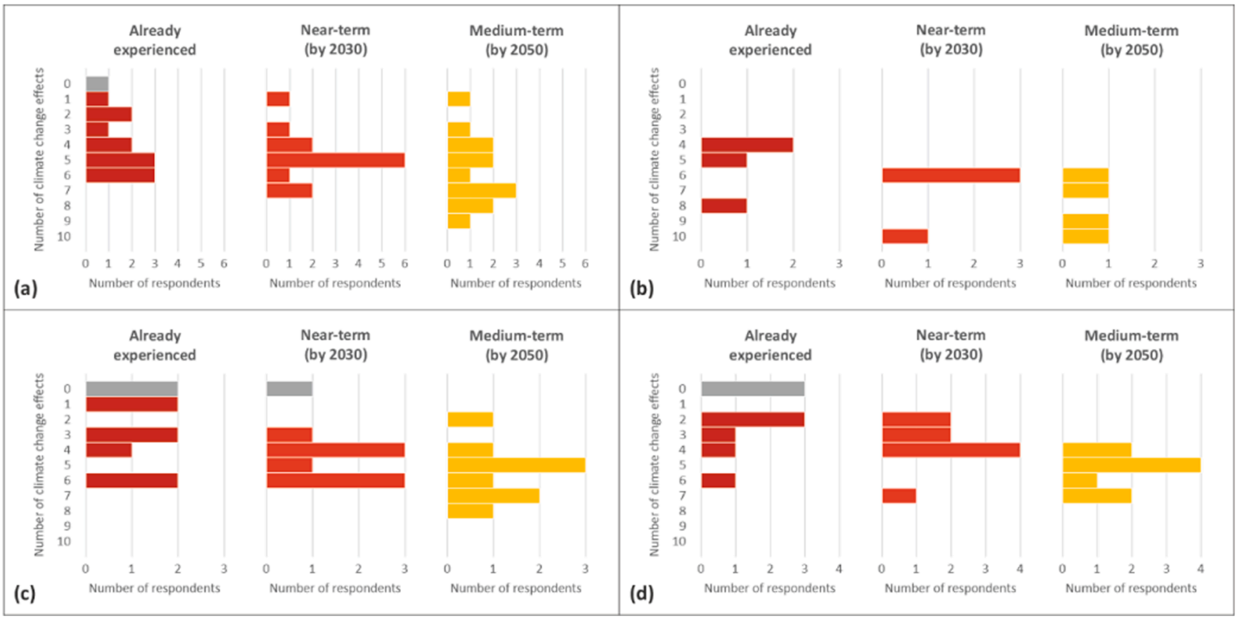

Fig. 6. Number of climate change effects which regional respondents had already experienced or expected to experience in the near to medium term future (a) Caribbean (n = 13); (b) Central America (n = 4); (c) Eastern South America (n = 9); (d) Western South America *(n = 9)*.

effects and associated impacts in rank order by number of responses and the immediacy with which they were (expected to be) experienced, based first on the effect and then the impact. Impacts were also ranked across all effects based on the number of respondents currently experiencing them ('now') and the number who expected to experience them in the future, where this provides a first order indication of relative order of concern.

As might be expected, the impacts with the highest ranking were associated with the effects being most widely experienced. For example, the majority of respondents were already experiencing an increase in cooling demand for infrastructure, in line with the reported increase in temperatures. One respondent highlighted that incoming passengers from cooler climates have an unpleasant experience waiting outside the airport terminal for transportation in high temperatures, while another respondent noted that the hot season used to end a month earlier.

Operational disruption due to storms and precipitation was already widely experienced. Two respondents noted that an increase in lightning occurrence was impacting operational efficiencies as ground handling and refuelling cannot take place during lightning activity. An increase in precipitation was also identified as attracting more birds to the airport, increasing the risk of bird strikes. A number of respondents noted seasonal changes such as storms out of season or atypical rainfall and a longer rainy season, which in turn has potential impacts on tourism and operations. Conversely, one respondent noted that due to lack of availability of water, particularly during dry periods, the airport was forced to use treated groundwater for many activities, and that this lack of water availability is expected to worsen in the future. From a business and economics perspective, one airport noted that they were already experiencing the impact of higher temperatures and decreased rainfall on operating costs, whilst a respondent from CAR noted that SLR has already reduced beach area which is impacting tourism numbers.

As climate effects increase over time, the relative ranking of impacts changes. For example, heat stress for passengers and employees moves from twenty-fifth in rank order to fourth. Moreover, as business and economic effects become more widely experienced there is a marked shift in ranking of the associated impacts, with an increase in operating costs moving to fifth and an increase in insurance costs to sixth. Nevertheless, the main impacts of concern continue to be related to the effects of temperature, storms and precipitation.

Of note is the uncertainty level for some impacts. For example, the two impacts with the highest number of airports either responding don't know or not answering were temperature impacts to take-off performance (10/30) and an increase in lightning strikes (8/27), both of which have potentially significant operational impacts. Conversely, for impacts such as an increase in cooling demand due to higher temperatures or a business and economics-related increase in insurance premiums, uncertainty levels are zero.

4. LAC airport engagement with climate risk assessment and adaptation planning

Airports were asked about climate risk assessment, adaptation planning and their self-assessed level of preparedness for the impacts of climate change. Results are presented in a Sankey Diagram (Fig. 8) showing the relationship between risk assessment and adaptation plan status and perceived level of preparedness. To understand to what extent the respondents expected their airport to be exposed to climate change effects, and how this may have influenced their propensity to carry out a risk assessment, the number of climate effects which they were already experiencing or expected to experience was also considered.

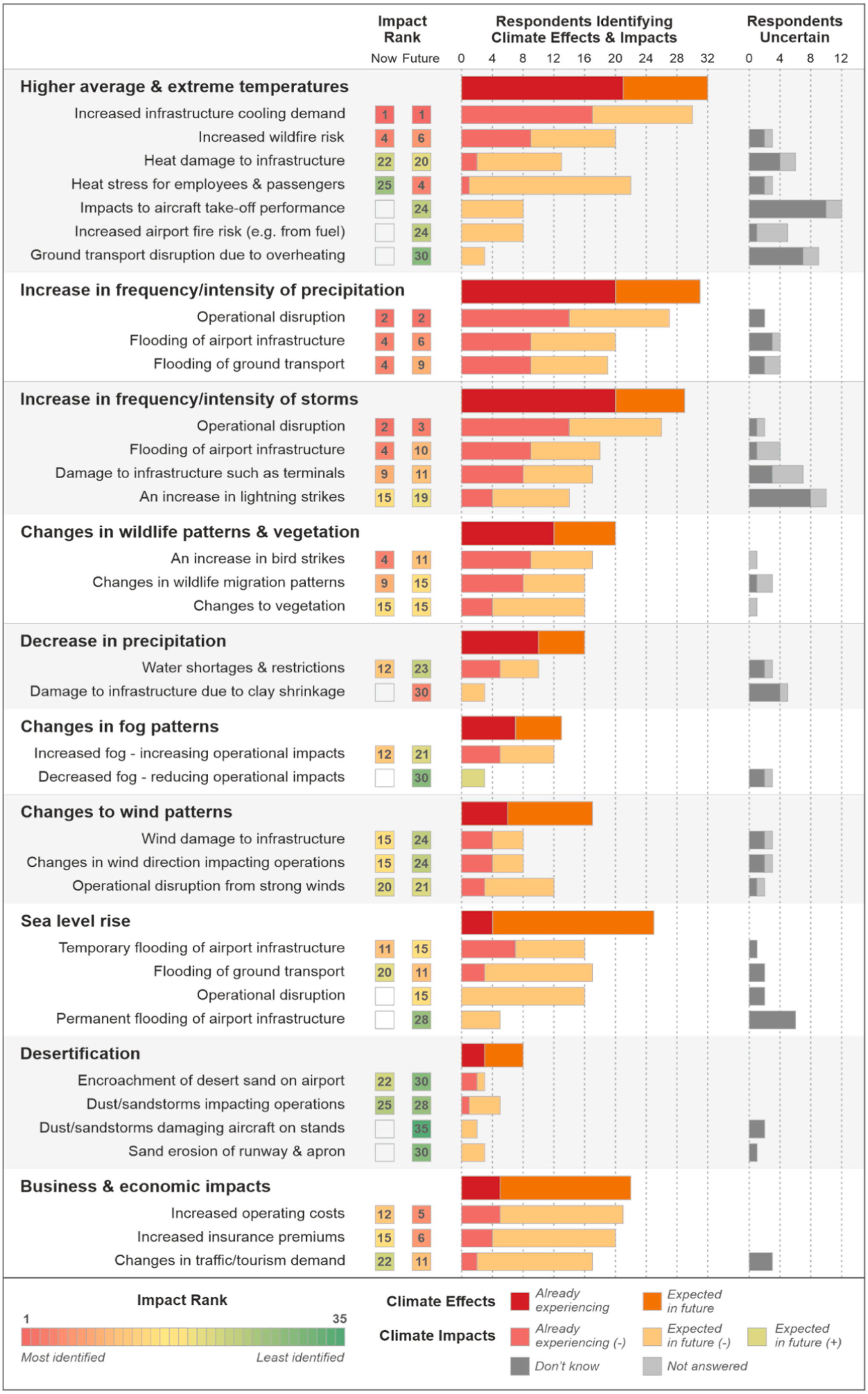

Fig. 7. Climate change impacts which respondents have already experienced or expect to experience in the future (n = 35).

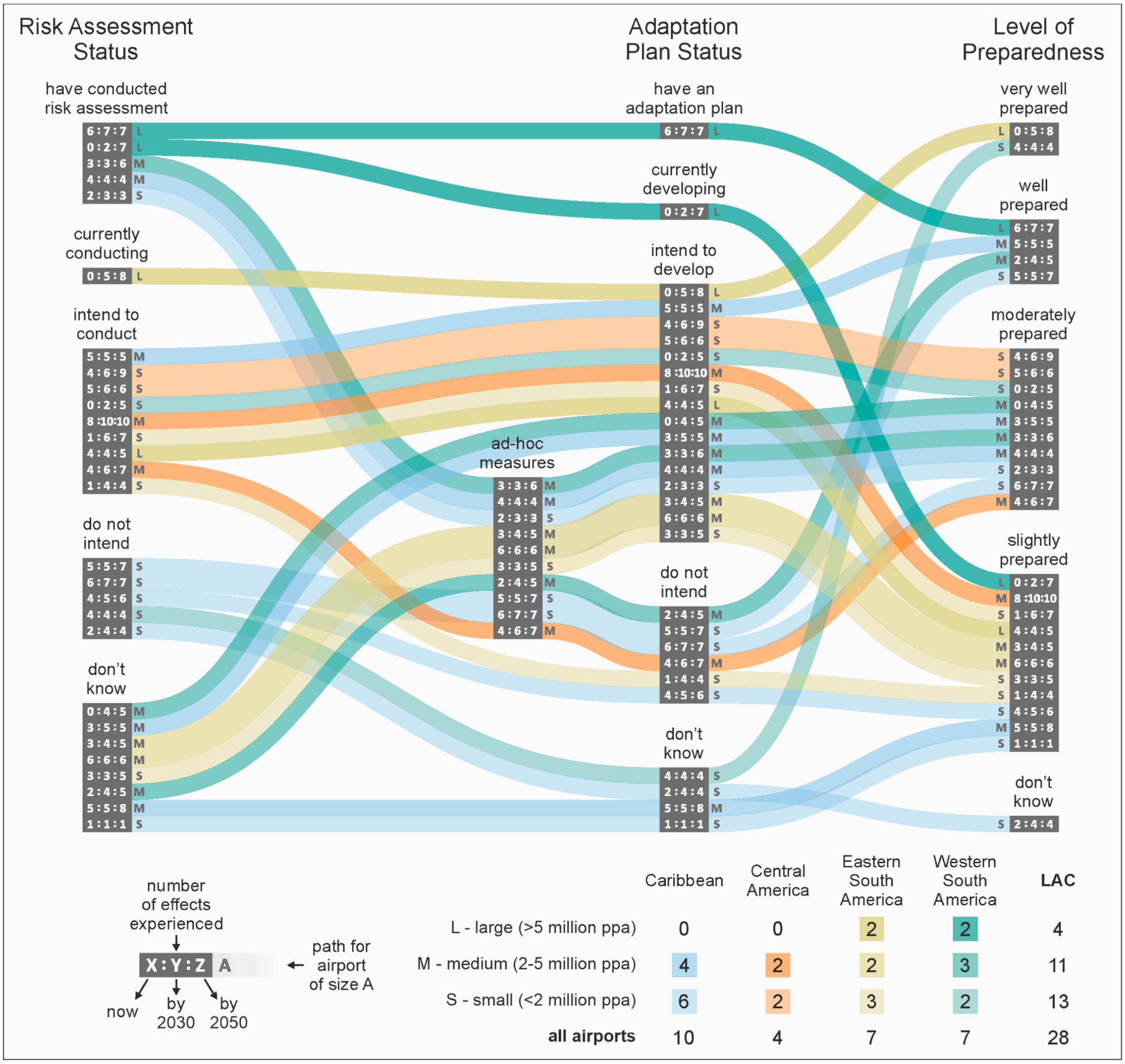

Fig. 8. Respondents risk assessment and adaptation status and assessed level of preparedness.

Of the 28 airports or airport groups that completed the risk assessment and adaptation section of the survey, just over half (54 %) had engaged with the climate risk assessment process. However, no clear patterns emerged between the number of effects that were being experienced or were anticipated in the future, their risk assessment and adaptation plan status, or their self-assessed level of preparedness. It is noted that the respondent already experiencing eight effects was an airport group and thus considering effects for more than one location.

The four large airports had all engaged with the risk assessment process, although at different stages. However, just one had implemented a climate adaptation plan, and one was in the process at the time of the survey. Of these, one was a large hub airport with comparatively significant resources committed to sustainability and the other was an important regional airport with a dedicated sustainability resource. Nevertheless, despite the general engagement of the large airports, the assessment of preparedness levels varied from slightly to very well-prepared, likely based on a combination of factors such as effects already experienced and expected, and progress with the risk assessment and adaptation plan process.

For medium and small airports there was more variation in both risk assessment and adaptation status. Of the three airports that had completed a risk assessment, one small airport stated that they had government support and funding from an international organisation. None had yet begun the adaptation plan process, although ten airports had implemented ad-hoc adaptation measures, of which six intended to develop an adaptation plan in the future. Ad-hoc measures being implemented included improved drainage for, or elevation of, areas at risk of flooding, shoreline protection along coastal perimeters, upgrading of air conditioning systems and the establishment of emergency plans and risk management committees. Of the airports that had implemented ad-hoc measures, the three that had completed a risk assessment and intended to develop an adaptation plan considered themselves moderately prepared, whereas, with one exception, those that intended to develop a plan but did not know whether a risk assessment has been completed only considered themselves slightly prepared. One airport had implemented ad-hoc measures and did not intend to develop a plan, but considered themselves well-prepared. Seven small and medium airports that had not implemented ad-hoc measures did intend to implement an adaptation plan, although none had yet performed a risk assessment. All seven considered themselves slightly or moderately prepared.

Of the airports that did not have and did not intend to carry out a climate risk assessment and/or adaptation plan, no existing requirement, mandate or obligation was cited as the main reason, although resources and expertise were also concerns. A review of the 18 survey respondent countries' National Adaptation Plans, and other relevant legislation, identified that, at the time of the survey, just one had legislation in place mandating its airports to take action, although one other is understood to have been implementing a national level requirement for the 2024–2025 period. One airport clarified that although no specific climate change risk assessment was planned, all risks were regularly looked at as part of the airport's overall risk management programme, although it is not known to what depth climate change risks are considered within this. For this group, assessed level of preparedness showed higher variability. However, those airports that had implemented ad-hoc measures considered themselves at least moderately prepared. Perhaps a little surprisingly, one airport that did not intend to carry out a risk assessment and did not know if they will implement an adaptation plan considered themselves very well-prepared.

Airports that had conducted or intended to conduct a climate risk assessment cited lack of guidance, information and data as the main challenges faced or anticipated. Lack of data on historical weather events and climate projections at a sufficient level of granularity were identified. With respect to guidance needs, airports highlighted the need for methodologies, completed risk assessments as exemplars, case studies and examples of good practices. Financial and human resources were the second and third biggest challenges identified. The prioritisation of other factors over climate change risk analysis and lack of top management commitment were also cited. The only airport that responded that they had not faced any challenges noted that their risk assessment was carried out as a government initiative with funding from an overseas aid agency.

Similarly, for airports that were not currently planning a risk assessment, climate data, risk assessment guidance and methodologies, examples and case studies were identified as the support which would be most valuable if they were to proceed with an assessment.

5. Enhancing airport engagement in building climate resilience

This first evaluation of how LAC airport professionals perceive that climate change has and will impact airports across the region has demonstrated that climate change effects are already widely experienced and are expected to increase significantly in the short to medium term. This clearly highlights an urgent and increasing need to adapt. However, to date, action in the sector is lagging, as evidenced by only five survey respondents having carried out a risk assessment and only one having developed an adaptation plan. That almost half of respondents either do not know if a risk assessment is planned or do not intend to conduct one, indicates both uncertainties as to what the process entails and a lack of awareness of the threat that climate change poses. This significant mismatch between exposure and action must be addressed. While responsibility to build climate resilience ultimately rests with airports themselves, this study has identified a number of barriers that are limiting or preventing engagement with the risk assessment and adaptation process. Building on the findings presented above, this section takes a deeper look at the challenges and opportunities identified, examining potential barriers and how to address them, and highlighting positive measures. Whilst this discussion focuses on the LAC region the findings are also of direct relevance to the wider airport sector.

Lack of information, data and guidance were identified by respondents as key barriers when engaging with the risk assessment and adaptation process. This applied to all steps of the process from understanding how the climate will change to identifying appropriate adaptation responses.

Respondents' concerns echoed the observations of the IPCC (2022) that, in particular for the Caribbean, the generation of climate projections at local-to-regional scale is hindered by the unavailability of climate baseline data. Therefore, it is crucial to work with regionally based meteorological organisations and climate scientists to expand both historical datasets and future climate projections so as to inform assessments. One enabler to expanding data availability would be for sector organisations and national governments to engage with academia and other research bodies to identify knowledge gaps in the LAC region and promote regionally focused research on climate change effects, impacts and adaptation measures (Burbidge et al., 2023). However, notwithstanding the need for detailed climate projections, there is a clear necessity to better disseminate existing information and provide further guidance.

Survey responses identified several areas of uncertainty regarding whether or when an effect might be experienced or whether it would cause a specific impact, even for those effects and impacts widely discussed in the literature. Therefore, to enable airports to better understand the potential challenges they may face it is crucial to raise awareness of possible effects and impacts by providing information to address these uncertainties. This demonstrates a need to translate disparate sources such as IPCC reports and scientific research into synthesised and accessible sources of information. Overviews of climate effects and impacts for airports do exist at a generic level (Burbidge et al., 2023; ICAO, 2020). However, there would be value in expanding on this by developing more detailed regionally focused information on potential impacts and how they can be addressed.

The risk assessment and adaptation plan process may be led internally by airport personnel, by a third party such as a consultancy or aid agency, or a combination of the two. Whatever the approach, developing and maintaining in-house capacity is essential to facilitate understanding of and engagement with the process, and for managing future risks. Therefore, when a risk assessment is carried out by external parties it is essential for airport personnel to be involved to ensure that the outputs of the process are understood, valued and used. This both enhances internal capacity and ensures that knowledge and expertise is maintained and disseminated across the organisation. Similarly, when personnel change, processes need to be in place to ensure that knowledge and capacity is embedded and retained in the organisation.

There is also an important role for airport personnel not directly involved in the assessment. Much has been written in the literature and industry reports about the various climate impacts which airports might be at risk from, and which should therefore be considered in risk assessments (c.f. Burbidge et al., 2023; ICAO, 2020). However, survey respondents identified a number of impacts that had not, to date, been identified in the literature. For example, one respondent noted that an increase in rain has attracted more birds to the airport, increasing the risk of bird strikes, whilst a number of respondents noted that atypical rainfall and/or a longer rainy season were becoming a challenge with potential impacts on both operations and tourism. Such observations are invaluable to uncover specific local impacts, where this anecdotal evidence acts as a forerunner to formal assessment of future risks. This emphasises the importance of engaging with in-house experts, local monitoring of effects and impacts, and the need to share observations regionally, so as to develop knowledge and understanding of how local–regional climate changes are impacting airports.

Sufficient guidance is essential for carrying out an effective assessment. Some broad industry guidance is available. For example, ACI World (2018) have released a Policy Paper providing high-level guidance, whilst ICAO (2022) have produced step-by-step guidance on risk assessment and adaptation planning. However, this is intentionally generic as it is intended for use by aviation organisations around the globe. Therefore, there may be value in the development of more detailed, regionally focused, airport-specific guidance, and in languages other than English. Survey respondents also called for risk assessment examples and case studies from similar airports in the region to act as exemplars, as well as knowledge and capacity building, for example through workshops. This suggests that provision of seminars, forums and training may be of benefit. Here, there is a role for both industry bodies and government partnerships with NGOs and intergovernmental organisations.

Lack of a mandatory requirement was identified by some airports as a reason they had not engaged with the risk assessment and adaptation process. Although many airports do initiate risk assessments without a mandatory requirement, legislation can provide the impetus to act. For example, in the United Kingdom the Climate Change Act (2008) mandated the ten busiest airports to carry out a climate change risk assessment and develop an adaptation plan. The one LAC airport respondent that had completed both a risk assessment and adaptation plan was located in the only respondent country to have applicable legislation in place at the time of the survey.

In a differing approach, the adaptation process is stimulated by enabling the critical first step of carrying out a risk assessment. For example, in France there was no legislative requirement (at the time of writing) for airports to carry out a risk assessment. However, the French Directorate General of Civil Aviation has produced the Vulclim tool to support airports with climate risk assessment (DGAC-STAC, 2022). Similarly, in the United States the national Airport Cooperative Research Programme has produced the ACROS tool to support US airports with climate risk assessment (ACRP, 2014). In LAC, the Jamaica Systemic Risk Assessment Tool (J-SRAT) is under development by Oxford University in collaboration with the Jamaican Government and with support from the Coalition for Climate Resilient Investment (CCRI) and the UK's Foreign Commonwealth and Development Office (CCRI, 2022). Once validated the tool will be deployed to assess and track transportation infrastructure exposure and susceptibility to climate hazards (Government of Jamaica, 2022). The potential is there to develop it for airports throughout the region, demonstrating the benefit of such partnerships, combined investment, and government support.

These two approaches are thus different, with one implementing a mandatory requirement but not necessarily addressing the skills, expertise, knowledge, or resources gap needed to meet that requirement, and the other providing tools as enablers rather than mandating. It is not yet possible to compare the effectiveness of the two approaches as the number of French and US airports that have carried out risk assessments is not available. However, whilst there may be hesitancy to mandate an action which airports may not have the expertise or resources to fulfil, providing regionally focused tools and support appears to be a win–win to achieving resilience, noting of course that the skills and resources to develop and use the tools themselves would need to be identified.

When implementing an adaptation plan it is important to take an integrated approach to adaptation and mitigation (IPCC, 2022). Some decarbonisation measures such as increasing energy efficiency can contribute to adaptation and resilience. Conversely, failing to consider resilience when implementing decarbonisation measures can increase vulnerabilities (IPCC, 2022). For example, an ICAO partnership with Sangster and Norman Manley airports in Jamaica to install photovoltaic panels originally envisaged designing them to be resilient to a Category 3 hurricane. However, following Hurricanes Irma and Maria, both Category 5, the specification was upgraded, and the panels are now designed to withstand a Category 5 hurricane (ICAO, 2019). A number of adaptation actions identified by respondents did represent integrated adaptation and mitigation. Specifically, around half of the airports were implementing energy security or efficiency measures, including transitioning to renewable and self-generated energy-sources such as solar, improvements in cooling systems to render them more effective and energy efficient, and measures to reduce and optimise energy consumption such as intelligent building management systems. Decreasing energy demand and increasing self-supply are clear win-wins, both rendering an airport more resilient to disruptions to energy supply from external sources and reducing carbon emissions. This offers a potential route to address the previously identified barrier of competing priorities, when a stronger emphasis is placed on mitigation to the detriment of adaptation. Here, case studies of integrated mitigation-adaptation measures could help to promote action.

Although just one survey respondent had, to date, implemented a full adaptation plan, 10 of the 28 respondents (all small and medium airports) had implemented ad-hoc adaptation measures, including some potentially significant actions to protect or upgrade infrastructure. Implementing ad-hoc measures neither precludes nor replaces developing and implementing an adaptation plan. However, for smaller airports and/or airports with constrained resources it may be more feasible to make the business justification and gain approval for a single ad-hoc adaptation measure that can be more easily demonstrated as critical, such as increasing surface drainage after a flooding incident, rather than the potentially expensive and resource-intensive implementation of a full adaptation plan. This may therefore offer a route to more quickly and efficiently instigating adaptation action where it is most urgently needed. Nevertheless, this should be a short-term option, should always be based on an informed understanding of risks, and some caution is required. For example, two of the airports that had implemented ad-hoc measures had not yet carried out a risk assessment. Whilst such an assessment is not an essential prerequisite in situations where one is not currently possible, or a more rapid response is required, such simplified approaches are not without risk. Not performing an assessment runs the risk of missing potentially significant effects and impacts, whilst decisions taken without the relevant knowledge or expertise risk under- or mal-adaptation. Therefore, as well as the provision of risk assessment tools, there may be value in the development of a simplified step-by-step risk assessment framework for airports to follow, such as a decision-tree, to identify potential impacts. Nevertheless, a thorough climate risk assessment and comprehensive adaptation plan remains the gold standard and provides the greatest certainty of fully identifying and addressing climate-specific risks.

As a more flexible option that could encourage greater engagement with the risk assessment process, airports could consider integrating or mainstreaming climate change risk management into existing airport management practices such as risk management plans (ACRP, 2018). Whilst it is essential to ensure that all climate risks are included and assessed at sufficient depth, this may bring some organisational efficiencies as well as facilitating the periodic reassessment of climate risks as risk management plans are usually reviewed regularly.

As the effects of climate change increase in LAC, airports will have no choice but to adapt so as to protect critical infrastructure and service continuity. To ensure this is done in sufficient time, and following good practices, the key recommendations of this study are to:

1) Enhance awareness raising of climate effects and impacts;
2) Increase provision of data and guidance; and
3) Develop and promote capacity-building mechanisms such as risk assessment tools and training.

These are all clearly essential to support adaptation action by airports, with a crucial role for national governments, sector bodies, intergovernmental organisations and other relevant stakeholders to augment capacity-building in the region, further building on the support already provided and partnerships developed. Such partnerships have already proven successful with, for example, the development of the J-SRAT tool.

However, capacity building alone will not be sufficient and must be supported by a clear policy framework. Ideally, a regional or subregional roadmap would be developed to set out a clear step-by-step framework for airports to engage with the risk assessment and adaptation process alongside targeted information on the benefits of doing so and how to access support. Progression against the roadmap should be monitored, enabling the identification and recognition of progress, and the possibility for additional support to be provided if progress is not being made. If mandates are adopted, it is essential that the necessary support and resources are available.

This paper has presented a novel and valuable evaluation of the adaptation action being taken by LAC airports and the barriers being experienced. However, it is recognised that the survey sample does not provide a comprehensive overview of all LAC subregions, and that there would be additional value in more in-depth, targeted research. Research that holistically addresses the above recommendations would be of particular value, for example combining climate model downscaling with stakeholder engagement to develop user-oriented climate adaptation services could significantly enhance adaptation action.

Nonetheless, this first evaluation of LAC airports' risk assessment and adaptation planning status has identified a significant exposure-adaptation gap. Failure to act risks considerable future impacts for airports. Immediate action is thus essential to promote effective adaption and limit future disruption, damages and costs. The challenges and action areas identified in this paper are not unique to airports in LAC and are applicable to airports in all global regions. Given the interconnectedness of the global aviation network, the more airports that are prepared for the impacts of climate change, the greater the overall level of resilience will be.

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CRediT authorship contribution statement

Rachel Burbidge: Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Conceptualization. **Christopher Paling:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Rachel M. Dunk:** Writing – review & editing, Visualization, Supervision, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declarations

None.

Appendix A. Survey of LAC airport professionals — questionnaire

Section 1**: Information about the airport**
Q5: Approximately how many passengers does your airport serve in one year?
Please select one answer

- Under 2 million passengers per year
- 2 to 5 million passengers per year
- 5 to 15 million passengers per year
- 15 to 25 million passengers per year
- 25 to 40 million passengers per year
- Over 40 million passengers per year

Q6: Approximately how many aircraft movements does your airport handle in one year?
Please select one answer

- Less than 50,000 movements per annum
- 50,000 – 99,999 movements per annum
- 100,000 – 249,999 movements per annum
- 250,000 – 400,000 movements per annum
- More than 400,000 movements per annum

Section 2**: Climate change effects and impacts**
The Latin America and Caribbean region will experience a range of effects from climate change. This section will ask you about eleven climate change effects and their associated impacts. It will take approximately 5–10 min to complete depending on your answers.
Q7: Have you already experienced, or do you expect to experience, **an increase in the frequency and/or intensity of storms**?
Please select one answer

- Already experienced [→Q7b]
- Expected in the near-term (before 2030) [→Q7b]
- Expected in the medium term (by 2050) [→Q7b]
- Expected in the longer term (after 2050) [→Q7b]
- Do not expect to experience [→Q8]
- Don't know / not sure [→Q8]

Q7b [optional]: For an increase in frequency and/or intensity of storms which of the following impacts have you already experienced or do you expect to experience?
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
Damage to infrastructure such as airport terminals	●	●	●	●
Flooding of infrastructure from heavy precipitation or storm surge	●	●	●	●
Disruptions to operations (delays, diversions, cancellations)	●	●	●	●
An increase in lightning strikes	●	●	●	●
Other – please identify any other impacts from an increase in frequency and/or intensity of storms that you have already experienced or expect to experience:				

Q8: Have you already experienced, or do you expect to experience, **higher average and/or extreme temperatures**?
Please select one answer

- Already experienced [→Q8b]
- Expected in the near-term (before 2030) [→Q8b]
- Expected in the medium term (by 2050) [→Q8b]
- Expected in the longer term (after 2050) [→Q8b]
- Do not expect to experience [→Q9]

- Don't know / not sure [→Q9]

Q8b [optional] : For higher average or extreme temperatures which of the following impacts have you already experienced or do you expect to experience?
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
An increase in cooling demand for infrastructure	●	●	●	●
Heat damage to infrastructure – e.g. pavement melting	●	●	●	●
Increase in fire risk at airport – e.g. from fuel	●	●	●	●
Health impacts (heat stress) for employees and passengers	●	●	●	●
Increased risk of wildfire	●	●	●	●
Impacts to aircraft take-off performance	●	●	●	●
Disruptions to ground transport due to overheating	●	●	●	●
Other – please identify any other impacts from higher average and extreme temperatures that you have already experienced or expect to experience:				

Q9: Have you already experienced, or do you expect to experience, **sea level rise**?
Please select one answer

- Already experienced [→Q9b]
- Expected in the near-term (before 2030) [→Q9b]
- Expected in the medium term (by 2050) [→Q9b]
- Expected in the longer term (after 2050) [→Q9b]
- Do not expect to experience [→Q10]
- Don't know / not sure [→Q10]

Q9b [optional] : For sea level rise which of the following impacts have you already experienced or do you expect to experience?
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
Temporary flooding of infrastructure such as airport terminals and runways	●	●	●	●
Permanent flooding of infrastructure such as airport terminals and runways	●	●	●	●
Disruption of operations (delays, diversions, cancellations)	●	●	●	●
Flooding of ground transport	●	●	●	●
Other – please identify any other impacts from sea level rise that you have already experienced or expect to experience:				

Q10: Have you already experienced, or do you expect to experience, an **increase in frequency and/or intensity of precipitation**?
Please select one answer

- Already experienced [→Q10b]
- Expected in the near-term (before 2030) [→Q10b]
- Expected in the medium term (by 2050) [→Q10b]
- Expected in the longer term (after 2050) [→Q10b]
- Do not expect to experience [→Q11]
- Don't know / not sure [→Q11]

Q10b [optional] : For an increase in frequency and/or intensity of precipitation which of the following impacts have you already experienced or do you expect to experience?
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
Temporary of infrastructure such as airport terminals and runways	●	●	●	●
Disruption to operations (delays, cancellations, diversions)	●	●	●	●
Flooding of ground transport	●	●	●	●
Other – please identify any other impacts from an increase in frequency and/or intensity of precipitation that you have already experienced or expect to experience:				

Q11: Have you already experienced, or do you expect to experience, **a decrease in frequency and/or intensity of precipitation**?

Please select one answer

- Already experienced [→Q11b]
- Expected in the near-term (before 2030) [→Q11b]
- Expected in the medium term (by 2050) [→Q11b]
- Expected in the longer term (after 2050) [→Q11b]
- Do not expect to experience [→Q12]
- Don’t know / not sure [→Q12]

Q11b [optional]: For a decrease in frequency and/or intensity of precipitation which of the following impacts have you already experienced or do you expect to experience
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don’t know / not sure
Water shortages and restrictions	●	●	●	●
Damage to infrastructure due to shrinking of clay	●	●	●	●
Other – please identify any other impacts from a decrease in the frequency and/or intensity of precipitation that you have already experienced or expect to experience:				

Q12: Have you already experienced, or do you expect to experience, **changes to wind patterns** (e.g. direction, speed or seasonality)?
Please select one answer

- Already experienced [→Q12b]
- Expected in the near-term (before 2030) [→Q12b]
- Expected in the medium term (by 2050) [→Q12b]
- Expected in the longer term (after 2050) [→Q12b]
- Do not expect to experience [→Q13]
- Don’t know / not sure [→Q13]

Q12b [optional]: For changes to wind patterns which of the following impacts have you already experienced or do you expect to experience?
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don’t know / not sure
Wind damage to infrastructure	●	●	●	●
Disruption to operations due to strong winds (delays, diversions, cancellations)	●	●	●	●
Deviations from prevailing wind directions and/or an increase in crosswinds impacting operations	●	●	●	●
Other – please identify any other impacts from changes to wind patterns that you have already experienced or expect to experience:				

Q13: Have you already experienced, or do you expect to experience, an **increase in desertification and/or dust storms**?
Please select one answer

- Already experienced [→Q13b]
- Expected in the near-term (before 2030) [→Q13b]
- Expected in the medium term (by 2050) [→Q13b]
- Expected in the longer term (after 2050) [→Q13b]
- Not expected / do not expect to experience [→Q14]
- Don’t know / not sure [→Q14]

Q13b [optional]: For an increase in desertification and/or dust storms which of the following impacts have you already experienced or do you expect to experience?
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don’t know / not sure
An increase in dust/sandstorms impacting operations (visibility, delays, cancellations)	●	●	●	●

(*continued on next page*)

(*continued*)

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
Increase in dust/sandstorms damaging aircraft on stands	●	●	●	●
Encroachment of desert sand on airport	●	●	●	●
Sand erosion of runway and apron	●	●	●	●
Other – please identify any other impacts from an increase in desertification and/or dust storms that you have already experienced or expect to experience:				

Q14: Have you already experienced, or do you expect to experience, **changes to fog patterns and/or occurrence** (either an increase or decrease)?

Please select one answer

- Already experienced [→Q14b]
- Expected in the near-term (before 2030) [→Q14b]
- Expected in the medium term (by 2050) [→Q14b]
- Expected in the longer term (after 2050) [→Q14b]
- Do not expect to experience [→Q15]
- Don't know / not sure [→Q15]

Q14b [optional] : For changes to fog patterns and/or occurrence which of the following impacts have you already experienced or do you expect to experience?

Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
An increase in fog occurrence impacts operations (visibility, delays, cancellations)	●	●	●	●
A decrease in fog occurrence reducing operational impacts (visibility, delays, cancellations)	●	●	●	●
Other – please identify any other impacts from changes to fog patterns and/or occurrence that you have already experienced or expect to experience:				

Q15: Have you already experienced, or do you expect to experience, **changes to the occurrence of icing** (increase or decrease)?

Please select one answe

- Already experienced [→Q15b]
- Expected in the near-term (before 2030) [→Q15b]
- Expected in the medium term (by 2050) [→Q15b]
- Expected in the longer term (after 2050) [→Q15b]
- Do not expect to experience [→Q16]
- Don't know / not sure [→Q16]

Q15b [optional] : For changes to the occurrence of icing which of the following impacts have you already experienced or do you expect to experience?

Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
An increase in de-icing requirements	●	●	●	●
A decrease in de-icing requirements	●	●	●	●
Other – please identify any other impacts from changes to the occurrence of icing that you have already experienced or expect to experience:				

Q16: Have you already experienced, or do you expect to experience, **changes to wildlife patterns and/or vegetation** (e.g. changes to wildlife migration patterns which would impact the airport, an increase in bird strikes or changes to vegetation which might attract wildlife)?

Please select one answer

- Already experienced [→Q16b]
- Expected in the near-term (before 2030) [→Q16b]
- Expected in the medium term (by 2050) [→Q16b]
- Expected in the longer term (after 2050) [→Q16b]
- Do not expect to experience [→Q17]
- Don't know / not sure [→Q17]

Q16b [optional] : For changes to wildlife patterns and vegetation which of the following impacts have you already experienced or do you expect to experience?

Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
Changes in wildlife migration patterns	●	●	●	●
An increase in bird strikes	●	●	●	●
Changes to vegetation	●	●	●	●
Other – please identify any other impacts from changes to wildlife patterns and/or vegetation that you have already experienced or expect to experience:				

Q17: Have you already experienced, or do you expect to experience, climate related **business and economic impacts**?
Please select one answer

- Already experienced [→Q17b]
- Expected in the near-term (before 2030) [→Q17b]
- Expected in the medium term (by 2050) [→Q17b]
- Expected in the longer term (after 2050) [→Q17b]
- Do not expect to experience [→Q18]
- Don't know / not sure [→Q18]

Q17b [optional]: For business and economic impacts which of the following have you already experienced or do you expect to experience?
Please select one answer per row

	Already experienced	Expect to experience in the future	Do not expect to experience	Don't know / not sure
Climate change driven changes in traffic / tourism demand	●	●	●	●
An increase in operating costs	●	●	●	●
An increase in insurance premiums	●	●	●	●
Other – please identify any other business and economic impacts that you have already experienced or expect to experience:				

Section 3: **Climate change risk assessment and adaptation**

This section will ask whether your airport is taking or planning to take any measures to understand what climate change impacts it might be at risk of and to adapt and build resilience to those impacts.

Definitions

- ***Adaptation***: "In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects". **(IPCC 2018, p. 542).**
- **Resilience:** "The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation". **(IPCC 2018, p. 557)**

IPCC (2018) Annex II: Glossary, Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, Switzerland (2018). https://www.ipcc.ch/site/assets/uploads/2018/02/WGIIAR5-AnnexII_FINAL.pdf.

Section 3.1**: Climate change risk assessment**

Q18: Is your airport subject to any legislation which requires it to carry out a climate change risk assessment and/or implement a climate change adaptation plan?
Please select one answer

- Yes [→Q18b]
- No [→Q19]
- Don't know / not sure [→Q19]

Q19: Has your airport carried out a climate change risk assessment to identify which climate change effects it might be at risk from?
Please select one answer

- Yes, we have carried out a climate change risk assessment [→Q20]
- We are currently carrying out a climate change risk assessment [→Q23]
- We intend to carry out a climate change risk assessment [→Q23]
- We do not currently intend to carry out a climate change risk assessment [→Q26]
- I don't know if we intend to carry out a climate change risk assessment [→Q27]

Q20 [optional]: When you carried out your climate change risk assessment what challenges did you face?
Please select all that apply.

- Leadership buy-in
- Resources (personnel)
- Resources (financial)
- Lack of information or data
- We did not face any challenges
- Other – Please identify any other challenges you faced whilst carrying out the climate change risk assessment

Q23 [optional]: When carrying out or planning your climate change risk assessment what challenges are you facing or do you anticipate?

Please select all that apply.

- Leadership buy-in
- Resources (personnel)
- Resources (financial)
- Lack of information or data
- We did not face any challenges
- Other – Please identify any other challenges you faced whilst carrying out the climate change risk assessment

Section 3.2**: Climate change adaptation**

Q28: Does your airport have a climate adaptation strategy or plan?

Please select one answer.

- Yes, we have an adaptation strategy or plan [→Q31]
- We are currently developing an adaptation strategy or plan [→Q31]
- We intend to develop an adaptation strategy or plan [→Q31]
- We do not have an adaptation strategy or plan but we have implemented ad-hoc measures to address some impacts [→Q29]
- We do not currently intend to develop an adaptation strategy or plan [→Q30]
- I don't know if we intend to develop an adaptation strategy or plan [→Q31]
- Other (please specify) [→Q31]

Q31: Do you think your airport is well-prepared to deal with the impacts of climate change?

Please select one answer

- Not at all prepared
- Slightly prepared
- Moderately prepared
- Well prepared
- Very well prepared
- Don't know / not sure

Section 3.3**: Sharing best practices to support climate adaptation in the sector**

One of the intentions of this survey is to identify and share examples of climate change adaptation good practices for the aviation sector.

Q32 [optional]: We would appreciate it if you could tell us about any adaptation measures you have implemented, plan to implement or anticipate.

Infrastructure measures

Please identify any specific measures you have implemented, plan to implement or anticipate.

Operational measures

Please identify any specific measures you have implemented, plan to implement or anticipate.

Health measures (passengers and employees)

Please identify any specific measures you have implemented, plan to implement or anticipate.

Business and economic measures

Please identify any specific measures you have implemented, plan to implement or anticipate.

Other measures

Please identify any other specific measures you have implemented, plan to implement or anticipate.

Appendix B:. Key climate effects in LAC

According to the Intergovernmental Panel on Climate Change (IPCC) climate change effects are already visible throughout the LAC region (IPCC, 2021a). Fig. 2 presents key climate effects for the 10 IPCC LAC subregions and provides their three letter regional codes (used hereafter).

Projected changes, and the resulting impacts for airports, vary across the LAC region. However, there is high confidence that mean temperatures have already increased in all Central and Southern American subregions and are projected to continue increasing at rates greater than the global average (IPCC, 2021a). In CAR temperatures are projected to increase, but by less than the global mean (IPCC, 2021a).

Mean precipitation is projected to change throughout the region, with changes to overall precipitation, extreme rainfall events and potential seasonal shifts in rainfall patterns (IPCC, 2021a). Whilst for NWS and SES, an increase in precipitation is projected, for CAR, NCA, SCA, NSA and SWS a mean decrease is projected, with drought conditions either forecast or already observed in CAR, NCA, SCA, and NSA. Notwithstanding an overall decrease in precipitation, NCA, NSA and NES, along with SAM and SSA (no overall change) and SES (overall increase), may experience an increase in *extreme* rainfall events (IPCC, 2021a). While an increase in heavy precipitation events has already been observed in CAR, it is uncertain whether this will continue in the future (and therefore is not included in the Fig. 1 projections for the subregion; IPCC, 2021a).

An increase in the severity of tropical cyclones and severe storms is projected along the Pacific and Atlantic seaboards affecting Central America (NCA, SCA), NSA and CAR, although frequency of occurrence may decrease (IPCC, 2021a). There is high confidence that relative SLR will continue leading to increased coastal flooding and shoreline retreat (IPCC, 2021a). This is a geographically specific effect directly affecting low-lying, coastal airports. However, there may be indirect impacts for other airports due to traffic disruption or temporary or permanent closures.

Global climate models project an increase in wind speeds in most parts of Central and South America, particularly in NES (IPCC, 2021a). The exception is SSA where wind speeds are projected to decrease. There is limited data on changes in wind patterns available for the Caribbean, although some suggestion of a slight increase in wind speed under higher climate change scenarios. Dust storms are projected to become more extreme, particularly in NCA and SCA, while an increase in frequency, intensity and duration of heatwaves and increased risk of wildfires is projected to cause an increase in desertification (IPCC,2021a). In NES 94 % of the region is moderately or highly susceptible to desertification (IPCC, 2021a).

Changes to fog are uncertain and will vary geographically, although there is a lack of identified research for the region. Glaciers across South America are projected to continue losing mass and area, with the greatest thermal regime disturbance projected in the central Andes (IPCC, 2021a). Permafrost thaw will also continue in the Andes. Both this and glacier loss have the potential to cause significant flooding (IPCC, 2021a). Climate change will also alter ecosystems and change species migration patterns. For example, migration patterns for birds in Latin America are projected to change in latitude and longitude, with wintering grounds shifting to higher regions (Da Silveira et al, 2021). However, as with other effects, changes will vary subregionally.

As well as physical climate effects there may be business and economic effects. Changes in climatic conditions, such as more extreme weather or higher temperatures, are expected to influence tourists' destination choices. This may reduce tourist arrivals at some locations, increase tourism at other locations or cause seasonal changes in tourists' destination preferences (Burbidge, 2016; Dimitriou, 2016; Gössling et al., 2023).

This Appendix has provided an overview of the current and projected climate in LAC at the level of IPCC subregion. A more granular analysis was beyond the scope of this study. However, for future work there would be value in using higher resolution climate data, such as the CMIP6 model projections, to perform a down-scaled analysis of projected climate effects at airport level.

Appendix C:. Overview of industry surveys on climate change impacts and adaptation

To date, four surveys have been carried out by international organisations on climate impacts and adaptation actions for the aviation sector at global level. The table below gives an overview of the results of each survey, highlighting information of relevance to the Latin America and Caribbean (LAC) region.

Table C1
Overview of results of industry surveys on climate impacts and adaptation actions for the global aviation sector.

	Survey and year			
	ICAO Climate Adaptation Synthesis Report 2020	**ACI World 2019 Climate Change Resilience and Adaptation Survey**	**WMO 2020 Survey on the Impacts of Climate Change and Variability**	**CDRI 2023 Global Study on Disaster Resilience of Airports**
Respondent Profile	88 responses from global aviation sector stakeholders including States, Civil Aviation Authorities, airports and ANSPs.	121 responses covering 288 airports.	71 responses from aviation professionals. 65 % were airline operators or pilots and flight crew. Four respondents (6 %) were airports.	91 complete responses from 81 airports (115 partial responses from 111 airports).
LAC respondents	Results analysed by ICAO region, therefore results for Central America and the Caribbean were included in the North America, Central America and Caribbean region and cannot be considered independently. For the ICAO	18 responses from LAC covering 78 airports.	13 respondents (18 %) were from the wider Americas region, although this cannot be further broken down to the LAC region. Eight responses (11 %) were multi-continent with no further breakdown available.	12 responses from LAC: five complete and seven partial responses.

(*continued on next page*)

Table C1 (*continued*)

	Survey and year			
	ICAO Climate Adaptation Synthesis Report 2020	**ACI World 2019 Climate Change Resilience and Adaptation Survey**	WMO 2020 **Survey on the Impacts of Climate Change and Variability**	**CDRI 2023 Global Study on Disaster Resilience of Airports**
	South America region, seven responses were received (breakdown of respondent profiles not known).			
Coverage of effects in LAC	All 7 LAC respondents are already being or expect to be affected by changing precipitation (no differentiation between an increase or a decrease in precipitation). Other main effects being experienced/expected: increased intensity of storms (6/7), higher average and extreme temperatures (6/7), sea level rise (5/7), changes to wind (5/7).	For climate effects, 67 % of LAC respondents highlighted the impact of adverse weather events, patterns and conditions." The main physical impacts expected were a change in intensity of storms (11/18) and changing precipitation (9/18). Just four respondents cited higher average and extreme temperatures and 3 cited SLR, although it is not stated how many airports each individual response covered or, of particular relevance in the case of SLR, the geographical location of the respondents.For climate impacts, 13/18 LAC respondents cited disruption in operations, 7/18 temporary/permanent damage to infrastructure and 6/18 financial losses.	No specific findings are identified for LAC airports, survey respondents identify airfield flooding due to heavy rain and storm surge as having the greatest potential airport infrastructure impact. Notably, the four airport respondents did not consider this a significant issue, however their geographical location is unknown. For airport operations longer take-off and landing distances due to higher temperatures and reduced runway capacity due to higher runway occupancy times were identified as the most significant potential impacts.	Extreme storms, wind and wildlife invasion identified as the effects which will have the greatest impacts for LAC airports in the future.
Coverage of risk assessment in LAC	No regional breakdown of results on risk assessment.	Four LAC respondents had carried out a risk or vulnerability assessment, four intended to carry one out and 10 had not carried one out. It is not stated how many airports each individual response covered.	No regional breakdown of results on risk assessment.	60 % of LAC respondents have carried out vulnerability assessments, 80 % have carried out resilience assessments and 80 % have disaster recovery plans.

Data availability

The data that has been used is confidential.

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