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A GLOBAL APPROACH TO ASSESSING THE CLIMATE RESILIENCE OF AIRPORTS

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Abstract

The results of assessing the climate resilience of eight representative airports are presented to demonstrate how recent ICAO guidance on climate resilience can be applied consistently to better inform airport managers. The approach uses the sixth iteration of IPCC climate projections to specify climate conditions in terms of event thresholds that can be directly associated with consequences and hence, the climate risk to airport operations. This is a step change from existing methods of assessing the climate resilience of airports which tend to refer to more general statements such as “average summer temperatures may increase by 3-5°C” from which a general list of consequences is identified. This step change is in line with ICAO guidance. The results of testing the method with eight globally representative airports are also presented, illustrating how this method can be used to provide a consistent assessment of climate risk for airports around the world. This is considered not only useful for assessing physical risks at individual airports but also for assessing the potential loss of revenue associated with climate related disruption at destination airports.

Keywords: climate resilience, risk assessment, Climate Resilience Assessment of Airports Tool (CRAAT)

1. Introduction

> “*A climate resilient airport is one that has taken steps to prepare for the challenges that climate change and severe weather bring. Airport planning is conducted for many reasons, and they increasingly include consideration of the risks and impacts associated with climate changes and plans for future climate conditions.*” [1]

Since at least 2016 the International Civil Aviation Organisation (ICAO) has identified climate adaptation and resilience as a key topic for concern. This has recently culminated in the 2021 Eco Airport Toolkit on Climate Resilient Airports, from which the above quotation is taken.

The ICAO toolkit provides a framework methodology for airport stakeholders including managers, owners, operators, airlines and governments, to identify and assess the risks that changes to different climatic conditions may have on airport operations, maintenance and future design changes. This methodology is based on the following steps:

1. *Develop a project team and identify stakeholders that may include airlines, tenants, community members, and others. External partners such as local utilities and transportation agencies may also play critical roles in airport resilience.*
2. *Research climate projections for the location and understand the risks they pose to airport assets and operations.*
3. *Prioritise those risks based on the comparison of risk and exposure.*
4. *Consider short and long term adaptation strategies that can minimise risk and exposure.*
5. *Develop a climate adaptation plan to mitigate the expected effects on operations and infrastructure at the airport. This may include integrating actions into airport planning documents and procedures to enhance resilience.*
6. *Measure and track actions as they are implemented in order to report on their success. Some may be easy to assess with metrics, others may be qualitative in nature.*

In this paper we describe the Climate Resilience Assessment of Airports Tool (CRAAT) developed to support airport operators in undertaking the above steps. In particular, we describe how future climate data has been assembled and defined in a way that relates directly to airport specific climate-related event risks. We then go on to describe how we have tested the CRAAT methodology on a number of airports around the world to demonstrate robustness and to highlight some of the benefits of using a consistent approach based on location-specific climate data.

2. Extending the methodology

The CRAAT methodology for assessing the climate resilience of airports is illustrated below in Figure 1, noting the inclusion of climate projection data specific to the airport and some adaption from the ICAO methodology to assess residual risk after including implementation of control measures.

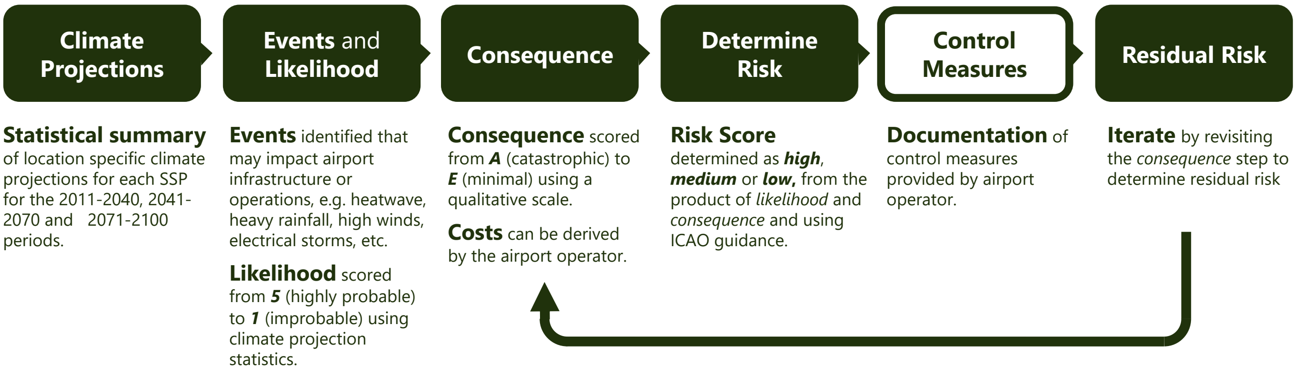
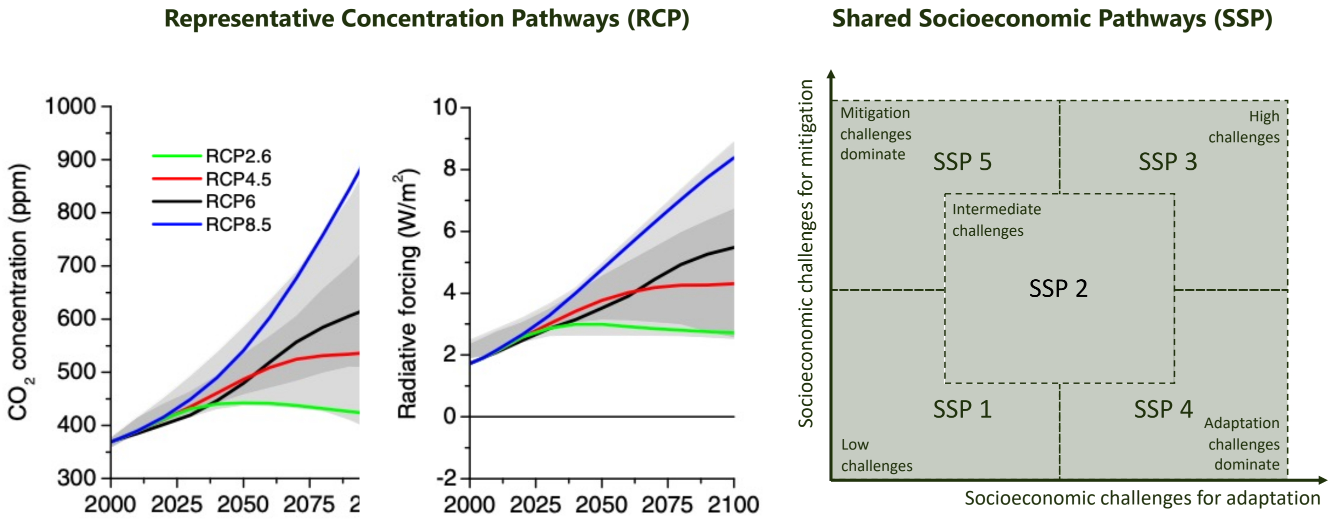


Figure 1 – CRAAT method for assessing the climate resilience of airports.

In undertaking a climate risk assessment, the first step is to decide which future climate scenarios are relevant and which future climate periods fit best with wider airport planning objectives. In drawing together a global body of research into the causes and effects of climate change, the Intergovernmental Panel on Climate Change (IPCC) refers to two interlinked sets of scenarios; the Representative Concentrations Pathways (RCP) and the Shared Socioeconomic Pathways (SSP) – see Figure 2 [2,3]. RCPs refer to scenarios based on different projections of greenhouse gas concentrations and consequent climate change. SSPs refer to scenarios of socio-economic conditions that would result in emissions giving rise to different greenhouse gas concentrations. Note that SSPs also account for ‘feedback’ in terms of how socioeconomic conditions may be affected by climate change. In terms of climate risk assessment, the most common scenario to consider is the ‘most likely worst case’ known as SSP5-8.5 or “4°C world”. However, we could also refer to SSP1-2.6 (“well below 2°C”), which represents the most likely best case scenario and SSP1-1.9, which is equivalent to meeting the Paris commitment to limiting global warming to 1.4°C. Modelling of climate change for these scenarios has been undertaken by different academic and government research bodies around the world, typically for the period from 1850 to 2300 AD.

To maintain focus in the climate risk assessment, it is common practice to consider existing scenario conditions, a short term future scenario and a longer term future scenario. In describing the climate conditions of each scenario, care must be taken to use data that is representative of the climate during the scenario period and does not reflect extreme or unusual conditions. This is usually done by considering climate as representative of weather conditions over a 20-year or 30-year period, conventionally starting in the first or sixth year of the first decade (year ending with ‘1’ or ‘6’) and ending in the last year of the second or third decade (year ending with ‘0’ or ‘5’). The sixth assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) [4] refers to 20-year climate periods. Introducing flexibility in the tool to select different climate periods is possible but may limit the potential to provide consistent climate risk assessment across airports globally. We are keen to receive feedback on this matter. At this time, the tool uses the default climate periods of: 2011 – 2040 (current baseline); 2041 – 2070 (short term future); and 2071 – 2100 (long term future). Note that some statistics, such as sea level rise, use a reference climate period to report change. In this instance, the methodology determines the change in future scenarios using the current baseline period as a reference.



	SSP 1 Sustainability	**SSP 2 Middle of the Road**	**SSP 3 Regional Rivalry**	**SSP 4 Inequality**	**SSP 5 Fossil-fueled Development**
Technology	• Tech change directed away from fossil fuels, towards efficiency and renewables • Low carbon and energy intensity	• Some investment in renewables but continued reliance on fossil fuels • Medium carbon intensity • Mixed energy intensity; higher in low income countries	• Slow tech change, directed towards domestic energy sources • High energy and carbon intensity in regions with large domestic fossil fuel resources	• Diversified investments including efficiency and low-carbon sources • Low/medium carbon and energy intensity	• Directed towards fossil fuels, alternative sources not actively pursued • High carbon intensity
Environment and natural resource	• Preferences shift away from fossil fuels	• No reluctance to use unconventional fossil resources • Continued degradation	• Unconventional fossil resources for domestic use • Serious degradation	• Anticipation of fossil fuel constraints drives up prices • Environment highly managed and improved in high/middle income living areas	• No constraints on fossil fuel usage • Highly engineered approaches to successfully managing local issues
Mitigation: shared climate policy assumptions	• 2020: transition to globally uniform carbon price by 2040	• 2020: transition to globally uniform carbon price by 2040	• 2020: medium/high income countries transition to global carbon price by 2040 • Other countries start transition from 2030 up until 2050	• Transition to globally uniform carbon price from 2020	• 2020: transition to globally uniform carbon price by 2040

Figure 2 – Representative Concentration Pathways and Shared Socioeconomic Pathways[2,3].

International policy on climate change is developed through the Intergovernmental Panel on Climate Change (IPCC), drawing on evidence from the Climate Model Intercomparison Project, now in its sixth iteration (CMIP6) [5]. This project brings together resources of some 134 climate models from 53 modelling centres around the world, requiring the climate models to be run with an agreed set of input parameters (forcings) and configured to produce a set of standardised output. The results of this multi-model dataset (referred to as the 'CMIP6 multi-model ensemble') were used to inform the sixth assessment report (AR6) of the IPCC, due to be published in full in September 2022 [6].

As part of providing wider climate data services, we have accessed this dataset and can provide location specific statistics describing specific climate conditions that are relevant to an airport manager. Rather than provide these statistics in general terms, we have developed an extensive (and growing) database of specific climate-related EVENTS which have known or expected direct CONSEQUENCES to the operation, maintenance or future design of an airport. For example, knowing the summer may be hotter in the future is only of limited use to a Buildings Manager wanting to know how to ensure a heating, ventilation and air conditioning (HVAC) system continues to function. Far better would be to provide specific statistics such as the likelihood of daily temperatures exceeding 50^{o}C or the likelihood of an extended heatwave. A further example would be to know how much wetter winters might become or the propensity for periods of intense rainfall which may overwhelm existing drainage systems and cause airports to be temporarily operate at reduced capacity.

Examples of EVENTS and possible CONSEQUENCES are provided in Table 1. In contrast to describing climate conditions, such as annual temperature for example, EVENTS are described in terms of whether the climate condition could occur or not. The LIKELIHOOD of each EVENT is determined from the number of modelled years within the relevant climate period that return a result that the EVENT occurred. The number of modelled years is simply the product of the number of climate models providing the relevant data and the number of years within the climate period. Almost 200 EVENTS have been identified to date although, in theory, an unlimited number of EVENTS could be included. When the tool is configured for an airport, the CIMP6 database is interrogated and statistical analysis undertaken to build up airport-specific LIKELIHOOD scores for each EVENT (see Table 2) and for each climate period / scenario.

From experience working with airport operators and reviewing published Climate Resilience Reports, we have included in our database of EVENTS the possible CONSEQUENCES that may occur if an EVENT happens. These CONSEQUENCES are based on either previous experience at an airport if the EVENT had occurred in the past, shared experience at other airports or understanding the technical limitations of, for example, HVAC systems or drainage networks. As a global industry, there is significant potential to learn from others. The future summers at Arlanda, for example, will be already experienced at airports located at lower latitudes. Of course, the potential for cross learning also applies to airports in drier climes who may expect wetter conditions that are already experienced at some airports. We fully expect the database of EVENTS and CONSEQUENCES to grow and to manage that we have designed CRAAT to enable airport operators to select a CONSEQUENCE for each EVENT and provide comments as appropriate. We will regularly review these comments along with other forms of communication to provide updates to the database.

Using specific definitions of EVENTS and associated CONSEQUENCES represents a step change from existing methods of assessing the climate resilience of airports. These tend to refer to more general statements such as "average summer temperatures may increase by 3-5^{o}C" from which a general list of consequences is identified. Although this change does require more detailed discussions at the start of the risk assessment process, our experience suggests it can lead to greater engagement from stakeholders. This is particularly the case when scoring CONSEQUENCES (see Table 3) as this often leads to discussions about previous experiences at the airport and subsequent costs to the business.

TABLE 1 : Example climate EVENTS and potential CONSEQUENCES at airports.

EVENT	**Potential CONSEQUENCE**
Sea level rise > 0.1m	Groundwater raised, impacting on drainage system
Sea level rise > 0.25m	Flooding of runways and taxiways
Storm surge : >= 5 days with high probability of waves > 7m	Localised flooding of local roads and infrastructure
Storm surge : >= 1 day with high probability of waves > 9m	Flooding of runways and taxiways
Maximum daily temperature > 60 °C for > 1 day	Impacts on maximum take-off weight
Maximum daily temperature > 40 °C for at least one period of > 5 days	Impacts on thermal comfort of staff and passengers in terminal buildings and aircraft on stands
Maximum daily temperature > 60 °C for at least one period of > 10 days	Sensitive electronic equipment and mechanical operating mechanisms may fail to operate correctly
Cumulative daily precipitation > 50 mm for at least one period of 3 days	Flooding of car parking infrastructure
Cumulative daily precipitation > 100 mm for at least five periods of 3 days	Exceedance of drainage infrastructure capacity associated with surface (pluvial) flooding events
>1 day with violent storms / hurricanes (>= 31m/s)	Damage to high-sided structures
>5 days of blizzard conditions	Disruption to surface access preventing passengers and staff reaching the airport
>5 days with a high probability of fog	Minor delays as increased spacing for aircraft landing and taking off

TABLE 2 : Describing the LIKELIHOOD of climate EVENTS[1,6].

LIKELIHOOD Level	**Score**	**Qualitative Description**	**Quantitative Description**
Frequent	5	EVENT is expected to occur in most circumstances. Almost certain.	>90%
Occasional	4	EVENT should occur at some time. Possible to occur.	>33% to 90%
Remote	3	EVENT could occur at some time. Possible but not likely.	>10% to 33%
Improbable	2	EVENT may occur in exceptional circumstances. Should virtually never occur.	>5% to 10%
Extremely Improbable	1	EVENT may occur in very exceptional circumstances.	5% or less

Notes:
LIKELIHOOD levels and scores from ICAO guidance [1].
Qualitative and quantitative descriptions based on approximate alignment with IPCC descriptions of likelihood; see AR6 Working Group I Report, page 1-181 [6].

Having scored the LIKELIHOOD and CONSEQUENCE of each EVENT, the next step is to determine the level of risk the EVENT represents. This is done using the ICAO matrix, reproduced as Table 4 for convenience. CRAAT then includes a step enabling the user to consider the uncertainty in estimating the LIKELIHOOD of an EVENT occurring and the uncertainty of knowing the impact of a CONSEQUENCE. This step is introduced to encourage the airport operator to ensure any risk outcomes are robust and able to be challenged.

The final steps in the process are to consider what CONTROLS could be applied, the cost of implementing them and the residual climate-related risk. Note that any CONTROLS applied would not impact on the LIKELIHOOD of an EVENT occurring but would reduce the CONSEQUENCE of that EVENT.

TABLE 3 : ICAO Scoring of CONSEQUENCES[1].

CONSEQUENCE Level	Score	Qualitative Description
Catastrophic	A	A critical event with devastating consequences. Potential or actual disaster for the business. Loss of life.
Hazardous	B	A large event that requires a high level of engagement, special arrangements and effective management. Crisis Management Teams activated.
Major	C	A significant event that requires prompt action to prevent escalation. Can usually be managed under normal circumstances.
Minor	D	An event which can be managed via existing processes. Minor adverse consequences.
Negligible	E	Noticeable event but manageable or absorbed through normal activity.

Notes:
CONSEQUENCE levels and scores from ICAO guidance [1].

TABLE 4 : ICAO Risk Matrix[1].

🟧 High risk
🟨 Medium risk
🟩 Low risk

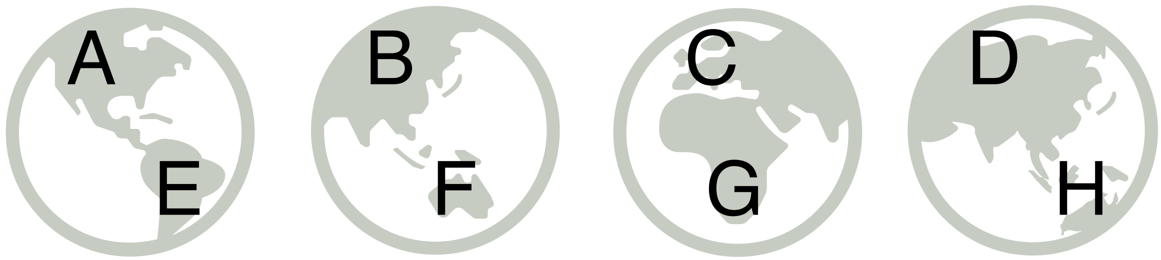
			CONSEQUENCE (severity)				
			Catastrophic	Hazardous	Major	Minor	Negligible
			A	B	C	D	E
LIKELIHOOD (probability)	Frequent	5	🟧 5A	🟧 5B	🟧 5C	🟨 5D	🟨 5E
	Occasional	4	🟧 4A	🟧 4B	🟨 4C	🟨 4D	🟨 4E
	Remote	3	🟧 3A	🟨 3B	🟨 3C	🟨 3D	🟩 3E
	Improbable	2	🟨 2A	🟨 2B	🟨 2C	🟩 2D	🟩 2E
	Extremely Improbable	1	🟨 1A	🟩 1B	🟩 1C	🟩 1D	🟩 1E

3. Selection of representative airports

The tool has been developed in line with ICAO guidance, drawing upon first-hand experience and from published climate resilience studies for airports. To test the tool and to demonstrate its global application, we selected eight airports, nominally representative in terms of geographical spread, size, proximity to the sea coast and altitude; see Table 5. Note that we have anonymised the data as the aim of this study was to demonstrate if the tool works rather than to assess the climate resilience of an individual airport. As a note of interest, we used the search terms “climate change”, “climate change adaptation” and “climate resilience” along with the name of each airport to determine if a climate resilience assessment had been published. Only one out of the eight selected airports has published such an assessment, highlighting the vulnerability of the airport to: sea level rise;

hotter air (limiting take-off weight); additional burden on cooling systems for buildings; more thunderstorms resulting in safety restrictions; and increased frequency of heavy rain causing flooding.

TABLE 5 : Representative airports used to test the CRAAT method.



	A	B	C	D	E	F	G	H
Size[1]	Very large	Medium	Large	Medium	Medium	Medium	Large	Medium
Proximity to coast[2]	Adjacent	Not near	Near	Not near	Not near	Adjacent	Near	Not near
Altitude[3]	40 m	680 m	0 m	40 m	750 m	30 m	10 m	580 m

Notes:

1. Size: defined as *very large* (>700,000 aircraft movements in 2017), *large* (200,000 – 500,000) or *medium* (<200,000)
2. Proximity to the coast: defined as *adjacent to the coast* (< 2km), *near to the coast* (2 – 20 km) or *not near the coast* (> 20 km)
3. Above mean sea level, to the nearest 10 m.

4. Testing the CRAAT method

With over 200 climate-related EVENTS to select from, we took a sample of EVENTS encompassing sea level rise, storm surges, summer and winter temperatures, rainfall intensity and duration, high winds and summer thunderstorms (high probability of lightning). The sample EVENTS are listed in Table 6 along with examples of potential CONSEQUENCES and the reasons for selection. This is not an exhaustive list and the EVENTS and CONSEQUENCES do not apply to all airports. Important to note is that the same EVENT can result in more than one CONSEQUENCE and that each of these CONSEQUENCES may demand different management approaches or CONTROLS. CRAAT has been specifically designed to enable the airport operator to repeat EVENTS and consider different CONSEQUENCES and different CONTROLS that may be implemented.

5. Results

The results of using CRAAT with location specific climate data are presented in Table 7 for each sampled EVENT and for each representative airport (A-H).

Future sea level rise has been determined as the change from existing levels. None of the airports is considered to be at risk at in the existing scenario, reflecting the assumption that current designs are sufficient. Airport A, and its associated surface access, may be at medium risk of sea level rises in the short and longer term future scenarios. Airports C, F and G, and associated surface access, are considered to be at high risk in both the short and longer term future scenarios. Note that the catastrophic nature of this risk means that airports are either at high risk or at medium risk depending on their proximity to the coast. Airports not near to the coast were not assessed for this risk.

Airport A is immediately adjacent to the coast with surface access inland of the airport. This airport is considered to be at medium risk of storm surges in the existing scenario although this risk does not increase. This risk may be lowered if, on investigation, existing measures to protect the airport from storm surges are already in place. Surface access to this airport is at low risk. Airports C, F and G are at low risk of storm, surges in all three scenarios. This is also true for the associated surface access at these airports.

TABLE 6 : EVENTS and CONSEQUENCES used to test the CRAAT method.

EVENT	CONSEQUENCE	Description
Sea level rise: > 0.1m above 1991 – 2010 reference period	Catastrophic Catastrophic	Airports adjacent to the coast may be permanently impacted. Surface access to airports adjacent and near to the coast may be permanently impacted.
Storm surge: >3 days/year with high probability of waves > 9m	Major Minor	Airports adjacent to the coast likely to periodically impacted without sea walls and flood protection. Surface access to airports adjacent and near to the coast may be disrupted by localized flooding.
Summer hot day: >= 1 day/year > 50°	Minor Major	Aircraft may require longer runway or reduced take-off weight. Sensitive electronic equipment and mechanical operating mechanisms may fail to operate correctly.
Summer heat wave: >= 1 period/year of 5 days (or more) > 40°C	Minor Major	HVAC systems of terminal buildings may become overloaded and fail, resulting in passenger and staff discomfort. Infrastructure damage affecting the structural integrity of airfield structures such as runway / apron tarmac and terminals / airfield buildings.
Winter cold spell: >= 1 period/year of 10 days (or more) < 0°C	Minor Minor	Increased need for heating buildings. Increased need for de-icing.
Rainfall intensity: >= 1 day/year > 50mm	Minor Minor	Flooding of car parking infrastructure Flooding of local surface roads and transport infrastructure.
Rainfall duration: >= 1 period/year of 5 days (or more) with cumulative daily precipitation > 100mm	Hazardous Minor	Drainage network overwhelmed, disrupting airport operations and reducing surface access. Pollution Control System failure.
High winds: >= 1 day/year > 27m/s (strong gale)	Hazardous Major	High wind speeds or gusts impacting take off procedures; airport operations restricted leading to delays. Tree fall due to strong winds leading to road and rail disruption.
Summer lightning: >= 1 day/year with minimum temp >= 25°C AND rainfall > 25mm	Minor Minor	Airport operations restricted with increased spacing between aircraft landing and taking off, leading to delays. Delays due to damage to navigation systems.

This analysis identified airports A and G likely to experience medium climate risk associated with hot summer days, with the risk to airport G already present and expected in the longer term future for airport A. The CONSEQUENCES of daily temperatures exceeding 50°C depends to some extent on the current climate experienced by the airport and whether the airport has been designed for such conditions. Some airports are already experiencing daily temperatures greater than 50°C or are at higher altitudes, meaning that runways have already been designed for such conditions. In any event, modern aircraft design will continue to include for operating globally which may represent the most effective CONTROL. In contrast, the operating temperature specification of electronic instrumentation and mechanical equipment may not be sufficient in the future at airports where this has not already been considered. This is a good example where a climate risk assessment can identify an appropriate CONTROL that can be programmed into ongoing preventative service and maintenance.

Airports A, B, G and H are identified at medium risk of summer heat waves affecting operations, with airport A becoming a high risk in the longer term future. The HVAC systems of most airport terminal buildings are able to cope with the occasional day of high temperatures. However, when sustained periods of high temperatures (or heat waves) occur then these systems can rapidly start to become overloaded and may even fail. This can result in passenger and staff discomfort, leading to complaints. Understanding the operational limits of HVAC systems and assessing the LIKELIHOOD of when these limits may be breached is a key requirement for climate risk assessment. This was achieved for all eight representative airports, noting that different thresholds could have been selected from the one used in this study (40^{o}C). The impact of heat waves on airport infrastructure represents a risk across a wider range of airports, reflecting the major CONSEQUENCE in terms of damaging infrastructure directly associated with the aircraft operations. The temperature limits of key materials such as tarmac and concrete can be specified to reduce the CONSEQUENCE of heat wave EVENTS through preventative maintenance.

The risk of winter cold spells is currently medium for airports A, B, C, D and F. This is expected to reduce to low risk for airport C over the shot term and for airport A over the longer term. This example was included to demonstrate that not all EVENTS have negative CONSEQUENCES. However, warmer winters are generally associated with wetter conditions.

Airports F and H are already considered to be at medium risk of extreme rainfall (in terms of intensity) with airport G also being medium risk in the longer term. A one day period of intense rainfall is likely to lead to localised flooding of airport and surface access infrastructure, representing only an occasional disruption to the airport and hence, being a low risk. Although not shown here, a further EVENT to consider would be the number of days each year that extreme rainfall occurs to understand more how many days of disruption may occur and hence, at what point this becomes a higher risk to the airport. Periods of sustained rainfall can result in hazardous CONSEQUENCES, such as overloading of the site drainage network and representing large scale disruption to the airport operations, including surface access. In this study, airports F and H are considered to be already at high risk of drainage networks being overwhelmed and at medium risk of pollution control systems failing. In the medium and longer term futures, the risk of the drainage network at airport G being overwhelmed increases to medium.

The LIKELIHOOD of strong gales remains low at all airports although this may be an example where the EVENT could be assessed at different thresholds (i.e. 19 m/s or 23 m/s) as a sensitivity analysis and to differentiate between potential CONSEQUENCES of high winds impacting take off procedures or causing tree fall and hence, disruption to road and rail services. Note that we have presented these results in preference to ‘chasing’ risks.

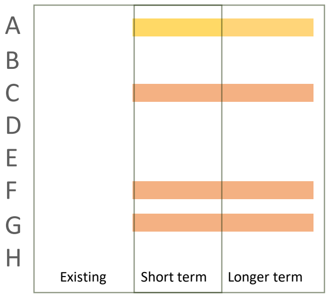
The CIMP6 model dataset does not provide data on thunderstorms or lightning. However, lightning during summer months is more likely on days with minimum temperatures above 25^{o}C and 25mm or more of rainfall. These conditions have been used to identify days when there is a higher probability of lightning. Airport F is currently at medium risk of lightning slowing down runway operations and disrupting navigation systems and this is not expected to change without further CONTROL. Airport H is expected to move from low to medium risk in the short term and airport G in the longer term.

The results are also presented graphically in Figures 3 and 4 using green, orange and red colours to denote low, medium and high risks for each CONSEQUENCE assessed at each airport. This graphic provides a clear and visual means of presenting the results to determine where key risks are likely and trends in risks over time. In general, climate risks are low at the airports and CONSEQUENCES studied. Some EVENTS, such as summer heatwaves, clearly result in increasing risk over time whereas the risks resulting from winter cold spells reduce.

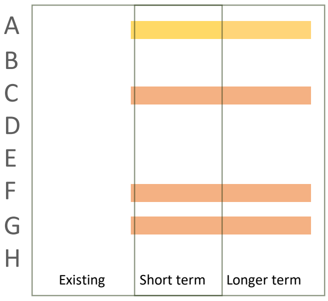
TABLE 7 : Results of testing the CRAAT method.

EVENT	CONSEQUENCE	RISK (high, medium, low)		
		Existing	Short term	Longer term
Sea level rise: > 0.1m above 1991 – 2010 reference period	Catastrophic: airports adjacent to the coast may be permanently impacted.	*Not applicable*	A C F G	A C F G
	Catastrophic: surface access to airports adjacent and near to the coast may be permanently impacted.	*Not applicable*	A C F G	A C F G
Storm surge: >3 days/year with high probability of waves > 9m	Major: airports adjacent to the coast likely to periodically impacted without sea walls or flood protection.	A C F G	A C F G	A C F G
	Minor: surface access to airports adjacent and near to the coast may be disrupted by localised flooding.	A C F G	A C F G	A C F G
Summer hot day: >= 1 day/year > 50°C	Minor: aircraft may require longer runway or reduced take-off weight.	A B C D E F G H	A B C D E F G H	A B C D E F G H
	Major: sensitive electronic equipment and mechanical operating mechanisms may fail to operate correctly.	A B C D E F G H	A B C D E F G H	A B C D E F G H
Summer heat wave: >= 1 period/year of 5 days (or more) > 40°C	Minor: HVAC systems of terminal buildings may become overloaded and fail, resulting in passenger and staff discomfort.	A B C D E F G H	A B C D E F G H	A B C D E F G H
	Major: infrastructure damage affecting the structural integrity of airfield structures such as runway / apron tarmac and terminals / airfield buildings.	A B C D E F G H	A B C D E F G H	A B C D E F G H
Winter cold spell: >= 1 period/year of 10 days (or more) < 0°C	Minor: increased need for heating buildings.	A B C D E F G H	A B C D E F G H	A B C D E F G H
	Minor: increased need for de-icing.	A B C D E F G H	A B C D E F G H	A B C D E F G H
Rainfall intensity: >= 1 day/year > 50mm	Minor: flooding of car parking infrastructure	A B C D E F G H	A B C D E F G H	A B C D E F G H
	Minor: flooding of local surface roads and transport infrastructure.	A B C D E F G H	A B C D E F G H	A B C D E F G H
Rainfall duration: >= 1 period/year of 5 days (or more) with cumulative daily precipitation > 100mm	Hazardous: drainage network overwhelmed, disrupting airport operations and reducing surface access.	A B C D E F G H	A B C D E F G H	A B C D E F G H
	Minor: Pollution Control System failure.	A B C D E F G H	A B C D E F G H	A B C D E F G H
High winds: >= 1 day/year > 27m/s (strong gale)	Hazardous: high wind speeds or gusts impacting take off procedures; airport operations restricted leading to delays.	A B C D E F G H	A B C D E F G H	A B C D E F G H
	Major: tree fall due to strong winds leading to road and rail disruption	A B C D E F G H	A B C D E F G H	A B C D E F G H
Summer lightning: >= 1 day/year with minimum temp >= 25°C AND rainfall >25mm	Minor: airport operations restricted with increased spacing between aircraft landing and taking off, leading to delays.	A B C D E F G H	A B C D E F G H	A B C D E F G H
	Minor: delays due to damage to navigation systems.	A B C D E F G H	A B C D E F G H	A B C D E F G H

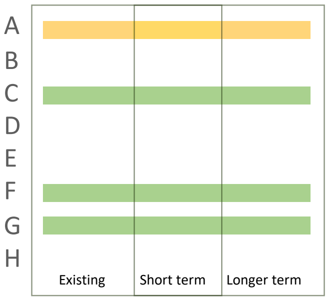
Sea level rise:
Catastrophic: airports adjacent to the coast may be permanently impacted.



Sea level rise:
Catastrophic: surface access to airports adjacent and near to the coast may be permanently impacted.

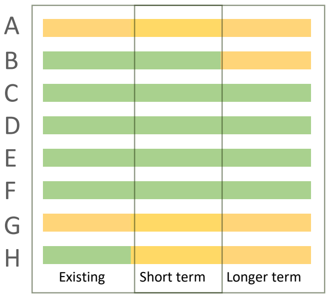


Storm surge:
Major: airports adjacent to the coast likely to periodically impacted without sea walls and flood protection.

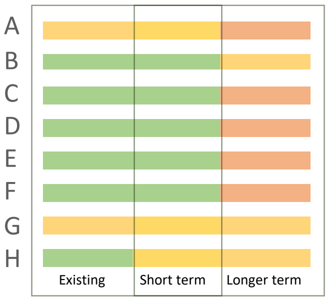


Summer hot day:
Major: sensitive electronic equipment and mechanical operating mechanisms may fail to operate correctly.

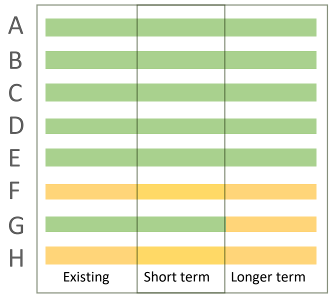
Summer heat wave:
Minor: HVAC systems of terminal buildings may become overloaded and fail, resulting in passenger and staff discomfort.



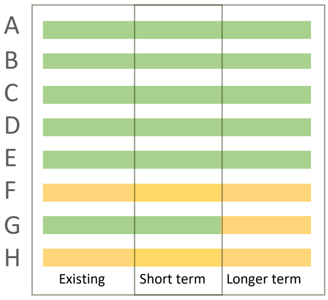
Summer heat wave:
Major: infrastructure damage affecting the structural integrity of airfield structures such as runway / apron tarmac and terminals / airfield buildings.



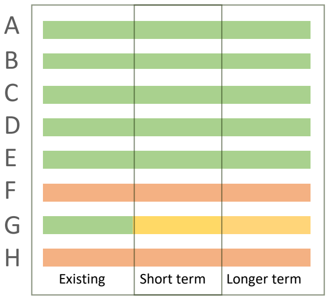
Rainfall intensity:
Minor: flooding of car parking infrastructure



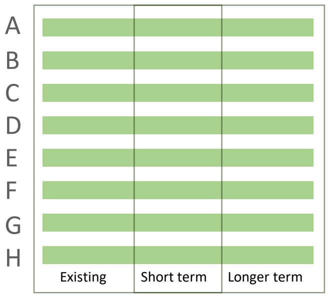
Rainfall intensity:
Minor: flooding of local surface roads and transport infrastructure.



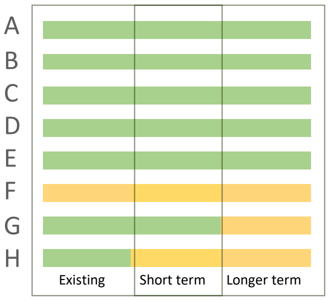
Rainfall duration:
Hazardous: drainage network overwhelmed, disrupting airport operations and reducing surface access.



High winds:
Major: tree fall due to strong winds leading to road and rail disruption



Summer lightning:
Minor: airport operations restricted with increased spacing between aircraft landing and taking off, leading to delays.



Summer lightning:
Minor: delays due to damage to navigation systems.

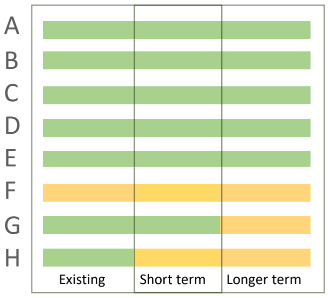
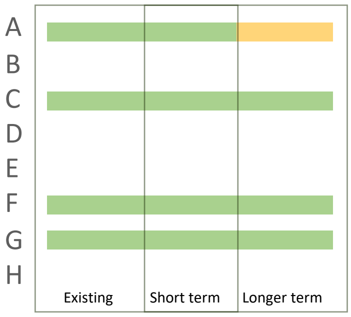


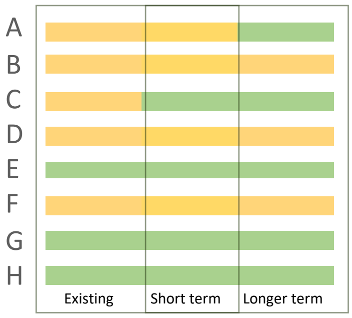
FIGURE 3: Results of testing the CRAAT method

Storm surge:
Minor: surface access to airports adjacent and near to the coast may be disrupted by localized flooding.

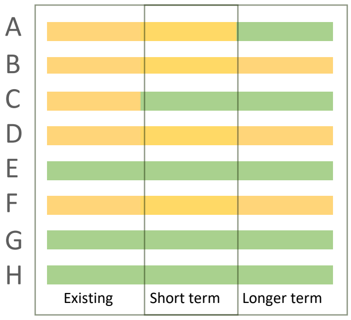


Summer hot day:
Minor: aircraft may require longer runway or reduced take-off weight.

Winter cold spell:
Minor: increased need for heating buildings.



Winter cold spell:
Minor: increased need for de-icing.



Rainfall duration:
Minor: Pollution Control System failure.

High winds:
Hazardous: high wind speeds or gusts impacting take off procedures; airport operations restricted leading to delays.

FIGURE 4: Results of testing the CRAAT method (continued)

6. Discussion

The ICAO toolkit for climate resilience assessment provides an appropriate framework methodology that can be applied to any airport. This toolkit highlights the need to provide airport specific climate data to support any assessment. This paper describes the climate resilience assessment of airports tool (CRAAT) developed by susteer AB that is based on the ICAO toolkit and provides airport specific climate data. In developing CRAAT we consider the following is applicable in extending the ICAO toolkit:

1. **Airport-specific climate risk data can be provided in terms of climate-related EVENTS.** For example, rather than referring to 'the maximum daily temperature in the year' we propose using a threshold such as, for example, 'the maximum daily temperature exceeding 50°C'. Although there is no limit to the number of climate-related EVENTS that could be defined, and not all would be relevant to every airport, our expectation is that the number of climate-related EVENTS that would be used for climate resilience assessment of airports will stabilise over time. Importantly, the assessment methodology is not limited by the number of climate-related EVENTS that can be referred to.

2. **The LIKELIHOOD of climate-related EVENTS can be determined using CMIP6 data.** CMIP6 can tell us what the maximum daily temperature in the year is and it can also tell us the LIKELIHOOD of the maximum daily temperature exceeding 50°C.
   The Climate Model Intercomparison Project provides a large database of climate projections from multiple models from institutions around the world and hence, can be considered globally

democratic. Moreover, the evidence from CMIP is used by the Intergovernmental Panel on Climate Change (IPCC) to assess how the climate might change under different scenarios. This information underpins international policy on climate change. A climate resilience assessment undertaken for an airport using CIMP6 data will therefore be consistent with international studies and policies on climate change.

3. **The methodology for identifying and describing EVENTS in terms of specific climate conditions can be applied consistently at all airports.**
   This is a key benefit of using CMIP6 data, regardless of the climate-related EVENT being considered. Although airports are fixed assets, aircraft are not and the climate risks they might experience need to be assessed consistently at both origin and destination airports.

4. **Specific climate-related EVENTS can be directly related to airport-specific CONSEQUENCES.**
   Using threshold EVENTS to describe climate conditions rather than values enables the airport operator to directly relate climate to critical thresholds that impact airport operations, maintenance or future design.
   As for climate-related EVENTS, there is no limit to the number of CONSEQUENCES that could be defined. However, our expectation is to see a large degree of commonality in the CONSEQUENCES identified by different airports and for the number to stabilise over time.
   In many circumstances, the same CONSEQUENCE will occur with different thresholds in the climate-related EVENT. For example, a one-day failure of a HVAC system may occur if daily temperatures exceed 40^{o}C at one airport or 55^{o}C at another airport. This the same CONSEQUENCE as a result of the same type of EVENT but with different temperature thresholds and so is defined as two different EVENTS. With reference to Figure 1, this suggests CONSEQUENCES should be identified first and EVENTS then assigned to them, reflecting the circumstances of the airport. In our experience, both are considered together.
   In studying the collective resilience of all airports in the world, we are currently assessing whether this EVENT threshold could be better defined as 'the maximum daily temperature exceeding 5^{o}C above the summer average for the current baseline'.

5. **A common database of EVENTS and CONSEQUENCES can be shared.**
   In developing and testing CRAAT we have built up a relatively extensive database of EVENTS and CONSEQUENCES. We are fully aware it is not exhaustive and as it is used by more airports around the world, we expect this database to be extended. Indeed, we see this as a strength of CRAAT in that it enables the specific circumstances of each and every airport operator to be described consistently in terms of EVENTS and CONSEQUENCES and hence, assessed consistently in line with the ICAO framework methodology.

6. **Common learning can be extended to design and implementation of CONTROLS.**
   There is significant overlap and commonality in the EVENTS and CONSEQUENCES that may be experienced by different airports, with opportunity for shared learning not only in risk assessment but also in adaptation.

Beyond a simple desire to follow ICAO guidance, assessing the climate resilience of an airport in terms of its physical risks is one aspect of managing climate related risks and opportunities. The Taskforce on Climate-related Financial Disclosure (TCFD) was established on the premise that "*financial markets need clear, comprehensive, high-quality information on the impacts of climate change. This includes the risks and opportunities presented by rising temperatures, climate-related policy, and emerging technologies in our changing world*" [7]. Although TCFD originated in the UK, the principles are being adopted internationally with comparable policies and regulations emerging in several countries globally. Referring to the TCFD guidance, Figure 5 has been compiled to identify both physical and transition risks as well as opportunities for the aviation sector. As airport operators seek to continue financing operations and attract investment for future development, the need to provide climate-related financial disclosure is increasing. This includes understanding the potential costs required to maintain the operational capacity of an airport and ensure resilience to a changing climate. However, airports are connected to each other and there is a need for the aviation sector to be collectively resilient. An airport may itself be climate resilient but if the destination airports are not, then the business remains at risk. Auditors might reasonably expect climate resilience assessments to be undertaken in a consistent manner across a sector such as aviation. In this paper we have demonstrated that CRAAT provides airport stakeholders with the ability to follow the ICAO methodology, utilise internationally accepted and robust climate data, and assess climate related risks that can be compared to other airports globally.

Physical risks
Result from events (acute risks) or longer-term shifts (chronic risks) in climate patterns. May cause direct damage to assets and indirect impacts due to supply chain disruptions.

Functionality of the airport, i.e. the ability to transport cargo and passengers.

Performance i.e. customer experience at the airport and the efficiency of processes.

Operations (non-aviation), e.g. terminal building operations and safety procedures.

Transition risks
Transition to a lower-carbon economy entails policy, legal, technology, and market changes to address mitigation and adaptation requirements. May vary in speed and may have financial or reputational risks to organisations.

Cost of compliance in terms of meeting international or national requirements to reduce carbon emissions.

Technology i.e. will new aircraft and fuel technologies be delivered.

Demand for passengers and freight may decline if transition is not proven.

Opportunities
Efforts to mitigate and adapt also produce opportunities, e.g. enhanced resource efficiency and cost savings, development of new products and services and access to new markets.

Asset value safeguarded.

Competitive i.e. more reliable transport hub.

Changing Tourism e.g. destinations will change, by geography and season.

Changing Freight i.e. resilience of airports and their hinterlands will impact supply and demand of goods and services.

FIGURE 5: Climate related physical and transition risks and opportunities for aviation

7. Conclusions

The methodology described in this paper has been developed to be consistent with the recent ICAO guidance on the assessment of climate resilience airports. By responding specifically to the ICAO recommendation to "*research climate projections for the location and understand the risks they pose to airport assets and operations*", this paper describe how the sixth iteration of IPCC climate projections can be used to specify climate conditions in terms of event thresholds that can be directly associated with consequences and hence, the climate risk to airport operations. This is a step change from existing methods of assessing the climate resilience of airports and is in line with ICAO guidance. We have called this method the Climate Resilience Assessment of Airports Tool (CRAAT). The results of testing the method with eight globally representative airports illustrate how CRAAT can be used to provide a consistent assessment of climate risk for airports around the world. In terms of physical risks at an individual airport, this requires knowledge of the airport location in relation to the coast and needs to take account of the current climatic conditions; what is considered a hot day in Stockholm may not be the case in Brisbane, Dubai or New Delhi. As the risks of climate change become more embedded within financial reporting, airport operators also need to consider the potential loss in revenue of climate related disruption to their destination airports. This further underlines the value of having a tool such as CRAAT to consistently assess climate risks globally.

8. Further information

A demonstration version of CRAAT will be available at www.susteer.com where further information on CRAAT can also be accessed.

9. Contact Author Email Address

For further information, please mail: matt.osundireland@susteer.com.

10. Copyright Statement

11. Citation

We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF.

Following CMIP data licensing requirements, the full list of models used to develop the airport location specific EVENT statistics is presented in Table 8. Note that not all models provide data for each location and each climate period selected.

12. References

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[4] https://www.ipcc.ch/assessment-report/ar6/

[5] Veronika Eyring, Sandrine Bony, Gerald A. Meehl, Catherine A. Senior, Bjorn Stevens, Ronald J. Stouffer, and Karl E. Taylor, 2016, Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organisation, Geosci. Model Dev., 9, 1937–1958, https://doi.org/10.5194/gmd-9-1937-2016, 2016

[6] https://www.ipcc.ch/assessment-report/ar6/

[7] Details of the Taskforce on Climate-related Financial Disclosure are available at https://www.fsb-tcfd.org/

TABLE 8 : CMIP Models.

Model	Institution ID(s)	Released	Model	Institution ID(s)	Released
LBLRTM 12.8	AER	2017	NICAM16-9D-L78	MIROC	2017
RRTMG-LW 4.91	AER	2017	NICAM16-7S	MIROC	2017
RRTMG-SW 4.02	AER	2017	KIOST-ESM	KIOST	2018
HiRAM-SIT-HR	AS-RCEC	2018	EMAC-2-53-Vol	MESSy-Consortium	2017
HiRAM-SIT-LR	AS-RCEC	2018	EMAC-2-54-AerChem	MESSy-Consortium	2018
TaiESM 1.0	AS-RCEC	2018	MIROC-ES2H	MIROC	2018
AWI-CM 1.1 HR	AWI	2018	MIROC-ES2H-NB	MIROC	2019

Model	Institution ID(s)	Released	Model	Institution ID(s)	Released
AWI-CM 1.1 LR	AWI	2018	NICAM16-9S	MIROC	2017
AWI-CM 1.1 MR	AWI	2018	HadGEM3-GC31-LM	MOHC	2016
AWI-ESM 1.1 LR	AWI	2018	HadGEM3-GC31-MH	MOHC	2016
AWI-ESM 2.1 LR	AWI	2019	HadGEM3-GC31-MM	MOHC	2016
BCC-CSM 2 HR	BCC	2017	HadGEM3-GC31-HH	MOHC NERC	2016
BCC-CSM 2 MR	BCC	2017	HadGEM3-GC31-HM	MOHC NERC	2016
BCC-ESM 1	BCC	2017	HadGEM3-GC31-LL	MOHC NERC	2016
BNU-ESM 1.1	BNU	2016	UKESM1.0-MMh	MOHC NERC	2018
CAMS-CSM 1.0	CAMS	2016	UKESM1.ice-LL	MOHC NERC	2019
CAS-ESM 2.0	CAS	2019	UKESM1.0-LL	MOHC NERC NIMS-KMA NIWA	2018
FGOALS-f3-H	CAS	2017	UKESM1.1-LL	MOHC NERC NIMS-KMA NIWA	2021
FGOALS-f3-L	CAS	2017	ICON-ESM-LR	MPI-M	2017
FGOALS-g3	CAS	2017	MPI-ESM1.2-XR	MPI-M	2017
CanESM5	CCCma	2019	MPI-ESM1.2-LR	MPI-M AWI DKRZ DWD	2017
CanESM5-CanOE	CCCma	2019	MPI-ESM1.2-HR	MPI-M DWD DKRZ	2017
IITM-ESM	CCCR-IITM	2015	MRI-AGCM3-2-H	MRI	2017
CMCC-CM2-HR4	CMCC	2016	MRI-AGCM3-2-S	MRI	2017
CMCC-CM2-SR5	CMCC	2016	MRI-ESM2.0	MRI	2017
CMCC-CM2-VHR4	CMCC	2017	GISS-E2.1G	NASA-GISS	2019
CMCC-ESM2	CMCC	2017	GISS-E2-1-G-CC	NASA-GISS	2019
CNRM-CM6-1	CNRM-CERFACS	2017	GISS-E2.1H	NASA-GISS	2019
CNRM-CM6-1-HR	CNRM-CERFACS	2017	GISS-E2-2-G	NASA-GISS	2019
CNRM-ESM2-1	CNRM-CERFACS	2017	GISS-E2.2H	NASA-GISS	2021
CNRM-ESM2-1-HR	CNRM-CERFACS	2017	GISS-E3-G	NASA-GISS	2020
VRESM 1.0	CSIR-Wits-CSIRO	2016	CESM1-1-CAM5-CMIP5	NCAR	2011
ACCESS-ESM1.5	CSIRO	2019	CESM1-CAM5-SE-HR	NCAR	2012
ACCESS-CM2	CSIRO-ARCCSS	2019	CESM1-CAM5-SE-LR	NCAR	2012
ACCESS-OM2	CSIRO-COSIMA	2020	CESM2	NCAR	2018
ACCESS-OM2-025	CSIRO-COSIMA	2020	CESM2-FV2	NCAR	2019
E3SM 1.1 ECA	E3SM-Project	2019	CESM2-SE	NCAR	2019
E3SM 1.0	E3SM-Project LLNL UCI	2018	CESM2-WACCM	NCAR	2018
E3SM 1.1	E3SM-Project RUBISCO	2019	CESM2-WACCM-FV2	NCAR	2019
EC-Earth3	EC-Earth-Consortium	2019	NorCPM1	NCC	2019
EC-Earth3-AerChem	EC-Earth-Consortium	2019	NorESM1-F	NCC	2018
EC-Earth3-CC	EC-Earth-Consortium	2019	NorESM2-HH	NCC	2018
EC-Earth3-GrIS	EC-Earth-Consortium	2019	NorESM2-LM	NCC	2017
EC-Earth3-HR	EC-Earth-Consortium	2019	NorESM2-LME	NCC	2017
EC-Earth3-LR	EC-Earth-Consortium	2019	NorESM2-LMEC	NCC	2017
EC-Earth3-Veg	EC-Earth-Consortium	2019	NorESM2-MH	NCC	2017
EC-Earth3-Veg-LR	EC-Earth-Consortium	2019	NorESM2-MM	NCC	2017
EC-Earth3P	EC-Earth-Consortium	2017	KACE1.0-G	NIMS-KMA	2018
EC-Earth3P-HR	EC-Earth-Consortium	2017	GFDL-AM4	NOAA-GFDL	2018
EC-Earth3P-VHR	EC-Earth-Consortium	2017	GFDL-CM4	NOAA-GFDL	2018
ECMWF-IFS-HR	ECMWF	2017	GFDL-CM4C192	NOAA-GFDL	2018
ECMWF-IFS-LR	ECMWF	2017	GFDL-ESM2M	NOAA-GFDL	2012
ECMWF-IFS-MR	ECMWF	2017	GFDL-ESM4	NOAA-GFDL	2018
FIO-ESM 2.0	FIO-QLNM	2018	GFDL-GLOBAL-LBL	NOAA-GFDL	2019
MPI-ESM1.2-HAM	HAMMOZ-Consortium	2017	GFDL-GRTCODE	NOAA-GFDL	2019
BESM 2.9	INPE	2019	GFDL-OM4p5B	NOAA-GFDL	2018
4AOP-v1-5	IPSL	2019	GFDL-RFM-DISORT	NOAA-GFDL	2019
IPSL-CM5A2-INCA	IPSL	2019	TaiESM1-TIMCOM	NTU	2020
IPSL-CM6A-ATM-HR	IPSL	2018	TaiESM1-TIMCOM2	NTU	2021
IPSL-CM6A-ATM-ICO-HR	IPSL	2021	NESM v3	NUIST	2016
IPSL-CM6A-ATM-ICO-LR	IPSL	2021	PCMDI-test 1.0	PCMDI	1989
IPSL-CM6A-ATM-ICO-MR	IPSL	2021	CAM-MPAS-HR	PNNL-WACCEM	2018

Model	Institution ID(s)	Released	Model	Institution ID(s)	Released
IPSL-CM6A-ATM-ICO-VHR	IPSL	2021	CAM-MPAS-LR	PNNL-WACCEM	2018
IPSL-CM6A-ATM-LR-REPROBUS	IPSL	2021	RTE+RRTMGP (2018-12-04 full-resolution)	RTE-RRTMGP-Consortium	2019
IPSL-CM6A-LR	IPSL	2017	SAM0-UNICON	SNU	2017
IPSL-CM6A-LR-INCA	IPSL	2019	CIESM	THU	2017
IPSL-CM6A-MR025	IPSL	2021	MCM-UA-1-0	UA	1991
IPSL-CM6A-MR1	IPSL	2021	CESM1-WACCM-SC	UCI NCAR	2011
MIROC-ES2L	MIROC	2018	ARTS 2.3	UHH	2015
MIROC6	MIROC	2017	UofT-CCSM4	UofT	2014
NICAM16-8S	MIROC	2017	CSIRO Mk3L 1.3	UTAS	2006

Institution IDs:

AER	Research and Climate Group, Atmospheric and Environmental Research, 131 Hartwell Avenue, Lexington, MA 02421, USA
AS-RCEC	Research Center for Environmental Changes, Academia Sinica, Nankang, Taipei 11529, Taiwan
AWI	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany
BCC	Beijing Climate Center, Beijing 100081, China
BNU	Beijing Normal University, Beijing 100875, China
CAMS	Chinese Academy of Meteorological Sciences, Beijing 100081, China
CAS	Chinese Academy of Sciences, Beijing 100029, China
CCCma	Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, BC V8P 5C2
CCCR-IITM	Centre for Climate Change Research, Indian Institute of Tropical Meteorology Pune, Maharashtra 411 008, India
CMCC	Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Lecce 73100, Italy
CNRM-CERFACS	CNRM (Centre National de Recherches Meteorologiques, Toulouse 31057, France), CERFACS (Centre Europeen de Recherche et de Formation Avancee en Calcul Scientifique, Toulouse 31057, France)
CSIR-Wits-CSIRO	CSIR (Council for Scientific and Industrial Research - Natural Resources and the Environment, Pretoria, 0001, South Africa), Wits (University of the Witwatersrand - Global Change Institute, Johannesburg 2050, South Africa), CSIRO (Commonwealth Scientific and Industrial Research Organisation, Aspendale, Victoria 3195, Australia)Mailing address: Wits, Global Change Institute, Johannesburg 2050, South Africa
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Aspendale, Victoria 3195, Australia
CSIRO-ARCCSS	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Aspendale, Victoria 3195, Australia), ARCCSS (Australian Research Council Centre of Excellence for Climate System Science). Mailing address: CSIRO, c/o Simon J. Marsland, 107-121 Station Street, Aspendale, Victoria 3195, Australia
CSIRO-COSIMA	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), COSIMA (Consortium for Ocean-Sea Ice Modelling in Australia). Mailing address: CSIRO, c/o Simon J. Marsland, 107-121 Station Street, Aspendale, Victoria 3195, Australia
DKRZ	Deutsches Klimarechenzentrum, Hamburg 20146, Germany
DWD	Deutscher Wetterdienst, Offenbach am Main 63067, Germany
E3SM-Project	LLNL (Lawrence Livermore National Laboratory, Livermore, CA 94550, USA); ANL (Argonne National Laboratory, Argonne, IL 60439, USA); BNL (Brookhaven National Laboratory, Upton, NY 11973, USA); LANL (Los Alamos National Laboratory, Los Alamos, NM 87545, USA); LBNL (Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA); ORNL (Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA); PNNL (Pacific Northwest National Laboratory, Richland, WA 99352, USA); SNL (Sandia National Laboratories, Albuquerque, NM 87185, USA). Mailing address: LLNL Climate Program, c/o David C. Bader, Principal Investigator, L-103, 7000 East Avenue, Livermore, CA 94550, USA
EC-Earth-Consortium	AEMET, Spain; BSC, Spain; CNR-ISAC, Italy; DMI, Denmark; ENEA, Italy; FMI, Finland; Geomar, Germany; ICHEC, Ireland; ICTP, Italy; IDL, Portugal; IMAU, The Netherlands; IPMA, Portugal; KIT, Karlsruhe, Germany; KNMI, The Netherlands; Lund University, Sweden; Met Eireann, Ireland; NLeSC, The Netherlands; NTNU, Norway; Oxford University, UK; surfSARA, The Netherlands; SMHI, Sweden; Stockholm University, Sweden; Unite ASTR, Belgium; University College Dublin, Ireland; University of Bergen, Norway; University of Copenhagen, Denmark; University of Helsinki, Finland; University of Santiago de Compostela, Spain; Uppsala University, Sweden; Utrecht University, The Netherlands; Vrije Universiteit Amsterdam, the Netherlands; Wageningen University, The Netherlands. Mailing address: EC-Earth consortium, Rossby Center, Swedish Meteorological and Hydrological Institute/SMHI, SE-601 76 Norrkoping, Sweden
ECMWF	European Centre for Medium-Range Weather Forecasts, Reading RG2 9AX, UK
FIO-QLNM	FIO (First Institute of Oceanography, Ministry of Natural Resources, Qingdao 266061, China), QNLM (Qingdao National Laboratory for Marine Science and Technology, Qingdao 266237, China)
HAMMOZ-Consortium	ETH Zurich, Switzerland; Max Planck Institut fur Meteorologie, Germany; Forschungszentrum Julich, Germany; University of Oxford, UK; Finnish Meteorological Institute, Finland; Leibniz Institute for Tropospheric Research, Germany; Center for Climate Systems Modeling (C2SM) at ETH Zurich, Switzerland
INPE	National Institute for Space Research, Cachoeira Paulista, SP 12630-000, Brazil
IPSL	Institut Pierre Simon Laplace, Paris 75252, France
KIOST	Korea Institute of Ocean Science and Technology, Busan 49111, Republic of Korea
LLNL	Lawrence Livermore National Laboratory, Livermore, CA 94550, USA. Mailing address: LLNL Climate Program, c/o Stephen A. Klein, Principal Investigator, L-103, 7000 East Avenue, Livermore, CA 94550, USA
MESSy-Consortium	The Modular Earth Submodel System (MESSy) Consortium, represented by the Institute for Physics of the Atmosphere, Deutsches Zentrum fur Luft- und Raumfahrt (DLR), Wessling, Bavaria 82234, Germany
MIROC	JAMSTEC (Japan Agency for Marine-Earth Science and Technology, Kanagawa 236-0001, Japan), AORI (Atmosphere and Ocean Research Institute, The University of Tokyo, Chiba 277-8564, Japan), NIES (National Institute for Environmental Studies, Ibaraki 305-8506, Japan), and R-CCS (RIKEN Center for Computational Science, Hyogo 650-0047, Japan)
MOHC	Met Office Hadley Centre, Fitzroy Road, Exeter, Devon, EX1 3PB, UK
MPI-M	Max Planck Institute for Meteorology, Hamburg 20146, Germany
MRI	Meteorological Research Institute, Tsukuba, Ibaraki 305-0052, Japan
NASA-GISS	Goddard Institute for Space Studies, New York, NY 10025, USA
NASA-GSFC	
NCAR	
NCC	

Model	Institution ID(s)	Released	Model	Institution ID(s)	Released
NERC NIMS-KMA NIWA NOAA-GFDL NTU NUIST PCMDI PNNL-WACCEM RTE-RRTMGP-Consortium RUBISCO SNU THU UA UCI UHH UofT UTAS	NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA National Center for Atmospheric Research, Climate and Global Dynamics Laboratory, 1850 Table Mesa Drive, Boulder, CO 80305, USA NorESM Climate modeling Consortium consisting of CICERO (Center for International Climate and Environmental Research, Oslo 0349), MET-Norway (Norwegian Meteorological Institute, Oslo 0313), NERSC (Nansen Environmental and Remote Sensing Center, Bergen 5006), NILU (Norwegian Institute for Air Research, Kjeller 2027), UiB (University of Bergen, Bergen 5007), UiO (University of Oslo, Oslo 0313) and UNI (Uni Research, Bergen 5008), Norway. Mailing address: NCC, c/o MET-Norway, Henrik Mohns plass 1, Oslo 0313, Norway Natural Environment Research Council, STFC-RAL, Harwell, Oxford, OX11 0QX, UK National Institute of Meteorological Sciences/Korea Meteorological Administration, Climate Research Division, Seoho-bukro 33, Seogwipo-si, Jejudo 63568, Republic of Korea National Institute of Water and Atmospheric Research, Hataitai, Wellington 6021, New Zealand National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540, USA National Taiwan University, Taipei 10650, Taiwan Nanjing University of Information Science and Technology, Nanjing, 210044, China Program for Climate Model Diagnosis and Intercomparison, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA PNNL (Pacific Northwest National Laboratory), Richland, WA 99352, USA AER (Atmospheric and Environmental Research, Lexington, MA 02421, USA); UColorado (University of Colorado, Boulder, CO 80309, USA). Mailing address: AER c/o Eli Mlawer, 131 Hartwell Avenue, Lexington, MA 02421, USA ORNL (Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA); ANL (Argonne National Laboratory, Argonne, IL 60439, USA); BNL (Brookhaven National Laboratory, Upton, NY 11973, USA); LANL (Los Alamos National Laboratory, Los Alamos, NM 87545); LBNL (Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA); NAU (Northern Arizona University, Flagstaff, AZ 86011, USA); NCAR (National Center for Atmospheric Research, Boulder, CO 80305, USA); UCI (University of California Irvine, Irvine, CA 92697, USA); UM (University of Michigan, Ann Arbor, MI 48109, USA). Mailing address: ORNL Climate Change Science Institute, c/o Forrest M. Hoffman, Laboratory Research Manager, Building 4500N Room F106, 1 Bethel Valley Road, Oak Ridge, TN 37831-6301, USA Seoul National University, Seoul 08826, Republic of Korea Department of Earth System Science, Tsinghua University, Beijing 100084, China Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA Department of Earth System Science, University of California Irvine, Irvine, CA 92697, USA Universitat Hamburg, Hamburg 20148, Germany Department of Physics, University of Toronto, 60 St George Street, Toronto, ON M5S1A7, Canada Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania 7001, Australia				