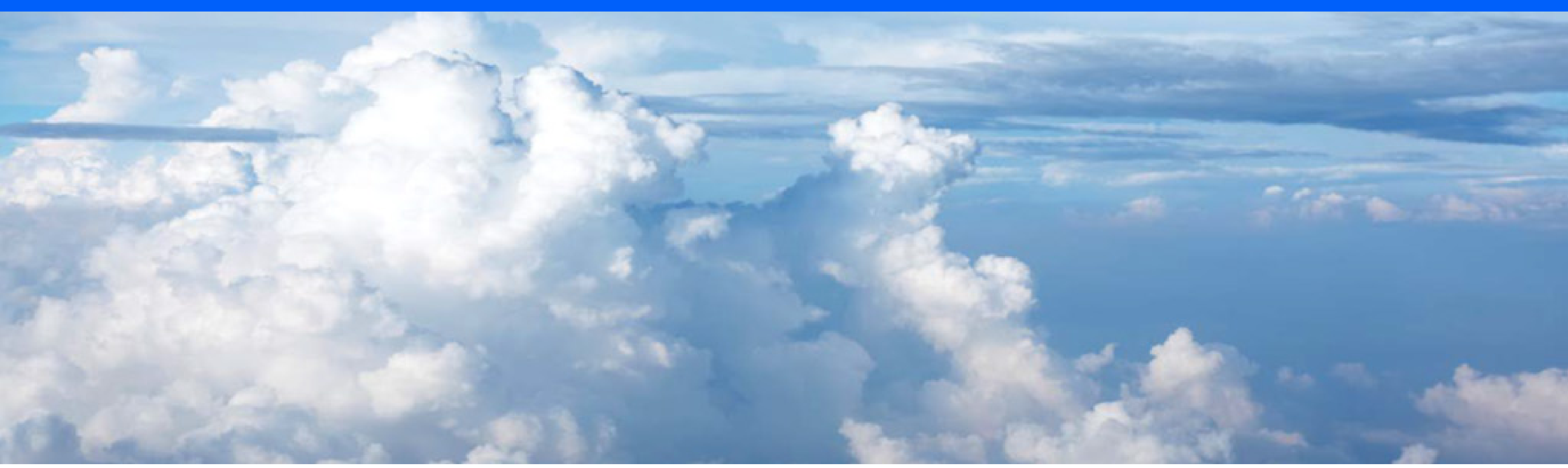
ICAO

ENVIRONMENT

Climate Adaptation Synthesis



2018

2018 ICAO Climate Adaptation Synthesis

Contents

Executive Summary

Background

According to the U.N. Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) (2014), there is scientific consensus the climate is changing, and will continue to change for the foreseeable future. While the aviation sector operates safely and efficiently in a variety of climates, climate change is likely to pose a number of risks in the future, including an increased frequency or intensity of disruptive weather events in some areas of the world, potentially beyond the current capacity for resilience of the aviation system. In the CAEP/10 cycle, the CAEP Impacts and Science Group (ISG) initiated work on assessing the scientific knowledge of these risks. In the CAEP/11 cycle, CAEP Working Group 2 (WG2) was tasked with looking at the specific infrastructure and operational impacts of climate change on aviation via a literature review and survey, the results of which are described in this synthesis report.

Methodology

This report synthesizes 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 AR5, and supplemented with other peer-reviewed scientific information, as required. The scientific content was also reviewed by the ISG. This synthesis was conducted in two stages:

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

2) Survey: A survey was designed and sent via State Letter and CAEP Memo. 88 responses were received, with at least one response from every ICAO Region. Respondents were comprised of fifty-nine (59) States, eighteen (18) airports, six (6) airlines, four (4) ANSPs, and one (1) global organisation.[2]

[1] Shortly before the finalisation of this synthesis report the IPCC published its Special Report on Global Warming of 1.5 degrees. This is briefly addressed in Section 1.1.4 Climate Change Science Background.

[2] 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.

Key Findings

Figure ES-1 presents one of the key findings of the survey results. 65 of 88 of respondents (74 percent) said that they are already experiencing some impacts from climate change. None of the respondents indicated that they do not expect to be impacted by climate change.

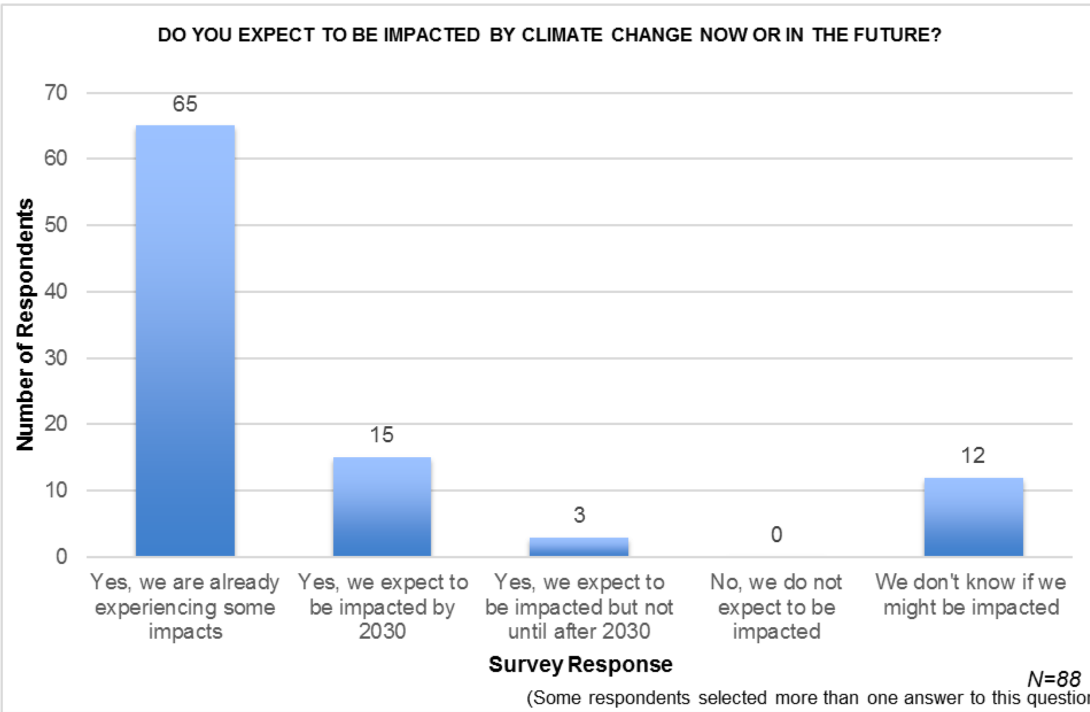


Figure ES-1: Timescales in which respondents expect to be impacted by climate change

The Survey asked respondents if they are affected today or expect to be affected in the future by nine impact categories. In eight 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 the figure below.[3]

[3] Respondents only had “Expect to be affected” and “Don’t expect to be affected” as options to answer this question.

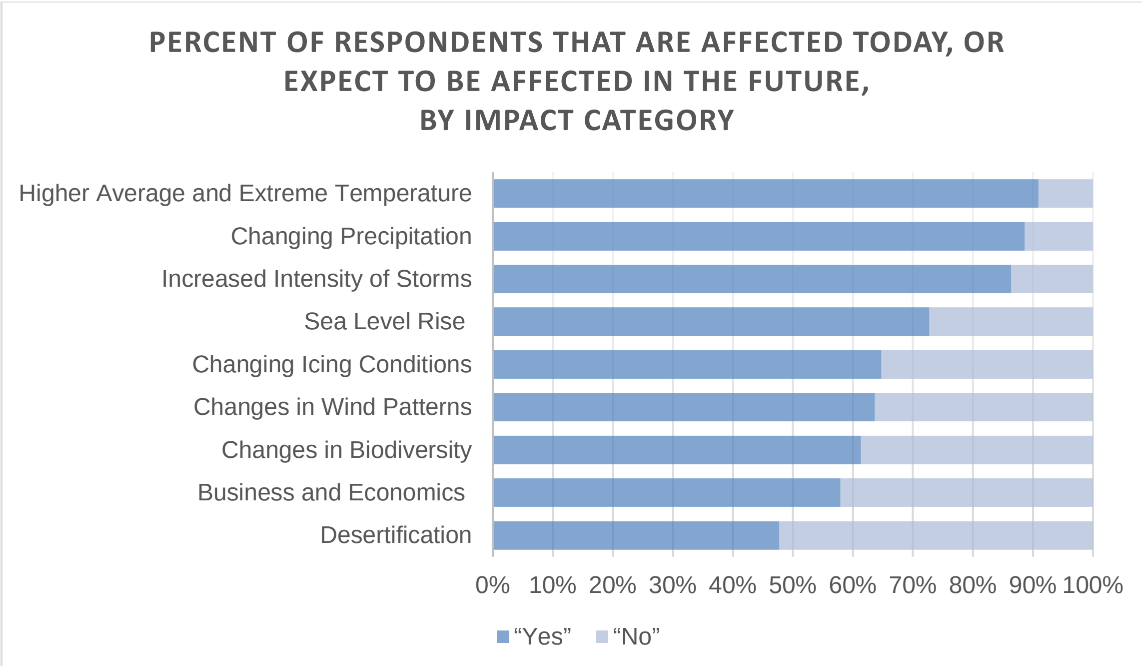


Figure ES-2: Percent of respondents that are affected by impact category **N=88**

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:** 80 of 88 respondents stated they are affected today or expect to be affected in the future by higher average and extreme temperatures (91 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, destabilizing infrastructure and contributing to erosion.
- **Changing Precipitation:** 78 of 88 respondents stated they are affected today or expect to be affected in the future by changing precipitation (89 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 AR5 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:** 76 of 88 respondents stated they are affected today or expect to be affected in the future by increased intensity of storms (86 percent). Storms are projected to become stronger and potentially more frequent and the IPCC AR5 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 developing an adaptation strategy or plan: 1) Find out how the climate will change, 2) Identify risks, and 3) Review and repeat the assessment periodically. 58 out of 88 of respondents (63 percent) indicated that they have already carried out a risk assessment or intend to do so in the future. 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. 26 out of 87 respondents (30 percent) stated that they are already implementing adaptation and resilience measures while 13 out of 87 respondents indicated they plan to do so in the next five years (15 percent) and 9 out of 87 indicated they plan to do so in the next 10 years (10 percent)[4]. Despite the implementation – or planned implementation – of adaptation and resilience measures, 74 out of 88 respondents (85 percent) believe that the global aviation sector still has work to do in order to prepare for the impacts of climate change.

Conclusion

This synthesis report represents opinions from a range of ICAO members, observers and stakeholder organisations from all ICAO regions. It also presents a synthesis of the current understanding of climate change impacts and how those impacts may directly and indirectly affect 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.

[4] Note: One response to this question referred to climate change mitigation measures and was not included in the total.

1. Introduction

According to the U.N. Intergovernmental Panel on Climate Change Fifth Assessment Report (2014), there is scientific consensus the climate is changing and will continue to change for the foreseeable future. While the aviation sector already 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 some 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 impacts and the specific challenges they may bring to the aviation industry. As a result, in the CAEP/10 cycle, the CAEP Impacts and Science Group (ISG) initiated work on assessing the scientific knowledge of these risks. In the CAEP/11 cycle, Working Group 2 (WG2) was tasked with looking at the specific infrastructure and operational impacts of climate change on aviation via a document review and survey, the results of which are described in this synthesis report. The information collected in this task, in combination with climate change scenario projections, will facilitate CAEP Members and Observers in identifying potential impacts of climate change which may affect the global aviation sector, 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.

This CAEP Report collates 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, infrastructure, and other operational factors. The synthesis includes considerations for how projected climate impacts 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 work builds on the ISG's CAEP/10 Climate Impacts on Aviation Paper, which presents the climate change projections that are most applicable to aviation infrastructure, operations and planning. Information in this report has been reviewed by the ISG.

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 both a CAEP Memo and a subsequent State Letter to broaden the geographical coverage of the information from respondents.

1.1 Guide to the Synthesis

1.1.1 Definitions

The definitions for climate change adaptation, climate change resilience, and climate change vulnerability applied in this synthesis are those used by the 2014 IPCC Synthesis Report (IPCC[4], pp. 118, 127, 128):

- **Adaptation:** The process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effect.
- **Resilience:** The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.
- **Vulnerability:** The propensity or predisposition to be adversely affected by a particular risk or impact. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt to such impacts and harm.

1.1.2 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 impact category.

The CAEP Memo and 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). Question three in section two asked respondents to indicate all applicable climate impacts and their expected timescales, and were described as: already experiencing, expect to experience in the future, do not expect to be affected, and do not know.

1.1.3 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 'impacts' to refer to physical climate changes (e.g., temperature change, sea level rise) and the term 'effects' to refer to the potential consequences of climate change impacts on the aviation system. Any regional analysis is based on ICAO regions (see figure 3). However, it is noted that even within regions there are differences in impacts and effects as there can be multiple climate zones within one ICAO region. Therefore, these analyses can only give a high-level indication of regional differences.

1.1.4 Climate Change Science Background

This report mainly draws on the scientific information presented in the IPCC Fifth Assessment Report (AR5). The IPCC AR5 covers many aspects of climate change that are not addressed in this CAEP 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 impacts which have been identified as relevant for the global aviation sector by WG2 and the ISG. This synthesis report also draws from other scientific publications for information on how projected climate change impacts may affect aviation, as appropriate.

The IPCC AR5 utilizes four Representative Concentration Pathways (RCPs)[5] to "…describe four different 21st century pathways of [greenhouse gas (GHG)] emissions and atmospheric concentrations, air pollutant emissions and land use" (IPCC[3], p.8). These RCPs include one low-emissions scenario (RCP2.6), one high-emissions scenario (RCP8.5) and two scenarios in between (RCP4.5 and RCP6.0). These four scenarios determine the rate of change projected for each impact 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.

[5] "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[3], 2014)

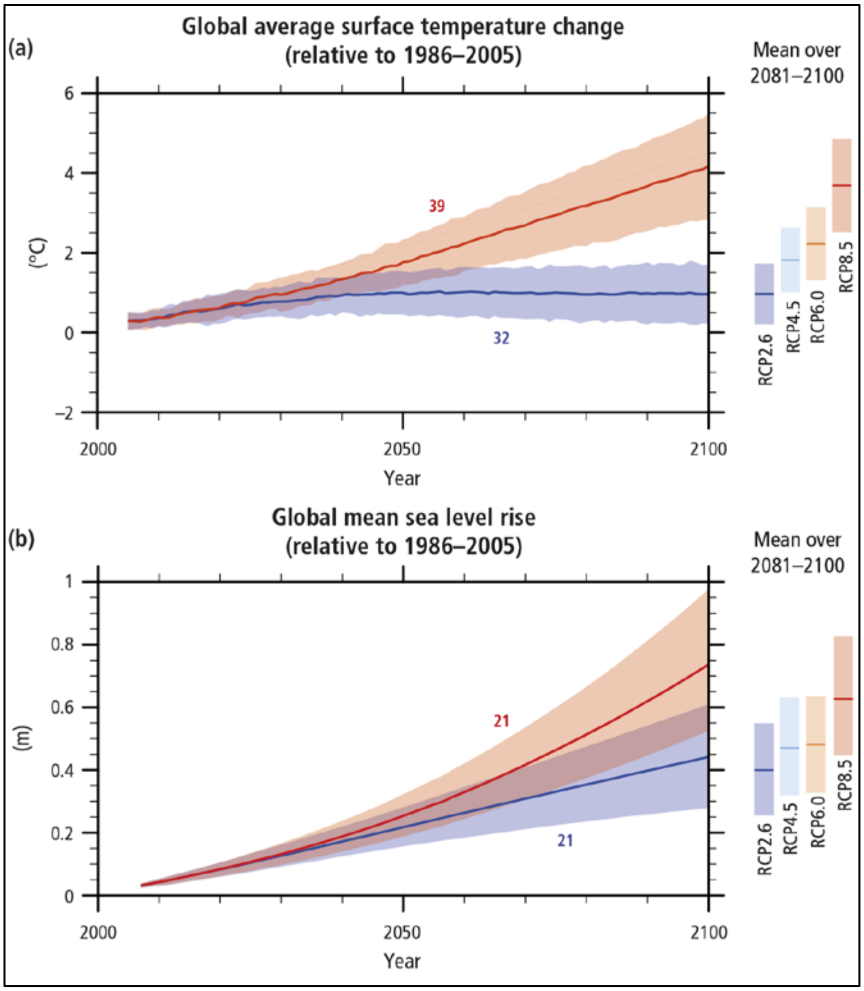


Figure 1 From the IPCC AR5 Summary for Policy Makers, "Global average surface temperature change (a) and global mean sea level rise (b) from 2006 to 2100 as determined by multi-model simulations. All changes are relative to 1986–2005. Time series of projections and a measure of uncertainty (shading) are shown for scenarios RCP2.6 (blue) and RCP8.5 (red). The mean and associated uncertainties averaged over 2081–2100 are given for all RCP scenarios as coloured vertical bars at the right hand side of each panel. The number of Coupled Model Intercomparison Project Phase 5 (CMIP5) models used to calculate the multi-model mean is indicated." {IPCC[3], *SPM.6*}

The figure above is included as an example of how the RCP scenarios work in practice and shows the correlation between the four IPCC emissions scenarios and global mean sea level rise projected out to 2100 relative to a 1986 to 2005 baseline. For more climate change science and background, please refer to the full IPCC AR5 publications.

IPCC Special Report

Global Warming of 1.5°C

an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emissions pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (IPCC[5], October, 2018)

The report responds to the invitation for the IPCC "... to provide a Special Report in 2018 on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways' contained in the Decision of the 21st Conference of Parties of the United Nations Framework Convention on Climate Change to adopt the Paris Agreement" (IPCC[5], SPM-3). The report concludes with high confidence that "global warming is *likely* to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate" (IPCC[5], SPM-4). Climate change impacts are already being experienced. With global warming of 1.5°C above pre-industrial levels those impacts will be greater, even more so if warming reaches 2°C above pre-industrial levels.

The report highlights with medium to high confidence that there will be differences in the magnitude of impact for 1.5°C and 2°C for impacts such as mean temperature, hot extremes, heavy precipitation, the probability of "drought and precipitation deficits in some regions" and sea level rise (IPCC[5], SPM-8). In consideration of current trends, the level of risk for extreme weather events was also assessed to have increased since the IPCC's Fifth Assessment Report, published in 2014.

These impacts from climate change will be disproportionate; Small Island Developing States, least developed countries, dryland regions, and Arctic ecosystems are most vulnerable. For example, "increased warming amplifies the exposure of small islands, low-lying coastal areas and deltas to the risk associated with sea level rise for many human and ecological systems, including increased saltwater intrusion, flooding and damage to infrastructure" (IPCC[5], SPM-9).

The report notes with high confidence that adaptation and mitigation are already occurring, but that future climate-related risks would be reduced by additional, more robust and accelerated action. (IPCC[5], SPM-4) The report notes that adaptation needs will be greater at 1.5°C than they are currently, and greater still at 2°C than 1.5°C. For the aviation sector, these findings have implications for the timelines in which adaptation efforts should be considered at the regional and local levels, particularly in the most vulnerable areas.

2. Methodology

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

2.1 Literature Review

The Task Group identified and reviewed seventeen 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 impacts, effects on the aviation sector, adaptation and resilience measures and other pertinent information were extracted and synthesised. The intent was to provide a high-level synthesis of the best available information rather than to reproduce the detailed information already available in other sources. It was agreed upon 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.

The Task Group also identified links between this task and the WG2 task to update the 2018 ICAO Airport Planning Manual, Part II completed in the CAEP/10 cycle. It was therefore decided to leverage information from that document to form the basis of the climate change impacts that have been assessed in this analysis.

The main part of the literature review was completed in early 2017. 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 in February 2018. A special report from the IPCC on Global Warming of 1.5°C[6], which is a significant contribution to climate change knowledge, was published just before the final Working Group meeting of the CAEP/11 cycle. For these reasons, the information from this report is included in a special call-out box in section 1.1.4 Climate Change Science Background. A more thorough update of information could be considered post-CAEP/11 either through updating this synthesis report or other means.

The Task Group coordinated with the ISG co-rapporteurs throughout the literature review process.

2.2 State Letter, CAEP Memo and Survey

In addition to the document review, the Task Group collected information via a survey on aviation and climate change impacts and effects, and adaptation measures. The objective of the survey was to better understand the perception within States and organisations of potential impacts of climate change, and the effects that these may have for their aviation sectors. Initially the survey was sent as a CAEP Memo,

[6] **<u>Full Title:</u> Global Warming of 1.5 °C** *An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*

but was followed by a State Letter at the request of the CAEP Steering Group to ensure broader geographical coverage and a larger range of response. The survey sent with the State Letter was identical to the survey sent with the CAEP Memo.

The survey was designed by the Task Group and tested by the full Working Group before being sent. A total of 37 replies from 14 States and organisations were received in response to the Memo. Fifty-one replies to the State Letter, covering all ICAO regions as well as specific groups of interest, such as Small Island Developing States (SIDS) were received. Two States responded that they were unable to respond to the survey, and are therefore not included in the total number of responses. One State sent in an anonymous response and was included in the total responses. Three States sent identical responses to both the CAEP Memo and State Letter; the survey analysis and results reported in the synthesis includes the response from each State only once.

All of the responses were incorporated into a spreadsheet for analysis, with the CAEP Memo and State Letter responses combined into one dataset.

In reviewing the responses to the surveys, the Task Group identified cases where respondents provided multiple answers to a single question. In some cases, these answers may have seemed contradictory. However, the Task Group accepted all answers to any question and included them in the analysis. Questions that received multiple responses from individual respondents are identified in the relevant sections.

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

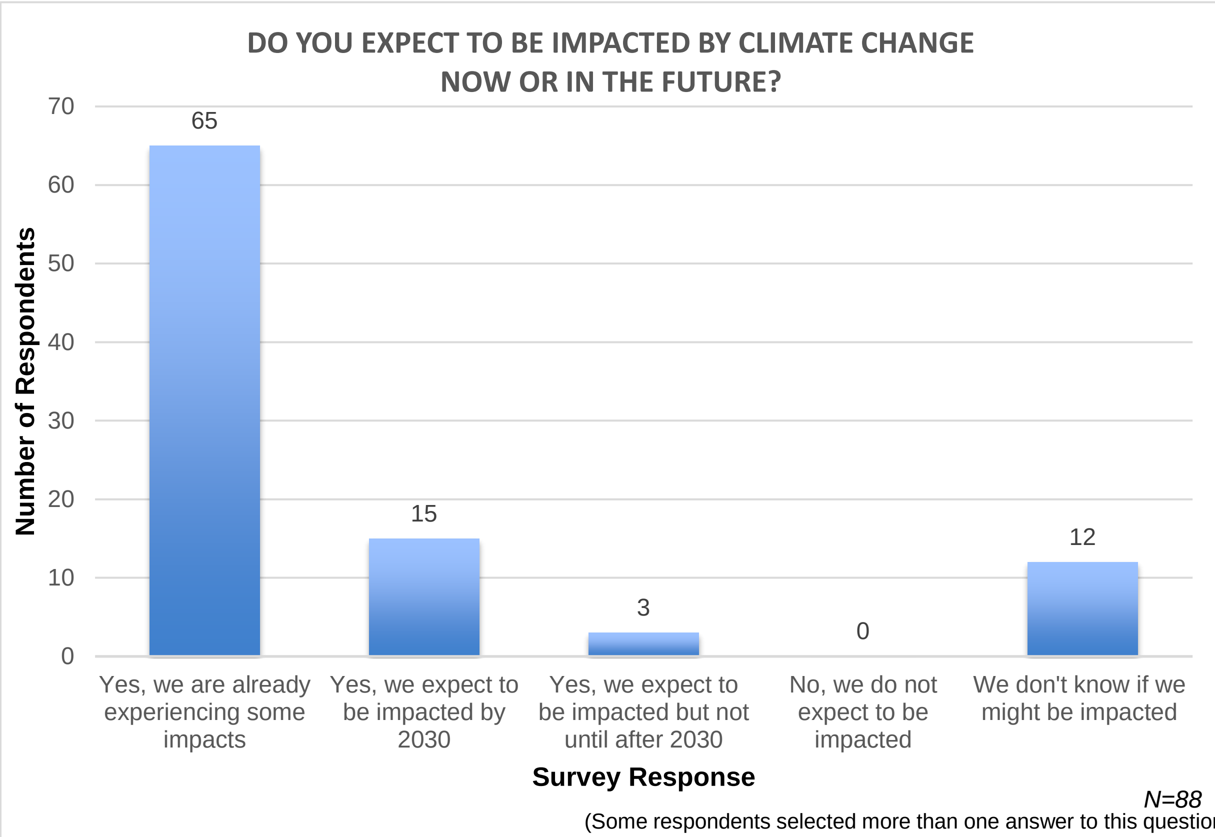


Figure 2: Do you expect to be impacted by climate change now or in the future?

The first question of the survey asked respondents if they expect their aviation sectors to be impacted by climate change now or in the future. Of the 88 respondents, 65 answered that they are already experiencing some impacts while 15 respondents expect to be impacted by 2030. Six respondents answered both that they are already experiencing some impacts and that they expect to be impacted by 2030. Only three respondents expect to be impacted after 2030 whilst 12 respondents answered that they do not know if they will be impacted. There were no respondents that answered that they did not expect to be impacted.

It is unclear if there is some degree of self-selection bias in responses (i.e., only States or organisations with an interest or concern in climate change risks and adaptation responded).

4. Overview of Survey Demographics

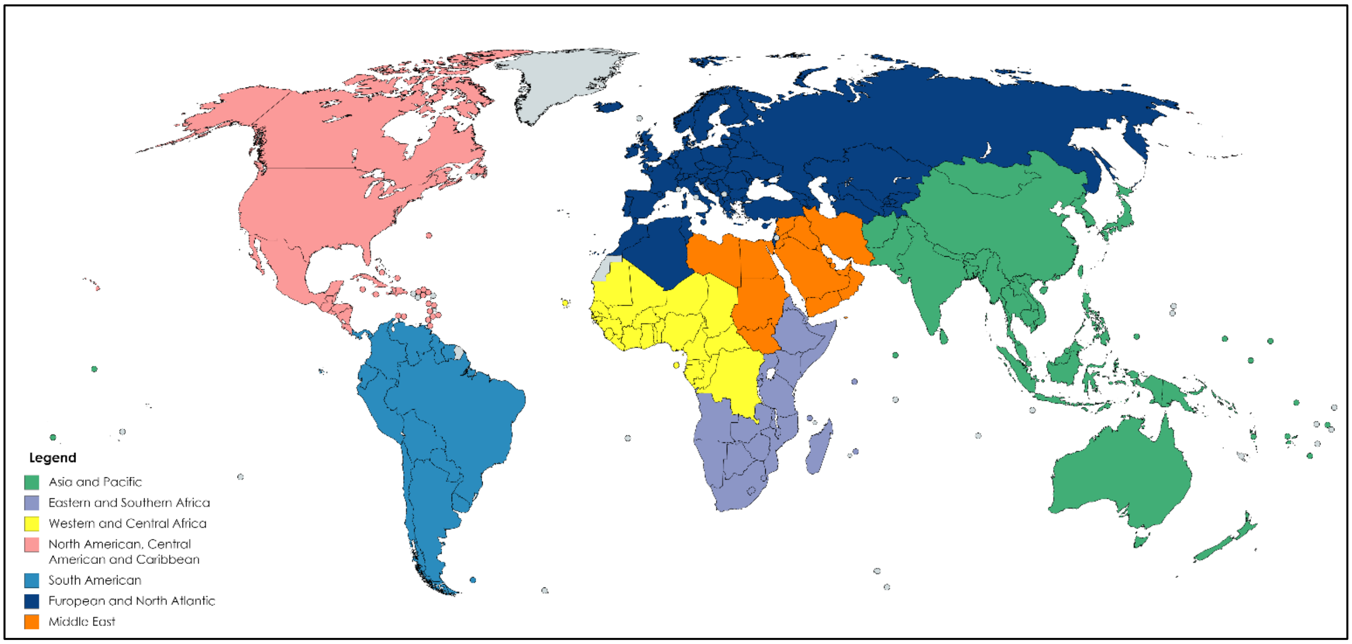


Figure 3: ICAO Regions[7]

Survey responses were received from every ICAO region thus representing broad geographical coverage and ensuring that a wide range of climate zones and economic diversity were represented.

ICAO Region	Number of Responses Received by Respondent Type
Asia and Pacific	7 States 1 Airline
Eastern and Southern Africa	5 States
Western and Central Africa	1 State
North American, Central American, and Caribbean	6 States 5 Airlines 10 Airports
South American	6 States 1 ANSPs
European and North Atlantic	30 States 8 Airports 3 ANSPs
Middle East	3 States

Figure 4: Number of respondents received by respondent type, organized by ICAO region ***Note: The anonymous State and one global organisation are not included in this data***

[7] Figure 3 was generated using mapchart.net

One State provided an anonymous response and one global organisation responded to the survey. Neither of these respondents are included in the table above. In cases where a respondent could potentially fit in more than one "respondent type" category we have included them in the category which we judged to be their primary role. Each respondent is counted only once.

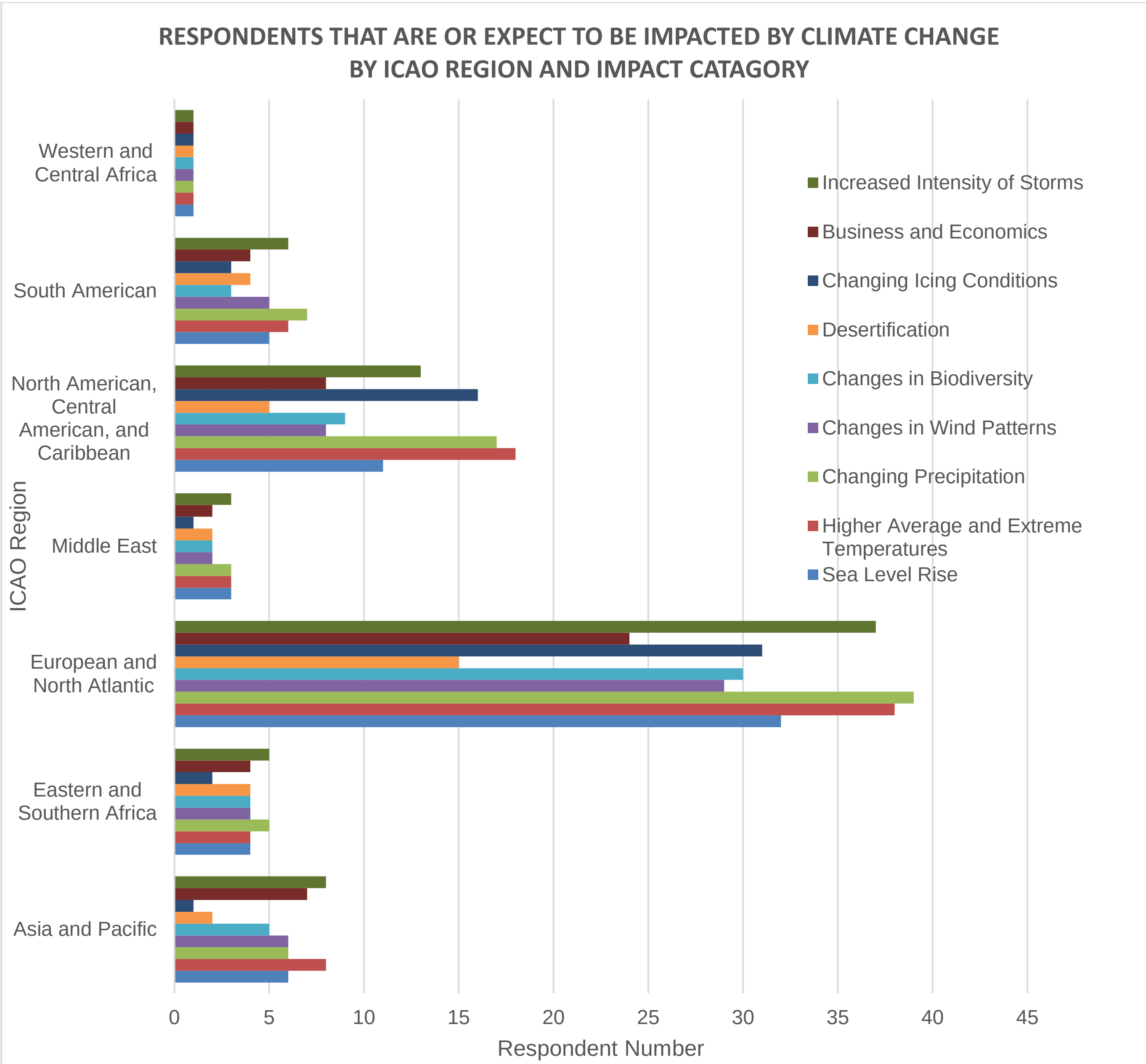


Figure 5: Number of respondents that are impacted today or expect to be impacted by climate change in the future by ICAO region and impact category ***Note: The anonymous State and one global organization are not included in this data***

Figure 5 demonstrates that primary concern varies by ICAO region. This figure also indicates some of the most prominent concerns by region. In South America the prominent concerns are changing precipitation (7 of 7 respondents), increased intensity of storms (6 of 7 respondents) and higher average and extreme temperatures (6 of 7 respondents). In the North American, Central American, and Caribbean region, the prominent concerns are higher average and extreme temperatures (18 of 21 respondents) and changing precipitation (17 of 21 respondents). In the Middle East region, the most prominent concerns are sea level rise, higher average and extreme temperatures, changing precipitation and increased intensity of storms, all with three respondents (the total number of respondents from this region). In the European and North Atlantic region the most prominent concerns are changing precipitation (39 of 41 respondents) and higher average and extreme temperatures (38 of 41 respondents). In the Eastern and Southern Africa region, the most prominent concerns are from changing precipitation and increased intensity of storms, both with five respondents (the total number of respondents from this region). In the Asia and Pacific region, the most prominent concerns are higher average and extreme temperatures and increased intensity of storms, both with eight respondents (the total number of respondents from this region).

5. Analysis of Climate Change Impacts and Effects

5.1 Sea Level Rise

5.1.1 Summary of Impact and Timescales

According to the IPCC Fifth Assessment Report WG1 Glossary (2013), Sea level "can change, both globally and locally due to (1) changes in the shape of the ocean basins, (2) a change in ocean volume as a result of a change in the mass of water in the ocean, and (3) changes in ocean volume as a result of changes in ocean water density" (IPCC[1], p. 1462). Based on the IPCC Fifth Assessment Report (2013) and the documents reviewed for this synthesis, there is consensus that global average sea level is rising. The ICAO ISG White Paper on Climate Impacts on Aviation states, "There is high confidence that sea level rise is occurring and will continue as climate change progresses" (Puempel, et al., p.E-3). Sea level rise is caused by both "increases in ocean warming and loss of mass from glaciers and ice sheets" (IPCC[1], p.1140). Sea level rise can increase flooding, both in frequency and in area flooded, contribute to greater coastal land erosion, and, in some areas, cause permanent sea water inundation. The projected impacts of sea level rise vary locally. For example, in some areas, sea level rise is already contributing to more frequent flooding (IPCC[2], 2014), while in other places, vertical land motion, known as glacial isostatic adjustment, is actually causing the sea level to fall. However, the IPCC concludes that by the end of the 21st century, it is very likely that for about 95% of the world's ocean, regional sea level rise will be positive (IPCC[1], 2013). While the specific projections vary regionally, generally speaking, low-lying coastal areas will be impacted the most. Moreover, sea level rise can increase the height of sea level extremes, such as storm surges, "regardless of any changes in the storm-related component." (IPCC[1], p.1200).

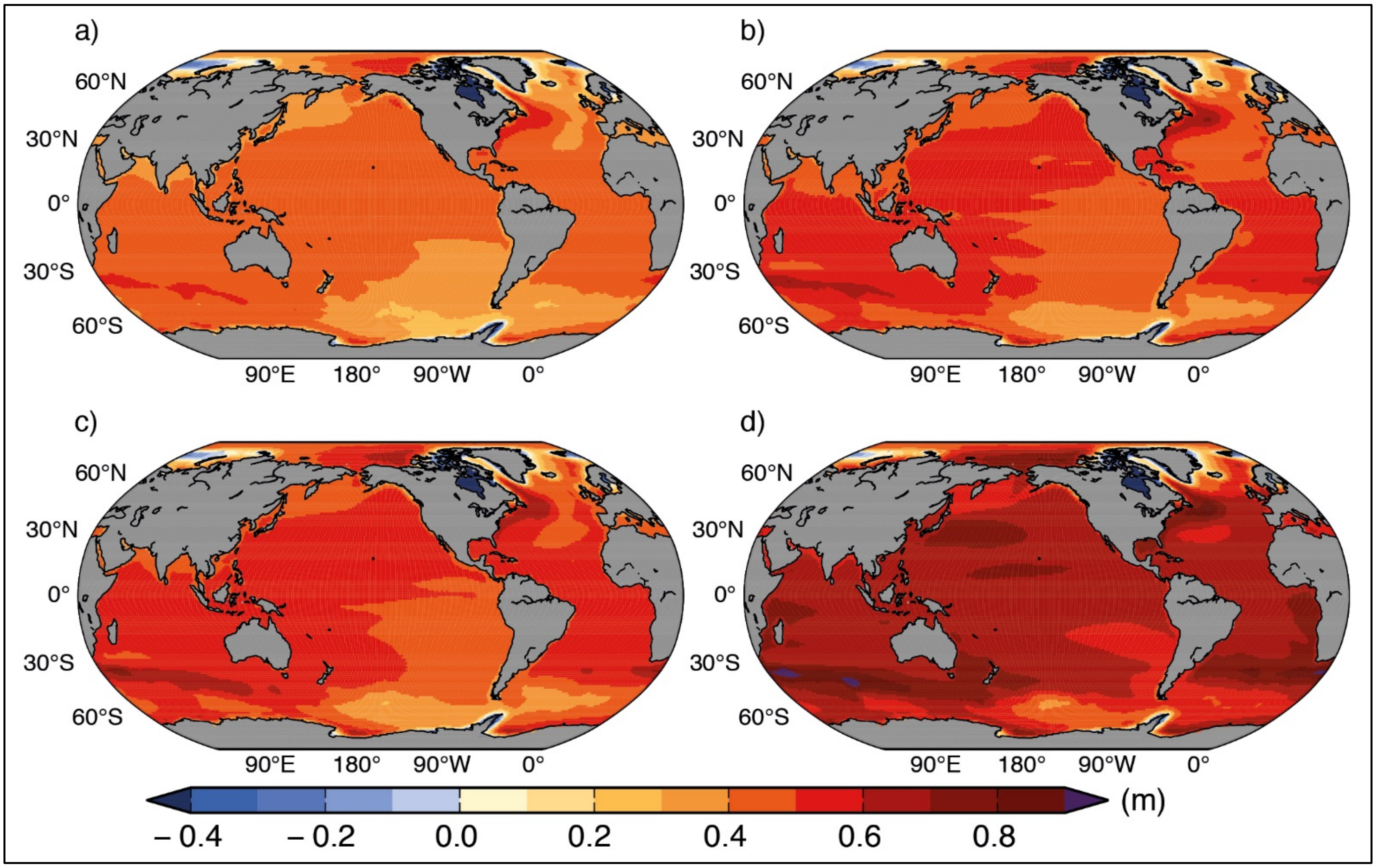


Figure 6: Sea Level Change: From the IPCC AR5 WG1 Report, "Ensemble mean regional relative sea level change (meters) evaluated from 21 CMIP5 models from the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986-2005 and 2081-2100. Each map includes effects of atmospheric loading, plus land ice, glacial isostatic adjustment (GIA) and terrestrial water sources". {IPCC[1], Chapter 13, 13.20}

The above figure from the IPCC AR5 WG1 Report shows how sea level rise may change around the world according to each RCP emission scenario between 2081 and 2100 relative to a 1986 to 2005 baseline.

Small Island Developing States (SIDS)

SIDS are particularly vulnerable to the impacts of sea level rise (IPCC[2], 2014). 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).

Across the documents reviewed, timescales for changes to sea level rise range from near-term (currently observed or with timescales of 2020 or 2030), to 2050 for mid-term impacts and 2080-2100 for long-term impacts.

5.1.2 Potential Effects on Aviation from Sea Level Rise

Low-lying coastal infrastructure such as aviation navigation and communication equipment, airport assets, the airfield, and ground transportation, may be vulnerable to the effects of sea level rise. The effects of sea level rise may damage infrastructure or prevent aviation sector employees, passengers and freight from being able to access an airport. According to the chapter on Climate Change Resilience and Adaptation in the 2018 Airport Planning Manual Part II, “A rise in sea levels will exacerbate all other water issues at airports near coastal waters. Ground water tables will be higher, drainage systems will be less effective, and flooding from surface waters or storms will be more frequent and damaging… Airports located near rivers and streams may also be at risk from sea level rise or flooding” (p. 9-5). Although the global sea level has been rising and is projected to continue rising at a progressively faster rate in many areas, the projected impacts from sea level rise may still be far in the future for some locations (e.g., after 2100) whereas in others it may be experienced sooner.

5.1.3 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 being taken to identify specific vulnerabilities and timeframes (ACRP, 2012; IPCC[2], 2014; San Francisco Bay Conservation and Development Commission, 2017) and improve operational resilience, and install sea defenses and other protective measures for vulnerable areas (ACRP, 2014; Puempel, H. and Williams, P., (2011); SESAR[1] (2012); IPCC[1], (2013); San Francisco Bay Conservation and Development Commission, (2017); FLYSFO, (undated); EUROCONTROL, (2013); BOS Sustainable Management Plan, 2016)). 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-defenses, 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)). 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.

5.1.4 Survey Analysis

The following charts present the combined results of the survey questions on sea level rise from the CAEP Memo and State Letter.

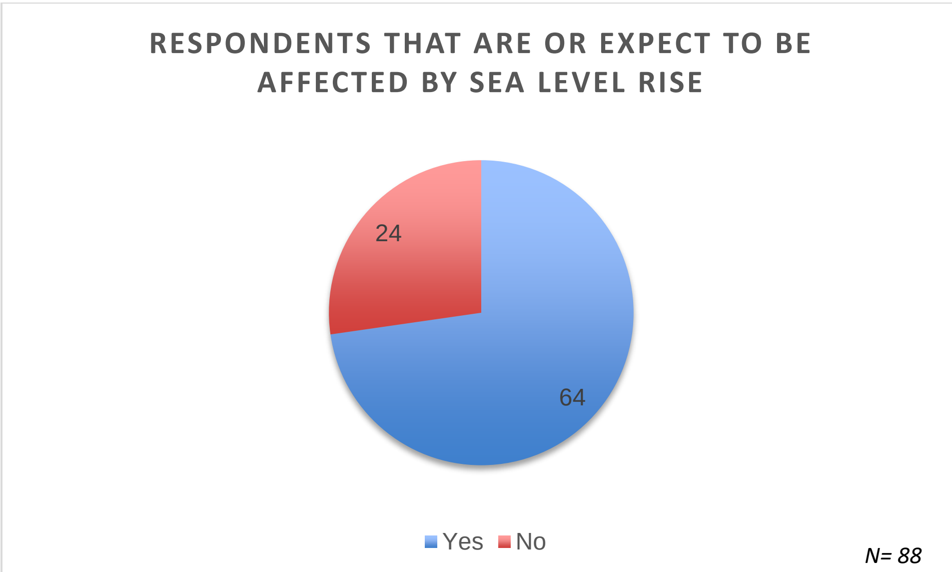


Figure 7: Number of respondents that are affected today or expect to be affected in the future by sea level rise

Of 88 respondents, 64 expect to be affected by sea level rise. 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.

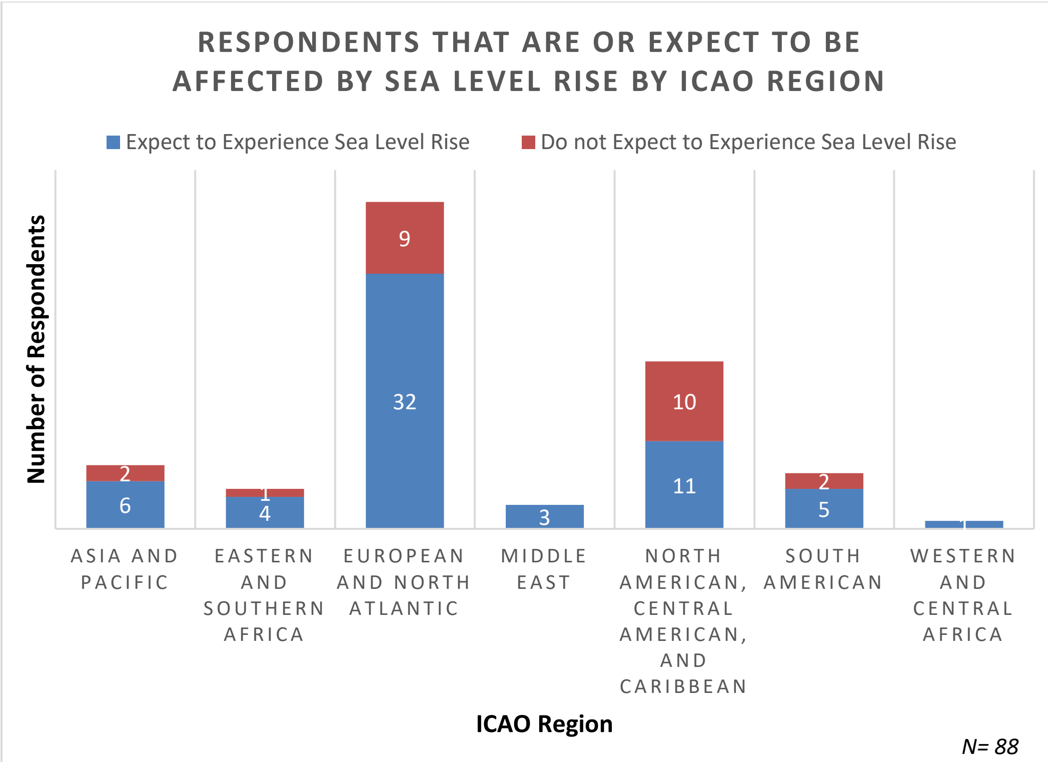


Figure 8: Number of respondents that are affected today or expect to be affected in the future by sea level rise by ICAO region

The chart above shows the number of respondents that expect to be affected by sea level rise by ICAO region. The red bars represent the number of respondents that do not expect be affected by sea level rise while the blue bars represent the number of respondents that do expect to be affected by sea level rise. For example, in the Asia Pacific region, six respondents said they expect to experience effects of sea level rise and two respondents said they do not expect to experience effects of sea level rise. All of the respondents from the Middle East, four respondents from Eastern and Southern Africa, and 32 respondents from Europe and the North Atlantic region expect to be affected by sea level rise. The one respondent from Western and Central Africa also indicated they would be affected by sea level rise. Geography, particularly whether or not a respondent is landlocked, played a large role in the response to this question. No respondents from the Asia Pacific, Middle East, or North American, Central American, and Caribbean regions are landlocked. Two respondents from the Eastern and Southern Africa region are landlocked, six respondents from five States in the European and North Atlantic region are landlocked, and two respondents from the South American region are landlocked. In general respondents that were landlocked indicated that they did not expect to be affected by sea level rise. However, one respondent from the Eastern and Southern Africa region, two respondents from the European and North Atlantic region, and both respondents from the South American region who are landlocked indicated that they expect to be affected by sea level rise.

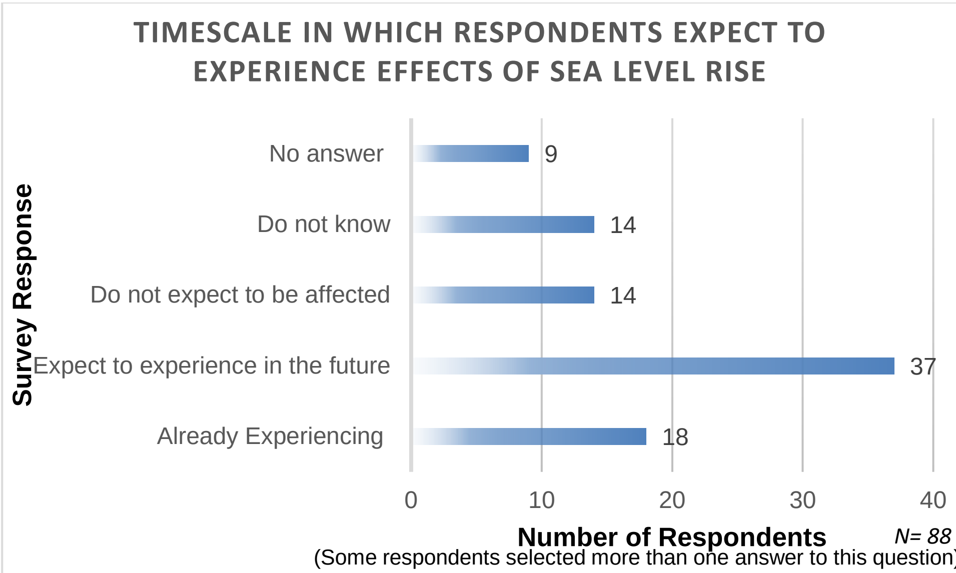


Figure 9: Timescale in which respondents expect to experience effects of sea level rise

Eighteen respondents are already experiencing the effects of sea level rise and 37 expect to experience effects in the future. However, it was not always clear whether respondents expect sea level rise to have direct effects on their aviation sector, or more general effects on their country or organization. Fourteen respondents do not expect to be affected and an additional 14 do not know whether they will be affected, indicating that for some respondents there are still some uncertainties regarding this impact.

Note that in some cases respondents that indicated they did not expect to be affected in the previous question either did not answer this question or answered "do not know". This is why there is not a direct match between the answers in Figures 7 and 9 for the response "do not expect to be affected".

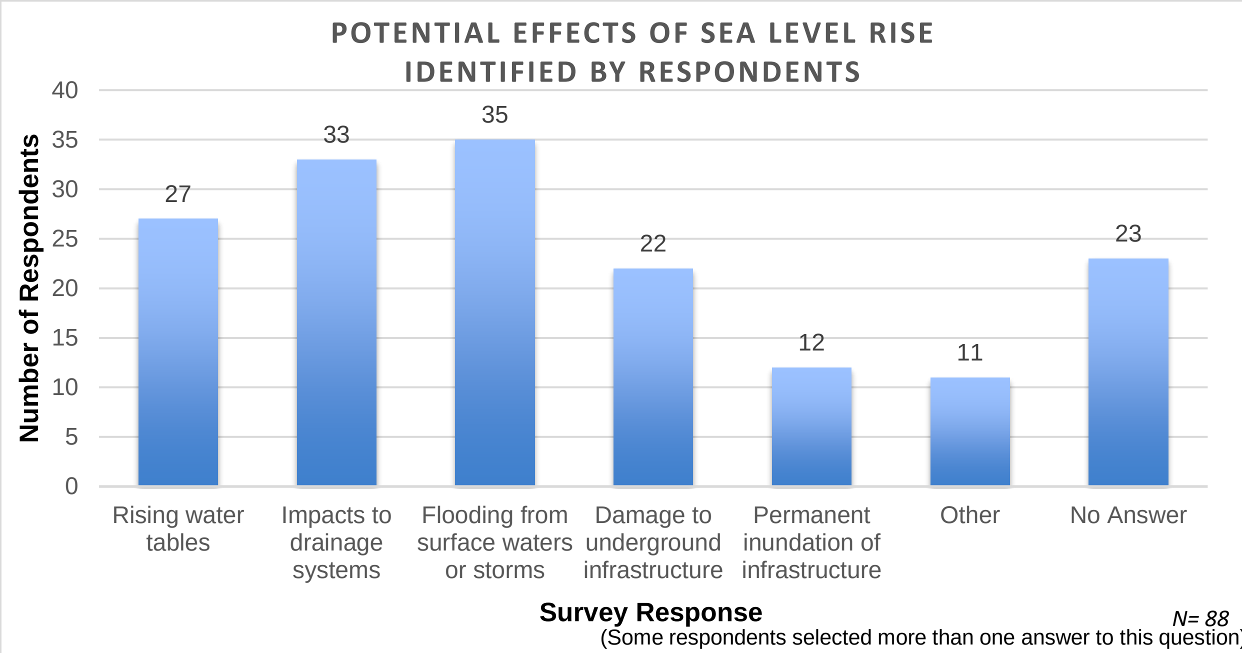


Figure 10: Potential effects of sea level rise identified by respondents

The main effects that respondents expect to experience from sea level rise are impacts to drainage systems and flooding from surface waters or storms. Many respondents gave more than one answer. The respondents who selected "Other" identified, "loss of airport infrastructure", "increased erosion of boundary banks", "damage to coastal Infrastructure", "coastal erosion", "salinization of waters", "coastal floods", "not known yet", "land degradation/fills", and "uncertain". One respondent indicated that they were landlocked, and one response was unspecified.

5.2 Increased Intensity of Storms

5.2.1 Summary of Impact and Timescales

There is broad consensus among the documents reviewed that, overall, storms are projected to become stronger as the climate changes but the frequency of these future storms is less conclusively understood. The types of storms discussed in the documents reviewed include both winter storms and tropical cyclones (also classed as hurricanes or typhoons depending on the region in which they occur), extra-tropical cyclones, arctic cyclones, convective systems, and lightning. 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, the storms may become more powerful and more frequent, while in others they may only become more powerful (Heathrow Airport, 2011; EUROCONTROL, 2013; International Transport Forum, 2015). 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).The SESAR Environmental Risk Papers noted the likely projection that "…intense tropical cyclones will increase as well as intensity of local storms, together with a growing frequency and intensity of convective weather in all layers of the troposphere" (SESAR[1], p.14). The same paper also projects that storm tracks and locations may change from what is currently observed.

The IPCC AR5 Synthesis Report illustrates how as temperatures increase the risk of extreme weather events, such as extreme storminess, will also increase relative to a 1986 to 2005 baseline; "Climate change related risks from extreme events, such as heat waves, heavy precipitation and coastal flooding, are already moderate (*high confidence*). With 1°C additional warming, risks are high (*medium confidence*). Risks associated with some types of extreme events (e.g., extreme heat) increase progressively with further warming (*high confidence*)" (IPCC[3], p.72).

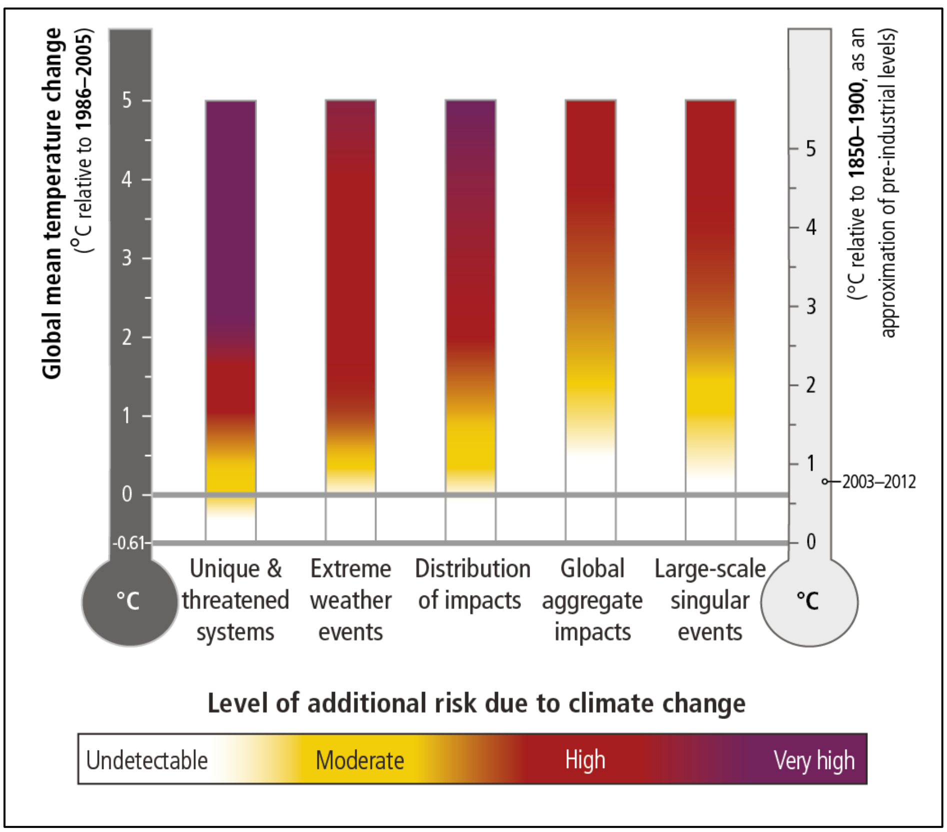


Figure 11: Reasons for Concern Regarding Climate Change, "Risks associated with Reasons for Concern at a global scale are shown for increasing levels of climate change. The colour shading indicates the additional risk due to climate change when a temperature level is reached and then sustained or exceeded. White indicates no associated impacts are detectable and attributable to climate change. Yellow indicates that associated impacts are both detectable and attributable to climate change with at least medium confidence. Red indicates severe and widespread impacts. Purple, introduced in this assessment, shows that very high risk is indicated by all key risk criteria" {IPCC[3], Box 2.4, Figure 1}.

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 2014 WGll 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)" (IPCC[2], p. 1773). Eight of the seventeen documents reviewed for this synthesis included a description of the impacts of storm surge. 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 2020 or 2030, 2050 for mid-term impacts and 2080-2100 for long term impacts.

5.2.2 Potential Effects on Aviation from Increased Intensity of Storms

Potential effects on aviation from increased intensity of storms vary widely. The documents reviewed for this analysis described direct effects to aviation, including strains on "…commercial power, landlines, cell phones, gasoline, Jet A fuel, parking spaces, staff, air conditioning" as stated in the 2012 U.S. Airport Cooperative Research Program (ACRP) Synthesis 33 (p. 16). Storms may also damage or destroy infrastructure (ACRP, 2012; Heathrow Airport, 2011, Palko and Lemmen (Eds.)) and disrupt ATM operations (Puempel et al., 2016; NATS, 2011; SESAR[1], 2012; ICAO, 2016; Palko and Lemmen (Eds.), 2017) with the SESAR[1] 2012 Environmental Risk Review noting that "Extreme winds may even lead to runway closure" and "Convective weather activity already causes demonstrable deteriorations in en-route airspace and airport capacity in Europe" (p.15). As well as the local effects, there may be network-wide effects as loss of capacity at one airport can impact the airspace system as a whole. Operational costs may also increase for the aviation sector (Rapaport et al, 2017). Indirect effects on aviation from increased intensity of storms - as described in the documents reviewed - include access to ground transportation to and from airport facilities and a potential effect on the "Performance and maintenance requirement of jet engines" due to storm damage, as described in the Adaptation Chapter of the ICAO 2016 *Environment Report,* (Puempel and Williams, p.207).

As global temperatures increase, lightning is projected to also increase (Romps, et al, 2014). An article published in the journal Science states that over the United States, lightning strikes are likely to increase as a function of global mean temperature at a rate of 12 ± 5% per °C. The eleven Global Climate Models (GCMs) used for the study predicted an approximate 50% increase in the rate of lightning strikes over the contiguous United States over the 21st century, which is about 12% for every degree of rise in global average air temperature (Romps, et al, 2014). Lightning strikes to aircraft are not uncommon but commercial aircraft are engineered to protect the people, electrical equipment, and fuel system onboard when they do occur (Rupke, 2001). However, the aircraft may require maintenance checks and repair after a lightning strike. An increase in costs may be incurred for more frequent maintenance work and for additional adaptation and resilience measures to accommodate increased lightning strikes to aircraft and other aviation infrastructure.

Storm Surge: Potential Effects 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 can damage infrastructure or 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. According to the 2012 SESAR Environmental Risk Papers, storm surge inundation of the airfield can cause "…impacts ranging from increased ground delays to runway closure or even temporary airport closure" (SESAR, p.14). Because the aviation industry is so interconnected, an impact at one airport or aviation facility may have ripple-effects across a wide geographical area. Puempel and Williams (2016) stated storm surge "Effects [are] likely to be exacerbated through very intense precipitation episodes linked to [the] storms, which can lead to excess flooding where run-off collides head-on with storm tides" (p. 205). EUROCONTROL has identified 34 European airports in their 2013 *Climate Change Risk and Resilience* document as, "…potentially at risk from sea level rise, storm surges and flooding by the end of the century" (p.17). 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).

5.2.3 Adaptation and Resilience Measures

The reviewed documents indicate that storms are predominantly responded to after they occur, rather than prepared for before they happen (Palko and Lemmen (Eds.), 2017; IPCC[22], 2014). As the climate continues to change and storms increase in their intensity, better understanding and forecasting of weather events is needed to prepare for storms before they happen (EUROCONTROL, 2013; Puempel et al, 2016). 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 preemptively 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).

Storm Surge: Adaptation and Resilience Measures

According to the documents reviewed for this synthesis, it is important to gather information on the projected effects of storm surge for decision making. There is also a recognition that facilities need to be more resilient to storm surge (BOS Sustainable Management Plan, 2015) and that 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).

5.2.4 Survey Analysis

The following charts present the combined results of the survey questions on increased intensity of storms from the CAEP Memo and State Letter.

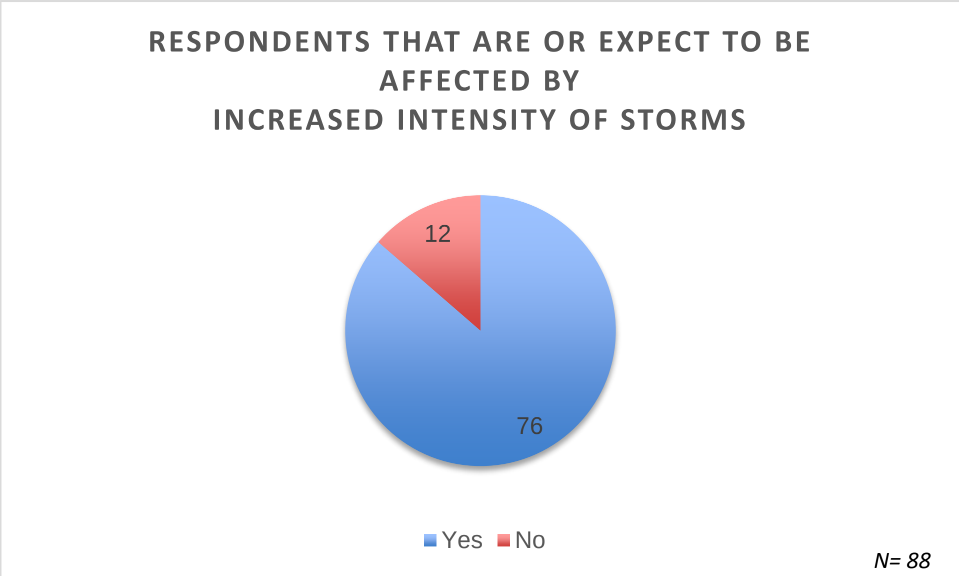


Figure 12 Number of respondents that are affected today or expect to be affected in the future by increased intensity of storms

Seventy-six out of 88 respondents expect to be affected by increased intensity of storms, indicating that this impact is expected to be widely experienced.

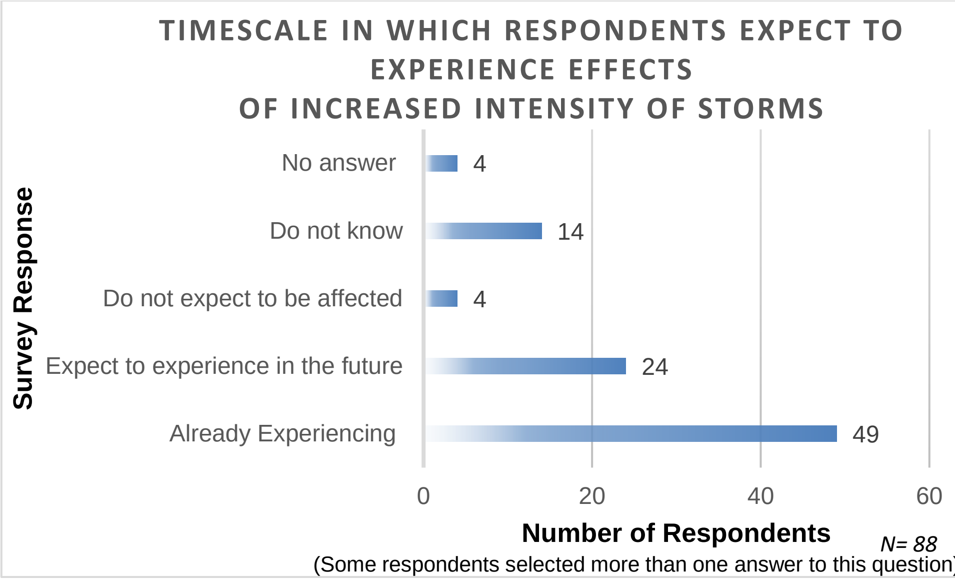


Figure 13 Timescale in which respondents expect to experience effects of increased intensity of storms

Forty-nine respondents are already experiencing the effects of increased intensity of storms and 24 expect to experience it in the future. Only 4 respondents do not expect to be affected, and 14 do not know.

Note that in some cases, respondents who indicated that they did not expect to be affected previously (Figure 13) either did not answer this question or answered “do not know”. This is why there is not a direct match between the answers in Figure 12 and Figure 13 for the response “do not expect to be affected”.

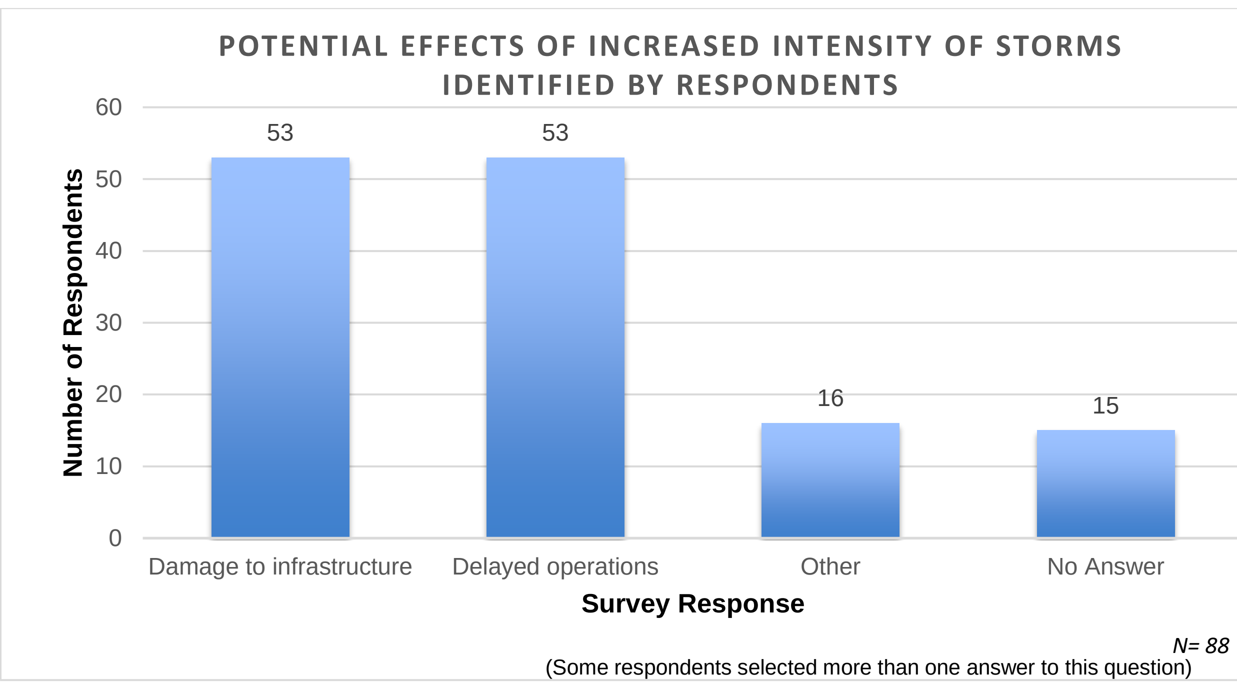


Figure 14 Potential effects of increased intensity of storms identified by respondents

The main effects that respondents expect to experience are damage to infrastructure and delayed operations. Many respondents gave more than one answer to this question. The respondents who selected "Other" identified, "flooding", "increased operating costs", "impacts on design standards", "higher occurrence of storms and increase of aircraft deviations", "deforestation and accidents", "cancellation of air operations", "land degradation/pollution", "damage to crops leading to reduced productivity", "damage to asphalt layers on runway", "not yet affected", and "not known yet". One indicated higher intensity of storms in the northern region of their country; one respondent indicated that while they have observed increased intensity of storms in both strength of winds and frequency, they have not observed structural damage or operational disruption to their aviation sector. Two respondents answered "uncertain" and one response was unspecified.

5.3 Temperature Change

5.3.1 Summary of Impact and Timescales

While global average annual temperatures are rising (IPCC[2], 2014; Heathrow Airport, 2011; SESAR, 2016; SESAR[1], 2012), there are regional differences to temperature change rates. 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), whilst the IPCC WG1 Report Summary for Policy Makers (2013) states that "Multiple lines of evidence support very substantial Arctic warming since the mid-20th century" (IPCC[1], p.9). More frequent occurrence and longer lasting high-heat days are also projected for some regions, particularly in the summer months (EUROCONTROL, 2013; Heathrow Airport, 2011; International Transport Forum, 2015; SESAR, 2016; SESAR[1], 2012). A 2012 Airport Cooperative Research Program Synthesis Report described how higher temperatures have an effect on air density and pollution concentrations, "[U.S. Environmental Protection Agency] estimates that a 10°C increase in temperature doubles emissions of [NOx and VOC]" (p.15).

Higher temperatures may also cause "Significant decreases in air density" as described by Puempel and Williams (2016) (p. 205). The timescales for the projected changes vary across the documents reviewed. There are changes that are already being experienced or that are expected over the next 20 years and mid-range projections that extend into the middle of the century (EUROCONTROL, 2013; Heathrow Airport, 2011; IPCC[2]IPCC[22], 2014; Pendakur, 2017). In the long term (2080-2100), projections vary greatly according to the potential emissions trajectory (e.g., IPCC RCP emissions scenarios).

According to the IPCC AR5 report, "The increase of global mean surface temperature by the end of the 21st century (2081–2100) relative to 1986–2005 is *likely* to be 0.3°C to 1.7°C under RCP2.6, 1.1°C to 2.6°C under RCP4.5, 1.4°C to 3.1°C under RCP6.0 and 2.6°C to 4.8°C under RCP8.5" (IPCC[3], p.10).[8] For example, in some regions of Canada, as described by Phillips and Towns (2017), there may be an increase in the "frequencies of freeze-thaw cycles over the short term, damaging... runways" (p.117) and underground infrastructure (Heathrow Airport, 2011). Additionally, according to a 2015 report by the International

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[8] Please see the Guide to the Synthesis for more background on RCPs.

Transport Forum (ITF), "Arctic regions will warm more than other regions, leading to deeper permafrost melting with loss of summer sea and land ice" (ITF, p.6).

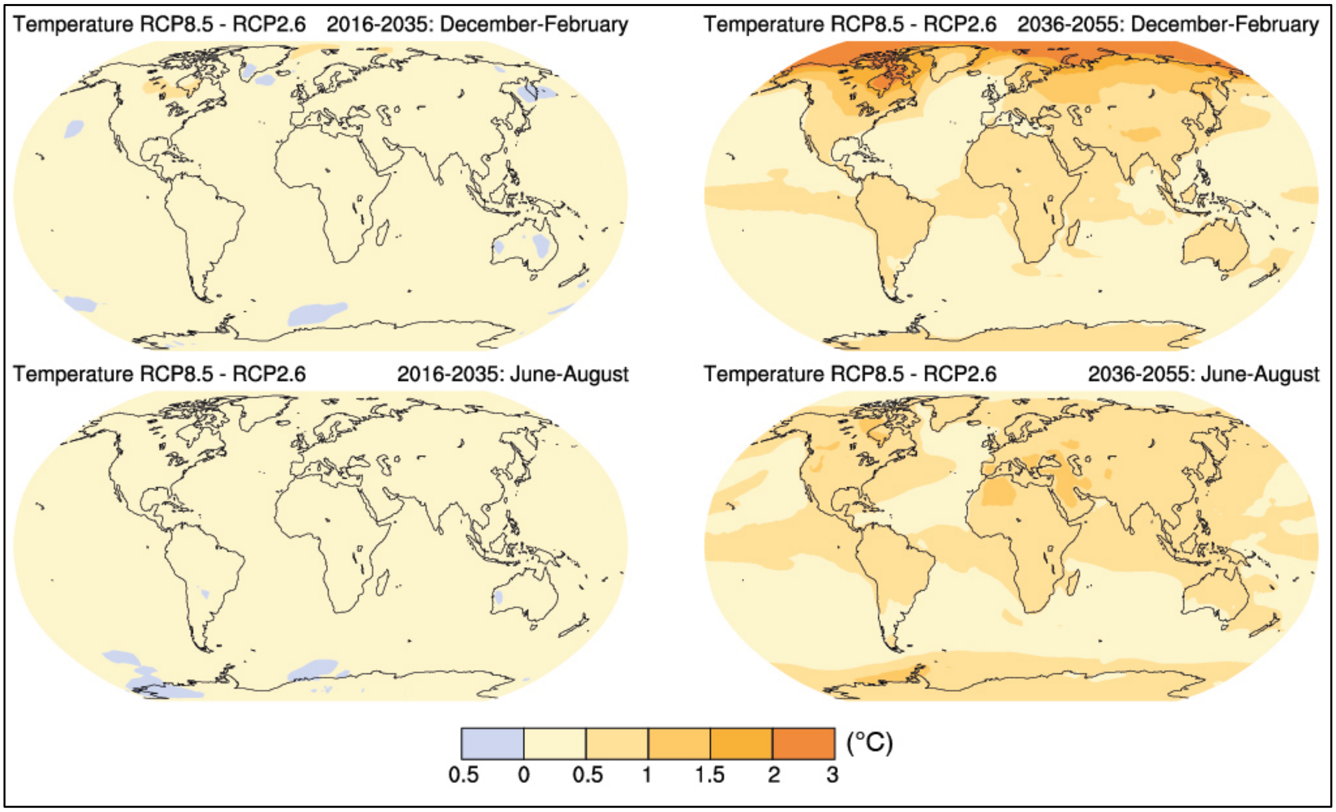

Figure 15: Near-term Climate Change: From the IPCC AR5 WG1 Report, "Global maps of near-term differences in surface air temperature across the RCP scenarios. Differences between (RCP8.5) and low (RCP2.6) scenarios for the CMIP5 model ensemble (31 models) are shown for averages over 2016–2035 (left) and 2036–2055 (right) in boreal winter (December, January and February; top row) and summer (June, July and August; bottom row)" {IPCC[1], Chapter 11, 11.24b}.

As global average temperatures rise, the IPCC AR5 report projects that "It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is *very likely* that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur" (IPCC[3], p.10).

In some regions increased humidity may lead to more fog in the mornings (SESAR, 2016).

5.3.2 Potential Effects on Aviation from Temperature Change

Changes to air density caused by rising temperature affects aircraft lift and the ratio of lift to weight, which may affect the required runway length to maintain normal operations or may limit climb performance (Boston Logan International Airport, 2016; Heathrow Airport, 2011; Puempel et al., 2016; Puempel and Williams, 2016; NATS, 2011; SESAR[1], 2012; ICAO, 2016; Palko and Lemmen (Eds.), 2017). The 2011 ACI World "Planning Airport Adaptation to Climate Change" publication explains how more thrust for aircraft to takeoff in less dense air may create "greater noise impact and CO_2 emissions" (p.4). The maximum take-off weight may be restricted due to higher temperatures. A recent study from Coffel et al (2017) identifies a number of airports where weight restrictions to aircraft maybe required due to an increase in high-heat days.

High-heat days may stress existing cooling systems and according to the IPCC Impacts, Adaptation, and Vulnerability (Part A) report, “adaptation costs for securing cooling capacities and emergency shelters during heat waves will be substantial” (IPCC[2], p. 109). Employees may be affected by higher temperatures, creating more of a demand for cooling (Heathrow Airport, 2011). High-heat days can contribute to increased risk of fire at airport facilities (Heathrow Airport, 2011). The 2011 ACI World publication also explains that as temperature increases in cold-weather areas, requirements for “aircraft and tarmac de-icing and snow removal” may change (p.4).

More extreme cool temperature days in northern 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).

In northern areas, 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).

As temperature changes, demand for air travel to certain locations may also change, which may stress capacity in some areas (SESAR[1], 2012, ACI World, 2011). There may also be costs associated with repairing or replacing damaged or vulnerable infrastructure (NATS, 2011).

5.3.3 Adaptation and Resilience Measures

Per the 2018 ICAO Airport Planning Manual, “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).

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, 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[9], can help to better understand the permafrost underlying runways and airport infrastructure (Ibid.).

Airports located in colder climates may be able to learn how airports in warmer climates consider and adapt to warmer temperatures while maintaining operations. When renovations or changes are made at airports, projected temperature change should be considered in the decision-making and design (Heathrow Airport, 2011). The 2014 IPCC Report Impacts, Adaptation, and Vulnerability (Part A) states, "Warning systems for heat waves have been planned and implemented broadly, for example in Europe, the United States, Asia, and Australia" (IPCC[2], p.1145). In order to adapt to potential demand shifts, more research is needed (EUROCONTROL, 2013).

Adaptation measures for extreme cold can include proactively deploying warming stations to protect ground support crews during unusually cold weather 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).

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

5.3.4 Survey Analysis

The following charts present the combined results of the survey questions on temperature change from the CAEP Memo and State Letter.

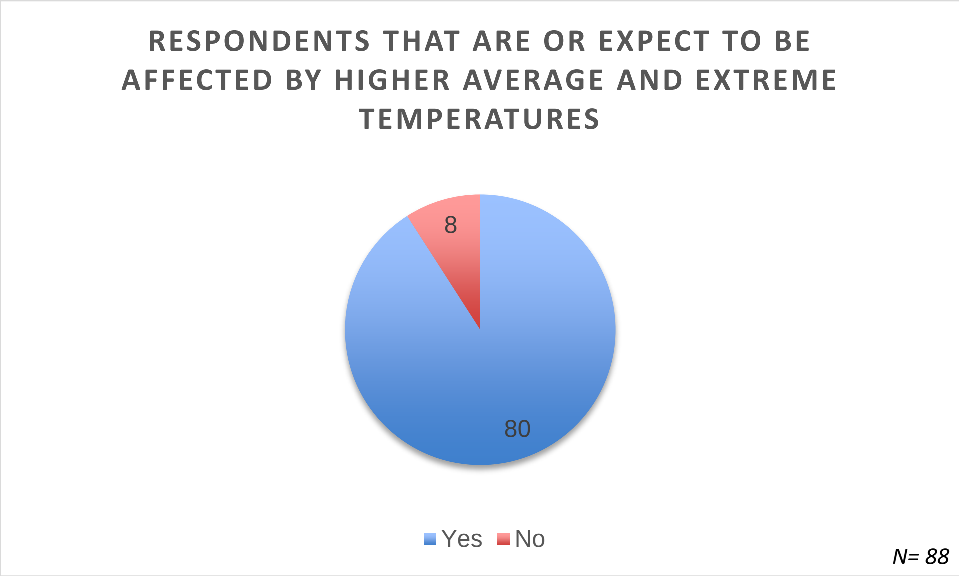

Figure 16: Number of respondents that are affected today or expect to be affected in the future by higher average and extreme temperatures.

Out of 88 respondents, 80 expect to be affected by higher average and extreme temperatures, indicating that this impact may be widely experienced.

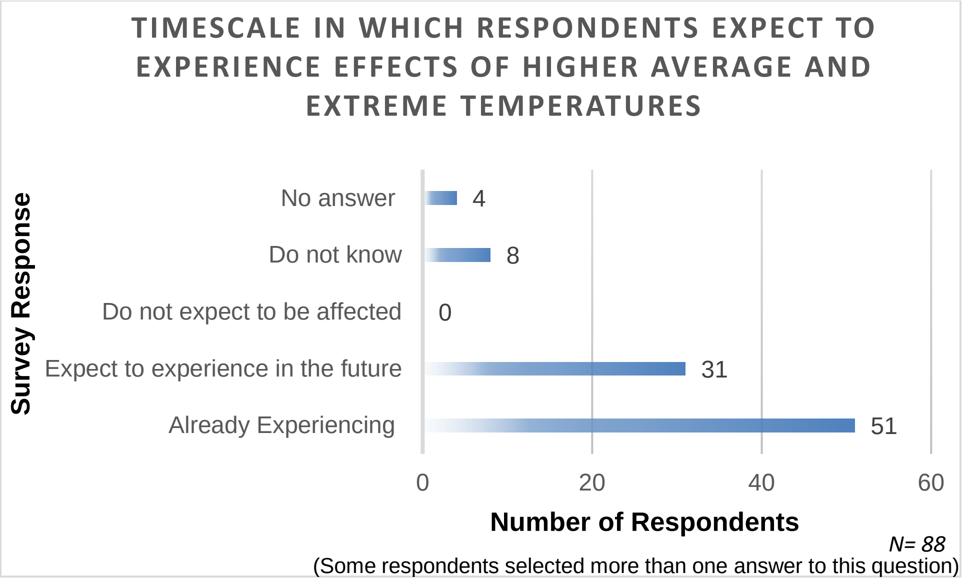

Figure 17: Timescale in which respondents expect to experience effects of higher average and extreme temperatures

Out of 88 respondents 51 are already experiencing the effects of higher average and extreme temperatures, indicating that this is already an issue for many stakeholders. Thirty-one respondents expect to experience effects in the future. No respondents answered that they do not expect to be affected. This is not a direct match between the answers in Figure 16, however, respondents that indicated they did not expect to be affected (Figure 17) either did not answer this question, answered "do not know" or gave potentially conflicting responses.

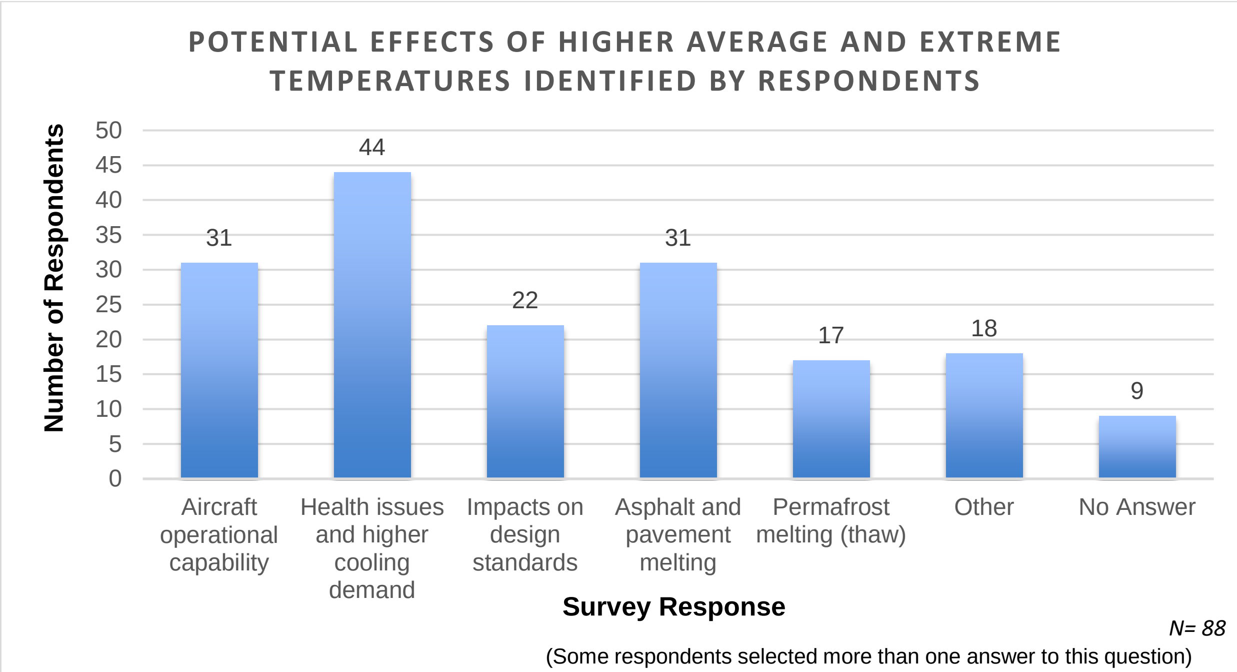

Figure 18: Potential effects of higher average and extreme temperatures identified by respondents

The main effects that respondents expect to experience are health issues and higher cooling demand, aircraft operational capability and asphalt and pavement melting. Many respondents gave more than one answer. The respondents who selected "Other" identified, "changes in performance and noise", "heat damage to airport surface", "increase cooling and demand for building and preconditioned air for aircraft", "more winter days with above zero temperatures being experienced" (2 respondents), " increase in average temperatures by approximately 1-4 degrees Celsius" (6 respondents), "aircraft performance impacted by higher temperatures", "higher average temperatures in winter time", "impacts on soil, vegetation and forest management", "diseases of the cardio vascular", "increased risk of forest fires, thus increasing demand for aircraft and operations", "air pollution", "not yet affected" , and "not known yet". Two responses were not specified.

5.4 Changing Precipitation

5.4.1 Summary of Impact and Timescales

The UK Met Office defines precipitation as "any form of water - liquid or solid - falling from the sky. It includes rain, sleet, snow, hail and drizzle plus a few less common occurrences such as ice pellets, diamond dust and freezing rain" (UK Met Office). 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, climate change is likely to affect, and potentially exacerbate, these conditions in all regions (IPCC[1], 2013).

The IPCC AR5 WG1 illustrates changes in precipitation by season (December, January, February; March, April, May; June, July, August; and September, October, November) for the near term (2016-2035).

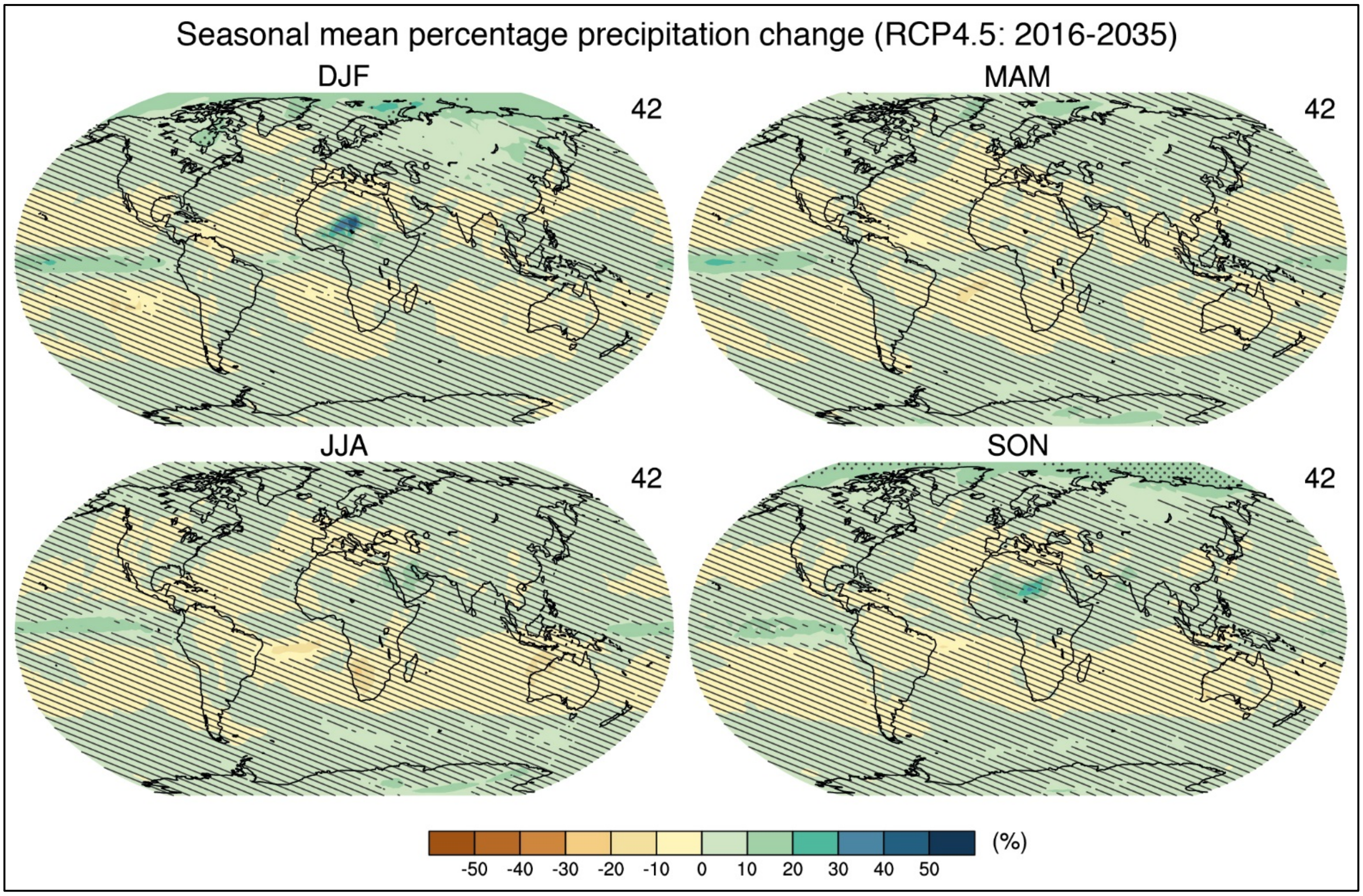

Figure 19: Near-term Climate Change: The IPCC AR5 WG1 Report states, "CMIP5 multi-model ensemble mean of projected changes (%) in precipitation for 2016–2035 relative to 1986–2005 under RCP4.5 for the four seasons. The number of CMIP5 models used is indicated in the upper right corner". {IPCC[1], Chapter 11, 11.12} Hatching indicates "areas where projected changes are small compared to the internal variability (i.e., smaller than one standard deviation of estimated internal variability), and stippling indicates regions where the multi-model mean projections deviate significantly from the simulated 1986–2005 period (by at least two standard deviations of internal variability) and where at least 90% of the models agree on the sign of change". {IPCC[1], Chapter 11, 11.10}

As the previous figure shows, there are 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[1], 2013). In the literature reviewed, there is broad consensus on timescales in which changes in precipitation will begin to be experienced, with impacts expected within 20 years, if not sooner (EUROCONTROL, 2013; SESAR[2], 2012; IPCC[2], 2014).

There may also be shifts in the distribution of rainfall. For example, the *SESAR Base Level Environmental Risk Review* (2012) stated there may be "shifts in the distribution of precipitation over different latitudes, new areas subject to snowfalls and freezing rains" (SESAR[1], p.13) and the IPCC AR5 WGI Report states, "Zonal mean precipitation will very likely increase in high and some of the mid latitudes, and will more likely than not decrease in the subtropics" (IPCC[1], p.956). According to the 2016 *Projected Impacts of Climate Change on Aviation* report prepared for the CAEP Impacts and Science Group, there may also be "significant winter precipitation events in the semi-arid areas" (Puempel, et al, p.E-2). Whilst the 2012 SESAR *Base Level Environmental Risk Review* found it "very probable that intense precipitation events will become more frequent" in some areas (SESAR[1], p.14) there will also be a future heightening of intense drought conditions for other regions (Ibid.). SESAR (2012) *Environmental Regulatory and Risk Scenarios Guidance* noted that "Annual average precipitation trends disguise potential seasonal extremes" (SESAR[2], p.27).

There is more uncertainty relating to snowfall projections. The IPCC AR5 Synthesis Report notes that since the 1950s "the amounts of snow and ice have diminished" (IPCC[3], p.40) and will continue to decrease although the extent varies according to the RCP scenario. However, 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 we have a broad understanding of the effects 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.

5.4.2 Potential Effects on Aviation from Changing Precipitation

The two main effects identified from more frequent or more intense precipitation were risk of flooding and flood damage to both runways and infrastructure, and storm drainage systems not being able to handle the increased volumes of water. This could affect operations leading to capacity reduction, delays and cancellations and inundation of infrastructure (ACRP, 2012; EUROCONTROL, 2013; Heathrow Airport, 2011; San Francisco Conservation and Development Commission, 2017; Puempel and Williams (2016); SESAR[1], 2012). Failure of drainage systems could cause failure of pollution control systems with risks of contaminating ground water (Heathrow Airport, 2011; ACI World, 2011). Ground transport links may also be disrupted (ITF, 2015).

According to the 2011 NATS Climate Change Adaptation 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. Reduced visibility 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 (SESAR[1], 2012; Palko and Lemmen (Eds.), 2017), and could also affect air traffic for major events, if the two coincide. For example, in February 2011, the Dallas, Texas region received 2.6 inches 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 deicer 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).

It may also become more challenging to forecast conditions and precipitation type (e.g., rain, snow, freezing rain) due to warmer temperatures at higher latitudes leading to temperatures fluctuating around the freezing point. This may make forecasts less reliable (San Francisco International Airport, undated). Too little precipitation leading to drought conditions may lead to reduced water availability with restrictions imposed on water intensive activities (Heathrow Airport, 2011).

As stated by EUROCONTROL (2013), changes in snow conditions may lead to "…increased requirements for snow clearing and de-icing equipment" at some locations but reduced requirements at others (p.15). 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). 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, 2011). 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).

5.4.3 Adaptation and Resilience Measures

Adaptation and resilience measures proposed or already being implemented include: operational measures to increase robustness and flexibility, augmented low visibility procedures, for example, using ground based augmentation system (GBAS), improved use of MET forecasting, 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 (EUROCONTROL, 2013), 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, 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.).

Specific measures already implemented include a strategy for snow and ice removal at airports, such as Dallas/Fort Worth International Airport and Toronto Pearson International Airport (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).

For drought conditions, measures to reduce water consumption and build drought resistance are needed. 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 "ensure appropriate design standards are applied to new buildings to address risks from water ingress/flooding" (Heathrow Airport, 2011, p.89).

5.4.4 Survey Analysis

The following charts present the combined results of the survey questions on changing precipitation from the CAEP Memo and State Letter.

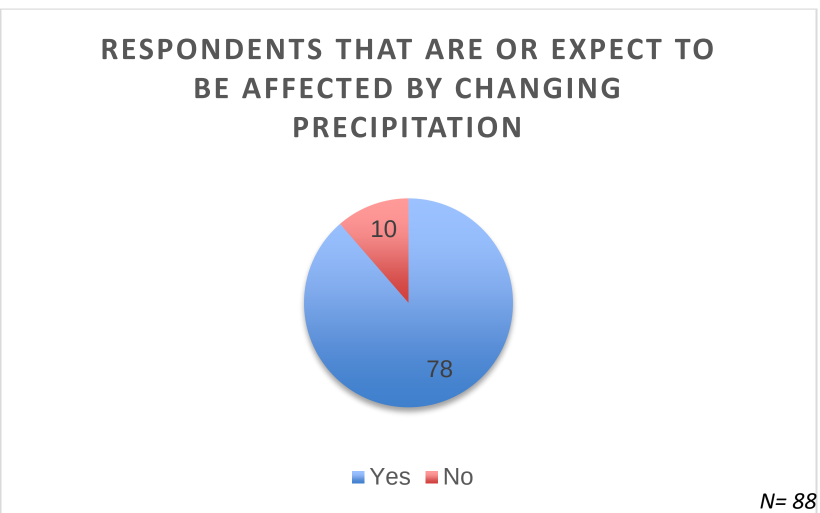

Figure 20: Number of respondents that are affected today or expect to be affected in the future by changing precipitation

Out of 88 respondents, 78 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.

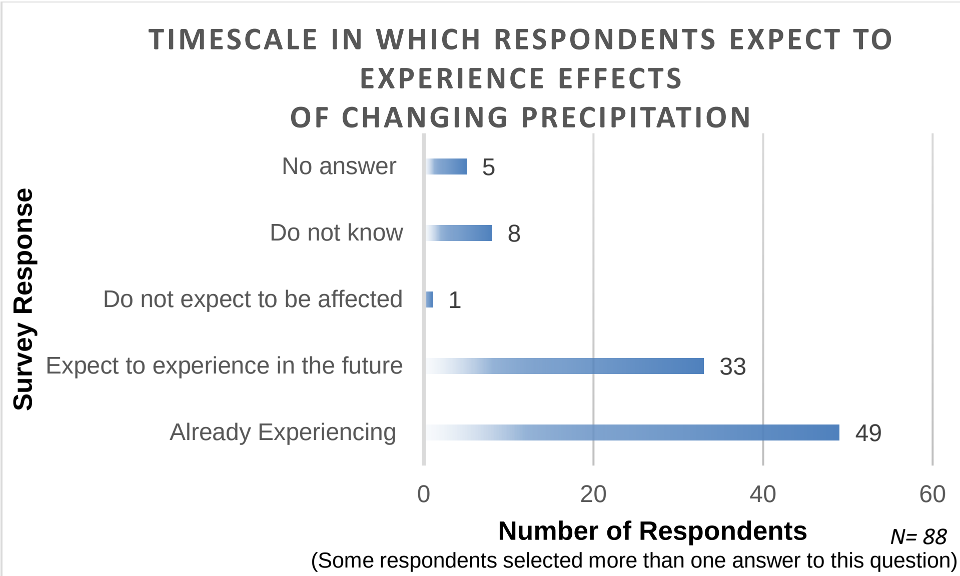

Figure 21: Timescale in which respondents expect to experience effects of changing precipitation

Forty-nine respondents are already experiencing the effects of changing precipitation and 33 expect to experience effects in the future. However, it is not always clear whether this is a direct effect for their aviation sector or a more general effect. Just one respondent does not expect to be affected and eight do not know.

One respondent selected two answers, “Already experiencing” and “Expect to experience in the future”, both answers are included in Figure 21.

Note that in some cases respondents that indicated that they did not expect to be affected (Figure 21) either did not answer this question or answered “do not know”. This is why there is not a direct match between the answers in Figures 20 and 21 for the response “do not expect to be affected”.

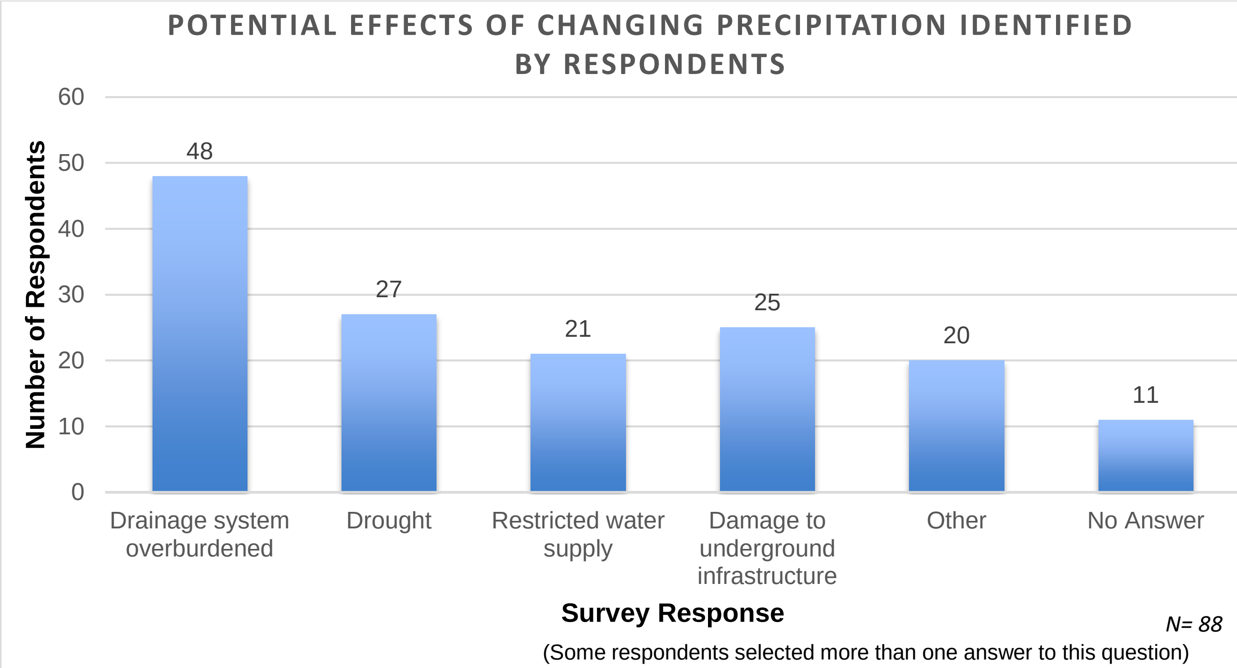

Figure 22: Potential effects of changing precipitation identified by respondents

The main effects from changing precipitation that respondents expect to experience are drainage system overburden, damage to underground infrastructure, and drought, again indicating that impacts from changing precipitation can be due to either an increase or a decrease.

Many respondents gave more than one answer to this question. The respondents who selected “Other” identified: “drainage system capacity”, “inundation of underground infrastructure”, “inundation of ground surface access”, “potential impacts in boil water advisories (potable water)”, “more freezing rain precipitation being experienced” (2 respondents), increase in annual rainfall by approximately 5% by 2050 (5 respondents), one respondent referred to a catastrophic flood, “damage to coastal infrastructure”, “coastal erosion”, “severe flooding of fields and destruction of bridges”, “not affected yet”, and “need more data”. One respondent recognized that as storms increase in frequency, precipitation amounts may be above-average. One respondent indicated that they expect more extreme rainfall in the northern area of their country. One answered “uncertain” while one was not specified.

5.5 Changing Icing Conditions

5.5.1 Summary of Impact and Timescales

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" (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), 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. 23) while "High altitude icing is likely to increase with more intense 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).

5.5.2 Potential Effects on Aviation from Changing Icing Conditions

Ground icing: Increased de-icing requirements and operational risks from freezing rain were identified as risks. De-icing requirements will change, but may increase in some areas and decrease in others (EUROCONTROL, 2013). For example, increased temperatures in some regions may lead to a reduction in de-icing (ACRP, 2013; EUROCONTROL, 2013). There is also a risk that operations may be affected, causing the delay or cancellation of flights. Pendakur (2017) recognized that, "rain and 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" (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 effect of changing icing conditions (ACRP, 2012).

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.

5.5.3 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 underground infrastructure from freeze-thaw 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 note that for safety reasons regulations for twin-engine aircraft operations over oceanic airspace should be reviewed (Puempel and Williams, 2016). Aircraft manufactures also may need to assess airframes for performance in changing climatic conditions (Puempel, 2016).

5.5.4 Survey Analysis

The following charts present the combined results of the survey questions on changing icing conditions from the CAEP Memo and State Letter.

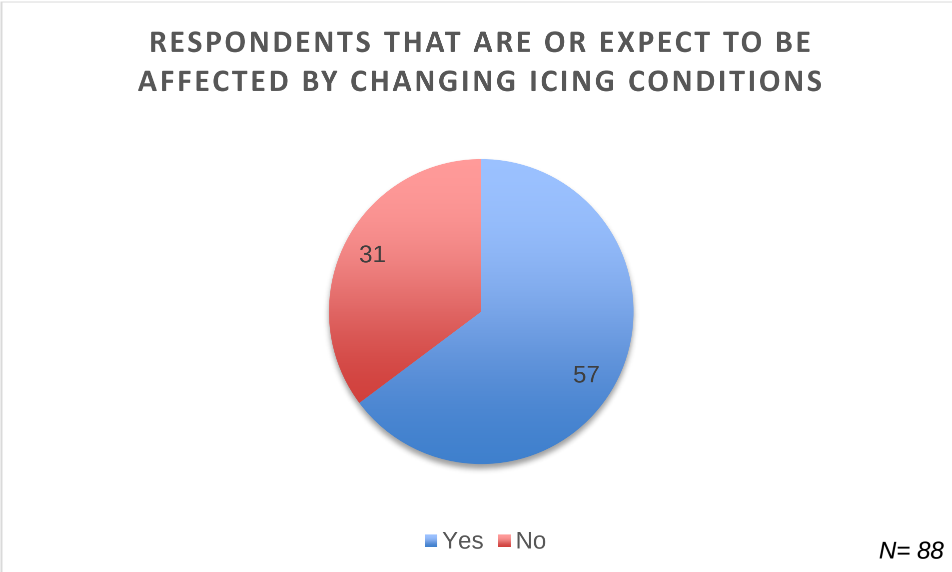

Figure 23: Number of respondents that are affected today or expect to be affected in the future by changing icing conditions

Fifty-seven out of 88 respondents expect to be affected by changing icing conditions. Respondents had differing interpretations of this impact. For example, some 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.

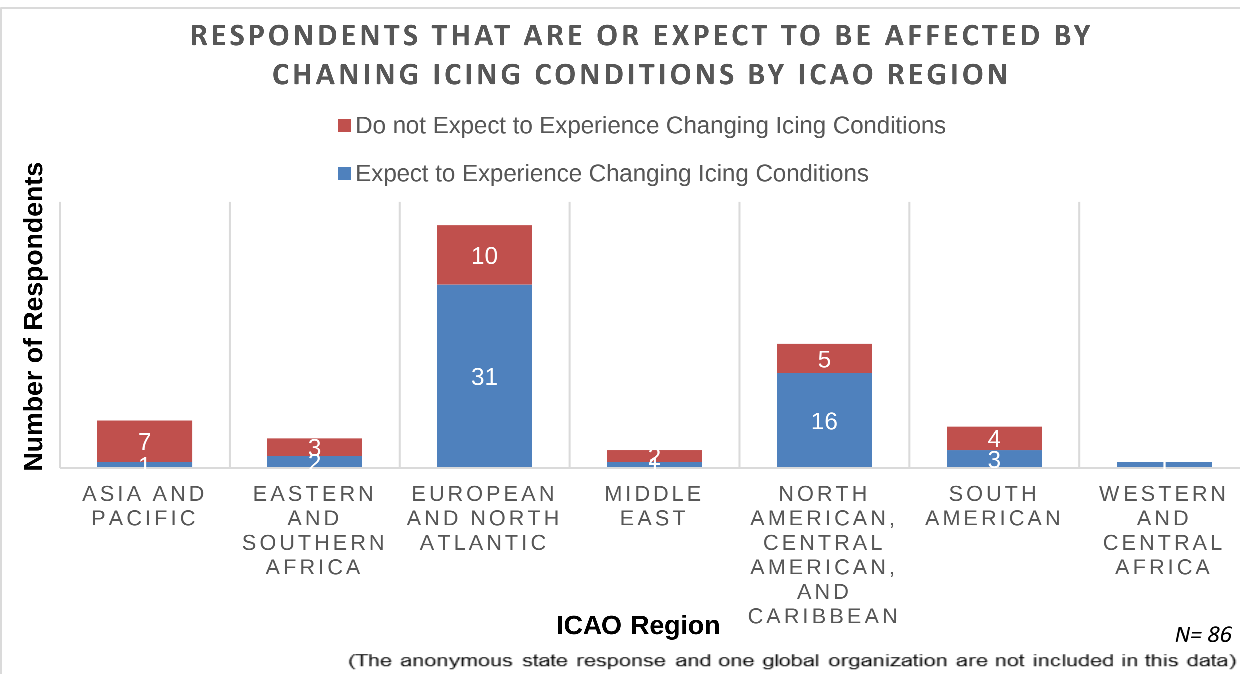

Figure 24: Number of respondents that are affected today or expected to be affected in the future by changing icing conditions by ICAO region

The chart above shows the number of respondents that expect to be affected by changing icing conditions by ICAO region. Fifty-five of the 86 respondents represented in this chart expect to be affected by changing icing conditions. However, this is almost certainly influenced by regional differences such as underlying climate and geography. The red bars are the number of respondents that do not expect to be affected by changing icing conditions while the blue bars indicate how many respondents do expect to be affected by changing icing conditions. For example, in the Asia and Pacific region, seven respondents indicated that they do not expect to be affected by changing icing conditions, while one respondent does expect to be affected. Two of five respondents from the Eastern and Southern Africa region, 31 of 41 respondents from the European and North Atlantic region, two of three respondents from the Middle East region, 15 of 21 respondents from North America, Central America, and the Caribbean region, and 3 of 7 respondents from the South American region, expect to be affected by changing icing conditions. The one respondent from the Western and Central Africa region also 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.

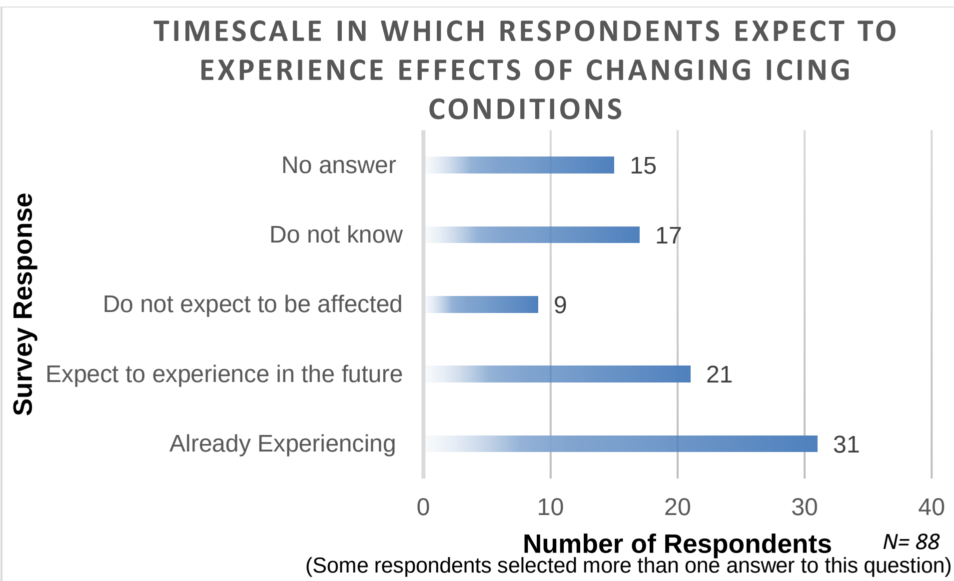

Figure 25: Timescale in which respondents expect to experience effects of changing icing conditions

Out of 88 respondents, 31 are already experiencing the effects of changing icing conditions and 21 expect to experience effects in the future. Nine do not expect to be affected and 17 do not know, indicating that for some respondents there are still some uncertainties regarding this impact.

Note that in some cases, respondents that indicated that they did not expect to be affected (Figure 25) either did not answer this question or answered "do not know". This is why there is not a direct match between the answers in Figures 23 and 25 for the response "do not expect to be affected".

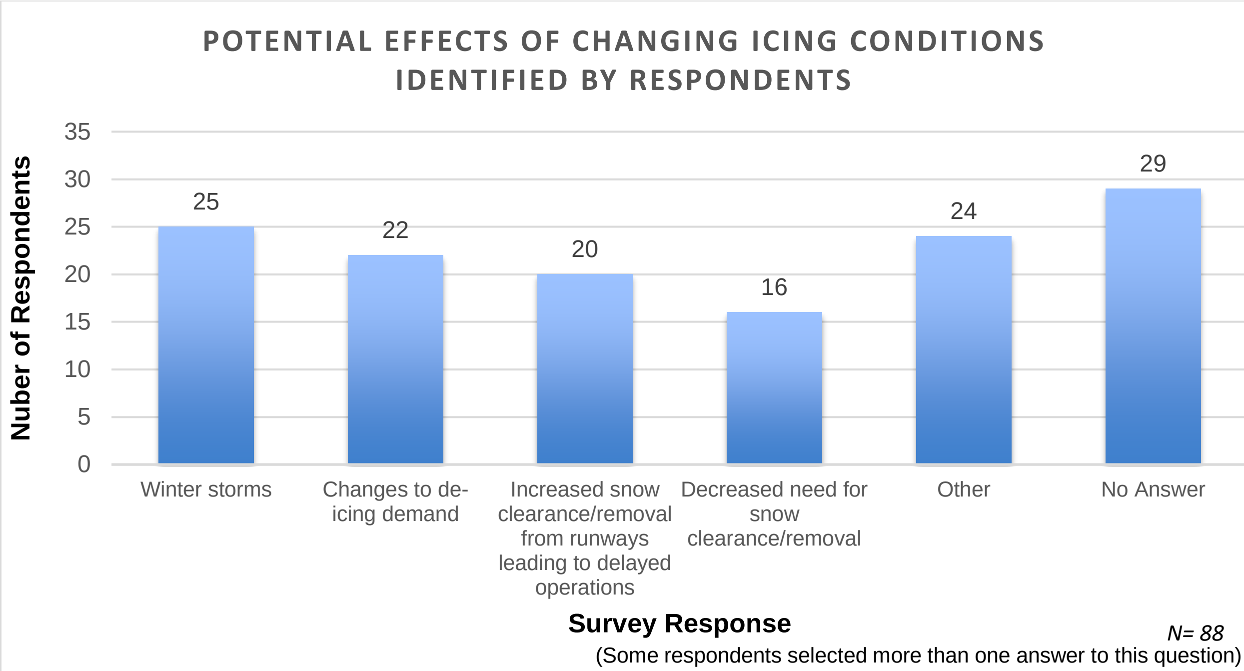

Figure 26: Potential effects of changing icing conditions identified by respondents

The main effects that respondents expect to experience are winter storms and changes to de-icing demand. 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: "decrease in annual snow cover by about 60 days by 2050" (5 respondents), "more freezing precipitation being experienced" (2 respondents), "decreased temperatures in wintertime", "temperatures around the freezing point which will lead to more ice conditions", and "higher frequency of hail storm events". One respondent indicated that there may be a possibility of short term change. Additionally, there were four responses of "not applicable", and one response each for "nothing documented yet on this" and "uncertain".

5.6 Changing Wind

5.6.1 Summary of Impact and Timescales

There are two distinct but connected issues identified with the impacts of changing wind: changes or deviation in prevailing wind direction and shifts in the location and speed of the jet stream. Changes in wind speed will vary by region. In the lower atmosphere, changes in wind strength and direction are projected, while in the upper troposphere, changes to the jet stream are projected (EUROCONTROL, 2013; SESAR[1], 2012). 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).

For the jet stream, we can expect to see changes in the average strength, latitude, altitude, and waviness across the North Atlantic (NATS, 2011; SESAR, 2016) and, as a 2016 ICAO report states, "wintertime jet stream winds are projected to strengthen, shift poleward, and increase in altitude." (ICAO, p.13). Although, as stated in the 2016 SESAR *Second Reporting and Analysis of Environment-Related Risks*, in the northern hemisphere the west-to-east wind flow in the polar jet is slowing and weakening" (SESAR, p.22).

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). Recent work from Storer et al. (2017, p.1) finds 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”.

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, 2013; Palko and Lemmen (Eds.), 2017) whilst changes to the jet stream and wind shear are expected by mid-century (ICAO, 2016).

The IPCC AR5 WG1 Report states, “In the [Northern Hemisphere], some Atmosphere-Ocean General Circulation Models (AOGCMs) indicate changes to atmospheric circulation from anthropogenic forcing by the mid-21st century, including a poleward shift of the jet streams and associated zonal mean storm tracks Miller et al., 2006; Pinto et al., 2007; Paeth and Pollinger, 2010) and a strengthening of the Atlantic storm track (Pinto et al., 2007)” (IPCC[1], p.988).

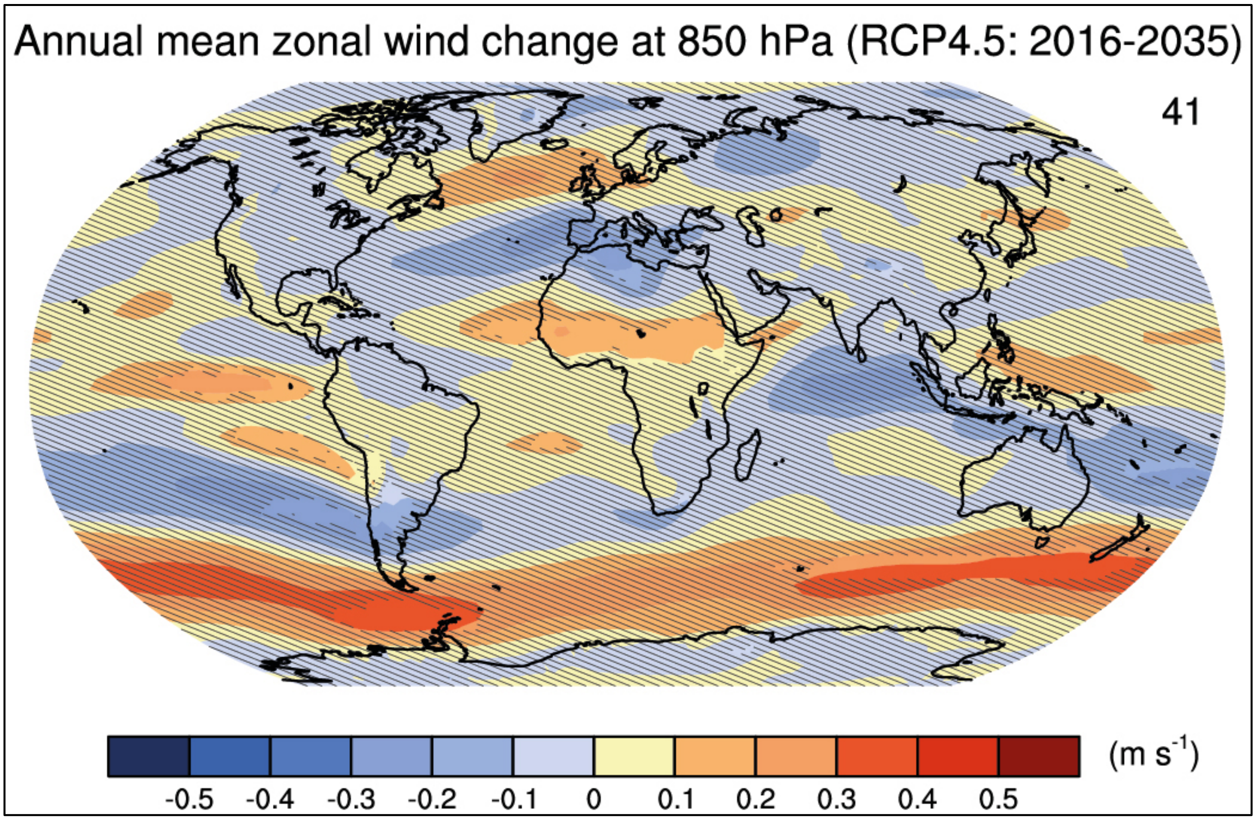

Figure 27 Near-term Climate Change: From the IPCC AR5 WG1 Report, "CMIP5 multi-model ensemble mean of projected changes (m s–1) in zonal (west-to-east) wind at 850 hPa for 2016–2035 relative to 1986–2005 under RCP4.5. The number of CMIP5 models used is indicated in the upper right corner." {IPCC[1], Chapter 11, 11.15} Hatching indicates "areas where projected changes are small compared to the internal variability (i.e., smaller than one standard deviation of estimated internal variability), and stippling indicates regions where the multi-model mean projections deviate significantly from the simulated 1986–2005 period (by at least two standard deviations of internal variability) and where at least 90% of the models agree on the sign of change". {IPCC[1], Chapter 11, 11.10} The figure above from the IPCC AR5 WG1 Report depicts changes in wind based on one RCP scenario over the timeline 2016-2035 relative to a 1986-2005 baseline.

5.6.2 Potential Effects on Aviation from Changing Wind

Changes to, or deviation from, the prevailing wind direction at airports could affect runway utilisation and schedules. Flights might be cancelled, delayed or redirected when crosswinds are too strong for aircraft to safely take off or land (Heathrow Airport, 2011; SESAR1, 2012; ACI World, 2011; Palko and Lemmen (Eds.), 2017). In turn, this could reduce airport and aircraft operating efficiency, capacity and safety (SESAR, 2016). 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 (EUROCONTROL, 2013).

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).

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. This 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) states 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 Clear Air Turbulence leading to greater diversions and "bumpier" flights (NATS, 2011; 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) notes 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), identifies, 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"[10] of system propagation: this may bring extreme weather events, such as heavy snows, to airports which have not been previously affected (SESAR, 2016.)

5.6.3 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).

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 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;

[10] "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)

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 increased information on areas with likely Clear Air Turbulence and enable them to take preventative measures (Vrancken et al., 2016).

5.6.4 Survey Analysis

The following charts present the combined results of the survey questions on changing wind patterns from the CAEP Memo and State Letter.

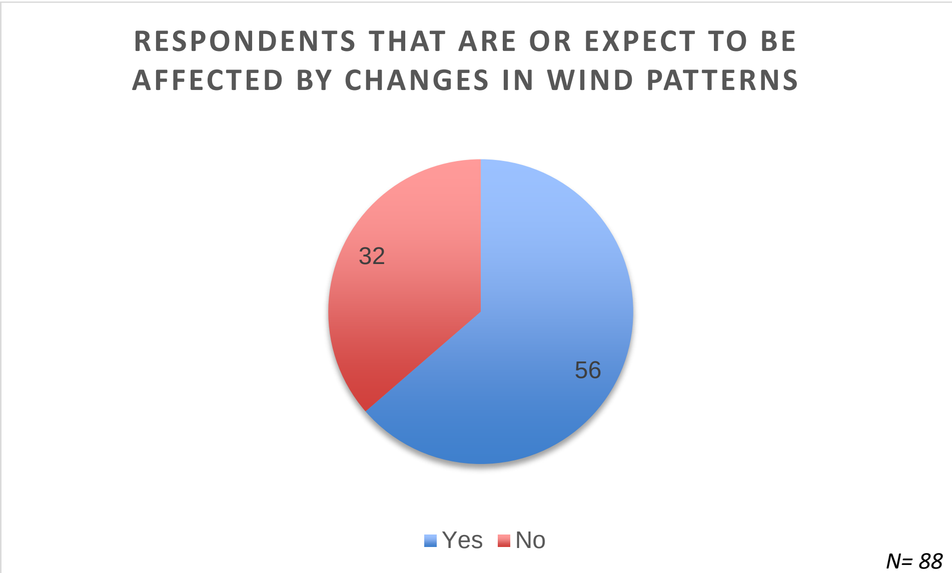

Figure 28: Number of respondents that are affected today or expect to be affected in the future by changes in wind patterns

Out of 88 respondents, 56 expect to be affected by changes in wind patterns.

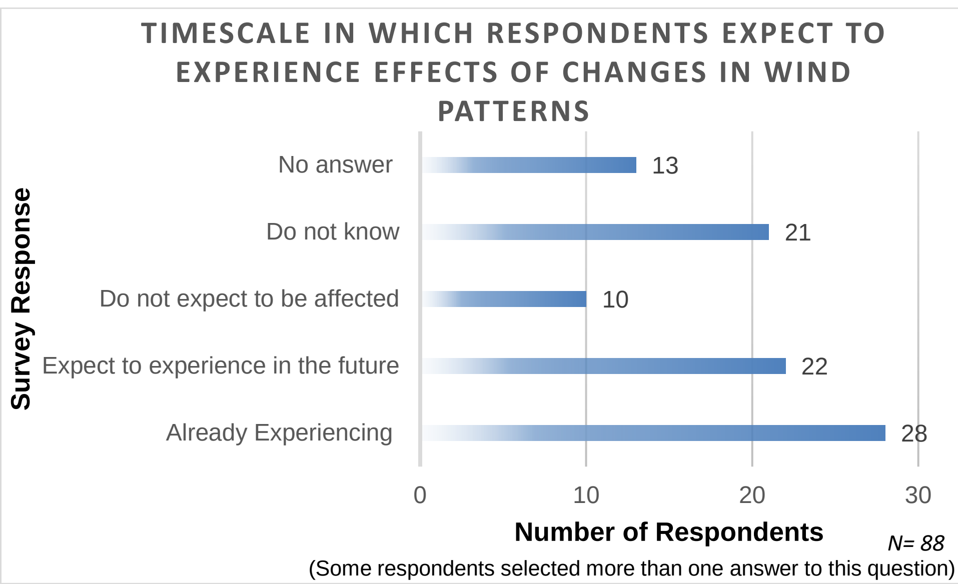

Figure 29: Timescale in which respondents expect to experience effects of changes in wind patterns

Out of 88 respondents 28 are already experiencing the effects of changing wind patterns and 22 expect to experience it in the future. Ten do not expect to be affected and 21 do not know, indicating that for some respondents, there are still some uncertainties regarding this impact.

Note that in some cases, respondents that indicated that they did not expect to be affected (Figure 29) either did not answer this question or answered “do not know”. This is why there is not a direct match between the answers in Figures 28 and 29 for the response “do not expect to be affected”.

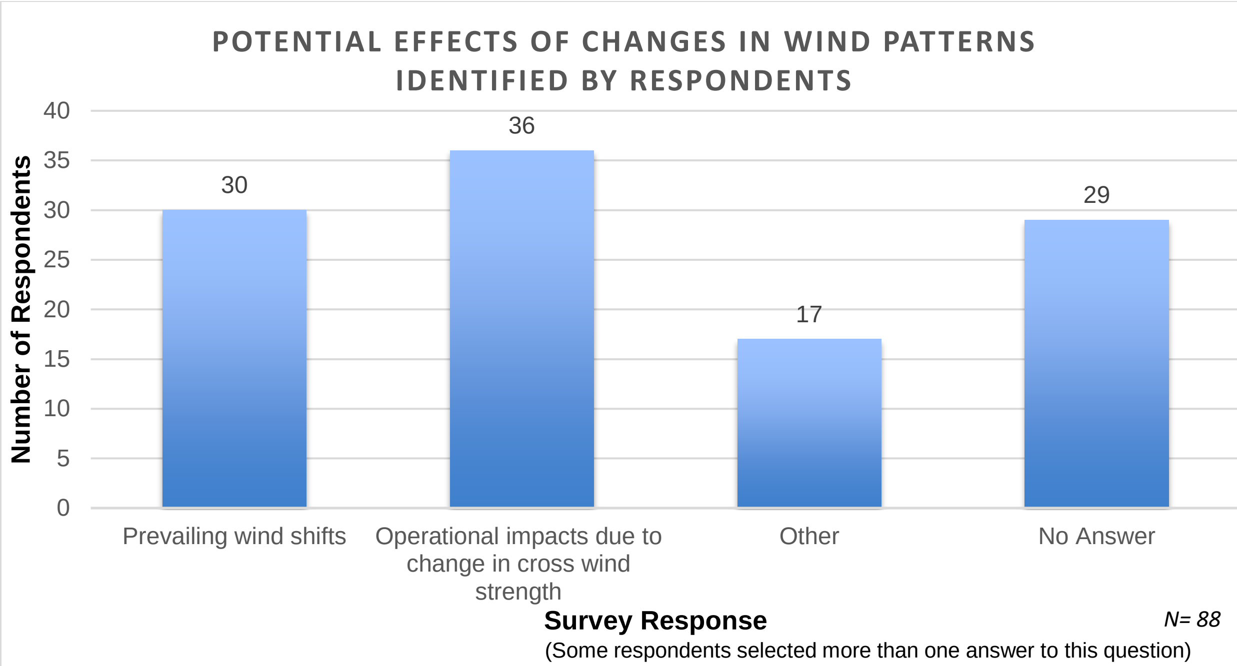

Figure 30: Potential effects of changes in wind patterns identified by respondents

The main effects that respondents expect to experience are operational impacts due to changes in crosswind strength and prevailing wind shifts. Twenty-nine respondents answered “no answer”, reflecting the proportion of respondents that do not expect to be impacted, but possibly also indicating uncertainties regarding this impact.

Many respondents gave more than one answer. The respondents who selected “Other” identified “wind directions will vary more”, “convective weather and local wind patterns”, “changes to distribution of noise patterns”, “jet stream modelling”, “delay onset of raining season in the country”, “increased wind shear”, “increase in wind speed in general”, “there is no evidence of changes in winds”, and “nothing documented on this”. One respondent stated that prevailing winds are expected to change in their south central region, and one respondent stated that an increased number of storms will lead to a higher occurrence of extreme winds at aerodromes. Other responses were “uncertain”, “not yet affected”, “not applicable”, “no effect”, and one was not specified.

5.7 Desertification

5.7.1 Summary of Impact and Timescales

According to the 2018 ICAO Airport Planning Manual Part II, Chapter on Climate Change Resilience and Adaptation, “Desertification is the process in which more land becomes desert. 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 sand storms in many regions" (ICAO, p.9-7).

Desertification may also lead to an increase in dust storms in particular geographic areas that experience longer drought (Puempel and Williams, 2016; SESAR, 2016). No timescales were identified in the literature review for this impact.

The rate of desertification is dependent on many factors including precipitation, evaporation, runoff, vegetation, and soil moisture. The IPCC AR5 WG1 Report projects that changes in evaporation are likely to grow overland globally (IPCC[1], 2013).

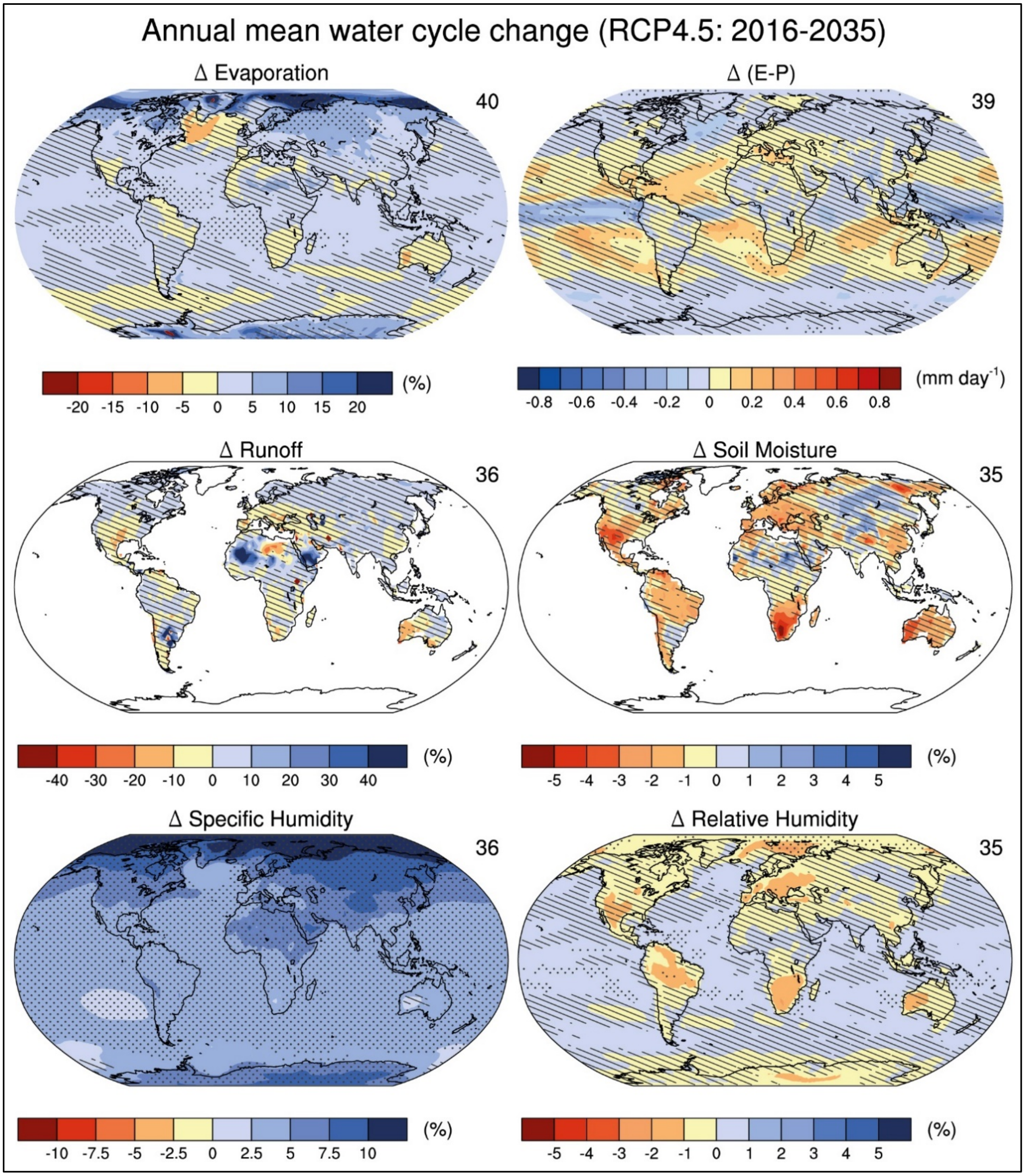

Figure 31: Near-term Climate Change: Annual mean water cycle change, "CMIP5 multi-model annual mean projected changes for the period 2016–2035 relative to 1986–2005 under RCP4.5 for: (a) evaporation (%), (b) evaporation minus precipitation (E – P, mm day–1), (c) total runoff (%), (d) soil moisture in the top 10 cm (%), (e) relative change in specific humidity (%), and (f) absolute change in relative humidity (%)" {IPCC[1], Chapter 11, 11.14}. Hatching indicates "areas where projected changes are small compared to the internal variability (i.e., smaller than one standard deviation of estimated internal variability), and stippling indicates regions where the multi-model mean projections deviate significantly from the simulated 1986–2005 period (by at least two standard deviations of internal variability) and where at least 90% of the models agree on the sign of change" {IPCC[1], Chapter 11, 11.10}.

Figure 31 depicts annual mean water cycle changes in evaporation, evaporation minus precipitation, runoff, soil moisture, specific humidity, and relative humidity projected for 2016-2035 relative to a 1986-2005 baseline. This figure does not depict a projection of desertification directly but all of these factors can contribute to desertification, along with other factors that are not depicted here including changes in vegetation.

5.7.2 Potential effects on Aviation from Desertification

Puempel and Williams (2016) identified that desertification may have potential effects on aviation. For example, desertification may lead to increased dust storms, which may affect aircraft engine design for fuel efficiency; 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” (p.207). Puempel explains in another paper that impacts from desertification and an increase in dust storms may also result in “introducing safety risks or increasing maintenance costs” due to degradation of equipment and increased maintenance requirements (Puempel, p.116).

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

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

5.7.3 Adaptation and Resilience Measures

ICAO stated (2018), “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.

5.7.4 Survey Analysis

The following charts present the combined results of the survey questions on desertification from the CAEP Memo and State Letter.

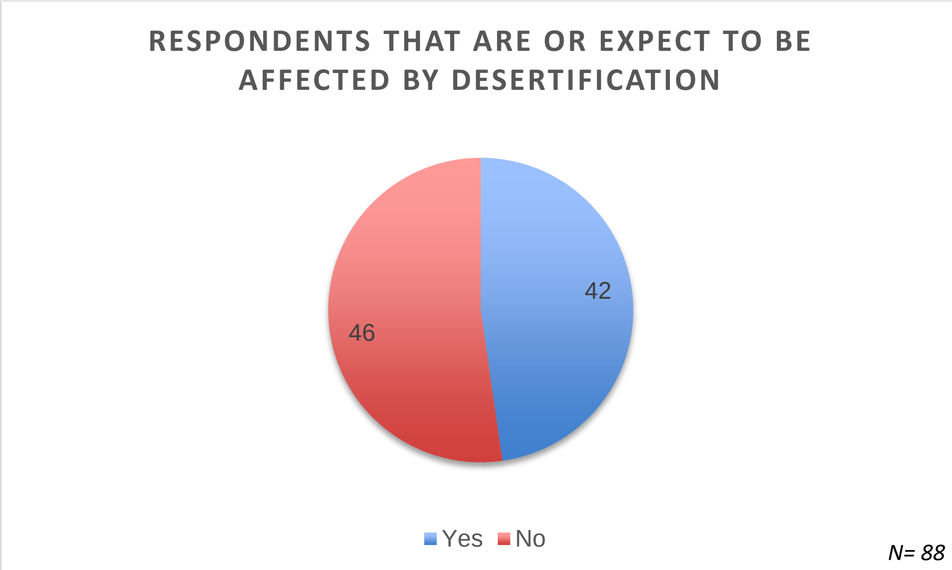

Figure 32: Number of respondents that are affected today or expect to be affected in the future by desertification

Out of 88 respondents 42 expect to be affected by desertification. However, this is almost certainly influenced by regional differences such as the underlying climate and geography.

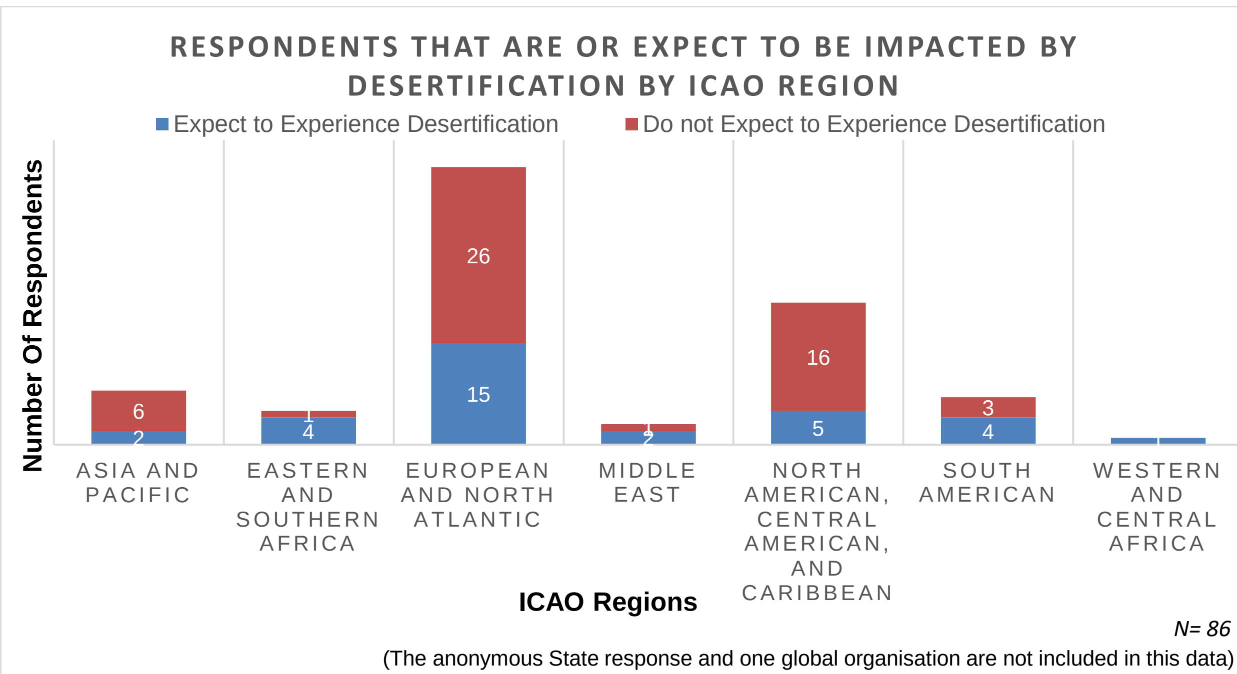

Figure 33: Number of respondents that are affected today or expect to be affected in the future by desertification by ICAO region

The chart above shows the number of respondents that expect to be affected by desertification in each ICAO region. The red bars indicate the number of respondents that do not expect to be affected by desertification while the blue bars represent the number of respondents that do expect to be affected by desertification. For example, in the Asia Pacific region, there were eight respondents in total, two of which said they expect to experience effects from desertification and six that said they did not expect to be impacted by desertification. Four of five respondents from Eastern and Southern Africa, fifteen of forty-one respondents from Europe and North Atlantic, two of three respondents form the Middle East, and three of four respondents from South America expect to be affected by desertification. Conversely, only five of twenty-one respondents from North America, Central America and the Caribbean expect to be affected by desertification. The one respondent from Western and Central Africa also indicated they would be affected by desertification.

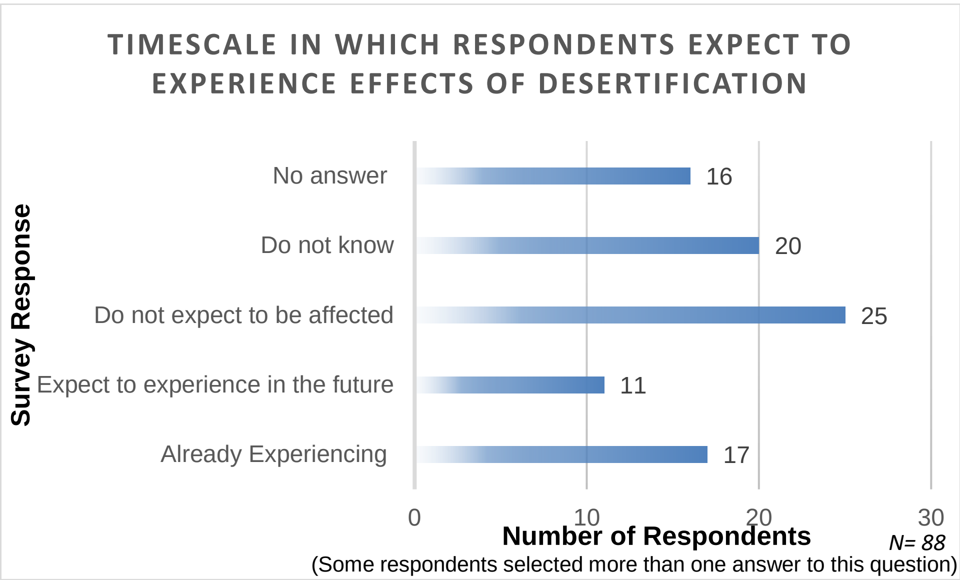

Figure 34: Timescale in which respondents expect to experience effects of desertification

Seventeen respondents are already experiencing the effects of desertification and 11 expect to experience effects in the future. This includes not only respondents in desert regions but also states in “warmer climates” that are not necessarily desert regions. However, it is not always clear whether this is a direct effect for their aviation sector or a more general effect. Twenty-five do not expect to be affected and 20 do not know, indicating regional differences as well as some uncertainties regarding this impact. It can be noted that there are differences even within regions. However, this is likely because within one ICAO region - there can be multiple climate zones.

Note that in some cases respondents that indicated they did not expect to be affected (Figure 34) either did not answer this question or answered “do not know”. This is why there is not a direct match between the answers in Figure 32 and Figure 34 for the response “do not expect to be affected”.

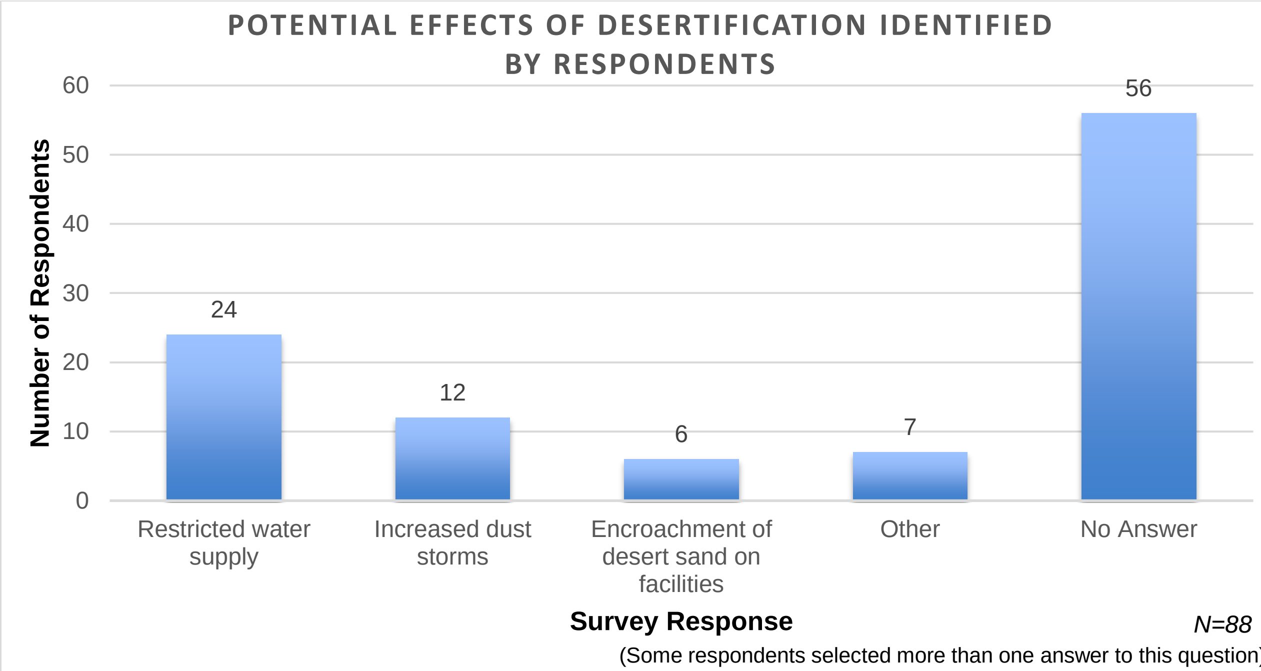

Figure 35: Potential effects of desertification identified by respondents

The main effects that respondents expect to experience are restricted water supply and increased dust storms. The highest response, 56 respondents, was for "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, "rural-urban population drift", "steppe formation, erosion", "not applicable" and "uncertain."

5.8 Changes to Biodiversity

5.8.1 Summary of Impact and Timescales

According to the United Nations Environment Programme (2010) biodiversity refers to biological variation at the genetic, species and ecosystem level. This section refers to potential wildlife impacts, namely variation in flora and fauna and potential regional changes to biodiversity which may affect the aviation sector. Relatively little information is available in the current literature regarding the effects of biodiversity changes on aviation. However, the main biodiversity risks identified in the reviewed literature are wildlife migration and propagation of invasive species (ACRP, 2012). Composition of ecosystems may 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 (SESAR[1], 2012; ICAO, 2018). 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.

Information from the World Birdstrike Committee suggests that, although climate change will be detrimental to many bird species, some big, flocking birds are increasing their population numbers and changing their range and distribution. In particular, large birds such as geese, bald and white-tailed eagles, brown pelicans, and ospreys, are already experiencing population growth and their distribution and range will move closer to human habitats. Flocking birds that commonly use aerodromes (gulls, starlings, crows, pigeons) will also continue expanding populations and distribution. This 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 birds species (Dr. Michal Skakuj, email to authors, July 5, 2017). 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 (Dr. Michal Skakuj, email to authors, July 5, 2017; Van Eekereen, undated).

In the longer term, according to Dr. Skakuj and a presentation from Van Eekereen, climate change impacts are expected to lead to species loss, habitat loss especially for waterbirds and large bird species, loss of breeding grounds, “much less wintering and migrating geese, duck and shorebirds [and] much less intense migration” (Van Eekereen, p.3).

5.8.2 Potential Effects on Aviation from Changes to Biodiversity

The changes described above may lead to shifts in the diversity of bird species that are present at 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 larger birds mentioned above (ICAO, 2018; Van Eekereen, undated). 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 (Dr. Michal Skakuj, email to authors). However, in the longer term the changes described above such as less wintering and migrating are expected to lower the risks identified above from big bird species (Dr. Michal Skakuj, email to authors).

One general effect may be damage to landscaping and an increase in maintenance costs due to changes in local wildlife or an increase in invasive species (ACRP, 2012). 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.).

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).

5.8.3 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 organisations and of course take into account environmental protection (Dr. Michal Skakuj, email to authors, July 5, 2017; ICAO, 2018). Expanded use of bird strike avoidance models is one potential measure, which was identified by the World Birdstrike Association (Van EeKereen, undated).

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 organisations will be crucial … up-to-date information will allow [us] to prepare and use the most effective methods in wildlife hazard reduction" yet take account of nature protection and relevant regulations (Dr. Michal Skakuj, personal communication, July 5, 2017).

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). A preferred solution may be permanent removal e.g. though pulling them out or landscaping changes so that the plants do not grow.

5.8.4 Survey Analysis

The following charts present the combined results of the survey questions on changes in biodiversity from the CAEP Memo and State Letter.

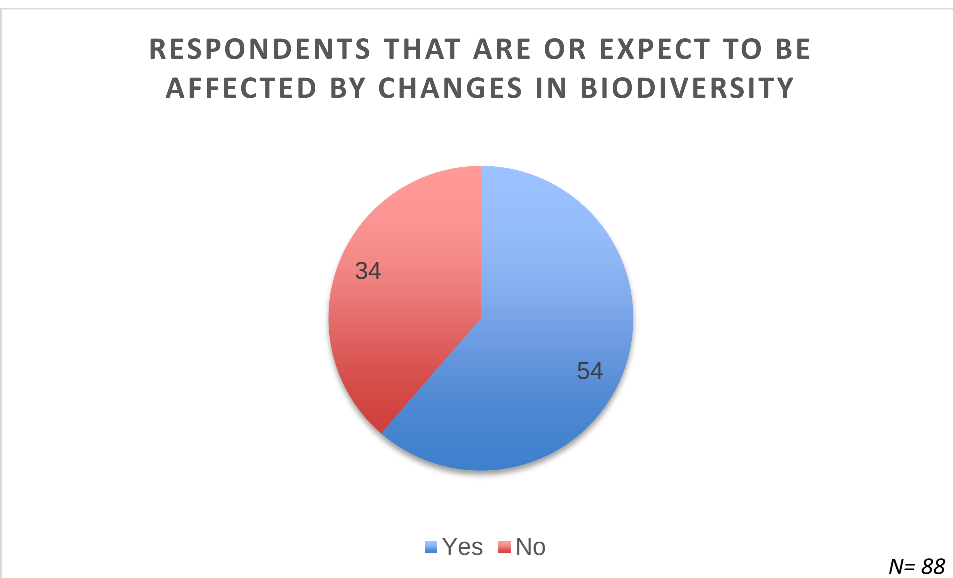

Figure 36: Number of respondents that are affected today or expect to be affected in the future by changes in biodiversity

Out of 88 respondents, 54 expect to be affected by changes in biodiversity.

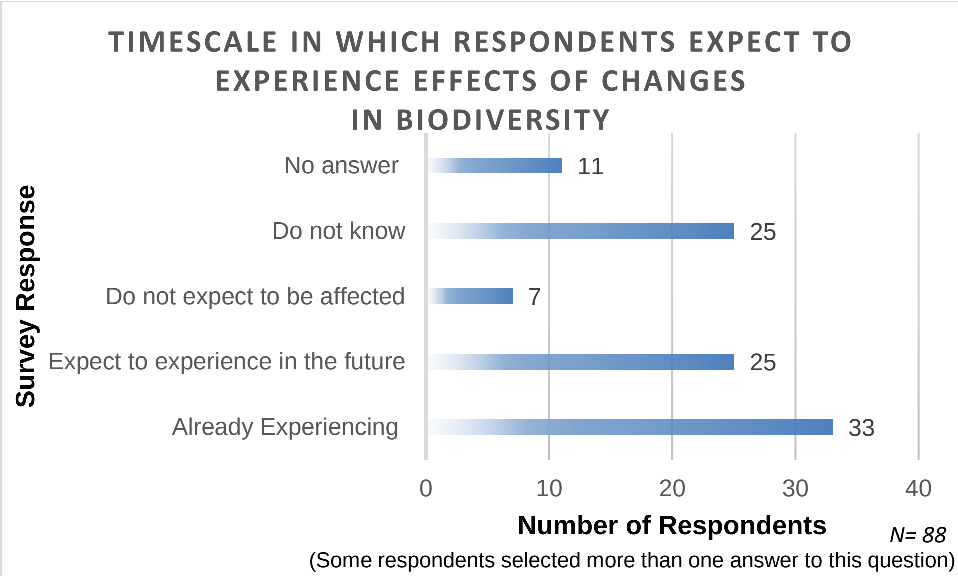

Figure 37: Timescale in which respondents expect to experience effects of changes in biodiversity

Out of 88 respondents, 33 are already experiencing the effects of changes in biodiversity and 25 expect to experience effects in the future. However, it is not always clear whether this is a direct effect for their aviation sector or a more general impact. Seven do not expect to be affected and 25 do not know if they will be affected, indicating that for some respondents there are still some uncertainties regarding this impact.

Note that in some cases respondents that indicated that they did not expect to be affected (Figure 37) either did not answer this question or answered "do not know". This is why there is not a direct match between the answers in Figure 36 and Figure 37 for the response "do not expect to be affected".

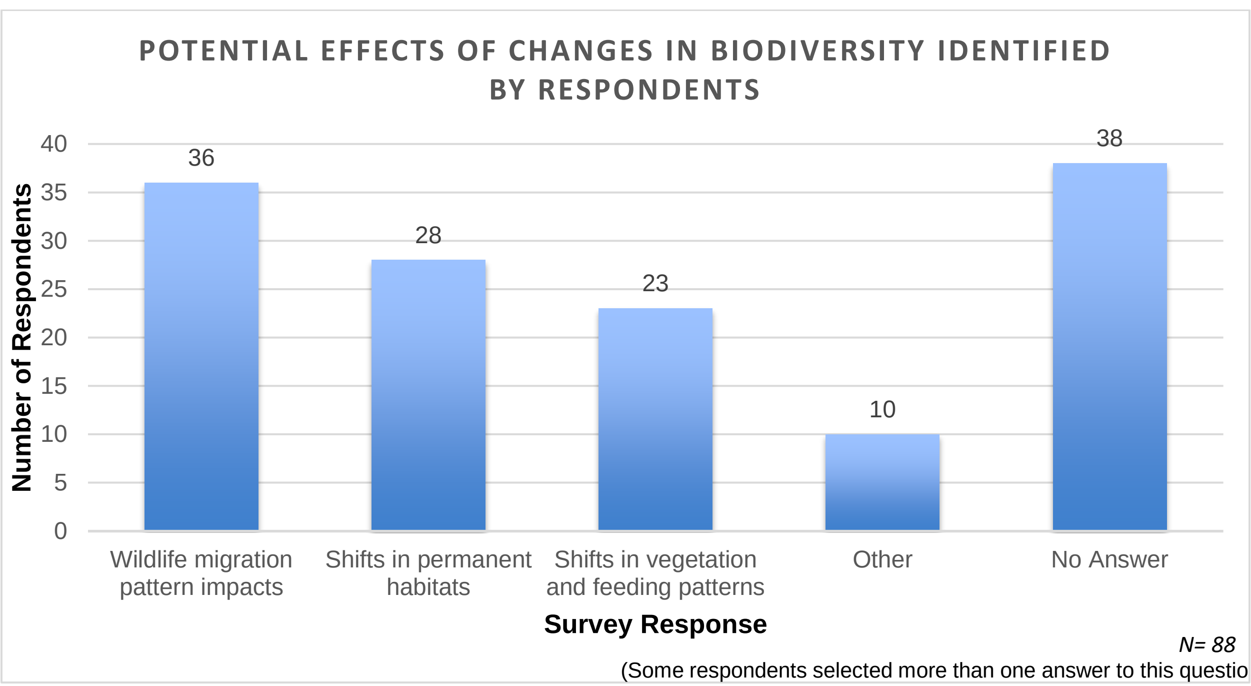

Figure 38: Potential effects of changes in biodiversity identified by respondents

The main effects that respondents expect to experience are wildlife migration patterns and shifts in permanent habitats. The highest response, 38 respondents, was for “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: “vector-borne disease (aviation might participate in the global distribution of disease; e.g. mosquito-borne diseases)”, “polar bear migration onto sea ice delayed due to late formation, creating a hazard while they remain in the airport vicinity”, “rural-urban population shift, new settlements acquired”, “coral bleaching”, “deforestation e.g., logging”, “migration of birds, non-indigenous, invasive species”, “there is no evidence of these changes”, and “not applicable”.

5.9 Potential changes in Business and Economics

5.9.1 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 impacts identified in the previous sections over varying timeframes. In the shorter-term, effects 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. In the longer-term, gradual but persistent impacts, such as temperature change or sea level rise, may lead to business and economic effects such as changes in tourist demand and damage or loss of infrastructure (EUROCONTROL, 2013).

5.9.2 Potential Effects on Business and Economics from Climate Change Impacts to 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 literature 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. According to the 2012 SESAR *Environmental Regulatory and Risk Scenarios Guidance "*Increased weather volatility will 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)." (p.29)

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).

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 (EUROCONTROL, 2013). 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 (ACRP, 2012; ITF, 2015; NATS, 2011; SESAR[1], 2012; ACI World, 2011; IPCC[2], 2014; Palko and Lemmen (Eds.), 2017). This may be a particular challenge for Small Island Developing States (IPCC[2], 2014; 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 (Puempel et al., 2016; NATS, 2011; SESAR[1], 2012, ICAO, 2016; Palko and Lemmen (Eds.), 2017; EUROCONTROL, 2013). 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). ACRP (2012) stated airports may also be used during a weather event to "... provide shelter, support for aviation in disaster relief, and other essentials" which can have business and economic effects (p.9). 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.

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 (SESAR[1], 2012; ACI World, 2011; EUROCONTROL, 2013). 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 (Thompson, 2017). 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. 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 (IPCC[2], 2014; Heathrow Airport, 2011; ACI World, 2011).

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. Effects on aircraft from rising temperatures may necessitate a reduction in payload (passengers or cargo) which would have an economic penalty. 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 (ACRP, 2012; EUROCONTROL, 2013; Heathrow Airport, 2011; San Francisco Bay Conservation and Development Commission, 2017; Puempel and Williams, 2016; SESAR[1], 2012; NATS, 2011; Rapaport et al., 2017). Ground transport links may also be disrupted preventing crew and passengers from reaching the airport (International Transport Forum, 2015). 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 (SESAR[1], 2012; Heathrow Airport, 2011; ACRP, 2012).

Changes in wind: Changes to, or deviation from, the prevailing wind direction at airports could affect runway utilisation and schedules, reduce airport and aircraft operating efficiency, capacity, and may impact safety (Heathrow Airport, 2011; SESAR[1], 2012; ACI World, 2011; Rapaport et al., 2017; SESAR, 2016). It may also change the criteria for approach and departure procedures and reduce flight arrival and departure punctuality, all of which will incur costs (SESAR[1], 2012; ACI World, 2011; EUROCONTROL, 2013).

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 transatlantic flights. According to a 2015 article in 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, and the extra carbon dioxide emissions would be in the region of 10,000 million kg per annum. There may also be an increase in Clear Air Turbulence leading 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 (Palko and Lemmen (Eds.), 2017; ACRP, 2016; EUROCONTROL, 2013).

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, TBD).

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 (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).

5.9.3 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, 2011; ACRP, 2014; ITF, 2015).

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).

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.

5.9.4 Survey Analysis

The following charts present the combined results of the survey questions on business and economics from the CAEP Memo and State Letter.

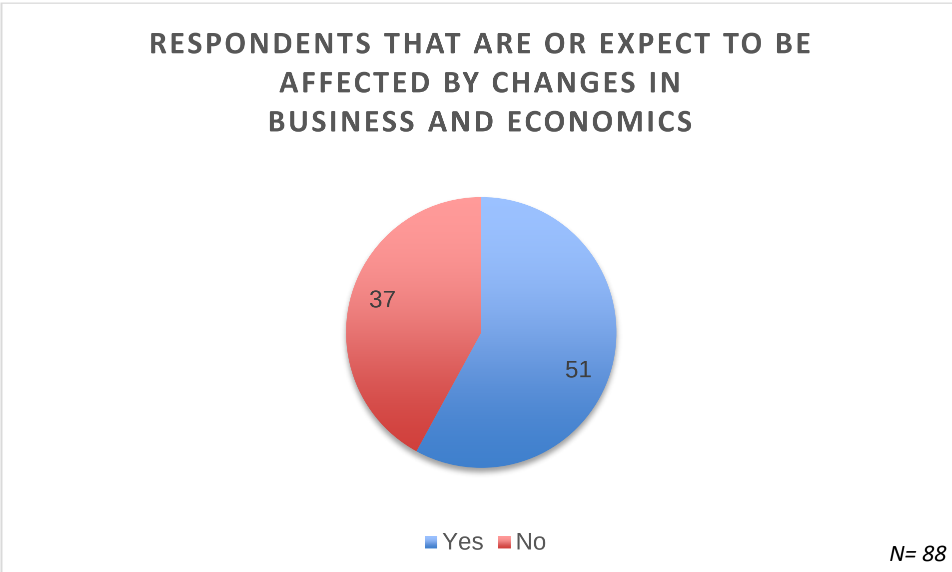

Figure 39: Number of respondents that are affected today or expect to be affected in the future by changes in business and economics

Out of 88 respondents, 51 expect to be affected by changes in business and economics.

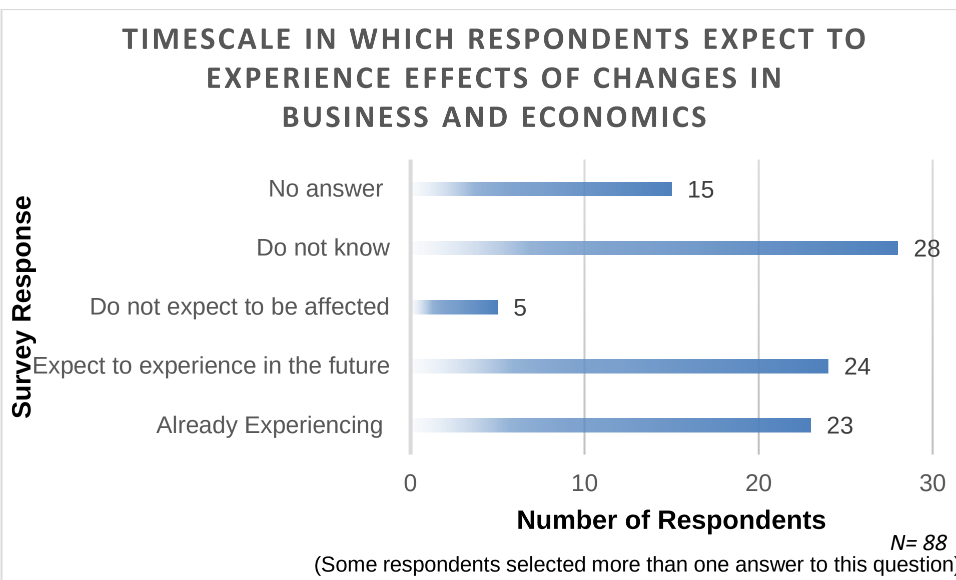

Figure 40: Timescale in which respondents expect to experience effects of changes in business and economics

Out of 88 respondents, 23 respondents are already experiencing the effects of changes in business and economics and 24 expect to experience effects in the future. Five do not expect to be affected and 28 do not know, indicating that for some respondents there are still some uncertainties regarding this impact.

Note that in some cases respondents that indicated that they did not expect to be affected (Figure 40) either did not answer this question or answered "do not know". This is why there is not a direct match between the answers in Figures 39 and 40 for the response "do not expect to be affected".

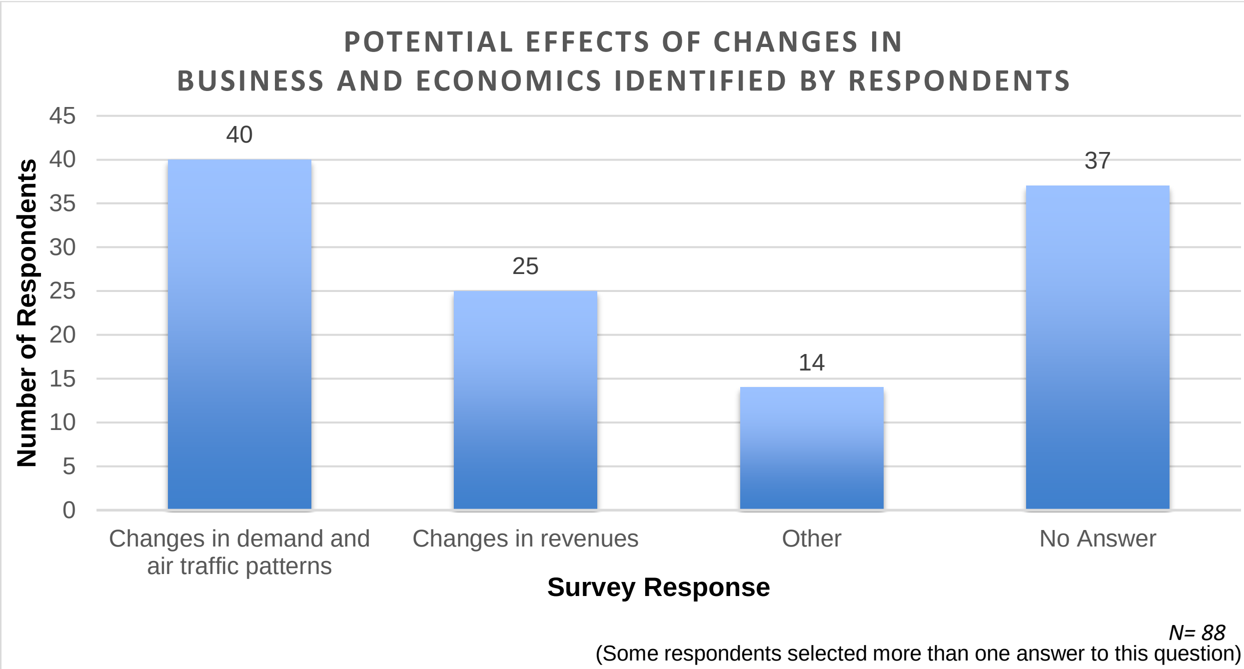

Figure 41: Potential effects of changes in business and economics identified by respondents

The main effects that respondents expect to experience are changes in demand and air traffic patterns and changes in revenues. Thirty-seven respondents answered "no answer", reflecting the proportion of respondents that do not expect to be affected, but possibly also indicating broader uncertainties regarding this impact.

Many respondents gave more than one answer. The respondents who selected "Other" identified: "Airport operations (e.g. temporary closure, delays, etc.)", "reduced revenue due to increased charges/fees", "changes in risk assessment and insurance needs", "energy security and increased energy costs", "cancellation of flights due to bad weather", "population growth", "not yet affected" (2 respondents), and "not applicable". One response was unspecified.

6. Analysis of Impacts Which Stakeholders Expect to be the Biggest Challenge

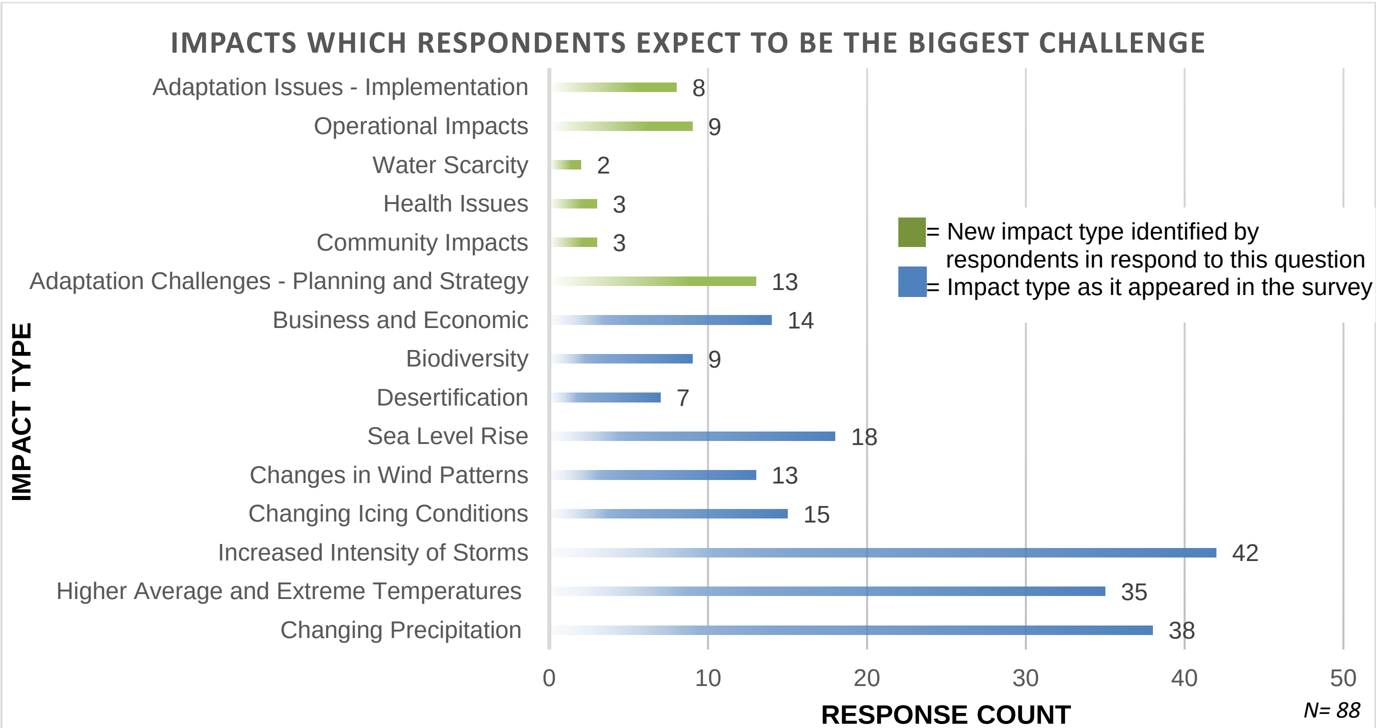

Figure 42: Impacts which respondents expect to be the biggest challenge

The impacts which most respondents expect to be the biggest challenges are increased intensity of storms (42 respondents), changing precipitation (38 respondents), and higher average and extreme temperatures (35 respondents).

This question was an open question and so respondents were able to list their individual top three challenges. Many impacts which respondents listed fit into the impact categories previously determined. However, others addressed different challenges. These were grouped according to the impact types in green in Figure 42. For example, “Adaptation challenges – planning and strategy” included responses such as increasing the level of knowledge regarding climate impacts on air navigation services, and identification of lack of finance, whilst “Operational Impacts” included responses such as operational disruption due to adverse weather and concerns about an increase in Clear Air Turbulence (CAT).

7. Synthesis of Information on Risk Assessment Methodologies and Progress

7.1 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. As depicted by the ITF (2015), this is an analysis of impact x probability equating to risk or "what can happen?", "How likely is that?" and "what are the consequences?" (p.7). In order to carry out a risk assessment, it is important to identify the scope. For example, the scope could be at the organisation level, sub-organisational 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. Organisation and coordination with the appropriate entities is also important to carrying out a climate change risk assessment. One respondent to the survey stated that while they have completed a risk assessment, the work has been fragmented and still needs to be consolidated so it can be used for decision making. Communication is also an important component of risk assessment planning. At least one airport respondent is waiting to conduct an assessment specific to their airport because they have an understanding that there will be a national-level assessment that will cover aviation completed by the State government. Communication ensures that work is not duplicative.

To carry out a climate change risk assessment an organisation can either choose to use its existing risk assessment methodology, use a climate change risk assessment methodology or tool developed by another organisation, or develop its own climate change risk assessment.

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).

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 organisation 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 organisational level as appropriate, for example at sub-organisational 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. 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 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.).

Although the generic steps are similar, methodologies will need to be fine-tuned for different types of organisations. For example, the same ARCP Synthesis Report quoted above also states, 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).

It may be beneficial to include key stakeholders in the risk assessment and planning process (LHR, 2011).

3) Review and repeat the assessment periodically

All risks should be monitored regularly. Review and revise the assessment as new information becomes available (NATS, 2011; ACRP, 2012). As SESAR[1] (2012) stated, this will “serve to monitor progress of actual events versus predictions, and give a periodic re-evaluation of the climate change risks" (p.25).

7.2 Progress on Climate Change Risk Assessments Survey Analysis

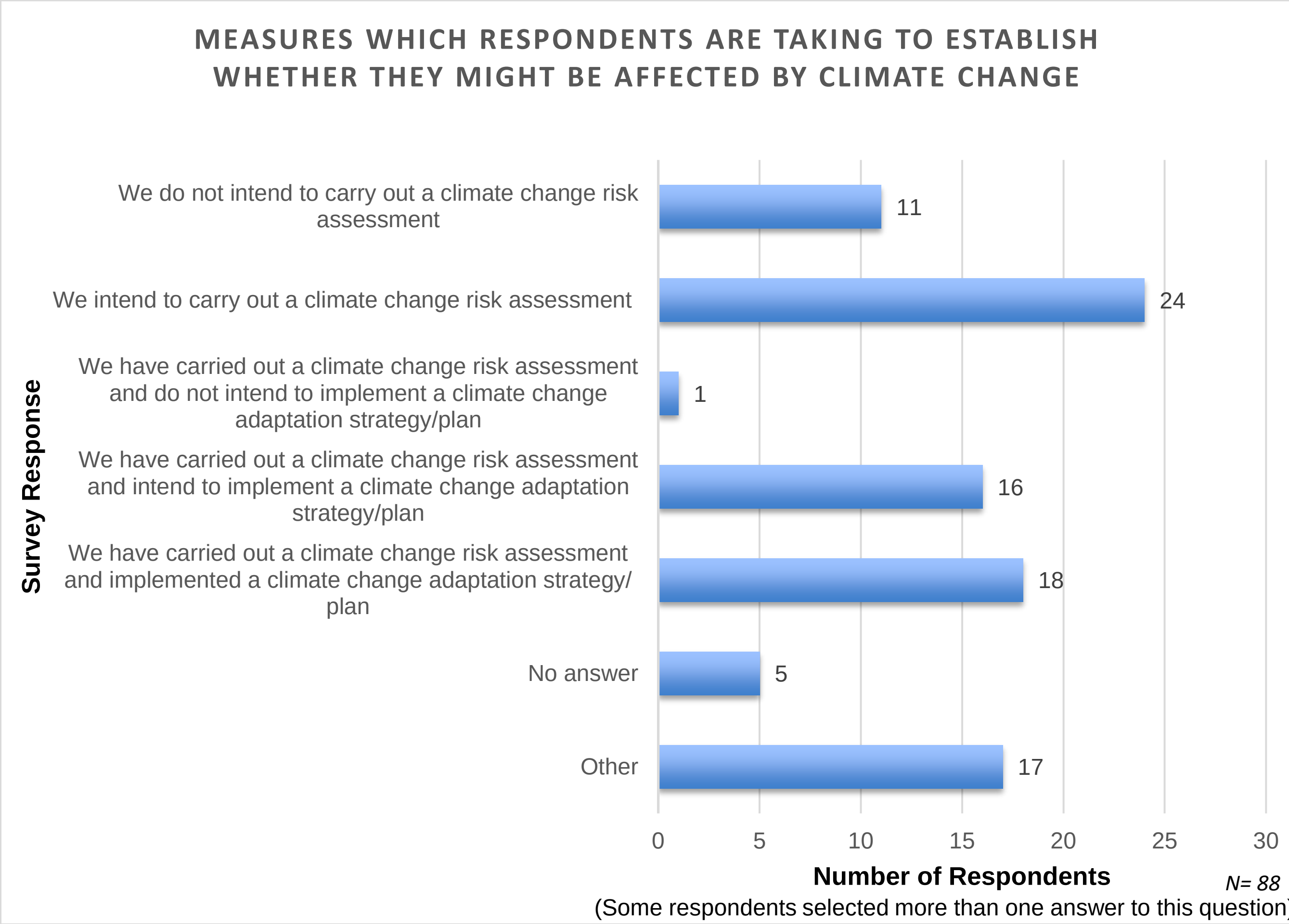

Figure 43: Measures which respondents are taking to establish whether they might be affected by climate change

This was a multiple-choice question with the option to add additional responses. Thirty-five respondents indicated that they have carried out a climate change risk assessment. Only one respondent indicated that following the risk assessment they would not be implementing a climate change strategy or plan. The other 34 respondents have either already implemented or intend to implement a climate change strategy or plan. Twenty-four respondents intend to carry out a risk assessment whereas 11 respondents do not intend to carry out a risk assessment. However, nine of those responses were from the same State and some indication was given that they do not intend to carry out a risk assessment because the risk assessment may be carried out at State level rather than individually. However, this could not be confirmed.

In some cases, respondents gave more than one answer and both have been included. Respondents that answered 'Other' included "no decision has been taken yet", "we expect it to be done in the near future," "no risk assessment carried out", and "not yet".

For this question, all respondents were asked to explain their answers; they gave a variety of answers. In several cases respondents indicated that climate change risk assessments and adaptation strategies had been carried out at the national level. However, it was not always clear whether or not these risk assessments or strategies looked specifically at, or included the aviation sector. Given the context of the survey, when it was not specified, it was assumed that a national-level risk assessment, strategy or plan was relevant to the aviation sector.

Eighteen of the **respondents that have carried out a climate change risk assessment and implemented a climate change adaptation strategy or plan** provided information on the adaptation strategy developed. Some of these 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 into other governing bodies. Since transportation is a highly interconnected sector, at least one State recognized the importance of a risk assessment that covers air, sea, and land transportation modes. One airport operator has developed plans and procedures to address weather disruptions based on their risk assessment.

Sixteen **respondents that have carried out a climate change risk assessment and intend to implement a climate change adaptation strategy or plan** gave details of the risk assessments they have carried out and the strategies they intend to implement. The respondents to this question covered the entire timeline for implementation. At least one State is in the proposal stage for its adaptation plans, while another has already integrated climate change risk assessments into existing plans but also plans to create a standalone adaptation plan. Some States have national-level climate risk assessments and adaptation strategies that are not specific to aviation. For example, one State recognized that its risk assessment considered all government sectors, but it did not have accurate data specific to the risk to aviation operations. Another State explained that while it does not have a climate change risk assessment or strategy, it does have assessments and plans regarding employee and passenger health, and flight safety.

One respondent that **had carried out a climate change risk assessment and does not intend to implement a climate change adaptation strategy or plan** explained that a national climate adaptation plan has been implemented, but nothing specific to the aviation sector.

Twenty-four **respondents intend to carry out a climate change risk assessment** and gave details of the assessments that are planned. Some of these risk assessments will be climate change specific, while others will include climate change as one of many environmental risks (e.g., noise, water, air pollution). Some respondents seem to be waiting on national-level action to be taken first before conducting an aviation-specific assessment, or they now intend to carry out an aviation-specific plan as a result of a completed national-level plan. For example, one State indicated that a national-level assessment is in progress and an aviation-sector specific assessment may follow. Some States noted specific climate impacts they want to include in their assessment (e.g., changing precipitation, increased frequency of storms). To complete a risk assessment, two State respondents plan to form a team or working group, and one airline respondent recognized the need for data and analysis covering the short and medium time frames.

The eleven respondents that **do not intend to carry out a climate change risk assessment** were either individual airports that believed a national-level risk assessment was planned and therefore they did not plan to conduct an airport specific assessment, or were States that did not have any plans to conduct a risk assessment.

8. Synthesis of Information on Adaptation Planning

8.1 Information on Adaptation Planning from Literature Review

If an organisation 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. This may include incorporating climate risk considerations into planning and organisational decision-making so as to “better define the problem from a corporate or enterprise perspective”, as described by ACRP (2012) (p.51).

The ACRP (2012) recommended airports to 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, 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 may also be important, 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). It was also noted that in at least one example having to face real climate impacts has helped adaptation planning efforts to evolve (Ibid.).

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).

8.2 Analysis of Survey Responses

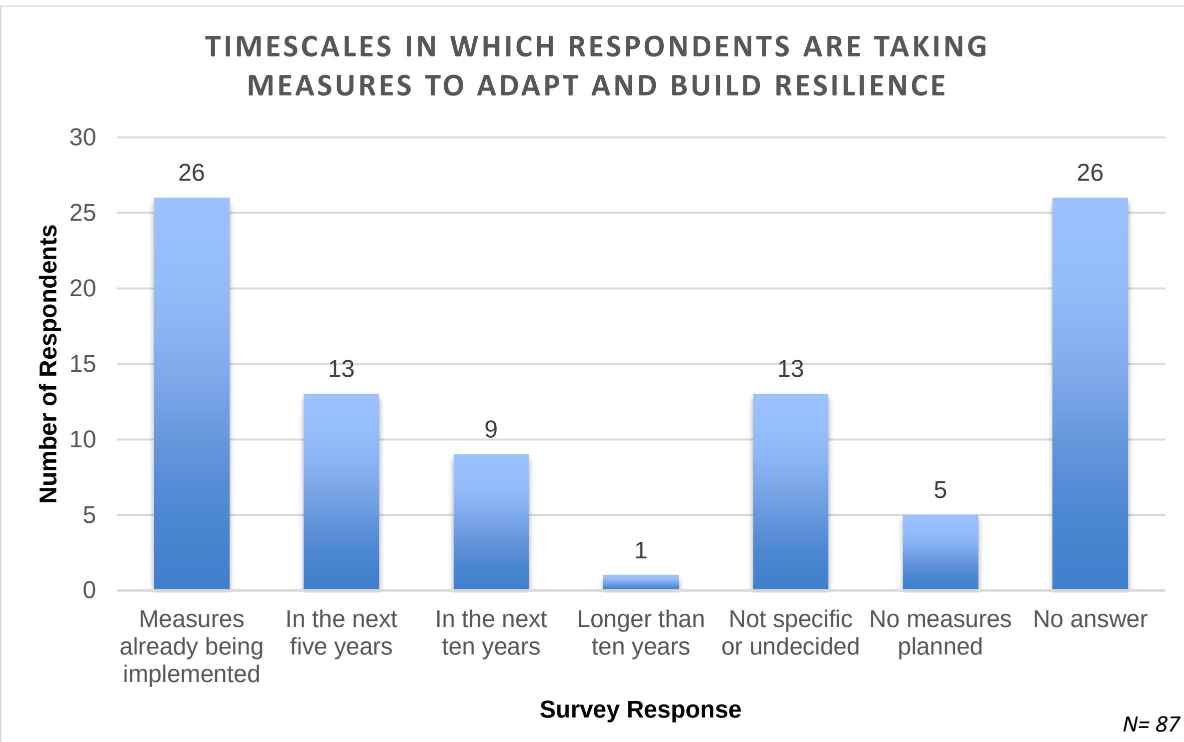

Figure 44: Timescales in which respondents are taking measures to adapt and build resilience

The timescales in which respondents indicated they are taking measures varies widely from "measures already being implemented" (26 respondents) to "no measures planned" (5 respondents). Several respondents either did not specify the time frame in which they would be taking measures or were undecided as to when they would take measures (13 respondents).

One response referred to greenhouse gas mitigation and thus was not included.

9. The Global Aviation Sector and Adaptation to Climate Change

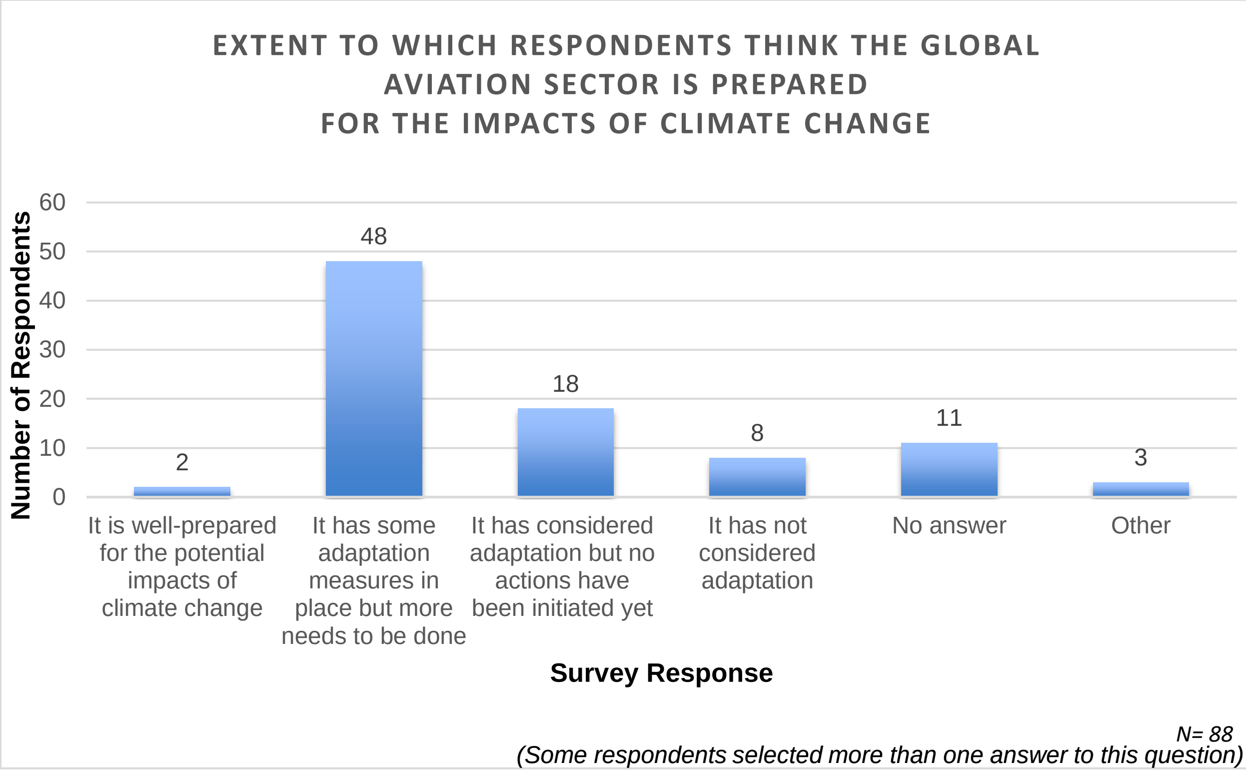

Figure 45: Extent to which respondents think the global aviation sector is prepared for the impacts of climate change

Some States provided more than one response and in this case both answers have been included. The majority of respondents consider that the global aviation sector has some adaptation measures in place but that more needs to be done. Just two respondents think that the sector is well-prepared for the potential impacts of climate change, but both of these respondents selected more than one answer and also responded that the sector has some adaptation measures in place but more needs to be done. Eighteen other respondents either responded that the sector has considered adaptation but not initiated any actions and eight respondents have not considered adaptation.

Several responses to this question seemed to focus on greenhouse mitigation rather than, or as well as, adaptation. Explanation of responses which exclusively refer to mitigation have not been included in the examples below.

Two States responded that **the global aviation sector is well-prepared for the potential impacts of climate change,** for which one State explained that this is because the aviation sector has many international agreements and regulations, but it is not clear if that referred to climate adaptation international agreements and regulations, or to climate change mitigation. The second State provided an explanation that was clearly rooted in the actions the international community has taken for climate mitigation. It is also important to note that both of these States also selected the option that the aviation sector has some adaptation measures in place but more needs to be done.

Respondent's Voice

Q: Is the global aviation sector prepared for the impacts of climate change?

A: Guidance material has been developed but training and raising awareness should be conducted as well. (State)

Raising awareness and capacity building for climate change among community and aviation stake holders, and promote environment friendly strategy. (State)

Forty-eight respondents think that **the global aviation sector has some adaptation measures in place but that more needs to be done.** Respondents stated that while the international community has engaged in efforts to address climate change mitigation, more attention needs to be given to climate change adaptation. Respondents recognized that while some work has been conducted at the State or regional level, more coordination globally on this issue is needed. In addition to more coordination, a better understanding of what the specific vulnerabilities from climate change may be is needed, along with more awareness, training, and capacity building for climate change within the aviation community and its stakeholders. Some respondents recognized that the aviation sector may be further along in implementing climate change adaptation measures and in a better position to adapt compared to other global sectors. One State suggested that more needs to be done at the international level to encourage climate change adaptation at the State and local levels. Another State proposed that the State Climate Action Plans should include adaptation to climate change.

Respondent's Voice

Q: Is the global aviation sector prepared for the impacts of climate change?

A: The aviation sector is not yet aware of its vulnerability. (State)

Eighteen respondents said **the global aviation sector has considered adaptation but no actions have been initiated**. Some States responded that the aviation sector has begun considering climate change adaptation in their aviation sectors, but are only at the beginning and no actions have been taken. Another State indicated that climate change adaptation has only recently become a subject of consideration. One State described various climate change impacts that it anticipates being a concern for the global aviation sector and suggested that the work within ICAO needs to be strengthened to support adaptation. Another State mentioned the international attention the global aviation sector is giving to this topic by including discussions on it in the agendas for ICAO and other international organisations.

Respondent's Voice

Q: is the global aviation sector prepared for the impacts of climate change?

…the aviation industry needs to be prepared to face severe alterations due to climate change, needing to make use of clean technologies and adaptation actions, bearing in mind that high temperatures will affect the ability of aircraft to fly, increase turbulence during the flight, there will be freezing incidents and sandstorms that can seriously threaten the engines. While rising sea levels will affect airports, especially those in island countries, which will also be affected by the increase in strong winds that will prevent aircraft from landing safely. (State)

Eight respondents think that **the global aviation sector has not considered adaptation.** All eight of these respondents came from States. One cited a lack of international regulatory requirements on climate adaptation for aviation and another did not have any knowledge of measures or plans for climate adaptation. Another State responded that the global aviation sector has not considered adaptation because it does not know it is vulnerable to climate change.

9.1 What the Global Aviation Sector is Doing Well

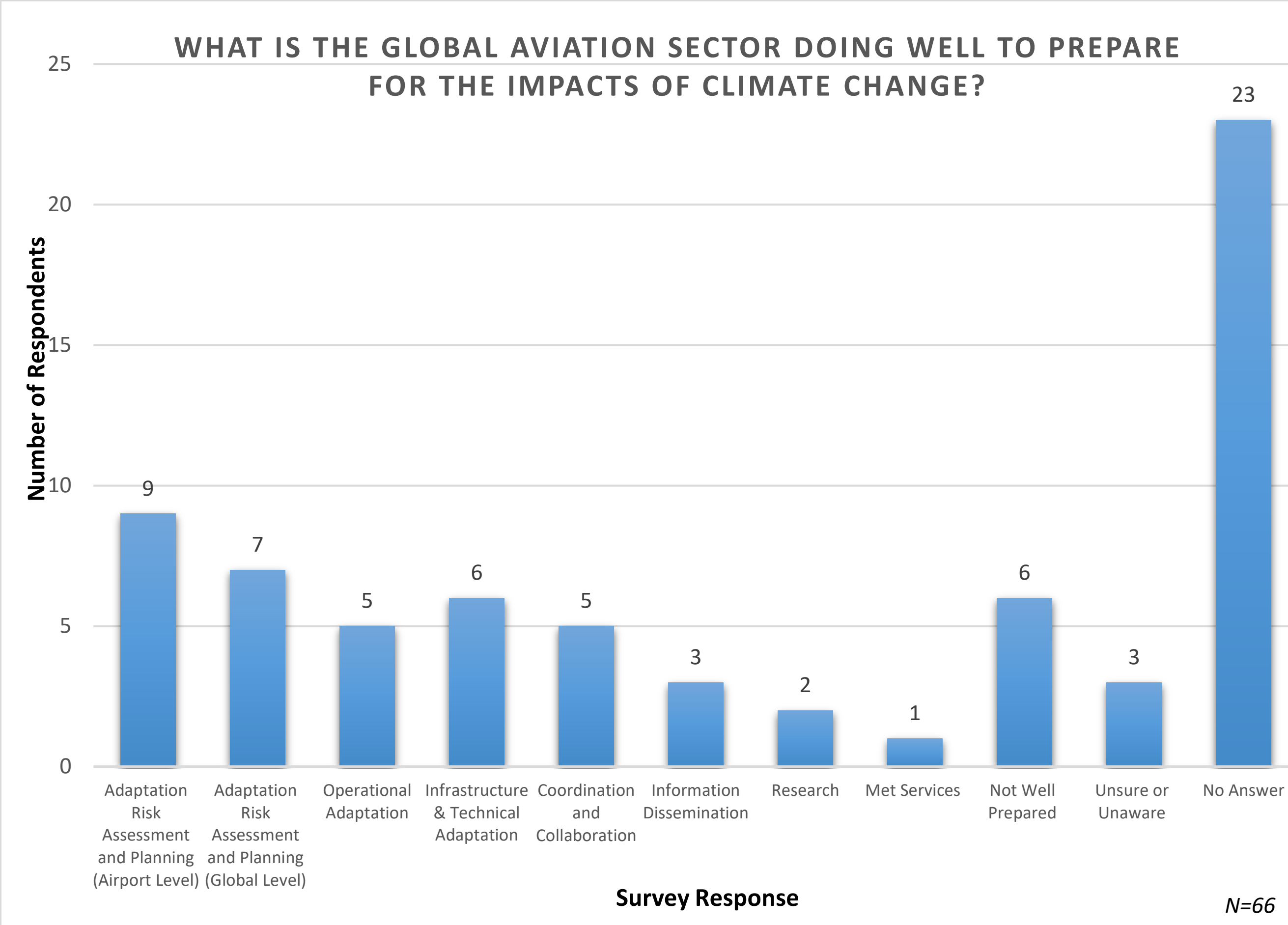

Figure 46: What is the global aviation sector doing well to prepare of the impacts of climate change? ***(Note: 22 respondents stated that the global aviation sector is preparing for the impacts of climate change by engaging in climate mitigation actions, since this answer did not address adaptation, these responses were omitted for this analysis, making the total number of respondents for this question 66.)***

The things that respondents think the global aviation sector is doing best to prepare for the impacts of climate change include adaptation and risk assessments at both airport and global levels (Nine respondents and Seven respondents) and Infrastructure and Technical Adaptation (Six respondents). However, six respondents indicated that they think the sector is not well-prepared, three were unsure or unaware and 22 answered “don’t know”, possibly indicating that for some respondents there are still some uncertainties regarding this issue. Some answers indicated that a lack of regulation or understanding of climate change impacts and adaptation for the aviation sector may contribute to uncertainties.

This was an open question and respondents gave a range of answers which have been grouped into the following categories. A small number of responses referred solely to climate change mitigation and have not been included. Some answers could be interpreted as also talking about things that the global aviation sector should do. They have been included in the categorisations as they were given as answers to the question. However, when the interpretation is ambiguous they have not been included in the examples below.

Risk Assessments at the airport level and global level were given as examples by sixteen respondents as something the global aviation sector is doing well to prepare for the impacts of climate change. This assessment broke out these risk assessment examples into two different categories **Risk assessment and Adaptation planning: Airport level** and **Risk assessment and Adaptation planning: Global level.** At the airport level, State respondents indicated that airports throughout their aviation systems have been conducting their own risk assessments. At the global level, State respondents discussed the importance of international coordination efforts including ICAO's 2016 Environmental Reports. Climate adaptation was also considered by one State as part of disaster readiness plans.

Respondent's Voice

Q: What is the global aviation sector doing well to prepare for the impacts of climate change?

Airport Level Adaptation Planning:
We see a lot of good examples of risk assessments carried out. We believe such assessments are the most important basis for a rational approach to climate adaptation. (Airport)

Global Level Adaptation Planning:
The global aviation sector is rolling out disaster readiness plans to respond to all possible contingencies.
(State)

Five respondents gave examples of **Operational Adaptation** air traffic actions that have been taken into account for climate change, including Severe Weather Avoidance Programs (SWAP). One State respondent said that while operational adaptation measures have been implemented, this work will be on going.

Respondent's Voice

Q: What is the global aviation sector doing well to prepare for the impacts of climate change?

A: The global aviation sector is doing well at sharing and learning from operators in other parts of the world who experience extremes in weather conditions. (State)

A: The aviation sector is doing well at coordinating internationally on this topic through ICAO. (State)

Six respondents gave examples of **Infrastructure and Technical Adaptation** actions that have been taken to address climate change impacts. Infrastructure actions include incorporating features to address specific climate change projections into the design of new or existing infrastructure. Another State has developed a tool to help airport operators assess their vulnerabilities to climate change.

Respondent's Voice

Q: What is the global aviation sector doing well to prepare for the impacts of climate change?

A: Seminars, workshops and conferences to improve the understanding and the ability to address the needs of the aviation sector is being carried out in all the regions of the world. (State)

Five respondents addressed actions specific to **Coordination and Collaboration** that they believe the global aviation sector is doing well. Generally speaking, respondents felt that coordination and collaboration internationally has been positive on this topic, particularly with regards to the work within ICAO. Some respondents also indicated that collaboration and coordination between States regionally and within States locally has been successful. Some respondents emphasized that current coordination and collaboration has been good but needs to be improved or increased.

Three respondents provided **Information Dissemination** examples as something they believe the sector is doing well with regards to climate change adaptation. Two State respondents spoke to the advances in **Research** as something the aviation sector is doing well to adapt to climate change. Both respondents focused on changing weather events as a result of climate change, rather than on long term projections.

Respondent's Voice

Q: What is the global aviation sector doing well to prepare for the impacts of climate change?

A: Research and development into prediction capability, mitigations and contingency for extreme weather, including in-flight weather hazards. (State)

A: Research and development related to changes in deicing. (State)

Respondent's Voice

Q: What is the global aviation sector doing well to prepare for the impacts of climate change?

A: The aviation sector does not appear to be prepared for the long-term effects of climate change. (Airline)

One State responded stated that **MET Services** are an example of something the aviation weather service providers are doing well to prepare for some of the impacts of climate change by developing new methods for advanced planning and forecasting.

Six respondents stated that they believe the global aviation sector is **Not well prepared** for the impacts of climate change. Respondents either felt there has not been enough consideration for the long-term projections of climate change or simply stated that the sector is not well prepared for climate adaptation with no further explanation.

Three respondents were **Unsure or Unaware** of any actions the global aviation sector is taking to prepare for the impacts of climate change. Some of these respondents stated that they are aware of the actions that are being taken in the sector to mitigate climate change by reducing greenhouse gasses, but did not have any knowledge of climate adaptation actions.

9.2 What the Global Aviation Sector Could Do Better

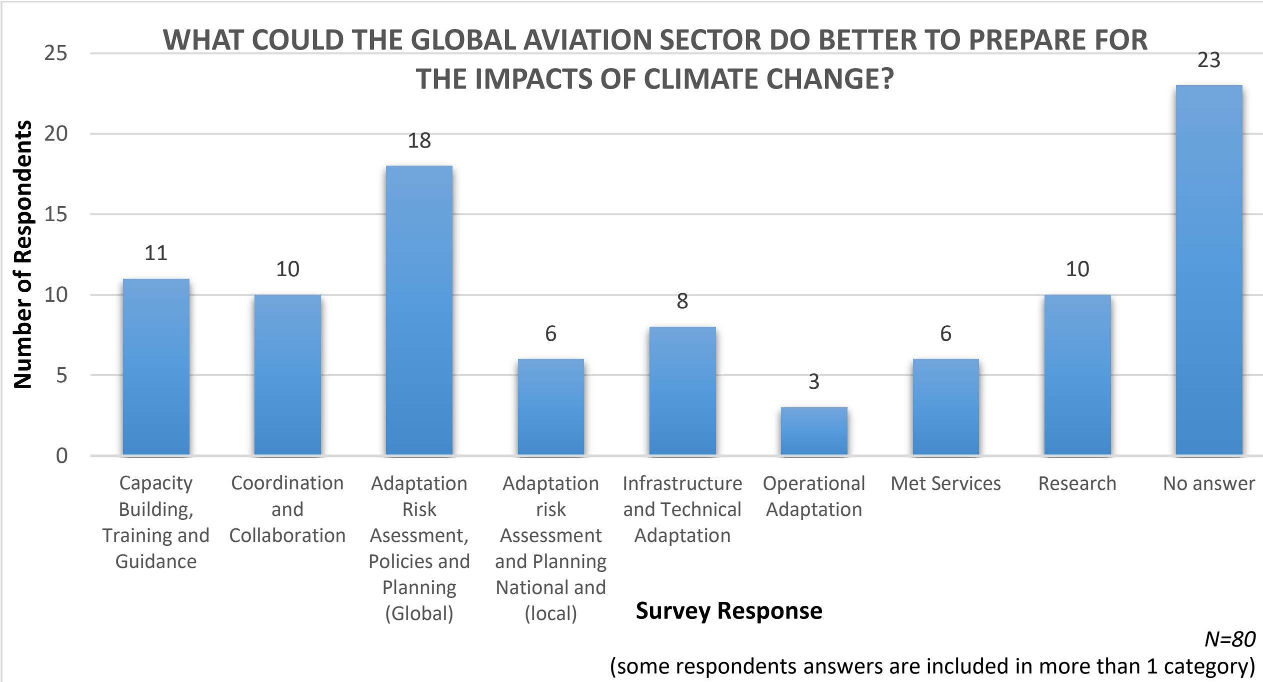

Figure 47: What could the Global Aviation Sector do better to prepare for the impacts of climate change? ***(Note: 8 respondents gave answers specific to climate change mitigation. Since these answers did not address adaption, they have been omitted, making the total number of respondents for this question 80.)***

When respondents were asked what they think the global aviation sector could do better to prepare for the impacts of climate change, the measure that was identified as most important was the development of adaptation risk assessments, policies and planning at the global level (18 respondents). Six respondents also referred to measures which could be categorized as adaptation risk assessments, policies and planning at the national or local level. However, as the question specifically asked about action at the global level this is more likely to have been respondents' focus. Capacity building, Training and Guidance (11 respondents) and Coordination and Cooperation (10 respondents) were also identified as important measures by respondents.

This was an open question and respondents gave a range of answers which have been grouped into the following categories. Eight responses referred solely to mitigation actions and have not been included.

Eleven respondents identified improvements that could be made in **Capacity Building, Training and Guidance** to better prepare for the impacts of climate change. These respondents proposed that at an international level there needs to be more support, information and awareness-raising for States to help them to prepare and adapt their aviation sectors to the potential impacts of climate change. In general, States suggested awareness-raising about the latest science in climate change and how it may affect aviation through a variety of methods including guidance, training, conferences, seminars, and Webinars. Some respondents also noted that some States may need assistance in the form of expertise for capacity building and adaptation planning

.

Ten respondents identified ways in which **Coordination and Collaboration** could be improved to better prepare the global aviation sector for the impacts of climate change. These responses referred to coordinated actions between States and at a global level, and collaboration between all stakeholders to prepare for and address the impacts of climate change, suggesting that measures are more effective when they are not made in isolation, especially given that climate change is a global challenge. One State also highlighted that adaptation is not solely an environmental issue so coordination is also needed with operational, safety and infrastructure experts.

Respondent's Voice

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

A: "Promote awareness at global level" (State)

A: "Place a special emphasis to make sure that no one is left behind." (State)

A: "Particular information should be disseminated on the results of the investigations concerning projections of the extent to which air operations will suffer (wind strength, changes in the frequency of precipitation, increases in temperatures, etc.)" (State)

Respondent's Voice

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

A: Focus on the [projected climate change] impact for aviation safety as well as on the local impact geographically. (State)

Eighteen respondents identified ways in which **Global Adaptation Risk Assessment, Policies and Planning** could be improved on. Responses in this category referred to the need to develop an adaptation response for the sector at a global level, so as to have a coherent set of policies and plans to address the challenge from a global perspective. It was suggested that this would also support individual States in developing their own adaptation policies and plans.

It was also highlighted that climate change is not solely an environmental issue and needs to be addressed in a range of fora. Additionally, while the survey was focused on questions regarding climate adaptation, some respondents expanded their answers to include climate change mitigation by noting that limiting climate change as much as possible by reducing emissions could also be an effective strategy to reduce potential adaptation requirements.

Respondent's Voice

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

A: Work with meteorological services to better plan and prepare in advance. (State)

A: Participate more effectively in the collection of meteorological data on international routes to form a basis for forecasting, studies and climatology. (ANSP)

Six respondents identified ways in which **National or Local Adaptation Risk Assessment, Policies and Planning** could be improved to help the global aviation sector better prepare for the impacts of climate change. These respondents referred to the need to look at adaptation from a local *in addition to* a global level. It was proposed that adaptation should be integrated into the planning and implementation of infrastructure design. The need to find financial means to support adaptation was also highlighted.

Respondent's Voice

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

A: A lot of the work considering climate adaptation is often carried out far down in the organisations and in many cases not properly anchored. We see that to increase the focus, this topic should be lifted up to the top levels and that someone is given the role of climate adaptation advisor. (Airport)

A: Realistic contingency plans should be provided but simultaneously financial means should be secured in advance via insurance like processes. (State)

Eight respondents offered ideas on improvements to **Infrastructure and Technical Adaptation** to better prepare the global aviation sector for the impacts of climate change. These respondents identified the need to both make infrastructure improvements so as to be more resilient to the potential impacts of climate change, e.g. strengthening infrastructure, and also at looking for technological solutions e.g. in the manufacture of aircraft.

Three respondents suggested ways in which **Operational Adaptation** actions could be taken to better prepare the global aviation sector for the impacts of climate change. These respondents identified the need to develop operational measures to improve resilience to climate change, also at a local level, and the need to develop early warning systems. Once again, the need to consider safety implications was raised.

Six respondents offered ways in which **Met Services** can be better utilized to prepare for the impacts of climate change. These respondents talked about the specific role which MET Services have to play in building resilience to climate change. They highlighted the need to collect more MET data to inform both forecasting and studies, to better understand what MET capabilities are available and to improve them where required, and to work with MET Services. The review and potential updating of meteorological minima in light of potential changes in weather norms was also highlighted as key, and again has links with safety.

Ten respondents identified the need for more **Research** to help to identify both risks and responses. Their responses focused on the need to improve the understanding of the risks to climate change for the sector, monitoring of changes in climate and the development of modelling techniques to forecast impacts. This research can then be used to develop and improve adaptation measures. It was highlighted that research will need to be carried out for the different elements of the sector, such as en-route, but that an interdisciplinary approach will also be required.

Respondent's Voice

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

A: Promote research and financing frameworks on accurate forecast and simulation models in order to support both investment and stakeholders driven. (State)

A: Airlines require data modeling on expected weather changes. (Airline)

A: Basic and applied interdisciplinary work will need to be conducted both in terms of integrated climate-impact modelling and socio-economic issues. A better knowledge of the impacts of climate change on meteorological conditions for en-route navigation would also be useful in order to adapt and prepare the air navigation infrastructures and procedures. (State)

10. Conclusion

This report has presented a synthesis of relevant, recent 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 scientific information from the IPCC AR5, a broad literature review, and responses from a survey on climate change adaptation and resilience which was distributed to aviation sector stakeholders via a State Letter and CAEP Memo. The IPCC AR5 and the documents reviewed during the literature review provided an 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 expected to be affected by a range of these impacts, and to what extent they consider both their organisation and the global aviation sector are prepared for the effects that climate change impacts may have on aviation.

One of the key findings from the survey analysis was that 65 of 88 respondents (74 percent) have found that their aviation sectors are already experiencing some impacts of climate change while 15 of 88 respondents (17 percent) expect their aviation sectors to be impacted by 2030. Just three respondents expect to be impacted after 2030 whilst 12 of 88 respondents (14 percent) answered that they do not know if they will be impacted. None of the respondents answered that they did not expect to be impacted 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 organisations with an interest or concern in climate change impacts on aviation.

Potential climate effects on the aviation sector were identified for eight climate impact categories: sea level rise, increased intensity of storms, temperature change, changing precipitation, changing icing conditions, changing wind, desertification and changes to biodiversity. For each impact 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 the expected impacts varied between ICAO regions, the three climate impact 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 the literature review, a climate change risk assessment should be conducted to determine where vulnerabilities to climate change may exist, before an organisation develops a climate change adaptation strategy or plan. Although 65 of 88 respondents to the survey (74 percent) are already experiencing some impacts of climate change, with a further 15 of 88 respondents expecting to be impacted by 2030 (17 percent), fewer have begun taking measures to address those potential impacts. The timescales in which respondents indicated they are taking measures to adapt to the impacts of climate change vary widely with 26 of 88 respondents (30 percent) indicating that they are already implementing measures and 22 of 88 respondents planning to do so in the next five to ten years. (25 percent). Five of eighty-eight respondents indicated that they have no measures planned (6 percent). Several respondents either did not specify the time frame in which they would be taking measures or were undecided as to when they would take measures.

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 organisational level, to the local or State government level. Climate change adaptation can also provide different degrees of resilience; it will be up to individual organisations 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 organisational level.

When asked about the level of preparedness of the global aviation sector for the impacts of climate change, the majority of respondents stated that the global aviation sector has some adaptation measures in place but that more needs to be done. Respondents recognised the global sector has engaged heavily in climate change mitigation efforts, but thought that more effort should now be given to climate change adaptation, and that while some work has been conducted at the State or regional level, more coordination globally on this issue may also be needed. Many respondents identified the need for more awareness-raising, training, and capacity building, as well as increasing our understanding of what the specific vulnerabilities for the sector might be. Respondents also thought that the development of adaptation risk assessments, policies and planning for resilience at the global level could be required. However, while global adaptation risk assessments and policies were raised as general recommendations, neither the survey results nor the literature review provided any concrete direction on how this could be done in a way that would be both effective and globally applicable.

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 effects the projected impacts may have on aviation. Many States and organisations are beginning to take action to build resilience. In addition to State and organisational-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
ATC	Air Traffic Control
ATM	Air Traffic Management
BFE	Base Flood Elevation
CAEP	Committee on Aviation Environmental Protection
CAT	Clear Air Turbulence
CBA	Cost Benefit Analysis
CO_2	Carbon Dioxide
DFW	Dallas/Fort Worth International Airport
EUROCONTROL	European Organisation 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 Organisation
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	IPCC Fifth Assessment Report
ISG	Impacts and Science Group
ITF	International Transport Forum
MET	Meteorology
Met Office	Meteorological Office
NATS	National Air Traffic Control Services
NO_x	Nitrogen Oxide
PIREP	Pilot Weather Report
RDM	Robust Decision Making
ROA	Real Option Analysis
RVSM	Reduced Vertical Separation Minima
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
WBA ICAO	World Birdstrike Association

WGI	Working Group 1 (IPCC)
WG2	Working Group 2 (ICAO CAEP)
WGII	Working Group 2 (IPCC)

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