Aviation and Climate Change: A Scientific Perspective

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Global aviation operations combust fossil fuel and emit gases and aerosol to the atmosphere, altering its composition. In addition, aviation produces linear and spreading contrails that increase global cloudiness, and modify natural background clouds. Atmospheric composition and cloudiness largely control the balance in Earth's atmosphere between incoming radiation from the Sun and outgoing radiation from the atmosphere and surface. Any imbalance caused by human activities can lead to long-term changes in climate. At present, aviation emissions and cloudiness do contribute to an imbalance (i.e., net positive radiative forcing) in Earth's climate system that contributes to surface warming and other changes. The magnitude of the imbalance is a few percent of that caused by all human activities since pre-industrial times. Principal emissions that arise from aviation fuel combustion are carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), sulfur species (SO_x), black carbon particles (BC), and water vapor (H_2O). This paper addresses the scientific understanding of the processes that connect aviation emissions and aviation impacts on cloudiness to climate change, and highlights important remaining uncertainties. Scientific understanding helps guide choices concerning how climate change from aviation operations can be reduced in coming decades.

I. Introduction

International aviation operations contribute substantially to our world economy and societal wellbeing by carrying cargo and people to many points on the globe. Successful operations over many decades and the world's expanding population and improving quality of life imply continued growth in the coming decades. Aviation operations have long been known to contribute to Earth's changing climate, as first summarized in a Special Report by the Intergovernmental Panel on Climate Change (IPCC) in 1999.[1] The Report comprehensively laid out the scientific and technical aspects of how aviation operations influence climate and relied on computer models of the atmosphere to evaluate the quantitative aspects of climate change from aviation and all other human activities. Since 1999, a number of follow-on reports and studies have been conducted in response to improved understanding of aviation effects and increased skill in atmospheric modeling.

Aviation operations have grown substantially over the past decades. Growth in aviation fuel use has been linear since 1970, with use more than doubling by 2005, and has persisted despite global financial and other crises over that period.[2] The growth in passenger volume has been even stronger than fuel use because of improvements in aviation efficiency through changes in engines and aircraft designs and in routing and other operational features.[3] The strong growth in fuel use in response to increased demand is projected in a variety of stud-

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[1] IPCC (Intergovernmental Panel on Climate Change), *Aviation and the Global Atmosphere: A Special Report of IPCC Working Groups I and III* (Cambridge: Cambridge University Press, 1999).

[2] David Lee et al., "Aviation and Global Climate Change in the 21st Century", 43 *Atmospheric Environment* (2009), 3520-3537.

[3] Ibid.

ies and reports.[4] This future growth increases the importance of continuing the development of a comprehensive and quantitative scientific understanding of aviation and climate processes. The impact on climate from future growth will depend on many factors such as the use of alternative and renewable fuels, further improvement in technology and operational efficiency, the new International Civil Aviation Organization (ICAO) CO_2 aircraft emission standard, and future possible market-based measures.

In the following, we describe the connection between aviation operations and climate changes, quantify the influences on climate using the metric of radiative forcing (RF), and compare aviation RF to other climate agents. In looking to the future, brief discussions are included on the role of alternative fuels and potential of contrail mitigation.

II. The Connection between Aviation Operations and Climate Change

1. Emissions and Cloudiness

Aviation operations connect to climate change as outlined in Figure 1. Fossil fuel, which is the dominant fuel source at present, combusts to produce a number of emissions. The principal gaseous emissions by mass are CO_2 and water vapor (H_2O) from the oxidation of fossil fuel kerosene containing long-chain hydrocarbon molecules (H_xC_y). The high temperatures of combustion lead to the formation and emission of reactive nitrogen species, primarily nitric oxide (NO) and nitrogen dioxide (NO_2) ($NO_x = NO + NO_2$). In addition, incomplete combustion leads to emissions of unburned fuel [hydrocarbons (HC) and carbon monoxide (CO)]. Emissions include sulfur species (SO_x) since most aviation fuel derived from fossil fuel contains sulfur [typically 400-600 parts per million (ppm)]. Sulfur is emitted in various forms (sulfur dioxide (SO_2) and sulfuric acid [H_2SO_4)] and forms aerosol (small particles) in the exhaust plume. Black carbon (BC) is another product of incomplete combustion emitted in the form of aerosol.

Physical and chemical processes influence or transform emission products after emission. They include ocean and land uptake, photochemical reactions involving sunlight, microphysical processes involving the formation and transformation of small aerosol particles, and interactions between aerosol particles and cloud formation or cloud properties. On multi-decadal timescales, a large fraction of CO_2 from aviation (and all fossil fuel combustion) is absorbed in the ocean or taken up in land-based processes. The remaining fraction stays in the atmosphere for millennia since CO_2 is chemically inert in the atmosphere and, therefore, is particularly important for influencing the future climate state.

In contrast to chemically inert CO_2, emitted NO_x in the lower atmosphere (troposphere) participates in a series of photochemical reactions that lead to increases in ozone (O_3) formation and reductions in the lifetime and atmospheric concentrations of methane (CH_4).[5] NO_x emissions per se have a negligible direct effect on climate. Both methane and ozone are also important greenhouse gases produced in other natural and human-related processes.[6] The atmospheric lifetimes of ozone (weeks to months) and methane (a decade) result in substantial transport of these species around the globe, and thus large spatial scales (hemispheric) for the aviation-induced changes in the abundances of ozone and methane. The combined contribution to climate change from aviation-NO_x-induced ozone and methane changes is dominated by ozone increases (see Table 1).

Hydrocarbons and carbon monoxide are generally considered minor emissions by mass from jet engine operations and have minor impacts on background atmospheric abundances produced by other natural and anthropogenic sources. As such, these emissions do not influence climate and are decomposed or transformed in photochemical reactions in the atmosphere.

Sulfur species are also minor mass emissions from jet engines and a small contribution to the background sulfur abundances produced by other natural and anthropogenic sources. Photochemical reactions involving emitted sulfur lead to the production of sulfuric acid (H_2SO_4) which condenses to form

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[4] Ibid.; see also Martin Cames et al., *Emission Reduction Targets for International Aviation and Shipping: Study for the ENVI Committee*, IP/A/ENVI/2015-11 (Brussels: European Parliament, 2015), and Figure 2 infra.

[5] Seth C. Olsen et al., "Comparison of Model Estimates of the Effects of Aviation Emissions on Atmospheric Ozone and Methane", 40 *Geophysical Research Letters* (2013), 6004-6009.

[6] IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2013).

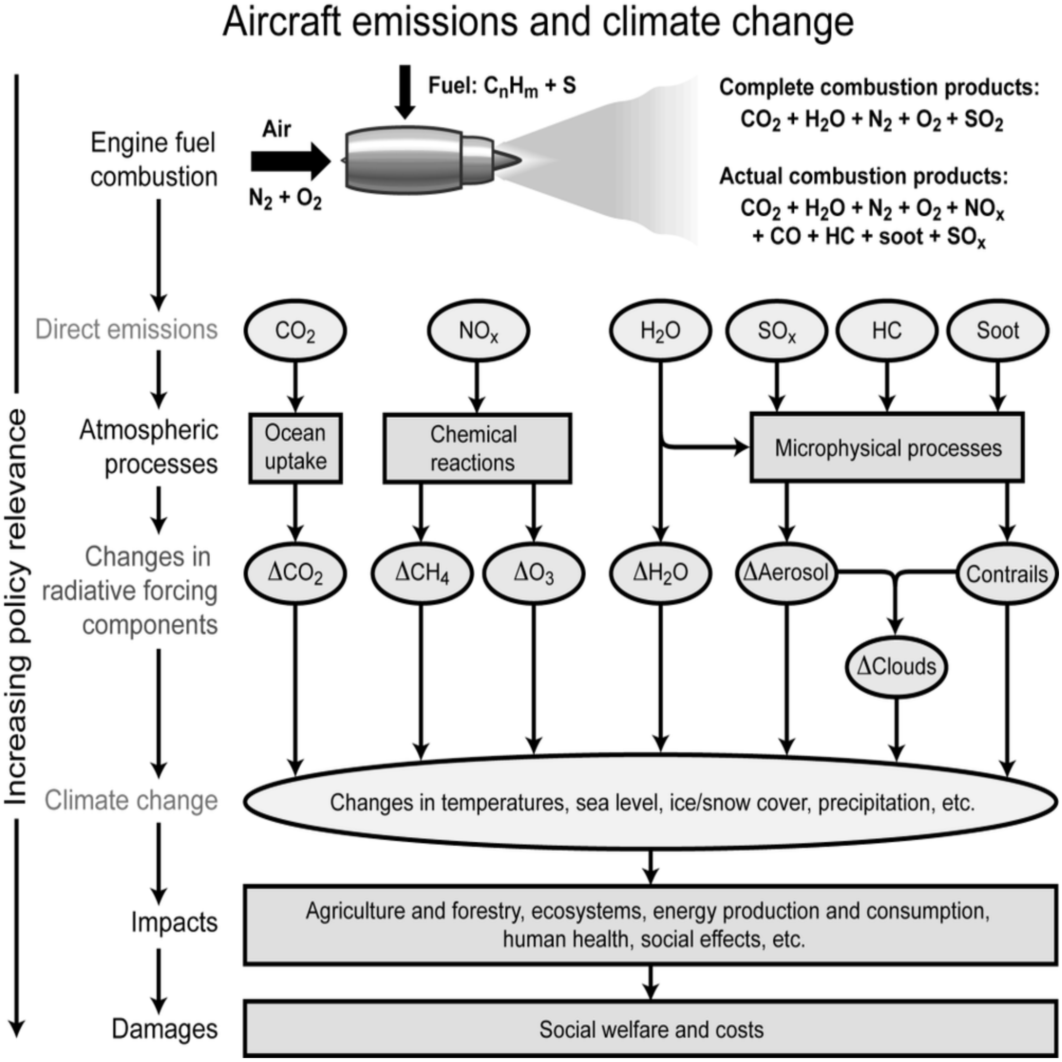

Figure 1*: Schematic of the principal emissions from aviation operations that combust fossil fuel in in the upper atmosphere. The direct emissions are carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC) and sulfur species (SO_x), black carbon particles (BC), and water vapor (H_2O). Computer models simulate how these emissions are transformed and transported in the atmosphere, leading to direct or indirect changes in atmospheric composition or cloudiness that in turn change radiative forcing of climate and ultimately physical climate parameters such as temperature and sea levels.*
Source: Lee et al., "Aviation and Global Climate Change", supra, note 2.

aerosol particles in the exhaust plume and after plume dispersion. New particles are formed and add to the background abundances of particles, and these can subsequently form cloud droplets under the right meteorological conditions long after the exhaust plume disperses. The resulting changes in cloud properties are an indirect effect of aviation operations.

Black carbon aerosol (also known as soot) is chemically inert in the atmosphere. It rapidly becomes coated by condensation of various gas-phase species, especially those containing sulfur (sulfuric acid). Black carbon emissions cause a small increase in aerosol mass compared to other natural and anthropogenic sources. Particles containing black carbon and other materials, such as sulfuric acid, participate

Table 1: *Radiative forcings in the industrial era from aviation emissions and increased cloudiness as evaluated in 2005.*

Emissions and cloudiness	**Radiative forcing terms (W m^{-2})**[a]
Cloudiness	
Linear persistent contrails	0.0118[b]
Induced cirrus cloudiness	0.033
Carbon dioxide (CO_2)	0.028[b]
Nitrogen oxides (NO_x):	
Ozone (O_3) component	0.0263
Methane (CH_4) component	-0.0125
Total NO_x effect	0.0138
Hydrocarbons (HC) and carbon monoxide (CO)	Negligible
Sulfur and sulfate aerosol (SO_x)	-0.0048
Black carbon (BC) or soot aerosol	0.0034
Water vapor (stratosphere)	0.0028
Total aviation contribution	**0.078 (38 - 139)**
Percentage of total forcing from human activities	**4.9% (2 - 14%)**[c]

[a] Estimates for 2005 aviation operations from Lee et al., "Aviation and Global Climate Change", supra, note 2. Numbers in parentheses are 90% likelihood ranges. Uncertainty estimates for other terms are provided in Lee et al.

[b] These terms have been updated in IPCC, Climate Change 2013, supra, note 6, at 592 for 2011 aviation operations to 0.05 (+0.02 to 0.15) W m_{-2} for linear contrails plus contrail cirrus and to 0.010 W m_{-2} for linear contrails.

[c] For reference, CO_2 radiative forcing from all human activities was estimated to be 1.6 W m_{-2} in 2005, see IPCC, Climate Change 2013, supra, note 6.

in processes that form cloud particles. Resultant changes in cloud properties are also an indirect effect of aviation and represent human-caused changes in an important climate process.

Finally, water vapor emissions add to its atmospheric background abundance. Water vapor in the background atmosphere serves as one of Earth's most important greenhouse gases, helping maintain its temperature suitable for life. For flights in the troposphere (less than 8-10 km altitude), where clouds and precipitation occur, the additional water vapor is considered negligible. For flights in the stratosphere, where the background water vapor is much lower [less than 20 parts per million (ppm)], increases in water vapor from aviation represent a small contribution to climate change.

The more important role of water vapor emissions from jet engines is to initiate contrail formation. Contrails are defined as the line-shaped (linear) cirrus clouds trailing behind aircraft operating at cruise altitudes (8-12 km) and are readily seen with the unaided human eye from the ground. In the expanding and cooling exhaust plume immediately behind a jet engine, the amount of emitted water vapor and aerosol particles along with the ambient meteorological conditions near the aircraft determine whether condensation occurs to form liquid water droplets. If formation occurs, the droplets subsequently freeze to form ice particles, typically at ambient temperatures in the range of -30 to -60°C. The new ice particles then grow in size through condensation of ambient background water vapor, which is the source of most of the water contained in contrail ice particles. Contrails increase cloudiness along the flight track and represent a change in radiative balance because clouds interact with solar radiation and infrared radiation from the surface. As such, contrails are visible, large-scale evidence that human activities are changing the climate system.

As linear contrails persist in the atmosphere for minutes to hours after formation, they spread and drift with the local winds near the formation altitude, eventually losing their linear feature and becoming indistinguishable from background clouds. As a consequence, atmospheric cloud models must be relied upon to quantify the contribution of contrails to background cloudiness beyond linear contrails. These spreading contrails are often called contrail-induced cloudiness or contrail cirrus.

2. Radiative Forcing

The emissions and cloudiness from global aviation operations influence Earth's climate through changes in the radiative balance in the atmosphere.

The changes are expressed using the metric of *radiative forcing (RF)* which is quantified as energy per unit time per unit surface area of the Earth, with formal units of Watts per meter squared (W m^{-2}). In the unperturbed state, the atmosphere and Earth's surface are in balance, with the energy absorbed from the Sun equal to that emitted to space. A major feature of the radiative balance is the role of gases and aerosol in the atmosphere. Greenhouse gases absorb heat energy radiating from the surface, thereby trapping heat and elevating surface temperatures. The most important greenhouse gases are CO_2 and water vapor, which act together to elevate surface temperature to values suitable for life. These and other greenhouse gases [e.g., ozone, methane and nitrous oxide (N_2O)] have significant natural sources. Atmospheric aerosols reflect or absorb solar radiation depending on their location and type; hence, some cool and some warm the atmosphere and the surface. Humans cause a radiative forcing when their activities change the composition of the atmosphere, with greenhouse gases, aerosol particles, or cloudiness being principal agents. The increase in radiative forcing from CO_2 emissions is the largest among all climate forcing agents related to human activities as evaluated between the beginning of the industrial era and present day. Increases in RF since the pre-industrial era lead to surface warming and decreases lead to surface cooling. A valuable description of the fundamental principles controlling Earth's climate and the contributions from all human activities is available from the Intergovernmental Panel on Climate Change (IPCC).[7]

The RF terms for 2005 aviation operations are shown in Table 1.[8] The list of terms follows the discussion above of the individual emissions and cloudiness changes caused by jet engine operations at cruise altitudes. The largest term is total cloudiness changes (linear contrails plus contrail cirrus) followed by CO_2 and the total NO_x effect from methane and ozone changes. These three terms are all positive (leading to climate warming) and represent a large fraction of the estimated net positive radiative forcing from aviation. The other agents in Table 1, namely sulfur species (negative contribution), black carbon and water vapor, together represent a net positive, but smaller, contribution to the net radiative forcing from aviation. Hydrocarbons and carbon monoxide are not included in Table 1 due to their negligible contributions. Thus, aviation operations contribute to a net positive forcing of the climate system, which leads to the impacts noted in Figure 1.

Arguably, CO_2 is the most important, yet most difficult, emission to reduce following decades of efficiency improvements.[9] Because of the long lifetime of CO_2 after emission, CO_2 radiative and climate effects persist for millennia. Projections for aviation operations and emissions all indicate substantial growth in coming decades[10] with growth of CO_2 emissions of up to a factor of 5 between 2010 and 2050. These projections are likely to be revised substantially in coming years due to ongoing changes in the industry to reduce its carbon footprint and decisions in the international policy arena to reduce the global carbon footprint from all human activities. For example, life-cycle CO_2 emissions per passenger kilometer could decline substantially in coming decades for some aircraft types due to changes in technology, air traffic management and airline operations.[11] Modern airframe and engine design are at the forefront of engineering sophistication to maximize fuel efficiency and, hence, further step-changes to improve technology in the longer term will require radically different technologies, such as the "open-rotor" engine or blended-wing body, that are relatively costly.

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[7] IPCC, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press, 2007). See also IPCC, "Frequently Asked Questions (FAQ)", available on the Internet at <https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-faqs.pdf> (last accessed on 25 July 2016). The IPCC conducts assessments mandated by the United Nations Framework on Climate Change (UNFCCC) to evaluate the science basis of climate change (Working Group I). It draws upon hundreds of scientific and technical experts around the world to collect information and analysis and then to prepare a written assessment.

[8] The uncertainties in Table 1 values, as documented in Ref. 2 and 6, vary from high confidence to very low confidence due to combined limitations in scientific understanding, atmospheric modeling, or observational data. The highest confidence is in CO_2 RF, in part because it is well measured in the atmosphere and has a very long lifetime. Other terms have lower confidence, such as for contrails and contrail cirrus. The total RF without contrail cirrus from Ref. 2 of 0.055 W m^{-2} has an estimated uncertainty of ±60%. Further, IPCC notes low confidence in the updated total contrails plus contrail cirrus term because of important remaining uncertainties in contrail spreading rate, interaction of contrails with atmospheric radiation (optical depth), ice particle shape and radiative transfer processes.

[9] See Lee et al., "Aviation and Global Climate Change", supra, note 2.

[10] Ibid., and Cames et al., *Emission Reduction Targets*, supra, note 4.

[11] Andreas W. Schäfer et al., "Costs of Mitigating CO_2 Emissions from Passenger Aircraft", 6 *Nature Climate Change* (2016), 412-417.

In representing the climate change contribution of aviation, the distinction is often made between CO_2 and non-CO_2 RF terms. The reason is that CO_2 has a long lifetime, as noted above, whereas the lifetime of other RF terms is much shorter. If aviation operations ended today, the RF from all the non-CO_2 terms would be negligible within a few months – in contrast to CO_2 RF which would be essentially unchanged in that time period. The larger uncertainty of the non-CO_2 terms also leads to the CO_2 versus non-CO_2 distinction in policy discussions. One prominent challenge in considering non-CO_2 terms in emission trading schemes as CO_2-equivalent emissions is that the ratio of CO_2 to non-CO_2 terms changes with time even for a constant operations scenario. The change occurs because CO_2 RF increases as CO_2 accumulates in the atmosphere, whereas non-CO_2 RF terms remain essentially constant for constant operations, under the assumption of unchanging atmospheric conditions.[12] Ideally, mitigation efforts regarding future aviation contributions to climate change would address both CO_2 and non-CO_2 terms to optimize climate benefits. The contrast between CO_2 and non-CO_2 terms highlights the challenge of choosing the metrics most suitable to represent the climate change contribution from aviation as it is projected into the future and compared with contributions from other sectors.[13]

The difference in lifetime between CO_2 and non-CO_2 terms also creates variability in the spatial patterns of aviation climate effects. The global distribution of accumulated CO_2 emissions from aviation (or other CO_2 sources) is nearly uniform because the long atmospheric lifetime of CO_2 affords mixing over the entire globe. Thus, there is no substantial "fingerprint" in the global-scale geographical pattern of present-day RF from aviation CO_2. In contrast, the associated ozone and methane RF terms from NO_x emissions vary on regional to hemispheric scales, and contrail and contrail cirrus RF distributions are confined to air traffic regions. A further complexity is that the geographical distribution or pattern of a temperature response to any RF term is determined by both the RF geographical distribution and the internal dynamics and feedbacks of the climate system. Thus, any comparison of climate responses to non-CO_2 RF terms with other RF terms only in terms of a global-mean geographic distribution overlooks the potentially important role of regional variability in temperature and other climate responses.[14]

3. Comparison of Aviation RF to other Climate Agents

A wide range of human activities lead to increased RF in addition to aviation operations. The principal causes are the release of CO_2 in fossil fuel combustion and increases in cloudiness. Total CO_2 release in other transportation sectors (passenger cars, trucks, ships) and in energy production far exceeds that in aviation. Present day RF from road transportation is larger than that from shipping and aviation.[15] Other greenhouse gases are enhanced, such as methane and nitrous oxide from agricultural activities (food production and animal husbandry). The IPCC provides best estimates for a comprehensive list of greenhouse-gas RF terms for 2005 and 2011.[16] The CO_2 RF in 2005 is estimated to be 1.66 W m^{-2} with a 1.7% contribution from aviation CO_2 (0.028 W m^{-2}).

The total radiative forcing from all human activities is 1.6 W m^{-2} in 2005 and 2.3 W m^{-2} in 2011 based on the latest IPCC assessment.[17] Besides the well-mixed greenhouse gases (CO_2, methane, nitrous oxide, and synthetic compounds used in refrigeration, air conditioning, etc.), the total includes contributions from tropospheric and stratospheric ozone, which is a short-lived greenhouse gas; a variety of aerosols (black carbon, sulfate, and organic, mineral dust); changes in land use which change the reflectivity of the surface for incoming solar radiation; similar changes in surface reflectivity from black carbon aerosol depositing on snow and ice which enhances melting and removal; and aviation terms as discussed above. These additional terms include both positive and negative values which cancel out in aggregate, leaving the total RF nearly equal to that of CO_2 alone. In this context, the aviation total RF of 0.078 W m^{-2}

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[12] Piers M. de Forster, Keith P. Shine, and Nicola Stuber, "It Is Premature to Include Non-CO_2 Effects of Aviation in Emission Trading Schemes", 6 *Atmospheric Environment* (2006), 1117-1121.

[13] Jan S. Fuglestvedt et al., "Transport Impacts on Atmosphere and Climate: Metrics", 44 *Atmospheric Environment* (2010), 4648–4677.

[14] Marianne T. Lund et al., "How Much Information is Lost by Using Global-mean Climate Metrics? An Example Using the Transport Sector", 113 *Climatic Change* (2012), 949-963.

[15] Dirk J.L. Olivié et al., "Modeling the Climate Impact of Road Transport, Maritime Shipping and Aviation over the Period 1860–2100 with an AOGCM", 12 *Atmospheric Chemistry and Physics* (2012), 1449-1480.

[16] IPCC, *Climate Change 2013*, supra, note 6, Table 8.2.

[17] Ibid., Table 8.6.

in 2005 represents approximately 4.9% of total RF from all human activities.

Since 2005, emissions from aviation and most other sectors have steadily increased. If the comparison were to be made for 2011 as was done by the IPCC in 2013,[18] similar aviation percentages of total RF would likely be obtained. However, no detailed assessment for all aviation RF terms supersedes that published in 2009 for 2005 aviation operations.[19] The infrequency of full aviation assessments increases uncertainty in comparisons of aviation climate forcings to those of other sectors in interim years.

4. Alternative Fuels

Non-fossil fuels are being considered as alternative aviation fuels for their potential to lower the climate change contribution from global aviation operations. Aircraft using alternative fuels from biomass and other feedstocks would still produce CO_2 emissions in flight but these emissions would be partially offset in the fuel production process.[20] Lifecycle analyses show that use of biomass feedstock does not guarantee a carbon offset and that the offset depends a number of variable factors.[21] Examples of alternative fuels are Fischer-Tropsch (FT) hydroprocessed synthesized paraffinic kerosene (SPK), synthesized paraffinic kerosene from hydroprocessed esters and fatty acids (HEFA), and synthesized iso-paraffins (SIP) from hydroprocessed fermented sugars. Some fuels have been developed, certified, and demonstrated in flight but are not available in quantities necessary to satisfy commercial-scale demand at present. Other bio-derived fuels may become available that offer substantial net reductions in CO_2 emissions based on the manufacturing process. Nonetheless, strong efforts are underway to develop alternative fuels that could be produced in economically viable quantities over the next decade or so. Until the market potential is established, alternative fuels are unlikely to completely replace fossil-based kerosene in aviation for the foreseeable future.[22]

NO_x and CO emissions are similar or reduced for biofuels and fuel blends compared with standard aviation fuels. However, alternative fuels tested to date in current jet engines show significantly lower emissions of the small soot particles that control contrail formation.[23] Thus, substantial reductions in contrail frequency can be expected from alternative fuels. Further in-flight measurements with alternative fuels are required to quantify contrail formation changes in current engine/aircraft configurations. It is also important to note that alternative fuels lack the sulphur content of fossil fuel, which will reduce sulphate aerosol formation in the aircraft exhaust plume.

5. Contrail Mitigation

Alternative means to reduce contrail and contrail-cirrus effects are being considered though the avoidance of atmospheric conditions conducive to initial contrail formation. A reduction can be achieved by modifying aircraft routes to avoid ice-supersaturated, low-temperature air masses by lateral or vertical (flight level) diversions.[24] Since ice-supersaturated regions tend to be tens of kilometers across but often rather shallow vertically, a change of one or two flight levels en route may avoid them. Should such maneuvers result in additional fuel use, and therefore CO_2 emissions, complex decisions may need to be made to balance short-term against long-term climate effects. These decisions may require the consideration of climate metrics, which are not purely technical in nature, and which require prioritizing climate effects (e.g., total RF versus temperature response) and time horizon (e.g., decade versus century response).[25]

Contrail avoidance with current technology would require an additional sophistication of the air traffic

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[18] IPCC, *Climate Change 2013*, supra, note 6.

[19] Lee et al., "Aviation and Global Climate Change", supra, note 2.

[20] Russell W. Stratton, Hsin Min Wong and James I. Hileman, "Quantifying Variability in Life Cycle Greenhouse Gas Inventories of Alternative Middle Distillate Transportation Fuels", 45:10 *Environmental Science & Technology* (2011), 4637-4644.

[21] Ibid.

[22] Carolyn Davidson, Emily Newes, Amy Schwab, and Laura Vimmerstedt, *An Overview of Aviation Fuel Markets for Biofuels Stakeholders*, Technical Report NREL/TP-6A20-60254 (Golden, Colo.: National Renewable Energy Laboratory, 2014), available on the Internet at <http://www.nrel.gov/docs/fy14osti/60254.pdf> (last accessed on 25 July 2016).

[23] Bernd Kärcher et al., "The Microphysical Pathway to Contrail Gormation", 120 *Journal of Geophysical Research: Atmospheres* (2015), 7893–7927; Guy P. Brasseur et al., "Impact of Aviation on Climate", 97:4 *Bulletin of the American Meteorological Society* (2016), 561-583.

[24] Christine Frömming et al., "Aviation-induced Radiative Forcing and Surface Temperature Change in Dependency of the Emission Altitude", 117 *Journal of Geophysical Research: Atmospheres* (2012).

[25] Ibid.

management system, whereby areas of likely contrail formation are efficiently predicted on a dynamic basis so that air traffic might be routed to avoid them. Whether such additional complexity can be introduced is a topic still under discussion. Over and above the technical and scientific uncertainties of such an avoidance system, it is unclear whether the aviation sector would be motivated to develop and introduce such a system before reduction or limitation of contrail cirrus effects are part of an international agreement or policy. Persistent contrail formation may also be reduced by future aircraft technology changes related to fuels, combustors or cruise altitudes.

III. Concluding Remarks

Global aviation consumes significant amounts of fossil fuels. The combustion products emitted at cruise altitudes lead to changes in the atmospheric abundances of greenhouse gases and aerosols. Aircraft also produce persistent contrails and increase contrail cirrus cloudiness. These effects cause a net positive radiative forcing of climate, which leads to surface warming and other climate changes. There is substantial understanding of the physical processes that underlie how aviation emissions and cloudiness contribute to climate forcing, especially for CO_2 combustion emissions. There remain important uncertainties associated with the quantitative best estimates of aviation forcing components and, hence, these uncertainties are topics of ongoing research. The best estimate of total forcing for the 2005 global fleet is 0.078 $W\ m^{-2}$, which is approximately 4.9% of the forcing from all human activities. An important distinction within aviation climate effects is that between CO_2 and non-CO_2 effects. The radiative forcing of CO_2 emissions from aircraft movements last up to millennia after emissions occur whereas that from all non-CO_2 forcings last from weeks to months.

The climate effects of global aviation are expected to increase in the future as a result of increased passenger volume and aircraft movements, despite significant efficiency improvements in technology and operations. Alternative fuels with lower carbon-footprint offer an opportunity to reduce CO_2 emissions from global aviation for a given capacity and routing scenario, but they are not available at sufficiency economic scale at present, and are unlikely to be so for some time to come. The formation of contrails and contrail-cirrus might be reduced by avoidance of the high-humidity conditions in the background atmosphere that result in their formation and persistence; however, any avoidance that increases CO_2 emissions, even at a net reduction of overall radiative forcing, introduces a complex policy issue of mitigating short-term versus long term climate effects. Moreover, given that contrails and contrail cirrus are not part of any climate agreement, and that uncertainty concerning their radiative effects remains large, there may be reluctance to tackle this effect in the short term.