ICAO

ENVIRONMENT

2024 ICAO Climate Adaptation Synthesis Report

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Executive Summary

Background

According to the *U.N. Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC AR6)* (2021), climate change is already affecting weather and climate extremes in all global regions. Global surface temperatures will continue to increase until at least mid-century under all emissions scenarios, which will in turn increase the frequency and intensity of effects such as heat extremes and heavy precipitation. Therefore, while the aviation sector currently operates safely and efficiently in a variety of climates, climate change will pose risks to aviation infrastructure and operations in the future as new climate realities breach the resilience capacity of legacy systems, infrastructure and operations which were designed for the climate of the past. In recognition of the potential for climate change to negatively impact aviation safety and global operations, in the eleventh cycle of the International Civil Aviation Organization (ICAO) Committee on Aviation Environment Protection (CAEP) (2016-2019), Working Group 2 (WG2) was tasked by CAEP with producing the first edition of this Climate Adaptation Synthesis, which examined the specific infrastructure and operational impacts of climate change on aviation by conducting a literature review and analysing results of a survey sent to all ICAO Members and Observers. The information from the literature review and the results of the survey were then collated to produce a compilation of existing information on climate change effects and impacts for the global aviation, the results of which are presented in the *2018 Climate Adaptation Synthesis Report*.

The *2018 Climate Adaptation Synthesis Report* has become a key resource for ICAO States and aviation organizations to prepare for the impacts of climate change, but more than six years have passed since the *2018 Report* was written. Therefore, to ensure the content of this document stays current, CAEP tasked WG2 with updating the 2018 Synthesis during the thirteenth cycle (2022-2025). This included re-running a version of the CAEP/11 Synthesis Report Stakeholder Survey, to see to what extent adaptation action has been taken and whether stakeholder concerns have evolved.

This new edition of the Synthesis, the *2024 ICAO Climate Adaptation Synthesis Report*, provides an updated compilation of existing information on the range of projected climate effects on the aviation sector, and the resulting impacts, to better understand risks to airports, Air Navigation Service Providers (ANSPs), airlines, infrastructure, and other operational factors. The information collected in this report, in combination with climate change scenario projections, will facilitate ICAO Members and Observers, and other relevant aviation stakeholders, in identifying potential effects of climate change which may impact their individual organizations, national aviation sectors and the global aviation network, together with adaptation and resiliency measures that may be beneficial. This is a synthesis of best current information for aviation stakeholders, and not a guidance document.

Methodology

This report synthesises existing information on the range of projected climate impacts on the aviation sector to better understand risks to airports, Air Navigation Service Providers (ANSPs), airlines, and other aviation infrastructure. The science content of the report is based on the findings of IPCC AR6, and supplemented with other peer-reviewed scientific information, as required. This synthesis was conducted in two stages:

1) Literature Review: The literature review collated information from documents relevant to aviation climate change adaptation issues.

2) 2022 Survey: A survey was designed and sent via State Letter. 259 responses were received, with at least one response from every ICAO Region. Respondents were comprised of sixty-three (63) States, sixty-three (63) airports, fifty-nine Civil Aviation Authorities, forty (40) airlines, sixteen (16) ANSPs, six (6) original equipment manufacturers and twelve (12) that didn't fit into any of the main categories and so were categorised as other.[1]

Key Findings of 2022 Survey

Figure ES-1 presents one of the key findings of the survey results. 188 of 259 respondents (73 percent) said they are already experiencing some impacts from climate change. Just five respondents (2 percent) indicated that they do not expect to be impacted by climate change.

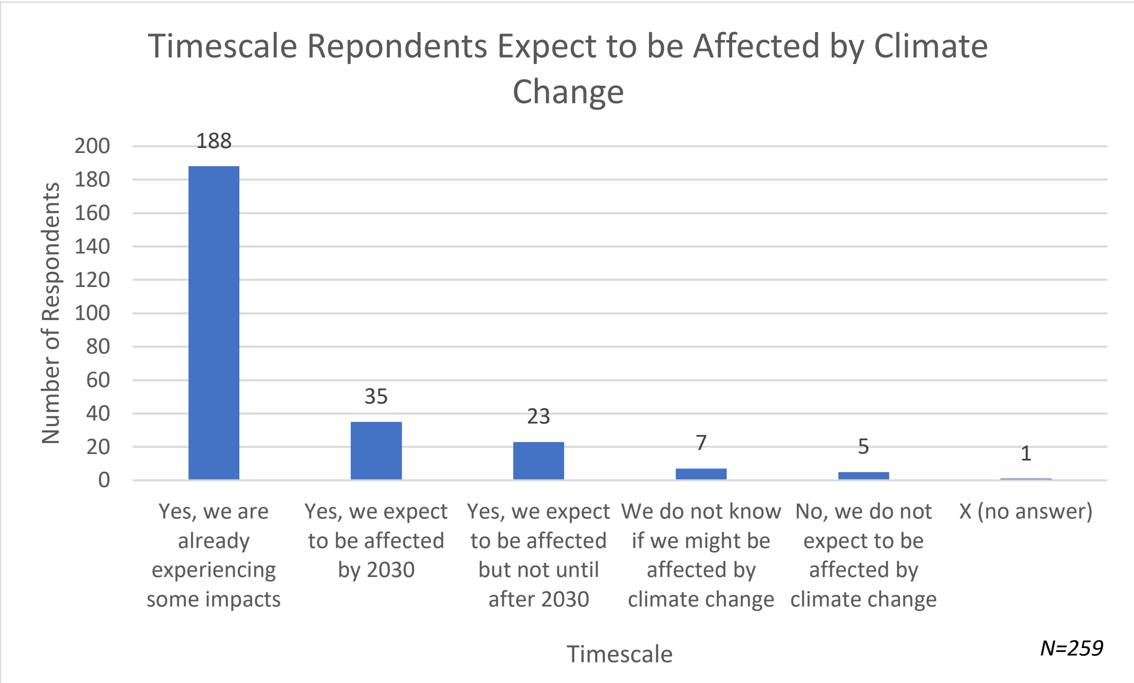


Figure ES-1: Timescales in which respondents expect to be impacted by climate change

The 2022 Survey asked respondents if they are affected today or expect to be affected in the future by nine impact categories. In seven of these categories 50 percent or greater of the respondents said they are affected today or expect to be affected in the future, as depicted in Figure ES-2 below.[2]

[1] As with any survey, there may be some degree of self-selection bias, which may result in a disproportionate amount of responses from States or organisations that have a particular interest or concern in climate change impacts on aviation.

[2] Respondents only had "Expect to be affected" and "Don't expect to be affected" as options to answer this question.

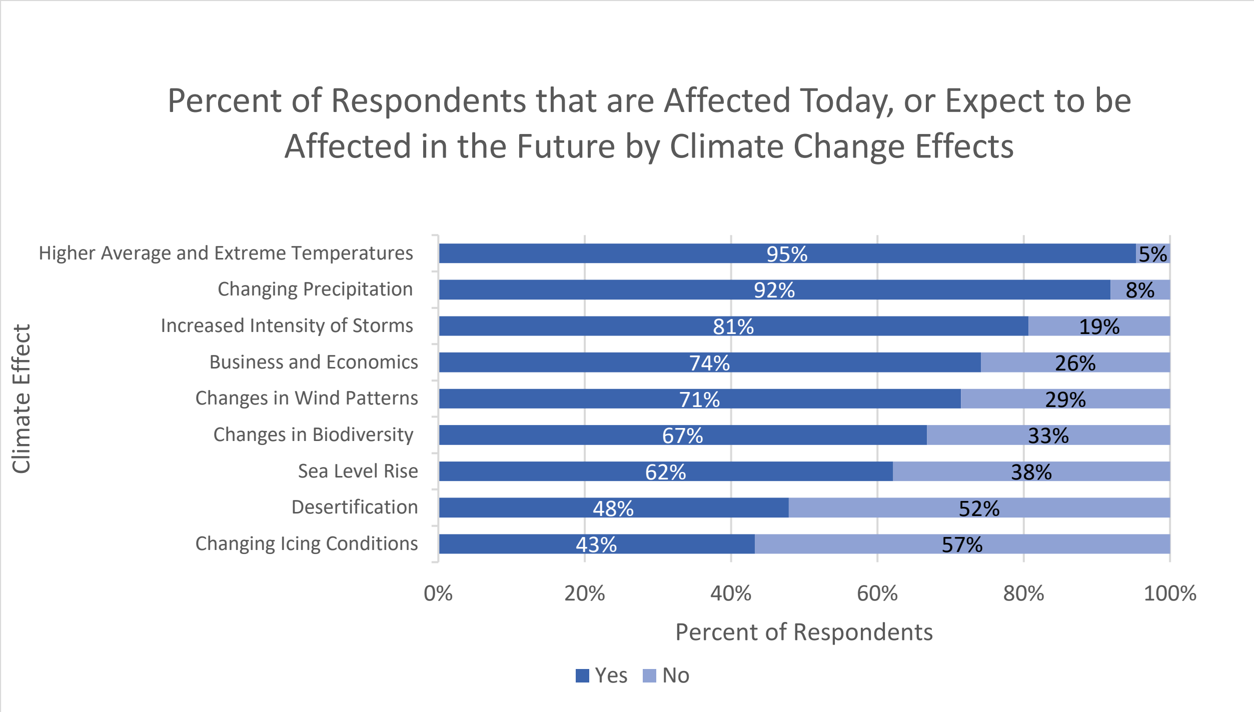


Figure ES-2: Percent of respondents that are affected by impact category **N=259**

Respondents expected the biggest challenges to be from higher average and extreme temperature, changing precipitation, and increased intensity of storms:

- **Higher Average and Extreme Temperatures:** 247 of 259 respondents stated they are affected today or expect to be affected in the future by higher average and extreme temperatures (95 percent). Both average global mean temperatures and extreme high-heat days are expected to increase. The impacts to aviation from higher temperatures are wide-reaching. For example, high heat days can stress cooling systems or damage the airfield surface if temperatures exceed design standards. Higher temperatures can also reduce air density, which can affect aircraft take-off requirements. Additionally, higher temperatures may cause permafrost to thaw in northern regions, destabilising infrastructure and contributing to erosion.
- **Changing Precipitation:** 238 of 259 respondents stated they are affected today or expect to be affected in the future by changing precipitation (92 percent). This impact category includes changes in precipitation type (e.g., rain, snow, hail), as well as precipitation frequency, potentially leading to extreme rainfall or prolonged drought. There is considerable variation in precipitation forecasts globally, but the IPCC AR6 WGI report states that climate change is likely to bring a change, and potential exacerbation, of these conditions to all regions. Extreme rainfall may cause flooding of airport surfaces and infrastructure, while drought may lead to reduced water availability.
- **Increased Intensity of Storms:** 209 of 259 respondents stated they are affected today or expect to be affected in the future by increased intensity of storms (81 percent). Storms are projected to become stronger and potentially more frequent and the IPCC AR6 Synthesis Report illustrates how, as temperatures increase, the risk of extreme weather events, such as extreme storminess, will also increase. Increased intensity of storms may cause damage to aviation infrastructure and cause delays or cancelations to commercial air service.

This Synthesis identifies three high-level steps to performing a climate change risk assessment: 1) Find out how the climate will change, 2) Identify risks, and 3) Review and repeat the assessment periodically. 191 out of 259 respondents (74 percent) indicated that they have already carried out a risk assessment or intend to do so in the future.

After completing a climate change risk assessment, the Synthesis identifies four steps for developing an adaptation strategy or plan: 1) Defining adaptation and resilience objectives, 2) Identifying adaptation and resilience measures, 3) Developing and implementing a climate adaptation plan, 4) Periodic monitoring and review. Respondents also stated that adaptation risk assessment and planning both at the global and the airport level are some of the more effective things the global aviation sector can do or is doing to prepare for the impacts of climate change.

This Synthesis also illustrates some specific measures for the aviation sector to adapt and build resilience to climate change. 32 out of 259 respondents (12 percent) stated that they are already implementing adaptation and resilience measures while 43 out of 259 respondents indicated they plan to do so in the next five years (17 percent) and 24 out of 259 indicated they plan to do so in the next 10 years (9 percent). Despite the implementation – or planned implementation – of adaptation and resilience measures, 225 out of 259 respondents (87 percent) believe that the global aviation sector still has work to do in order to prepare for the impacts of climate change.

Comparison to 2017 Survey Results

Responses to the 2022 survey increased by approximately 290 percent from the 88 responses received for the 2017 survey. In both 2022 and 2017, there was at least one response from every ICAO region. In addition to the increase in the number of respondents to the survey, there was also a broadening of the type of respondents between 2017 and 2022. In 2017, respondents were from States, Airports, Airlines, and Air Navigation Service Providers (ANSPs). In 2022, respondents were from States, Airports, Airlines, ANSPs, Civil Aviation Authorities (CAAs), Original Equipment Manufacturers (OEMs), and organizations that identified as “Other” (which included a flight school, ground handling, a regional safety oversight organization, and meteorological services organizations).

Conclusion

This Synthesis Report represents opinions from a range of ICAO members, observers and stakeholder organizations from all ICAO regions. It also presents a synthesis of the current understanding of climate change effects and how they can directly and indirectly impact the global aviation system. This Synthesis Report illustrates the magnitude of interest that States and aviation stakeholders are now taking in climate change impacts, and the actions they are taking or plan to take to strengthen their climate resilience.

1. Introduction

According to the U.N. Intergovernmental Panel on Climate Change Sixth Assessment Report (2021), climate change is already affecting weather and climate extremes in all global regions. Global surface temperature will continue to increase until at least mid-century under all emissions scenarios, in turn increasing the frequency and intensity of effects such as heat extremes and heavy precipitation. Therefore, while the aviation sector currently operates safely and efficiently in a variety of climates, climate change will pose a number of risks in the future, including an increased frequency or intensity of extreme weather events in some areas of the world, potentially beyond the current resilience capacity of the aviation system. Current experiences with addressing extreme weather and climates offer an existing baseline portfolio of effective adaptation practices. However, a better understanding of the extent to which climate change impacts will occur, how to assess the effects on aviation, and what adaptation solutions could be employed, is critical for effective planning at local, regional, and global levels.

Within the ICAO Committee on Aviation Environmental Protection (CAEP), and the aviation sector in general, there has been a growing awareness of climate change effects and the specific challenges they may bring to the aviation industry. As a result, in the CAEP/10 cycle (2013-2016), the CAEP Impacts and Science Group (ISG) initiated work on assessing the scientific knowledge of these risks. In the CAEP/11 cycle (2016-2019), Working Group 2 (WG2) was tasked with producing the first edition of this Climate Adaptation Synthesis looking at the specific infrastructure and operational impacts of climate change on aviation via a document review and survey. This was then collated to produce a compilation of existing information on climate change effects and impacts for the global aviation, the results of which are presented in the 2018 Climate Adaptation Synthesis Report.

The 2018 Climate Adaptation Synthesis has become a key resource for ICAO States and aviation organizations to prepare for the impacts of climate change. Therefore, it is important to ensure the information in the Synthesis stays current and incorporates the latest scientific information. The science and knowledge of climate change impacts for aviation and adaptation and resilience measures has already evolved since the completion of the final draft of the Climate Adaptation Synthesis in Autumn 2018 and there is new knowledge which should be incorporated to ensure that the information provided is as current as possible. Therefore, for the CAEP/13 cycle Working Group 2 was tasked with updating the 2018 Synthesis, including re-running a version of the CAEP/11 Synthesis Report Stakeholder Survey, originally run in 2017, to see to what extent adaptation action has been taken, whether stakeholder concerns have evolved and whether there are any lessons to be learned from the challenges they encountered and how they addressed those challenges.

This Synthesis therefore provides an updated compilation of existing information on the range of projected climate effects on the aviation sector, and the resulting impacts, to better understand risks to airports, Air Navigation Service Providers (ANSPs), airlines, infrastructure, and other operational factors. The Synthesis includes considerations for how projected climate effects relate to safety, capacity, and efficiency. It identifies impacts that are already being experienced and that may relate to climate change, on local, regional and global levels, including information and examples of how the risks of these impacts are assessed and quantified. Examples of adaptation and resiliency efforts and actions, which are either identified, or already being implemented, are also provided.

This Synthesis Report provides information at local, regional, and global levels and covers timescales to 2050, and beyond when appropriate or available. Information on climate change projections and impacts of climate change on the aviation sector has been gathered through a literature review of current documents. This has been supplemented by a survey to gather direct stakeholder views and experiences. The survey was sent as a State Letter to ICAO Member States and Observers, then further circulated by those States and organizations. The results of the survey are compared against the results of the 2017 Survey to monitor evolving changes in stakeholder perspectives and levels of resilience over time.

ICAO (2022) highlights that "Small Island Developing States (SIDS) are particularly vulnerable to climate change, and impacts of a changing climate can be magnified by other local issues. For example, SIDS often have constraints on personnel, funding, and limited land and water resources. For this reason, it is especially critical for SIDS to identify and prioritize vulnerabilities" (ICAO[2], 2022 no page number). Therefore, when relevant, particular challenges and solutions for SIDS will be highlighted.

The information collected in this report, in combination with climate change scenario projections, will facilitate CAEP Members and Observers, and other relevant aviation stakeholders, in identifying potential effects of climate change which may impact their individual organizations, national aviation sectors and the global aviation network, together with adaptation and resiliency measures that may be beneficial. It should be noted that this is a synthesis of best current information and not a guidance document.1.1 Guide to the Synthesis

1.1 Definitions

The definitions for climate change adaptation, climate change resilience, and climate change vulnerability applied in this Synthesis are those used by the IPCC Sixth Assessment Report Glossary (IPCC[3] AR6 WGII, pp. 2898, 2921, 2927):

- **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.
- **Resilience:** The capacity of interconnected social, economic and ecological systems to cope with a hazardous event, trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure.
- **Vulnerability:** The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

1.2 Timescales

Since this Synthesis draws on information from multiple documents, the timescales used in the Synthesis are fairly broad to accommodate the wide range of input. In most sources, the timescales are organized broadly by near-term, mid-term, and long-term, though the exact definition of these timescales vary by source document and climate effect category.

The State Letter survey was organized into broad timescales. In the first question, the survey asked respondents if they are currently impacted by climate change, expect to be impacted by 2030, or expect to be impacted after 2030 (this question also included response options if the respondent does not expect to be impacted or does not know). The following question asked respondents to indicate all applicable climate effects and their expected timescales, and were described as: already experiencing, expect to experience in the future (<5 years), expect to experience in the future (5-10 years), expect to experience in the future (<10 years), do not expect to be affected, and do not know.

1.3 Parameters of the Analysis

For the purpose of this analysis, 'aviation sector' covers: aircraft operators, airport operators, ANSPs, and regulatory authorities. Aviation sector components included in this analysis are: infrastructure, aircraft operations (en-route and airport), airport operations (e.g. ground operations), and airport ground transportation access.

This analysis uses the term 'effects' to refer to physical climate changes (e.g., temperature change, sea level rise) and the term 'impacts' to refer to the potential consequences of climate change effects on the aviation system. Note that in the 2018 Climate Adaptation Synthesis these terms were used in reverse. However, this has been updated for the 2024 Climate Adaptation Synthesis to align with IPCC terminology. Any regional analysis is based on ICAO regions (see figure 2). However, it is noted that even within regions there are differences in effects and impacts as there can be multiple climate zones within one ICAO region. Therefore, these analyses can only give a high-level indication of regional effects, impacts and differences.

1.4 Climate Change Science Background

This report mainly draws on the scientific information presented in the IPCC Sixth Assessment Report (AR6), complemented by reports from the World Meteorological Organization. The IPCC AR6 covers many aspects of climate change that are not addressed in this 2024 Climate Adaptation Synthesis Report including, the observed changes in climate in the past, and causes of climate change. This Synthesis Report examines only those projections of future climate change effects which have been identified as relevant for the global aviation sector by CAEP WG2. This Synthesis Report also draws from other scientific publications for information on how projected climate change effects may impact aviation, as appropriate.

The IPCC Fifth Assessment Report (AR5) utilized four Representative Concentration Pathways (RCPs)[3] to "…describe four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use" (IPCC, 2014 p.8). These RCPs include one low-emissions scenario (RCP2.6), one high-emissions scenario (RCP8.5) and two mid-range scenarios (RCP4.5 and RCP6.0). These four scenarios determine the rate of change projected for each effect category as the IPCC finds a positive correlation between increased emissions and increased global temperature change, which in turn correlates to other changes including sea level rise and precipitation.

For the Sixth Assessment Report, the IPCC introduce an additional set of climate scenarios, Shared Socioeconomic Pathways (SSP), to complement the RCP scenarios. According to the IPCC Working Group 1 Glossary "Shared Socio-economic Pathways (SSPs) have been developed to complement the Representative Concentration Pathways (RCPs). By design, the RCP emission and concentration

[3] "Scenarios that include time series of emissions and concentrations of the full suite of greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover" (IPCC, 2014)

pathways were stripped of their association with a certain socio-economic development. Different levels of emissions and climate change along the dimension of the RCPs can hence be explored against the backdrop of different socio-economic development pathways (SSPs) on the other dimension in a matrix. This integrative SSP-RCP framework is now widely used in the climate impact and policy analysis literature, where climate projections obtained under the RCP scenarios are analysed against the backdrop of various SSPs. As several emissions updates were due, a new set of emissions scenarios was developed in conjunction with the SSPs. Hence, the abbreviation SSP is now used for two things: On the one hand SSP1, SSP2, …, SSP5 are used to denote the five socio-economic scenario families. On the other hand, the abbreviations SSP1-1.9, SSP1-2.6, …, SSP5-8.5 are used to denote the newly developed emissions scenarios that are the result of an SSP implementation within an integrated assessment model. Those SSP scenarios are bare of climate policy assumption, but in combination with so-called shared policy assumptions (SPAs), various approximate radiative forcing levels of 1.9, 2.6, …, or 8.5 W m–2 are reached by the end of the century, respectively" (2021[3] p.2243). The IPCC AR6 uses both SSP and RCP scenarios, therefore this Synthesis will use both as appropriate.

2. Methodology

Research was conducted in two stages: the first stage was a literature review of materials on this topic identified by the CAEP WG2 Task Group; the second stage was a survey designed by the Task Group and sent out via a subsequent State Letter.

2.1 Literature Review

The update of the Synthesis sections on effects, impacts and adaptation was carried out in two parallel stages.

Stage 1: According to the Methodology to Review the Synthesis developed and approved during the CAEP/12 cycle (2019-2022), each individual chapter of the Synthesis was reviewed to determine whether additional information was required or existing information should be updated. Proposals for the additional or updated information were collected using the template agreed at CAEP Steering Group 2020. This was not a "re-drafting" exercise, but rather an exercise to identify and include pertinent new information, or to update outdated information.

Stage 2: Involved identifying new scientific sources for the update to the Synthesis. This included the latest Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report. In total, the Task Group identified and reviewed nine new documents relevant to aviation climate adaptation issues and challenges. Some of the documents were global in context, while others were regionally or nationally specific. Each document was analysed separately and the relevant information on climate effects, impacts on the aviation sector, adaptation and resilience measures and other pertinent information were extracted and synthesised with the information in the 2018 Synthesis. The intent, as with the original Synthesis was to provide a high-level report of the best available information rather than to reproduce the detailed information already available in other sources. It was agreed by the Task Group that supplemental information from documents that were not included in the initial document review, but were relevant and from credible sources, could also be cited in the Synthesis. As a result a number of scientific papers and additional reports were cited. All sources of information included in the Synthesis are cited in the main text and listed in the References section at the end of the document.

The main part of the literature review was completed in 2023. However, as the global research community continued to produce new material on this topic the Task Group considered further updates to this analysis, as relevant. The full literature review was completed by June 2023.

2.2 State Letter and Survey

In addition to the document review, the Task Group collected information via a survey on aviation and climate change effects and impacts, and adaptation measures. The 2017 Stakeholder Survey which informed the original 2018 Synthesis was revisited and targeted changes were made for the 2022 update. The objective of the survey was to understand the current perceptions within States and aviation organizations of potential climate change effects, and the impacts that these may have for their aviation sectors, and to see to what extent adaptation action has been taken and whether stakeholder concerns have evolved since the original survey in 2017. The survey was sent as ICAO State Letter AN 1/17 – 22/95 in 2022.

The survey was updated by the Task Group and tested by the full Working Group before distribution. The survey was available online and most responses were received in this format. Respondents also had the option to return the completed survey in PDF format. All of the responses were incorporated into a spreadsheet for analysis, with the online and PDF responses combined into one dataset. After review 259 responses were classed as eligible[4] and included in the analysis and results.

3. Respondents' Expectations of Climate Change Impacts on their Aviation Sectors

In response to the 2022 ICAO State Letter AN 1/17 – 22/95, CAEP Working Group 2 received 259 eligible responses to a survey for the update to the 2018 ICAO Climate Adaptation Synthesis in both online and PDF format. The 2022[5] Survey contained many of the same questions so the data could be compared between years. The 2017 Survey received 88 responses, so the number of respondents increased by more than 290% in the 2022 Survey.

The 2022 respondents were comprised of States, Air Navigation Service Providers (ANSPs), Civil Aviation Authorities (CAAs), Airports, Airlines, aviation associations, original equipment manufacturers, research and development firms, and ground handling. The largest number of respondents came from States and Airports with 63 responses each, followed by Civil Aviation Authorities with 59 responses. There were 40 airline respondents. The survey asked the respondents to categorize themselves; it is very possible that a respondent could fit into more than one category (e.g., a CAA may be operated by a State) so the respondent would have needed to select the category that they felt fit best. The "other" responses included ground handlers, air taxis, meteorological organizations and a flight school.

Of the 259 respondents, 188 (73%)[6] stated that their organization or State aviation sector is already experiencing some impacts of climate change, with 35 (14%) additional respondents expecting to be

[4] Responses were classed as ineligible if they were duplicates or did not meet the inclusion criterion of being an aviation sector stakeholder.
[5] Note: The State Letter was sent in December 2022 with a due date for responses in February 2023. This synthesis report will therefore refer to the survey as the "2022 Survey".
[6] Note that due to rounding the individual percentages total 101%

affected by 2030, 23 (9%) respondents expecting to be affected after 2030, and seven (3%) respondents unsure if they will be affected. Five respondents (2%) indicated that they do not expect to be affected by climate change (see Figure 1, below).

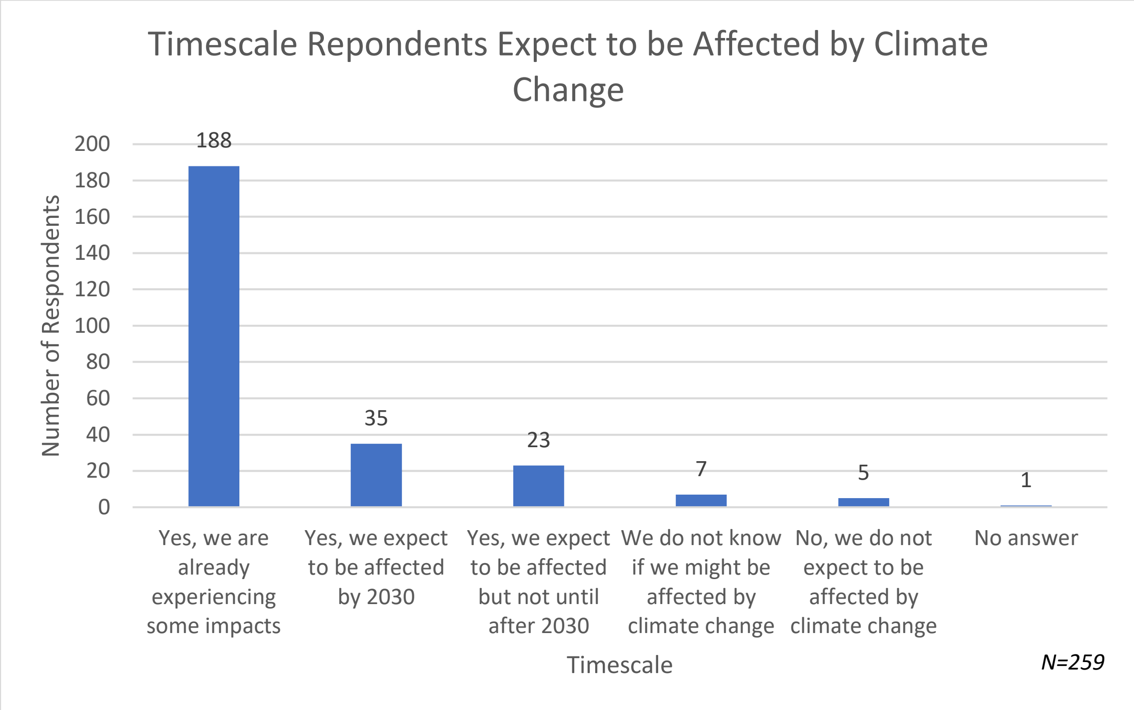


Figure 1 Timescale Respondents Expect to be Affected by Climate Change

The survey asked respondents if they are affected today or expect to be affected in the future by nine categories of effect: 1) Sea Level Rise, 2) Increased Intensity of Storms, 3) Higher Average and Extreme Temperatures, 4) Changing Precipitation, 5) Changing Wind, 6) Changes to Icing, 7) Desertification, 8) Changes in Biodiversity, 9) Changes to Business and Economics. In seven of these effect categories, fifty percent or more of respondents indicated that they are currently or anticipate being affected by that effect. The two effect categories where less than 50% of respondents anticipate being affected are Changes to Icing and Desertification, both effects which may be specific to geographical location or, for airlines, place of operation. The survey also asked questions on risk assessment and adaptation planning. This Synthesis is organized by category of effect, with a section on risk assessment and adaptation planning at the end.

The 2022 Survey also asked respondents to identify any other climate-related effects that may impact the aviation sector in their state. While there were many responses that seemed to overlap with the nine climate effect categories the survey asked about specifically, there were a few unique issues that respondents raised. Four respondents indicated that seasonal shifts may occur, which could have impacts both on when effects are experienced and on aviation demand (this may be particularly true for destinations that have high seasonal traffic). One respondent indicated that the effects of climate change may increase civil unrest in their state, which could impact civil aviation. Another suggested terrorism or war may increase, which may affect civil aviation. Four respondents mentioned increases in diseases

Non-climate threats that may increase due to climate change and impact aviation, identified by respondents:

- Increase in civil unrest
- Increase in terrorism
- Increase in war
- Increase in disease and viruses
- Increases in litigation or other legal action

and viruses, such as COVID-19. Another said that ground transportation access to the airport may be compromised by an increase in severe meteorological events. One respondent said their flight training program may be affected if there are more severe weather days. Two respondents indicated a potential increase in litigation and legal action. One respondent said increased turbulence may create the need for complex flight paths. Multiple respondents indicated higher visual disturbances, including sandstorms and fog. A small number of respondents submitted answers related to higher greenhouse gas emissions or increased noise impacts. 141 respondents left this question blank or otherwise indicated no answer (e.g., "NA", "None").

4. Overview of Survey Demographics

This section will present the survey demographics by ICAO region and organization type. It will also consider how the 2022 survey demographics compare to the 2017 survey demographics.

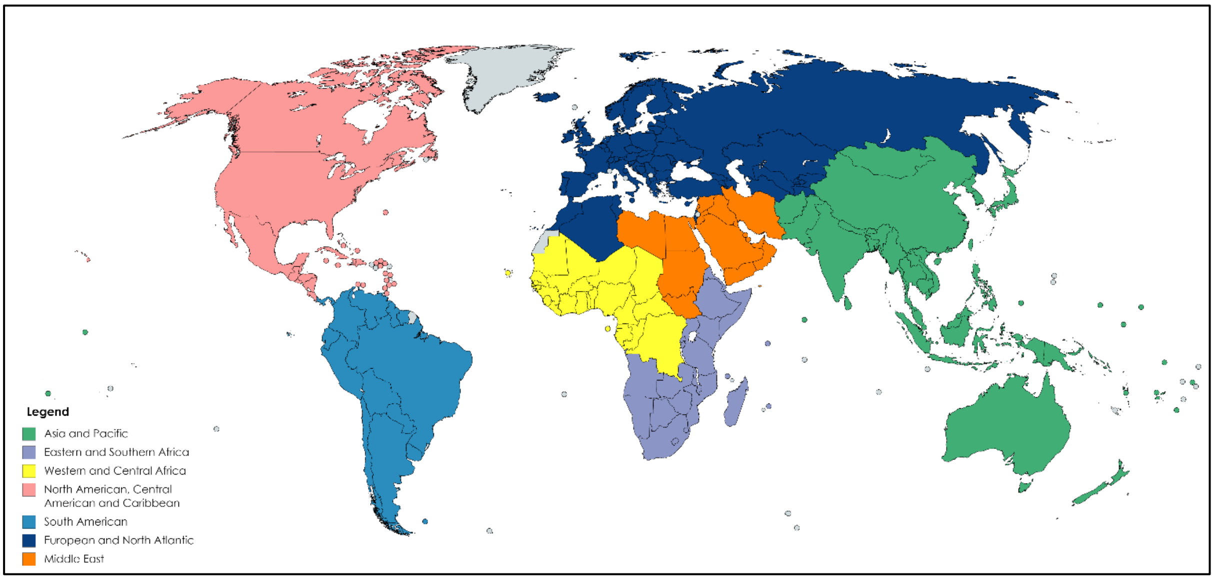


Figure 2 Map of ICAO Regions

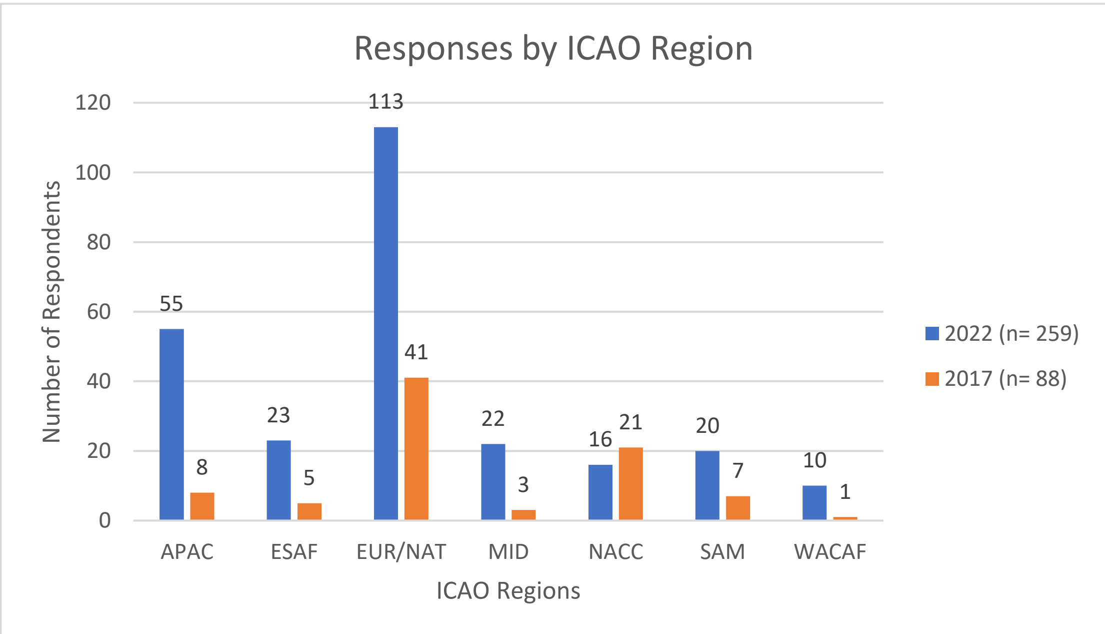


Figure 3 Responses by ICAO Region

ICAO received responses from every ICAO Region to both the 2022 and the 2017 Climate Change Adaptation Surveys. In 2022, there were 113 responses from the European and North Atlantic (EUR/NAT) region, 55 from the Asia and Pacific (APAC) region, 23 from the Eastern and Southern African (ESAF) region), 22 from the Middle East (MID) region, 20 from the South American (SAM) region, 16 from the North American, Central American and Caribbean (NACC) region, and 10 from the Western and Central African (WACAF) region. Compared to the 2017 Climate Change Adaptation Survey, which also had respondents from each of the seven ICAO regions, the distribution of responses shifted; for both surveys, the EUR/NAT region had the most respondents (41 in 2017 compared to 113 in 2022), but in the 2017 Survey, the region that had the second most respondents was NACC (with 21 in 2017, compared to 16 in 2022). In 2017, the APAC region had the third most responses (7 in 2017 compared to 55 in 2022), and the fourth most responses came from the SAM region (6 in 2017 compared to 20 in 2022). The fifth most responses came from the ESAF region in 2017 (5 compared to 23 in 2022), and the sixth most responses came from the MID region in 2017 (3 compared to 22 in 2022). Finally, in both 2017 and 2022, the WACAF region had the fewest number of respondents, but the largest percentage increase from one respondent in 2017 to 10 in 2022. A further breakdown of the respondent type by region is in Table 1 and Figure 5 below.

Of the 259 respondents, 13 were from Small Island Developing States, distributed across four ICAO regions (NACC, APAC, WACAF, and ESAF). While this Synthesis Report will predominantly focus on a regional breakdown by ICAO region, when meaningful, special attention will be given to the 13 SIDS respondents representing SIDS across four ICAO regions.

In 2017, there were 41 responses from the EUR/NAT ICAO region, 21 responses from the NACC region, 8 responses from the APAC region, 7 responses from the SAM region, 5 from the ESAF region, 3 from the MID region, and 1 from the WACAF region. Two responses to the 2017 survey were not included in the regional breakdown to maintain anonymity. Proportionally, the largest increase in responses between 2017 and 2022 came from the WACAF region with a ten-fold increase (from 1 to 10 respondents). The APAC region saw the second-largest increase of more than six-fold (from 8 to 55 respondents).

Interestingly, although the total number of global responses increased from 2017 to 2022, and most regions also saw increases in the number of respondents, the NACC region actually had five fewer respondents. It is important to note, however, that there were five years between the surveys and there was no indication in the 2017 Survey that another survey would follow. There was no prerequisite that respondents to the 2022 Survey must have completed the 2017 Survey. The survey, in both years, was sent out to ICAO Members and Observers. ICAO Members and Observers distributed the survey further through their networks, as the individual Members and Observers deemed appropriate. Therefore, while the global increase in respondents from 88 in 2018 to 259 in 2022 may indicate an increase in attention on the impacts of climate change to the global aviation sector and potentially an increase in the concern about what these impacts could bring, and/or reflect the wider distribution and promotion of the 2022 Survey, at the regional level it is much more difficult to ascertain why there may have been increases (or a decrease for NACC).

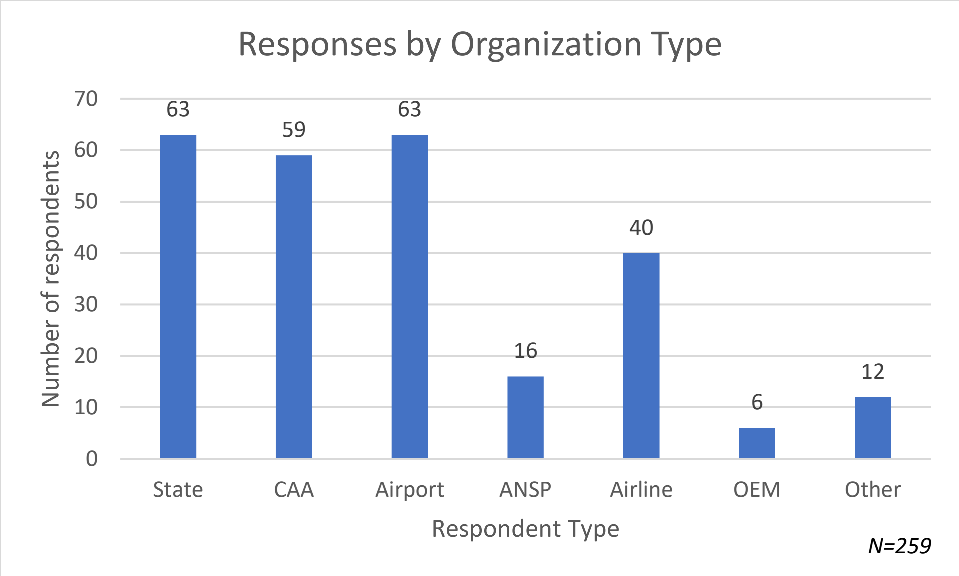


Figure 4 Responses by organization type

Of the 259 responses, 63 respondents identified as "States" and another 63 identified as "Airports". 59 identified as "CAA", 40 as "Airline", 16 as "ANSP", 12 as "Other" and 6 as OEM. The "Other" respondents included a flight school, ground handling organization, a regional safety oversight organization, meteorological organizations, industry associations, and an air taxi company. Respondents were required to answer this question but could only select one option. It is important to recognize however, that some respondents may have been able to categorise themselves as multiple options. For example, an airport could be owned or operated by a State – in this instance, the respondent would have needed to choose which organization type was the best fit, a potentially subjective decision based on their role in the organization. Similarly, a respondent responding on behalf of a "State" may be an employee of a CAA but may have chosen "State" as a representation of the whole State rather than only CAA. Therefore, while this information is helpful in understanding the big picture of respondent type, the data should not be interpreted to mean that States and Airports are more interested in climate change adaptation than any of the other respondent groups.

ICAO Region	2017 Number of Responses Received by Respondent Type	2022 Number of Responses Received by Respondent Type
Asia and Pacific	7 States 1 Airline	8 States 12 Airlines 17 Airports 13 CAAs 2 ANSPs 1 OEM 3 Other
Eastern and Southern Africa	5 States	1 State 8 Airlines 2 Airports 7 CAAs 2 ANSPs 3 Other
Western and Central Africa	1 State	2 States 8 CAAs

North American, Central American, and Caribbean	6 States 5 Airlines 10 Airports	6 States 3 Airlines 3 CAAs 2 ANSPs 1 Other
South American	6 States 1 ANSPs	6 States 3 Airlines 3 Airports 4 CAAs 1 ANSP 1 OEM 2 Other
European and North Atlantic	30 States 8 Airports 3 ANSPs	34 States 7 Airlines 35 Airports 16 CAAs 11 ANSPs 4 OEMs 7 Other
Middle East	3 States	3 States 6 Airlines 3 Airports 6 CAAs 3 Other

Table 1 Comparison between 2017 and 2022 Respondent Type by ICAO

As noted above, responses increased across all seven ICAO regions between 2017 and 2022, and across each respondent organization type with one exception. There were 21 respondents to the 2017 Survey from the ICAO NACC region; there only 15 respondents to the 2022 Survey from the ICAO NACC region. In 2017, 10 of the respondents from the ICAO NACC Region identified as airports. In 2022, none of the respondents from the ICAO NACC region identified as airports.

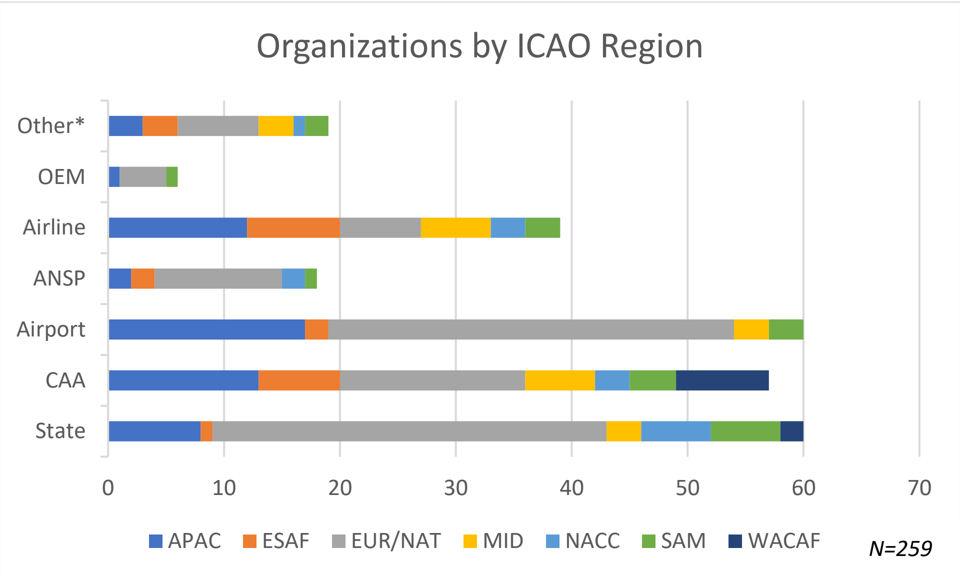


Figure 5 Organizations by ICAO Region

Three regions (APAC, EUR/NAT and SAM) have representation across every organization type. ESAF has representation from every organization type except OEM. MID has representation from every organization type except ANSP and OEM. NACC has representation from every organization type except airport operators and OEM. WACAF only has representation from States and CAAs. In general, there is a greater diversity of organization types in 2022 compared to 2017 with most regions having respondents from five to eight different types of organization compared to one to three in 2017.

5. Analysis of Survey Results on Climate Change Effects and Impacts

This section presents the survey results on climate change effects and impacts. It identifies the key climate effects which survey respondents expect to experience and considers any changes since the 2017 Survey. It also provides a breakdown by region of expected climate change effects.

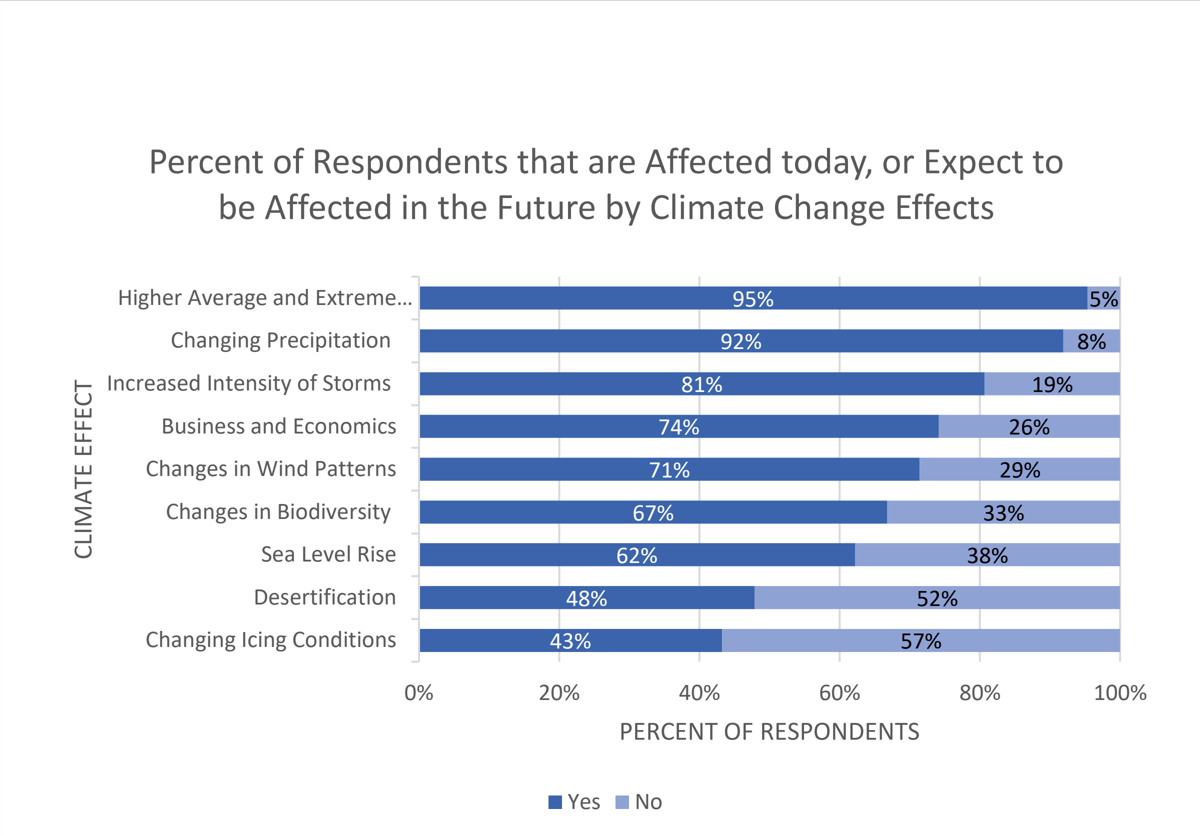


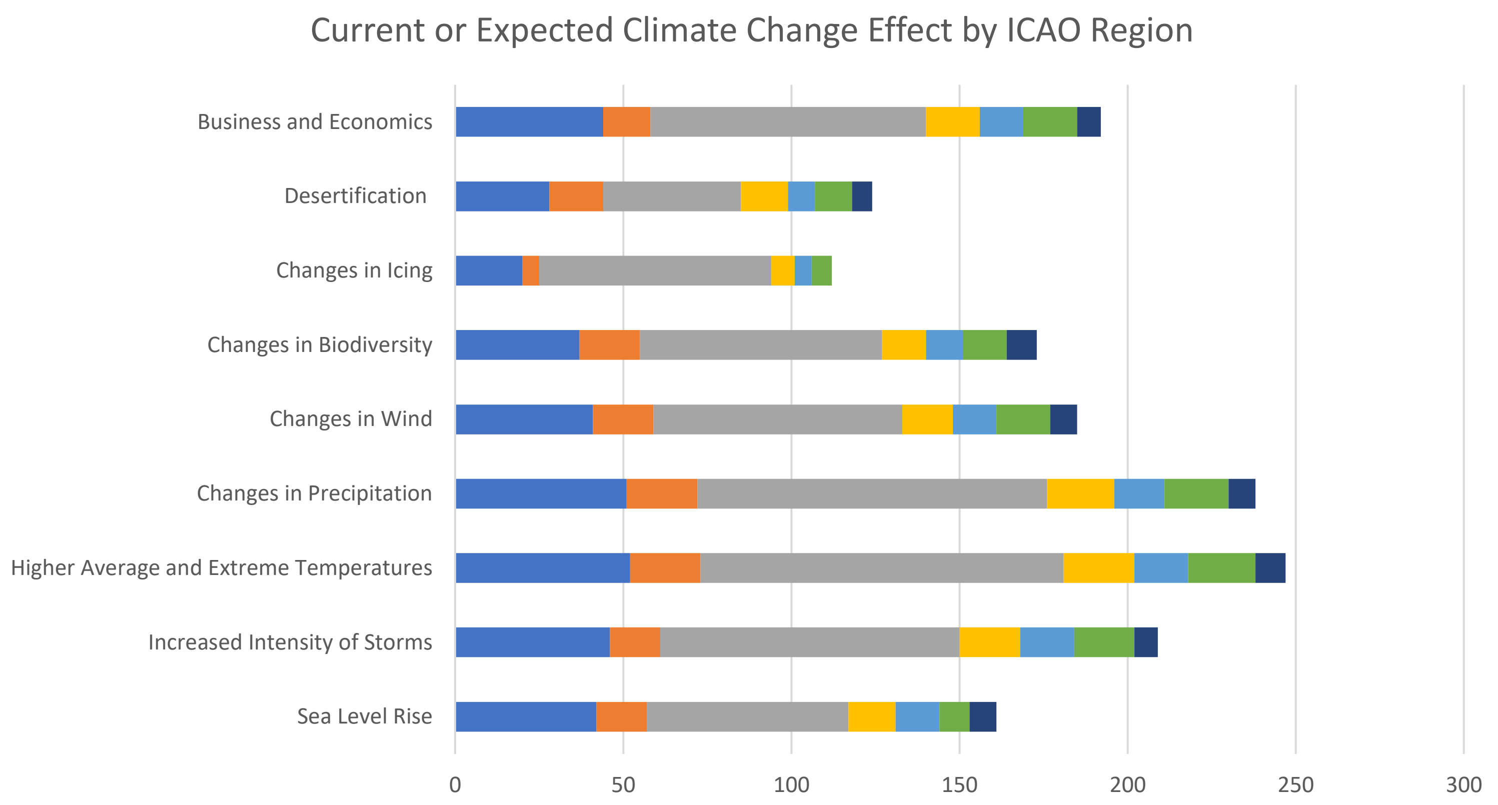
Figure 6 Percentage of Respondents that are affected today or expect to be affected in the future by climate change effect

The 2022 Survey asked respondents if they are already experiencing effects of climate change by climate effect category. Each climate effect category was a separate question and respondents were asked to answer each question individually. The top three climate effects categories respondents are already being affected by or anticipate experiencing are Higher Average and Extreme Temperatures, Changing Precipitation, and Increased Intensity of Storms. 95% of respondents to the 2022 Survey indicated that they are affected today or expect to be affected by future climate change impacts from higher average and extreme temperatures, 92% of respondents indicated that they are affected today or expected to be affected by changing precipitation, and 81% indicated they are affected today or expect to be affected in the future by increased intensity of storms. The majority of respondents indicated they are already or expect to experience every climate effect except for Desertification and Changing Icing Conditions, both of which just over 50% of respondents do not anticipate experiencing. It is important to note that both geographic region and respondent organization type may have influenced the responses to this question.

			Comparison of percentage respondents that are or expect to be impacted by climate effect type	
2022 Rank	Change in Rank	Climate Effect Type	**2022**	**2017**
1	-	Higher Average and Extreme Temperatures	95%	91%
2	-	Changes in Precipitation	92%	89%
3	-	Increased Intensity of Storms	81%	86%
4	+5	Business and Economics	74%	58%
5	+1	Changes in Wind	71%	64%
6	+1	Changes in Biodiversity	67%	61%
7	-3	Sea Level Rise	62%	73%
8	+1	Desertification	48%	48%
9	-4	Changes in Icing	43%	65%

Table 2 Comparison of percentage of respondents that are or expect to be impacted by climate effect type

This reflects the 2017 Survey results where respondents also identified Higher Average and Extreme Temperatures (91%), Changes in Precipitation (89%), and Increased Intensity of Storms (86%) as the top three climate change effects they anticipate being impacted by. While the percentage number decreased from 2017 to 2022 for Increased Intensity of Storms, the actual number increased from 76 in 2017 to 209 in 2022. Figure 7 illustrates the number of respondents that are or expect to experience impacts from climate change effects across each ICAO region.



	Sea Level Rise	Increased Intensity of Storms	Higher Average and Extreme Temperatures	Changes in Precipitation	Changes in Wind	Changes in Biodiversity	Changes in Icing	Desertification	Business and Economics
APAC	42	46	52	51	41	37	20	28	44
ESAF	15	15	21	21	18	18	5	16	14
EUR/NAT	60	89	108	104	74	72	69	41	82
MID	14	18	21	20	15	13	7	14	16
NACC	13	16	16	15	13	11	5	8	13
SAM	9	18	20	19	16	13	6	11	16
WACAF	8	7	9	8	8	9	0	6	7

APAC ESAF EUR/NAT MID NACC SAM WACAF

Figure 7 Current or Expected Climate Change Effect by ICAO Region

Figure 7 above illustrates the number of respondents from each ICAO Region that are either currently experiencing or expect to experience impacts from the nine climate change effect categories in the 2022 survey. The bar graph represents the cumulative responses received, colour-coded for each ICAO region. The table shows the number of respondents per ICAO region. This figure illustrates that across all ICAO regions, respondents are experiencing or expect to experience each of the nine climate effect categories, with the exception of Changes in Icing, which none of the respondents from the ICAO WACAF region anticipate experiencing. Figures 8-14 below present the same information, focusing individually on each ICAO Region to better illustrate the regional expectations for each of the climate effect categories.

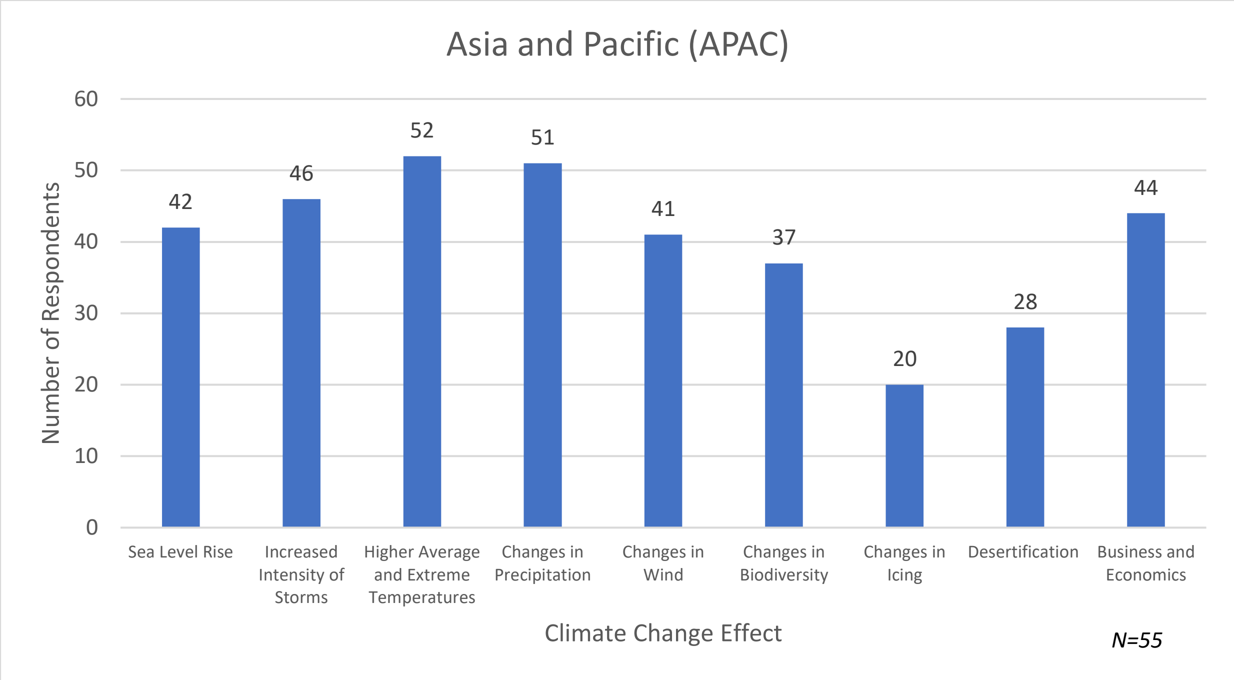


Figure 8 Distribution of responses from the APAC region

In APAC, consistent with the responses at global level, the effects which the majority of respondents are already experiencing or anticipate they will experience are Higher Average and Extreme Temperatures (52 of 55 respondents, 95%), Changes in Precipitation (51 respondents, 93%) and Increased Intensity of Storms (46 respondents, 84%). Also as per the global level, the fourth-placed effect is Business and Economic effects (44 respondents, 80%).

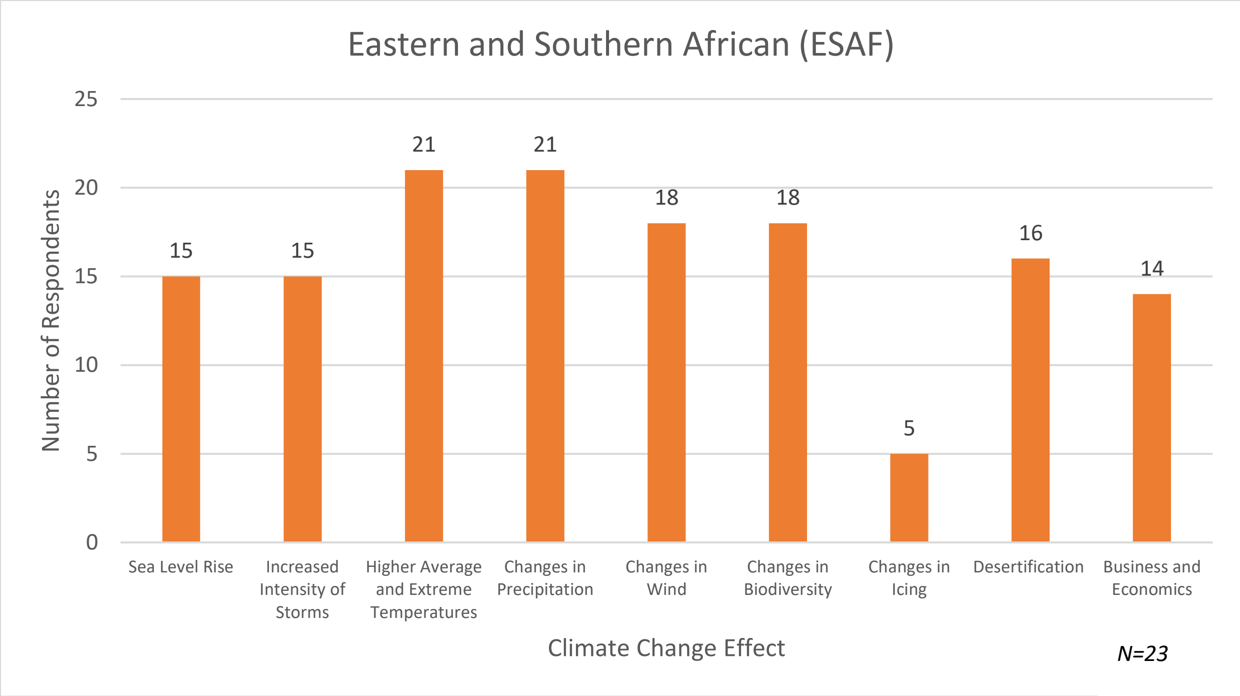


Figure 9 Distribution of responses from the ESAF region

In ESAF, the two effects the majority of respondents are already experiencing or anticipate they will experience are Higher Average and Extreme Temperatures (21 of 23 respondents, 91%) and Changes in Precipitation (21 respondents, 91%). This was followed by Changes in Biodiversity and Changes in Wind (18 respondents, 78%, each).

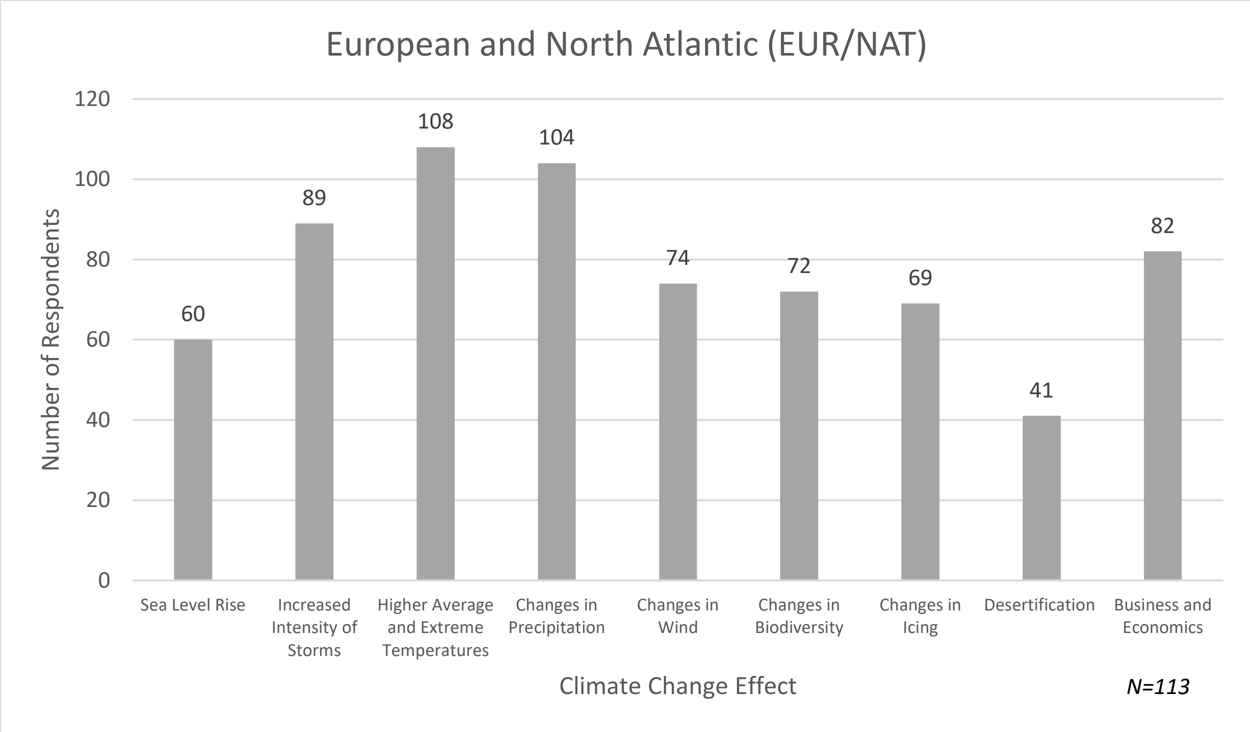


Figure 10 Distribution of responses from the EUR/NAT region

In EUR/NAT, consistent with responses at a global level, the effects which the majority of respondents are already experiencing or anticipate they will experience are Higher Average and Extreme Temperatures (108 of 113 respondents, 96%), Changes in Precipitation (104 respondents, 92%) and Increased Intensity of Storms (89 respondents, 79%). Also as per the global level, the fourth-placed effect is Business and Economic effects (82 respondents, 73%).

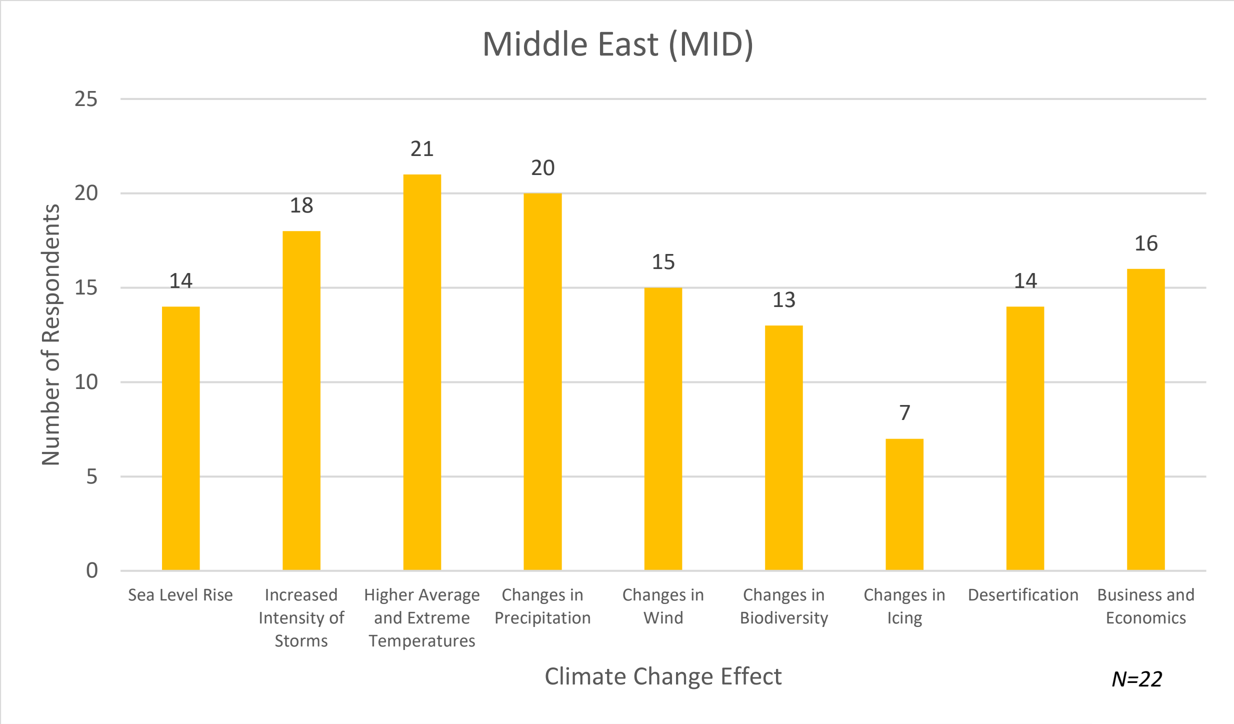


Figure 11 Distribution of responses from the MID region

In MID, consistent with responses at a global level, the effects which the majority of respondents are already experiencing or anticipate they will experience are Higher Average and Extreme Temperatures (21 of 22 respondents, 95%), Changes in Precipitation (20 respondents, 91%) and Increased Intensity of Storms (18 respondents, 82%). Also as per the global level, the fourth placed effect is Business and Economic effects (16 respondents, 73%).

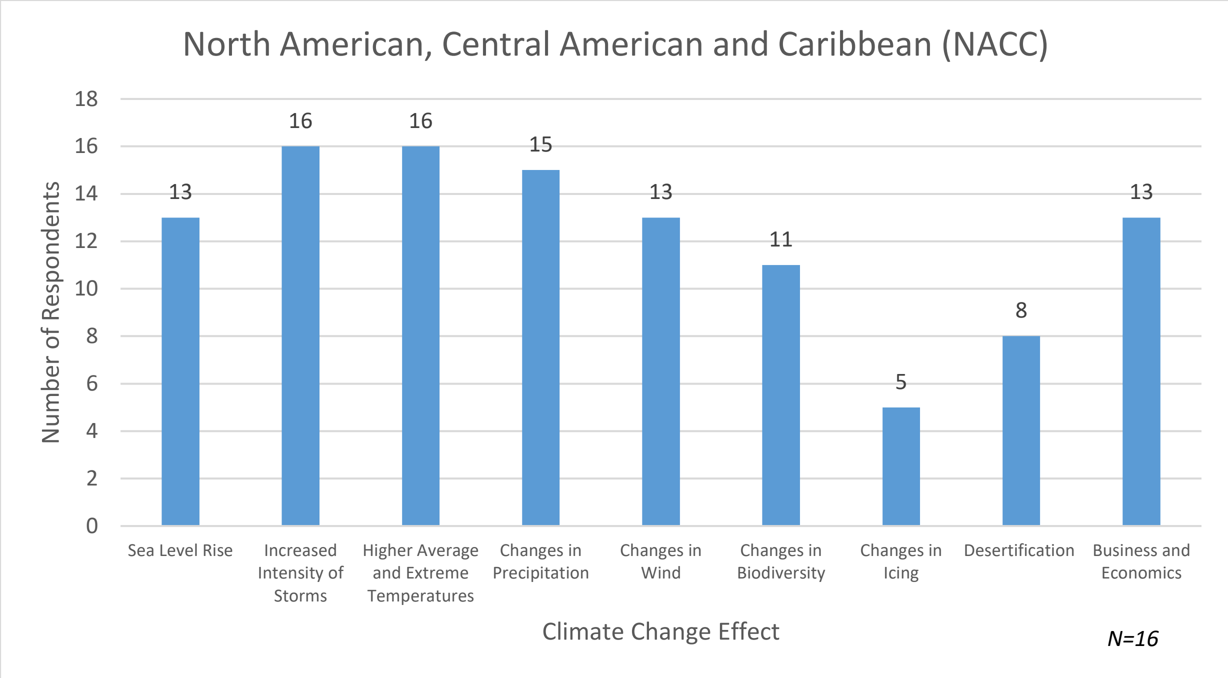


Figure 12 Distribution of responses from the NACC region

In NACC the effects the majority of respondents are already experiencing or anticipate they will experience are Higher Average and Extreme Temperatures (16 of 16 respondents, 100%), Increased Intensity of Storms (16 respondents, 100%) and Changes in Precipitation (15 respondents, 94%). Sea Level Rise, Changes in Wind and Business and Economic effects are already being experienced or anticipated by 81% of respondents (13 of 16).

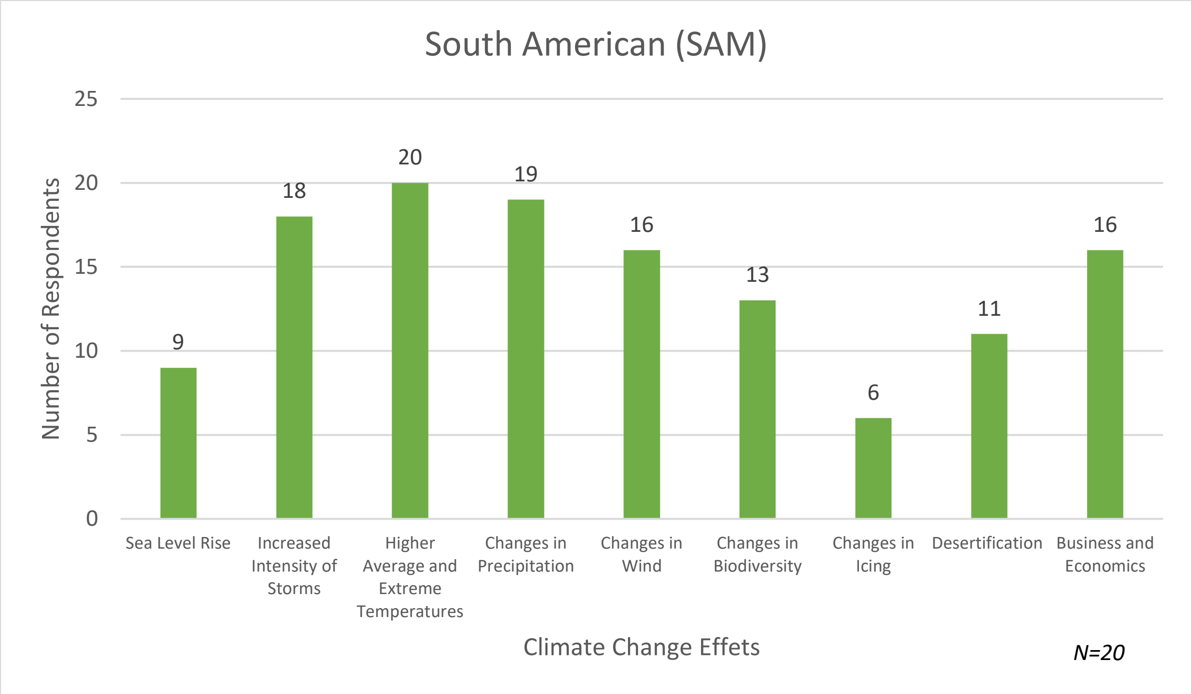


Figure 13 Distribution of responses from the SAM region

In SAM, the effects the majority of respondents are already experiencing or anticipate they will experience are Higher Average and Extreme Temperatures (20 of 20 respondents, 100%), Changes in Precipitation (19 respondents, 95%) and Increased Intensity of Storms (18 respondents, 90%). Changes in Wind and Business and Economic effects are already being experienced or anticipated by 80% of respondents (16 respondents).

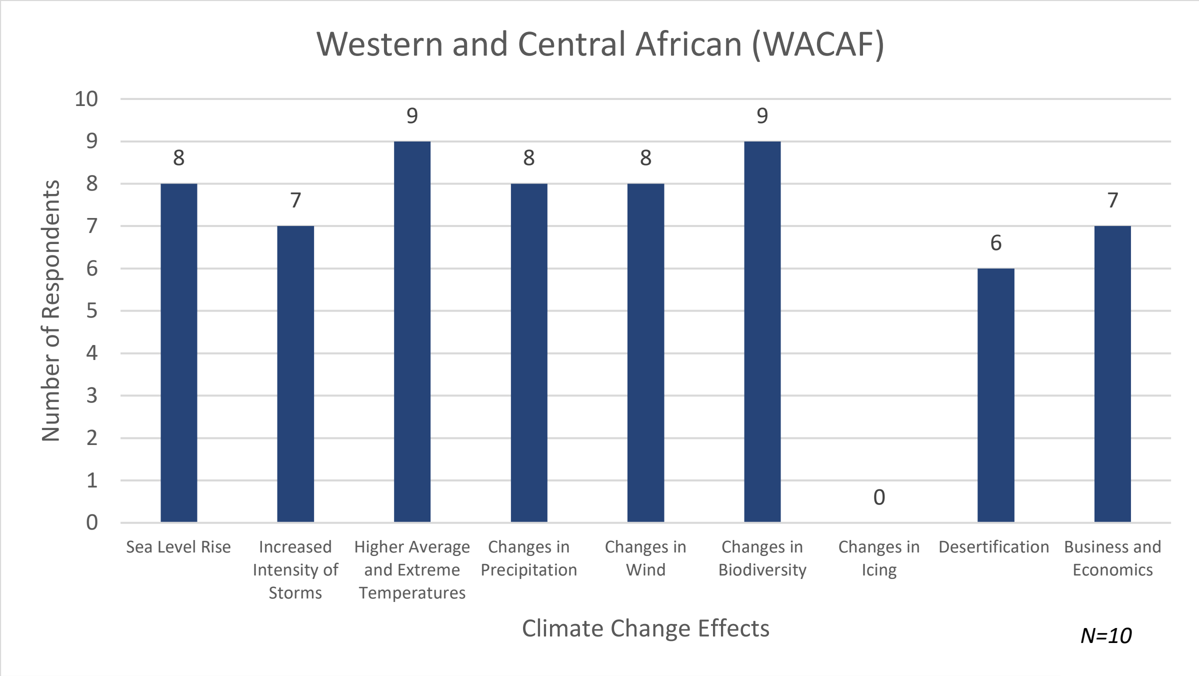


Figure 14 Distribution of responses from the WACAF region

In WACAF, the two effects the majority of respondents are already experiencing or anticipate they will experience are Higher Average and Extreme Temperatures and Changes in Biodiversity (9 of 10 respondents, 90%). Changes in Precipitation, Changes in Wind, and Sea Level Rise are already being experienced or anticipated by 80% of respondents (8 respondents).

6. Climate change Effects, Impacts and Adaptation Measures for the Aviation Sector

This section will consider each of the eight physical climate effects identified, and business impacts on and economics to assess how the effect is projected to evolve, over what timescale this is projected, the impacts of that effect for the aviation sector, and potential adaptation measures identified.

6.1 Sea Level Rise

6.1.1 Summary of effects and timescales

According to the IPCC, sea level can change both globally and locally “due to (i) a change in ocean volume as a result of a change in the mass of water in the ocean (e.g., due to melt of glaciers and ice sheets), (ii) changes in ocean volume as a result of changes in ocean water density (e.g., expansion under warmer conditions), (iii) changes in the shape of the ocean basins and changes in the Earth’s gravitational and rotational fields, and (iv) local subsidence or uplift of the land” (IPCC, 2018, p. 1-46). Based on the IPCC Sixth Assessment Report (2021) and the documents reviewed for this Synthesis, there is consensus that global average sea level is rising. The WMO State of the Climate Report 2022 assesses that "Global mean sea level continued to rise in 2022, for the satellite altimeter record (1993-2022). The rate of global mean sea level rise has doubled between the first decade of the satellite record (1993-2002, 2.27 mm per year) and the last (2013-2022, 4.62 mm per year)" (WMO, 2022[1]). In parallel the IPCC Sixth Assessment Report Summary for Policy Makers projects that “It is virtually certain that global mean sea level will continue to rise over the 21st century” (IPCC[1], 2021, p21). This will cause an increase in extreme sea level events, such as storm surge, an increase in frequency and severity of coastal flooding in low-lying areas, and greater coastal erosion (IPCC[1], 2021, p25; WMO, 2022[2], p25).

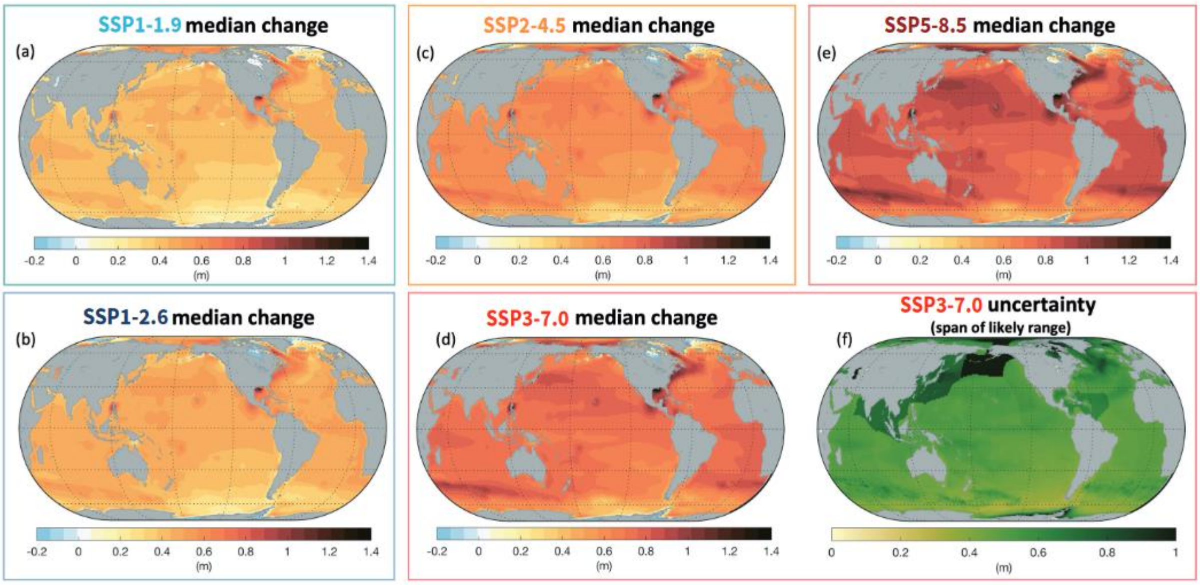


Figure 15 Sea Level Change: From the IPCC AR6 WG1 Report: regional sea level change at 2100 for different scenarios (with respect to 1995–2014). Median regional relative sea level change from 1995–2014 up to 2100 for: (a) SSP1-1.9; (b) SSP1 2.6; (c) SSP2-4.5; (d) SSP3-7.0; (e) SSP5-8.5; and (f) width of the likely range for SSP3-7.0. The high uncertainty in projections around Alaska and the Aleutian Islands arises from the tectonic contribution to vertical land motion, which varies greatly over short distances in this region (IPCC[2], 2021, Figure 9.28)

The above figure from the IPCC AR6 WG1 Report shows how sea level rise may change around the world according to each Shared Socioeconomic Pathways SSP emission scenario by 2100 relative to a 1995 to 2014 baseline.

Small Island Developing States (SIDS)

SIDS are heavily dependent on coastal transport infrastructure such as airports for economic activity (UNCTAD, 2018) yet are particularly vulnerable to the impacts of sea level rise, with vulnerability rising rapidly in low-lying small islands (IPCC, 2022). In extreme cases the entire State may be threatened by sea level rise. According to the chapter on Climate Change Resilience and Adaptation in the 2018 Airport Planning Manual Part II, "The United Nations (UN) General Assembly has recognized the criticality of this group of countries and raised awareness of the challenges these regions are facing, including the impact of climate change on such States. Small island developing states face unique challenges because of their reliance on aviation for connectivity with other States and tourism development. For example, the UN has identified that Maurice Bishop International Airport (the main airport servicing Grenada and located on the southern coast of the island) would likely be inundated in a 50-centimeter sea level rise scenario and a 1-meter rise would inundate the Maldives" (ICAO, p. 9-5).

Sea level rise as a climate change phenomenon is unstoppable in the foreseeable future and projections for future sea level rise are considered over hundreds to thousands of years. For the purpose of this Synthesis however, across the documents reviewed the timescales considered for impacts due to changes to sea level rise range from very near-term (currently observed or with timescales of 2030), to 2050 for mid-term impacts and 2080-2100 for long-term impacts.

6.1.2 Potential Impacts on Aviation from Sea Level Rise

Low-lying coastal infrastructure such as airport terminals, runways, taxiways, and assets, aviation navigation and communication equipment, and ground transportation, may be vulnerable to the impacts of sea level rise at airports near sea-level, proximal to the sea and/or built on land reclaimed from the sea. The impacts of sea level rise, manifesting through coastal inundation, saltwater intrusion and groundwater elevation rise, may damage infrastructure or inundate ground transport access, preventing aviation sector employees, passengers and freight from being able to access or leave an airport.

According to Yesudian and Dawson (2021) the "sea level rise associated with a global mean temperature rise of 2 °C [by 2100] would place 100 airports below mean sea level, whilst 1238 airports are in the Low Elevation Coastal Zone," with many being key hubs for global connectivity. EUROCONTROL highlight the potential costs of an airport closure due to sea level rise or storm surge positing the average cost of a 1-day closure of a medium-sized European airport (30-100K movements per annum) at 3 million euros per day and of a large airport (over 100k movements per annum) at 18 million euros per day (EURCONTROL[2], 2021).

Although the global sea level has been rising and is projected to continue rising at a progressively faster rate in many regions, the projected impacts from sea level rise may still be far in the future for some locations (e.g., after 2100) whereas in others they may be experienced sooner.

6.1.3 Adaptation and Resilience Measures

In areas where projected impacts from sea level rise are expected in the near to mid-term, there are some adaptation and resilience measures already being taken to address vulnerabilities and improve operational resilience, such as installing sea defences and other protective measures (ACI World, 2018; San Francisco Bay Conservation and Development Commission, 2017).

According to Yesudian and Dawson (2021, p.8) "Coastal airports have four main adaptation choices: (i) Protect, (ii) Raise, (iii) Relocate, and (iv) Reclaim or Float. The size of an airport, and the nature of their operations, usually means that adaptation requires costly engineering works." This includes, as the ICAO Airport Planning Manual (2018) explains, "…building infrastructure higher or reinforcing existing infrastructure (e.g., using salt water-resistant materials and/or sealants), building or reinforcing sea defences, retaining or introducing natural barriers, allowing a certain degree of inundation as long as safety is not compromised" (p. 9-5). Relocating vulnerable infrastructure and even developing new secondary airports that will not face the same sea level impacts are also potential options (ACRP, 2014; San Francisco Bay Conservation and Development Commission, (2017); Palko and Lemmen, (Eds., 2017); ICAO[3], 2022).

Corrosion from sea water can damage infrastructure as well as equipment such as weather sensors, that are not designed to be salt water-resistant. With more frequent coastal flooding due to SLR, they will be corrupted more quickly (ACRP, 2015).

Planning of new airports in coastal regions should take sea level rise projections into account. Since the effects of sea level rise will vary by locality, there is no single strategy that will be appropriate for the entire aviation sector. Based on the documents reviewed for this Synthesis, there seems to be a broad recognition that sea level rise projections and vulnerabilities must be assessed at the local level.

SIDS may face particular challenges in adapting to sea level rise due to lack of data, sea-locked and constrained land areas, logistical constraints due to remote locations, economic reliance on air transport and potential lack of human and financial resources (UNCTAD, 2018).

6.1.4 Survey analysis

The following charts present the results of the survey questions on sea level rise. Figure 16 presents an overview of the timeframe in which respondents expect to experience sea level rise. Figure 17 provides a regional breakdown of responses. Figure 18 presents the impacts which respondents expect from sea level rise.

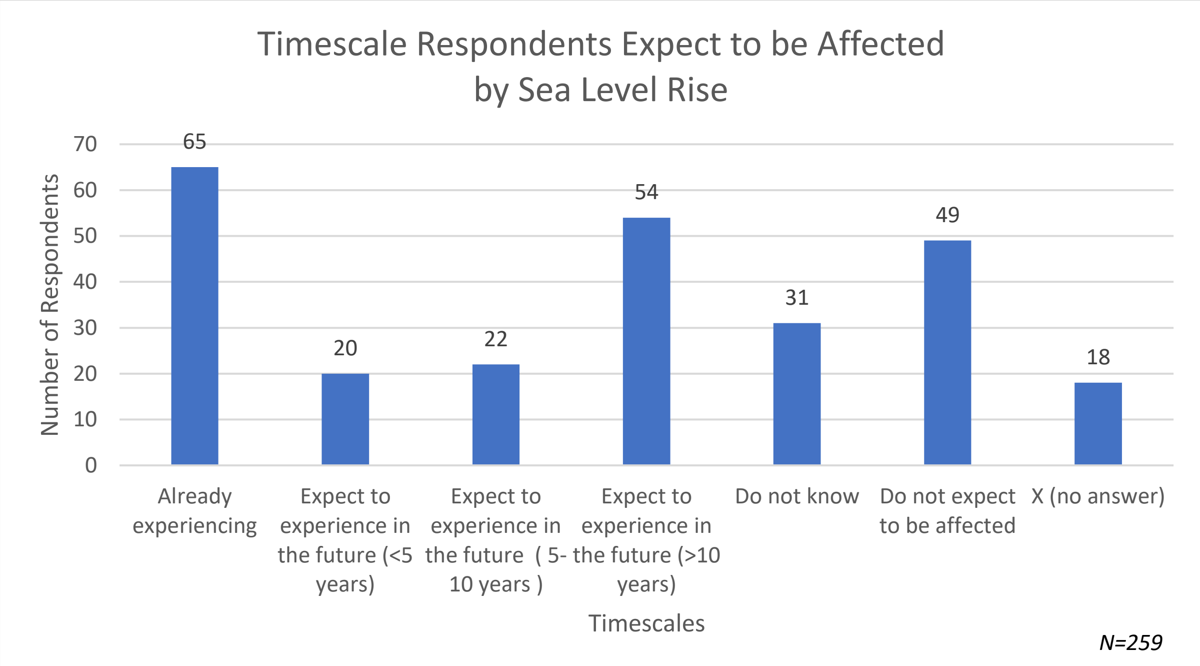


Figure 16 Timescales Respondents expect to be affected by Sea Level Rise

Overall, of 259 respondents, 161 expect to be affected by sea level rise now or in the future. However, this number may be influenced by regional differences, such as whether a State is landlocked, or whether it has airports or infrastructure in close proximity to bodies of water. Lake level rise was also identified as a potential effect by one respondent.

Sixty-five respondents are already experiencing the effects of sea level rise and 96 expect to experience it in the future. Forty-nine respondents do not expect to be affected, and 31 do not know.

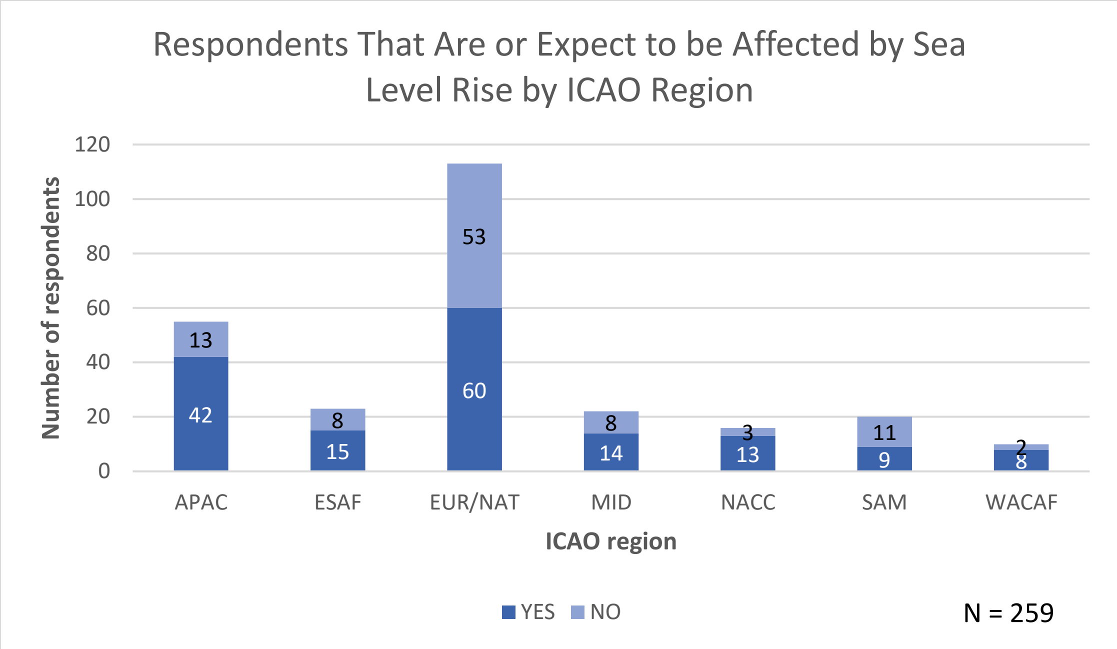


Figure 17 Number of respondents that are affected today or expect to be affected in the future by sea level rise by ICAO region

The chart above shows the number of respondents that expect to be affected by sea level rise by ICAO region. The light blue bars represent the number of respondents that do not expect be affected by sea level rise while the dark blue bars represent the number of respondents that do expect to be affected by sea level rise. For example, in the Asia Pacific region, 42/55 respondents (76%) said they expect to experience effects of sea level rise and thirteen respondents (24%) said they do not expect to experience effects of sea level rise. Fourteen respondents (64%) from the Middle East, fifteen respondents (68%) from Eastern and Southern Africa, and 60 respondents (53%) from Europe and the North Atlantic region expect to be affected by sea level rise. Eight out of ten respondents (80%) In Western and Central Africa and thirteen respondents (81%) North American, Central American, and Caribbean indicated they would be affected by sea level rise. The South American region is the only region where less than 50% of respondents expect to be affected by sea level rise with nine respondent (45%) expecting to be affected and 11 (55%) not expecting to be.

Geography, particularly whether or not a respondent is landlocked, played a large role in the response to this question. In total, 29 respondents from 14 different States are landlocked. No respondents from the Middle East, or North American, Central American, and the Caribbean or Western and Central Africa regions are landlocked. One respondent from the Asia Pacific region is landlocked. Six respondents from four States in the Eastern and Southern Africa region are landlocked, eighteen respondents from twelve States in the European and North Atlantic region are landlocked, and four respondents from the South American region are landlocked, all in the same State. In general respondents that were landlocked either indicated that they did not expect to be affected by sea level rise, did not know, or did not answer the question. However, three respondents from the Eastern and Southern Africa region, two respondents from the European and North Atlantic region, and one respondent from the South American region who are landlocked indicated that they are either already experiencing or expect to be affected by sea level rise. Two of the respondents are airlines, therefore the answers could relate to destinations to which they fly. The other respondents are States and CAA.

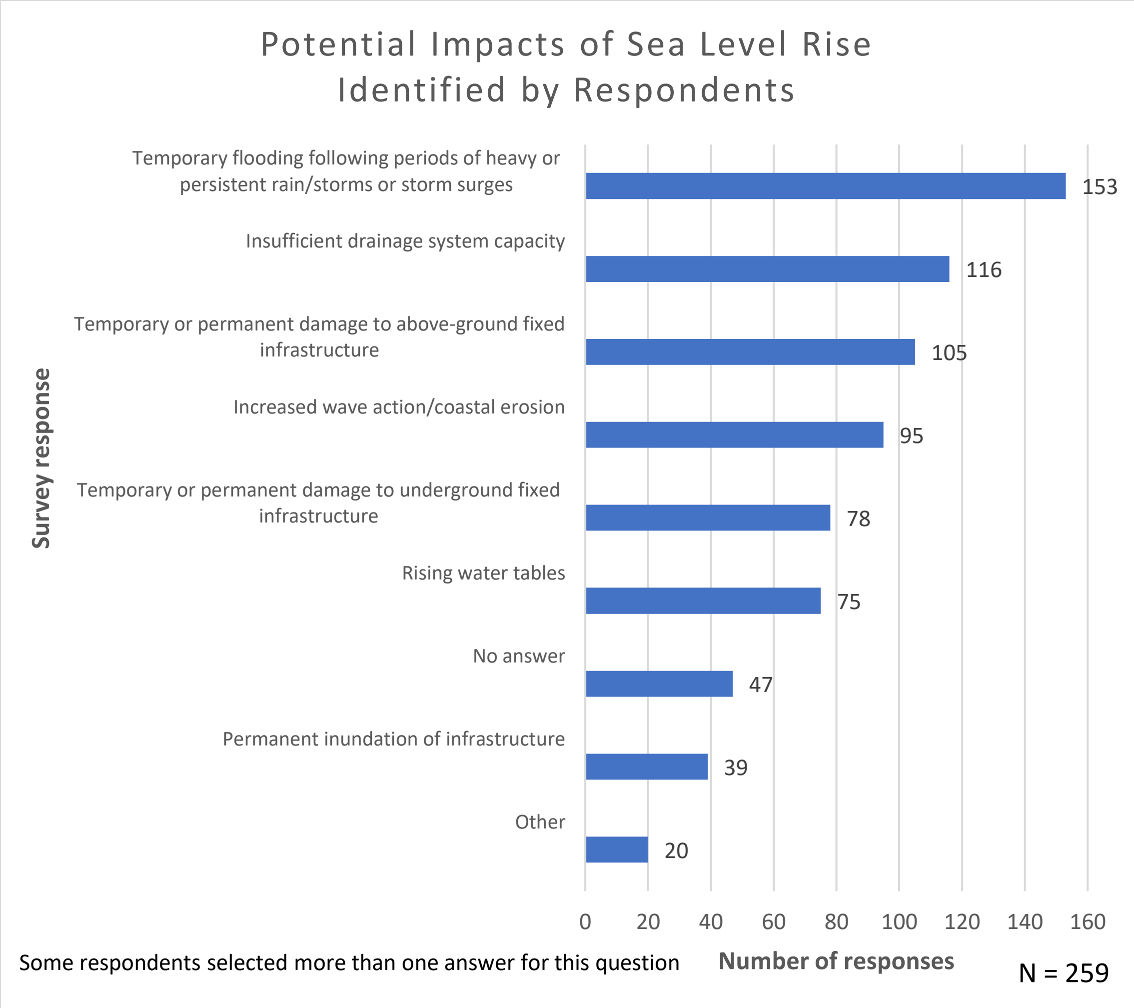


Figure 18 Potential impacts of sea level rise identified by respondents

The main impacts that respondents expect to experience from sea level rise are temporary flooding following periods of heavy or persistent rain/storms or storm surges and insufficient drainage system capacity. Many respondents gave more than one answer. The respondents who selected "Other" identified, "Increase of tidal flood that affect disruption of airport operation (ex: close runway)", "Soil salinization and seawater seepage into fresh groundwater reserves", "future development areas constrained due to inundation", "Deterioration of coastal eco-systems", "landslides, high erosion intensity" and "Difficulty for adequate drainage at the mouth of rivers."

6.2 Increased Intensity of Storms

6.2.1 Summary of Effect and Timescales

The WMO (1992) define a storm as "(1) An atmospheric disturbance involving perturbations of the prevailing pressure and wind fields, on scales ranging from tornadoes (1 km across) to extratropical cyclones (2000-3000 km across). (2) Wind with a speed between 48 and 55 knots (Beaufort scale wind force 10)." The types of storms discussed in the documents reviewed included winter storms, tropical cyclones (also classed as hurricanes or typhoons depending on the region in which they occur), extra-tropical cyclones, arctic cyclones, and convective systems, including those accompanied by lightning.

There is broad consensus among the documents reviewed that, overall, storms are projected to become stronger, i.e. to increase in wind strength, as the climate warms but the frequency of these storms in the future is less conclusively understood. The IPCC AR6 states that "the proportion of intense tropical cyclones (Category 4–5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (high confidence)" (IPCC[1], 2021 p.6). However, there is uncertainty about the frequency and intensity of storms in the future at the regional level; the projected changes are not expected to be uniform for all storm systems and in some areas, storms may become more powerful and more frequent, while in others they may only become more powerful (IPCC[2], 2021; EUROCONTROL[1], 2021).

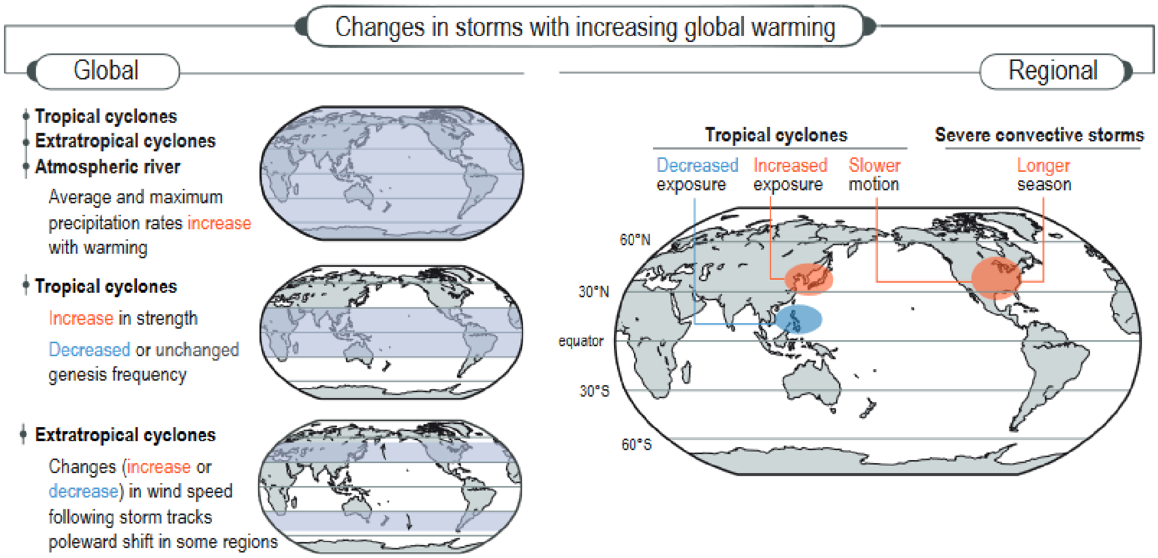


Figure 19 Projected changes in storms: From the IPCC AR6 WG1 Report: Summary schematic of past and projected changes in tropical cyclone (TC), extratropical cyclone (ETC), atmospheric river (AR), and severe convective storm (SCS) behaviour. Global changes (blue shading) from top to bottom: (i) Increased mean and maximum rain rates in TCs, ETCs, and ARs [past (low confidence due to lack of reliable data) and projected (high confidence)]; (ii) Increased proportion of stronger TCs [past (medium confidence) and projected (high confidence)]; (iii) Decrease or no change in global frequency of TC genesis [past (low confidence due to lack of reliable data) and projected (medium confidence)]; and (iv) Increased and decreased ETC wind speed, depending on the region, as storm tracks change [past (low confidence due to lack of reliable data) and projected (medium confidence)]. Regional changes, from left to right: (i) Poleward TC migration in the western North Pacific and subsequent changes in TC exposure [past (medium confidence) and projected (medium confidence)]; (ii) Slowdown of TC forward translation speed over the contiguous USA and subsequent increase in TC rainfall [past (medium confidence) and projected (low confidence due to lack of directed studies)]; and (iii) Increase in mean and maximum Severe Convective Storm (SCS) rain rate and increase in spring SCS frequency and season length over the contiguous USA [past (low confidence due to lack of reliable data) and projected (medium confidence) (IPCC[2], 2021, Figure 11.20)

One of the challenges with this impact category is that storm systems are very diverse depending on geographical location. The 2016 ICAO ISG White Paper on Climate Change states, “Some evidence suggests that both frequency and intensity of tropical cyclones may develop differently in different ocean areas (e.g., Caribbean, East Pacific, etc.), and a possibly noticeable increased role of the El Niño Southern Oscillation cycles on weather patterns” (Puempel, et al., p.E-3). Meanwhile, the *Climate Risks & Adaptation Practices for the Canadian Transportation Sector 2016* report states, “there is strong evidence that the frequency and intensity of storms in the Arctic is increasing …[and] Increasingly-large areas of open water result in more intense cyclonic storms – these storms will grow larger and stronger as sea-ice extent is projected to decrease even further” (Pendakur, p.37). Moreover, there is “low confidence in most regions in potential future changes in … hail, ice storms, severe storms, dust storms” (IPCC[1], 2021 p25).

The IPCC AR6 WG1 Summary for Policy Makers Report illustrates how as temperatures increase the risk of extreme weather events, such as extreme storminess, will also increase. “Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation, and, in some regions, agricultural and ecological droughts; an increase in the proportion of intense tropical cyclones; and reductions in Arctic sea ice, snow cover and permafrost" (IPCC[1] p.15). It is noted that "with every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (very likely), and heavy precipitation (high confidence). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5°C of global warming. Projected percentage changes in frequency are larger for rarer events (high confidence)" (IPCC[1] p.15).

Timescales for the effects of increased intensity of storms vary across the documents reviewed and include currently observed to 2020 or 2030 for short-term impacts, 2050 for mid-term impacts and 2080-2100 for long term impacts.

Storm Surge: Summary of Impact and Timescales

According to the IPCC 2021 WG1 Glossary, storm surge is "The temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place" (IPCC[3], p. 2250). Storm surge already impacts coastal communities, and is projected to have greater impacts as the climate continues to change due to sea level rise and an increased frequency and severity of storms. Depending on local geography, storm surge can inundate areas that are not considered "coastal" (e.g., storm surge "impacts [can extend] 30km inland on the Mackenzie Delta" in Canada) according to the *Climate Risks & Adaptation Practices for the Canadian Transportation Sector 2016* report (Pendakur, p. 37)).

Timescales for changes to storm surge vary across the documents reviewed and include currently observed, to 2030 for short-term impacts, 2050 for mid-term impacts and 2080-2100 for long term impacts.

6.2.2 Potential Impacts on Aviation from Increased Intensity of Storms

Potential impacts on aviation from increased intensity of storms vary widely. They can include disruption to air traffic operations, including delays and cancellations, damage to airport infrastructure, disruption to ground transportation and airport access, inundation of drainage systems, and impacts to availability of commercial power and telecoms (ICAO[2], 2022). The ICAO guidance on Key Climate Change Vulnerabilities for Aviation Organisations (2022) also notes that loss of capacity in one part of the network can have knock-on impacts across the wider network. EUROCONTROL also note that storms can impact horizontal flight efficiency, for example due to deviations around a storm, and cause an increase in fuel burn and emissions (EUROCONTROL[1], 2021).

As global temperatures increase, lightning is projected to also increase (Romps, et al, 2014). Lightning strikes can delay or cancel flights, restrict and delay airport operations, damage aircraft, airport, or air traffic infrastructure and increase safety risks for personnel (ICAO[2], 2022).

Storm Surge: Potential Impacts on Aviation

Low-lying coastal infrastructure may be vulnerable to the temporary inundation caused by storm surge. This infrastructure includes aviation navigation and communication equipment, airport assets, the airfield, and ground transportation. Storm surges cause inundation which may prevent aviation sector employees, passengers and freight from being able to access an airport. Storm surge inundation can damage or destroy infrastructure (ICAO, 2022). Because the aviation industry is so interconnected, an impact at one airport or aviation facility may have ripple-effects across a wide geographical area. EUROCONTROL (2021) projected that two-thirds of coastal and low-lying airports in the ECAC region will be at risk of inundation from sea level rise or storm surge by 2090. The 2014 U.S. National Climate Assessment has identified, "Thirteen of the nation's 47 largest airports have at least one runway with an elevation within the reach of moderate to high storm surge." (Melillo, Richmond and Yohe, (Eds., p.134).

6.2.3 Adaptation and Resilience Measures

In their Menu of Adaptation Options, ICAO recommends reinforcing or designing facilities for higher intensity hurricanes, typhoons, and other extreme events. This can include both grey measures to reinforce and strengthen infrastructure and nature-based measures such as mangrove or wetlands to help with wind reduction (ICAO[3], 2022).

There is a need for improved weather data availability and quality so as to prepare for storms before they happen (ICAO[3], 2022). This can also support operational decision-making during a disruptive event. In preparation for the projected increased intensity of storms, an ACRP synthesis report (2012) described how two airports in Jackson, Mississippi, located in the southern United States, prepare for an increased intensity of storms by "…keeping the airfield open, securing fuel for generators, ensuring that lights and navigational aids are in working order, and requiring staff to clear debris" (p.16). Alternatively, when forecasted storms are severe, some airports or airlines may pre-emptively cancel flights to ensure the safety of their operations and to reduce business impacts. Puempel and Williams (2016) stated that "a thorough analysis of [an increased severity of storms] on the safety and regularity of flights" is needed (p.207).

Improved lightening detection systems around airports and lightning protection shelters on the air side of an airport can help to build resilience to a potential increase in lightning strikes (ICAO[3], 2022).

Early warning systems and emergency management plans are essential. However, ICAO highlights the importance of not only having contingency plans in place for storms or other disruptive weather events, but that they should be practiced regularly so all stakeholders are prepared to implement them during an actual event (ICAO[3], 2022).

Storm Surge: Adaptation and Resilience Measures

Facilities need to be more resilient to storm surge (BOS Sustainable Management Plan, 2015, ICAO, 2022) and vulnerable people or infrastructure will either need to be protected or moved to mitigate the effects of storm surge (San Francisco Bay Conservation and Development Commission, 2017). Any new airports that are built should consider storm surge projections during the planning process (ICAO, 2018).

6.2.4 Survey analysis

The following charts present the results of the survey questions on increased intensity of storms.

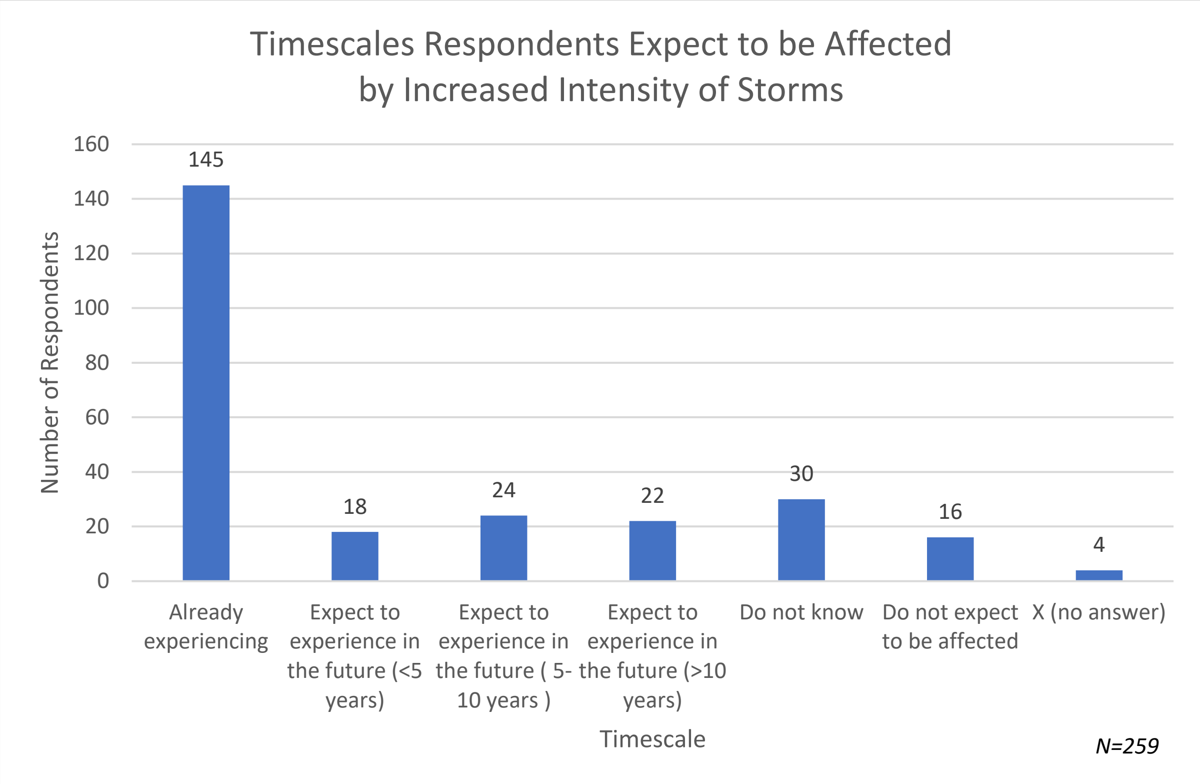


Figure 20 Timescales respondents expect to be affected by increased intensity of storms

Two hundred and nine out of 259 respondents expect to be affected by increased intensity of storms, indicating that this impact is expected to be widely experienced. One hundred and forty-five respondents are already experiencing the effects of increased intensity of storms and 64 expect to experience it in the future. Only 16 respondents do not expect to be affected, and 30 do not know.

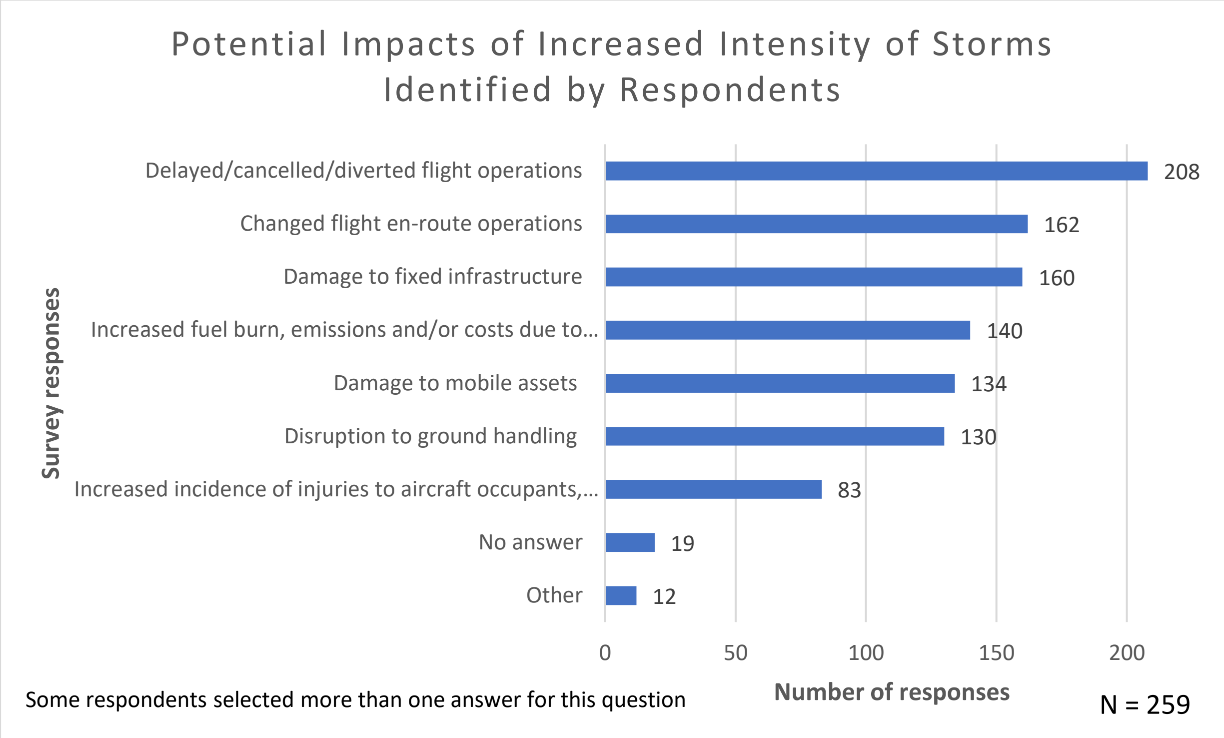


Figure 21 Potential effects of increased intensity of storms identified by respondents

The main impacts that respondents expect to experience are delayed, cancelled or diverted flight operations, changed flight en-route operations and damage to fixed infrastructure. Many respondents gave more than one answer to this question. The respondents who selected "Other" identified, "Disruption to access to the airport (both passengers and emergency services) due to flooding of key roading infrastructure", "reduced asset life and increased maintenance costs due to damage and wear and tear from salt impacts from storm surge and more intense storm;", "high cost of fuel consumption due to diversion of flights, discomfort of passengers", "Early deterioration/destruction of infrastructure" and "flooding".

6.3 Temperature Change

6.3.1 Summary of Effect and Timescales

According to the WMO State of the Global Climate report (2022) global mean temperature in 2022 was around 1.15 ± 0.13 °C above the 1850–1900 pre-industrial average (WMO[1], 2022, p3) while the "annual mean global near-surface temperature for each year between 2022 and 2026 is predicted to be between 1.1°C and 1.7°C higher than preindustrial levels" (WMO[2], 2022, p.2). The IPCC AR6 WG1 Summary for Policy Makers states that "global surface temperature will continue to increase until at least mid-century under all emissions scenarios" (IPCC[1], 2021, p4). Moreover, many other changes in the climate system are increased in direct relation to increasing global warming. This includes 'increases in the frequency and intensity of hot extremes, marine heatwaves, heavy precipitation [and] an increase in the proportion of intense tropical cyclones; and reductions in Arctic Sea ice, snow cover and permafrost" (IPCC[1], 2021 p15). For example, "every additional 0.5°C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (very likely), and heavy precipitation (high confidence)" (IPCC[1], 2021, p15). There will also be an increase of previously unprecedented extreme events as well as an increase in permafrost thaw and loss of seasonal snow cover and land ice (IPCC[1], 2021).

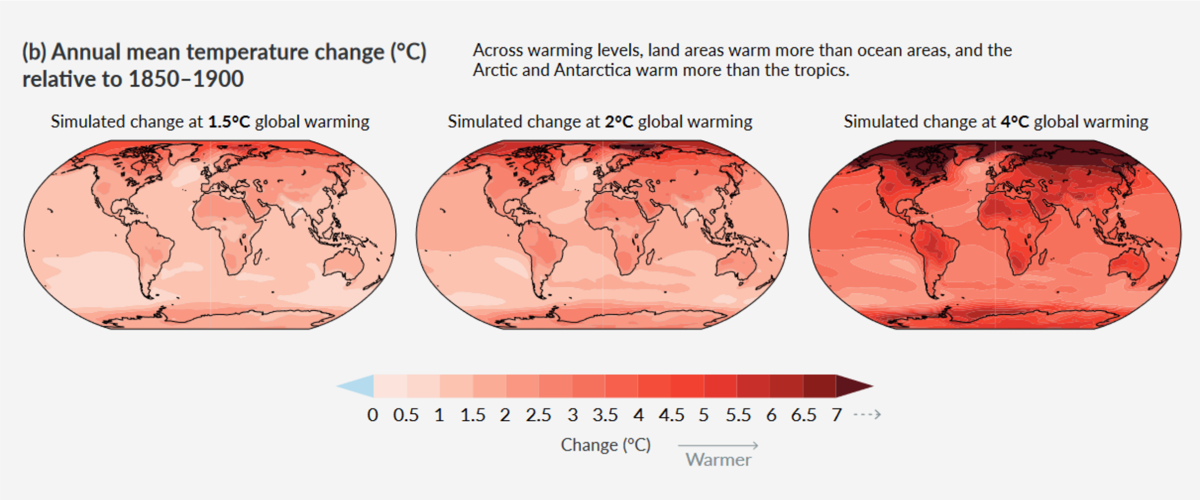


Figure 22 Temperature Change: From the IPCC AR6 WG1 Summary for Policy Makers: Simulated annual mean temperature change (°C)) at global warming levels of 1.5°C, 2°C and 4°C (20-year mean global surface temperature change relative to 1850–1900). Simulated changes correspond to Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model mean change (median change for soil moisture) at the corresponding global warming level (IPCC[1], 2021 SPM, Figure SPM5 panel (b))

There are regional differences in the extent of warming projected. For example, according to Palko and Lemmen (Eds.2017), Arctic temperatures are rising at a faster rate "…than most regions of the world", with the largest average changes occurring in the winter months (p.36). In Latin America and Europe warming is projected to increase at rates greater than the global average (IPCC[2], 2021). In Africa "a substantial increase in heatwave magnitude and frequency over most of the Africa domain is projected for even 2°C global warming" (IPCC[2], 2021 p1791). In Asia, Australasia and North America warming trends are also projected to continue. Almost all subregions are projected to experience an increase in extreme heat (IPCC[2], 2021).

The timescales for the projected changes vary across the documents reviewed from projections for the next five-years (WMO, 2022) to mid-century or longer (IPCC[2], 2021).

6.3.2 Potential Impacts on Aviation from Temperature Change

Rising temperatures affect aircraft lift and the ratio of lift to weight, due to change in air density, but also the maximum available engine thrust when ambient temperature exceeds a specific threshold defined by the engine manufacturer (called corner point temperature). This may affect the required runway length to maintain normal operations or may limit climb performance (ICAO[2], 2022). An analysis of 19 major international airports demonstrated that 10–30% of flights may require weight restrictions during daily maximum temperature periods by mid- to late century (Coffel et al., 2017). Analysis by Gratton et al (2020) of the impacts of higher temperatures on Greek Island airports found that this would cause a steady reduction in payload at airports with shorter runways.

Higher temperatures may increase the risk of fire either due to increased prevalence of conditions conducive to wildfires or when the ambient temperature exceeds the flashpoint of fuel in the presence of an ignition source (ICAO[2], 2022). They can also accelerate permafrost thaw, destabilizing and damaging ground infrastructure such as runways and access roads (Avinor, 2022; ICAO[2], 2022).

Higher average and extreme temperatures will increase cooling requirements causing stress to Heating, Ventilation and Air Conditioning (HVAC) systems and increasing HVAC costs (ICAO[2], 2022). If cooling requirements cannot be met then there are health and safety impacts for personnel and passengers (ICAO[2], 2022).

In northern parts of the northern hemisphere, warmer temperatures may cause permafrost to thaw, which can destabilize and damage ground infrastructure, including the airfield and contribute to erosion (ACRP, 2012; EUROCONTROL, 2013; Puempel et al., 2016; Palko and Lemmen (Eds.), 2017). In warmer climates, higher temperatures can damage the airfield surface if temperatures exceed design standards (Heathrow Airport, 2011). An additional factor to take into account is the influence of groundwater on permafrost thaw. Several studies suggest that the combination of higher temperatures and advective heat transfer from groundwater flow can accelerate permafrost thaw. Therefore, this is a factor to consider in areas where permafrost thaw is a risk (Zottola et al, 2012).

More extreme cold temperature days in cold climates also have direct effects on aviation. For example, as stated by Phillips and Towns (2017), "…in the cold winter of 2013-2014, some U.S. carriers' scheduled flights to western Canada were cancelled because the aircraft were only certified to -30°C. Such scheduling disruptions have been reported to occur with greater frequency in response to more rapid temperature shifts" (p.131). Unusual extreme cold spells, especially for an extended period, can also cause equipment underperformance, chemicals to lose their effectiveness in melting ice and snow, an increase in aircraft turnaround times leading to congestion, fueling delays due to equipment freezing and issues within the terminal facilities themselves, including for example, burst water pipes and challenges to maintain acceptable indoor temperatures in extreme cold weather (GTAA, 2014). For example, at Bozeman Yellowstone International Airport in the winter of 2013, "temperatures dropped to -30°F, below the -25°F threshold minimum required for aircraft deicing chemical agent. Flights were therefore prevented from taking off until temperatures rose a few hours later. Because the frigid temperatures were sustained for 10 days straight, the cold temperatures penetrated deeper into the facilities. One of the airport's automatic entry doors failed to close, exposing the sprinkler line in the vestibule to cold temperatures and freezing it." (ACRP, 2016 p.CS-3).

Climate change may impact air travel demand at both regional and global scale (Koetse and Reitvald, 2009). For example, as temperature changes, demand for air travel to certain locations may also change, which may impact capacity in some areas. EUROCONTROL posits that by 2050 a wider area of Europe will become favourable for tourism in both the summer and spring and autumn shoulder months, leading to a slight season and geographical shift in tourism passenger demand. In parallel, other European regions may become less favourable at certain times of year due to changing local climatic conditions (EUROCONTROL[3], 2021).

6.3.3 Adaptation and Resilience Measures

To adapt to the impacts of higher temperatures on take-off performance, the ICAO Menu of Adaptation Options proposes moving departure times for heavier aircraft to cooler times of day, for example early morning or later in the evening, although noting that this may change noise disturbance near an airport, or reducing payload of aircraft (ICAO[3], 2022). The 2018 ICAO Airport Planning Manual notes that "in areas where higher temperatures may be a challenge for aircraft take-offs, future temperature and aircraft runway length calculations may need to be reconsidered when determining the appropriate runway length" (ICAO, p.9-6).

Cooling capabilities may need to be increased in buildings and aircraft. Measures to promote heat health and safety for ground staff will be required (ICAO[3], 2022).

In areas affected by permafrost thaw, adaptation and resilience measures are being taken, including, "reinforcement or elevation of runways and access roads, and relocation" of facilities as described in the 2012 ACRP Synthesis 33 (ACRP, p.14). In Alaska (USA), a few coastal communities are relocating and moving their airports due to permafrost thaw and the subsequent erosion of land (Ibid.). Pendakur (2017) states that, in northern areas, airports with "…gravel runways can correct for ground settlement resulting from permafrost thaw by adding material to the runway/taxiway" (p.52). Monitoring of permafrost depth and of land subsidence, through actual instrumentation or through remote sensing[7], can help to better understand the permafrost underlying runways and airport infrastructure (Ibid.).

Adaptation measures for extreme cold can include proactively deploying warming stations to protect ground support crews during unusually cold weather (for the location in question) and developing procedures to service frozen equipment and fuel hydrants as required. Back-up and additional measures for heating terminal areas should also be considered (GTAA, 2014).

Schedule changes to allow fog to dissipate could mitigate the effects of more frequent fog events. This could mean moving early morning departures to late morning for some locations (Phillips and Towns, 2017).

6.3.4 Survey analysis

The following charts present the results of the survey questions on temperature change.

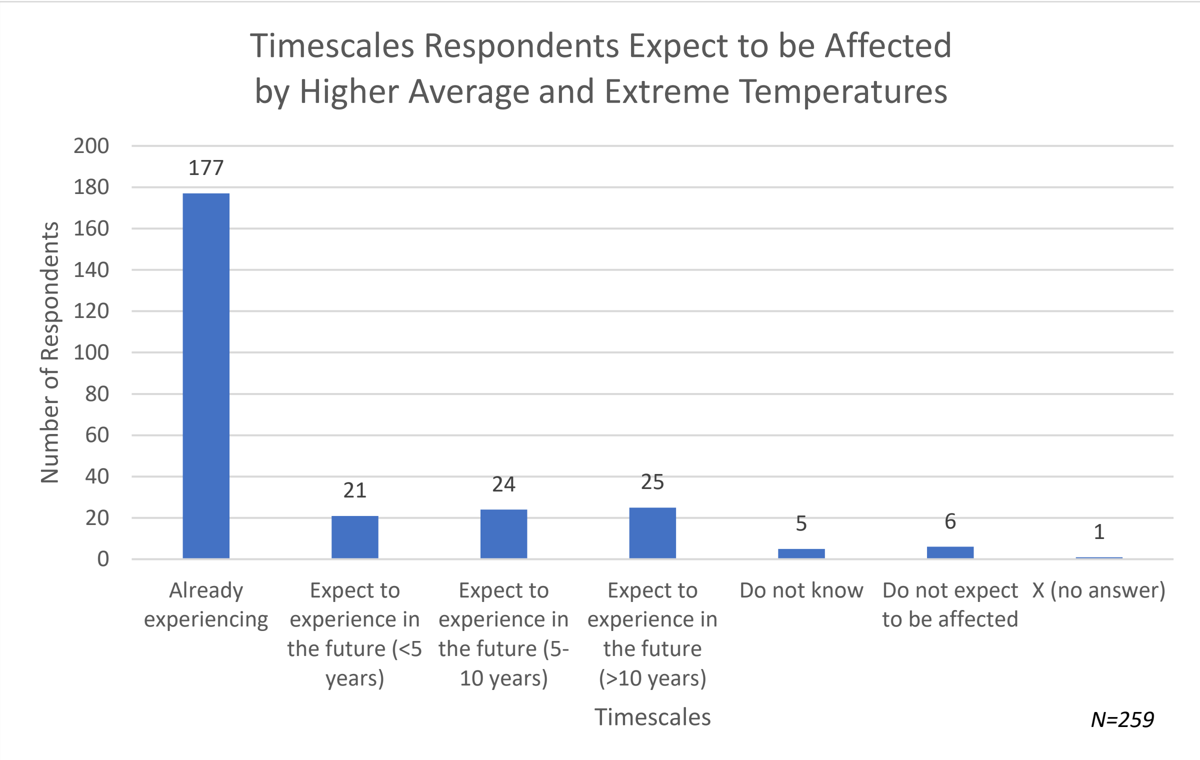


Figure 23 Timescales respondents expect to be affected by higher average and extreme temperatures

Out of 259 respondents, 247 are already experiencing or expect to be affected by higher average and extreme temperatures, indicating that this impact may be widely experienced. One hundred and

[7] "*Remote sensing* is the science of obtaining information about objects or areas from a distance, typically from aircraft or satellites" (NOAA, Undated)

seventy-seven are already experiencing the effects of higher average and extreme temperatures, indicating that this is already an issue for many stakeholders. Seventy respondents expect to experience effects in the future. Just six respondents answered that they do not expect to be affected and five respondents do not know if they will be affected.

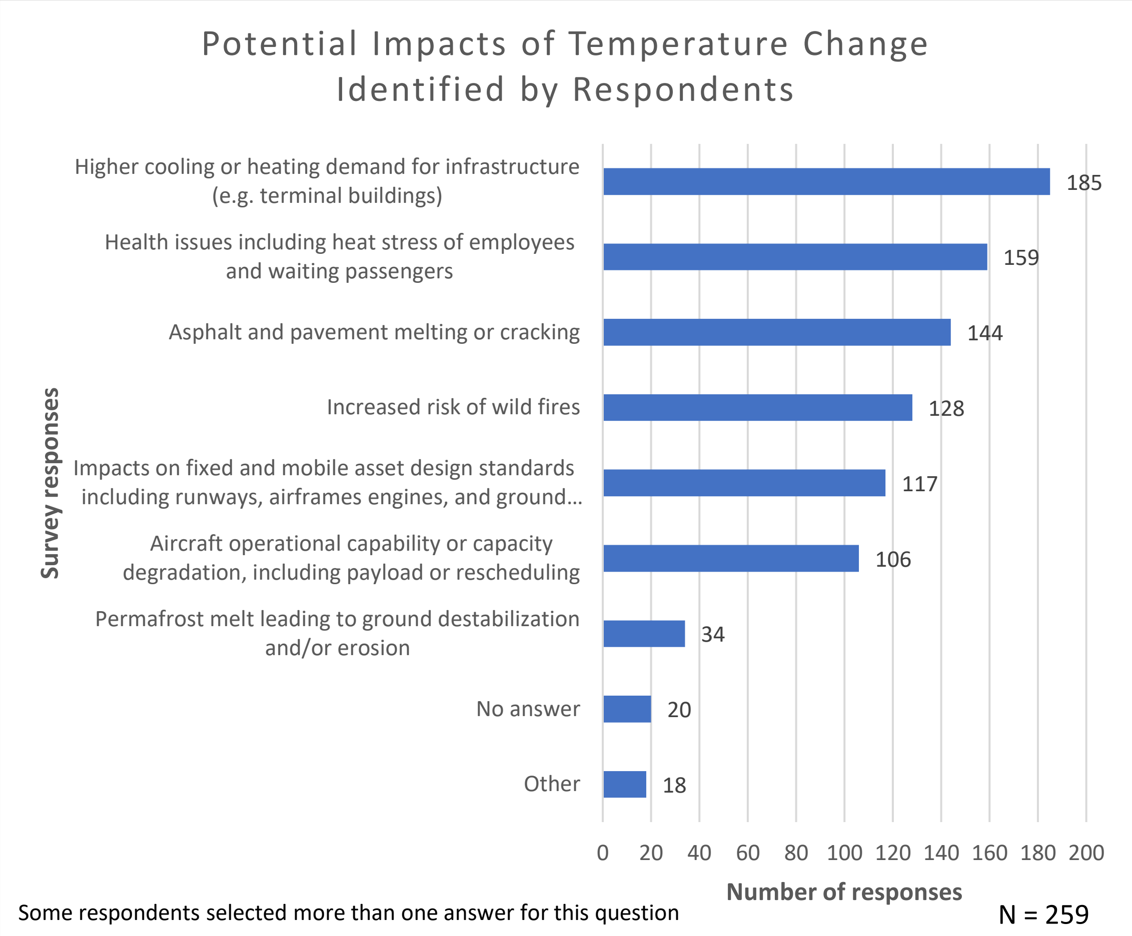


Figure 24 Potential impacts of temperature change identified by respondents

The main impacts that respondents expect to experience are higher cooling or heating demand for infrastructure, health issues and asphalt and pavement melting. Many respondents gave more than one answer. The respondents who selected "Other" identified, "problems with metro/train reaching the airport due to rail distortion", "drying of airport vegetation", "traffic patterns and demand re-distribution (geographical + seasonal)" (two respondents), "reduction in working hours and productivity of labour force", "aircraft performance: slower climb-rates may necessitate airspace re-design", "extreme heat has potential to affect the operation of ATM systems & delivery of service.", "water cooling is sometimes deployed in summer highs which can disrupt operations", "extreme heat events could cause damage to equipment components, either limiting or stopping their operation. As the temperature approaches 40°C, from 38 – 40°C components can start to malfunction", "Impact on infrastructure and CNS equipment", "limit climb performance, which could result in noise impact", "increasing fuel consumption due to using APU for cooling or heating aircraft on the ground", "dehydration", "loss of landscaping when combined with drought" and "introduction of alien invasive species into the airport precinct".

One potential benefit was also identified, namely "from the near future, a reduction in the number of frost days could reduce the negative effects of icing."

6.4 Changing Precipitation

6.4.1 Summary of Effect and Timescales

The WMO (1992) define precipitation as "Hydrometeor consisting of a fall of an ensemble of particles. The forms of precipitation are: rain, drizzle, snow, snow grains, snow pellets, diamond dust, hail and ice pellets". This section will consider changes in types and quantities of precipitation. There is already considerable variation in the average precipitation experienced in the different regions around the world and most, if not all, regions experience extreme precipitation events of some kind, such as extreme rainfall or prolonged drought. However, the IPCC project that "It is very likely that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7% for each 1°C of global warming (high confidence)" (IPCC[1], 2021 p16), with a warmer climate intensifying extreme wet and extreme dry weather and thus exacerbating flooding or drought (high confidence) "but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks" (IPCC[1], 2021 p19)

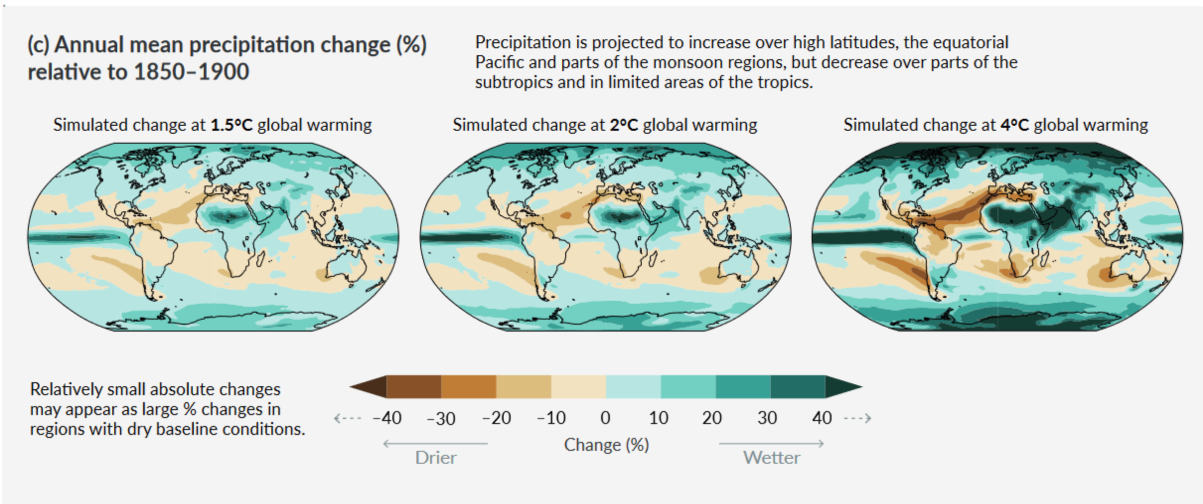


Figure 25 From the IPCC AR6 WG1 Summary for Policy Makers: Simulated annual mean precipitation change (%) at global warming levels of 1.5°C, 2°C and 4°C (20-year mean global surface temperature change relative to 1850–1900) (IPCC, 2021 SPM, Figure SPM5 panel (c))

Figure 23 above, from the IPCC AR6 WG1 Summary for Policy Makers demonstrates the broad geographic and seasonal differences to changes in precipitation. There is likely to be significant variation in impacts both globally and within regions or States, with some areas likely to experience a decrease in precipitation and others an increase (IPCC, 2021 WG1 SPM). The IPCC concludes that "projected changes of seasonal mean precipitation in the near term [2021-2040] will increase at high latitudes. Near-term projected changes in precipitation are uncertain mainly because of natural internal variability, model uncertainty, and uncertainty in natural and anthropogenic aerosol forcing (medium confidence)" (IPCC[2], 2021 p585).

The IPCC project changes in precipitation on the basis of increased warming rather than specific timeframes. For example, "At 1.5°C global warming, heavy precipitation and associated flooding are projected to intensify and be more frequent in most regions in Africa and Asia (high confidence), North America (medium to high confidence) and Europe (medium confidence)" (IPCC[1], 2021 p. 24) whilst with 2°C of warming heavy precipitation, and associated flooding events, are projected to become more intense and more frequent.

According to the IPCC “additional warming is projected to further amplify … loss of seasonal snow cover” (IPCC[1], 2021 p16). However, “there is low confidence in most regions in potential future changes in … hail, ice storms [and] heavy snowfall” (IPCC[1], 2021 p24). Moreover, in some regions some large scale ‘chaotic’ climatic phenomena, such as the jet stream and Arctic Oscillation influence snowfall and it is possible that changes to such systems could result in increased snowfall days or increased snowfall amount compared to today (Heathrow Airport, 2011). Additionally, as temperatures change this may also influence the types of precipitation experienced. For example, in cold regions of Canada there may be combinations of snow, freezing rain, rain or melt events which can cause problems for airport operations (Pendakur, 2017). From a regional perspective, Northern Europe may experience an increase in freezing rain (EUROCONTROL, 2013) whilst, according to the 2012 ACRP Synthesis 33, some regions of Canada may experience **“**less snow and more precipitation mix … with more wing ice a possible effect” (p.20).

This suggests that, while there is a broad understanding of the effects of changes in precipitation on the aviation sector, this may be a very locally-specific impact for aviation stakeholders to address. Nevertheless, there can also be a significant network effect as disruptions to one part of the aviation sector may have knock-on effects for other areas. Moreover, the shift in distribution of impacts will mean that stakeholders may have to address effects which are different or more serious than those that they already address.

6.4.2 Potential Impacts on Aviation from Changing Precipitation

Changing precipitation patterns could affect operations leading to capacity reduction, delays and cancellations and inundation of infrastructure (ICAO[2], 2022). There may be flooding and flood damage to runways and infrastructure. Higher and more frequent peak rainfall events result in water standing on the runway. Inundation leading to overloading of drainage systems could cause failure of pollution control systems with risks of contaminating ground water (ICAO[2], 2022).

According to the 2021 NATS Climate Risk and Adaptation Progress Report and other sources (Heathrow Airport, 2011; SESAR, 2012; Rapaport et al. 2017 (Eds.), 2017), if take-off and landing conditions become hazardous, this may result in closure or reduction in capacity of airports, or reduction of capacity of ATC sectors, or both. Heavy precipitation events could require increased separation distances (EUROCONTROL, 2013). Reduced visibility due to heavy precipitation may lead to increased application of low visibility procedures (SESAR[1], 2012; SESAR[2], 2012; Palko and Lemmen (Eds.), 2017).

The cancellation or delay of flights due to disruptive or extreme weather conditions have financial implications due to lost revenues and increased operating costs, not to mention passenger inconvenience (ICAO[2], 2022; Palko and Lemmen (Eds.), 2017), and could also affect air traffic for major public events, if the two coincide. For example, in February 2011, the Dallas, Texas region received 2.6 inches (6.6 cm) of snow just two days before a major sporting event. Although this may not be considered as heavy snowfall in some regions, “at DFW, runways and taxiways could not be cleared quickly enough because the existing snow and ice removal equipment had significant limitations; the existing equipment could only clear one of DFW’s seven runways in one hour after a de-icer had been applied” As a result, more than 300 arriving flights were cancelled at Dallas/Fort Worth International Airport (DFW), a hub for American Airlines (ACRP, 2012, p.20).

Warmer temperatures may also result in an increase in ice events in some locations (as snow events are replaced by rain, freezing rain, and sleet), presenting more severe adverse impacts such as flight disruptions and damaging infrastructure and equipment (ICAO[2], 2022). Freeze and thaw cycles can cause quicker deterioration of pavement materials (Woudsma and Towns, 2017). ICAO highlight that it may become more challenging to "forecast conditions and precipitation type (e.g., rain, snow, freezing rain) resulting in less reliable forecasts to plan for operations (ICAO[2], 2022, no page number). Conversely, too little precipitation can lead to reduced water availability or even drought conditions, resulting in restrictions imposed on water intensive activities (ICAO[2], 2022). According to ICAO changes in snow conditions may lead to "…increased requirements for snow clearing [including equipment] and aircraft and runway de-icing equipment at some locations but reduced requirements at others (ICAO[2], 2022). Perturbation from snow events at airports that have not previously been affected by snow was identified as one of the more significant effects (SESAR, 2012). For example, in December 2022, unusually heavy snowfall and freezing temperatures led to mass cancellations of flights at Vancouver International Airport (CBC, 2022). Heathrow Airport stated in their 2011 Climate Change Adaptation Reporting Power Report that, "Increasing variability of snowfall challenges winter contingency plans, de-icing supplies and staff experience" (p.13). Customers may also be affected by delays and cancellations. There could be staffing issues during heavy snow events if personnel cannot reach airports or control centres (NATS, 2021). In some regions of Canada, as described by Pendakur (2017), "Increased snowfall may cause flooding in the thaw seasons, damaging permafrost under runways/taxiways" (p.51).

6.4.3 Adaptation and Resilience Measures

Adaptation and resilience measures proposed or already being implemented include: measures to increase operational robustness and flexibility such as dynamic capacity balancing, low visibility procedures, using ground based augmentation system (GBAS), improved or expanded use of MET forecasting services, decision making procedures such as Airport Collaborative Decision Making (A-CDM) and "soft" measures such as information sharing and training.

For snow, the need for adequate snow and ice removal equipment was identified (ICAO[3], 2022), as well as the need to ensure staff are available, for example, by "using Land Rovers to shuttle staff to work and providing hotel accommodation close to work for key personnel" (NATS, 2011., p.23). Pendakur (2017) stated that to "mitigate the impacts of high snowfall on permafrost (thermal insulation) snow should be removed as quickly as possible" (p.52). In Canada's North, sand is applied to surfaces "in order to counter the effects of standing water and freezing rain" (Ibid.). It may also be necessary to adapt to different types of precipitation, for example new procedures for de-icing or operating procedures for heavy precipitation or freezing rain (ICAO[3], 2022).

ICAO recommend developing a strategy for snow and ice removal at airports, such as has been done at Dallas/Fort Worth International Airport and Toronto Pearson International Airport (ICAO[3], 2022; ACRP, 2012). This might include snow and ice removal targets, keeping a specified number of runways open, measures to enable better access during weather disruptions (ACRP, 2012; GTAA, 2014), and grooving of runways to improve traction and drainage during heavy precipitation events at Norman Wells Airport and Ottawa International Airport (Pendakur, 2017).

During drought conditions, defined as “a period of abnormally dry weather long enough to cause a serious hydrological imbalance” (UNTERM, undated), measures to reduce water consumption and build drought resistance are needed such as, planning for drought and water supply limitations, water storage to counter water supply issues, rainwater catchment systems to adapt to potential water scarcity (ICAO[3], 2022). For example, Dallas/Fort Worth International Airport is taking several measures to reduce its water consumption and support the city's plan to develop a new reclaimed water facility. The airport calculates that this will lead to millions of dollars in savings through the use of reclaimed water and also provides a secondary benefit of drought resistance (ACRP, 2012). It is important to take precipitation projections into account when planning and developing new infrastructure and design for higher categories of extreme precipitation events (ICAO[3], 2022, no page number).

6.4.4 Survey analysis

The following charts present the results of the survey questions on changing precipitation.

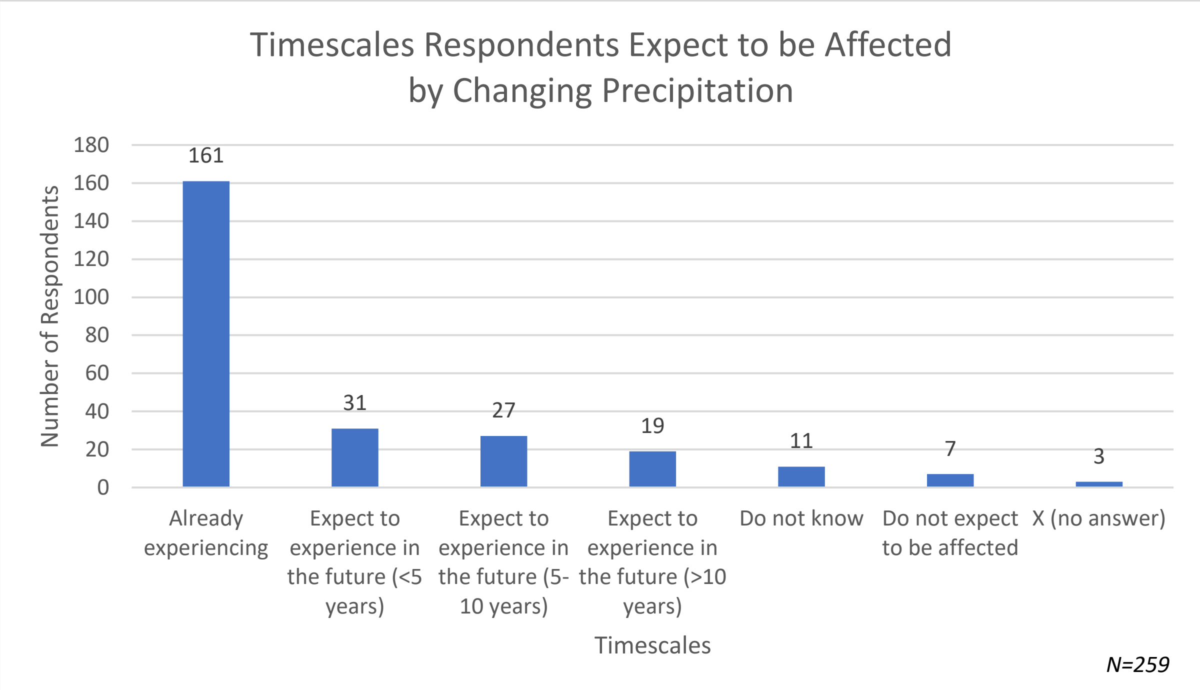


Figure 26 Timescales respondents expect to be affected by changing precipitation

Out of 259 respondents, 238 are already experiencing or expect to be affected by changing precipitation, indicating that this impact is expected to be widely experienced. However, the impacts of changing precipitation may result in an increase of precipitation in some areas, while in other areas, precipitation is projected to decrease.

One hundred and sixty-one respondents are already experiencing the effects of changing precipitation and 77 expect to experience effects in the future. Just seven respondents do not expect to be affected and eleven do not know.

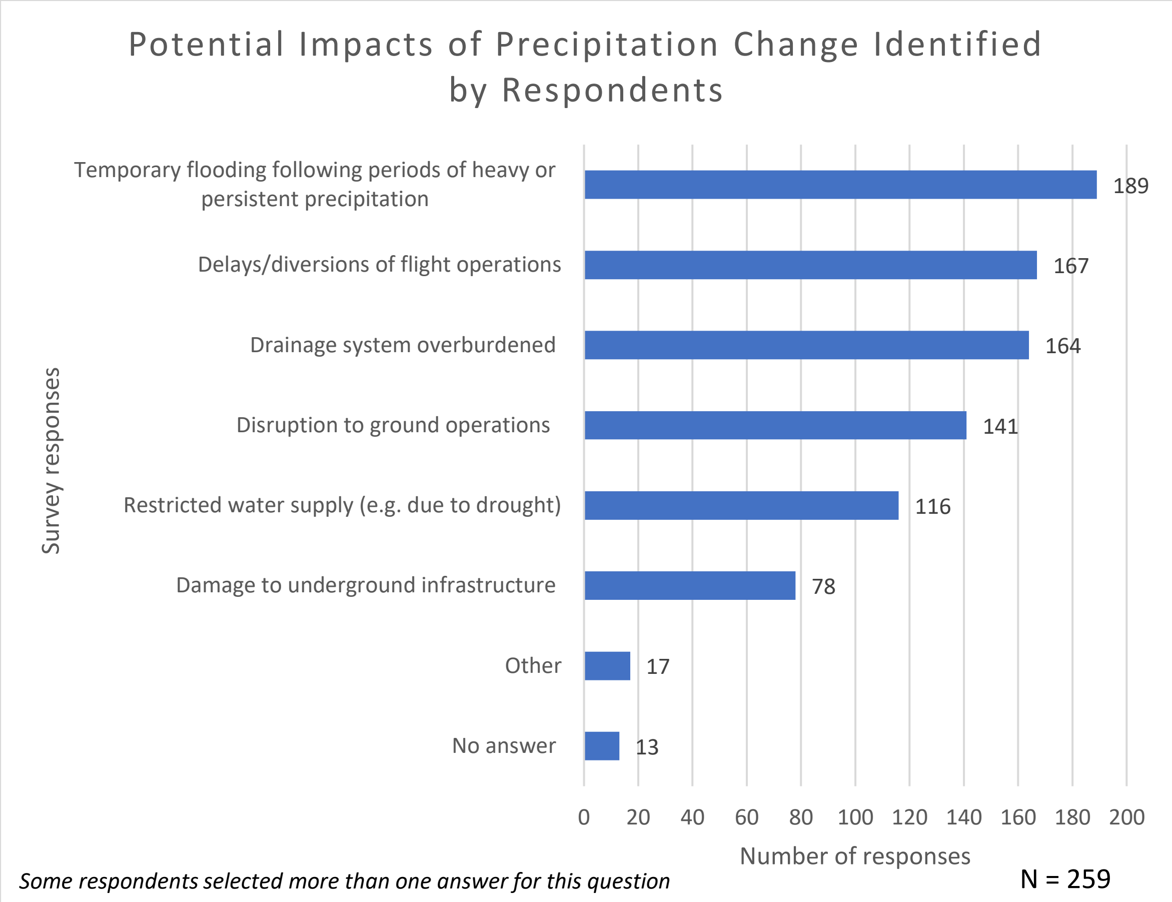


Figure 27 Potential impacts of changing precipitation identified by respondents

The main impacts from changing precipitation that respondents expect to experience are temporary flooding following periods of heavy or persistent precipitation, delays/diversions of flight operations, and drainage system overburden, all related to an increase in precipitation rather than a decrease.

Many respondents gave more than one answer to this question. The respondents who selected "Other" identified impacts related to both an increase and a decrease in precipitation such as: "road access to disrupted airports", "insufficient rainfall in summer", "airport availability (capacity/delay) and demand re-distribution", "increased electricity price due to 'dry' hydro-electric rivers and storage lakes", "all remote communications, radar and navigation sites could be highly impacted by lightning strikes or heavy precipitation", "low visibility risk during heavy precipitation", "poor braking action during heavy precipitation", "increased landslides", "Ground personnel have difficulty in carrying out their work", "damage on buildings and infrastructure due to soil dryness".

6.5 Changing Icing Conditions

6.5.1 Summary of Effect and Timescales

The WMO define icing as "Any deposit or coating of ice on an object caused by the impact of liquid hydrometeors, usually supercooled" (WMO, undated). This section covers atmospheric icing, which includes both ground icing and airborne icing. Transport Canada provided definitions that apply to this section for ground icing and airborne icing in their 2010 *Advisory Circular: Airport Icing Ground /Flight Training Programmes*: "Ground icing is icing accumulated while an aircraft is on the ground, whilst airborne icing is icing accumulated while the aircraft is in flight, when all protection from ground-applied anti-icing fluids ceases” (Transport Canada, online). Prevention and removal of icing is differentiated as anti-icing, that is the prevention of icing, and de-icing, the removal of ice once icing has occurred. This section does not cover ice that may form as a result of precipitation (e.g., hail, freezing rain), which is addressed in the changing precipitation section of this document. However, although freezing rain is a form of precipitation, there is some reference to it as it can contribute to the need for de-icing and it was often addressed alongside de-icing in the literature reviewed.

Impacts identified from changing icing conditions may affect both ground icing and airborne icing:

- **Ground icing:** There is an increased risk of conditions which lead to the likelihood of ground icing, and thus the need for de-icing (Puempel and Williams, 2016; Heathrow Airport, 2011; Puempel et al., 2016; ICAO, 2016). Many regions, as projected in the 2012 ACRP Synthesis 33, “will experience changes away from historical weather patterns, and this will require potential use of more de-icing" on the ground (ACRP, p.13)
- **Airborne icing:** There is likely to be “increased chance of occurrences of conditions favourable to icing, and also to an extension of the upper limit of icing layers due to higher temperatures" (Puempel and Williams, 2016, p. 207) while “High altitude icing is likely to increase with more intense cumulonimbus (CB) clouds"(Ibid., p.207). There is greater risk of both freezing fog and in-flight icing (NATS, 2011). This could lead to increased risk of in-flight icing, especially for smaller aircraft with limited engine power.

Information on timescales in the reviewed documents varies from less than 20 years to the end of the century. However, Puempel and Williams (2016) noted that the timescale for changing icing conditions is “well below that of sea level rise” (p.206).

6.5.2 Potential Impacts on Aviation from Changing Icing Conditions

Ground icing: Icing increases aircraft weight and drag, which in turn reduces lift (Gultepe et al, 2019). Increased de-icing requirements and operational risks from freezing rain were also identified as risks (Avinor, 2022). De-icing requirements will change but may increase in some areas and decrease in others (EUROCONTROL, 2013; ACI, 2018). For example, increased temperatures in some regions may lead to a reduction in de-icing (ACRP, 2013; EUROCONTROL, 2013). For areas where de-icing needs increase, there is also a risk that operations may be affected, causing the delay or cancellation of flights (ACI, 2018). Pendakur (2017) recognized that, "freezing rain can also have an impact on operations by decreasing traction on runways and taxiways, necessitating the use of de-icing products prior to take-off " (p.51). As a knock-on effect, the 2012 ACRP Synthesis 33 states, "an increase in the use of de-icing fluids may increase concentrations in run-off, potentially triggering increases to the surcharge agreements” (ACRP, p.20), which EUROCONTROL (2013) recognized can also cause a breaching of environmental limits. This is because it increases concentrations of chemical pollutants in the water supply as it runs off the airfield, which can cause various water issues. For many airports, this may be a regulated aspect of the airport; the airport must maintain a permit or agreement regarding discharges, and water quality is tested on a regular basis to ensure water quality standards are being met (ACRP, 2012).

Airborne icing: The main risk identified by the 2016 ICAO publication *Operations over the North Atlantic*, is in-flight icing causing a safety risk as "the formation of ice on the airframe modifies the airflow around the wings, which can result in a loss of aerodynamic lift. Ice may also block the pitot tubes" resulting in a false indication of the air speed (ICAO, p.4). This is noted as a specific risk for "northernmost parts of some transatlantic flight tracks" (Ibid., p.5). More wing ice may be a possible consequence of changing icing conditions (ACRP, 2012). Gultepe et al. (2019) noted that icing is a significant safety hazard which can cause instrument error resulting in false altitude and airspeed data.

Puempel and Williams (2016) noted that "for twin-engine aircraft over oceanic airspace, cabin pressure loss or the loss of power in one engine would force such aircraft to fly at levels still affected by icing" (p.207). Increased de-icing requirements and operational impacts from freezing rain were also identified as risks.

6.5.3 Adaptation and Resilience Measures

Measures identified to mitigate changing icing conditions include ensuring future development and contingency plans to account for climate changes. It is also noted that a better understanding of this risk is required to be able to predict and plan for future scenarios. More specific measures include:

Ground icing: Consideration should be given to both protecting pavement and underground infrastructure from more freeze-thaw events and subsequent damage and to strategies for the use of de-icing agents (Woudsma and Towns, 2017). The *Climate Risks & Adaptation Practices for the Canadian Transportation Sector 2016* report notes that at remote northern Ontario airports "portable forced air heaters [are used] to combat ice build-up on aircraft" (p.167). In the future, operators could adopt “changes to engine and wing de-icing procedures ... This could include a greater use of glycol-based de-icing and anti-icing agents" (Ibid.).

Airborne icing: Puempel and Williams noted that for safety reasons regulations for twin-engine aircraft operations over oceanic airspace should be reviewed (Puempel and Williams, 2016). Aircraft manufacturers also may need to assess airframes for performance in changing climatic conditions (Puempel, 2016). Better global and regional tools and systems are needed to predict potential icing, which can in turn assist air traffic control with assigning flight levels (Burbidge et al., 2023). More research is needed to improve numerical weather prediction models and reduce operational risk (Gultepe et al., 2019). The World Area Forecast System is being enhanced with a higher-resolution airborne icing forecast capability which should come into operation at end of 2024 and a new probabilistic forecast capability, expected at the end of 2027 (ICAO Annex 3 Amendment 82).

6.5.4 Survey analysis

The following charts present the results of the survey questions on changing icing conditions.

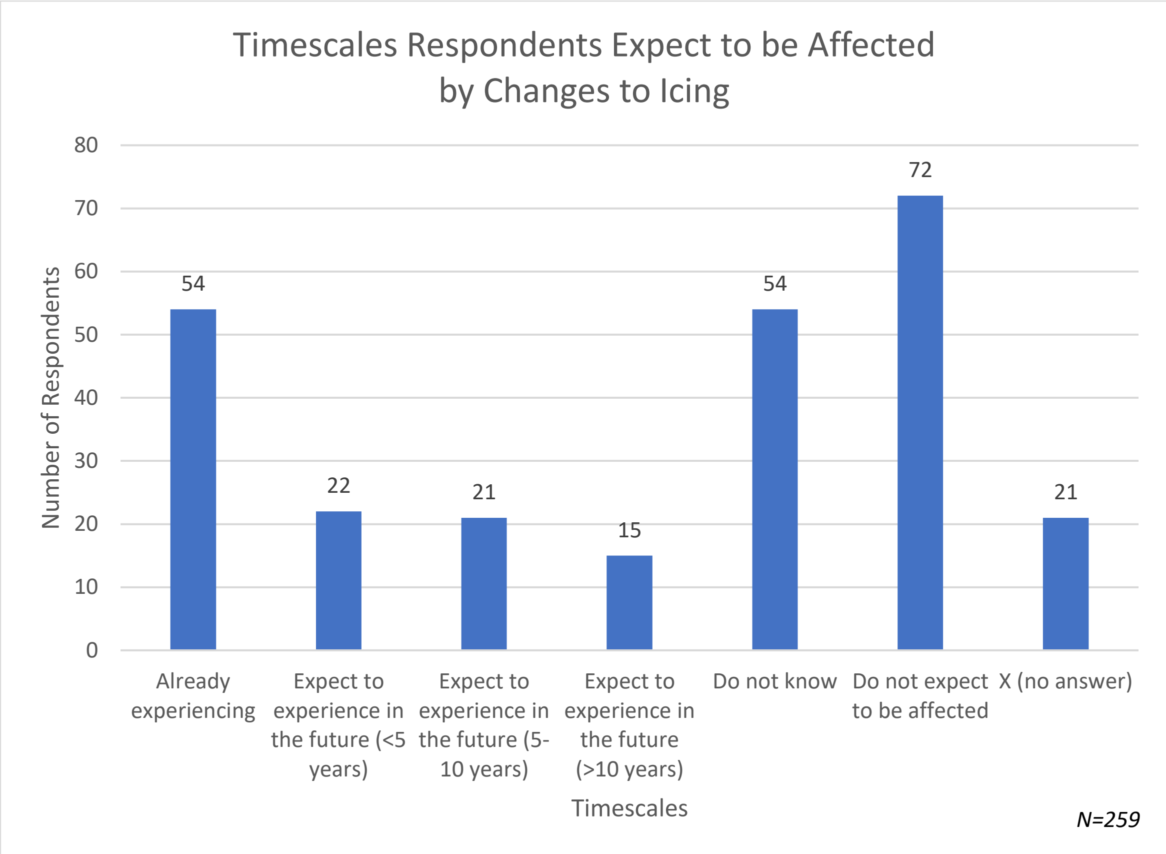


Figure 28 Timescales respondents expect to be affected by changes to icing

One hundred and twelve out of 259 respondents expect to be affected by changing icing conditions. Respondents had differing interpretations of this impact. For example, some may have considered changing icing conditions in terms of atmospheric change, whereas others considered it more in terms of precipitation change. Additionally, responses may be influenced by regional differences associated with those interpretations, or by stakeholder type.

Fifty-four respondents are already experiencing the effects of changing icing conditions and 58 expect to experience effects in the future. Seventy-two do not expect to be affected and 54 do not know, indicating that for some respondents there are still some uncertainties regarding this impact.

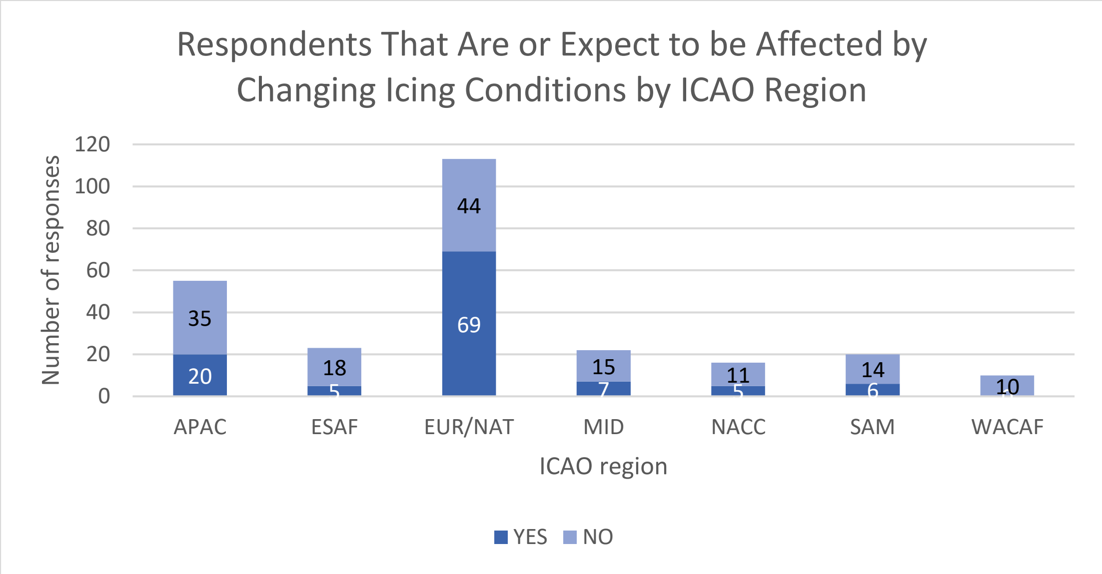


Figure 29 Number of respondents that are affected today or expected to be affected in the future by changing icing conditions by ICAO region

The chart above shows the number of respondents that expect to be affected by changing icing conditions by ICAO region. In total, 112 of the 259 survey respondents expect to be affected by changing icing conditions. However, this is almost certainly influenced by regional differences such as underlying climate and geography, as well as potentially by stakeholder type. The light blue bars are the number of respondents that do not expect to be affected by changing icing conditions while the dark blue bars indicate how many respondents do expect to be affected by changing icing conditions. For example, in the Asia and Pacific region, 35 respondents (64%) indicated that they do not expect to be affected by changing icing conditions, while 20 respondents (36%) do expect to be affected. Five of the twenty-three respondents (22%) from the Eastern and Southern Africa region, 69 of 113 respondents (61%) from the European and North Atlantic region, seven of twenty-two respondents (32%) from the Middle East region, 5 of 16 respondents (31%) from North America, Central America, and the Caribbean region, and 6 of 20 respondents (30%) from the South American region, expect to be affected by changing icing conditions. In Western and Central Africa region no respondents indicated they would be affected by changing icing conditions. It should be noted that the question in the survey did not differentiate between ground icing and airborne icing, and it is possible that respondents in regions that do not expect to be affected by ground icing may still be affected by airborne icing. It is also possible that respondents only considered one type of icing, and not the other, and based their answer on that type.

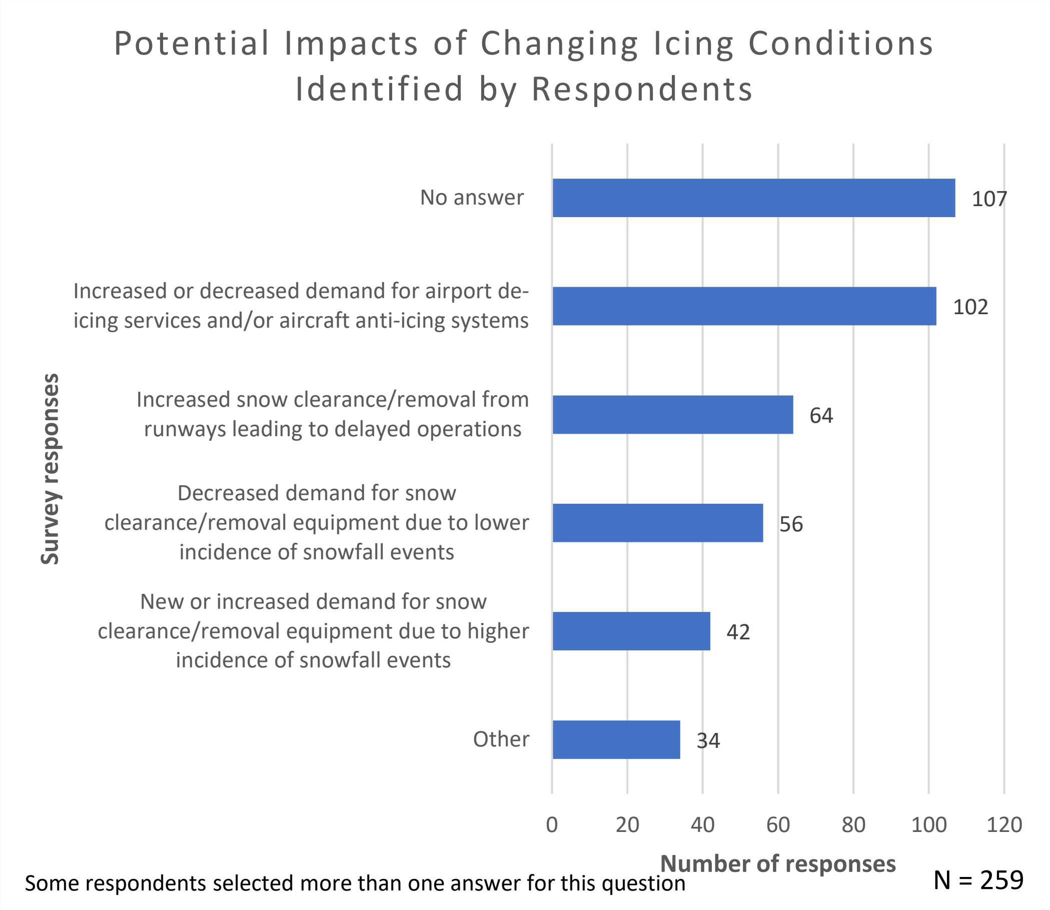


Figure 30 potential impacts of changing icing conditions identified by respondents

The main impacts that respondents expect to experience are increased or decreased demand for airport de-icing services and/or aircraft anti-icing systems and Increased snow clearance/removal from runways leading to delayed operations. However, the highest response was for “no answer”, reflecting the proportion of respondents that do not expect to be affected, and possibly also indicating uncertainties regarding this impact. Some respondents used the “other category” to state that this impact is not applicable or they do not have any information.

Many respondents gave more than one answer. The respondents who selected “Other” identified the following: “safety concerns”, “frost causes runway lights to rise off the ground and break”, “Costly airport ground operations”, “performance of navigational aids”, “lack of usage of winter equipment. Equipment standing idle and still is not good for operational readiness”, and “average winter temperatures, leading to more icing and fewer snow events”. One respondent indicated that they do not know yet what the impacts will be.

6.6 Changing Wind

6.6.1 Summary of Effect and Timescales

There are two distinct but connected issues identified with the impacts of changing wind: changes or deviation in prevailing wind direction and strength, and shifts in the location and speed of the jet stream. Changes in wind speed will vary by region. In the lower troposphere, changes in wind strength and direction are projected, while in the upper troposphere, changes to the jet stream are projected (EUROCONTROL[5], 2021). Additionally, changes in the jet stream and storm tracks will themselves instigate changes in prevailing wind direction (EUROCONTROL, 2013). Overall, there remains much uncertainty regarding future changes in dominant wind patterns (Heathrow Airport, 2011; ICAO, 2016; EUROCONTROL[4], 2021).

For the jet stream, we can expect to see changes in the average strength, latitude, altitude, and waviness (amplitude) across the North Atlantic. The IPCC cites a "poleward shift of the North Atlantic jet stream exit" (IPCC[2], 2021 p1824) with analysis by EUROCONTROL also finding that "the jet stream is projected to strengthen and shift poleward under climate change" (EUROCONTROL[4], 2021, p13).

Changes to the temperature difference between the poles and the tropics may lead to stronger jet-stream wind shears which in turn increase Clear Air Turbulence (CAT) (Puempel and Williams, 2016; ICAO, 2016). Storer et al. (2017, p.1) found that "large relative increases in CAT, especially in the mid-latitudes in both hemispheres, with some regions experiencing several hundred per cent more turbulence. The busiest international airspace experiences the largest increases, with the volume of severe CAT approximately doubling over North America, the North Pacific, and Europe. Over the North Atlantic, severe CAT in future becomes as common as moderate CAT historically".

There will also be regional differences. For Europe and North America, the IPCC assess that "mean surface wind speeds have decreased … as in many other areas of the Northern Hemisphere over the past four decades (medium confidence) (AR5 WGI), with a reversal to an increasing trend in the last decade (low confidence)" (IPCC[2], 2021 p.1824, p1832). In Africa, a decrease in mean wind speed and strong winds is projected in North Africa whereas a significant future increase in wind speed is projected in Western and Southern Africa (p1795). In Asia, the general trend is for a decrease in wind speed, although with the rate of decrease varying across the region (p1801). In almost all of Central and South America "global climate models project an increase in wind speeds, under all future scenarios" (IPCC[2], 2021, p1817). Figure 31 depicts wind speed projections for around the globe.

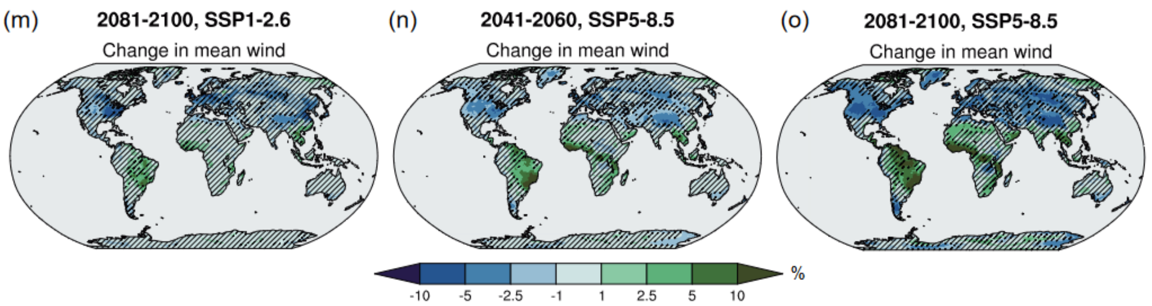


Figure 31 From the IPCC AR6 WG1 Report: Median projected changes in mean wind speed (%) based on CMIP6 models. (IPCC[2], 2021, Figure 12.4 m-o)

The documents reviewed did not use consistent timescales for changing wind conditions, but generally implied that changes in local wind are being felt now and may increase in the future (EUROCONTROL[4], 2021; IPCC[2], 2021; Palko and Lemmen (Eds.), 2017) whilst changes to the jet stream and wind shear at altitude are expected by mid-century (EUROCONTROL[4], 2021; ICAO, 2016).

6.6.2 Potential Impacts on Aviation from Changing Wind

Changes to, or deviation from, the prevailing wind direction at airports could affect runway utilisation and schedules and necessitate changes in flight paths (approach routes, landing, and take-off) (ACI, 2018; Burbidge et al, 2023). Flights might be cancelled, delayed or redirected when crosswinds are too strong for aircraft to safely take off or land (ACI, 2018; Heathrow Airport, 2011; SESAR[1], 2012; ACI World, 2011; Palko and Lemmen (Eds.), 2017). In turn, this could reduce airport and aircraft operating efficiency, capacity and safety (ACI, 2018). It may also change the criteria for approach and departure procedures (SESAR, 2012). According to ACI World (2011), changing wind may also "reduce flight arrival and departure punctuality" (p.2). Changes to procedures due to deviation from prevailing wind direction could have environmental impacts, such as noise and increased emissions (Burbidge et al, 2023; EUROCONTROL, 2013). A slowing of wind speed in parallel with higher temperatures could have impacts on aircraft take-off performance (Gratton et al., 2020). Above a certain intensity, wind represents a serious threat to the safety of ground operations. This danger can be continuous (strong winds) or sporadic (gusts of wind). The risks are as much about managing aircraft parking as they are about handling and securing equipment.

On the ground in spite of its considerable weight, a poorly secured aircraft can move under the effect of strong winds, causing damage to other aircraft, equipment or infrastructure. Moreover, in strong winds, any object can become a projectile, with serious consequences for the safety of personnel and the integrity of parked or moving aircraft (DGAC, 2022). Properly securing materials (equipment, vehicles, etc.) is essential. In addition to direct collisions, there is also a real risk of generating foreign object damage (FOD). Moreover, empty containers have a high wind load and low mass. A gust of wind can be enough to blow or tip empty containers over. When loading/unloading empty containers, special care must be taken to take account of weather conditions, and in particular the risk of gusts of wind. In the event of strong winds, this type of operation should be suspended until such time as conditions have abated (DGAC, 2022).

According to Rapaport, Starkman and Towns (2017), extreme storms and strong winds, "can result in flight delays and cancellations, associated economic losses, and passenger inconvenience" (p.246) and according to a 2015 publication from the International Transport Forum, "may damage or destroy transport assets" (ITF, p.3) including navigational equipment and aircraft (ACI, 2018).

Changes to the jet stream could impact en-route traffic, for example the most efficient routings and flight times for transatlantic flights (expected to be faster eastbound and slower westbound) might change. An analysis of changes to high altitude wind patterns by EUROCONTROL identified that by 2050 for routes between Europe-North Atlantic, North Europe–Canary Islands and Europe-North Asia, flights were shorter in duration by an average of 1-5 minutes in both directions and in both the summer and winter season, with the exception of North Europe to the Canary Islands in the winter when a slight increase was projected (EUROCONTROL[5], 2021).

Changes to the jet stream may result in modification of en-route flight levels and ANSPs and airlines will have to react to changing flow patterns and sector loading (SESAR, 2016; SESAR[1], 2012; ICAO, 2016). SESAR (2016) stated this "could affect fuel critical operations on Transatlantic and other long-haul flights" (SESAR, p.23). There may be a knock-on effect for airports due to reduced arrival reliability (ACI World, 2011).

There may also be an increase in frequency and strength of Clear Air Turbulence, disrupting operations, leading to greater diversions and "bumpier" flights (NATS, 2021; ICAO, 2016). This, according to the same 2016 SESAR report, may also "affect the application of [Reduced Vertical Separation Minima] RVSM and lead to a reduction in airspace capacity" (p.23) and could lead to increased injuries to passengers and crew and damage to aircraft (SESAR, 2016; ICAO, 2016). Although Williams (2017, p.583) noted that "the projected increases in the prevalence of clear-air turbulence do not necessarily imply more in-flight injuries or greater levels of passenger discomfort" as aircraft may be able to avoid CAT entirely if forecasts for affected areas are accurate. Pilots may also relay information on un-forecasted CAT back to the ANSPs and other pilots as they experience impacts. However, as Puempel (2016) identified, as the climate changes, "engineers may have to review maintenance intervals and inspection methods needed to detect any signs of fatigue, or equivalent, particularly when assessing new, not yet fully-tested compound elements of modern aircraft."

Changes in the jet stream can cause "blocking"[8] of [weather] system propagation: this may bring extreme weather events, such as heavy snows, to airports which have not been previously affected (SESAR, 2016.)

6.6.3 Adaptation and Resilience Measures

Measures proposed or already being implemented are more limited for changes in wind conditions. Implications of prevailing winds need to be assessed at the local level and operational measures identified to maintain safety and increase robustness and flexibility (EUROCONTROL, 2013). Some sources stated more scientific research is needed as many uncertainties remain (Puempel and Williams, 2016; SESAR, 2016).

Updating design standard, reinforcing infrastructure and regular maintenance can enable airport buildings to withstand more extreme wind conditions (Vogiatzis et al., 2021).

Expanding the World Area Forecast System[9] to use probabilistic multi-model forecasts rather than deterministic models to forecast turbulence could improve accuracy and therefore assist pilot and flight-planner decision-making (Storer et al., 2019, 2020) and risk management. The IATA Turbulence Aware platform provides pilots and flight planners with automated turbulence reports so that they can make informed decisions on routing and take safety measures in the cabin in good time (IATA, undated).

Technologies for aircraft that can assess wind and turbulence changes in real time are being studied (Vrancken et al., 2016). Technologies under development may be able to identify Clear Air Turbulence up to 10-15 kilometres ahead, which would be enough time to alert passengers and crew, (e.g., to make sure everyone was strapped in, or to attempt a diversion around the area). However, at the

[8] "Weakening jet streams tend to have larger north-south waves. When these waves get larger, they move more slowly from west to east, which can cause weather systems to also move more slowly and even become stuck in place. This in turn increases the likelihood of disasters caused by persistent weather conditions, including droughts, heat waves, floods, long cold spells, and heavy snows…." (Climate Nexus, 2015)

[9] "World Area Forecast System (WAFS) is digital data set DSI-9939, archived at the National Climatic Data Center (NCDC). WAFS is a system for the world wide broadcast of aviation related weather information via satellite. It is a joint effort of the International Civil Aviation Organization (ICAO), the U.S. Federal Aviation Administration (FAA), NOAA/National Weather Service (NWS), with additional contributions from the World Meteorological Organization (WMO), the United Kingdom, Finland, Canada, and others." (https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00543 NOAA, 2018)

moment the technology is not deemed economically viable (Williams, 2017; Vrancken et al., 2016). It is possible that airframe design may need to be adjusted to adapt to changing turbulence beyond the features manufacturers have already built in to accommodate CAT, especially as "Many of the aircraft that will be flying in the second half of the present century are currently in the design phase" (Storer et al., 2017, p.8; Puempel, 2016). For example, "Some modern aircraft are fitted with an accelerometer in their nose cone. If the accelerometer registers a sudden change in altitude, which is large enough to be indicative of turbulence, then the wing flaps are rapidly adjusted in an attempt to damp the vertical motion and reduce the acceleration." (Williams, p.583). However, both Storer et al. (2017) and Williams (2017) also highlighted the "need to improve the skill of operational CAT forecasts" (p.8) so as to be able to avoid areas of CAT to the extent possible. Increased use of Pilot Weather Reports (PIREPs - brief reports from pilots of observed in-flight weather conditions) could help to provide pilots with (near) real-time increased information on areas with likely Clear Air Turbulence and enable them to take preventative measures (Vrancken et al., 2016).

Taking account of projected future changes to wind speed and direction is also important for airport design to ensure orientation of runways is correct and ensure capacity can be maintained (Koetse and Rietveld, 2009).

6.6.4 Survey analysis

The following charts present the results of the survey questions on changing wind patterns.

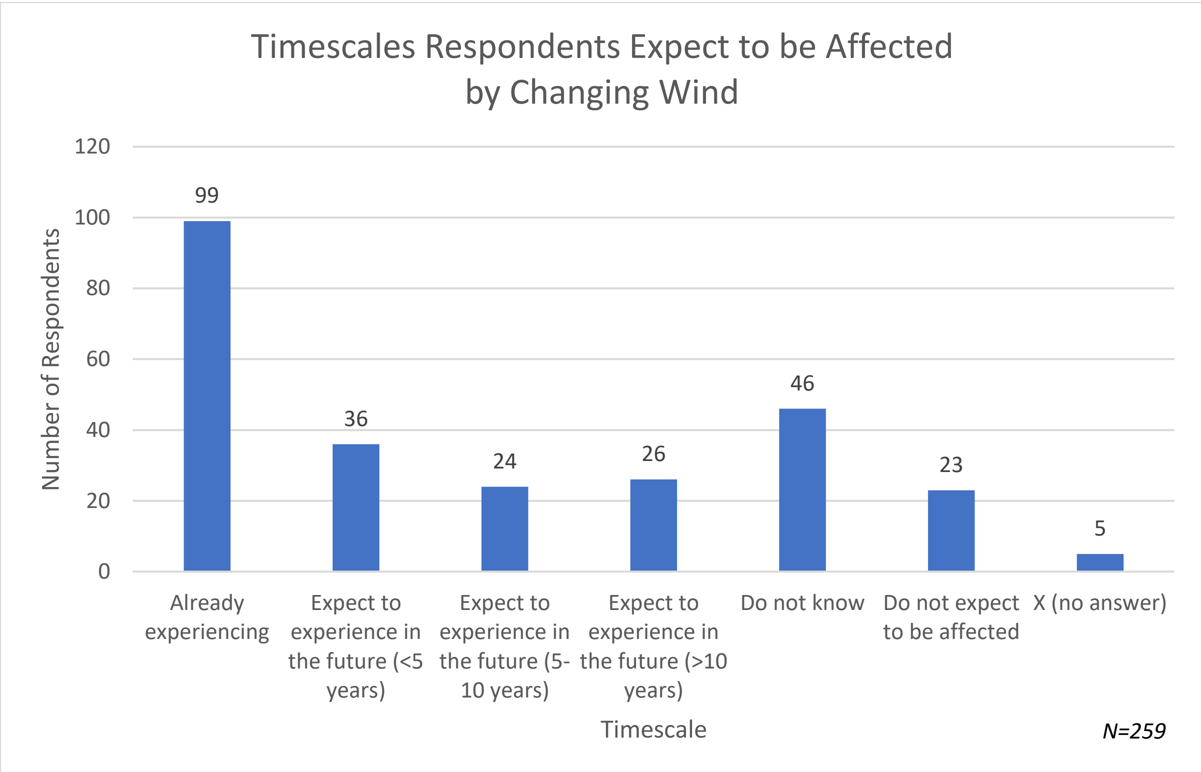


Figure 32 Timescales respondents expect to be affected by changing wind

Out of 259 respondents, 185 are already experiencing or expect to be affected by changes in wind patterns. Ninety-nine are already experiencing the effects of changing wind patterns and 86 expect to experience it in the future. Twenty-three do not expect to be affected and 46 do not know, indicating that for some respondents, there are still some uncertainties regarding this impact.

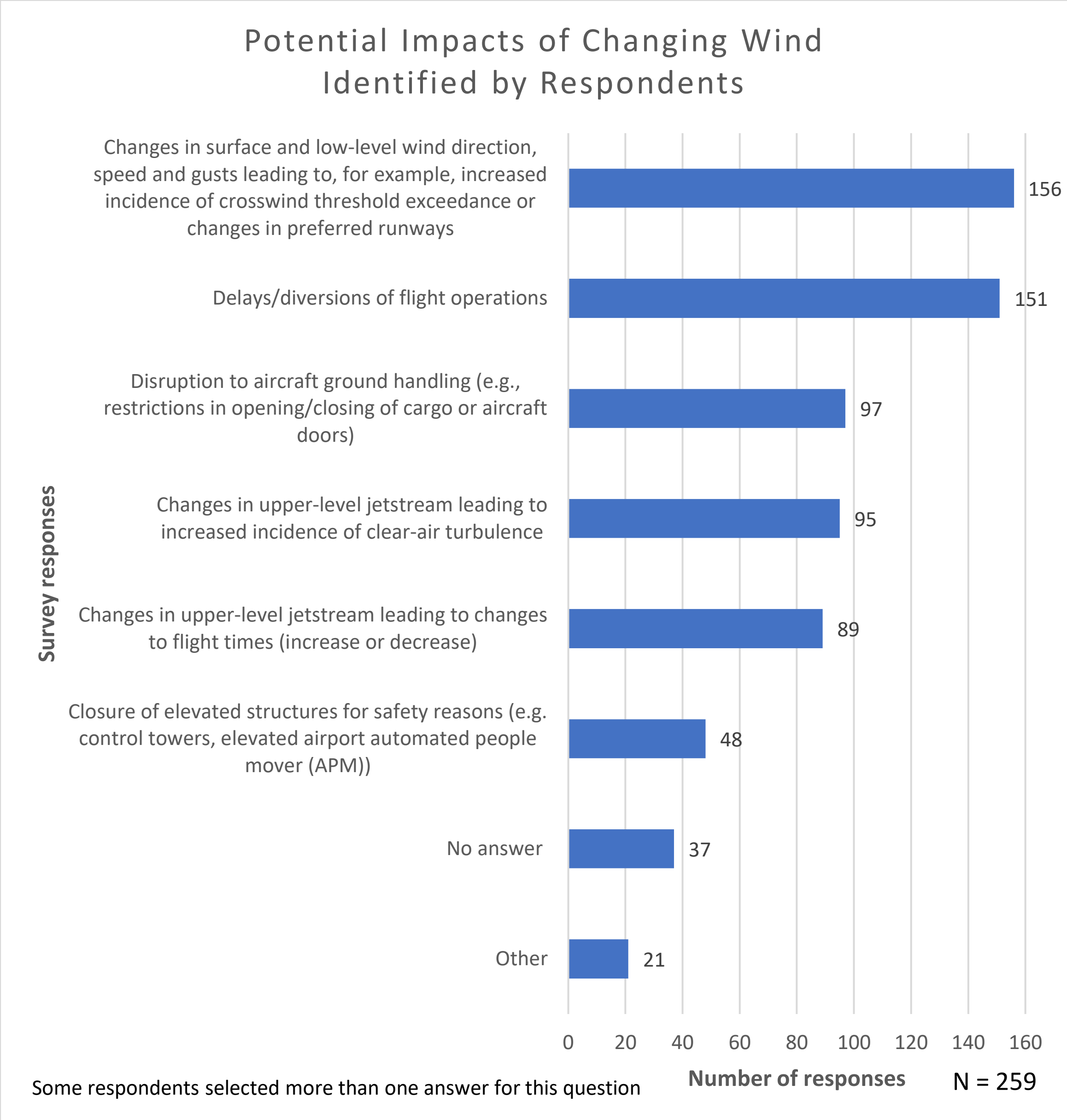


Figure 33 Potential impacts of changing wind identified by respondents

The main impacts that respondents expect to experience are changes in surface and low-level wind direction, speed and gusts leading to, for example, increased incidence of crosswind threshold exceedance or changes in preferred runways and delays/diversions of flight operations.

Many respondents gave more than one answer. The respondents who selected “Other” identified “non-use of certain gateway-type infrastructures”, “Go-around due to crosswind”, “damage to fixed infrastructure”, “Changes in traffic patterns and punctuality”, “changes in noise contours due to changing wind patterns, resulting in increased noise mitigation obligations for the airport company”, “Increase in gusts”, “failure of ground-based communications towers (change in surface and low-level wind intensity/gusts)”, “increased wind will increase fuel burn”, “potential impact on long term airport master planning due to the change of main wind direction and the need to reconsider runway orientation”, “episodes of ‘calima’ haze (desert dust that the winds carry over long distances, causing visibility and air quality problems).”

One respondent noted that they had already "experienced damage and loss of radar and antenna due to high winds. The simultaneous loss of multiple sites or assets can ultimately lead to reduced operational service". One respondent noted that although wind patterns are not expected to change at their airport, conditions at other airports could indirectly impact the airport. One respondent indicated that they do not know yet what the impacts will be.

6.7 Desertification

6.7.1 Summary of Effect and Timescales

The United Nations Convention to Combat Desertification defines desertification as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities" (UNCCD, undated). According to the 2018 ICAO Airport Planning Manual Part II, Chapter on Climate Change Resilience and Adaptation, "Climate change is contributing to desertification by leading to many dry regions becoming dryer and hotter and having more dust or sand in the air. Unprecedented heat waves are already being recorded in many regions, especially in the tropics. Desertification is also responsible for increased water scarcity and increased frequency of weather events such as high-intensity tropical cyclones and sandstorms in many regions" (ICAO, p.9-7).

The IPCC WG1 project that "continued warming will exacerbate desertification processes" (IPCC[2], 2021, p84). However, it is noted that drivers of desertification can also include land-cover changes and land-use management (p1849). No timescales were identified.

Desertification may also lead to an increase in dust storms frequency and intensity, although there will be regional differences and uncertainty as to the expected changes (IPCC[2], 2021). Dust storms in North America are becoming more extreme (IPCC[2], 2021) whereas in Africa changes to the frequency and intensity of dust storms "remain largely uncertain due to uncertainty in future regional wind and precipitation as the climate warms" but also due to factors such as land use and land cover change (IPCC[2], 2021 p1795). In West Asia, "the frequency of dust events has increased markedly in some areas" whereas in some Northern parts of Asia there is a decreasing trend due to the decrease in surface wind speed (IPCC[2], 2021, p1802).

6.7.2 Potential impacts on Aviation from Desertification

ICAO (2018), identified the following potential effects for aviation (p.9-4):

- Increased risk of soil erosion around apron and runway
- Water shortages
- Sand or dust storms disrupting operations
- Risk of encroachment of sand dunes
- Effects of sand dune on aircraft operations
- Effects of sand damage on airframes and engines

There can also be health effects for ground personnel (WMO, 2023[3])

Puempel (2016) explains that impacts from desertification may also result in "introducing safety risks or increasing maintenance costs" due to degradation of equipment and increased maintenance requirements (Puempel, p.116).

An increase in dust storms due to desertification may impact operations and safety, damage aircraft and even cause engine failure (Gultepe et al., 2019; Puempel, 2016). In turn this may affect aircraft engine design for fuel efficiency as in order to burn fuel more efficiently, engines become hotter and as a result, "silicates contained in typical sand and dust storms will melt [during the combustion process] and thus affect the performance and maintenance requirements of jet engines" (Puempel and Williams, 2016 p.207).

6.7.3 Adaptation and Resilience Measures

ICAO (2018) stated, "Airports planners and designers may need to design windbreaks to reduce dust and sand, plant trees that require little water and that do not attract wildlife, and use recycled water for irrigation" (p.9-8). However, the relative lack of material available on this impact at the time of writing suggests that more research is needed to understand the projected impacts of desertification and the direct and indirect effects on aviation.

From an engine design and safety perspective, there may be a need for trade-offs between fuel efficiency and safety, due to increasing combustor temperatures to reduce fuel consumption leading to greater safety risks from melting dust particles (Puempel, 2016).

6.7.4 Survey analysis

The following charts present the results of the survey questions on desertification.

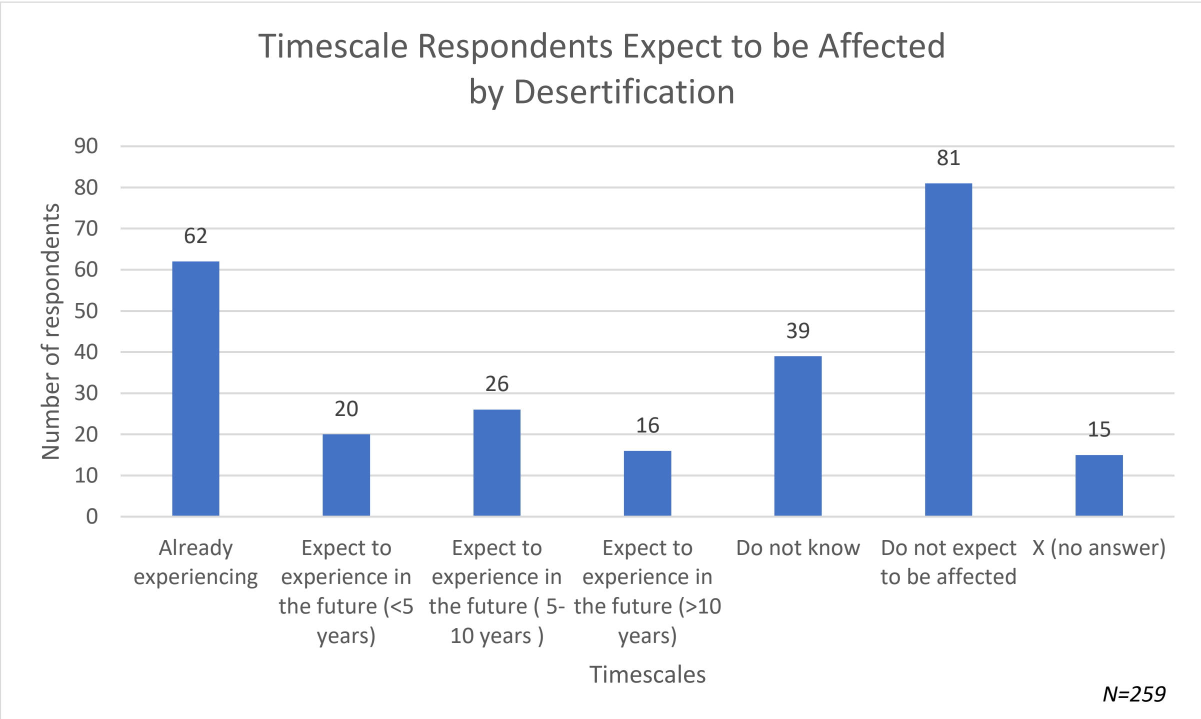


Figure 34 Timescales respondents expect to be affected by desertification

Out of 259 respondents 124 are already experiencing or expect to be affected by desertification. However, this is almost certainly influenced by regional differences such as the underlying climate and geography.

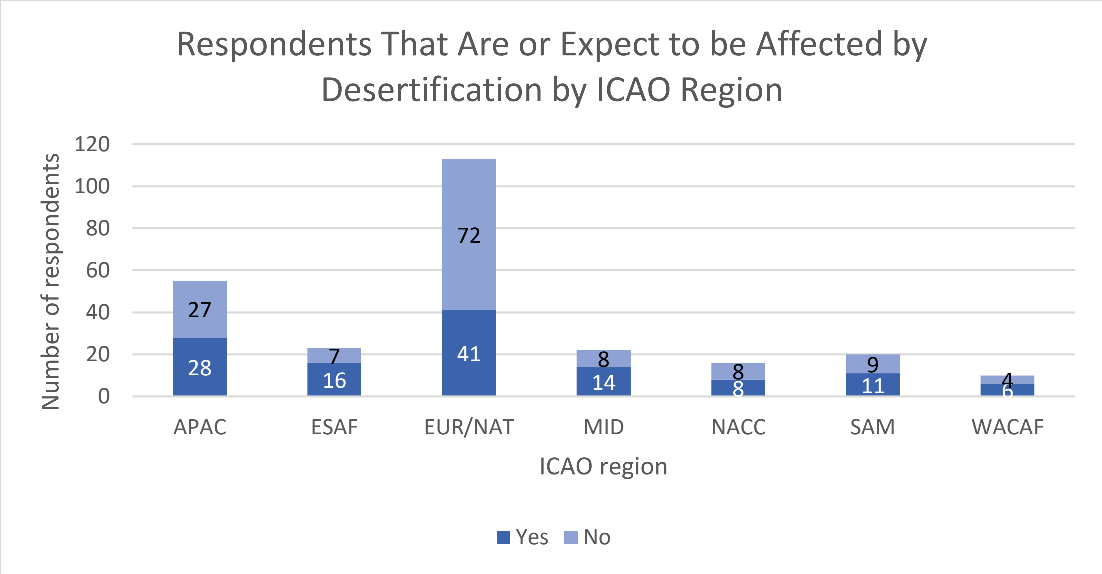


Figure 35 Number of respondents that are affected today or expect to be affected in the future by desertification by ICAO region

The chart above shows the number of respondents that expect to be affected by desertification in each ICAO region. The light blue bars indicate the number of respondents that do not expect to be affected by desertification while the dark blue bars represent the number of respondents that do expect to be affected by desertification. For example, in the Asia Pacific region, there were 55 respondents in total, 28 (51%) of which said they expect to be affected by desertification and 27 (49%) that said they did not expect to be affected. Sixteen of twenty-three respondents (70%) from Eastern and Southern Africa, fourteen of twenty-two (64%) respondents form the Middle East, eleven of twenty respondents (55%) from South America, eight of sixteen respondents (50%) from North America, Central America and the Caribbean and six of ten respondents (60%) from Western and Central Africa indicated they would be affected by desertification. The Europe and North Atlantic region is the only region where less than 50% of respondents expect to be effected by desertification with forty-one of one hundred and thirteen respondents (36%) expecting to experience this effect.

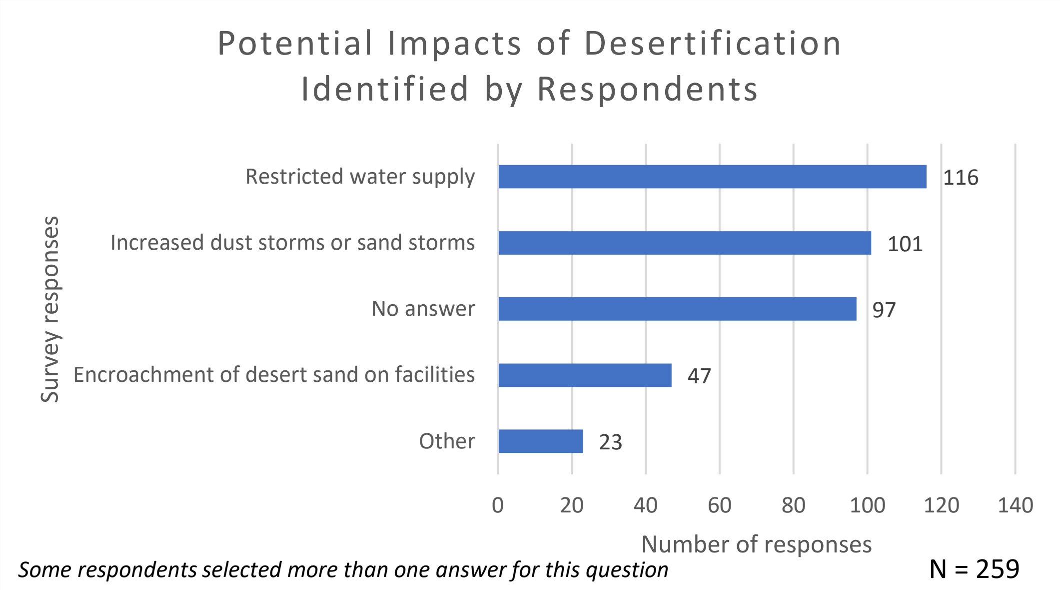


Figure 36 Potential impacts of desertification identified by respondents

The main impacts that respondents expect to experience are restricted water supply and increased dust or sand storms. However, 97 respondents, indicated "no answer", reflecting the proportion of respondents that do not expect to be affected, but possibly also indicating uncertainties regarding this impact.

Many respondents gave more than one answer. The respondents who selected "Other" identified "increased deforestation", "damage to the aircraft due to increased dust storm intensity", "the entry of sand atoms into aircraft engines, which increases maintenance work", "changes in vegetation affecting wildfire risk to facilities", "invasion of the desert sand in the facilities", "bushfires increased in places, especially in the centre-north of the country", "loss of natural habitat, feeding and nesting sites etc., changes in wildlife patterns". One respondent noted that although they don't expect to be affected by desertification, water restrictions are increasing. One respondent indicated that they do not know yet what the impacts will be.

6.8 Changes to Biodiversity

6.8.1 Summary of Effect and Timescales

According to the United Nations Environment Programme (undated) biodiversity refers to the variety and variability of nature at the genetic, species and ecosystem level. This section refers to potential wildlife effects and impacts due to climate change, namely variation in flora and fauna and potential regional changes to biodiversity which may affect the aviation sector. Although there is plenty of literature on the impacts of climate change on biodiversity, relatively little information is available regarding the effects of climate change-driven biodiversity changes on aviation. However, the main biodiversity risks identified in the reviewed literature are wildlife migration and propagation of invasive species (ACRP, 2012).

The World Birdstrike Association (WBA online, undated) state that wildlife, such as birds and other animals, is attracted to airports due to reasons such as water sources and food availability, noting that "Some wildlife have no other places to habitat but airports as they have lost their natural habitats due to urban encroachment and climate change. While wildlife near airports is natural, it poses serious risks to aviation safety … birds, especially, can collide with aircraft, leading to accidents." Moreover, composition of ecosystems may change due to climate change, leading to changes in both local biodiversity and wildlife migration patterns, both of which may lead to an increase in wildlife hazards, including but not limited to bird migration patterns (ICAO, 2018; Vogiatzis et al., 2021). Although this section mainly focuses on birds, it is recognised that there may be effects on aviation from other fauna. However, the documents reviewed for this Synthesis included relatively little beyond changes to bird migration patterns and populations.

Although climate change will be detrimental to many bird species some, long-living and warm-dwelling birds are increasing their population numbers and changing their range and distribution (Chen et al., 2011; Jørgensen et al., 2016). In particular, large birds such as geese, bald eagles, and brown pelicans, are already experiencing population growth and their distribution and range will move closer to human habitats (Miller et al. 2019; Dolbeer 2020). Flocking birds commonly habiting aerodromes (gulls, starlings, crows, pigeons) may also expand their populations and distribution. This pattern is expected to continue for the next twenty to fifty years and then to decrease as large areas of habitat are lost especially for waterbirds and large bird species (Fox and Madsen 2017; Van Eekeren, 2017; Nothrup et al., 2019). Other changes may include earlier migration or more birds staying in more Northern temperate climate zones, longer breeding seasons, increased breeding area range and density or breeding area changes (Vikkala and Lehikoinen, 2014; Hällfors et al., 2020; Hu et al., 2020; Rushing et al., 2020). Dolbeer et al. (2014) posit that the Canadian goose population has "increased 4.5 fold from 1.26 million in 1970 to 5.69 million in 2012." (p.89) and caused over 1,403 bird strikes in North America between 1990 and 2012, of which around 50% caused damage. In the European Union, 46% of wintering bird populations have increased between 2007 and 2018 although 27% of wintering bird populations have decreased (EEA, 2020). Moreover, the decline of long-distance migrant birds has been observed in Europe (23%) and in East-Asia (25% to 50%) (Higuchi and Morishita, 1999; Vickery et al., 2014).

In the longer term, climate change impacts are expected to lead to species loss and habitat loss especially for waterbirds and long-distance migrants (Both et al. 2009; Ramírez et al. 2018; Román-Palacio and Wiens 2020). Northward shift in the wintering distributions of bird populations have already been observed in several duck and goose species (Lehikoinen et al., 2013; Ramo et al., 2015). Climate change may also increase the spread of invasive alien species (IAS). As noted by the International Union for Conservation of Nature "Invasive Alien Species are compounded by climate change. Climate change facilitates the spread and establishment of many alien species and creates new opportunities for them to become invasive." (IUCN, 2021, p1).

6.8.2 Potential Impacts on Aviation from Changes to Biodiversity

The changes described above may lead to shifts in the diversity of bird species that are present at and in the vicinity of an airport. For example, ICAO (2018) stated in some areas, "there could be an increase of heavy weight migratory bird populations (e.g. grey goose, white stork)" (p.9-8). Migratory birds are a challenge at airports in many regions due to their potential effect on aircraft operations, particularly the large birds mentioned above (DeVault et al., 2016; Lopez, 2016; Van Eekereen, 2017; ICAO, 2018). Biodiversity changes may also change or increase other wildlife hazards at, or in the vicinity, of an airport. For instance, an increase in flocking birds that commonly use aerodromes. Changes in bird populations or migratory behaviour, or a combination of both, can increase the risk of bird-strikes (Blackwell et al., 2009; Dolbeer 2020).).

One general impact may be damage to landscaped areas, the need to change landscaping practices and an increase in maintenance costs due to changes in local wildlife or an increase in invasive species

(ACRP, 2012; House et al., 2020). The ability of invasive plants species to spread rapidly can cause a deterioration in the visibility necessary for the proper conduct of operations (wildlife management staff, firefighters, air traffic controllers, pilots, etc.) if not well trimmed. For instance, for the Asian Knotweeds, plants that can be found on some French airports: "Its growth is rapid with the stalks surging up to ten centimetres per day in the spring and reaching three to four meters in height" according to the French Invasive Alien Species resource center. The European Commission (2014) highlights how IAS "can damage infrastructure", "can also destroy landscapes", and "without rapid intervention, … will have an opportunity to spread further afield and cause even more damage". The increase of such species will lead to an increase of maintenance operations**.** In addition to increasing maintenance costs, it may also enhance aerodromes' attractiveness to birds during and after each maintenance operation (increased visibility of mice, worms…).

However, as stated by ICAO (2018), "biodiversity challenges are likely to be localized depending on the ecosystem and climate change impacts in a particular area" (p.9-8). For example, in North Africa and the Middle East changes in rain events have increased the potential for locust swarms (Ibid.), which can have impacts for airport operations. In Southern and Central Alaska, spruce beetles benefited from hotter summers, resulting in extensive tree mortality (Berg et al. 2006) which may contribute to wildfires.

Interactions between flora and fauna may also be possible as both are expected to migrate due to climate change. This migration may lead to introductions of alien species to new areas. For example, at Dallas/Fort Worth International Airport, the invasion of the airport operating area (AOA) by a species of pea plant particularly popular with pigeons led to an influx of pigeons to the AOA which led in turn to an increase in bird strikes (Boyles and Neill, 2016).

6.8.3 Adaptation and Resilience Measures

ICAO (2018) recommended that "wildlife evolution should be monitored to detect any change in populations" (p.9-8). Understanding how climate change will affect birds and wildlife is essential so as to assess the risk to aviation and to develop adaption and resiliency measures to reduce effects. Any measures should be developed in co-operation with environmental protection experts and organizations and of course take into account environmental protection (Blackwell et al., 2009; ICAO, 2018; ICAO, 2020). Expanded use of bird strike avoidance models is one potential measure, which was identified by the World Birdstrike Association (Van Eekereen 2017). Bird control or land management practices to discourage wildlife can be implemented (Blackwell et al., 2009). Flight paths may need to be temporarily altered to avoid large flocks of migrating birds (Burbidge, 2018).

The World Birdstrike Association also highlights that "the situation is very dynamic and we have to be prepared to react to possible rapid changes in wildlife risk … close co-operation with ornithological experts, studies, universities, wildlife protection organizations will be crucial … up-to-date information will allow [us] to prepare and use the most effective methods in wildlife hazard reduction" while at the same time taking account of nature protection and comply with relevant regulations (Blackwell et al., 2009; Van Eekeren, 2017; ICAO, 2020).

There are many ways to remove unwanted flora. For example, mowing or trimming can be a short-term fix. However, these strategies do not completely remove the plants, allowing them to regrow. It is also possible that mowing and trimming can attract birds as worms and mice become more visible. Herbicides may provide a more long-term solution but could lead to ground water contamination

(Boyles and Neil 2017) and may not be compliant with environmental regulations. A preferred solution may be permanent removal e.g. though pulling them out or landscaping changes so that the plants do not grow. Using herbicides can have environmental impacts such as ground water contamination and be detrimental for biodiversity and alternative options should be considered. Indeed, "It should be noted that these uses of herbicides generally do not attain the objective of eliminating the targeted plants [...] and that their effectiveness is in fact limited to one or two years. In addition to their toxicity, these products are not selective, i.e. they completely clear the treated zone, thus making them a method that must be used "with the utmost caution"", according to French IAS resource centre.

Indeed, each case of IAS at a site is different and does not necessarily require the same management (Anelli, Lefèvre 2023). Cutting before flowering or regular uprooting are part of the ways to manage expansion of IAS. (Kollman et al. 2009; Martens et al 2021). Particular attention should be paid to the transport of soil contaminated with plants fragments, and to stems left on wet land, which are major factors in their spread. Indeed, according to French IAS resource center, "management of soil contaminated with rhizome fragments is very difficult" and "among the potential problems inherent in many alien species, the capacity of small cuttings (fragments of stalks or rhizomes just a few centimetres long) to produce new plants is probably the issue to which environmental managers should pay the most attention".

6.8.4 Survey analysis

The following charts present the results of the survey questions on changes in biodiversity.

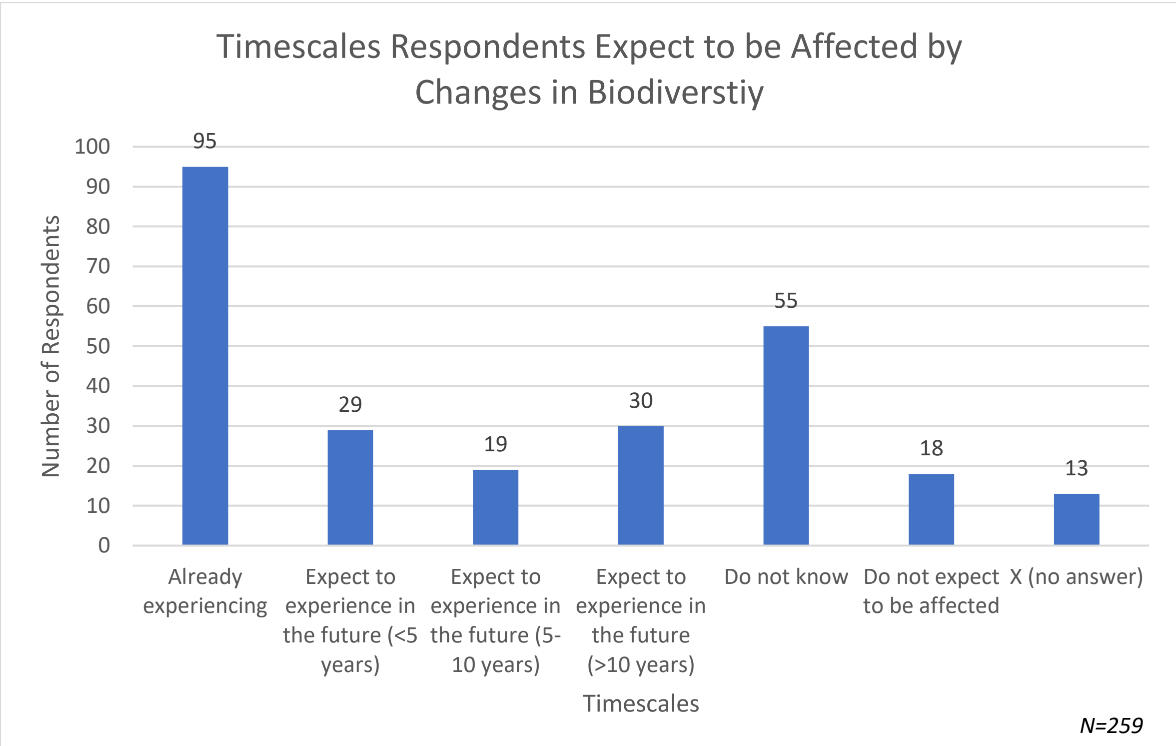


Figure 37 Timescale respondents expect to be affected by biodiversity

Out of 259 respondents, 173 expect to be affected by changes in biodiversity. Ninety-five are already experiencing the effects and 78 expect to experience effects in the future. Eighteen do not expect to be affected and 55 do not know if they will be affected, indicating that for some respondents there are still some uncertainties regarding this impact.

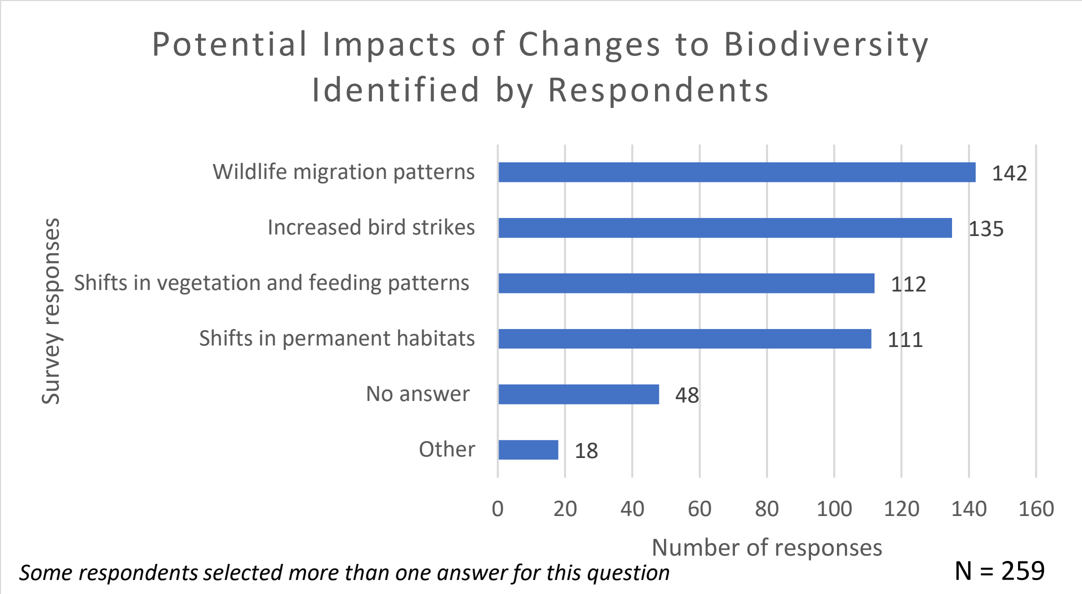


Figure 38 Potential impacts of changes to biodiversity identified by respondents

The main impacts that respondents expect to experience are changing wildlife migration patterns and increased birdstrikes. Many respondents gave more than one answer to this question. The respondents who selected “Other” identified “non-native turtles have increased in number and safe operations in some airports are affected”, “migration of birds, non-indigenous, invasive species (deer), “some of the areas will face outbreak of diseases which were not experience before”, “legislation around species preservation affecting operational facilities”, “numbers of protected species as well as non-protected species moving into areas where activities to support the ANS is required, changes in biodiversity may impact choice of destinations (travel destinations could shift away from areas that are experiencing important biodiversity loss)” (two respondents), “more invasive species” (three respondents).

One respondent identified a potential benefit of warmer winters at their airport leading to less migration and therefore less birdstrikes, noting that pattern changes were already visible for at least one bird species.

6.9 Potential changes in Business and Economics

6.9.1 Summary of Impact and Timescales

ACRP (2012) described business risks as "… those that affect the ability of the airport to meet its mission and responsibilities. Business risks may stem directly from physical risks, such as an airport closure resulting from hurricane damage. Business risks also may arise from the scarcity of a critical resource caused by climate change impacts” and includes “flight delays, airport closures, and related costs” and “risk to contractual, regulatory, and other legal compliance”, for example, health and safety requirements due to an increase in hot days or degraded air quality which threatens compliance with environmental laws (ACRP, 2012, p.43).

Economic and financial risks were described in the 2012 ACRP Synthesis 33 as follows: “Financial risks are those that compromise the ability of an airport to meet revenue targets, pay expenses, or otherwise remain a going concern. Factors that can affect the financial profile of an airport include unplanned expenditures, impaired performance on a contract, and litigation” (p.44). This includes “risk to factors of interest to investors" or changes "which will affect demand for airport services and infrastructure investments" such as changes in tourism demand (Ibid.).

Aviation business operations and financing may be affected by all of the potential climate change effects identified in the previous sections over varying timeframes. In the shorter-term, impacts to business and economics are more likely to be associated with disruptive events, such as extreme weather events like storms or extreme heat, which can lead to delays, cancellations and infrastructure damage (EUROCONTROL, 2021[1]; ICAO, 2022[2]). In the longer-term, gradual but persistent effects, such as temperature change or sea level rise, may lead to business and economic impacts such as changes in tourist demand and damage or loss of infrastructure (EUROCONTROL, 2021[3]; ICAO, 2022[2]).

6.9.2 Potential Business and Economics impacts of Climate Change on Aviation

Some of the potential business and economic effects have already been referred to in previous sections in conjunction with the specific impacts that may instigate them. The intention of this section is both to look at those business and economic effects more holistically, and to discuss those that were identified in the document review but not yet included in the other sections of the Synthesis.

Effects on business and economics from climate change impacts to aviation will be widespread. Increased weather disruption is expected to impact all aspects of airline operational performance from scheduling, flight planning, connectivity of flights, safety planning (e.g. cross wind operations) and non-optimum trajectory operations (vertical and lateral), horizontal flight efficiency, fuel burn and the associated emissions (EUROCONTROL, 2021[1]; ICAO, 2022[2]).

From an operational perspective, climate change impacts on aviation may increase the need for "Fuel reserves to cater for increased unpredictability and holding will need to increase thus creating an extra weight penalty and consequent increased fuel burn needed to 'tanker" this extra fuel. It will increase ground and airborne holding which will in turn compound congestion." (SESAR[2], p.29). An additional business impact may be the ripple-effect of delays and uncertainty of flight schedules (Ibid.).

From a staffing and infrastructure perspective, Thompson (2016) and the ACRP (2014) note that as climate change alters airport operating conditions this may increase costs as it may "challenge the experience of airport staff and the capacity of facilities and equipment" whilst "slowly undermining vulnerable capital investments" (Thompson, p.109).

From a revenue perspective, there may be revenue losses and/or increased costs linked to increased energy costs and requirements; changes in destination demand for air travel, increased repair and maintenance costs (airfield surfaces, infrastructure, access roads, etc.) and the need for additional firefighting services and wildlife management measures (ICAO[2], 2022). There may also be increasing pressure to disclose physical climate change risks to investors and insurers (Ambrosio et al., 2020; Tsalis et al., 2018).

Sea level rise: A key economic or business effect for aviation could be the potential need to reinforce or relocate airport infrastructure due to sea level rise, the latter having potential for significant impact (ICAO[2], 2022). Costs of an airport closure due to storm surge could be significant (EUROCONTROL, 2021[2]). For coastal locations, there could also be an associated effect on their tourism industries if airport use becomes constrained or parts of their territories become inundated (IATA, 2023; IPCC[2], 2022). This may be a particular challenge for Small Island Developing States whose tourism industries are highly dependent on arrivals by air (IATA, 2023; ICAO, 2018).

Increased intensity of storms: There are two main types of business and economic effects, which were identified by multiple sources in the literature review: namely, 1) costs from operational impacts such as delayed flights or, 2) cancelled operations and costs from damage to infrastructure (EUROCONTROL, 2021[1]; ICAO,[2] 2022). Access to ground transportation to and from airports may also be affected, whilst, according to Puempel and Williams (2016), there may be a potential effect on the "performance and maintenance requirement of jet engines" due to storm damage (p.207). ACI (2018) highlight that airports might be used during weather-related disaster to provide shelter and/or as a hub for relief operations which can have business and economic effects. Given this potential emergency response role, airports need to give consideration to having adequate energy, food and water supplies to care for stranded passengers during extreme events which may close the airport for a significant time, and to coordinate with airlines in the event of the need to evacuate passengers before or after an extreme event. The 2017 hurricanes that affected the Caribbean provide just one example of the critical role that transportation plays in emergency response and evacuation in the event of a severe storm, especially for small islands.

Temperature change: Persistently higher temperatures, particularly at popular tourist destinations, may also influence demand for air travel to certain locations which, in turn, may result in reductions or increases to revenue streams (ACI, 2018; EUROCONTROL, 2021[3]; ICAO, 2022[2]). In addition to higher temperatures, water availability may reduce passenger travel demand particularly to areas experiencing drought (Thompson, 2016). Travel demand to popular winter tourism destinations may also be noticeably affected if climate change contributes to less precipitation or higher temperatures that deteriorate skiing conditions or shortens the ski season. Demand changes have substantial impacts on fleet and schedule planning by airlines, as well as infrastructure and workforce planning by airports, airlines, and ANSPs (EUROCONTROL; 2021[3]; Thompson, 2016). More generally, high heat days will increase cooling costs in terminals and other infrastructure such as ATC towers, whilst employees may also be impacted by higher temperatures (ACI, 2018; ICAO[2], 2022). Hot weather is already acknowledged as causing health risks for airline passengers in airports, and this may be exacerbated by an increase in extreme heat days (ACI, 2018; ICAO[2], 2022).

Thawing of permafrost may lead to economic costs to reinforce or rebuild runways, whilst heat damage to airfield surfaces may also incur repair or replacement costs (ICAO[2], 2022). Effects on aircraft from rising temperatures may necessitate a reduction in payload (passengers or cargo) which would have an economic penalty (ICAO[2], 2022). There may also be a fuel penalty.

Conversely, colder temperatures in northern climates could lead to flight cancellations if aircraft are not certified for extremely low temperatures (Phillips and Towns, 2017). There may also be an increase in heating costs for terminals and other infrastructure (GTTA, 2014).

Precipitation Change: There may be economic and business continuity effects from flooding and flood damage to both runways and infrastructure due to increased precipitation. In turn, this could have impacts on operations leading to capacity reduction, delays and cancellations, all of which have financial implications due to lost revenues and increased operating costs, not to mention passenger inconvenience (AAHK, 2022; ACRP, 2012; EUROCONTROL, 2013; Heathrow Airport, 2011; San Francisco Bay Conservation and Development Commission, 2017; Puempel and Williams, 2016; SESAR[1], 2012; NATS, 2021; Rapaport et al., 2017). Ground transport links may also be disrupted preventing crew and passengers from reaching the airport (ACI, 2018; ICAO[2], 2022). Unexpected heavy snowfalls are assumed to have similar financial implications (SESAR, 2012).

Some geographic areas are projected to experience more drought. Drought may contribute to business and economic effects if water becomes scarce for aviation operations or if the demands of a tourist destination change (ACI, 2018; ACRP, 2012; ICAO[2], 2022).

Changes in wind: Changes to, or deviation from, the prevailing wind direction and strength at airports could affect runway utilisation and schedules, reduce airport and aircraft operating efficiency, capacity, and may impact safety (ACI, 2018; Rapaport et al., 2017). It may also change the criteria for approach and departure procedures and reduce flight arrival and departure punctuality, all of which will incur costs (ACI, 2018).

According to Rapaport et al. (2017) extreme storms and strong winds, “can result in flight delays and cancellations, associated economic losses, and passenger inconvenience" (p.246) and the International Transport Forum noted in 2015 that these impacts "may damage or destroy transport assets" (International Transport Forum, p.3).

Changes to the jet stream could have an impact on both flight times and fuel costs for en route air traffic. According to a 2015 article by Karnauskas et al in *Nature Climate Change,* if the average roundtrip journey time increases by one minute on all flight routes globally because of climate change, then the cost to the airlines of the extra fuel would be in the region of USD 3 billion per annum at 2014 prices. Conversely, a 2021 study from EUROCONTROL identified that by 2050 for some routes an overall reduction in flight times due to changes in high-altitude winds could have a positive effect on fuel burn and emissions with a corresponding decrease in costs (EUROCONTROL[5], 2021). There may also be an increase in Clear Air Turbulence leading to costs due to increased injuries to passengers and crew and damage to aircraft (SESAR, 2016; ICAO, 2016).

Changing Icing Conditions: Delay or cancellation of flights, from freezing rain for example, will have financial implications. There may also be increased de-icing requirements and associated costs and the risks of financial penalties if run-off breaches environmental limits (ACI, 2018; Palko and Lemmen (Eds.), 2017; ACRP, 2016).

Desertification: A potential effect on aviation from desertification and an increase in dust storms is that “silicates contained in typical sand and dust storms will melt and thus affect the performance and maintenance requirements of jet engines” which will have financial ramifications (Puempel and Williams, 2016). Sand may also damage airframes and engines whilst sand storms may disrupt operations with the attendant financial costs (ICAO, 2018).

Changes in biodiversity: There may be an increase in costs for wildlife management and also costs from wildlife damage to aircraft. There may also be damage to landscaping and an increase in maintenance costs due to changes in local wildlife or an increase in invasive species (ACI, 2018; ACRP, 2012).

Interconnections: More generally if one airport is directly impacted by climate change, other parts of the network may be affected indirectly, which may cause ripple effects across multiple business and economic sectors. The 2012 ACRP Synthesis 33 Airport Climate Adaptation and Resilience report states the interconnectedness of global and regional networks is a factor because as "...airports in one state or country deal with a climate risk, many other airports, both nationally and globally, are affected." (ACRP, p.9), whilst the International Transport Forum noted in 2015 that the effects of climate change may be much wider than the aviation network as, "connected networks and systems can propagate the initial impact beyond the directly affected infrastructure to other vital transport and non-transport systems." (International Transport Forum, p.7). In particular, SESAR (2016) identified the "Impact of growing weather disruptions on airline hubbing (knock-on effects)" as an issue to be considered (p.24). If there is disruption at a hub airport this will have a knock-on effect for the flights which depart from that airport, the airports to which they arrive, and of course passenger connections, all of which can have a financial cost.

Financial challenges as a barrier: There are of course financial costs associated with adaptation and one document reviewed noted that costs of implementing adaptation strategies could be prohibitive. The implications for buildings and assets, such as costs of redesign and long lead times were also noted (NATS, 2011). "However, changing climate conditions will drive an increase in infrastructure and operating costs, therefore the costs of adaptation need to be weighed against the costs of inaction" (Burbidge et al, 2023, p.22).

6.9.3 Adaptation and Resilience Measures

Specific adaptation and resilience measures for each impact have been discussed in the relevant sections. However, from a more general perspective, limiting business and economic effects involves good planning and well-informed business decisions, which may benefit from activities such as climate risk assessments (ACI, 2018; ACRP, 2014; ICAO[3], 2022).

In the case of infrastructure decisions such as retro-fitting, redesign or relocation, a decision-making process such as a cost benefit analysis may be required, as well as taking into account factors such as cost versus level of resilience and criticality (International Transport Forum, 2015). This will be discussed in more detail in the Adaptation Measures section.

Operational measures to increase robustness and flexibility, such as implementing augmented low visibility procedures e.g. using GBAS, improved MET forecasting capabilities, decision making procedures such as Airport Collaborative Decision Making (A-CDM) and "soft" measures such as information sharing and training may have an initial financial outlay but by improving resilience they may eventually reduce financial costs (EUROCONTROL, 2013; SESAR[2], 2012). Similarly measures to counter drought conditions by reducing water consumption can also have a financial benefit (ACRP, 2012; ICAO[3], 2022).

Financial challenges as a barrier: To facilitate the financial challenge to adaptation, top management buy-in will be necessary. It may not be possible to adapt all infrastructure and systems such that no projected impacts of climate change are ever realized. While the scientific community is in broad agreement that the global climate is changing, there is still some uncertainty surrounding when climate change impacts are projected for specific regions and what those impacts may be. Resilience will likely be a combination of adapting infrastructure and developing processes and plans to respond to impacts quickly and efficiently as they happen. It will be necessary to make decisions based on costs and benefits in order to ensure critical elements are protected.

6.9.4 Survey analysis

The following charts present the results of the survey questions on business and economics

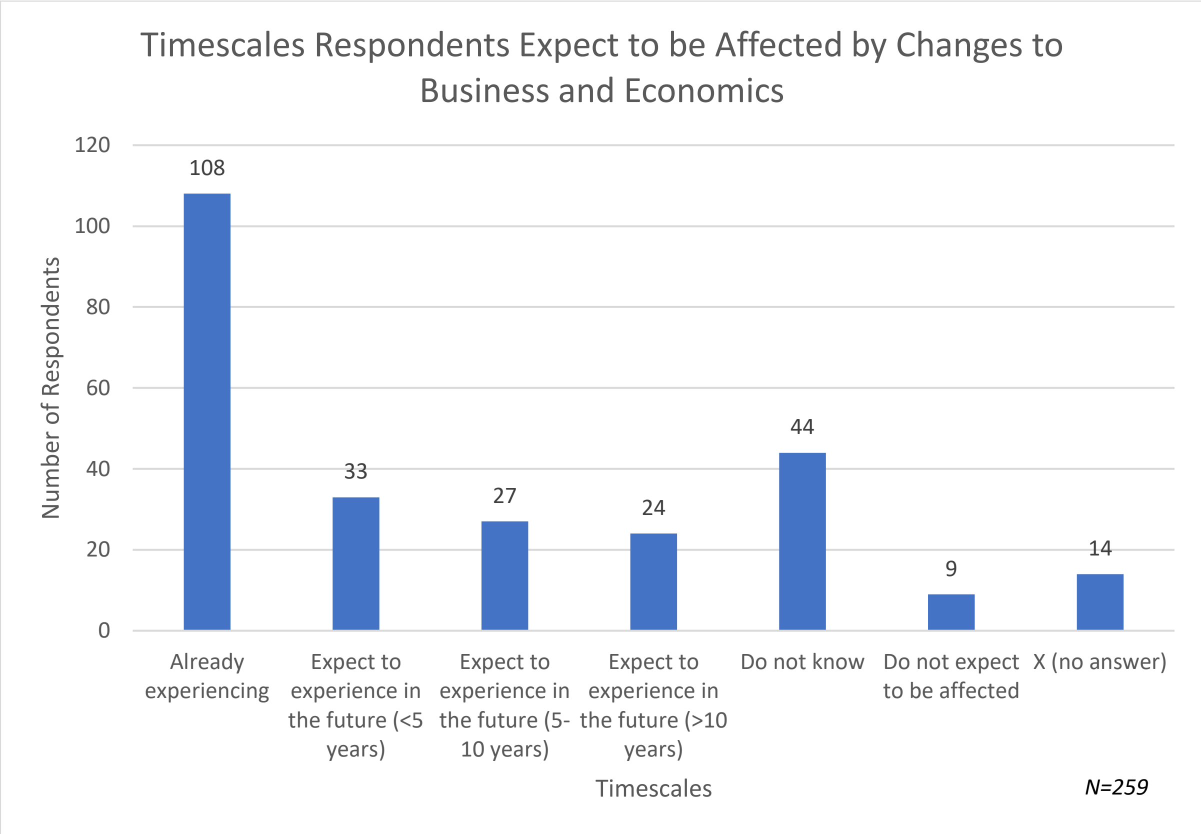


Figure 39 Timescales respondents expect to be affected by changes to business and economics

Out of 259 respondents, 192 are already experiencing or expect to be affected by changes in business and economics. One hundred and eight respondents are already experiencing the effects and 84 expect to experience effects in the future. Nine do not expect to be affected and 44 do not know, indicating that for some respondents there are still some uncertainties regarding this effect.

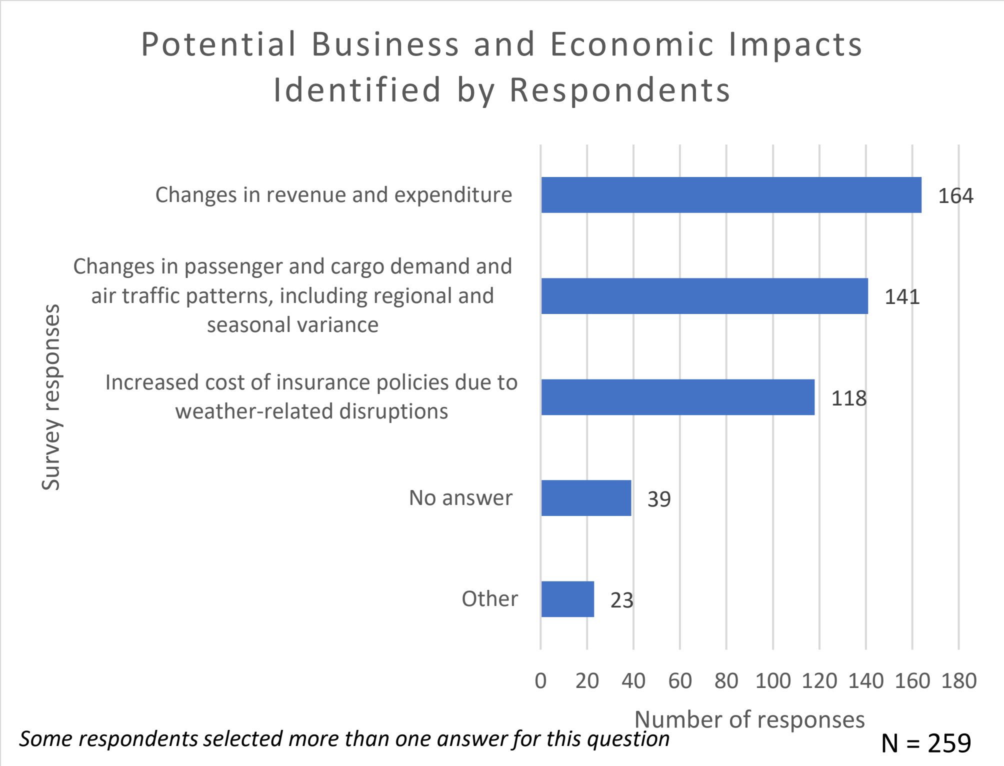


Figure 40 Potential business and economic impacts identified by respondents

The main impacts that respondents expect to experience are changes in revenue and expenditure and changes in passenger and cargo demand and air traffic patterns, including regional and seasonal variance demand and air traffic patterns.

Many respondents gave more than one answer. The respondents who selected “Other” identified “reduction in share price/investor attraction due to emissions exposure/climate change inaction”, “increased cost of maintenance”, “disruption to upstream/downstream supply chains and distribution networks arising from lack of preparedness and resilience by stakeholders”, “increased cost in design of new facilities and equipment as well as repairs/replacements of damages”, “significant increases in insurance costs for the corporation”, “increase in cooling and possibly electricity costs but decrease in heating costs, what the balance will be is currently unclear”, “insurance premium may increase due to storms”, “Increase in the cost of aircraft maintenance”, and “changes in demand for air freight and import/ export hubs as domestic regional economies adjust to new conditions”.

One respondent noted that they have already seen increased costs throughout their supply chain and climate impact has increased the cost for certain procurements. One respondent noted that specific analysis has not yet been performed.

7. Analysis of Impacts which Stakeholders Expect to be the Biggest Challenges

This section considers the climate change effects and impacts which survey respondents expect to be the biggest challenges. It also provides a breakdown of biggest challenges by ICAO region and for Small Island Developing States.

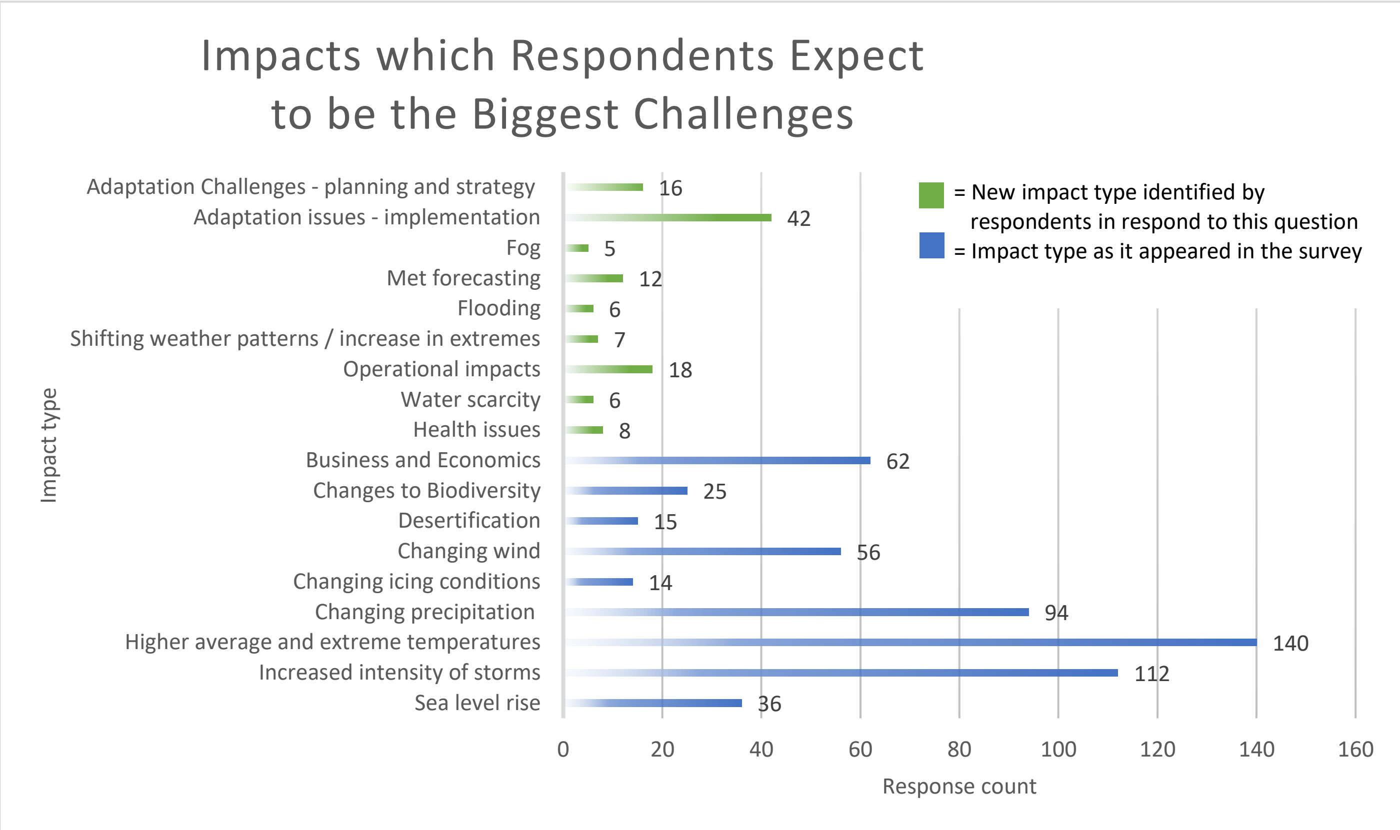


Figure 41 Impacts which respondents expect to be their biggest challenges

This question asked respondents to identify their top three expected challenges. Respondents could choose from one of the effects included in the survey (indicated in blue in the graph above) or insert their own challenges. Out of 259 respondents, 79 chose not to answer this question. Twenty-four of the respondents provided answers that were not applicable to the question (in most of these cases, respondents identified challenges related to greenhouse gas mitigation issues, not climate change adaptation).

Respondents were able to select (or write in) the same challenge multiple times; in those situations, each response was included in the total. Of the 18 impact categories respondents identified as their biggest challenges, nine of these were "new" categories identified by respondents; respondents indicated 42 times that "Adaptation issues – implementation" was in the top three of their biggest challenges. This category included issues such as identifying and implementing suitable adaptation and resilience measures and training of personnel. Eighteen times, respondents identified "Operational impacts" such as airport closures, delays or cancellations, as one of their biggest challenges. Sixteen times, respondents identified "Adaptation challenges – planning and strategy" as one of their top three biggest challenges. This covered challenges such as incorporating climate change adaptation criteria into strategic planning or implementing policies to support adaptation. Twelve times, respondents identified “Met forecasting” as one of their top three biggest challenges. Eight times, respondents identified “health issues”, for example the protection of aviation personnel whilst working, as one of their top three biggest challenges, and seven times respondents identified “Shifting weather patterns/increase in extremes,” such as an increase in extreme events or changes in frequency and intensity, as one of their top three biggest challenges. Six times, respondents identified “flooding” or “water scarcity” respectively as one of their top three biggest challenges. Five times respondents indicated that “fog” is one of the top three biggest challenges they face.

The other nine categories were climate effects that the respondents could select within the survey. Of these, 140 times respondents selected “Higher average and extreme temperatures” as one of three of their biggest challenges. One hundred twelve times, “Increased intensity of storms” was in the top three challenges for respondents, and ninety-four times respondents indicated “changing precipitation” was one of their biggest challenges.

7.1 Global and Regional Breakdown of Top Three Challenges

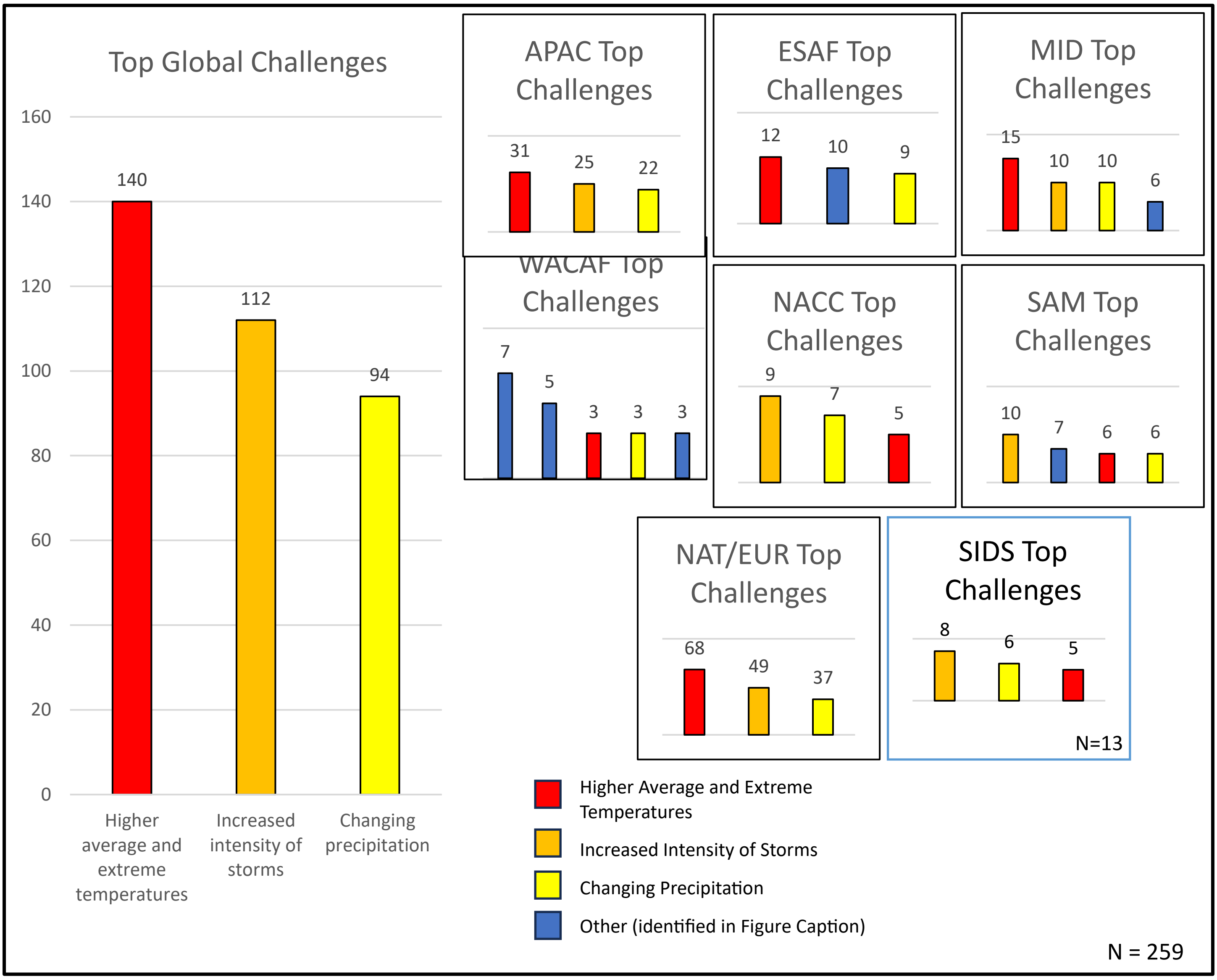


Figure 42 Top Three Challenges Globally and by Region (The "other" responses are ESAF: Business and Economics; MID: Adaptation Issues – Implementation; SAM: Business and Economics; WACAF: Changing Wind (7 responses) Adaptation Issues – Implementation (5 responses) Sea level rise (3 responses)

The top three challenges respondents identified align with the results to the earlier question in this survey which asked respondents which climate impact categories they anticipated being affected by either now, or in the future. For both questions, respondents selected higher average and extreme temperatures, changing precipitation, and increased intensity of storms as their top concerns. Interestingly, a higher percentage of respondents anticipate being affected by changing precipitation, but in response to this question, more respondents indicated that increased intensity of storms is a greater challenge than changing precipitation. This may be an indication that even though a respondent may have indicated they anticipate experiencing a climate change effect, they are not necessarily concerned about that effect. The number of respondents that anticipate experiencing a climate change effect should not be interpreted to identify the most significant challenges to the global aviation sector. Individually, and collectively, the answers to this question are perhaps a stronger representation of where the biggest challenges lie.

As with the effects expected to be experienced there are regional differences to what survey respondents expect to be their biggest challenges. Higher Average and Extreme Temperatures are in the top three challenges in all seven ICAO regions, being the top challenge in APAC, ESAF, MID and NAT/EUR. Changing Precipitation is also a top three challenge in all regions, although always the second or third biggest challenge rather than the first. Increased Intensity of Storms is a top three challenge in four regions, namely APAC, MID, NACC and EUR/NAT. Business and Economics is a top three challenge in ESAF and SAM. In WACAF the biggest challenge for respondents is Changing Wind. Adaptation Issues – implementation is the second biggest challenge and sea level rise is the joint third biggest challenge alongside Higher Average and Extreme Temperatures and Changing Precipitation. Therefore, as is to be expected there are some regional differences but, as per the overall results, Higher Average and Extreme Temperatures, Changing Precipitation and Increased Intensity of Storms are viewed as the biggest challenges in the majority of regions.

There were 14 respondents from Small Island Developing States to the 2022 Survey. These respondents also indicated Increased Intensity of Storms, Changing Precipitation, and Higher Average and Extreme Temperatures respectively as their top three challenges.

8. Synthesis of Information on Risk Assessment Methodologies and Progress

This section will present a synthesis of information on the climate change risk assessment process. It will also present the 2022 Survey results on respondents' progress on risk assessment and implementation of climate change adaptation strategies and plans. Finally, it provides a comparison between the risk assessment and adaptation implementation responses from the 2022 and 2017 Surveys.

8.1 Climate Change Risk Assessment Methodologies

In order to develop a climate change adaptation strategy or plan, it is first necessary to carry out a climate change risk assessment to determine where vulnerabilities to climate change may exist (ICAO[1], 2022). According to the Key Steps in Aviation Organisation Climate Change Risk Assessment and Adaptation Planning (ICAO[1], 2022) this is an analysis of likelihood x probability equating to risk or "what can happen?", "How likely is that?" and "what are the consequences?". The document provides a list of Six Key Steps and detailed guidance for aviation organizations to follow when carrying out a climate change risk assessment. The guidance highlights that in order to carry out a risk assessment, it is important to identify the scope. For example, the scope could be at the organization level, sub-organizational level, asset level, or, as indicated by some respondents to the survey questions, risk assessments can be carried out at the State level with a consideration for vulnerabilities to the aviation sector. ICAO note that "Decisions defining the scope will vary according to the type of organisation, and the specifics of the organisation itself." and "can include infrastructure and/or operations, location, age, lifespan and interdependencies." (ICAO[1], 2022, p10). However, the guidance also emphasises that if the assessment only focuses on a specific part of a system or organization it should be verified that "there are no unexpected consequences such as missing key issues or impacts that may have knock-on effects to other components of the organisation or system that were not assessed." (p10).

The Key Steps in Aviation Organisation Climate Change Risk Assessment and Adaptation Planning (ICAO[1], 2022) emphasises that senior leadership commitment is essential when initiating a climate risk assessment. Collaboration and coordination with key stakeholders and service providers is also important. Communication is also an important component of risk assessment planning.

To carry out a climate change risk assessment an organization can either choose to use its existing risk assessment methodology, use a climate change risk assessment methodology or tool developed by another organization, or develop its own climate change risk assessment (ICAO[1], 2022). For example, one respondent noted that climate change impacts had been considered as part of an overall sustainability risk assessment.

In some cases, aviation organizations may be included in wider national-level climate change risk assessments and adaptation plans. For example, one respondent noted that both a risk assessment and an action plan on climate adaptation are currently being carried out by their national government in cooperation with stakeholders.

In addition to the ICAO guidance, there are several climate adaptation risk assessment methodologies available but at a high-level they mainly follow the same three generic steps which are summarised below:

1) **Finding out how the climate will change.**

Finding out how the climate will change involves, "defining the climate change variables and projections, setting baseline conditions (e.g., current stressors)," before modelling or acquiring robust data on projected climate impacts (ACRP, 2012, p.33; ICAO[1], 2022).

It will need to be decided which climate variables to assess. For example the U.S. ACRP Airport Climate Risk Operational Screening (ACROS) tool includes the following climate vectors: Hot days (number of days >90°F), very hot days, freezing days, frost days (number of days with low temperatures < 32°F), heating day, cooling day (day's average temperature minus 65°F), cooling degree days, heating degree days, hot nights, humid days, snow days, heavy rain, dry days, sea level rise, sea level rise - base flood elevation (BFE), wind and fog, maximum 5-day rainfall (demonstrating a robust change) and storm days (ACRP, 2014).

2) **Risk Identification**

Risk identification involves analysing how the climate changes identified in the first section can affect the organization by assessing the potential effects and how likely they are to occur. As noted above, risk assessment can also be carried out at levels other than organizational level as appropriate, for example at sub-organizational or at the asset level.

Risks need to be identified and prioritised. This involves: evaluating the likelihood of occurrence, evaluating the likelihood of consequences, evaluating the severity of consequences and then establishing a risk priority based on likelihood and severity. Identification and prioritization of risks should be done for short-, medium- and long-term timescales (ICAO[1], 2022). As ACRP (2012) states, metrics may be "developed to evaluate the magnitude of the consequences, and these may include capital and operating costs, effects on society, health, economics, and the environment" (p.33). The same report also noted that "With respect to the likelihood of occurrence, one critical factor is whether there is a likelihood of occurrence of the impact in the lifetime of the asset" (Ibid.). Risk control measures and existing adaptive capacity which an organisation already has in place should also be taken into account. However, there may be many uncertainties to take account of such as uncertainty or level of confidence with the projections, limited data or factors such as the life-time of the asset/infrastructure (Ibid.; ICAO[1], 2022).

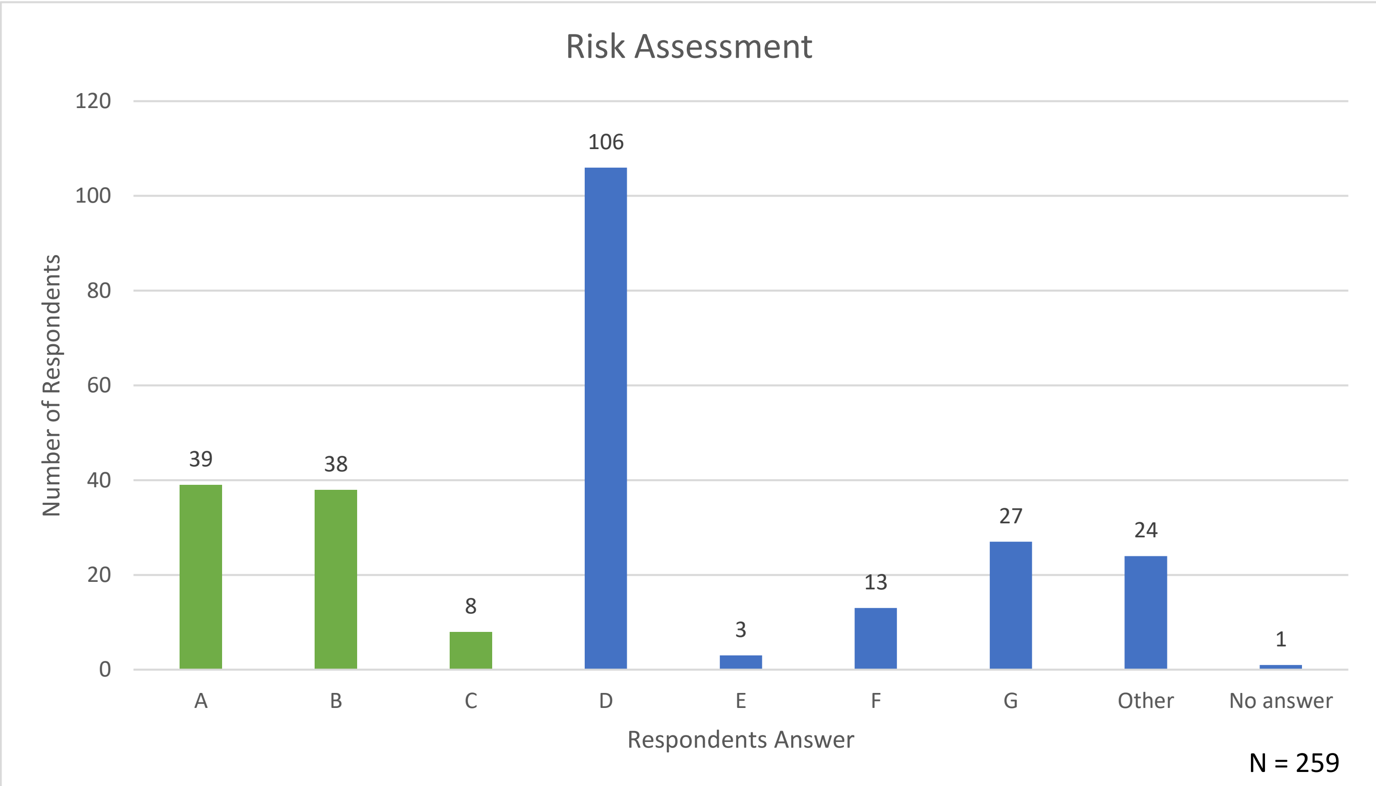
Although the generic steps are similar, methodologies will need to be fine-tuned for different types of organizations. For example, the same ARCP Synthesis Report quoted above also states that for airports this may involve, “developing asset inventories based on policy priorities, assessing vulnerabilities, analysing risks, prioritizing the assets, and developing adaptation strategies" (Ibid.), while ICAO (2016) recognized this may “require localized studies that are specific for their sites rather than global outlooks" (p. E-4). *The Key Steps in Aviation Organisation Climate Change Risk Assessment and Adaptation Planning* guidance notes that “Individual organisations and States should adapt the guidance according to their specific organisational or national situation” (ICAO[1], 2022 p.2).

It may be beneficial to include key stakeholders in the risk assessment and planning process (ICAO[1], 2022). The Key Steps in Aviation Organisation Climate Change Risk Assessment and Adaptation Planning guidance recommends that organizations should already initiate communication with key stakeholders once leadership commitment to carry out the risk assessment is in place.

3) Review and repeat the assessment periodically

All risks should be monitored regularly. Review and revise the assessment as new information becomes available (ACRP, 2012; ICAO[1], 2022). As the *Key Steps in Aviation Organisation Climate Change Risk Assessment and Adaptation Planning* guidance highlights “both climate projections and the organisation’s operations and assets, and the condition of those assets, may change” (ICAO[1], 2022, p24) so it is important to reassess periodically as well as monitoring how impacts and costs evolve over time.

8.2 Climate Change Risk Assessments Survey Analysis



A	**We have carried out a climate change risk assessment and *are implementing* a climate change adaptation strategy/plan**
B	**We have carried out a climate change risk assessment and *intend to implement* a climate change adaptation strategy/plan**
C	**We have carried out a climate change risk assessment but do not intend to implement a climate change adaptation strategy/plan**
D	**We intend to carry out a climate change risk assessment**
E	**We do not intend to carry out a climate change risk assessment because we do not believe it is needed**
F	**We do not intend to carry out a climate change risk assessment because we do not have the resources**
G	**We do not intend to carry out a climate change risks assessment because our organization is already part of, or will be included, in a larger Organisation/State's risk assessment**

Figure 43 Respondents progress on risk assessments

This question asked if respondents have carried out a climate change risk assessment and/or implemented a climate adaptation plan. It was a multiple-choice question and respondents could only select one answer. 39 of 259 respondents (15%) indicated they have carried out a climate change risk assessment and are implementing a climate change adaptation strategy or plan. 38 of 259[10]

[10] Note that due to rounding the sum of the individual percentages is 101% whilst 39 and 38 respondents both equate to 15%

respondents (15%) indicated they have carried out a climate change risk assessment and intend to implement a climate change adaptation strategy or plan. Eight of 259 respondents (3%) indicated they have carried out a climate change risk assessment and do not intend to implement a climate change adaptation strategy or plan. None of these eight respondents provided any additional information on why they are not carrying out an adaptation strategy or plan after conducting a risk assessment, yet, in response to the earlier question in the survey asking whether respondents except to be affected by climate change, seven of the eight respondents said they expect to be affected by climate change now or in the future, with one respondent stating that they do not know if they will be affected by climate change. Four of the eight respondents were states, three were airports, and one air navigation service provider.

More than one third of respondents (106/259, 41%) said they intend to carry out a climate change risk assessment. Twenty-seven of 259 respondents (10%) do not plan to carry out a climate change risk assessment because their organization is, or will be, a part of a larger climate risk assessment. Thirteen respondents (5%) (four CAAs, three Airports, three airlines, one OEM, one ANSP, and one State) do not plan to carry out a climate change risk assessment because they do not have the resources. Three respondents (3%) (two Airports and one CAA) indicated they do not plan to carry out a climate change risk assessment because they do not believe it is needed.

Twenty-four respondents (9%) selected “Other” and provided their own answer in the comment section for this question. Some of these respondents indicated they did not know whether or not their organization has carried out a risk assessment. Others pointed to related organizations (e.g., other ministries, airports), that have carried out their own assessments. One organization provided information on how to access their adaptation plan online.

8.3 Comparison with 2017 Risk Assessment Survey Results

To monitor evolving changes in stakeholder perspectives and levels of resilience over time, the results of the Risk Assessment and Adaptation Planning question in the 2022 survey are compared against the results of the 2017 Survey[11].

However, it should be noted that:

- As the number of responses is much higher for the 2022 Survey, only percentages of respondents giving a particular answer can be compared rather than actual numbers.
- The respondents to the 2022 Survey are, in many cases, different to the 2017 Survey, even when the response comes from the same organization or State. In addition, there is a much broader range of respondent types to the 2022 Survey, which could influence responses. Therefore, the results are an indication only, not a precise comparison.

Moreover, although the 2022 Survey questions have been kept as close as possible to the 2017 Survey questions, experience gained during the 2017 Survey led to the response “We do not plan to carry out a climate change risk assessment” being divided into three different response options to capture the differing reasons that an organization might not intend to carry out a risk assessment, namely:

1) We do not intend to carry out a climate change risk assessment because we do not believe it is needed

[11] Note that due to the format of the 2017 Survey it was possible for respondents to give more than one answer. Therefore the total number of inputs to the 2017 Survey was 92 rather than 88. Therefore when the percentage answers are totalled they add up to 105% rather than 100%

2) We do not intend to carry out a climate change risk assessment because we do not have the resources
3) We do not intend to carry out a climate change risks assessment because our organization is already part of, or will be included, in a larger organization/State's risk assessment.

Therefore, to present the results of the two surveys in as comparable form as possible the results from the 2017 Survey were split into the 2022 categories. Eleven respondents to the 2017 Survey selected the option "We do not plan to carry out a climate change risk assessment". Nine of the respondents indicated that they did not intend to carry out a risk assessment because the risk assessment may be carried out at State level rather than individually. Therefore, these responses have been categorised under option no 3, organization or State's risk assessment. The other two responses gave no further information as to why they were not planning to carry out a risk assessment. Therefore the 2022 option 1 and 2, namely no need for an assessment and no resources, have been combined and the remaining two 2017 responses classified here. Therefore, as discussed above, the results are an indication only, not a precise comparison.

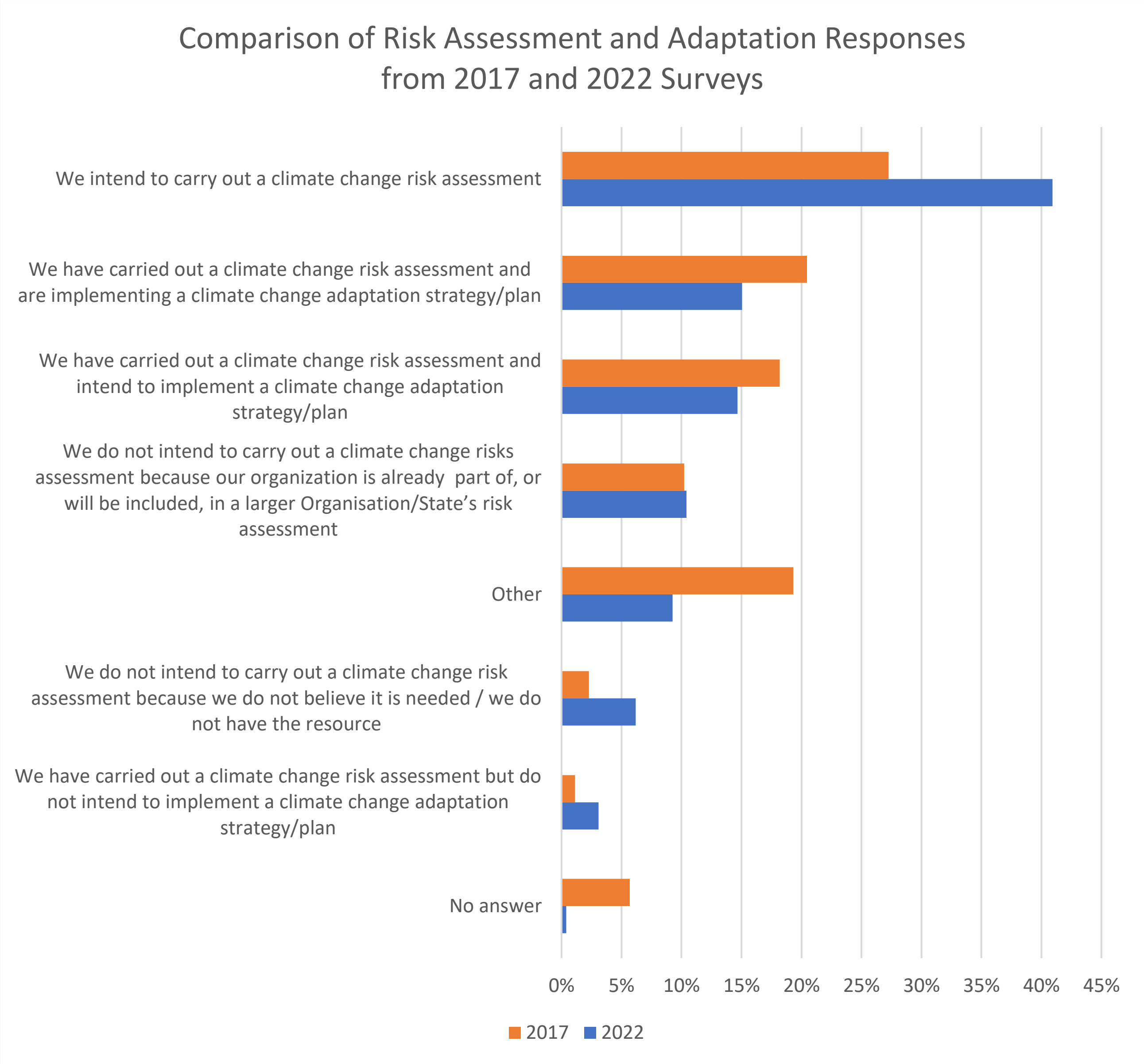


Figure 44 Comparison of Risk Assessment and Adaptation Responses from 2017 and 2022 Surveys

When comparing the 2017 and 2022 results, a slightly higher percentage had carried out a risk assessment and were implementing a climate adaptation plan in 2017 (20%) compared to 2022 (15%). However, in real terms the number is higher with 39 respondents having carried out an assessment and implementing an adaptation plan in 2022 compared to 18 in 2017. There is also a slightly smaller overall percentage of respondents that have already done a risk assessment and intend to implement an adaptation plan although, again, in real terms the number of respondents is greater in 2022 (39 respondents) compared to 2017 (16 respondents). In 2022 41% (106 respondents) intend to carry out a climate change risk assessment compared to 27% (24 respondents) in 2017, suggesting that, overall, there is starting to be much more engagement with climate risk assessment and adaptation than in 2017. Overall, 74% of respondents have either carried out or intend to carry out a risk assessment compared to 63% in 2017.

9. Synthesis of Information on Adaptation Planning

This section will present a synthesis of information on the adaptation planning process. It also presents the 2022 Survey results on the timescales in which respondents are taking climate adaptation and resilience measures, the challenges that respondents identified to implementing risk assessments and adaptation strategies, and the adaptation measures which respondents indicated are included in their adaptation plans.

9.1 Information on Adaptation Planning from Literature Review

If an organization has carried out a climate change risk assessment and identified risks that need to be addressed, the next stage is usually to develop a climate change strategy or plan, or combination thereof (ICAO[1], 2022). This may include incorporating climate risk considerations into planning and organizational decision-making so as to "better define the problem from a corporate or enterprise perspective", as described by ACRP (2012) (p.51). According to the *Key Steps in Aviation Organisation Climate Change Risk Assessment and Adaptation Planning* (ICAO[1], 2022) there are four key steps in aviation climate adaptation planning namely:

1) **Defining adaptation and resilience objectives:** this involves prioritizing the criticality of assets and operations and defining risk acceptance levels, noting that different elements may have different requirements and risk acceptance levels. The more critical the asset or operation then the lower the risk acceptance level would normally be.

2) **Identifying adaptation and resilience measures:** this involves drawing up a short-list of potential measures whilst taking account of the criticality of the elements being addressed risk acceptance levels identified and the available budget.

3) **Developing and implementing a climate adaptation plan**: this involves establishing an order of prioritization for each action and identifying a timetable and process for implementation.

4) **Periodic monitoring and review**: regular review will assess whether the measures that have been implemented are achieving the required results and, if not, then remedial action can be taken. Periodical review can also help identify any new risks so that adaptation measures can be developed and implemented in a timely manner.

The ACRP (2012) recommend airports use a set of tools or decision-making processes as part of the planning process such as: Scenario Planning; Economic Analysis; Climate Impacts Profile; Vulnerability Assessments; Risk Management, whilst the ITF (2015) noted that "Addressing climate considerations will therefore not be uniform across all asset classes." (p.7). Any risk "…assessment should also account for accessibility-reducing impacts … as well as the demand-weighted importance of each link" (Ibid., p.8). It is also suggested that due to "uncertainty upon climate impacts on transport authorities should no longer rely solely on Cost-Benefit Analysis (CBA) for appraisal of assets and networks" as this requires agreement on assumptions of what future impacts will be (Ibid., p.9).

- "Real Option Analysis" (ROA) is proposed as an option for "large, up-front irreversible investments" as this uses probabilistic inputs which allow flexibility with timing of decisions "as well as the ability for the infrastructure to adapt to changing conditions over time (e.g. "build for" not "build with") (Ibid.).

- "Robust Decision Making" (RDM) is proposed as an alternative approach "adapted to situations where no probabilistic information exists regarding impacts or outcomes. This approach seeks to select those strategies and investments that are consistently robust under the widest range of plausible climate outcomes and impacts" (Ibid.)

Specific measures for adaptation planning may include taking account of climate projections when carrying out maintenance or development for other reasons. For example, according to the ACRP (2012), at Oakland International Airport "planners and engineers included sea level rise as a factor in the design changes being developed to address compliance with new runway safety area requirements" p.10)

From an airspace perspective, Puempel and Williams (2016) recommend, "a thorough analysis of [the] impacts on the safety and regularity of flights in [North Atlantic] regions" (p.207). SESAR[2] (2012) suggested that specific measures might include "enhancement of Airspace Management and advanced flexible use of airspace (AFUA) will increase resilience to adverse convective conditions and airspace sector unavailability" (p.29). It was also noted by Nyland and Nodelman (2017, p.96) that while "adaptation tends to be primarily reactive… at the same time, aircraft technology is evolving with more frequent use of instrument landing systems and other innovations allowing aircraft to fly safely in less than ideal situations."

Awareness-raising among employees and stakeholders is also important (ICAO[1], 2022). For example, according to ACRP (2012), Atlanta, Jacksonville and San Diego airports "put into place the awareness-raising processes, research, and procedures [to] be the foundation to the adoption of a climate adaptation strategy and its incorporation into airport planning" (p.10).

Financing will also be required as climate change adaptation may require "investment in both capital expenditures and operations and maintenance" (ACRP, 2012, p.51). The costs of adaptation measures will vary according to location, organization and projected impacts. However, it is expected that as the changing climate causes an increase in costs then this will support the case for adaptation (Burbidge et al, 2023). For example, Melvin et al, (2017) demonstrate how well-planned and proactive adaptation of runways and buildings at Alaskan airports can reduce both risk of flooding and potential future costs (Melvin et al., 2017). The ACRP (2012) also note that in at least one example having to face real climate impacts has helped adaptation planning efforts to evolve (p.51).

The Challenges of Growth 2013 report identifies so-called soft measures such as "staff training, sharing of best practices, experiences and solutions, and the implementation of processes which facilitate collaborative responses to climate change challenges" as potentially some of the most useful and cost-effective components of adaptation planning (p.6). It also identifies what are known as "low-regrets", "no-regrets" and "win-win" measures as potentially cost-effective solutions as they can provide resilience to climate change whilst addressing other issues such as capacity (EUROCONTROL, 2013).

9.2 Analysis of Survey Responses

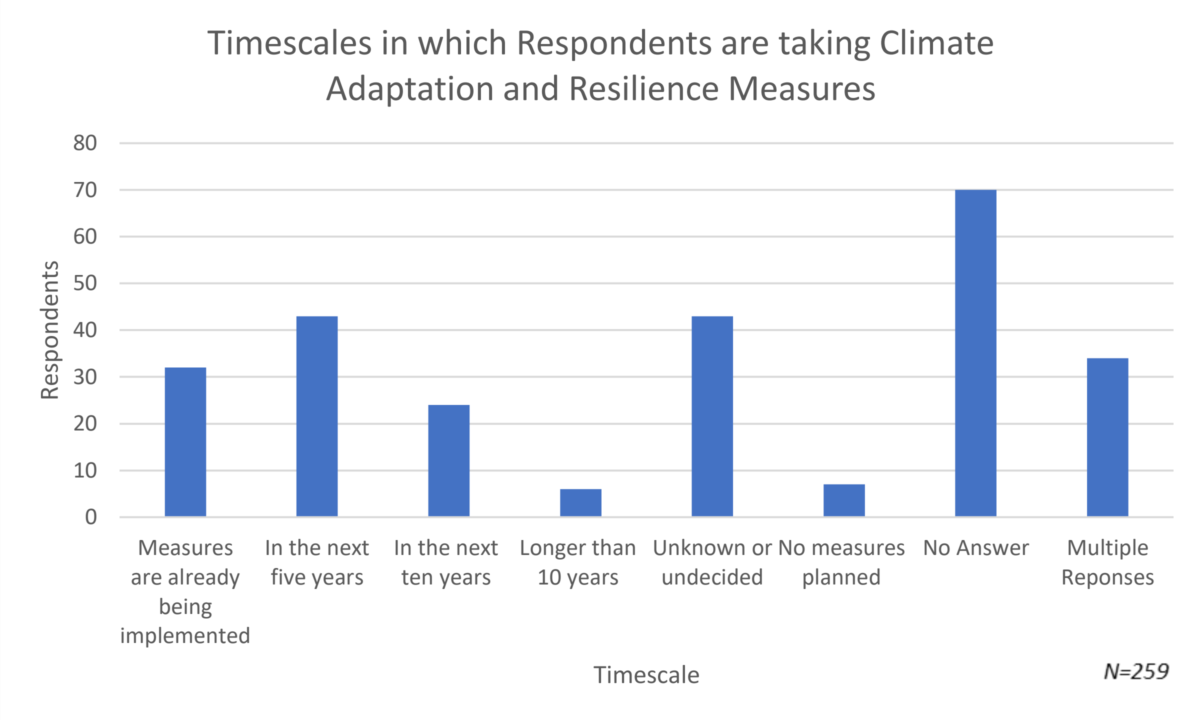


Figure 45 Timescales in which Respondents are taking Climate Change Adaptation and Resilience Measures

Respondents could select multiple answers to this multiple-choice question. Given so many organizations have not yet completed a climate adaptation risk assessment, it is not surprising that more than a third of respondents either chose not to answer the question regarding timescales in which their organizations are taking climate adaptation and resilience measures (70/259, 27%) or selected "Unknown or undecided" as their response (43/259, 17%). Seven respondents said no measures are planned. Forty-three of 259 respondents (17%) also said that they anticipate they will take climate change adaptation and resilience measures in the next five years. twenty-four respondents (9%) said they anticipate they will take these measures in the next 10 years. Six respondents (2%) said they will take them in more than 10 years.

Thirty-two (12%) respondents said they are already implementing adaptation and resilience measures.

Respondents that selected multiple answers (34/259, 13%) had a variety of possible combinations, but largely seemed to be indicating that measures were being taken on different timelines depending on what those measures are. For example, one respondent said that measures are already being implemented and also selected the option for measures being taken in the next five years. Just seven respondents (3%) have no measures planned.

This question asked respondents to select the timescale in which they are taking climate change adaptation and resilience measures so the assumption in the analysis is respondents know what adaptation and resilience measures encompass. However it is very possible that an organization is taking action to improve their operations or efficiency that could be considered a climate adaptation measure, but which the respondent did not account for because they may have considered it as regular maintenance (e.g., grooving a runway, changing signage) or updates to procedures (e.g., new area navigation (RNAV) approaches).

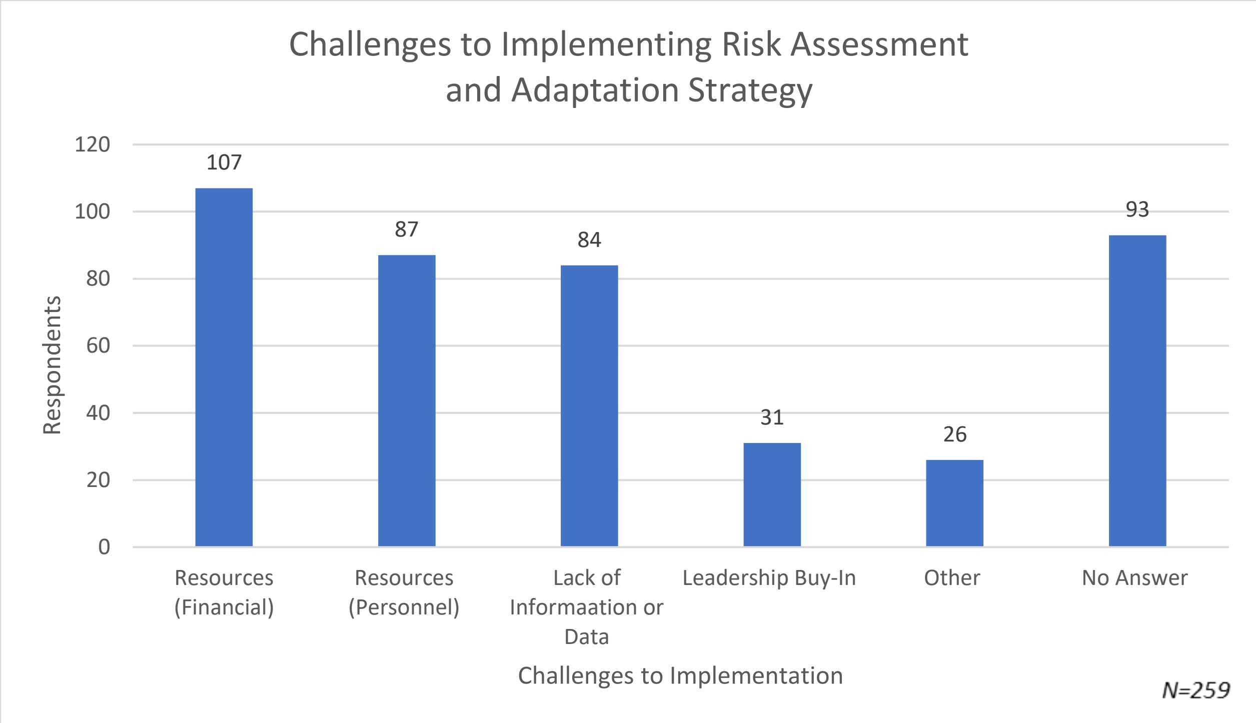


Figure 46 Challenges to implementing risk assessment and adaptation strategy

Respondents could select multiple answers to this multiple-choice question and also had the possibility to write answers in an "Other" section. The challenge to implementing a climate change risk assessment and adaptation strategy respondents selected most often was financial resources (107/259, 41%), followed by personnel resources (87/259, 34%), and lack of information or data (84/259). Only 31/259 respondents selected leadership buy-in as a challenge to implementing a risk assessment or adaptation strategy. More than a third of respondents (93/259, 36%) did not provide an answer to this question, but in the context of the answers to the previous question asking whether or not respondents had carried out a climate risk assessment, this seems to be aligned; it makes sense that a respondent that had not carried out a risk assessment would not respond to this question. About one tenth of respondents (26/259, 10%) provided "other" answers, which included that a strategy has not yet been developed, explanations that they need resources for an assessment, and a variety of answers to indicate a climate adaptation assessment has not happened yet or is otherwise not yet complete.

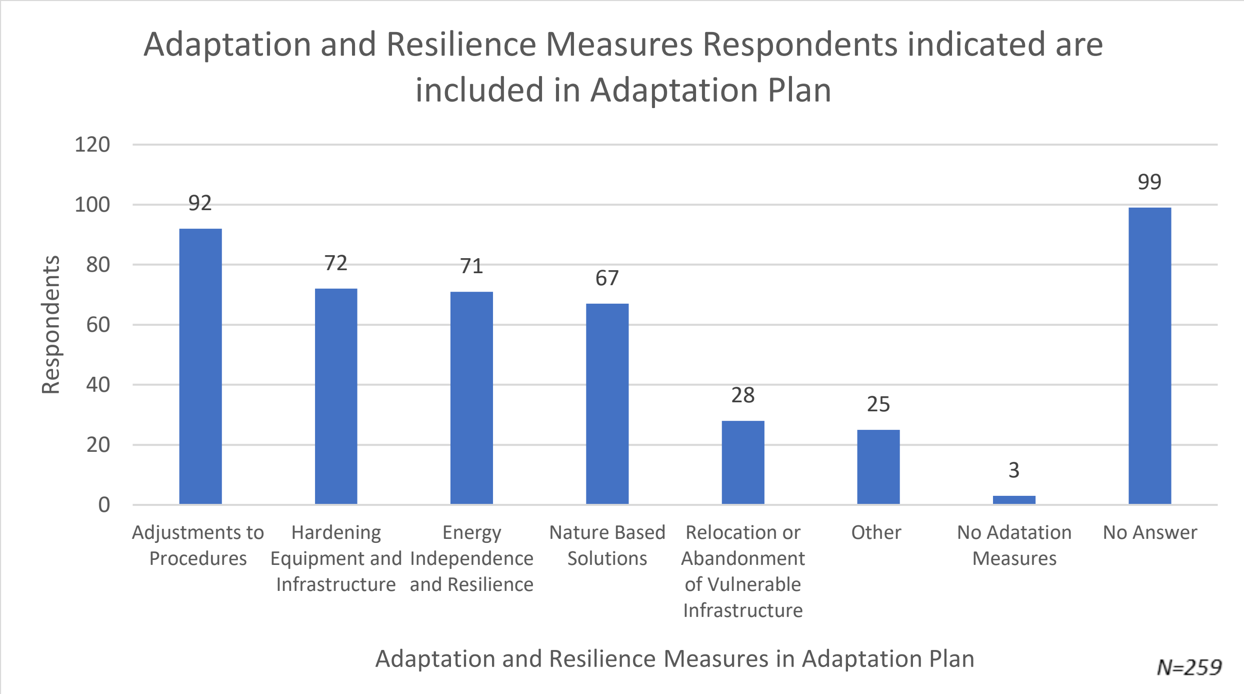


Figure 47 Adaptation and resilience measures respondents indicated are included in adaptation plan

Respondents could select multiple answers to this multiple-choice question and also had the ability to write answers in an "Other" section. Like the question before, more than a third of respondents (99/259, 38%[12]) did not answer this question. This once again makes sense as approximately the same number previously indicated their organization has yet to complete a climate change risk assessment. More than a third (92/259, 36%) of respondents said that adjustments to procedures are included in their organization's adaptation plan. Nearly an equal number of respondents said hardening equipment and infrastructure (72/259, 28%), energy independence and resilience (71/259, 27%), or nature-based solutions (67/259, 26%) are included in their organization's Adaptation Plans.

[12] Note that the percentages do not add up to 100% as respondents could select more than one answer.

10. The Global Aviation Sector and Adaptation to Climate Change

This section presents the survey responses on respondents' perspectives on the extent that they think the global aviation sector is prepared for the potential impacts of climate change, areas where respondents think the global aviation sector is doing well to prepare for the impacts of climate change, and areas where they think it could do better.

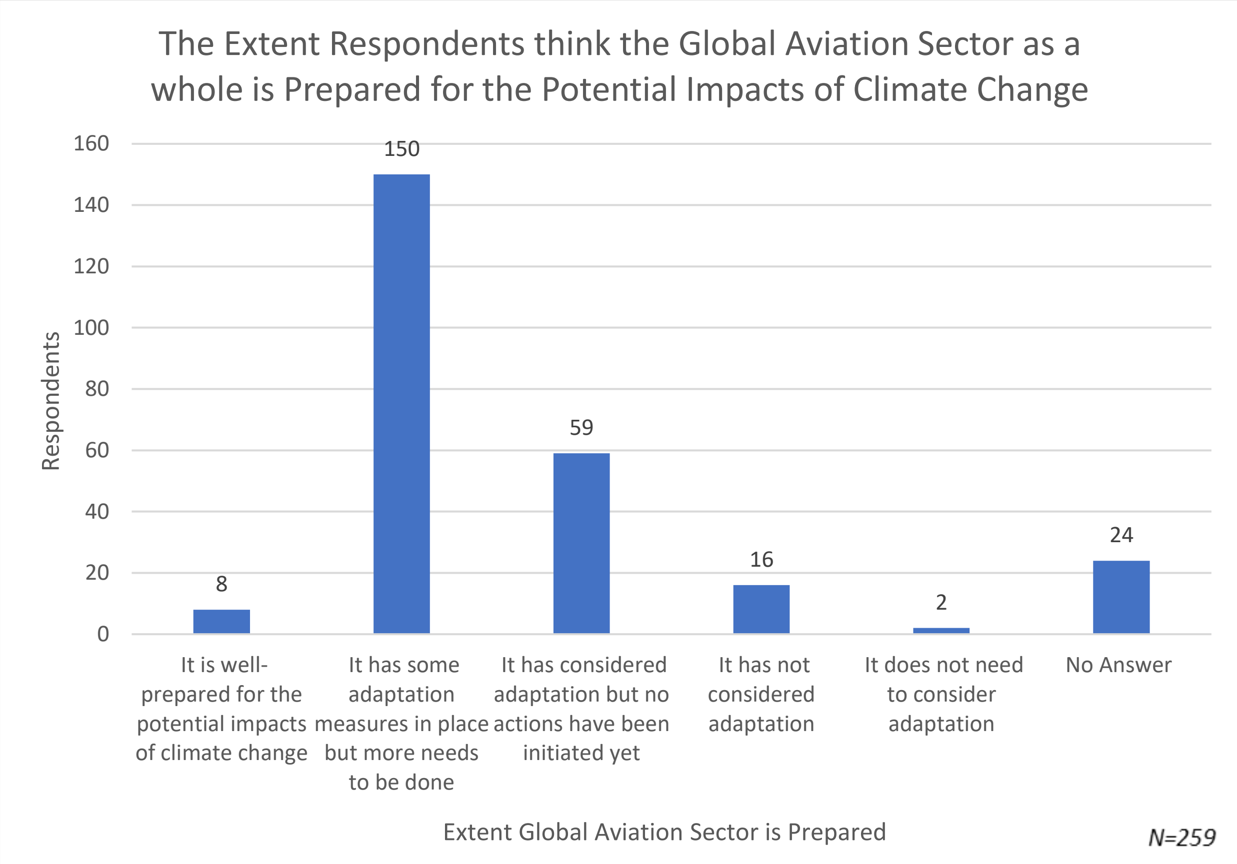


Figure 48 The extent respondents think the global aviation sector as a whole is prepared for the potential impacts of climate change

The majority of respondents (150/259, 58%) consider that the global aviation sector has some adaptation measures in place but that more needs to be done. Just eight respondents (3%) think that the sector is well-prepared for the potential impacts of climate change. Fifty-nine respondents (23%) think that the sector has considered adaptation but not yet initiated any actions and sixteen respondents (6%) answered that the sector has not considered adaptation at a global level. Two respondents (<1%) consider that the sector does not need to consider adaptation.

Respondent's Voice

Q: To what extent do you think the global aviation sector as a whole is prepared for the potential impacts of climate change?

A: We think it is prepared, however we do not know the veracity of this statement because we do not handle this information. (Translated - Meteorological Office)

A: There is a general recognition of the need for adaptation and adaptation measures. Some areas are already experiencing impacts of climate change. Some measures are implemented (or partly so) but much more needs to be done. (State)

A: Globally not prepared (CAA)

10.1 What the Global Aviation Sector is Doing Well

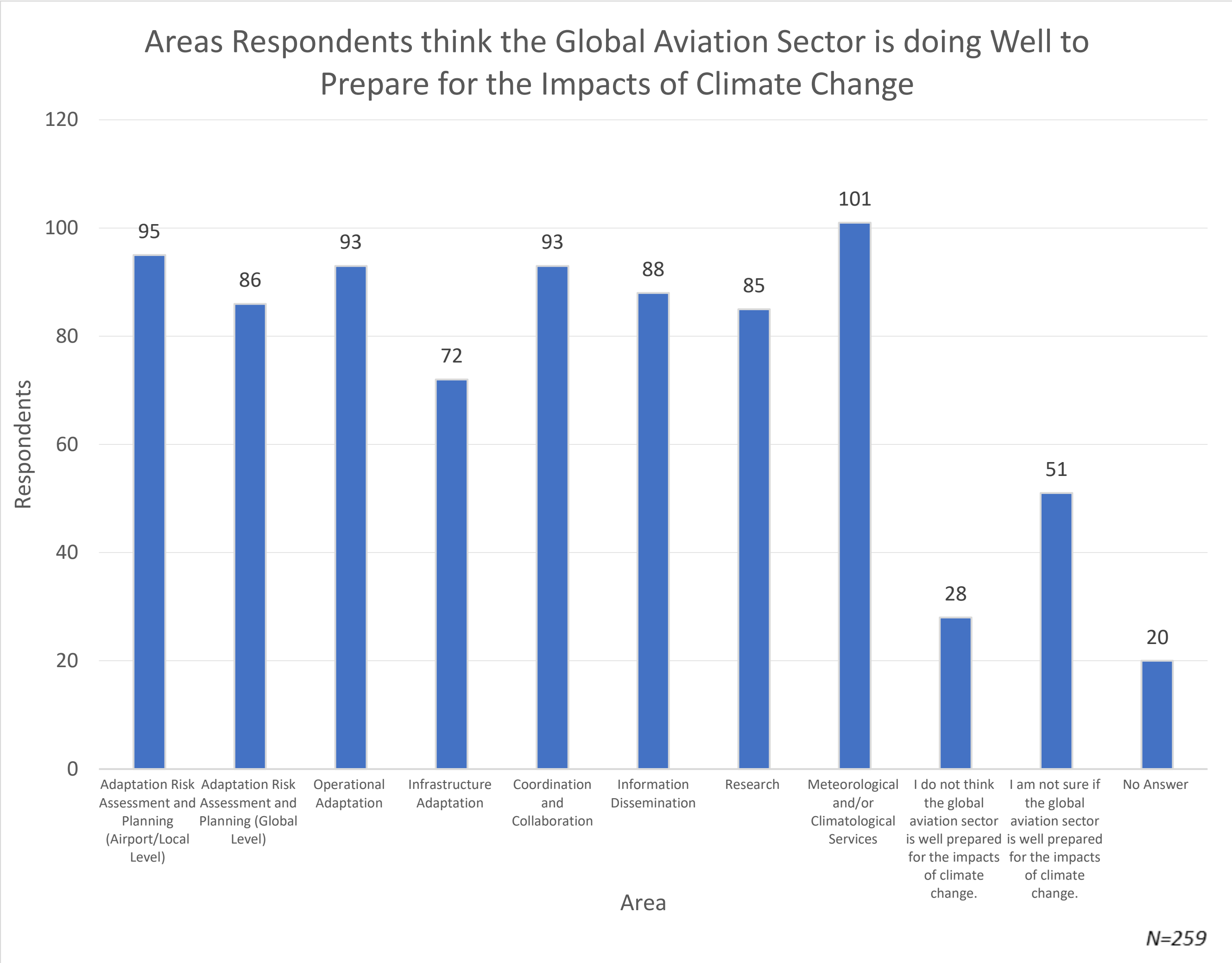


Figure 49 Areas respondents think the global aviation sector is doing well to prepare for the impacts of climate change

For this question, respondents could select as many responses as they wished. Seventeen of the 259 respondents consider that the global aviation sector is doing well in all of the areas included in the survey (excluding the options that the respondents do not think the global aviation sector is well-prepared and or are not sure the global aviation sector is well-prepared for the impacts of climate change). The area where the greatest number of respondents think the global aviation sector is doing well is Meteorological and/or Climatological services (101/259), followed by adaptation and risk assessment at an airport or local level (95/259), operational adaptation (93/259) and coordination and collaboration (93/259). Twenty-eight respondents do not think that the global aviation sector is well-prepared for the impacts of climate change in any of the areas identified while 51 were not sure if the sector is well-prepared.

> **Respondent's Voice**
>
> **Q: What do you think the global aviation sector is doing well to prepare for the impacts of climate change?**
>
> A: The aviation sector is aware of the challenge, but it is difficult to be well prepared before knowing more exactly how the future aviation system will look like on a regional and global scale. (State)
>
> A: Development of SARPS, tools and documents relating to environmental protection and the fight against climate change. Organization of seminars, workshops and others on the issue. (Translated – CAA)
>
> A: On the global scale efforts are already in place. However, on regional scale these efforts are almost absent except in developed economies in the world. (State)

Respondents highlighted that until recently the main focus of the sector has been on climate mitigation, but that the need for adaptation is increasing. They appreciated the actions that the sector is taking to share knowledge and raise awareness, to provide guidance on climate risk assessment and adaptation planning and means for discussion and collaboration. However, they noted that at local and regional scale some stakeholders are taking action and more is required, although this is increasing. The work of meteorological services and development of climate services was also highlighted by some respondents as an area where the global aviation sector is doing well.

10.2 What the Global Aviation Sector Could Do Better

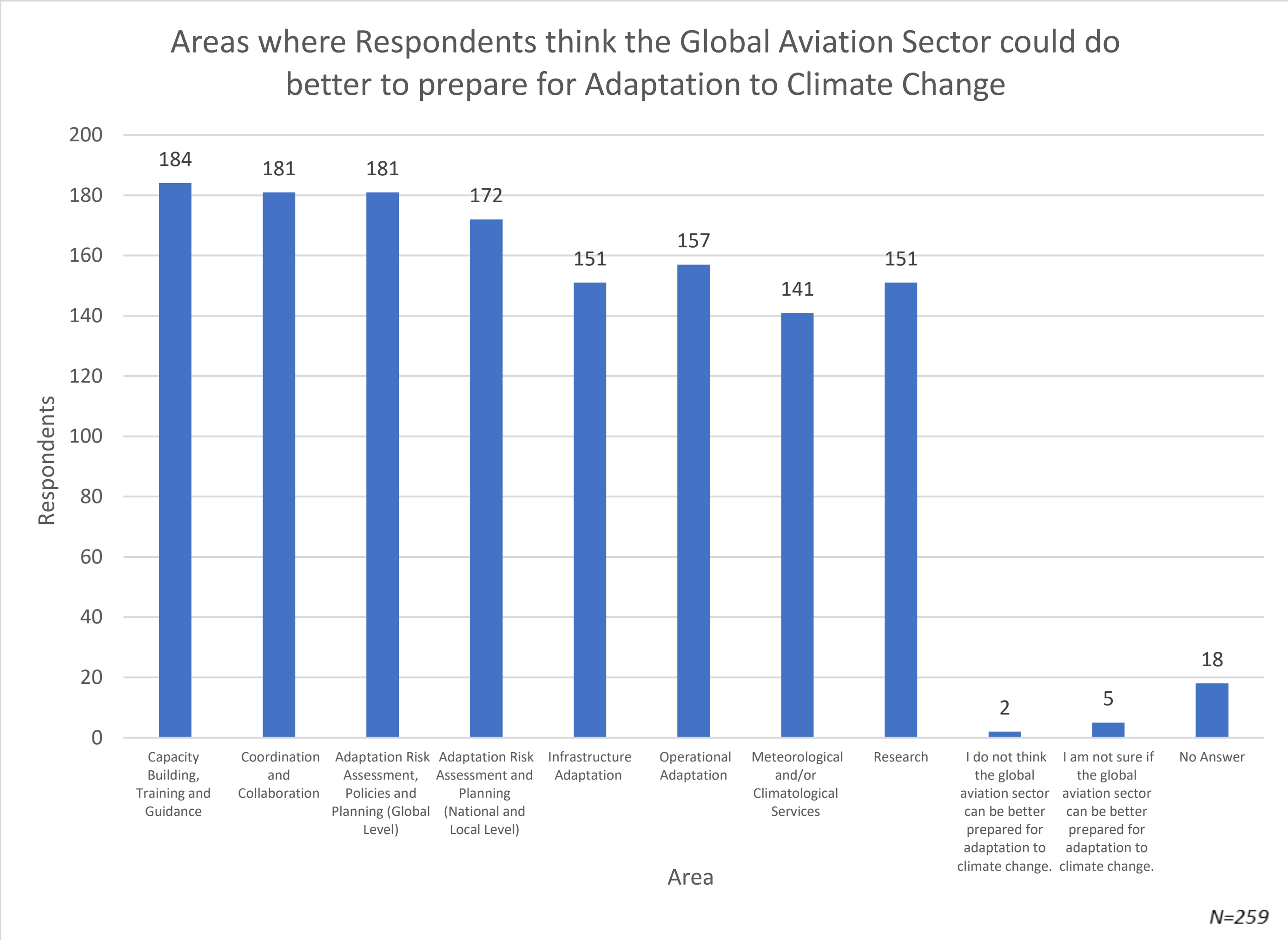


Figure 50 Areas where respondents think the global aviation sector could do better to prepare for adaptation to climate change

For this question, respondents could select as many responses as they wished. Seventy-eight of 259 respondents said the global aviation sector can do better in each of the categories listed in the survey. The area where the most respondents thought the global aviation sector could do better was capacity building, training and guidance (184/259). This is followed by adaptation and risk assessment policies at global level (181/259), coordination and collaboration (181/259) and adaptation and risk assessment at an airport or local level (172/151). Coordination and collaboration and adaptation and risk assessment at an airport or local level were also identified as top areas where the global aviation sector is doing well to prepare for the impacts of climate change and it is noted that for these and other areas some respondents did select them as both areas where the global aviation sector is doing well and areas where it could do better.

Respondents identified a need for greater collaboration across the sector to build and transfer knowledge, learn from experience and identify action gaps. In particular, an increase in capacity building was highlighted as essential to ensuring effective adaptation. Respondents noted that this should be supported by policies promoting adaptation and financing. They also identified a need for more research to better understand and manage potential impacts.

Respondent's Voice

Q: What could the global aviation sector do better to prepare for the impacts of climate change ?

A: Capacity building is the cornerstone to ensure effective adaptation to risk reduction measures and deepened cooperation and collaboration among States and at global level (RSO)

A: Research and policies will allow us to evidence and plan for the changes we will experience. (Airport)

11. Conclusion

This report has built on the original 2018 Climate Change Adaptation Synthesis to present an updated synthesis of relevant information on the potential impacts of climate change for the global aviation sector, and measures which could be taken to adapt and build resilience to them. It integrates new scientific information from the IPCC AR6, an updated literature review, and responses from a 2022 rerun of the Stakeholder Survey originally carried out in 2017. The IPCC AR6 and the documents reviewed during the literature review provide an updated overview of the current state of the science on climate change projections and how those projections may affect the global aviation sector. Respondents to the survey provided input on whether and to what extent they expect to be affected by a range of climate effects, and to what extent they consider the global aviation sector is prepared for the impacts that climate change effects may have on aviation.

One of the key findings from the survey analysis was that 188 of 259 respondents (73 percent) indicated that their aviation sectors are already experiencing some effects of climate change while 35 of 259 respondents (14 percent) expect their aviation sectors to be affected by 2030. Twenty-three respondents (9 percent) expect to be affected after 2030 whilst seven respondents (3 percent) answered that they do not know if they will be affected. Four respondents (2 percent) answered that they did not expect to be affected by climate change. However, it is not possible to establish whether there is any degree of self-selection bias in responses whereby responses were received disproportionally from States or organizations with an interest or concern in climate change impacts on aviation.

Potential climate impacts on the aviation sector were identified for eight categories of climate effects: sea level rise, increased intensity of storms, temperature change, changing precipitation, changing icing conditions, changing wind, desertification and changes to biodiversity. For each effect category, adaptation and resilience measures to reduce the potential effects for the aviation sector were identified. Consideration was also given to potential climate change impacts to business and economics, as well as climate change risk assessment and adaptation planning. Although there were differences between ICAO regions, the three climate effect categories that most respondents expected to be affected by were higher average and extreme temperatures, changing precipitation and increased intensity of storms. These were also the impacts which most respondents expect to be the biggest challenges to address, although respondents also identified issues such as actual adaptation planning, lack of finance and operational impacts as potentially challenging issues to address. While these impacts were identified globally as having effects on the aviation system, the range of effects varies widely by region.

According to industry good practice, a climate change risk assessment should be conducted to determine where vulnerabilities to climate change may exist, before an organization develops a climate change adaptation strategy or plan. Although 188 of 259 respondents to the survey (73 percent) are already experiencing some impacts of climate change, with a further 35 respondents expecting to be impacted by 2030 (14 percent), fewer have begun taking measures to address those potential impacts. Thirty-nine of 259 respondents (15%) indicated they have carried out a climate change risk assessment and are implementing a climate change adaptation strategy or plan. Thirty-eight of 259 respondents (15%) indicated they have carried out a climate change risk assessment and intend to implement a climate change adaptation strategy or plan and 106 respondents (41%) said they intend to carry out a climate change risk assessment. Twenty-seven respondents (10%) do not plan to carry out a climate change risk assessment because their organization is, or will be, a part of a larger climate risk assessment.

When comparing the 2017 and 2022 results, a slightly higher percentage had carried out a risk assessment and were implementing a climate adaptation plan in 2017 (20%). However, in real terms the number is higher with 39 respondents having carried out an assessment and implementing an adaptation plan in 2022. There is also a slightly smaller overall percentage of respondents that have already done a risk assessment and intend to implement an adaptation plan although, again, in real terms the number of respondents is greater in 2022 (39 respondents) compared to 2017 (16 respondents). However, in 2022 41% (106 respondents) intend to carry out a climate change risk assessment compared to 27% (24 respondents) in 2017, suggesting that overall, there is starting to be much more engagement with climate risk assessment and adaptation than in 2017.

The timescales in which respondents indicated they are taking measures to adapt to the impacts of climate change vary widely. Thirty-two respondents (12%) are already implementing adaptation and resilience measures while 43 of 259 respondents (17%) anticipate that they will take climate change adaptation and resilience measures in the next five years and 24 respondents (9%) anticipate that they will take these measures in the next 10 years.

In terms of actual adaptation planning, some respondents have integrated climate change risk assessments into airport planning and maintenance. Others have considered climate change risk assessments as part of their emergency management and disaster response portfolios, or have integrated it the planning of other governing bodies.

Overall, climate adaptation can include a variety of actions such as having a good contingency plan, re-enforcing infrastructure or introducing operational measures. Climate adaptation actions can be carried out at a range of levels from the individual organizational level, to the local or State government level. Climate change adaptation can also provide different degrees of resilience; it will be up to individual organizations to decide how and to what extent to adapt. Just as the projected impacts of climate change vary region to region, the adaptation options for addressing their effects on aviation will also vary and may be best decided at the local or organizational level.

When asked about the level of preparedness of the global aviation sector for the impacts of climate change, the majority of respondents (150/259, 58%) consider that the global aviation sector has some adaptation measures in place but that more needs to be done. Many respondents identified a need for more capacity building, training and guidance as well as adaptation and risk assessment policies at global level. Increased coordination and collaboration across the sector to address this challenge, as well as adaptation and risk assessment at an airport or local level were also identified as areas where more action is required.

Overall, this Synthesis illustrates that it is clear the risks to aviation from climate change are gaining greater importance in planning for the future as we better understand the impacts the projected effects may have on aviation. Many States and organizations are beginning to take action to build resilience. In addition to State and organizational-level actions, some guidance and planning may be helpful at the global level.

Acronym list

A-CDM	Airport Collaborative Decision Making
ACI World	Airports Council International World
ACROS	Airport Climate Risk Operational Screening
ACRP	Airport Cooperative Research Program
AFUA	Advanced Flexible Use of Airspace
ANSP	Air Navigation Service Providers
AOA	Airport Operating Area
APAC	ICAO Asia and Pacific Office
ATC	Air Traffic Control
ATM	Air Traffic Management
BFE	Base Flood Elevation
CAEP	Committee on Aviation Environmental Protection (ICAO)
CAT	Clear Air Turbulence
CBA	Cost Benefit Analysis
CO_2	Carbon Dioxide
DFW	Dallas/Fort Worth International Airport
ESAF	ICAO Eastern and Southern African Office
EUR/NAT	ICAO European and North Atlantic Office
EUROCONTROL	European Organization for the Safety of Air Navigation
GBAS	Ground Based Augmentation System
GTAA	Greater Toronto Airports Authority
GTTA	Greater Toronto Transportation Authority
ICAO	International Civil Aviation Organization
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	IPCC Fifth Assessment Report
IPCC AR6	IPCC Sixth Assessment Report
ISG	Impacts and Science Group (ICAO CAEP)
ITF	International Transport Forum
MET	Meteorology
Met Office	Meteorological Office
MID	ICAO Middle East Office
NACC	ICAO North American, Central American and Caribbean Office
NATS	National Air Traffic Control Services
NO_x	Nitrogen Oxide
PIREP	Pilot Weather Report
RDM	Robust Decision Making
ROA	Real Option Analysis
RSO	Regional Safety Organization
RVSM	Reduced Vertical Separation Minima
SAM	ICAO South American Office
SESAR	Single European Sky ATM Research
SIDS	Small Island Developing States
SWAP	Severe Weather Avoidance Programs
UN	United Nations

USA	United States of America
USGCRP	U.S. Global Change Research Program
VOC	Volatile Organic Compounds
WACAF	ICAO Western and Central African Office
WBA	World Birdstrike Association
WGI	Working Group 1 (IPCC)
WG2	Working Group 2 (ICAO CAEP)
WGII	Working Group 2 (IPCC)

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