THE IMPACTS OF CLIMATE CHANGE ON AVIATION: SCIENTIFIC CHALLENGES AND ADAPTATION PATHWAYS

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The International Civil Aviation Organization (ICAO) reached out to the climate science community almost 20 years ago in an effort to seek suitable mitigation measures to reduce the emissions of carbon dioxide (CO_2) and other atmospheric pollutants from aviation activities worldwide. The Organization adopted a comprehensive strategy to address international aviation CO_2 emissions, which culminated in the adoption of a CO_2 Standard in 2016. Emission reduction efforts such as market-based measures, operational changes, and technological improvements have significantly reduced fuel burn and thus CO_2 emissions from aviation over the past four decades. Going forward, operational measures such as new air traffic management (ATM) systems (e.g., NextGen, SESAR, CARATS, etc.), as well as new technological developments, have the potential to continue reducing the CO_2 emissions from aviation. Nevertheless, the robustness of aircraft and indeed the robustness of the entire aviation system should be monitored carefully, as the sector will have to prepare for the more extreme meteorological conditions that are expected in the future as the climate continues to change.

Adaptation to Climate Change: The Scientific Issues and Challenges

The scientific case for global climate change has been well established and rests on a firm understanding of the physical processes involved that drive up the temperatures in the lower atmosphere. The consequences of global climate change for aviation will be summarized in the following paragraphs. A schematic summary of some of the possible impacts is shown in **Figure 1**.

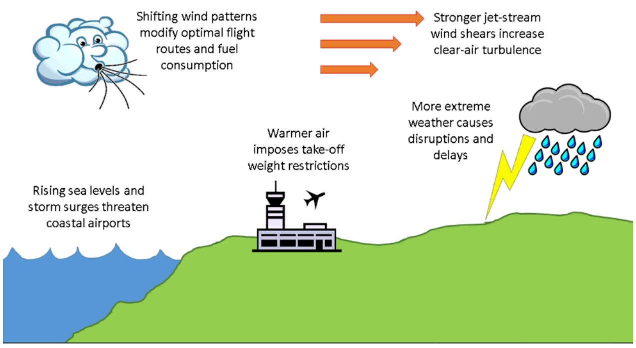

Figure 1. A Schematic Summary of Some of the Possible Impacts of Climate Change on Aviation.

Large-Scale Phenomena

Higher Temperature Maxima

Higher temperature maxima at ground level result in significant decreases in air density, reducing the lift force on the wings of departing aircraft. This reduction in lift could have severe consequences for aircraft take-off performance, where high altitudes or short runways limit the payload or even the fuel carrying capacity. These effects will require more detailed analyses for different geographic regions, with major concerns for high altitude airports in subtropical regions. The already established method of scheduling long-haul departures for the cooler evening and night hours will in some areas (e.g., Middle East, Central and Southern American high altitude airports) be affected further by the reduced cooling overnight where high cloud is often present. In these cases, the non-CO_2 effect of contrail-related cirrus clouds may have to be considered as an additional factor, potentially reducing the unproblematic hours of operation even further in some regions.

Rising Sea Levels

The rise in globally averaged sea level, through increased melting of ice sheets and glaciers and also thermal expansion of the oceans, is well understood and documented. Coupled with rising sea levels, storm surges linked to more intense extra-tropical cyclones may threaten the viability of low-lying airports at coastal locations unless protective measures are taken. These effects are likely to be exacerbated through very intense precipitation episodes linked to these storms, which can lead to excess flooding where run-off collides head-on with storm tides (e.g. the extreme floods in Myanmar during Tropical Storm Nargis in 2008). Planning of new airports in such regions will require hydrological, climatological, and technical expertise.

Jet Stream Changes

The response of the atmospheric jet streams to climate change is an area of active research in the scientific community. In essence, the mid-latitude jet stream in each hemisphere is created and sustained by the temperature difference between the cold poles and the warm tropics. Climate models, satellite observations, and physical theory all suggest that this temperature difference is changing in a complicated manner; it is decreasing at ground level because of amplified polar warming associated with melting sea ice, but it is increasing at flight cruising levels because of lower stratospheric cooling. One possibility is that changes in the prevailing jet stream wind patterns may modify optimal flight routes, journey times, and fuel consumption. Another possibility is that increased shear within the jet streams at cruising levels may reduce the stability of the atmosphere and increase the likelihood of clear-air turbulence breaking out.

Understanding Other Effects

For many of the above effects, a clear signal is apparent from both climate models and observed trends over the last 30 years, and the signal is consistent with our physical understanding of the climate system. Other questions, such as the interactions between various climate impacts, will clearly require a significant research effort and multi-disciplinary collaboration.

The scientific understanding of other effects is gradually increasing over time. An in-depth analysis of the El Niño-Southern Oscillation (ENSO) from the latest generation of climate models appears to support the evidence from paleo-climatological studies, pointing to an increase in the severity of El Niño during warmer climate episodes in the past. More extreme El Niño events will affect many regions of the world directly or indirectly, e.g. by exacerbating extreme droughts and heat waves in Australia and exacerbating massive floods in the West Coast of North and Central America. All of these extreme situations will have a significant negative impact on all forms of transport, including aviation.

Further Research Efforts

The role of seasonal, inter-annual, and decadal cyclic variations such as ENSO, the North Atlantic Oscillation (NAO), the Pacific Decadal Oscillation (PDO), and other recurring phenomena requires significant further research efforts. Given the overwhelming amount of data resulting from climate model runs, the initial approach to understanding future climate states was the analysis of a new quasi-equilibrium state valid for the end of the century. This state was described in latitudinal and regional means over extended periods of time, to isolate the sometimes conflicting signals between different models. Many climate models exhibit noticeable biases in some regions and variables (e.g. in the Equatorial Pacific Ocean temperatures) when compared with the current observed climate.

A Future Mean State

Adaptation measures being considered by societal and industrial sectors such as transport, and in particular aviation, need to address not only a future mean state for climate, but also the variable local and regional weather extremes likely to occur over the coming decades. Such extremes may already be exhibiting typical conditions that were only expected for the end of this century.

In order to provide robust scientific advice to stakeholders, the scientific community will need to address typical scenarios and try to describe impacts linked to these scenarios. As an example of such scenarios, we may consider the emerging evidence of a sequence of high-amplitude, low wave number regimes in the jet stream wind pattern (e.g. over the East Atlantic and Europe) in non El Niño years. This could well lead to the paradoxical occurrence of intense snowfall and low winter temperatures over large areas of Europe, contrasted by a significant northward displacement of the westerly jet streams, with very mild temperatures during the extreme El Niño years. These are probably closer to what the earlier, average-based predictions gave (i.e. high rainfall and strong winds over Northern Latitudes, and drought in the Mediterranean region).

Small-Scale Phenomena

Scientific research into the impacts of climate change on aviation encounters the inevitable problem that many high-impact weather phenomena are linked to space and time scales well below those resolved by current computer models of the atmosphere. Such phenomena typically include: low-level wind shear; hail and lightning strikes; clear-air turbulence and mountain wave turbulence; convective turbulence and turbulence near thunderstorm tops; icing; and low visibility. Intelligent ways of downscaling, statistical post-processing, and advanced conceptual models, will all be needed to obtain statistically reliable results.

Clear-Air Turbulence

Improving our physical understanding of the generation of small-scale processes can help. For example, although Clear-Air Turbulence (CAT) occurs on the micro-scale, the wind shear that generates CAT is driven on a much larger scale, and is potentially resolvable by the current generation of weather and climate models. More basic scientific research is needed to improve our understanding of these small-scale effects. This research will require better atmospheric observations and would benefit from access to operational turbulence data from aircraft.

Airframe Icing

The phenomenon of airframe icing is traditionally seen as a problem mostly by the general aviation and commuter aviation sectors, which operate aircraft with limited engine power and rudimentary anti-icing devices. Nevertheless, icing needs to be better understood to be able to predict future scenarios. The presence of large super-cooled droplets at a temperature range of between -4°C and -14°C depends on a number of conditions, including: availability of large amounts of water vapor, meso-scale bands of intense updrafts, and a limited concentration of suitable aerosols to prevent the formation of many small droplets.

The general warming trend and the increase of moisture in some latitude bands, with a generally more active dynamic flow, all tend to point to an increased chance of occurrences of conditions favorable to icing, and also to an extension of the upper limit of icing layers due to the higher temperatures. This suggests a need to have a fresh look at the current regulations for twin-engine aircraft operations over oceanic airspace, as cabin pressure loss or the loss of power in one engine would force such aircraft to fly at levels still affected by icing (i.e., in the range between FL130 and FL160). On the other hand, high-altitude icing is also likely to increase with more intense cumulonimbus (CB) clouds and a rise of the tropopause due to the higher temperatures and higher moisture of tropical air masses.

Sand and Dust Storms

The likely increase in occurrence and intensity of sand and dust storms caused by both longer drought periods and potentially stronger winds in the sub-tropical latitudes will require a thorough analysis of its impacts on the safety and regularity of flights in these regions. There is emerging evidence that the drive to achieve higher engine efficiency to reduce fuel consumption has pushed the operating temperatures in the combustion chambers of the most modern engines towards temperatures in excess of 1600°C. At these temperatures, the silicates contained in typical sand and dust storms will melt and thus affect the performance and maintenance requirements of jet engines.

Risk Management Considerations

In summary, a multi-disciplinary research effort by scientists, meteorologists, climatologists, engineers, biologists, and epidemiologists is needed to understand better the impacts of the changing climate on the entire aviation system, including aircraft and infrastructure. Thereafter, dedicated guidance material by ICAO could target climate adaptation correlated issues, based on models of best practice. Such guidance material would aim to support the risk management activities of all stakeholders, including operators and pilots, airport managers, aircraft manufacturers, governments, and regulators. It will be important for that guidance material to be regularly revised and updated, to keep it in sync with the evolving and non-stationary climate statistics.