WHITE PAPER ON CLIMATE CHANGE AVIATION IMPACTS ON CLIMATE: STATE OF THE SCIENCE

BY D. W. FAHEY, NOAA EARTH SYSTEM RESEARCH LABORATORY, BOULDER, COLORADO, UNITED STATES

S. L. BAUGHCUM, BOEING COMPANY, SEATTLE, WASHINGTON, UNITED STATES

J. S. FUGLESTVEDT, CICERO, OSLO, NORWAY

M. GUPTA, FEDERAL AVIATION ADMINISTRATION, WASHINGTON, DC, UNITED STATES

D. S. LEE, MANCHESTER METROPOLITAN UNIVERSITY, MANCHESTER, UNITED KINGDOM

R. SAUSEN, DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT (DLR), INSTITUT FÜR PHYSIK DER ATMOSPHÄRE, OBERPFAFFENHOFEN, GERMANY

P. F. J. VAN VELTHOVEN, ROYAL NETHERLANDS METEOROLOGICAL INSTITUTE (KNMI), DE BILT, THE NETHERLANDS

*This White Paper represents the summary of the scientific literature review undertaken by researchers and internationally-recognized experts. It does not represent a consensus view of ICAO.

Summary

Aircraft emit gases and aerosol that change the composition of the atmosphere, cause increases in cloudiness through contrail formation and spreading, and modify natural clouds. At present, these changes together are estimated to cause a net positive forcing of Earth's climate system, which contributes to surface warming and other responses. There is substantial understanding of the components of aviation climate forcing, particularly CO_2. Important uncertainties remain in quantifying some of the aviation non-CO_2 climate terms and in the underlying physical processes. This paper presents a summary of recent progress in the state of the science since the 2012 ICAO/CAEP/ISG paper, especially related to contrails and induced cloudiness, contrail avoidance, and aerosol and NOx effects. The number and diversity of newly available studies has created a need to re-evaluate best estimates of aviation climate forcings. Our understanding and confidence in aviation climate forcings would be enhanced by a new international scientific assessment.

Aviation represents an important component of the global economy by transporting people and goods between essentially all nations. The aviation sector is expected to grow in the coming decades as demand grows, especially in the developing world. Aviation operations at altitude and on the ground rely heavily on fossil fuels, which emit combustion by-products that contribute to regional and global air quality, and climate change. In addition, aircraft emissions lead to contrail formation and increased cloudiness. The Intergovernmental Panel on Climate Change laid out the basic concepts of aviation's role in climate change and quantified its contribution in a Special Report in 1999 (IPCC, 1999). Since then, progress has been made to fill gaps in our understanding and refine quantitative estimates of climate forcing. The present paper represents an updated summary of the state of the science following on from the 2012 ICAO/CAEP/ISG paper on this topic (Fahey *et al.*, 2012), (see ICAO Environmental Report, 2013, p 48-53).

The connections between aviation emissions and radiative forcing, climate change, and its impacts and potential damages are shown in **Figure 1.** Direct emissions undergo various chemical transformations and accumulate in the atmosphere leading to radiative forcing. Radiative forcing (RF) is a measure of the imbalance in the Earth's radiation budget caused by changes in the concentrations of gases and aerosols or cloudiness. The principal greenhouse gases (GHGs) emitted are carbon dioxide (CO_2) and water vapor (H_2O). Emissions of nitrogen oxides (NO_x) impact the concentrations of other GHGs, mainly ozone (O_3) and methane (CH_4). Black carbon (soot) is a directly emitted aerosol, and sulfur oxides (SO_x), NO_x, and hydrocarbons (HC) lead to aerosol production after emission. Water vapor emissions in combination with emitted or background aerosol lead to contrail formation. Persistent contrails, which form at high ambient humidity and low temperatures, increase cloudiness. Additionally, aviation aerosol may modify natural clouds or trigger cloud formation. There is high confidence that these are the primary pathways by which aviation operations affect climate.

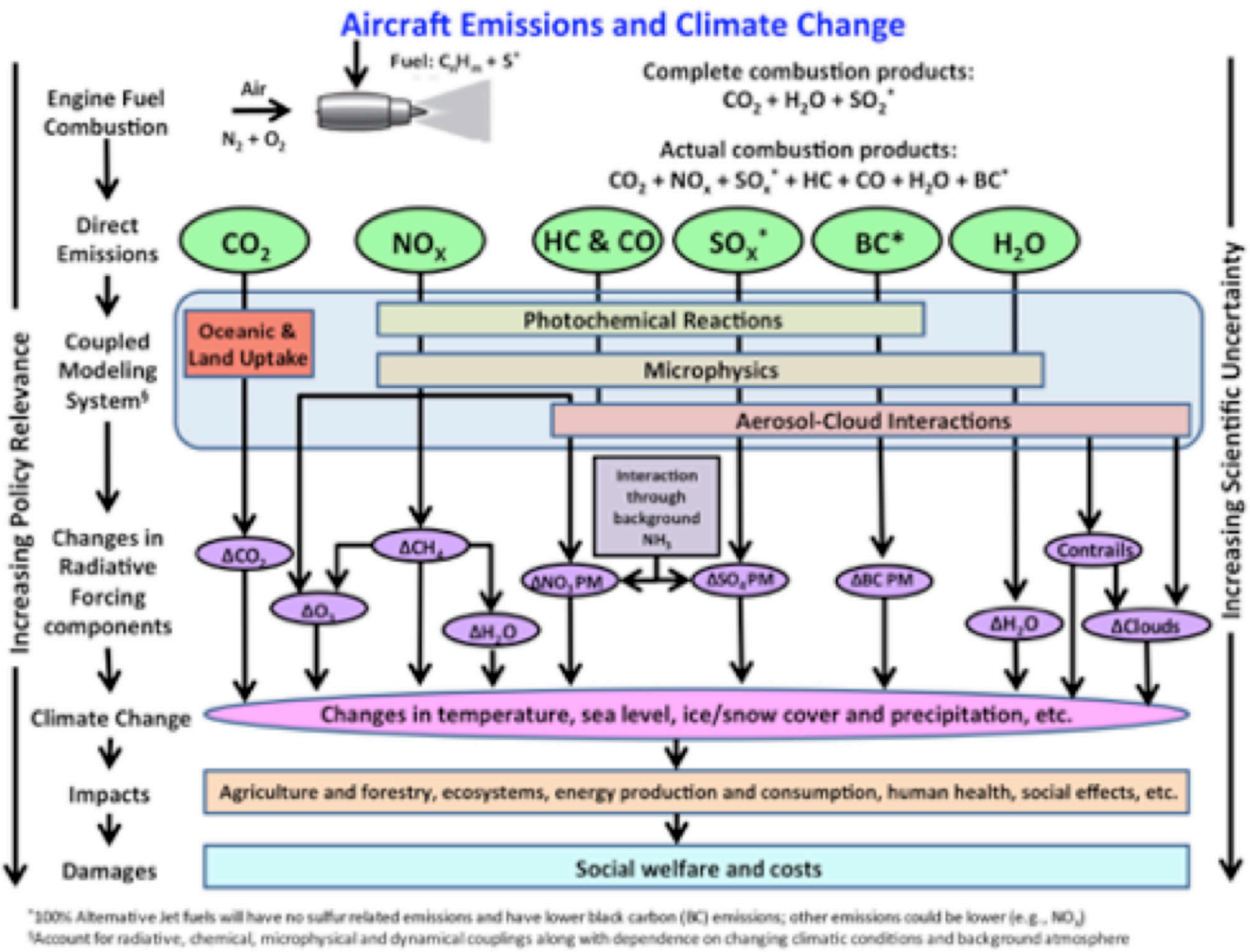

Figure 1. Updated schematic of the principal emissions from aviation operations and the relationship of emissions to climate change and impacts. The terminology, ΔX, indicates a change in component X. The term, Δclouds, represents contrail-induced cloudiness and aerosol-cloud interactions. (From Brasseur et al., 2015).

Aviation Fuel Use and CO_2 Emissions

All aircraft emit CO_2 as a fuel combustion product. Fuel use by the global aircraft fleet has increased approximately linearly over four decades (up to 2013) based on International Energy Agency estimates. Fuel use per revenue passenger kilometer (RPK) has decreased since the 1970s as aircraft structures, aircraft engines and aircraft operations have become more fuel efficient (Lee *et al.*, 2009). Aviation fuel use and CO_2 emissions are projected to continue increasing in the coming decades as aviation demand increases, even as CO_2 per RPK decreases due to technological and operational improvements.

Radiative Forcing of Current-Day Aviation from CO_2 and Non-CO_2 Agents

The RF of current-day aviation from CO_2 and non-CO_2 agents is established by a quantitative evaluation of each of the pathways shown in **Figure 1**. The evaluation requires knowledge of many physical and chemical processes in the atmosphere and requires summing over the global aircraft fleet operating under diverse meteorological conditions in the upper troposphere and lower stratosphere where most emissions occur. The Lee *et al.* (2009) study is the most recent assessment in the literature of the best estimates of aviation RF terms. The study updated estimates presented in the IPCC Special Report (IPCC, 1999) and Sausen *et al.* (2005). More recently, the Aviation Climate Change Research Initiative (ACCRI) program conducted by the Federal Aviation Administration in the USA provided important new results for aviation RF terms (Brasseur *et al.*, 2015).

With the passage of time, the scientific results underlying the best estimates of RF terms in Lee *et al.* (2009) are becoming superseded by more recent studies using updated methods and data. The exception is the CO_2 RF, which can be confidently and quantitatively calculated from fuel use and emission data over time (Lee *et al.*, 2009). For non-CO_2 terms, defining best estimates and their uncertainties, as outlined in the IPCC assessment process, requires a comprehensive synthesis of the available results in the scientific literature. Without such a synthesis, the newly available results generally form an incomplete and sometimes inconsistent picture, thereby leaving policymakers without a coherent basis for evaluation or other decisions. The recent ACCRI report drew similar conclusions in noting that recommendations for best estimates were precluded in their study due in part to the varied modeling approaches that did not all account for climate system couplings and feedback processes (Brasseur *et al.*, 2015). Continued progress in understanding and quantifying aviation climate forcings and responses requires continued focused research activities and would be enhanced by a new international scientific assessment that would assess new published results available, for example, for contrails, contrail cirrus and indirect cloud effects. An updated science assessment would also identify important remaining gaps in understanding and, hence, guide future research directions.

Another consequence of the lack of best estimates for aviation climate forcing terms is that the total RF from aviation cannot be computed with confidence. The total value and uncertainty rely on the addition of best estimates of various interdependent terms (and processes) and the propagation of underlying uncertainties. Comparison of RF terms with different lifetimes, such as those from CO_2 and contrails, in general require careful consideration as outlined in Section 8. Without a total RF, aviation's present contribution as a sector to climate change cannot be usefully compared to that from another sector. The exception is CO_2 for which emissions and RF comparisons over a defined time period are valid.

NO_x Effects

Aircraft NO_x acts as a catalyst to produce O_3 in the oxidation of CO, CH_4, and a variety of hydrocarbon compounds. While NO_x is not a greenhouse gas, it alters the abundance of two principal GHGs, O_3 and CH_4, through complex photochemical processes. Increased O_3 at cruise altitudes leads to a positive RF (warming). NO_x also increases the abundance of the hydroxyl radical (OH), which reacts with CH_4, thereby reducing its abundance and causing a negative RF (cooling). This long-term CH_4 reduction also leads to a relatively small long-term reduced production of O_3 and an associated small negative forcing. Recent studies, such as ACCRI and REACT4C, have included this term (Brasseur *et al.*, 2015; Søvde *et al.*, 2014). In addition, reductions of CH_4 result in small reductions of water vapor in the stratosphere, yielding another small negative forcing.

A principal difficulty in quantitatively evaluating the climate response to aviation NO_x is that the atmospheric lifetimes associated with O_3 and CH_4 responses lead to non-uniform hemispheric-to-global scale perturbations in these forcing agents. Furthermore, the magnitudes of the O_3 and CH_4 responses depend on the geographic location of the NO_x emissions and the NO_x background amounts from other anthropogenic and natural sources. This difficulty is reflected in differences between model simulations of O_3 and NO_x increases from 2006 aviation emissions as shown in **Figure 2** (Olsen *et al.*, 2013). The chemistry and climate models used were part of an ACCRI program effort to evaluate the agreement and consistency of NO_x effects across global models. General tendencies are seen in the results, such as an increase in O_3 and a reduction in OH, with large differences in magnitude in some cases. Model analyses by Holmes *et al.* (2011), Myhre *et al.* (2011), Søvde *et al.* (2014) show a spread of at least a factor of two in net NO_x RF values. These differences indicate that further evaluation of these results is required before a refined best estimate for RF from NO_x emissions can be derived from these community results (Olsen *et al.*, 2013).

Aviation Cloudiness

Increased cloudiness from aircraft operating at cruise altitudes is a key aspect of aviation impacts and one that is often visible to the human eye. The increases are typically divided into contributions from persistent (linear) contrails and contrail

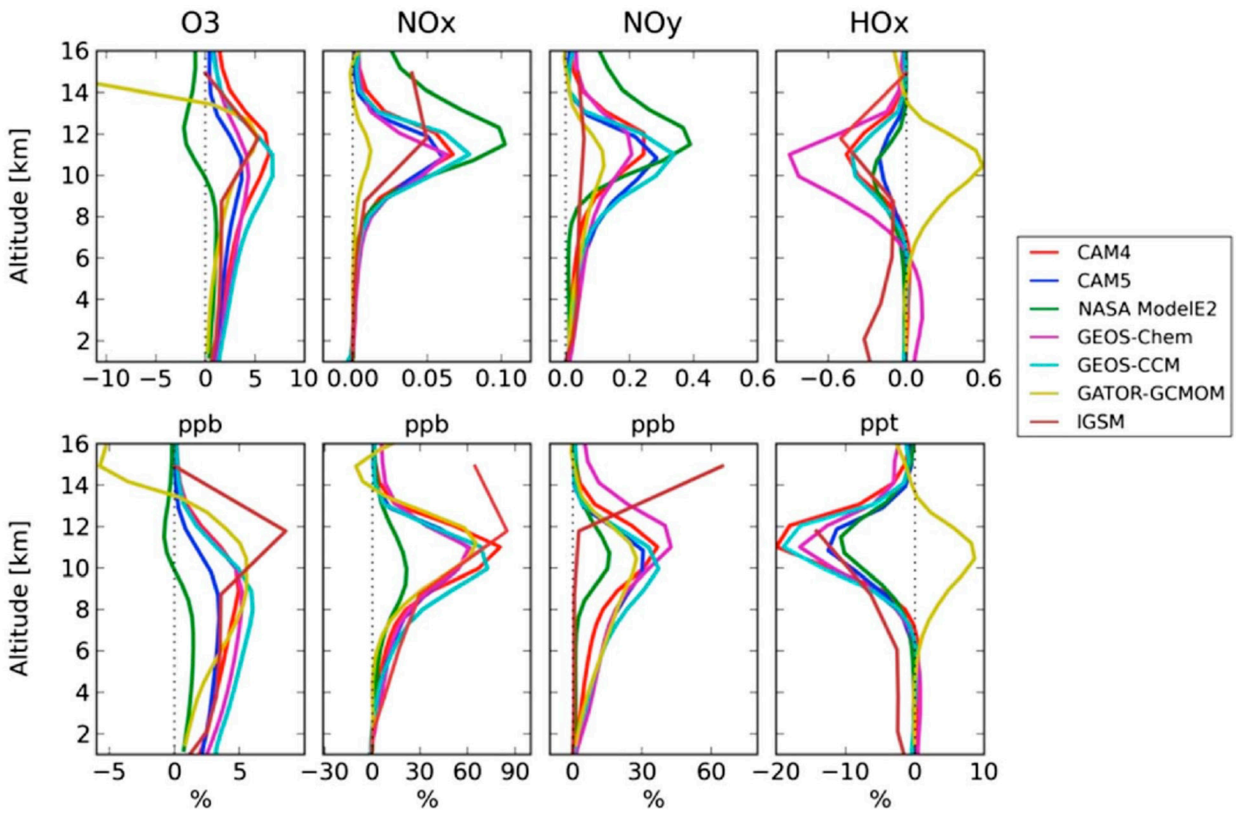

Figure 2. Effect of aviation emissions on O_3, NOx, NOy, and HOx amounts. Profiles are zonal means averaged over 30°N to 60°N from individual models (chemical transport models, chemistry-climate models, and 2D model). Absolute perturbation (top row) and percent perturbation (bottom row) at each altitude level are relative to the non-aviation background amounts. The study uses Aviation Environmental Design Tool (AEDT) 2006 aviation emissions. (From Olsen *et al.*, 2013)

cirrus. Aviation cloudiness causes an RF in a manner similar to natural cirrus clouds that cause a net warming (positive RF). Aviation cloudiness forcing estimates require integration over the lifecycle of contrail cloudiness from the diverse global aviation fleet operating in varying meteorological conditions. In the IPCC Special Report (IPCC, 1999) and many subsequent studies, only linear persistent contrails were evaluated, leaving contrail cirrus formed from spreading contrails unquantified. The updated evaluation in the most recent IPCC report (IPCC, 2013) now quantifies both these terms as discussed below.

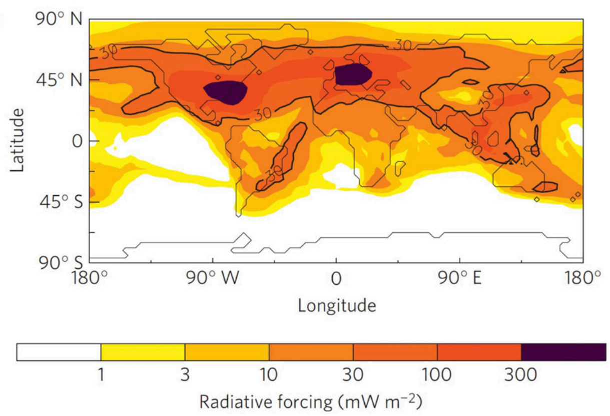

Figure 3. Global distribution of contrail cirrus radiative forcing for the aviation fleet in year 2002 from a global climate model with full contrail parameterization. (From Burkhardt and Kärcher, 2011)

A comprehensive treatment of the radiative forcing from contrails and contrail cirrus has been conducted in a global climate model for 2002 emissions (Burkhardt and Kärcher, 2011). Global contrails and their interactions with background (natural) cirrus are simulated by parameterizing the processes by which young persistent contrails are formed and age into spreading cirrus cover. This modeling effort represents a major advance in quantifying the aviation contribution to climate change. The resulting direct RF from contrails and induced cirrus cloudiness, including the reduction in background cirrus, is estimated to be 31 mW m^{-2} with the geographic distribution shown in **Figure 3**. A more recent evaluation with an improved climate model has yielded nearly identical results for the 2002 emission and yields a preliminary value of about 45 mW m^{-2} for 2006 emissions (Bock, 2014). For comparison, the estimate of CO_2 RF for 2005 is 28 mW m^{-2} (Lee et al., 2009). Another study derived a global annual contrail and contrail cirrus RF of 13 mW m^{-2} using a model that accounts for interactions of aircraft emissions with ambient clouds (Chen and Gettelman, 2013). The Burkhardt and Kärcher (2011) and Bock (2014) studies reveal the importance of accounting for contrail interactions with natural clouds by showing how contrails reduce natural cloudiness and how natural cloudiness shields a large fraction of contrails, thereby reducing the net radiative effect of contrails. These studies imply an increasing trend in cirrus coverage and properties from aviation operations that has not yet been confirmed by analyses of long-term observations of cirrus cloudiness from space.

Another major study has examined cloudiness the North Atlantic (NA) air traffic corridor using several years of satellite data for cirrus cover and outgoing longwave radiation (OLR) (Schumann and Graf, 2013). The diurnal cycle observed in OLR and cirrus cover is interpreted as a regional *aviation fingerprint*. A similar NA fingerprint is found with the Contrail Cirrus Prediction (CoCiP) model that simulates the lifecycle of contrail from reported air traffic data (Schumann *et al.*, 2012). The NA fingerprint features combined with certain assumptions, such as the natural cloud cover in the absence of aircraft, the absence of any other aviation cloud effects, the ratio of longwave to shortwave radiation effects, and the regional to global contrail cover, yields an RF estimate for total aviation cirrus of 50 (40–80) mW m^{-2} (2006 air traffic). The value of 50 mW m^{-2} is on the high end of the 13 - 49 mW m-2 range estimated from climate models. Based on a direct analysis of contrail spreading over land in otherwise clear skies using satellite data, Minnis *et al.* (2013) estimated for 2006 air traffic that the combined linear contrail and contrail-induced cirrus would also be ~50 mW m^{-2} globally in the absence of cloud shielding and with the assumption that all observed contrails have similar spreading rates. The actual global number is expected to be lower since the conditions in the study are optimal for maximizing the cirrus effect.

The most recent IPCC report (IPCC, 2013) provides an RF estimate for persistent contrails of 10 (5–30) mW m^{-2} for 2011, based primarily on the Burkhardt and Kärcher (2011) and Schumann and Graf (2013) results. This value and the recent 6 mW m^{-2} result from the first hemispherical analysis using 2006 satellite data (Spangenberg *et al.*, 2013) are both reasonably consistent with the 2005 best estimate from Lee et al. (2009) (12 mW m-2). Further, the IPCC estimates the combined contrail and contrail-cirrus effective RF from aviation to be 50 (20–150) mW m-2 with low confidence while noting important uncertainties of spreading rate, optical depth, ice particle shape, and radiative transfer processes.

Soot and Sulfur Emissions

Aviation engines emit aerosol (small particles) directly and aerosol precursor gases that subsequently form aerosol in the exhaust plume or after dilution in the background atmosphere. A large number of very small (i.e., with a diameter less than 0.050 µm) black carbon (i.e., soot) particles are directly emitted because they are products of incomplete combustion that have high vaporization temperatures. Emitted gaseous sulfur species form sulfate aerosol in the exhaust plume as it expands and cools. Soot and sulfate aerosol have direct radiative forcings of opposite signs: soot causes a positive RF, leading to warming, and sulfate causes a negative RF, leading to cooling. Direct effects result from aerosol interactions with solar radiation. Indirect effects

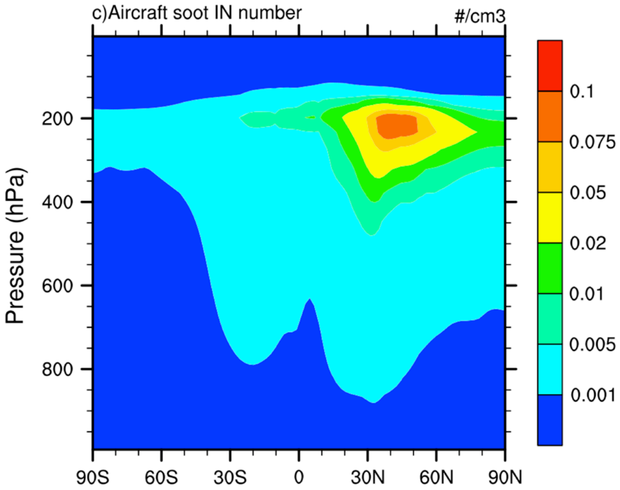

Figure 4. Annual and zonally averaged aircraft soot ice-nuclei number concentrations. All results are from the low sulfur and low dust case. (From Zhou and Penner, 2014)

result from aerosol induced changes in background cloudiness. Indirect effects are less well studied with few published RF estimates reflecting the difficulty in understanding and modeling the necessary nucleation processes. For example, IPCC provides no estimates of indirect effects of aviation aerosol (IPCC, 2013).

Recent results from general circulation model studies highlight the large uncertainties associated with aerosol indirect effects. Zhou and Penner (2014) calculate a range of –350 to +90 mW m^{-2} depending on the assumptions of the amount of sulfate and dust aerosol in the background atmosphere and the fraction (0.6%) of aviation soot that is active as ice nuclei to form clouds. **Figure 4** illustrates where soot emissions form ice nuclei for 2006 aviation emissions. In contrast, other studies find no significant effect (less than 10 mW m^{-2}) in part because of assuming a much less active soot fraction (0.1%) (Gettelman and Chen, 2013; Pitari *et al.*, 2015). The community currently lacks a sound basis to derive a best estimate from these most recent studies because of the poor process understanding and the absence of suitable measurements of the nature, abundance, and distribution of aviation aerosol in the background atmosphere. With the existing uncertainties, it is not possible to extrapolate soot impacts to future engines or conditions with confidence.

An important aspect of soot emissions is their influence on contrail formation. For typical fuel sulfur concentrations, the number of ice particles formed in the near-field plume of a contrail is nearly equal to the number of soot particles emitted (Kärcher *et al.*, 1998; 2015). Recently, Lewellen (2014) has evaluated parametrically how the integrated radiative forcing of an individual contrail over its lifetime varies with different atmospheric conditions for a single airplane type. A key conclusion of the study is that the forcing depends on the number of initial ice particles. Although this modeling result has not been experimentally validated, it suggests that engine combustor technology may also play a key role in reducing contrail effects. Efforts to reduce aviation soot mass and number emissions to protect air quality may have a dual benefit because of the consequential reductions in contrail RF.

Sulfate aerosol formed after emission has a small to negligible direct effect. Its indirect effect results from changes in liquid clouds in the background atmosphere well below flight altitudes. Few indirect cloud forcings have been estimated for sulfate and are typically absent from earlier assessments; one recent study estimates –46 mW m^{-2} (Gettelman and Chen, 2013). Righi *et al.* (2013) simulated the combined direct and indirect aerosol effects from aviation emissions via soot, sulfate and nitrate aerosols. The resulting cloud changes cause an RF of –15 mW m^{-2} (cooling) for the year 2000, with a range from –70 to +2 mW m^{-2} due to parameter uncertainty.

Metrics and Timescales

With the large number and diversity of anthropogenic climate forcing mechanisms associated with aviation, there is often interest in aggregating the effects by converting the non-CO_2 terms to so-called CO_2-*equivalent* terms, as is done under the Kyoto Protocol, or to use other scales or metrics. The application of an emission metric provides policymakers a basis to consider trading or other approaches to mitigation and affords scientists a framework to examine climate effects. The use of metrics is hampered by significant challenges related both to scientific

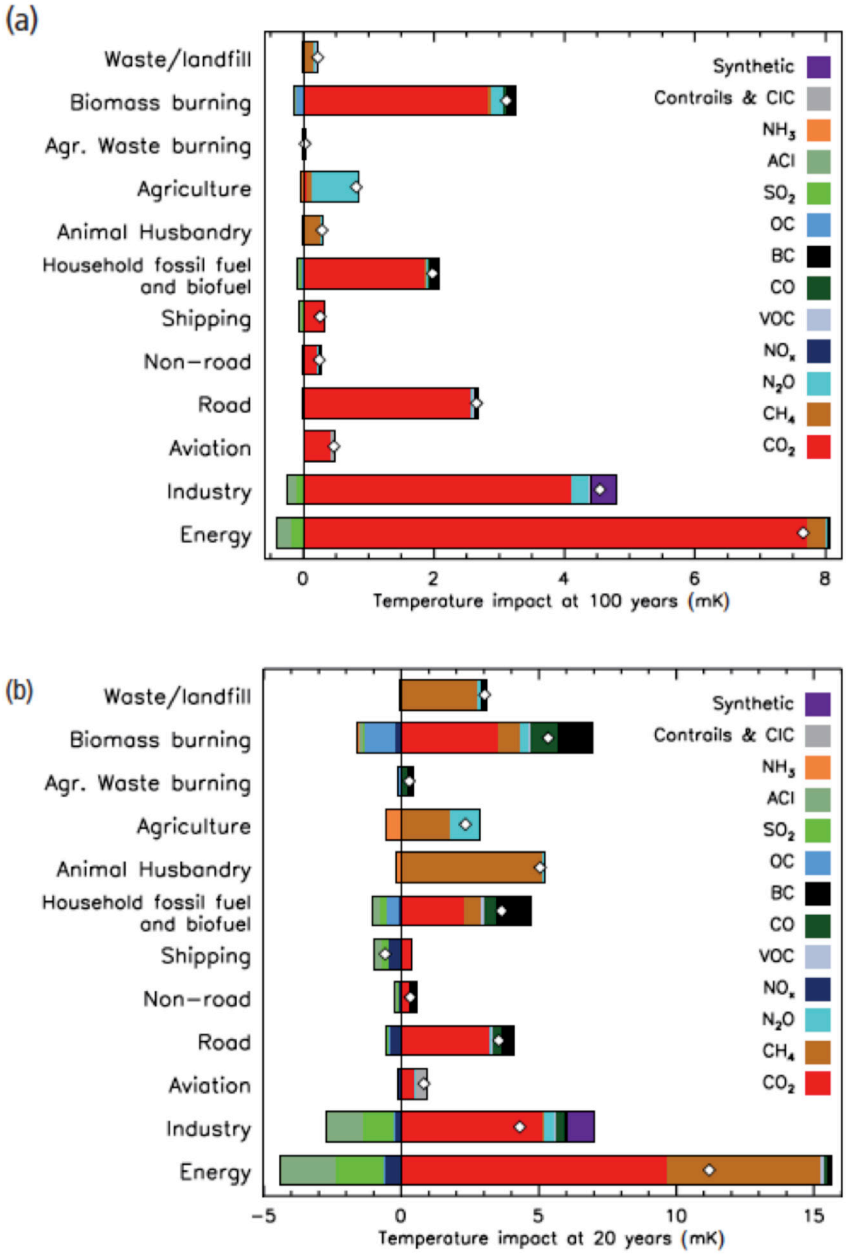

Figure 5. Net global mean temperature change by source sector after (a) 100 and (b) 20 years (for 1-year pulse emissions). Emission data for 2008 are taken from the Emission Database for Global Atmospheric Research (EDGAR) database. There are large uncertainties in the calculated temperature responses. (From IPCC, 2013)

issues and policy choices. For assessments of aviation effects and associated mitigation strategies, metrics such as the Global Warming Potential (GWP) or Global Temperature change Potential (GTP) (using integrated RF over a chosen time horizon and temperature change for a selected year, respectively) have been used in scientific studies. Metrics that capture regional patterns in response have also been explored for aviation (Lund *et al.,* 2012; Brasseur *et al.*, 2015), and some of these are based on experience from application of such metrics to surface sources (Collins et al., 2013; Lund *et al.*, 2014). Various approaches that adopt concepts and approaches from economics have also been evaluated (e.g., Azar and Johansson, 2011; Deuber *et al.*, 2014).

The emissions and RF mechanisms associated with aviation cause effects that operate on a broad range of time scales. The differences in lifetimes of climate forcing agents also lead to different spatial patterns of radiative forcing. Assessment of trade-offs between the climate impact of CO_2 and non-CO_2 effects involves weighing effects over time and therefore also value judgments. In particular, the comparison of climate forcing of contrails to that of CO_2 is challenging. While the RF and the temperature response from CO_2 emissions occur on a millennial time scale (IPCC, 2013), the lifetime and forcing of contrails is of the order of hours with a temperature response that may last for a few decades.

The importance of time scales in comparing aviation with other climate forcing agents is illustrated in **Figure 5**. The relative contributions of aviation induced cloudiness and CO_2 emissions to global temperature changes on 20- and 100-year time scales are compared with other emission sources for a 1-yr pulse of emissions. As the time scale increases, the warming from long-lived effects (e.g., CO_2) dominates those from short-lived effects (e.g., NOx and cloudiness). Overall, the global mean temperature changes after 20 and 100 years in response to one year of current emissions from aviation are small relative to other sectors.

Evaluation of the climate effects of aviation may also include estimates of the impacts and damages to natural systems and society, which are sometimes quantified in monetary units. Various damage-based metrics have been formulated. The Social Cost of Carbon (SCC) is an often-used metric based on a damage function that discounts future damages to the present and uses a baseline trajectory of emissions and the resulting temperature change (Kolstad *et al.*, 2014). There is an ongoing scientific debate on the estimate for SCC (e.g., Moore and Diaz, 2015; Marten and Newbold, 2012; IPCC, 2014). It is particularly difficult to estimate the social cost of climate change from aviation non-CO_2 agents due to methodological challenges and limitations in the knowledge about climate responses and damages.

In addition to challenges related to comparing effects over time, there are also issues related to the variability in the spatial patterns of aviation climate effects. The global distribution of enhanced CO_2 concentrations from aviation or other sources is essentially uniform because of its long lifetime. As a consequence there is no fingerprint of aviation CO_2 in the global-scale pattern of anthropogenic present-day RF or associated temperature changes. In contrast, O_3 increases from aviation, for example, vary on regional to hemispheric scales, while RF from contrails is much more confined to the areas of traffic. This is further complicated by the fact that the spatial distribution of temperature response to any RF mechanism is determined by both the RF pattern and the dynamics and feedbacks of the climate system. Thus, comparing non-CO_2 aviation effects with other forcing agents only in terms of a global-mean metric such as global mean RF GWP or GTP overlooks the potentially important role of regional variability in forcing responses (Lund *et al.*, 2012).

Emissions from Alternative Aviation Fuels

Recent studies have characterized the emissions from alternative fuels, using commercial engines in ground-based tests. Since 2011, three alternative fuels have been approved for blending with petroleum derived Jet-A/A1. They 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 (see ASTM D7566-14c for details). Research is underway to produce and evaluate other bio-derived fuels that offer substantial net reductions in CO_2 emissions based on a lifecycle or well-to-wake evaluation.

The reduced sulfur and aromatic contents in synthetic, paraffinic biofuel, or fuel blends with JP8 or Jet A result in significantly lower particulate matter emissions when measured as mass or number of particles (see Lobo *et al.* (2015) and Miake-Lye *et al.* (2012)). In a recent NASA project, emissions from HEFA biofuel blends measured on the ground produced similar results. The results are summarized in an evaluation of fuel properties on non-volatile particulate matter by Moore *et al.* (2015) and are described in more depth in the accompanying Miake-Lye *et al.* (2015) ISG air quality paper (see article page 75).

NOx and CO emissions are similar or reduced for FT fuels and JP8 fuel blends compared to JP8 while VOCs show a mixed response (Timko *et al.*, 2011). Preliminary ACCRI results indicate that deployment of alternative fuels leads to a decrease in modeled climate impacts from aviation sulfate and black carbon aerosols (Brasseur *et al.*, 2015). Thus, current understanding suggests that alternative fuels and blended fuels will have similar or reduced climate forcings from the non-CO_2 contributions, although important uncertainties remain concerning aviation cloudiness. A complication in the use of low aromatic fuels to reduce particulate matter is that current sealing materials in fuel systems require some aromatic content to swell in order to avoid fuel leakage in legacy aircraft.

Contrail Avoidance for Climate Change Mitigation

There is considerable interest in the potential of contrail avoidance to reduce aviation RF while accounting for potential tradeoffs such as increased fuel burn. This potential rests in part on the flexibility in aviation operations to change routing to avoid ice-supersaturated regions. Ice supersaturated conditions are required for persistent contrail formation and induced cirrus cloudiness. The first potential avoidance option is temporary altitude changes. It is particularly effective in prospect because ice-supersaturated layers are typically found in narrow vertical layers. The sensitivity of contrail forcing to altitude changes has been modeled in a parametric study as a function of zonal latitude regions for four vertical displacements of the global fleet routing (**Figure 6**) (Frömming *et al.*, 2012). The response is strongest in the northern hemisphere, consistent with air traffic density. The global mean changes in contrail RF are +7% and –49% for +2 kft and –6 kft, respectively. It is also important to note that CO_2 emissions increase for operations below optimum flight altitudes due to greater fuel burn rate. The second potential option is heading changes en route at constant altitude in order to avoid ice supersaturation regions. In practice, route changes generally increase both the flight length and associated CO_2 emissions, which offset any contrail RF reductions (Irvine *et al.*, 2014).

The effectiveness of both contrail avoidance methods depends, in part, on obtaining accurate, near real-time forecasts of the vertical and geographical extent of ice-supersaturated regions along a planned flight track. For example, a leading global meteorological forecast model was shown to have difficulty in reproducing ice-supersaturated regions where contrails form (Dyroff *et al.*, 2015).

Evaluating the tradeoff between contrail RF, which is short lived and has large uncertainty, and the more certain long-term CO_2 RF requires a choice of metric, such as the GWP or GTP, as well as a time horizon. Other short-lived climate terms are also likely to change if these avoidance methods are implemented. For example, the amount of O_3 formed from NOx emissions changes in response to altitude changes (Frömming *et al.*, 2012).

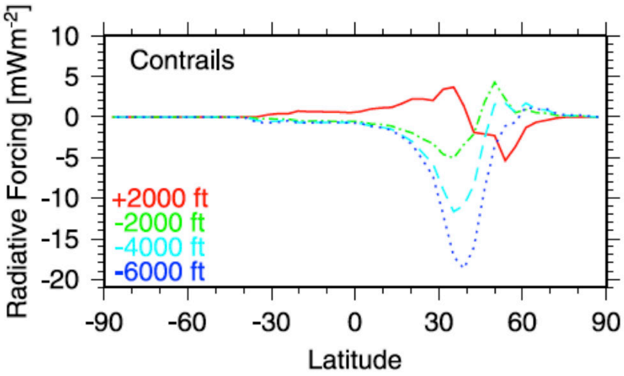

Figure 6. Changes of the zonal annual mean net radiative forcing (mW m^{-2}) of contrails in response to flight altitude changes by 2000 ft up, 2000 ft down, 4000 ft down, and 6000 ft down. Aircraft movements are from the TRADEOFF 2000 base case (25.4 x 10^9 km/yr flown distance, 152 Tg/yr fuel consumption, 0.6 Tg(N)/yr NOx emission). (From Frömming et al., 2012)

For contrail avoidance to be implemented in global aviation operations, a comprehensive approach would be needed that combines policy choices with scientific, operational and cost considerations (Irvine *et al.*, 2014; Deuber *et al.*, 2013; Grewe *et al.*, 2014). In practice, individual flight trajectories could be determined by minimizing a total climate cost function that combines contrails and induced cloudiness effects with CO_2 and all other non-CO_2 aviation effects. Within the European REACT4C project, Grewe et al. (2014) successfully applied such a procedure for selected weather situations.

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