Radiative Forcing Associated with Emissions from Air Travel

Literature Review to Inform Selection of a Radiative Forcing Factor

Executive Summary

In order to capture the non-CO2 climate impacts associated with aviation, a carbon dioxide (CO2) emissions multiplier – commonly referred to as a radiative forcing index (RFI) or radiative forcing factor (RFF) – of 2.7 to 3.0 is recommended for carbon accounting. While an RFI of 3.0 represents the conclusions from the most recent and robust scientific literature, 2.7 also represents a conservative RFI relative to alternatives discussed in this paper and is used more often due to its connection to the IPCC's landmark paper covering radiative forcing due to aviation. The summary table below lists the four RFI values explored in this paper, along with their years of publication, years of underlying data, key findings, and the scientific authors or institutions that endorse their use.

Summary Table: Overview of Commonly Used RFI Values

Proposed RFI	1.9	2.0	2.7	3.0
Year of Publication	2021[1]	2018	1999	2021
Year of Underlying Data	2005	Various (literature review)	1992	2018
Detail	Impact from contrails found to be lower than found in IPCC's 1999 report.	Argues that evidence for RFIs higher or lower than 2.0 are unsubstantiated based on available data.	Due to being the first major publication on RFI, many institutions currently use this factor.	Based on most recent data climate modeling, attributes large RF to contrails due to addition of contrail

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[1] DEFRA publishes methodology guidance to accompany its emission factors on an annual basis. On DEFRA's website, 1.9 has been endorsed in formal methodology guidance since at least 2012.

				cirrus RF estimates.
Endorsed by	DEFRA (2021)	Jungbluth & Meili (2019)	IPCC (1999)	Lee (2021)

Purpose

This memo aims to provide an overview of scientific literature on radiative forcing factors to inform the choice of an RFF for scope 3 carbon accounting.

Context

Aviation is believed to have indirect greenhouse gas (warming) effects beyond the direct effects of greenhouse gases emitted directly from jet fuel combustion. These indirect influences on the atmosphere are known as radiative forcing. The IPCC more specifically describes radiative forcing due to aviation as the following:

"Aircraft emit gases and particles directly into the upper troposphere and lower stratosphere where they have an impact on atmospheric composition. These gases and particles alter the concentration of atmospheric greenhouse gases…[that]contribute to climate change."[2]

To quantify the greenhouse gas effect of direct emissions, each greenhouse gas directly emitted is associated with a different global warming potential (GWP) in relation to its warming impact compared to carbon dioxide, which is assigned a GWP of 1.[3] The mass of each greenhouse gas emitted is multiplied by its GWP, leading to an estimate of the greenhouse gas effects in terms of carbon dioxide.[4] On the other hand, the indirect greenhouse gas effects associated with aviation are most commonly quantified using a "radiative forcing index" (RFI) or a "radiative forcing factor" (RFF), a multiplier applied to direct emissions to estimate the overall climatic impact of flight activity. However, scientific literature has produced varying estimates of the radiative forcing impacts of air travel, leading to some disagreement over the appropriate magnitude of the applied radiative forcing factor.

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[2] Penner et al., "Aviation and the Global Atmosphere" IPCC, prepared in collaboration with the Scientific Assessment Panel to the Montreal Protocol on Substances that Deplete the Ozone Layer, Cambridge University Press. 1999. https://www.ipcc.ch/site/assets/uploads/2018/03/av-en-1.pdf

[3] OECD Glossary of Statistical Terms, "Carbon Dioxide Equivalent." OECD. 2013. https://stats.oecd.org/glossary/detail.asp?ID=285

[4] For example, the GWP for methane is 25 and 298 for nitrous oxide, meaning that emissions of 1 million metric tons of methane and nitrous oxide respectively is equivalent to emissions of 25 and 298 million metric tons of carbon dioxide.

The following pathways are widely accepted as playing roles in the greenhouse gas impacts from aviation beyond the direct effects of greenhouse gases emitted from combustion of jet fuel:

- **Nitrogen Oxides (NOx):** Nitrogen oxides include nitrous oxide (N2O), nitric oxide (NO), nitrogen dioxide (NO2)[5], and nitrous oxide (N2O). **Nitrous oxide** is one of the key long-lived greenhouse gases directly emitted by fuel combustion, whose impact is typically quantified in standard carbon accounting since this gas has well understood global warming potential (GWP) with respect to carbon dioxide.[6] Due to its inclusion in direct emissions during greenhouse gas accounting, it is typically excluded from RFI analyses. **Other nitrogen oxides** are incorporated into RFI. NO is rapidly oxidized within a few minutes to nitrogen dioxide, so NO and NO2 are usually referred to and discussed collectively as NOx.[7] The radiative forcing effects of NOx involve the production and degradation of compounds, such as ozone (O3) and methane (CH4) at different timescales and rates.[8] The overall forcing impacts resulting from NOx emissions from air travel are subjects of continued study.
- **Contrails & Cirrus Clouds:** Contrails are visible line-shaped clouds that form in the wake of an aircraft, when the relative humidity in the plume of exhaust gases temporarily reaches liquid saturation in the ambient air, so that liquid droplets form on cloud condensation nuclei and freeze to form ice particles.[9] Linear contrails, which appear as thin, clear, continuous clouds, may lead to the formation of cirrus clouds, the most common form of high level clouds in the vicinity of the tropopause. Clouds play an important role in managing Earth's energy balance: clouds absorb and re-emit longwave rays from earth downward resulting in warming, and clouds scatter shortwave rays from the sun, and reflect many of these waves to space, resulting in cooling. Usually, the higher a cloud is in the atmosphere, as in the case of airplane contrails and cirrus clouds, the greater its greenhouse gas (warming) effect.[10] While contrails and resulting cirrus cloudiness are generally agreed upon as

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[5] EPA, "Technical Bulletin: Nitrogen Oxides (NOx), why and how they are controlled." EPA. 1999: Page 3. https://www3.epa.gov/ttncatc1/dir1/fnoxdoc.pdf

[6] According to the EPA's 2022 emission factor hub, the N2O factor of short, medium, and long flights are available (e.g., 0.0066 g N2O/passenger-mile for short-haul (<300 miles) flights), and their published GWP for N2O is 298, meaning N2O has 298 times the warming potential as carbon dioxide. Source: EPA, "Emission Factors for Greenhouse Gas Inventories," April 2022. Table 10 (page 6 of 7). https://www.epa.gov/system/files/documents/2022-04/ghg_emission_factors_hub.pdf

[7] Science Direct. "Nitrogen Monoxide." Hermann W. Bange, in Nitrogen in the Marine Environment (Second Edition), 2008. https://www-sciencedirect-com.stanford.idm.oclc.org/topics/earth-and-planetary-sciences/nitrogen-monoxide

[8] Jungbluth, Niels & Meili, Christoph. "Recommendations for calculation of the global warming potential of aviation including the radiative forcing index." *The International Journal of Life Cycle Assessment.* (2018): 1. https://doi.org/10.1007/s11367-018-1556-3

[9] Zerefos et al.," Evidence of impact of aviation on cirrus cloud formation," *Atmos. Chem. Phys.,* 2003: 1633. https://www.academia.edu/16605965/Evidence_of_impact_of_aviation_on_cirrus_cloud_formation

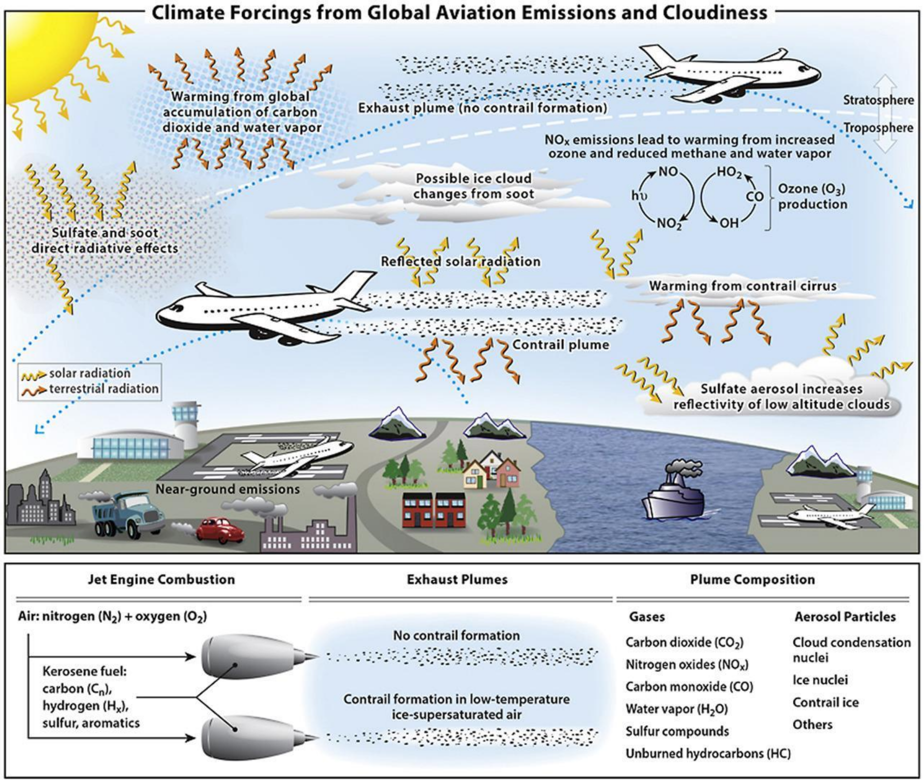
[10] NASA Earth Observatory, "Clouds & Radiation." NASA. 1999. https://earthobservatory.nasa.gov/features/Clouds

having an overall warming effect, the effects of linear contrails have been studied more than the effects of resulting cirrus cloudiness due to the lack of sophisticated modeling of cirrus cloud formation from contrails.

- **Sulfate & Soot Aerosols:** Aircraft engines emit compounds that form aerosols that lead to warming or cooling effects depending on their compositions. For example, airplane engines emit sulfur precursor compounds that oxidize in the ambient atmosphere to form sulfate aerosols.[11] Sulfate aerosols act as great condensation nuclei, playing a role in the formation of clouds that typically result in net cooling: sulfate aerosols lead to the formation of clouds that scatter short-wavelength solar radiation and lower shortwave reflective properties.[12] Additionally, aircraft engines emit soot, and soot aerosol is formed from the condensation of these unburnt aromatic compounds in the combustor. While the general net cooling effects of sulfate aerosols and the net warming effects of soot aerosols are generally agreed upon, quantification of these effects comes with relatively large uncertainty levels.[13]

A diagram of these factors' interactions can be found in Figure 1.[14]

<u>Figure 1.</u> Diagram of Radiative Forcing Impacts from Aviation



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[11] Lee et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018." 8.

[12] NASA Earth Observatory, "Aerosols." NASA. 2010. https://earthobservatory.nasa.gov/features/Aerosols/page3.php

[13] Lee et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018." 10.

[14] Lee et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018." 3.

RFI Calculations & Assumptions

Although RFI is meant to reflect the relative impact of a variety of chemical and physical processes, it should only be applied to the CO2 components of direct emissions (i.e., not also to the CH4 and N2O emissions components). The basic formula for an RFI multiplier is as follows:[15]

CF CO2, stratosphere = RFI all - (1 - Share CO2, stratosphere)

Where,

CF CO2, stratosphere = characterization factor for emissions of CO2 in the stratosphere
RFI all = RFI proposed for the total CO2 emissions of aircrafts
Share CO2, stratosphere = share of CO2 emissions in the stratosphere

To perform the above, the cumulative radiative forcing for the primary gases and particles involved (referred to as "RFI all") must be calculated, which presents a challenge. For example, some gases such as ozone have short-lived and long-lived effects and are influenced by location and season. To combat this, scientists estimate what can be assumed as the constant presence of these compounds due to the nonstop nature of global air travel. They also assume exponential growth in air travel and assume that emissions will be in a steady state to estimate their contributions to climate change.

However, the typical time-integrated approach is predicated on an assumed exponential growth of air travel, and an assumption that emissions will be in a steady state to estimate their contributions to climate change. Therefore, the appropriate RFI may be altered substantially if future aviation emissions deviate from their current growth trajectory. For example, the pandemic beginning in 2020 introduced some uncertainty that could negate the assumptions underlying the typical time-integrated approach. Future RFI studies may help elucidate the true effects of these assumptions.

As the methodologies for determining the RFI of all factors have proved challenging, a review of prominent methodologies and their associated RFIs is provided below.

Methodology & RFI Recommendations from Literature Review

In general, proposed RFIs have fluctuated in magnitude over time, from an initial value of 2.7 proposed by the IPCC (IPCC 1999) to 3.0 using most recent data (Lee 2021). Since the IPCC's landmark paper on RF due to aviation in 1999, various researchers have used values between 1 and 5. Below is an overview of four prevalent published RFI factors and their underlying data and/or modeling mechanisms, arranged in chronological order of publication. This information can be used to compare the strengths of the methodology behind each RFI.

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[15] Jungbluth, Niels & Meili, Christoph, "Recommendations for calculation," 5.

RFI 2.7

Dates: In 1999, the IPCC published its first paper on radiative forcing using data from 1992, proposing an RFI of 2.7.

Methodology: The IPCC's landmark study published in 1999 promoted an RFI of 2.7 based on research of the emissions associated with aircraft operation, an evaluation of how each emission would change the magnitude of corresponding radiative forcing phenomena in the atmosphere, and a determination of how those changes could alter concentrations of other "species," or compounds, in the atmosphere. Six scenarios of future greenhouse gas and aerosol precursor emissions were developed, based on assumptions concerning population and economic growth, land use, technological changes, energy availability, and fuel mix between 1990-2100.[16] Six models, consisting of general circulation models[17] and chemistry-transport models[18] were used to project various scenarios to model the consequences of global aviation.[19] Also, 1992 aircraft emissions inventory data were used as a baseline. The RFI of 2.7 is based on a mid-range emissions scenario considering these factors.

Contrail cirrus effects were only available for the RF of linear contrails; aging and spreading contrails were excluded. This is due to the difficulty of quantifying the contribution of aging and spreading contrails to cloudiness.

Findings: This landmark publication proposed an RFI of 2.7 to reflect the net positive radiative forcing of climatic features due to aviation. Based on the IPCC's analysis, C02, NOx (via ozone changes) and contrails contribute the most to radiative forcing from aviation. However, the uncertainty of their results is high due to modeling limitations; specifically, the uncertainty of linear persistent contrails is the highest.

Key differentiation: The strengths associated with this approach include its conservativeness and conventionality. In other words, it remains one of the higher aviation RFIs commonly used, which may be advantageous for benchmarking and aggressive emissions abatement planning. However, the IPCC's work in this landmark publication has a high level of uncertainty due to the lack of prior research available and modeling limitations. Additionally, the primary data underlying this research is from 1992, so the findings may be outdated.

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[16] Penner et al., "Aviation and the Global Atmosphere," 1999. https://archive.ipcc.ch/ipccreports/sres/aviation/017.htm

[17] General circulation models (GCMs) calculate temperature and transport circulation along with chemical composition. Please see https://archive.ipcc.ch/ipccreports/sres/aviation/017.htm for more details.

[18] Chemistry-transport models (CTMs) simulate the distribution of trace gases using temperature and transport circulation either from pre-calculated GCM results or derived from observations. Please see https://archive.ipcc.ch/ipccreports/sres/aviation/017.htm for more details.

[19] Penner et al., "Aviation and the Global Atmosphere," 1999. https://archive.ipcc.ch/ipccreports/sres/aviation/134.htm#931

RFI 1.9

Dates: Based on data from a 2005 report by the UN, the UK's Department for Environment, Food and Rural Affairs (DEFRA) endorses an RFI of 1.9.

Methodology: DEFRA's proposed RFI of 1.9 is based on data from a 2005 report produced by the UN in a project known as "TRADEOFF." Overall, this RFI is lower than some RFIs that preceded it (such as the IPCC's published 2.7 figure,) since the papers it refers to from the UN TRADEOFF project report reduced estimates of RF contributions due to contrails. The UN TRADEOFF project resulted in two papers by Zerefos and Stordal, in which satellite data between 1984-1998 (Zerefos) and 1984-1999 (Stordal) was used to study the relationship between contrails and cirrus cloud cover. Zerefos & Stordal both used data from the ISCCP, a project established to produce a global normalized radiance dataset for the infrared and visible spectra from which clouds could be derived.

Findings: Both Zerefos and Stordal use this historical satellite data to detect and define a relationship between aviation travel and cirrus cloudiness, finding that there are increasing trends in cirrus cloudiness between 1984 and 1998 over the high traffic aviation corridors of North America, North Atlantic, and Europe. They both maintain that these correlations are only moderate, with Zerefos writing those differences in cirrus cloudiness are statistically significant "only in the summertime over the North Atlantic and only in the wintertime over North America,"[20] and Stordal writing that "many other factors may also have contributed to changes in cirrus over the same time period."[21]

Key differentiation: An RFI of 1.9 suggests a more modest greenhouse gas effect from aviation compared to those included in previous publications, rendering it a less aggressive vantage point for emissions abatement measures. The key contributor to this lower RFI is reduced estimates of RF contributions due to contrails.

RFI 2.0

Dates: Jungbluth & Meili perform a literature review of papers spanning from 2000-2011 and argue that evidence published points to 2.0 as the best RFI available.[22]

Methodology: The authors identified 5 common RFI quantification approaches in use by scientific authors and assess the level of certainty associated with these approaches to determine the most appropriate option given the findings of existing literature.

Findings: Upon their evaluation, they argue that RFI factors between 2.7 and 3.0 are most appropriate to estimate the greenhouse gas effects of aviation emissions that occur at relatively high-flying altitudes but are not appropriate for flight miles that are lower in the atmosphere, which they argue have relatively lower RFIs. Additionally, they argue that the studies proposing 2.7 to 3.0 are based on outdated literature that is not easy

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[20] Zerefos et al." Evidence of impact," 1633.

[21] Stordal et al., "Is there a trend," 2162. https://acp.copernicus.org/articles/5/2155/2005/

[22] Jungbluth, Niels & Meili, Christoph, "Recommendations for calculation," 6.

to interpret, leading to further opportunity for misuse of higher RFIs.[23] Jungbluth & Meili argue that RFIs between 1.7 and 2.0 are also preferable since they are used in more recent papers published in scientific journals (Azar & Johansson 2012; Lee et al. 2009; Lee et al. 2010; Peters et al. 2011).[24] Additionally, they cite this factor as being used by the Stockholm Environment Institute, the German Umweltbundesamt, and one company providing carbon offsetting services (myclimate 2009).[25]

Key differentiation: Jungbluth & Meili argue that an RFI of 2.0 is preferable to an RFI of 2.7 as of the time of publication, given that an RFI of 2.0 is most reflective of current research, and used by a variety of other trusted institutions and peer-reviewed studies, which adds to the appeal of using 2.0.

RFI 3.0

Dates: In 2021, Lee et al. reviewed data from 2005, 2011, and 2018, recommending an RFI for 2018 of 3.0 to accurately capture the warming effects of aviation.

Methodology: Lee reviews literature published in the last two decades and uses new models to reconcile various radiative forcing impact values for relevant gases. To estimate the best radiative forcing factor to apply to aviation emissions, Lee focuses on the relationship between two metrics, RF (radiative forcing) and ERF (effective radiative forcing). Whereas RF is a predictor for the expected equilibrium that results from the introduction of climate forcers, such as additional atmospheric CO2 or a change in the solar irradiation, effective radiative forcing (ERF) refers to a more practical indicator of the eventual global mean temperature response after taking into account the effect of rapid adjustments in cloud cover, such as from aerosols, or changes in water vapor that either increase or decrease the initial RF.[26] Lee examines RF estimates from three climate-model based studies, and uses another model that allows him to determine an estimation of the ERF/RF ratio which he assumes to be constant with time. To provide a more granular understanding of the radiative forcing phenomenon, he examines the RF and ERF of specific atmospheric components that contribute to radiative forcing, such as for contrail cirrus, NOx, or water vapor.

Lee's paper also notably introduces improvements to the methodology for estimating the radiative forcing impact of contrail cirrus. As discussed in the background section, it is well-understood that aviation increases global cloudiness through the formation of persistent contrails in cold conditions, but there is quite a bit of variation in the magnitude of the estimated impact in the published literature due to the parameters of the contrails set in previous studies. Most existing literature focuses on linear contrails, which do not examine the cloudiness contribution of aging and spreading contrails. Lee improves upon these existing estimates by plugging previously published values for linear contrails into global climate models that simulate the complex microphysical processes of contrail spreading, overlap with natural clouds, radiative transfer, and the

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[23] Ibid.

[24] Ibid.

[25] Ibid.

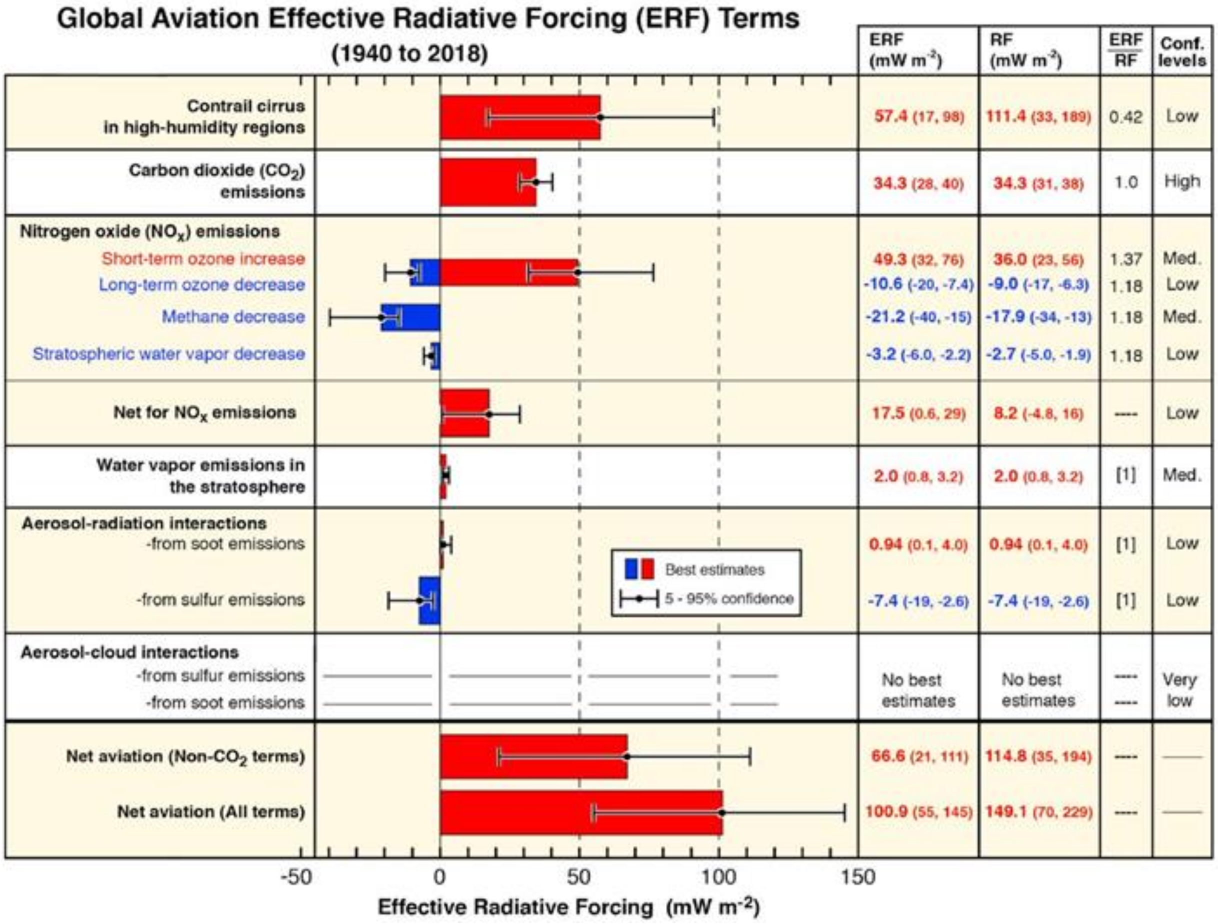
[26] Lee et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018." 10.

interaction with background cloudiness. Lee's overall RF result of 3.0 has an uncertainty lower than the IPCC's estimate, in part due to the development of process-based approaches to simulating contrail cirrus in recent years.

Findings: Lee's top-line recommendation to use an RFI of 3.0 reflects his finding that the net radiative forcings from non-CO2 forces comprise ⅔ of the net radiative forcing attributable to air travel. Specifically, contrail cirrus is believed to contribute significantly more radiative forcing than estimated in prior studies, taking its place as one of the top contributors to radiative forcing.

His findings are in Figure 2 below, showing that contrail formation and nitrous oxides are the two most impactful sources of non-CO2 indirect emissions.

Figure 2. Global Aviation Effective Radiative Forcing Terms by Greenhouse Gas



	ERF (mW m⁻²)	RF (mW m⁻²)	ERF / RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions				
-from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
-from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

Key differentiation: Notably, Lee finds that the cumulative radiative forcing impact of all factors was higher than estimated in previous studies—at 3.0—due primarily to more sophisticated modeling of contrails. While there is more work to do in the space, this new study has led to a more robust understanding of the full impact of contrails and the resulting cirrus cloud formation than previously existed in the literature.

Conclusion

Based on recent literature, larger RFIs (2.7 to 3.0) within the spectrum proposed by scientific literature are most appropriate to conservatively capture the radiative forcing impact of aviation. Based on Lee's research published in 2021, aviation emissions are currently warming the climate around three times faster than that associated with direct aviation CO2 emissions alone. Lee's data yields lower uncertainty than the IPCC's initial proposed figure of 2.7, which Stanford's Scope 3 Emissions Program currently employs. Papers discussed in this memo proposing 1.9 and 2.0 employ less aggressive approaches and are based on less timely data. An RFI of 3.0, but as low as 2.7, is suggested for use to remain in line with modern best practices. While an RFI of 3.0 is in line with the most robust and recent data, figures as low as 2.7 are also more conservative than alternatives and maintain conventionality for reporting and benchmarking. An RFI below 2.7 is not recommended based on Lee's calculations that estimate non-CO2 warming effects to be 66% of the warming associated with aviation.

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