CURRENT SCIENCE

Volume 115 Number 11 **10 December 2018**

EDITORIAL

Aircraft emissions and the environment

The Intergovernmental Panel on Climate Change (IPCC) reports have shown that global warming is due to increase in greenhouse gases (GHGs). Several studies have linked extreme weather to global warming and the frequency of extreme weather events is increasing. Global warming is projected to pose a major threat to the aviation sector; the direct consequence arising from the reduced lift (dependent on air density). It is projected that under extreme conditions, it would be difficult for aircraft to take-off during summer in the tropics. Storms such as cyclones and tornadoes pose challenges to the aviation sector. Cyclones can cause flooding of airfields and terminals. Underground power utilities are likely to short due to inundation, which can cause power outages. Strong winds can damage control towers and other ground equipment and installations. Due to the recent floods (August 2018), the international airport at Kochi, one of the busy airports of India, was shut down for nearly two weeks, consequent to extreme precipitation in the catchment areas of rivers. One of Japan's busiest airports, Kansai International Airport in Osaka, had to be closed recently (September 2018) because of flooding caused by typhoon *Jebi*, the strongest to hit Japan in 25 years. Flood waters covered runways, leaving several planes submerged up to their engines and more than 1000 flights were cancelled. Just a few years ago, the Chennai International Airport was completely shut down after the unusually heavy precipitation flooded the airfield. Blizzards and other extreme cold weather conditions can cause icy runways and frozen fuelling equipment. Icy runways make safe take-offs and landings extremely difficult. Airports need to close during heavy blizzards. Necessary safety precautions for open airports include gritting of runways and de-icing of aircraft.

Extreme weather events are not the only climate-related issue for the aviation sector. Some studies have shown that climate change can lead to increased vertical wind shears at higher atmospheric levels and strengthen shear instabilities that generate clear-air turbulence (CAT) (Williams P. D., *Adv. Atmos. Sci.*, 2017, **34**, 576–586). On-board radars in airplanes cannot detect CAT. Recent research using simulations has shown that CAT in the jet stream is likely to grow stronger due to climate change (Williams, P. D. and Joshi, M. M., *Nature Climate Change*, 2013, **3**, 644–648). It has also been shown that if the concentration of atmospheric carbon dioxide doubles, CAT will increase from ~50% (light CAT) to ~150% (severe CAT) (Williams, P. D., *Adv. Atmos. Sci.*, 2017, **34**, 576–586). Analysis of changes in CAT across the globe has indicated substantial increase by the second half of this century, especially in the mid latitudes which contain some of the busiest air routes (Storer, L. N., Williams, P. D. and Joshi, M. M., *Geophys. Res. Lett.*, 2017, **44**, 9976–9984). These studies have also found that severe CAT will increase the most. Recent climate modelling studies have indicated that the occurrence and magnitude of moderate to severe CAT will increase in the future with implications for the aviation sector.

One of the most significant contributions of the recent IPCC Fifth Assessment Report (AR5) is the assessment of maximum allowable/permissible carbon dioxide emission, in order to limit the global average temperature rise to 2°C above pre-industrial levels. This value has been agreed by countries as an appropriate threshold beyond which climate change risks become unacceptably high. The IPCC report presents various scenarios of climate change risks/consequences associated with different magnitudes of warming. Estimates show that a scenario in which global mean temperature is allowed to increase to 3°C above pre-industrial levels, for example, would involve sea-level rise of between 2 and 5 m, with the best estimate being at 3.5 m. 'Even if global warming is limited to 2 degrees Celsius as proposed, global-mean sea level could continue to rise, reaching between 1.5 and 4 metres above present-day levels by the year 2300, with the best estimate being at 2.7 metres', according to a report by Potsdam Institute for Climate Impact Research based on a paper published in *Nature Climate Change* (Schaeffer, M., Hare, W., Rahmstorf, S. and Vermeer, M., *Nature Climate Change*, 2012, **2**, 867–870). It is also important to note that many airports are located near coastal areas and sea-level rise will result in flooding of the runway. Some airports (New York, New Jersey, Hong Kong are examples) have already started planning for sea walls, tide gates and drainage systems designed to tackle any future flooding. Many upcoming airports are being planned to be at least 5 m above sea level, leading to increased construction and maintenance cost. Disruptions in air flights due to weather are expensive in the aviation industry. Flooding and infrastructure damage to airports are also expensive along with losses due to closure of airports and non-operation of flights. There are no quick solutions available to avoid losses due to extreme weather events, which are likely to be more frequent in the near future due to climate change.

While it is increasingly recognized that climate change and related weather extremes can adversely affect the aviation sector, recent studies indicate that aircraft emissions can impact climate. While earlier assessment reports (AR3 and AR4) of the IPCC almost ignored the climate forcing potential of the aviation sector, the AR5 considered it and put its value to be negligibly small compared to that of GHGs. However, on a global scale, the number of airplanes has increased dramatically and little is being done to quantify the climate/environment deterioration because of aircraft emissions. Thus, it is all the more important to address this issue on a priority basis.

Studies have reported that due to the emission of soot by airplanes, owing to burning of aviation fuel, strikingly sharp layers of soot are formed around the flying altitudes of aircrafts (Govardhan, G. *et al*., *Atmos. Chem. Phys*., 2017, **17**, 9623–9644). These layers absorb the solar radiation, which reduces the rate at which temperature decreases with altitude (also known as lapse rate), increases the atmospheric stability and modifies the local circulation patterns. In the early 1980s, many researchers demonstrated that the effect of smoke from a nuclear war depends on the altitude to which smoke is lofted. They have also noted that the effects of such smoke would be both greater in magnitude and extended in time, if a significant fraction of the smoke penetrated into the stratosphere, where scavenging rates are much less compared to the troposphere. Inspired by the series of publications on this topic, a research group from the University of Washington, Seattle, USA made measurements of smoke generated by controlled burning of aviation fuel (Radke, L. F., *J. Geophys. Res*., 1990, **95**, 14,071–14,076). From several fire episodes, they have demonstrated the strongly absorbing nature of soot from aviation fuel. Their calculations showed that the smoke layer imparts significant absorption of solar energy, which can cause intense warming of the smoke layer. The study confirmed that solar heating of the optically thick smoke caused it to be lofted above the temperature inversion in a matter of a few hours. The study indicates that if smoke near the boundary layer temperature inversion can penetrate the inversion due to intense solar heating, through a similar mechanism, soot from aircraft emission can get lofted to higher levels and can even penetrate the tropopause region and reach stratospheric heights.

Model simulations indicate that such sharp layers of soot can be self-lofted and enter the lower stratosphere (Govardhan, G. *et al*., *Atmos. Chem. Phys*, 2017, **17**, 9623–9644). The particles can reside in the lower stratosphere for a long duration in the absence of precipitation. Satellite-based lidar has been able to verify independently, the presence of such lofted soot. One of the possible implications of the presence of black carbon (BC) in the stratosphere is a chemical reaction involving the decomposition of ozone on BC, which would result in the depletion of ozone. Laboratory studies have shown that soot particles can provide surface area for catalytic chemical reactions leading to destruction of ozone. Potentially, the lofted upper tropospheric soot in the stratosphere could harm the Earth's protective blanket. Thus, while emissions from aircraft appear to be the cause of the sharp and confined high-altitude layers of soot, such layers when lofted to the stratosphere (under favourable conditions) have the potential to affect the ozone layer and have significant implications for the health of all living organisms. The expected recovery of the ozone hole owing to the discontinuation of chlorofluorocarbon subsequent to the Montreal protocol can be delayed by such processes. More observational studies using satellites, stratospheric balloons and modelling are required to address this important phenomenon, especially over regions of high aircraft traffic.

Ironically, even international conferences/workshops with an objective to tackle climate change and its consequences involve large number of personnel travelling long distances by aircraft. On an individual level, those who travel by air leave gigantic carbon footprints. A carbon footprint is defined as the total amount of GHGs produced (directly and indirectly) by any human activity, expressed in equivalent tonnes of carbon dioxide (CO_2). For example, the carbon footprint for a round-trip flight from London to New Delhi is approximately 1.2 tonnes of CO_2 per person (economy class). A news item published in *The Telegraph* in 2017 reported that commercial aircrafts carry nearly four billion passengers based on a report by the International Air Transport Association, which is nearly double the number of passengers just 12 years ago. Since zero-emissions airplanes are unlikely in the near future, replacing international and national meetings with video conferencing is one way to dramatically reduce the carbon footprint. Realizing the potential impact of emissions from aircraft, a recent article (Editorial, *Nature*, 2016, **530**, 253) recommends for regulations on emissions from airplanes.

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