

## **Chapter 2. An international dimension: Aviation**

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### **Structured Abstract**

**Purpose:** To examine the relationship between aviation and climate change, and the international dimensions of air transport,

**Methodology/approach:** An examination of aviation's impacts on the global climate, mitigation strategies to lessen aviation's climate change impact and on the possible consequences of climate change for commercial aviation.

**Findings:** Although a range of mitigation measures have been developed and implemented to reduce aircraft emissions in the short-term, with some environmental benefit, there is a real need for the aviation sector to identify the possible impacts of climate change on air travel operations, including both aircraft in flight and operations at airports. A further challenge will be to devise plans that will address the vulnerabilities and thus ensure safe aviation-related operations.

**Social implications:** The climate change impacts of aviation will adversely affect society. In addition, some individuals may have to reduce or stop flying as a result of increased taxes and legislation implemented in response to climate change.

**Originality/value of paper:** There is a novel focus on the adaptation challenges for the aviation industry in response to climate change.

### **Introduction**

In a little over one hundred years between the first tentative twelve-second flight of the Wright brothers' biplane and today, civil aviation has rapidly developed from a dangerous and unreliable form of mobility into a multi-billion dollar commercial enterprise that facilitates the routine international mobility of two billion passengers and tens of millions of tonnes of airfreight every year. Although the current economic downturn has, albeit temporarily, depressed consumer demand for air travel, one of the defining features of mid-twentieth and early twenty-first century commercial aviation has been its seemingly

inexorable expansion. Between 1945 and 2000 global air passenger traffic grew at an average rate of 12% per year (Hanlon, 2007), and current forecasts suggest that the industry will grow by 4-5% per annum between now and 2020 (IATA, 2011).

For affluent members of the global economy, flying constitutes a normal and routine mode of long-distance transportation that enables professional and personal relationships to be conducted at a distance and renders even the most far-flung destinations within reach. The aviation industry, furthermore, provides direct and indirect employment to hundreds of thousands of people worldwide, enabling individuals, goods, capital, and knowledge to flow around the world, and metaphorically bringing people and places closer together in time and space. Yet while Governments, businesses, and individual citizens have variously championed aviation's apparent socio-economic and cultural benefits, critics have drawn attention to the socio-spatial inequalities in the provision and use of air services, and climate scientists and environmentalists have alerted us to the unpalatable yet inescapable truth that aircraft operations, like so many processes of capitalist production and human activity, impose a significant burden on both the local and the global environment.

The manufacture, transportation, and decommissioning of airframe and engine components, for example, generates greenhouse gases and toxic waste, while routine aircraft operations are known to contaminate ground water, degrade the acoustic environment and local air quality around airports, and perturb the global climate. Growing public awareness of aviation's deleterious environmental effects, combined with consumer unease about airport expansion, has caused aviation to become an increasingly emotive subject with the 'rights' of airline passengers to fly, relatively unhindered, around the world juxtaposed against the rights of others to be protected from the noise, human health implications, and global environmental impacts such aerial mobility creates.

In a departure from much of the existing scientific and popular literature on the subject of aviation and the environment (see Bows, 2010; Cairns and Newson, 2006; Daley, 2010; Randles and Bows, 2009), this chapter focuses not only on aviation's impacts on the global climate, but also on the mitigation strategies that are being pursued to lessen aviation's climate impact and on the possible consequences of climate change for commercial aviation. In order to address these objectives, the chapter is split into three main sections. The first offers a brief review of current scientific understandings of aviation's contribution to anthropogenic climate change. The second examines the mitigation strategies that have been, and could be, adopted by airlines and airports to lessen some of the climate impacts that have been identified, while the final section discusses how a changing climate may impact on the aviation industry and describes some of the climate adaptation measures that may be required as a result.

### **Aviation and climate change**

While the development and use of global climate models and general circulation models to forecast changes in the world's climate remains controversial, by far the majority of scientific research contends that the earth's climate is changing rapidly. Moreover, it is widely accepted that the speed of this change is directly related to human activities which, since the start of the industrial revolution in the 19<sup>th</sup> Century, have released vast quantities of greenhouse gases into the atmosphere which perturb the global climate and lead to a net increase in world temperatures.

Although commercial aviation is by no means the largest anthropogenic source of greenhouse gas emissions (current estimates suggest the sector is responsible for generating 2-3% of all carbon dioxide (CO<sub>2</sub>) emissions and 12% of all transport-borne CO<sub>2</sub> pollution (IATA, 2011)), continued emissions reductions in other sectors combined with a net increase in flights means that commercial air travel represents one of the fastest growing sources of pollution (ibid. 2011). In the UK alone, growing demand for air travel means that CO<sub>2</sub> emissions from aviation are forecast to grow from 37.5 million tonnes in 2005 to 59 million tonnes by 2030 despite the introduction of new, more fuel

efficient, aircraft (Anderson et al, 2007; Department for Transport, 2007). At the global level, as much as 5% of all CO<sub>2</sub> emissions may be attributable to aviation by 2050 (IATA, 2011).

Although concern about the possible effects of aircraft pollution on the environment was first articulated in the late 1960s and early 1970s (Broderick, 1978), it is only within the last few years that scientists have begun to understand not only the complex chemical interactions that occur between different pollution species but also begin to quantify how their presence alters the atmosphere's radiative balance (the proportion of solar radiation that is absorbed by the atmosphere as opposed to being reflected back out into space) and thus contributes to climate change (see Bows, 2010; Bows et al, 2008; Bows et al, 2009; Lee et al, 2009; Mendes and Santos, 2008; Randles and Bows, 2009).

When jet fuel is burnt in an aircraft's engine a range of pollution species, including (but not limited to) water vapour, carbon dioxide, nitrous oxides, and particulates, are produced. While the production of certain chemical species, including CO<sub>2</sub>, is a direct function of fuel burn, the quantity and proportion of other pollutants that are formed varies according to a range of parameters, including core engine temperature, thrust settings, the age and the type of the engine, the precise chemical composition of the fuel, and how well an individual engine has been maintained. Furthermore, the impact these different pollutant species exert on the global climate is understood to vary depending on the altitude at which they are emitted and the prevailing atmospheric conditions at the time of their release (see Cairns and Newson, 2006).

Volumetrically, water vapour is the most significant component of aircraft exhaust yet its contribution to anthropogenic climate change has only recently been recognised. In the cold and rarefied air at 30,000ft, the water vapour that is contained within the exhaust plume immediately condenses. If the upper atmosphere is relatively dry, the vapour quickly evaporates, but if the air is saturated, evaporation cannot occur and white 'contrails' (condensation trails)

form behind the aircraft. Depending on the density of local air traffic and prevailing wind and atmospheric conditions, these contrails can persist for many hours and can seed vast cirrus cloud systems that can cover hundreds of square kilometres of sky.

It is believed that the presence of these anthropogenic cirrus clouds interferes with normal atmospheric thermal exchange processes. Depending on the latitude and the time of day that they form, contrails can variously cool the earth during daylight hours (by reflecting sunlight back out into space) but warm the planet at night by acting as a blanket and trapping heat. Research by Williams et al (2002) has suggested that one possible way to reduce the climate change effect of contrails would be to restrict cruise altitudes to prevent contrail formation. However, the balance between the potential climate benefits and dis-benefits of this proposal need careful consideration. Lower cruise altitude, while hindering contrail formation, would result in higher fuel burn and a net increase in emissions as most jet aircraft are at their most fuel efficient at cruising altitudes of around 35,000ft.

After water vapour, the second most voluminous component of aircraft exhaust is carbon dioxide (CO<sub>2</sub>). Possibly owing to the fact that its production can be easily quantified (3.16kg of CO<sub>2</sub> is always produced for every 1kg of fuel that is burnt, irrespective of flight stage, engine setting, or altitude) and that its impact on the global climate is well known, the causes and consequences of rising atmospheric concentrations of CO<sub>2</sub> have received considerable scientific and political attention. Although, molecule-for-molecule, CO<sub>2</sub> is a relatively weak greenhouse gas, the quantities with which it is released and the fact that it can remain in the atmosphere for over 100 years render it a considerable cause for concern (Archer, 1993). As a consequence, most of the existing mechanisms for mitigating greenhouse gas emissions, such as the European Union's Emissions Trading Scheme, have focused on carbon dioxide (see Mendes and Santos, 2008, for a discussion of the economic instruments that are being used to address CO<sub>2</sub> emissions in Europe).

In addition to water vapour and carbon dioxide, other non-CO<sub>2</sub> species, including nitrous oxides (which while not greenhouse gases themselves influence the production and destruction of the greenhouse gases ozone and methane), are also believed to exert a significant short-term influence on the radiative balance and further exacerbate aviation's climate impact (Cairns and Newson, 2006; Mendes and Santos, 2008).

Despite a lack of any global scientific or political consensus on what constitutes an 'acceptable' level of greenhouse gases or climate change, many scientists believe that any global temperature rise that exceeds 2°C above pre-industrialisation levels will have 'dangerous' consequences for the earth and its ecosystems (see Bows et al, 2009). Growing awareness of aviation's impact on the global climate has raised challenging questions about our reliance and apparent 'addiction' to flying. Environmental groups, including Greenpeace, enoughenough.org, Airport Watch, and Plane Stupid, local anti-airport expansion campaigns such as HACANClearskies (who oppose expansion at London's Heathrow airport), individual travellers, and even airlines, airports, and air transport regulators, have all expressed concern about aviation's environmental impact. Reflecting their different political (and often commercial) standpoints and ideologies, these groups have promoted a range of policy options, from imposing high taxes to dramatically reduce consumer demand, scrapping all proposed airport developments, and promoting alternative slower modes of travel, to operating existing aircraft in a more fuel-efficient manner and investing in new and less carbon intensive aircraft technologies, to reduce the sector's present and future climate impact.

### **Climate change mitigation measures for aviation**

In recognition that aviation contributes to climate change and the urgent need to improve the sector's environmental performance and mitigate some of its most serious environmental effects, a range of new technologies, operating procedures, and policy instruments have been introduced. The International Air Transport Association (IATA), for example, has identified a range of possible options, including retrofitting aircraft with winglets to reduce

aerodynamic drag, replacing the current fleet of aircraft with new designs, and using alternative fuels, which, it is claimed, could reduce aviation emissions by 20-30% per aircraft (IATA, 2009). Elsewhere, individual airports and air navigation service providers have reconfigured the airspace architecture around airports to accommodate more efficient flightpaths, while airlines are trialling alternative fuels and less carbon intensive operating practices. In the subsections that follow we review some of the new aircraft operating procedures and aeronautical technologies that are being developed, and discuss the behavioural changes individual travellers are pursuing in an effort to minimise the environmental impact of their flights.

### *New operating procedures*

During the last couple of years, a range of revised operating procedures have been introduced by airlines, airports, and air navigation service providers to reduce fuel costs and lower emissions. Many airlines, including easyJet at Stansted<sup>1</sup>, have implemented single-engine taxi operations at major airports and instruct their pilots to shut down one engine after vacating the runway on arrival and taxi to the gate using power from the remaining engine. This practice lowers engine wear and reduces fuel consumption, fuel costs, and emissions. The technique is, however, only currently certified for use with a limited number of aircraft and it does impose sequencing implications for air traffic control (aircraft taxiing on a single engine need to be given a clear and uninterrupted route to their gate) and is therefore not suited for use at all airports<sup>2</sup>. Other operational improvements include enhanced flight sequencing which helps ground movement controllers reduce the length of time (and associated emissions) aircraft spend queuing on a taxiway before take-off.

As well as improving environmental performance on the ground, new airspace protocols and increasingly sophisticated navigation and communications technologies are enabling more efficient use of airspace. Improved schedule coordination and slot control increasingly facilitates continuous climb departures (CCDs). CCDs expedite an aircraft's climb to its initial cruising

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<sup>1</sup> Airside operations manager, London Stansted Airport, personal communication, 2011.

<sup>2</sup> Air traffic controller, London Stansted Airport, personal communication, 2011.



altitude and dispense with the need for an aircraft to climb inefficiently in stages and be held at intermediate altitudes. Similarly, continuous descent arrivals (CDAs) enable aircraft to continuously descend from their cruising altitude to the runway without being held at intermediate flightlevels. Both CCDs and CDAs improve flight efficiency and reduce fuel burn and emissions, but they may require changes to be made to the airspace architecture around airports and demand that flightcrew and air traffic controllers are trained in their use.

In the en-route flight phase, the increased use of user-defined trajectories, the identification and use of optimum cruise altitudes, precision area navigation, flexible use of airspace, and functional airspace blocks are helping to maximise en-route capacity, minimise unnecessarily circuitous and inefficient routings, and reduce emissions. In Europe, the Single European Skies initiative ultimately aims to eliminate many of the current inefficiencies that result from the continent's fragmented airspace structure (a legacy of the airspace being divided along national boundaries). However, unresolved geopolitical issues have restricted the initiative's progress.

### *New technologies*

While new operating techniques do confer some environmental benefit, they do not tackle the root cause of the majority of aviation-borne pollution, that is, the aircraft themselves. Despite numerous advances in avionics and automated flight management systems since the end of Second World War, the fuels, propulsion systems, and basic airframe configurations (i.e. slender fuselages, jet engines, and swept back wings) have not changed substantially during the last 60 years and a number of new radical aircraft and engine designs have been proposed in the hope that they will confer improved aerodynamic and environmental performance (Marks, 2003). Radical designs, including blended wing airframes, strut-braced wings, and open rotor engines, have been proposed as one way to reduce fuel burn and lower emissions (Daviss, 2007). However, these ideas remain at the experimental stage and it will take many years of testing and development before they are certified for commercial use.

A further area that has seen considerable development in recent years is in the area of aviation alternative fuels, particularly biofuels (see Warwick, 2007). Worldwide, the commercial aviation industry consumes around five million barrels of jet fuel per day, (around 240 million tonnes per year). Fuel represents a major proportion of an airline's costs and airlines are particularly vulnerable to fluctuations in cost and supply. The dynamic price of oil, combined with concerns about long-term energy security and increasingly stringent international targets for reducing CO<sub>2</sub> emissions, have collectively driven the development of alternative, more environmentally sustainable, aviation fuels.

Although the process of transesterification, through which certain types of vegetable oil can be converted into biodiesel, has been performed since the 1940s, it is only very recently that aviation-grade biofuel has been produced. The earliest (so-called 'first generation') biofuels were used to power internal combustion engines in road vehicles, but while they were suitable for use in road transport, the high oxygen content and low freezing point of the fuels rendered them unsuitable for use in aircraft as the fuels were heavy and would congeal in the cold air at 35,000ft. New production techniques appear to have overcome many of the limitations associated with the earlier fuels and a growing number of major international airlines, including KLM, Virgin Atlantic, Air New Zealand, Iberia, Thomsonfly, and Continental Airlines, have performed test flights during 2009, 2010, and 2011 using different combinations and blends of biofuel derived from, amongst other things, algae, jatropha, coconuts, and camelina, an inedible green shrub (O'Connell, 2009).

While these flights confirmed that biofuels could be used to safely power large commercial jet aircraft, the challenges of ensuring an adequate supply of feedstock and accurately quantifying the life cycle emissions of the fuels remain, as yet, unresolved. Nevertheless, indications from within the industry suggest that major airlines think that biofuels are viable alternatives to conventional fuel. In February 2010, British Airways (BA) announced plans to construct a biofuel plant in East London that would convert domestic refuse

into aviation-grade biofuel that would power BA flights from London City Airport (Arnott, 2010). Later that year, the German national carrier, Lufthansa, announced its intention to use biofuels to power revenue passenger services between Hamburg and Frankfurt (Lufthansa, 2010).

In addition to pursuing biofuels, a number of independent research groups are experimenting with other alternative energy sources for aircraft, including solar power, hydrogen, and electricity (Bradbury, 2007; Bremner 2008; Harris, 2003). However, at the time of writing, these power sources remain at the early stages of development.

### *Behavioural change*

Despite the industry's focus on alternative technologies and more environmentally-efficient operating procedures, one the easiest and quickest ways in which the environmental impact of aviation could be reduced is if individual travellers flew less frequently, people consumed fresh, local produce that is in season and did not demand a ready supply of consumer goods which have been air-freighted half way around the world. Tellingly, however, recent research has indicated that while some individuals are prepared to be more 'green' in certain areas of their lives (by, for example, cycling or walking rather than taking the car for short journeys), the majority of people are unwilling to change their air-dependent lifestyles (see Barr et al., 2010; Becken, 2007; Department for Environment, Food and Rural Affairs, 2008a; Leroux, 2009). Ryley and Davison (2008) discovered that individual propensity to fly is so strong that only a small proportion, 8%, of their survey respondents were trying to reduce the number of flights they took for environmental reasons.

In an attempt to atone for some of the environmental damage a flight causes, a number of airlines and independent providers offer passengers the option to 'offset' the carbon emissions their flight creates by investing in schemes that remove an equivalent amount of carbon dioxide from the atmosphere, or prevent its release elsewhere by, for example, planting trees or supporting the use of alternative energy (Gössling et al, 2007). While some claim that carbon

offsetting is a useful tool for raising consumer awareness, critics have suggested offsetting constitutes little more than a way for profligate polluters to soothe their conscience (Ma'anit, 2006).

Given that many people are apparently unwilling to reduce their personal consumption of air travel and air-freighted goods, attempts to get people out of the air and on to the ground would appear doomed to failure. However, as the development of high speed rail lines in continental Europe has shown, trains have the potential to compete effectively with aircraft on short haul routes (Keeley, 2009).

When alternative modes of travel do not represent a viable option, whether because of time or monetary constraints (ironically it can be cheaper to take a domestic flight in the UK than undertake the same journey by rail), airlines and airports are actively trying to reduce the environmental impact of their operations. Airlines, including the UK-based FlyBE and easyJet have used consumer concerns about the environment in their marketing and have stressed that their modern, more fuel efficient aircraft and relatively high passenger load factors, mean that the environmental impact of their services is lower than that of many of their competitors. Such strategies may confer significant commercial benefit for the airlines concerned - a survey of passengers at Liverpool John Lennon Airport in the UK revealed that nearly half of the respondents differentiated between airlines based on their perceived environmental 'friendliness' (Mayer et al, 2011) – but may ultimately lead to a net increase in flights and emissions if passengers believe that certain services are less environmentally damaging and fly more as a consequence.

A further behavioural issue, and of key concern for airports, relates to surface access and the need to reduce the proportion of trips staff and passengers make by private transport (T. Budd et al., 2011). A range of technology and policy options have been proposed, including vehicle sharing, home telepresence (to reduce the numbers of so-called 'kiss and fly' trips), technologies for facilitating off-airport check-in and baggage drop off, and subsidises for

public transport. However, while there is a moral (and, increasingly regulatory) imperative for airports to increase public transport use to and from the site, there is also an understandable reluctance to reduce trips by private cars as car parking represents a valuable source of non-aeronautical revenue for airports.

However, all the interventions previously described, while undoubtedly well intentioned, invariably only offer modest or one-off efficiency gains. Consequently much more challenging, and politically unpalatable, demand management measures, such as higher ticket prices and aviation taxes and a moratorium on global airport expansion, may be required if aviation is to significantly reduce its climate impact.

#### *Taxation/legislation*

Green taxes are one way of restraining demand (and emissions) and encouraging an uptake of 'cleaner' technology. At a national level, different countries have imposed a range of policy and/or financial incentives to either actively encourage or dissuade people from flying. Discussions of the national aviation taxes that are applied across a range of countries revealed that competition between nations regarding domestic airlines, airports, and tourism influence national taxes and the provision of financial incentives.

In the UK a passenger charge, known as Air Passenger Duty (APD), is levied on all passengers flying out of the country. The APD was first introduced in 1994 and has been subsequently revised. It constitutes a flat fee which varies according to the distance flown and class of travel, with long-haul flights in first and business class attracting the highest charges. The APD has been criticised for not considering the age, size, fuel efficiency, or passenger load of the aircraft and for the fact that small aircraft (carrying fewer than 20 people) and cargo aircraft are exempt from the charge.

In order to assess the possible impact of APD on consumer behaviour, Mayor and Tol (2007) modelled domestic and international tourist flows in response to different APD charges. They discovered that an increase in APD in 2007 had a small but perverse effect on consumer behaviour because tourist

destination choice is driven by relative price. Thus, a departure tax can make distant destinations more appealing, not less, as the charge for longer routes constitutes a much lower proportion of the total holiday cost than it does for short-haul destinations. One possible outcome of this effect is that UK aviation emissions may increase as people choose to fly on long-haul routes which are flown using larger and heavier aircraft, or UK consumers may choose to fly from other airports in Europe which do not impose such charges. Although the levels of APD have since been tweaked so that there is currently a four-destination band structure based on geographical distance, each having two rates of duty depending upon the class of travel (for further details see HM Custom and Excise, 2010), the system arguably requires further refinement. Critics of the scheme have also called for greater transparency about where the APD revenue is spent, with Ryley et al (2010) suggesting that it should be spent on aviation-related mitigation measures.

At a European level, much of the focus on aviation-related mitigation measures relates to the European Union's Emission Trading Scheme (EU ETS), a 'cap and trade' system which aims to make the polluter pay by creating a market for carbon in which the 'right' to pollute is a tradable asset (Mendes and Santo, 2008). Phase one of the EU ETS, which represented the largest international multi-sector greenhouse gas emission trading system in the world, was introduced in January 2005 and covered 11,500 energy intensive installations, including oil refineries, iron and steel plants, and power stations, across the European Union. In 2006, the European Commission proposed that airlines should be included within the scheme as way to cap carbon dioxide emissions and provide a financial incentive to promote the uptake of new technologies and more environmentally sustainable operating practices.

The resulting directive, which was published in 2008, stipulated that all commercial flights operated by an aircraft with a maximum take off weight greater than 5,700kg which operate in to or out of any EU member airport would be included in the ETS from 2012. Under the regime, airlines would be given an initial set of free allowances. They would only be allowed to pollute

above their quota if they purchased additional allowances from other airlines or industrial sectors which had not used their full allocation (Albers et al, 2009). Using this mechanism, the EU hopes to be able to stabilise carbon emissions. The inclusion of aviation into the ETS is, however, highly controversial, with some non-EU airlines claiming that it contravenes existing international aviation regulations, including the 1944 Chicago Convention on International Civil Aviation.

### **Aviation adaptation for a changing climate**

Despite growing awareness of aviation's impact on the global environment and official recognition that some degree of climate change is now inevitable (IPCC, 2007), relatively little research has explored aviation's vulnerability to climate change. While aviation is, of course, not the only transport mode that will be affected by climate change (see Department for Transport, 2010; Dobney et al, 2009; Jaroszweski et al, 2010; and Koetse and Rietveld, 2009; for examinations of climate change's likely impacts on surface transport modes), the globally interconnected nature of contemporary airline networks, combined with rising numbers of flights and growing capacity constraints at major airports, render the sector particularly vulnerable to weather-related disruption and make schedule recovery following a disruptive event very difficult.

In December 2010 and January 2011, prolonged periods of heavy snowfall and sub-zero temperatures affected much of north-western Europe. Snow and ice disrupted power supplies, blocked roads, shut schools, and forced the temporary closure of dozens of major airports. Thousands of flights were cancelled, hundreds more re-routed or rescheduled and tens of thousands of passengers had their Christmas and New Year travel plans severely disrupted. The resulting chaos was quickly blamed not on the weather (which had been forecast) but on the failure of airlines and airport operators to be 'proactive' and prepare for such conditions (Milmo 2011; Rayner et al, 2010).

In the UK, the Labour Party Chairwoman of the Commons Transport Select Committee, Louise Ellman, argued that it was unacceptable for politicians and

airport operators to claim that that conditions were exceptional as the winter of 2010-2011 represented the “third bad winter in a row” that the UK had experienced (cited in McKie and Doward, 2010: 1). Leaving aside controversial, and perhaps irresolvable, questions concerning the extent to which the wintry conditions were either caused or exacerbated by global changes in weather and precipitation patterns brought about by climate change, the disruption brought aviation’s vulnerability to adverse weather conditions into sharp relief and highlighted an urgent need for the industry to strengthen resilience and preparedness planning and to develop effective strategies that will enable it to adapt to, and function in, a changing climate.

If past climate observations and future climate models are accurate, there can be little doubt that the earth’s climate is changing. Continually rising surface temperatures will accelerate the melting of glaciers and polar ice, promoting sea level rise and altering the salinity of the oceans which, in turn, will disrupt global weather patterns and alter existing precipitation regimes (Stern, 2006; IPCC, 2007). As a consequence of rising temperatures, there will be more energy in the climate system and extreme weather events, including hurricanes, storm surges, and thunderstorms, are predicted to occur more frequently. However, the impact of climate change will be uneven, with some regions of the world experiencing localised cooling even when average temperatures are increasing. In light of these predictions, the need to strengthen the aviation industry’s resilience to climate change is becoming increasingly acute. In the subsections that follow, we review how a changing climate may affect air transport in the future and examine how the industry might adapt its operations to reduce the potential adverse impacts of climate change and enhance its potential benefits.

#### *Growing industry recognition*

In 2008, Eurocontrol, the European Organisation responsible for the safety of air traffic within the continent, unequivocally stated that ‘climate change *will* affect aviation’ (Eurocontrol 2008: 2, our emphasis). In order to understand the nature of these effects and raise awareness that climate change will impact on the sector, the organisation commissioned a series of climate



adaptation studies. The resulting report (Eurocontrol, 2011) suggested that climate change may adversely affect the European aviation network by:

- Changing patterns of tourist demand (owing to increased thermal stress and water shortages in certain areas during the summer months and reduced snow cover in others in winter);
- Causing rising sea levels to inundate low-lying airports;
- Resulting in changes in weather patterns that will lead to increased delays, necessitate the re-routing of aircraft, damage airport and air navigation infrastructure, and make routine ground handling operations more difficult.

At a national level, Governments have also begun to examine the impact that climate change may have on key transportation and utility infrastructures. As a result of the 2008 Climate Change Act, the UK Government's Department for the Environment, Food, and Rural Affairs (DEFRA) has requested that the organisations responsible for operating assets of national importance, including energy suppliers, water companies, and transport providers, compile detailed assessments of their vulnerability to the short, medium, and long-term consequences of climate change and describe the steps that they are taking to mitigate or adapt to these threats (Department for Environment, Food and Rural Affairs, 2008b). In the context of aviation, London's Stansted Airport identified 35 separate risks that they consider climate change poses to the safety and integrity of their operations (Jefferson, 2011). Many of these risks were directly related to the consequences of rising surface temperatures and changes to existing weather and precipitation regimes.

#### *Rising surface temperatures*

Predicted rises in mean global surface temperatures will have a number of significant implications for the aviation industry. Some of these impacts will be felt immediately, whereas others may only begin to manifest themselves after many years. At a local level, the ambient air temperature has a direct and tangible impact on airport and airline operations. Very high temperatures

degrade the take-off performance of aircraft, can cause airport infrastructure to buckle or melt, and make normal aircraft turnaround operations more hazardous, while sub-zero temperatures can result in airside infrastructure freezing and necessitate the expensive and time-consuming removal of snow and ice.

Ambient air temperature affects air density, and air density affects the lifting capacity of a wing. Broadly speaking, lower air densities generate less lift at any given airspeed than higher air densities, as there are fewer molecules of air moving over the surface of the wing (Sealy, 1957). Consequently, when air density is low, take off and landing speeds have to be higher to generate sufficient lift to enable aircraft to become, and remain, airborne. Higher surface temperatures, therefore, degrade aircraft performance by lowering the air density and reducing a wing's ability to generate lift and the engine's ability to generate thrust. As a consequence, take off speeds have to be higher (increasing fuel burn, engine wear, and maintenance costs) and aircraft may require longer take-off runs before they can safely become airborne. In the case of 'hot and high' altitude airports with relatively short runways, higher surface temperatures may ultimately prevent certain larger aircraft type from operating into the facility and may demand that runways are extended so that payload restrictions do not have to be imposed.

In addition to reducing aircraft performance, higher surface temperatures can also damage airport infrastructure by causing it to buckle or melt. While runways are designed to withstand high temperatures and friction, the structural integrity of the tarmac used on aircraft aprons and taxiways begins to degrade when exposed to temperatures of 32°C and above (Jefferson, 2011). If sections of taxiways 'melt' in the heat and become unable to support the weight of aircraft, they must be taken out of service until the surface can be remade.

A related concern about rising surface temperatures and the temperature of airfield tarmac, relates to the safety of ground personnel who are involved in aircraft turnarounds. The flashpoint of jet fuel is 38°C. At London's Stansted

Airport, temperatures peaked at 37.3°C in the summer of 2003 and the temperature on the tarmac can reach 80°C (Jefferson, 2011). In the event of an overfill or fuel spillage there is a danger that the spilt fuel could spontaneously ignite when it comes into contact with a hot tarmac. As a result, any increases in surface temperatures will require changes to existing aircraft fuelling arrangements at airports where the 38°C threshold is likely to be reached or exceeded. New costly and potentially time consuming control measures, such as not allowing passengers to board at the same time as an aircraft is being refuelled and having fire vehicles attend all refuelling activities, may have to be considered to counter this threat. Such interventions, if suddenly imposed, would have serious financial implications for airlines (as aircraft couldn't be turned around as quickly) and airports (as individual aircraft would fly a reduced number of services as a result).

In the medium to longer term, rising temperatures may also lead to an increased fire risk on and around the airfield and alter energy demands in airport buildings. If, as is predicted, winters in the northern hemisphere become milder and wetter and summers hotter and drier (see Hulme et al, 2002), additional energy may be required during sustained periods of high temperatures to cool airport terminal buildings and supply pre-conditioned air to aircraft on stand. Airports will need to ensure a reliable and secure year-round supply of energy to power their facilities and buildings may have to be redesigned or reconfigured to maximise the use of natural light and ventilation and minimise energy consumption. New terminals will need to be designed to maximise the use of daylight, while operators of older facilities may consider retrofitting them with more energy-efficient lighting, ventilation, and heating systems to reduce energy costs and associated emissions.

A further concern about the effects of rising surface temperatures and their effects on aviation relates to a possible relationship between the melting of glaciers and polar ice and increased volcanic activity. The unprecedented closure of parts of northern European airspace that followed the eruption of Iceland's Eyjafallajokull volcano in April and May 2010 demonstrated the extent to which the presence of volcanic ash in the atmosphere can disrupt

normal air traffic flows (L. Budd et al., 2011). The initial six-day shutdown resulted in the cancellation of 108,000 flights, disrupted the travel plans of 10.5 million passengers, and cost airlines in excess of \$1.7 billion in lost revenue (Eurocontrol, 2010a). Although described as a 'natural' geological event, it has been tentatively suggested that climate change, rising global temperatures, and glacial retreat may ultimately promote an increase in volcanic activity in volcanoes that are no longer 'plugged' by a thick layer of ice (see Pagli and Sigmundsson, 2008).

### *Snow and ice*

The trend towards generally hotter summers and milder winters in the northern hemisphere means that airports in these regions will become less familiar at dealing with colder conditions and thus may be unprepared for sudden periods of colder weather. Snow and ice, as well as being notoriously difficult to forecast, can disrupt normal airport operations by blocking access roads, contaminating runways, and necessitating the costly and time-consuming mechanical and/or chemical removal of snow and ice from airside areas and aircraft.

Ice, in particular, represents a significant hazard to aircraft. If it is allowed to form on the wings, ice increases drag and makes the wing less aerodynamic. If, on the other hand, it accumulates on the airframe it can block pitot tubes and result in erroneous altitude and airspeed information being sent to the flightdeck. Both scenarios have the potential to cause serious accidents. In January 1982, 74 people died when an Air Florida Boeing 737 crashed into Potomac River shortly after take off from Washington National Airport. Ice on the wings and airframe increased the weight and drag on the airframe to such an extent that the aircraft was unable to climb (National Transportation Safety Board, 1982). This, and other ice-related accidents, resulted in existing operating procedures being strengthened to ensure that if the air temperature and humidity falls below a defined threshold, aircraft have to be de-iced within a set period of time before take off. The responsibility of ensuring that de-icing procedures are carried out in a timely and effective manner lies with individual

airline operators and their appointed handling agents, and the provision of adequate de-icing capacity is a prerequisite of operating into certain airports.

The process of de-icing usually involves the leading edges of the wings and the vertical and horizontal stabilisers (more commonly known as the 'tail' and the 'tailplane' respectively) being liberally sprayed with a de-icing solution before the aircraft pushes back from its stand and taxis to the runway. While the process ensures the safety of the airframe and its occupants, the solution is expensive (it costs over €7,000 to de-ice a Boeing 747) and contains toxic chemicals (EFM, 2011). In order to prevent de-icing fluids from contaminating local water courses, the run-off must be directed to balancing ponds where it is stored and treated before being discharged. During prolonged periods of cold weather, the capacity of these ponds is placed under considerable pressure and, if climate change is likely to increase the severity and/or length of wintry weather, airports that are likely to be affected may need to invest in larger water storage facilities or alternative de-icing facilities, such as overhead infra-red thermal gantries, which can melt ice without resorting to the use of chemicals.

In addition to endangering aircraft during take-off and in-flight, the presence of snow and ice on runways and taxiways degrades aircraft braking action and can result in a loss of directional control leading to aircraft over-running or veering off paved runway and taxiway surfaces. As a result, it is imperative that all aircraft manoeuvring areas are kept free of snow and ice and mechanical blowers and sweepers and/or specialist anti-icing and de-icing compounds are employed for this purpose. However, such specialist equipment is expensive and airports will only invest in such technology if rigorous cost benefit analyses identify a need for it.

As well as presenting a problem to aircraft, snow and ice also presents a danger to ground personnel by making surfaces slippery, increasing the risk of injuries and raising the risk of vehicle collisions, and by obscuring safety-critical ramp markings. If water penetrates gaps in the apron surface and then freezes, cracks can appear. This degrades the surface and requires costly

and time-consuming repairs to rectify. Clearly, any alteration in the current snowfall regime and/or changes in the frequency or location of freezing weather conditions will have very tangible material and financial impacts on airline and airport operations and revenues. As a result of climate change, some airports may find they have a greater need for de-icing and snow clearance, whereas others may rarely, if ever, be affected by snow and ice.

#### *Consumer demand and behavioural change*

Changing surface temperatures may also affect the aviation industry in more subtle ways by changing patterns of consumer demand for air services. Within the next 10-20 years, it has been suggested that certain summer holiday destinations may be rendered inhospitable due to increased thermal stress and water shortages, while changes in snowfall patterns may necessitate the relocation of winter sport activities to higher latitude and altitude resorts (Eurocontrol, 2008). Such changes would fundamentally alter patterns of demand for air travel and transform the spatial and temporal distribution of air traffic flows. They will also have a profound impact on the socio-economic fortunes of the airports and communities that will lose traffic or receive new inbound flows of tourists.

It has been suggested that growing public awareness of the environmental effects of aircraft operations, together with associated policy responses, may result in changes to consumer demand and travel behaviour (Davison and Ryley, 2010). Some of this may result from the imposition of new environmental taxes or a desire to reduce personal carbon footprints by reducing the number of flights that are taken and by choosing alternative modes of transport. As well as potentially altering flows of international tourism, rising surface temperatures and changing climatic conditions may also alter the spatial demand for air freight by altering patterns of agricultural productivity.

#### *Sea level rise*

In addition to affecting airport and airline operations and changing patterns of consumer demand, rising global temperatures are forecast to result in rising

sea levels and more frequent incidents of flooding and storm surges. Low-lying coastal airports may be inundated and critical air transport infrastructure damaged. A significant number of major airports around the world are located in low-lying coastal areas or are situated adjacent to tidal estuaries. Cairns airport in Australia, for example, is located only 10ft (3.05m) above mean sea level (MSL), while the maximum elevation of Nice's airport in southern France, John F Kennedy airport in New York, and Japan's Kansai facility, is only 12ft (3.66m), 13ft (4m) and 17ft (5m) above MSL respectively.

More vulnerable still are airports which are either located below mean sea level (usually on reclaimed land) or which have runways built on artificial peninsulas that stretch out into the sea. Amsterdam's Schiphol airport, for example, is situated on reclaimed land 11ft (3.4m) below MSL, while Louis Armstrong International Airport in New Orleans is situated some 4ft (1.2m) below MSL. Although a complex system of banks and levees has been constructed to protect the facilities from inundation, the risk of flooding is ever present as any breach in the existing defences would be catastrophic.

Other airports which are at risk from rising sea levels include those serving low-lying islands in the Indian Ocean and the Caribbean. The maximum elevation of Malé airport in the Maldives, for example, is only 6ft (1.83m) above MSL, while Princess Juliana International airport, on the eastern Caribbean island of Saint Maarten, is only 13ft (4m) above MSL.

Consequently, the risks sea level rise and/or any increase in the frequency and severity of storm surges pose to these facilities is considerable. While it may prove technically feasible and socio-culturally (if not economically) desirable to protect such facilities by constructing sea walls and other defences, any decision to protect or relocate an airport will be highly controversial.

#### *Wind and convective weather activity*

While increased surface temperatures and sea level rise are two of the most frequently cited consequences of climate change, they are not the only ones.

Anticipated changes to the distribution, frequency, duration, and/or intensity of severe weather activity, including storms, ice, snow, severe turbulence, and wind shear, as a result of climate change may cause considerable delays disruption to aircraft operations (see Pejovic et al, 2009), in addition to potentially endangering lives and damaging aircraft and airport infrastructure. Of all the weather phenomena that aircraft encounter, wind has the greatest potential to impact on the safety of the air transport system. In order to generate maximum lift in the shortest possible time, aircraft need to take off and land into the wind and runways are aligned in accordance with the prevailing wind direction. If, however, changing weather patterns cause the prevailing wind direction to alter, airports may be left with runways that are not optimally aligned and flightcrew will be obliged to perform more dangerous and cognitively demanding crosswind landings.

Wind also plays an important role during the en-route flight phase as wind speed and wind direction can hinder or expedite a flight's progress. Where possible, pilots will try and take advantage of favourable high-altitude winds and avoid strong headwinds which will slow their aircraft down and increase fuel consumption. For example, on transatlantic routes, the jet stream, a ribbon of fast moving air which blows from west to east across the northern Atlantic Ocean, enables transatlantic flights from North America to Europe to cross the Ocean more quickly than westbound services. While the strength and location of certain high-altitude winds, including the jet stream, can be predicated and forecast with considerable accuracy and air routes planned accordingly, other phenomena resulting from variable atmospheric pressure are much less predictable. Regions of clear air turbulence, which are usually found at the boundaries of neighbouring air masses, and thunderstorms, can produce violent downdrafts and moderate to severe turbulence that can damage aircraft and result in fear and injury to people onboard.

Thunderstorms, and associated convective weather activity, whether encountered at the airport or in the en-route flight phase can result in the delay, rerouting, diversion, or cancellation of flights and lead to a serious deterioration in normal schedule performance (Eurocontrol, 2010a; Janic,



2005, Pejovic et al, 2009; Sasse and Hauf, 2003). The atmospheric environment in and around a thunderstorm represents one of the most hazardous airborne environments an aircraft may encounter (Collins, 2002; Godwin, 2006). Microbursts, icing, wind shear, severe turbulence, hail, electrical discharges, heavy precipitation, reduced visibility, and sudden and unpredictable changes in atmospheric pressure are just some of the hazards that have been reported (Machol and Barnett, 1988). Hailstones can damage the airframe, crack flightdeck windows, and destroy paintwork, causing a safety hazard and costing tens of thousands of pounds' worth of damage, while electrical discharges have the potential to interfere with aircraft navigation and communication equipment (Godwin, 2006).

Though the sophistication of modern meteorological forecasts and weather radar means that the location and intensity of storms can be predicted, located, and often avoided with increasing accuracy, numerous fatal aircraft crashes have been attributed, at least in part, to aircraft encountering adverse weather conditions in the take-off, en-route, or final approach phases of a flight (Collins, 2002; Owen, 2006). At the time of writing, it is believed that turbulence associated with severe thunderstorm activity may have contributed to the loss of Air France flight AF447 over the Atlantic Ocean in June 2009, which killed 228 people (BEA, 2009). If such weather events become more common and more severe, there may be a need to enhance the minimum design standards for aircraft to ensure that the airframes can withstand the higher structural stresses that may be imposed on them.

While in-flight structural failures remain a mercifully rare occurrence, news reports attest to the injury, fear, and distress severe turbulence can cause (BBC News, 2010; BBC News, 2011; Friedman, 2009) and pilots will endeavour to avoid known areas of convective activity by requesting alternative headings and/or flightlevels and will often accept significant deviations from their filed flightplans (Gillingwater et al, 2009). This practice almost inevitably results in longer flight times, higher emissions, and greater operating costs for the airlines concerned. Convective weather already represents a significant cause of en-route air traffic delay (as much as 89% of

all delays recorded in one sector of central European airspace in 2009 were attributable to adverse weather) has the potential to reduce the capacity of a sector of airspace by 15-20%, close airports, reduce runway capacities for landings and take-offs, and hinder or prevent normal ground servicing and flight turnaround operations (Eurocontrol, 2010b; Eurocontrol, 2010c). Given that rising incidents of severe convective weather are a possible consequence of a changing climate, there is an urgent need to quantify the disruptive impacts of convective weather on air traffic flows and examine the extent to which a changing climate may affect the occurrence of such phenomena.

## **Conclusion**

Climate change is recognised as being one of the greatest challenges contemporary global society faces. Commercial aviation is a known contributor of greenhouse gases and one of the few industrial sectors where emissions are predicted to increase as demand for air travel outstrips our ability to deliver emissions reductions through technological and operational innovation. Although uncertainties remain concerning both aviation's exact contribution to climate change and also how climate change will affect the aviation industry, recent research from both academia and the aviation industry itself indicates that the potential for disruption is real and considerable.

In light of this, a range of mitigation measures have been developed and implemented to reduce aircraft emissions in the short-term. These include more efficient use airspace and the introduction of new aircraft technologies and alternative fuels which, it is hoped, will confer short to medium term efficiency gains when they are introduced. Other proposals, including the use of economic instruments to reduce consumer demand and thereby lower emissions have, unsurprisingly, been criticised by passenger groups and airlines for being unworkable, unduly bureaucratic, and/or ineffective.

Yet while these interventions may, either singularly or collectively, confer some environmental benefit, there is growing recognition from within both

Government and the air transport industry of the urgent need for the aviation sector to identify all the possible impacts of climate change on air transport operations, assess their severity, and devise appropriate preparedness plans to address these vulnerabilities and ensure its safe and continued operation. The key challenge will be to successfully align short-term priorities (including efficiency, regulatory demands, value for money, and shareholder returns) with the need for longer-term resilience measures. Many global airports and airlines are private enterprises and many national regulatory regimes do not explicitly require climate adaptation policies to be incorporated within their planning cycles (although the financial imperative for them to remain operational under all but the most extreme weather conditions will almost certainly drive investment in this field).

While the sector will not be able to eliminate all of its deleterious climate impacts in the short-term, a better understanding both of how aviation affects the global climate and how a changing climate will affect aviation will hopefully drive the creation of a more equitable and sustainable commercial aviation industry that is responsive to the needs and challenges of the Twenty First Century.

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