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Climate change influences on aviation: a literature review

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Abstract

While the aviation sector has long been referenced as contributing to the causes of climate change, the need for aviation to adapt to the consequences of climate change has not been as well researched or considered. The paper is a systematic quantitative literature review on climate change and aviation, which aims to explicate significant issues affecting aviation in a changing climate and to identify the aviation industry responses on climate change and adaptation. There are 46 references involved in the detailed assessment, selected according to variables such as methodology, paper outcomes and industry stakeholder. This emergent aviation and climate change adaptation literature could be broadened to cover more disciplines and approaches, an increased range of aviation stakeholders and go further beyond the larger airport case studies in developed countries. Further practical and policy developments are needed, particularly surrounding adaptation planning in aviation and the social justice implications of associated policies.

Keywords: Climate change, adaptation, aviation industry, literature review

1. Introduction

The growth in air travel has been accompanied by increasing concerns surrounding the associated environmental implications, seen as externalities (Dessens et al., 2014; Kilic et al., 2019). As such, the aviation sector is a major contributor to climate change, and the proportion attributed to aviation is set to increase because it is one of the hardest sectors to achieve greenhouse gas emission reductions (Andres and Padilla, 2018; Bows-Larkin et al., 2016; Schafer and Waitz, 2014). This is especially the case when compared to other forms of energy consumption, such as industrial and domestic use (Banister, 2019). Much of the research focus has been on greenhouse gas mitigation measures to reduce the environmental impacts from aviation.

Climate change has started to impact aspects of human environmental interactions (IPCC, 2014a). While the aviation sector has long been referenced as contributing to the causes of climate change through greenhouse gas emissions, the need for aviation to adapt to the consequences of climate change has not been well researched or considered (Burbidge, 2018; Thompson, 2016). Adaptation considers how impacts and risks caused by climate change can be reduced and managed, while emission reductions are designed to mitigate the causes of climate change (IPCC, 2014b). There are high levels of natural variability in the climate system, evidenced by extreme weather events causing heat waves, droughts and floods. According to Burbidge (2018), the projected climate impacts affecting aviation most directly are changes in precipitation and temperature, sea-level rise, wind changes and the impacts of more extreme weather events. In addition, climate change shifts the parameters of the systems that underpin weather patterns, to provide new sets of impacts and risks that will require different management strategies (Dilling et al., 2015).

The paper is a systematic quantitative literature review on climate change and aviation, with two associated aims. Firstly, to explicate significant issues affecting aviation in a changing climate. Secondly, to identify the aviation industry responses to climate change and adaptation. The focus is on aviation actors and interests considering climate change implications and policies rather than the chemistry, engineering and other physical drivers and constraints to accomplish a specific pathway to adaptation.

The next section outlines the methodology behind our systematic review of climate change and adaptation. Sections 3 and 4 discuss the review findings and present conclusions, respectively.

2. Methodology

The systematic quantitative literature review was conducted in October 2019. Three databases (Scopus, Web of Science and ProQuest) were searched to capture peer-reviewed industry and academic publications, using broad aviation and climate change search criteria. The search terms were "air transportation", "aviation" or "civil aviation" and "greenhouse gas", "global warming" or "climate change". The search included title, abstract and keywords and was limited to works published within the past 20 years. The search under these criteria in all three databases resulted in a total number of 6,222 publications.

In a second stage, all 6,222 publications were evaluated for their fit with our study. First, all duplicates and non-climate records were removed. In terms of non-climate records publications were rejected: where aviation was only related to remote sensing or data collection; where aviation was only related to environmental goals or sustainability but not climate change causes or consequences; where emissions related to pollution but not climate change, carbon dioxide or greenhouse gases; and where alternative fuels and practices were sought for cost saving, health and other goals without acknowledging climate change mitigation or adaptation issues. The relationship between aviation, climate change and vector-borne disease risk was another emerging area of concern, however, no records focused on the impacts these issues might have on aviation, so none were retained.

In a third stage, we removed all non-adaptation records. These could roughly be classified into three groups. The first group focused on mitigation related to the contributions of aviation to climate change through fuel emissions and contrails of frozen condensed water, or to the exploration of emission reduction solutions through engineering and alternative fuel innovations. The second group focused on trade and cost issues, especially on cost of emission reductions, or potential carbon trading or taxations schemes which had not yet included aviation. The third group of publications that were removed covered mainly passenger choices and behavioral change to achieve emissions reductions, as well as carbon neutral programs and additional energy efficiency aims. Even though references predominantly focused on mitigation measures were removed, some papers focusing on adaptation that also contain mitigation aspects, remained in the sample.

In a fourth stage, we removed any remaining publications that were not related to climate change influences on aviation. This left 92 records, which in a fifth stage underwent a full-text analysis that yielded 46 publications suitable for our study. A flow diagram for the selection of articles is shown in Figure 1. In a sixth stage, the 46 remaining publications were reviewed in more detail and classified according to the background of the research, industry response and outcomes generated, as shown in Table 1.

Figure 1. A flow diagram for the selection of articles

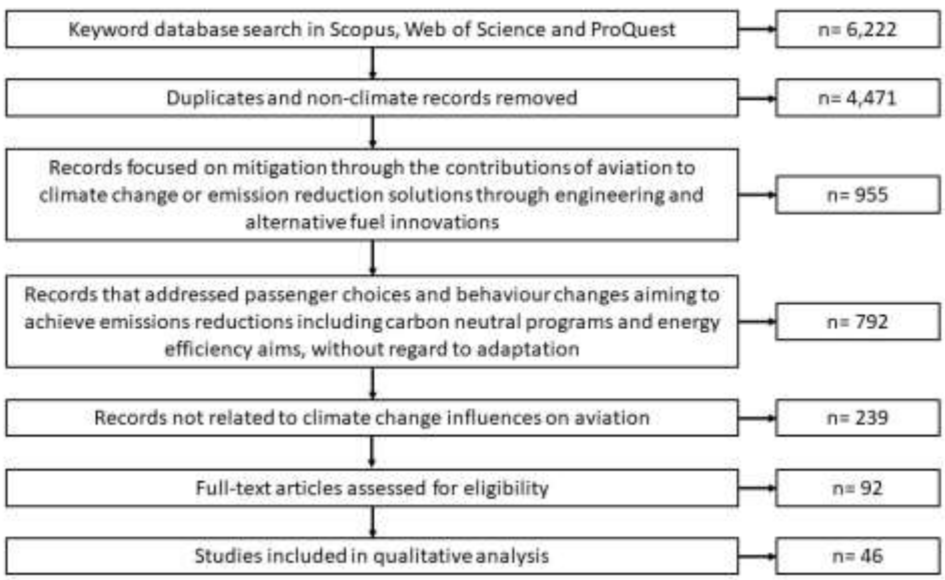

Table 1 The study background and primary outcome from the 46 full-text papers

n	Paper	Study background	Primary outcomes
1	Becken (2013)	Literature review on tourism and climate change.	Research linking climate impacts and tourism has increased to become a knowledge domain in its' own right. It now includes multiple dimensions (e.g. climate impacts, adaptation, mitigation & policy), and studies have become more integrative and critical.
2	Bows et al. (2008)	Chapter within book on aviation and climate change.	There are uncomfortable choices for governments. They will need to curb aviation growth to ensure efficiency improvement rates stay akin to passenger-km growth rates, while at the same time they will need to work on adaptation to prepare for climate change impacts.
3	Buckley (2011)	Investigation into whether slow travel tourism trips will supersede short breaks under climate change.	It is suggested that a group of slow travellers will emerge, to supersede those taking short breaks, accompanied by a new group of tourism providers (e.g. accommodation, food & communications).
4	Budd & Ryley (2012)	Chapter examining the relationship between aviation and climate change.	The aviation sector needs to identify the possible impacts of climate change on air travel operations, both to aircraft in flight and to operations at airports. A further challenge will be to devise adaptation plans that will address the vulnerabilities and thus ensure safe aviation-related operations.
5	Burbidge (2016)	Review of European airports adapting to climate change.	Knowledge gaps are identified, which are raising awareness and promoting collaboration as key steps in building climate change resilience for the European and global aviation sector.
6	Burbidge (2018)	Paper on climate change adaptation of aviation sector.	Further development of Burbidge (2006), paper 5, clarifying the expected impacts for the aviation sector. Risk assessment is a key step for airport adaptation. Adaption actions to address most key risks can be identified, though some, such as building resilience to cross-winds at an airport, may be more challenging to address, whilst low-regrets actions and softer measures such as training can be efficient and cost-effective.
7	Burbidge et al. (2011)	Paper on potential adaptation needs of air traffic management (ATM) to climate change.	Three key potential ATM climate change adaptation areas are Identified: changes in the timing and location of traffic peaks and flows; flooding risk to airports leading to runway closures; and an increase in convective activity (storminess). Some impacts will not be experienced in the short-term, but need to be considered in medium to long-term planning.
8	Butterworth-Hayes (2013)	Review on forecasting the effects involved with climate change and aviation.	Climate change resilience is now high on the political agenda for European and North American governments.
9	Chen & Wang (2019)	Review of the severe weather vulnerability of aviation and High Speed Rail (HSR) in China.	Based on data visualization and statistical analysis, the impacts of severe weather events on HSR and aviation's on-time performance vary spatially and temporally. HSR is generally less vulnerable. Operations in the southeast region of China are affected more frequently by rain and thunderstorms, central-eastern China is more vulnerable to snowstorms.
10	Coffel & Horton (2015)	Examination of climate change and the impact of extreme temperatures on aviation.	Aircraft improvements may help the situation, but airports will generally need longer runways and space-constrained airports are projected to have many more weight restriction days.
11	Coffel et al. (2017)	Examination of the impacts of rising temperature on aircraft take-off performance.	Medium/long-range aircraft and airports with short runways on high elevations are the most affected by rising temperatures.
12	Cooper et al. (2018)	Examination of the relationship between climate change and volcanism.	Isostatic unloading of glaciers will trigger more volcanic activity, leading to interruptions in aviation (e.g. from ash cloud).
13	Debortoli et al. (2019)	Analysis of the climate change vulnerability of Arctic aviation and marine transportation.	A climate change vulnerability index is developed using aviation and marine sectors to assess both biophysical and social components. Adaptation is needed to ensure a service to communities that are dependent on aircraft services.
14	Eijgelaar et al. (2010)	Exploration of the paradox of climate ambassadorship and 'last chance tourism'.	Operators increasingly take tourists to destinations threatened by climate change, with Antarctica and other polar regions as favourites and cruise ship and aircraft as main transport modes. A survey found no evidence for the

n	Paper	Study background	Primary outcomes
			hypothesis that the trips develop greater environmental awareness, change attitudes or encourage more sustainable future travel choices.
15	Gray (2008)	Think-piece in response to previous article on aviation and climate from a meteorology perspective.	Climate change impacts of airports at very low elevation are studied. Changes in humidity and flood patterns will affect low lying airports and aircraft performance.
16	Gultepe et al. (2019)	Review of high impact weather for aviation meteorology.	Even short duration weather extremes affect the take-off performance of aircraft. Improvements are needed to the measurement of weather and modelling approaches associated with aviation forecasting.
17	Hane (2016)	Comment on paper 10, climate change and the impact of extreme temperatures on aviation.	Climate change and extreme temperature may have less economic impact than previously assessed.
18	Hayhoe et al. (2009)	Modelling paper of the climate change impacts on urban energy and infrastructure: A Chicago case study.	A City of Chicago modelling framework enables quantitative estimates of the economic impacts of climate change. It is determined that energy and infrastructure impacts, including airport operations, and covering both costs and savings, are driven primarily by increases in mean annual temperature and secondarily by increases in the frequency of extreme-heat events and decreases in cold days. Even partial success at reducing emissions could produce a disproportionately large reduction in economic costs.
19	Hepburn & Muller (2010)	Article proposing an adaptation levy.	Given the nature and scale of the aviation greenhouse gas emissions challenge, the paper outlines a proposal for an International Air Travel Adaptation Levy (IATAL) to support developing countries.
20	Hu et al. (2016)	Examination of the spatial exposure of Chinese system infrastructure to flooding and drought hazards.	Infrastructure exposure across energy, transport, and waste sectors is considered. Regions identified in China to be particularly affected by flooding covers around 103 million infrastructure users. Sub-sectors including rail, aviation, shipping, electricity and waste water will be particularly affected.
21	Jenamani et al. (2009)	Assessment of the impact of thunderstorms and squalls at New Delhi airport on the environment.	Data between 1995-2005 on thunderstorms and squalls is analysed, with weather statistics generated (temperature, wind speed, humidity & sea level pressure). Overall, thunderstorms have increased 12% since 1950-1980, with a particularly high increase in June (51%) and May (26%).
22	Kim et al. (2016)	North Atlantic oscillation impacts on transatlantic flight routes and clean-air turbulence.	The wind-optimal routes that minimize the total flight time by considering wind variations are modelled between New York and London. Consequently, eastbound wind-optimal routes are faster but have higher probabilities of encountering clear-air turbulence than westbound ones.
23	Kreuz et al. (2012)	Report on consequences of extreme weather on European transportation networks.	Road traffic, freight transport on transport corridors and passenger flows in large cities are particularly affected by delays. Aviation will suffer from extreme weather events in the future due to increased wind gusts and to free capacity currently used as a buffer to weather events being occupied by additional flights.
24	Lee et al. (2019)	Examination of the wind shear increase in the North Atlantic upper-level jet stream.	Wind shear on the North Atlantic upper-level jet stream increased by 15% between 1979-2017. Results indicate climate change may be having a larger impact on the North Atlantic jet stream than previously thought. The effects of climate change and variability on the upper-level jet stream are being partly obscured by the traditional focus on wind speed rather than wind shear.
25	Lopez (2016)	Methodology trialled to assess climate change vulnerability of airports in France.	A vulnerability assessment method is presented, based on a climate change scenario that French airports might face by the year 2100. A risk matrix identifies strengths and weaknesses of the aerodrome. Airport operators can identify where to focus their effort in order to increase their resilience.
26	Mäkelä et al (2013)	Examination of the impact of cold-season thunderstorms in Finland on aviation safety.	Cold-season thunderstorms are rare events, which increase their threat to aviation safety; both pilots and forecasters can be surprised when they occur. Furthermore, especially at high latitudes, these thunderstorms occur often in the dark, which adds to their physiological effect on the pilots. Some of the forecasting tools used in the warm season can also be used in the cold season.
27	Moriarty & Honnery (2004)	Exploration of transport technology and travel volumes out to the year 2050, mainly in industrialised countries.	Major changes in transport technology and fuels are expected, in response to perceived constraints such as oil depletion and global warming. The inevitable uncertainty in long-term forecasting will be exacerbated by these constraints. A larger role for government is to reduce uncertainty and provide a more sustainable transport system.

n	Paper	Study background	Primary outcomes
28	Nemeth et al. (2018)	Analysis of the influence of climate change on European aviation.	The influence of climate change on selected aircraft types and consequently air traffic flow management, environment, fuel consumption, emissions, delays and aviation safety. In particular, changes in temperatures and flight altitudes leads to longer flight times and increased emissions
29	Neumann et al. (2015)	Examination of climate change risks to US infrastructure: roads, bridges, coastal development and urban drainage.	From model outputs, the impacts of climate change in this sector could be large as sea-level rises, temperature increases, and precipitation patterns become more extreme and affect the sustainability of long-lived infrastructure. Economic impacts can be reduced by proactive and cost-effective adaptation measures.
30	Palin et al. (2016)	Examination of seasonal forecast of Winter disruption to the UK transport system.	Relationships examined between the observed and forecast North Atlantic Oscillation and a variety of UK winter impacts on transport in the road, rail, and aviation sectors. This includes weather-related delays to flights leaving London Heathrow Airport.
31	Pejovic, Noland et al. (2009)	An Impact analysis of a short closure at London Heathrow Airport.	The system disruptions assessed are delays, flight rerouting or diversions to alternate airports, and flight cancellations. Estimates suggest values between €700,000 and €1,250,000 for a one-hour airport closure. Carbon costs associated with the closure could add €230,000–340,000, while external cost estimates can range up to €1,400,000.
32	Pejovic, Williams et al. (2009)	Examination of factors affecting the frequency and severity of airport weather delays.	A climate model has been developed for London Heathrow Airport over up to the year 2050. It demonstrates that extreme weather (thunderstorm, snow & fog) increase the chance of weather-related delay by more than 25%, and an increase in wind speed of 1 knot above the mean increases the probability of delay by 8%.
33	Pentelow & Scott (2011)	An impact analysis of international climate policies on the Caribbean tourism industry.	Results from a tourism arrivals model indicate that under current climate policy proposals, reductions in tourist arrivals from major European and North American markets would be negligible, given 'business as usual' growth projections. Only the most stringent policy scenario shows a significant decrease in tourist arrivals. An adaptation policy assessed could provide economic benefits to the Caribbean region.
34	Prussi & Lonza (2018)	A comparison of emission profiles on European aviation and High Speed Rail (HSR) routes.	The study assessed the environmental impact of modal substitution of air transport with HSR, based on seven routes in the EU. The results indicate the advantage of HSR in terms of direct carbon emissions per passenger km. Compared to a base-level scenario of an annual passenger increment of 3.5%, a HSR substitution of around a quarter of passengers is estimated to generate greenhouse gas emission savings of around 22%.
35	Pümpel (2016)	A review of regulatory responses to the impacts of intensifying weather events on aviation safety.	Climate change is likely to lead to a higher incidence of extreme weather events and may change the regional distribution of those events. Aviation regulators may wish to take action to reduce exposure to extreme weather events, and to provide robust safety procedures when such exposures occur.
36	Ren et al. (2019)	An Impacts study of climate warming on maximum aviation payloads.	Climate models are used to examine the impacts of high temperatures on aircraft maximum take-off weight (MTOW) and payload. The most extreme changes are at high latitudes in the Northern Hemisphere. This is a 5% decrease in MTOW, or a reduction in payload of between 8.5% and 19% (aircraft dependent). The global average change is about 1%.
37	Scott et al. (2016)	A report on the Paris Climate Change Agreement and its implications for tourism.	An overview of the key provisions of the Paris Agreement that are most relevant to tourism shows: much strengthened and world-wide participation in greenhouse gas emission reduction ambitions, an enduring framework for increased ambitions over time, improved transparency in emissions reporting and a greater emphasis on climate risk management through adaptation. International air travel is discussed, and aviation industry ambitions are broadly aligned with those in the tourism sector.
38	Storer et al. (2017)	A study on the global response to clear-air turbulence caused by climate change.	Climate model simulations over 2050-2080 are used study the impact that climate change could have on global clear-air turbulence, one of the largest causes of weather-related aviation incidents. Large relative increases in clear-air turbulence are especially found in the midlatitudes in both hemispheres, with some regions experiencing several hundred per cent more turbulence. The largest increases are also experienced in the busiest international airspace.
39	Storer, Gill et al. (2019)	A modelling study to better predict aviation turbulence.	This study applies multi-model ensemble forecasting to aviation turbulence for the first time. A 12 month global trial yields an improvement in forecast

n	Paper	Study background	Primary outcomes
			value at low cost/loss ratios. Using a multi-model approach is an effective way to improve the forecast skill and provide pilots and flight planners with more information about forecast confidence, allowing for more informed decisions about required actions such as diverting around turbulence or requiring passengers and crew to fasten their seatbelts.
40	Storer, Williams et al. (2019)	A review of the dynamics of aviation turbulence, its response to climate change and current forecasting methods.	Turbulence will increase in frequency and strength with climate change, and therefore, turbulence forecasting may become more important. Current methods of forecasting are unable to predict every turbulence event, and research is ongoing to find the best solution to this problem by combining turbulence predictors and using ensemble forecasts to increase skill.
41	Suhrbier (2008)	Impact study of climate change and variability on transport long-range planning and investment.	US Gulf Coast (Alabama to Texas) case study examines average and extreme temperatures and precipitation, along with changes in sea level, land subsidence, and the frequency and intensity of hurricanes. Transport planners are shown to have little or no understanding of the complex climate change issues and need to be increasingly multimodal and collaborative.
42	Thompson (2016)	An overview of climate impacts on the commercial air transport industry.	Sub-sectors such as airports, airlines, aircraft manufacturers, airspace safety and navigation organizations will encounter different climate change effects. Adaptation planning is perhaps most advanced for airports located in coastal regions and concentrates on storm-water management and inundation prevention. Other climate effects on aircraft performance and flight/passenger safety are being investigated but are not yet part of the adaptation-planning landscape.
43	Vorster et al. (2013)	Development of 2050 scenarios for long-haul tourism under the evolving climate change regime.	Three meta-level scenarios are developed and described. Two undesirable scenarios are labelled “grim reaper” & “fallen angel”. In contrast, the desired “green lantern” scenario represents a future where long-haul tourist destinations heed early warning signals and contribute towards realising the desired future. Scenarios show risks decrease if aviation-based tourism hedges against risks, and seizes new opportunities
44	Williams (2016)	A letter on transatlantic flight times and climate change.	Changes in transatlantic flights between London and New York are examined when the atmospheric concentration of carbon dioxide is doubled. A modelled strengthening of the prevailing jet-stream winds causes eastbound flights to significantly shorten and westbound flights to significantly lengthen in all seasons. The extrapolation of results to all transatlantic traffic, assuming no future growth, suggests that aircraft will collectively be airborne for an extra 2,000 hours each year, burning an extra 7.2 million gallons of jet fuel at a cost of US$ 22 million, and emitting an extra 70 million kg of carbon dioxide.
45	Yair (2018)	A review of lightning hazards to human societies in a changing climate.	Reviews trends to assess vulnerability to future lightning activity in different scenarios. Although it is hard to precisely predict what future lightning distributions will look like, the combination of large metropolitan areas, increased population and a warmer climate almost guarantee an intensification of the human exposure to lightning hazard. Aviation will be increasingly affected by thunderstorms, lightning and related weather phenomena, such as hail, heavy rain, turbulence and downbursts.
46	Zhou et al. (2018)	An examination of decreased take-off performance of aircraft due to climate change.	The effects of climate change on the take-off performance of aircraft, including take-off distance and climb rate, are examined and quantified. Changes of temperature and pressure altitude under climate change will lead to longer take-off distances and lower climb rates. For example, the Boeing 737-800 aircraft results show it will require additional 3.5–168.7 metres take-off distance in future summers.

The structure of the discussion of review findings has a logical flow. Initially there is a summary of the sample and paper methodology (Section 3.1), before presenting adaptation as a concept for aviation and climate change (Section 3.2). Sections 3.3 to 3.5 align with the first aim, to explicate significant issues affecting aviation in a changing climate. Section 3.3 covers studies that examine aviation in the wider context of transport and infrastructure. Sections 3.4 and 3.5 are methodological in nature, covering the literature with policy and modelling approaches respectively. The final discussion section (Section 3.6) aligns with the second aim, discussing the aviation industry responses on climate change and adaptation.

3. Discussion of the review findings

3.1 Summary of the sample and methodologies

The 46 references date from 2004 onwards and, as expected, increase in annual numbers until the search in October 2019. Most of the references are either review-based or have a quantitative modelling approach. One concern expressed in the literature is that research tends to focus more on developed than developing countries (Becken, 2013), which is also reflected within the 46 references. Without making a precise definition of a developing country, we note that most references focused on developed countries in North America and Europe. The four case study references outside these areas are studies on: tourism in Caribbean island states (Pentelow and Scott, 2011), the impact of weather at New Delhi airport (Jenamani et al., 2009), the exposure of Chinese infrastructure to flooding and drought (Hu et al., 2016) and the weather vulnerability of aviation and High Speed Rail in China (Chen and Wang, 2019).

Much of the data incorporated in the references is secondary in nature. However, one paper reports a survey to determine the level of environmental awareness amongst cruise passengers (Eijgelaar et al., 2010). Another study interviews tourists (Buckley, 2011) to determine attitudes towards slow travel for leisure travel short breaks. The review-based studies include book chapters (e.g. Bows et al., 2008) or academic journal articles (e.g. Becken, 2013). Many of the references consider climate change and aviation adaptation from a tourism perspective, either developing a review across the whole discipline (e.g. Becken, 2013), or a tourism-focused case study, such as the paper by Pentelow and Scott (2011) on some of the Caribbean island states. A more recent stream of literature focuses on meteorological changes and how aviation should adapt to those (e.g. Gultepe et al., 2019).

3.2 Adaptation as a climate change concept for aviation

In 2016, an international agreement to limit greenhouse gas emissions was brokered by the UN in Paris. This regulatory instrument was originally agreed by 196 countries at the 21st Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) (Scott et al., 2016). As described by Scott et al. (2016), the Paris Agreement provides a significant and much enhanced emphasis on adaptation and building climate resilience, in acknowledgement of the consequences of climate change which had become unavoidable. As reported within the sample publications, the adaptation concept for aviation can be categorized into three elements. Firstly, air travel faces climate change disruptions at airports due to greater and more frequent temperature extremes and changes in precipitation and wind, as well as rising sea levels (Burbidge, 2018; Chen and Wang, 2019; Yair, 2018). Secondly, disruptions occur in the air due to changing atmospheric patterns and less predictable extreme weather events (Cooper et al., 2018; Lee et al., 2019; Storer et al., 2019). Thirdly, there are disruptions from changing patterns in passenger demand as holiday destinations are affected by climate impacts which can make them less attractive and sometimes inaccessible (Debortoli et al., 2019; Hu et al., 2016).

Burbidge (2018) discussed widely the impacts of climate change on various aviation industry stakeholders and shows new pathways towards adaptation and climate change resilience. Based on the outcomes of a EUROCONTROL (European Organisation for the Safety of Air Navigation) workshop, Burbidge (2018) presented four key priorities for taking action: 1) understanding the problem, 2) assessing the problem, 3) actions to adapt and 4) communication and collaboration.

3.3 References linking transport and infrastructure to climate change

Within aviation studies, such as Palin et al. (2016), disseminated findings are broadly relevant across all Government and transport sectors. The sample also includes many references covering transport and infrastructure aspects to be considered in relation to climate change impacts.

There are US-based studies that examine nation-wide infrastructure (roads, bridges, coastal development and urban drainage) impacts (Neumann et al., 2015) or a more regional focus on transport planning practice for four US Gulf Coast states (Suhrbier, 2008). A case study in the city of Chicago (Hayhoe et al., 2010) addresses general weather impacts on energy and infrastructure stakeholders, citing aviation as one affected city department, particularly vulnerable to temperature and snowfall extremes. The goal of such papers is typically to quantify the economic impacts of future climate change effects to inform adaptation decisions.

Two studies in Europe and China consider climate change vulnerability of aviation and high-speed rail (HSR), focusing on the stability and reliability of the entire transportation system. The European study found that HSR is expected to be less affected by climate change and recommends a modal shift on routes where airlines currently compete with HSR, under a collaborative approach between air and rail (Prussi and Lonza, 2018). In contrast, the Chinese study (Chen and Wang, 2019) found that aviation and HSR are both affected by climate change, but in different ways, so interruptions might not appear simultaneously. Therefore, the study recommends that when one travel mode is interrupted, a modal shift should be made easier for passengers to switch their transport options.

A further Chinese study considers the spatial exposure of infrastructure to flooding and drought (Hu et al., 2016). The spatial modelling links users and infrastructure assets, to inform analysis of climate hot spots. Regions particularly affected by flooding and drought showed impacts on infrastructure organizations, including aviation stakeholders.

The European EWENT (Extreme Weather Impacts on European Networks of Transport) project considered the consequences of extreme weather across all transport modes (Kreuz et al., 2012). The study had a three-stage quantitative approach to: 1) examine weather impacts on transport, 2) identify corridors or hotspots, and 3) discuss cost implications. It determined that all transport modes will be affected by delay, particularly on high-density routes. Aviation stakeholders responsible for infrastructure, safety and operators will be particularly affected by more extreme weather events (an increase in wind gusts is stressed), and lower airport capacity from increased demand may add further stress to the system.

3.4 Policy and regulation responses within the literature

Several studies review aviation and climate change policy. As an extra-national sector, aviation was not included in the Paris Climate Agreement. The role of implementation for aviation instruments is the responsibility of International Civil Aviation Organization (ICAO). There has been a long-running debate of economic appraisal for an international air travel adaptation levy (IATAL), which could be international (now the ICAO example), regional (e.g. EU Emission Trading Scheme), or national (Hepburn and Muller, 2010). In a proposal for an adaptation levy, conceptions of financial advantage and social justice are employed to suggest that some profits from aviation generated through greenhouse gas emissions should be leveraged to pay for adaptation among the disadvantaged (Hepburn and Miller, 2010).

If aviation greenhouse gas emissions are counted similarly to national greenhouse gas emissions, it would rank as a top ten emitter (Campos, 2016), making the threat of inclusion in regulation a more immediate financial concern for aviation than adapting to the current effects of climate change on operations. However, when attention is shifted to the tourism sector, a significant stakeholder in civil aviation, the need to adapt to climate change impacts becomes more immediate. Almost all nations are included in the Paris Agreement which includes provision for both mitigation and adaptation through building climate resilience (Scott et al., 2016).

A policy response is also needed from a wide range of aviation stakeholders (Storer, Gill et al., 2019). For example, aviation safety regulators will have to respond to the impacts of intensifying weather events on flight safety, by developing more robust safety procedures and new meteorological services (Pümpel, 2016; Storer, Gill et al., 2019).

3.5 Modelling aviation adaptation to climate change

The modelling effort reported within the references ranges from initial calculations and statistical analysis to in-depth and complex quantitative modelling. Initial research into climate impacts affecting aviation were centred on traditional types of weather-related disruptions. These include increased wind speeds as well as changing patterns of thunderstorms, lightning, snow, and fog (Pejovic, Williams, Noland and Toumi, 2009; Yair, 2018). EUROCONTROL identified adaptation issues for air traffic management, particularly through projected changes in passenger demand based on local temperature changes, sea-level rise impacts on airport capacity and the effects of increased storminess for on-route operations (Burbidge et al., 2011).

The focus is typically on direct weather impacts (from climate change) on the aviation system, but some models can incorporate associated complications such as clear-air turbulence (e.g. Storer, Gill et al., 2019), and generate a range of outcomes, such as safety as well as the standard cost implications. To demonstrate the factors typically involved, Burbidge et al. (2011) model three aspects related to the effects of climate change on air traffic management: 1) shifts in demand, 2) loss of airport capacity, and 3) increase in extreme weather events.

Hane (2016) examines the impact of extreme temperatures on transatlantic aviation, calculating flight times between New York LaGuardia and Los Angeles airports that incorporate data on take-off weight, fuel, load, aircraft design and take-off power. Coffel et al. (2017) model rising temperatures on aircraft take-off performance across five aircraft designs and nineteen major airports. It is estimated that on average, 10%-30% of flights may require some weight restrictions, a non-trivial cost. Weight restrictions will particularly affect mid-to-large aircraft and airports with short runways, high temperatures and a high elevation. Similarly, Ren et al. (2019) found that an increase in extreme temperatures may lead to a decrease in aircraft maximum takeoff weight by 5% and decreased payload of 1% as a global average. Gultepe et al. (2019) findings further add, that as temperatures increase, airlines might have to reschedule flights in the future to avoid the hottest times of the day.

Nemeth et al. (2018) found that weather changes caused by climate change will lead to longer flight times, delays and increased emissions. By analyzing an actual flight in various conditions and flight levels they show the importance of changes in flight operations to adapt to the new conditions.

A cluster of references consider climate impacts to aviation through changes in clear-air turbulence (CAT). Storer, Gill et al. (2017) run climate model simulations 2050-2080 for CAT and show that under a high warming scenario it will more than double in some areas, particularly at higher altitudes. Kim et al. (2016) examine North Atlantic oscillation impacts on transatlantic flight routes, modelling the route between John F. Kennedy International Airport, New York and London Heathrow Airport. Climate change related weather impacts will cause deviations in flight speeds and pathways, affecting long-haul strategic planning. Williams (2016) generates climate simulation models of flights between London and New York to examine potential high-level impacts of climate change on transatlantic flight times. The effect of doubling atmospheric carbon dioxide from pre-industrial levels would increase flight times overall, although additional work is required to consider turbulence and contrails. Some research identifies where impacts can already be attributed to climate change. According to Lee et al. (2019) as an outcome of climate change, wind shears on the upper levels of the North Atlantic jet stream have increased by 15% during the studied period of 1979-2017 causing more turbulences and hazards for flights.

Coffel and Horton (2015) examine the impact of extreme temperatures on aviation using circulation models and projections for one aircraft (Boeing 737-800) and four airports (Phoenix, Denver, New York LaGuardia and Washington Reagan National). They demonstrate expected economic impacts from climate change on the airline industry, including airports that may need longer runways. Zhou et al. (2018) reported similar findings from takeoff performance data of a Boeing 737-800 at 30 major airports from 1976 to 2100. With increasing temperatures, takeoff distances increase while the climb rate decreases.

Mäkelä et al. (2013) statistically show the impact of cold-season thunderstorms in Southern Finland on aviation safety, using 2011 data. The rare and unusual nature of these severe weather events impede pilot training and cause knock-on effects for aviation safety and weather forecasting.

Modelling is also used to inform aviation scenario development. Moriarty and Honnery (2004) performed an initial review that considers world transport forecasts to 2050. They grouped studies into possible, preferred and probable transport futures to clarify different approaches to address uncertainty in future scenarios. Vorster et al. (2013) built a suite of four scenarios focused on long-haul tourism up to 2050, considering seven underlying drivers. These scenario storylines can be useful for aviation stakeholders, particularly for decision making by global bodies and policymakers.

In summary, many of the modelling approaches provided indicative and exploratory studies. More detailed quantitative approaches within a suite of models did not necessarily include methodological details in the publication. Suggested modelling improvements include increased spatial resolution, better data synthesis and clearly communicating uncertainty within forecasts (Thompson, 2016).

3.6 Aviation industry responses

This section discusses aviation industry responses within the same. There are 32 out of 46 papers which state an aviation industry stakeholder, either specifically (e.g. name a particular airport) or generically (e.g. as “airports”). The aviation industry has been categorised according to the main types stated: airports, airlines and other stakeholders. Table 2 shows the aviation industry stakeholder within these papers, together with the industry response (other current or needed), and these has either been directly stated within the paper or implicitly implied.

Table 2 The industry response from 32 full-text papers

		Industry stakeholder				
n	**Paper**	**Airport**	**Airline**	**Other**	**Stakeholders stated**	**Industry response**
4	Budd & Ryley (2012)	✓	✓	-	Airlines testing for biofuels and airports at risk of flooding are listed (e.g. Schiphol, Amsterdam and Louis Armstrong, New Orleans are below mean seal level).	Ways how the aviation industry should adapt are discussed. This includes airports developing effective strategies in response to adverse weather conditions, and Governments implementing vulnerability assessments for key national operators, including aviation stakeholders.
5	Burbidge (2016)	✓	-	✓	EU airports are generically stated. The work is based on a survey of 35 EU stakeholders, mainly Air Navigation Service Providers and airport operators.	The focus is on how European airports can adapt to climate change.
6	Burbidge (2018)	(✓)	(✓)	(✓)	This paper is a generic review across airports, airlines and other stakeholders (e.g. Eurocontrol).	A review of action points for adaptation in the aviation industry.
7	Burbidge et al. (2011)	✓	-	✓	34 European airports as stated as being at flooding risk, from 3 anonymous reviews. The role of air traffic management (ATM) operators is also discussed.	Various ways in which the ATM part of the industry needs to adapt to the impacts of climate change.
8	Butterworth-Hayes (2013)	✓	-	✓	Many airports are mentioned with current climate proofing plans such as LaGuardia and Schiphol airports. Other stakeholder responses include: Eurocontrol, TRB, NATS, ICAO & ACI.	Provides an overview of key bodies in the aviation industry with adaptive response.
9	Chen & Wang (2019)	(✓)	-	(✓)	Various generic mentions of airports and railways in China.	Cover disruption to the HSR (High Speed Rail) and aviation industry.
10	Coffel & Horton (2015)	✓	-	-	4 airports examined: Phoenix, Denver, London Gatwick & Ronald Reagan Washington.	Airports may need to develop longer runways and space-constrained airports will face more weight-constrained days.
11	Coffel et al. (2017)	✓	-	-	Performance models are developed using data from 19 airports around the world.	Airports will need to adapt, particularly those with short runways and high temperatures, or those at high elevations.
13	Debortoli et al. (2019)	(✓)	-	✓	Airports are stated generically, but the main paper focus is on local communities as stakeholders.	Airport infrastructure needs to be adapted such as runway size, lighting, low visibility equipment.
14	Eijgelaar et al. (2010)	-	-	✓	The cruise industry is stated a stakeholder.	The cruise industry needs a greater consideration of climate change adaptation.
15	Gray (2008)	✓	-	-	There is a useful summary of data from Denver & Phoenix airports.	Airports at very low-level elevations need to adapt.
18	Hayhoe et al. (2009)	(✓)	-	✓	City departments, including Aviation stated in the paper, are affected.	Extremes in temperature and snowfall will affect infrastructure costs, including airport operations.
19	Hepburn & Muller (2010)	(✓)	(✓)	✓	Generically covers a range of aviation stakeholders, particularly policymakers.	As well as airport and airlines, national, regional (e.g. EU ETS) and international policymakers are affected.

		Industry stakeholder				
n	Paper	Airport	Airline	Other	Stakeholders stated	Industry response
20	Hu et al. (2016)	✓	-	-	Assesses Chinese airport (around 140) assets, users and hazard risk.	Aviation industry in China is exposed to flooding hazards and will need to adapt.
21	Jenamani et al. (2009)	✓	-	-	Case study of a specific airport (India Gandhi International airport, New Delhi).	Weather patterns are changing, and the aviation industry needs to adapt.
22	Kim et al. (2016)	✓	-	-	The modelling covers routes between 2 international airports: John F. Kennedy, New York and Heathrow Airport, London.	Industry needs to adapt in terms of long-haul strategic flight planning.
23	Kreuz et al. (2012)	✓	(✓)	(✓)	Case studies cover 25 major EU airports. Airlines mentioned generically. General mention of stakeholders across all modes - for aviation it is infrastructure, safety & airport operators.	For the industry, flight operations will need to be modified and made more efficient in order to mitigate longer flight times caused by weather changes.
25	Lopez (2016)	✓	-	✓	The work is by STAC (French technical centre for civil aviation) in association with French airports (not named).	Develops a risk matrix of climate impacts and adaptation options for airports to use.
26	Mäkelä et al (2013)	✓	-	-	The work is based in Southern Finland and so there is reference to Helsinki-Vantaa airport.	Shows thunderstorm implications for pilot training, aviation safety and weather forecasting.
28	Nemeth et al. (2018)	✓	-	-	The analysis covers 3 international airports: Moscow Vnukovo, Pisa and Koŝice.	Flight operations need to become more efficient in order to moderate longer flight times.
29	Neumann et al. (2015)	-	-	✓	Study looks at US infrastructure in general, including aviation ground operations.	Work remains to better understand impacts on air transportation systems.
30	Palin et al. (2016)	✓	-	-	Covers UK airports, particularly London Heathrow Airport as the largest international airport.	More skilful seasonal weather forecasts can now be used by the aviation industry to manage major transport disruptions.
31	Pejovic, Noland et al. (2009)	✓	(✓)	-	London Heathrow Airport case study generates cost values applicable to other airports; it is flight focused but specific airlines are not named.	Airports need to prepare for more severe weather events resulting in airport closures.
32	Pejovic, Williams et al. (2009)	✓	(✓)	-	The London Heathrow Airport case study is like many similar studies (including paper 31 part of same research project) is flight focused but does not name specific airlines.	Changes in weather should be considered by the industry in future airport planning and expansions.
33	Pentelow & Scott (2011)	✓	-	-	The modelling is based on travel from 8 major international airports.	The tourism and aviation industries need to prepare for possible reduction in tourist arrivals due to stricter emission reduction policies.
34	Prussi & Lonza (2018)	✓	-	✓	There are 6 international airports in the comparison (London Heathrow, Paris Charles de Gaulle. Amsterdam Schiphol, Germany Frankfurt, Rome Fiumicino and Milan Linate) as well as the railway sector.	Airports in locations with High Speed Rail as a transport alternative need to be aware of carbon emission comparisons and modal shift implications.
35	Pümpel (2016)	(✓)	(✓)	✓	Only generic mention of airports and airlines. A range of aviation stakeholders are included (e.g. FAA, NOAA & ICAO).	A broad array of aviation stakeholders, including manufacturers, air traffic control specialists, airport operators,

		Industry stakeholder				
n	Paper	Airport	Airline	Other	Stakeholders stated	Industry response
						regulators, and air carriers will need to adapt their technologies as the frequency, intensity, and location of intense weather events changes.
37	Scott et al. (2016)	-	-	✓	As from tourism stakeholders, ICAO is covered in the review.	Aviation is excluded from the agreement, but there should be a new emphasis on climate risk management in industry adaptation plans.
41	Suhrbier (2008)	✓	-	✓	3 airports along the US Gulf Coast (Alabama to Texas) examined, particularly affected by climate change. Other transport planning stakeholders are also covered.	Transport planning practices need to be further developed by the industry. Adaptation can use existing transportation planning process if it includes greater range of impacts, institutional arrangements and partnerships.
43	Vorster et al. (2013)	(✓)	(✓)	-	Airports and airlines (national flag carriers & low-cost airlines) are generically stated.	The scenarios discussed require responses from the aviation industry.
44	Williams (2016)	✓	(✓)	-	The paper covers East Coast US to West EU flights. John F. Kennedy, New York and London Heathrow Airport are stated once; airlines are not specified but relevant.	The industry will need to consider trade-offs to plot transatlantic routes that minimise journey time but do not overly increase turbulence potential or climate impact.
46	Zhou et al. (2018)	✓	-	-	30 major international airports are under consideration.	Airports will need to consider that under climate impacts increased take-off distance and decreased climb rate can improve flight safety.

Note: ✓ = specifically state a stakeholder; (✓) = generically state a stakeholder

The most pertinent industry response in the references reviewed relates to airports, typically the significant hubs. For example, London Heathrow Airport analysis that addressed British Airways delays (Palin et al., 2016) and New Delhi Airport where weather impacts were studied (Jenamani et al., 2009). While sustainability plans do not address climate change impacts and adaption, airports with good practice climate-related components in such plans were reported by Thompson (2016) to be Atlanta, New York and London Heathrow.

Even short duration severe weather events can trigger airport closures with extensive implications. Based on a study of short closures at London Heathrow Airport, the resulting delays, cancellations, flight rerouting and diversions to alternate airports both increased emissions through additional fuel use and highlighted the need to adapt to increases in the frequency and severity of weather events (Pejovic, Williams et al., 2009). Airports at very low-level elevations are likely to be more affected by airport closure and aircraft performance (Gray, 2008) where Denver and Phoenix for example, will need adaptation plans for impacts such as flooding, low clouds and higher temperatures, while others will be exposed to sea level rise. As documented by Budd and Ryley (2012), many airports are only 10-20ft above mean sea level (Cairns Airport, Australia; Nice Airport, France; John F. Kennedy Airport, New York), with a few below mean sea level (Schiphol Airport, Amsterdam; Louis Armstrong International Airport, New Orleans). In addition, episodes of severe weather and lighting hazards, as discussed by Yair (2018), pose increased hazards to airport infrastructure, risking interruptions of flight operations. It could be summarised, therefore, that airports are currently having to adapt to adverse weather outcomes such as flooding, but most adaptation strategies presented in the literature focus on future requirements.

Although levels of climate change hazard understanding vary among airport operators, a lack of information and awareness are a barrier to action for airports (Burbidge, 2016). Some airports (e.g. New York LaGuardia, Amsterdam Schiphol) have developed an initial adaptation response, as have some aviation bodies (e.g. EUROCONTROL and ICAO), as documented by Butterworth-Hayes (2013). Lopez (2016) presents a practical methodology and potentially a tool, for airports to assess their vulnerability to climate change though identifying impacts, calculating probability of occurrence and evaluating the risks. Application of the tool could become automatic for aerodrome operators.

In terms of the non-airport industry stakeholders within the literature, and as shown in Table 2, airlines are only generically stated. It is typically harder for researchers to access data from airlines, given business sensitivities, but it is also a reflection that climate change adaptation measures are more urgently required at airports than airlines. A wide range of other aviation industry stakeholders are stated in the references, including air traffic management organisations, various policymaking and regulatory bodies, and wider transport planning and infrastructure departments.

4. Conclusions

Literature linking aviation and climate change is expanding as a response to the increasing occurrence and prominence of climate change impacts. While the aviation sector has long been referenced as contributing to the causes of climate change, the need for aviation to adapt to the consequences of climate change has not been as well researched or considered by the industry.

The literature on climate change and adaptation in aviation typically covers divergent approaches for social and physical issues. The social literature undertakes reviews of literature and policy-making, and physical research focuses more on quantitative modelling of aviation and weather data. Of the disciplines that align with aviation, tourism generates the most references linking aviation and climate change adaptation. Understanding climate change adaptation options for aviation faces methodological challenges associated with uncertainty in passenger behavior, policy constraints and technological innovation as well as uncertainty in the physical evolution of climate impacts. Research is hampered by the need for access to both aviation and weather data, and challenges from the multidisciplinary nature of the approaches.

The various international case studies offered a range of initial findings. One pertinent theme is the global reach but spatial context, such that aviation is locally situated in airports, represents regional interests though national airlines and crosses geopolitical boundaries in its operations. These extensive networks of responsibility and interest involve all levels of governance from city planning to the International Civil Aviation Organization, and a range of actors from individual passengers to multinational corporations and institutions.

Climate change impacts have policy implications for many aviation stakeholders. As in other sectors, many players within the aviation industry do not have the funding or are too short-term focused in their business, to invest in longer-term adaptation planning processes. Aviation industry stakeholders represented within the climate change adaptation literature tend to be the larger airports within the developed world. There is an increasing need for wider engagement within the aviation industry to develop and implement adaptation plans to anticipate and manage climate change risks. Social justice implications of aviation-related climate change policies will become more visible and urgent with continued impacts.

Much of the research identified has been engineering and data driven, and so there is scope for further research using more qualitative approaches from the social and behavioral sciences. As the growth in climate change adaptation literature for aviation shows, the concepts of climate change mitigation and adaptation are being reframed for the industry. Further research should also review, benchmark and provide best practice practical recommendations for the implementation of adaptation plans within the aviation industry.

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