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Full-length report

Accompanying the document

Report from the Commission to the European Parliament and the Council

Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)

{COM(2020) 747 final}

APPENDIX 4 – Task 3 Workshop on 12 March 2020

EASA

Impact of aviation non-CO_2 emissions on climate

Task 1 – The science

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Task 1

- What is the most recent knowledge on the climate change effects of non-CO_2 emissions from aviation activities? (the 'exam question')
- Report contents outline
  - Aviation emissions in context
  - Effects on climate and the 'impact metric'
  - Scientific uncertainties and developments in knowledge since 2008
  - CO_2 emission equivalent metrics
  - Mitigation opportunities

EASA 2

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EASA 3

Summary of main findings

- Significant uncertainties remain on non-CO_2 issues
- The main quantifiable non-CO_2 effects are from NO_x and contrail cirrus
- The general climate science move from RF to ERF affects both the above terms significantly
- Large uncertainties on aerosol-cloud interactions but a best estimate for these is not available

EASA 4

Summary of findings (cont.)

- A number of emission equivalence metrics exist, e.g. GWP, GTP, GWP*, ATR with a range of time horizons (TH) - none can be recommended over the other, since usage depends on concern and user choices such as TH
- 'Trades' of non-CO_2 against CO_2 need to be considered carefully to ensure no-regrets policies
- Future impacts of NO_x effects may change in sign, depending on background conditions for the same emission (non-linear chemistry)

EASA 5

Summary of findings (cont.)

- Reducing NO_x by technological means needs careful consideration
  - Tradeoffs vs CO_2
  - Technology lock-in
  - Uncertain future outcomes
- Operational mitigation of contrail cirrus could be possible and may be beneficial
  - Tradeoffs vs CO_2 (metrics, assumptions)
  - Only in oceanic airspace
  - Better quantification of uncertainties
  - Fit for purpose meteorological forecasting

EASA 6

Summary of findings (cont.)

- A simple single CO_2 emissions equivalent multiplier would be possible but:
  - Magnitude depends on metric and time horizon
  - Does not incentivize reduction of emissions
- Reducing aromatics in fuel (from bio/syn-fuels) has co-benefits for reducing contrail cirrus by ~60% (and co-benefits for air quality)
  - This requires more testing and evaluation (modelling and measurements) to firm up results

EASA 7

EASA

Questions?

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Aviation non-CO_2 climate impacts

Task 3: Potential policy action

CE Delft

Committed to the Environment

What should policies aim for?

- Reduce all emissions, but mainly CO_2
- Reduce overall climate impact
- Reduce NO_x emission impacts
  - Definitely not at the expense of CO_2 emissions
  - Possibly at the expense of CO_2 emissions
- Reduce contrails/cirrus impacts
  - Definitely not at the expense of CO_2 emissions
  - Possibly at the expense of CO_2 emissions
- Reduce all other emissions

- Are these all options?

2

Outline

- Progress on Task 3
- Presentation of the short-listed measures:
  1. NO_x charge;
  2. Inclusion of aircraft NO_x in the EU ETS;
  3. Reduction in maximum limit of aromatics within fuel specifications;
  4. Mandatory use of sustainable aviation fuels;
  5. Avoidance of ice-supersaturated areas; and
  6. A climate charge.

3

Progress on Task 3

	Literature review	Contact with key experts	Initial design	Review by consortium	Stakeholder review	Final design
NO_x charge	✓	✓	✓	✓	-	-
NO_x ETS	✓	✓	✓	✓	-	-
Aromatics standard	✓	✓	✓	✓	-	-
SAF mandate	✓	✓	✓	✓	-	-
Contrail avoidance	✓	✓	✓	✓	-	-
Climate charge	✓	✓	✓	✓	-	-

4

1. NO_x charge

- Member States would levy a charge to internalise the external costs of the climate impact of aviation NO_x emissions.
  - Eurocontrol may be best placed to levy the charge as it has access to all the relevant data, which Member States may not have.
- Charge on NO_x emissions over the course of the whole flight
  - Approximating cruise NO_x emissions from LTO NO_x emissions and the distance flown

1. NO_x charge

- The level of the charge would be aircraft- and route-specific, according to the following formulae:
  - $Charge_{i,j} = \alpha_{Clim\,NOx} \times Total\ NOx_{i,j}$
    - $Charge_{i,j}$ is the charge for aircraft i on mission j in Euro.
    - $\alpha_{Clim\,NOx}$ is the charge level in Euro per unit of mass (€/kg), set at the monetary value of the climate impact of NO_x
  - $Total\ NOx_{i,j} = \beta \times LTONOx_i \times D_j$
    - β is the factor that transforms the total LTO NO_x emissions to cruise NO_x emissions per kilometre.
    - $LTONOx_i$ is the emissions of NO_x per LTO cycle of aircraft i.
    - D_j is the distance of the route flown in kilometres.

1. NO_x charge

- The charge assumes a linear correlation between LTO NO_x emissions and cruise NO_x emissions which is constant for the whole fleet.
  - If that is not the case, aircraft-specific correlation factors would be needed.
- In principle, $\alpha_{Clim\,NOx}$ can be changed if the sign or magnitude of the climate impact of NO_x changes.
- There is a risk that the NO_x charge incentivises technological development where CO_2 emissions are increased in order to reduce NO_x emissions

1. NO_x charge

- Advantages:
  - Internalises costs of a well-understood non-CO_2 impact of aviation
  - Reduces demand and hence also CO_2 and other emissions
- Disadvantages:
  - Could incentivise technological development that leads to increased CO_2 emissions
  - Uncertainty about direction of climate impact of NO_x in the future
    - Warming/cooling is dependent on background concentrations of other pollutants

2. Inclusion of aircraft NO_x in the EU ETS

- The EU would include aircraft NO_x emissions in the ETS.
  - Aircraft would need to report emissions and surrender allowances.
- Emissions would be estimated and monitored according to the following formula:
  - $Total\ NOx_{i,j} = EINOx_i \times Fuel_j$
    - $EINOx_i$ is the emission index for NO_x at the cruise condition ($gNOx/g_{fuel}$). It is dependent on the engine type of the aircraft.
    - $Fuel_j$ is the amount of fuel used in mass units

9

2. Inclusion of aircraft NO_X in the EU ETS

- The equivalency between NO_x and CO_2 would be based on GWP_{100}, just as for other gases in the EU ETS
- The ETS cap would initially be increased by a (percentage) of the CO_2-equivalence of NO_x emissions in a base year.
  - From that point in time, the linear reduction factor would apply
- The initial allocation would be organised in the same way as for current allowances

10

2. Inclusion of aircraft NO_X in the EU ETS

- Advantages:
  - Internalises costs of a well-understood non-CO_2 impact of aviation
  - Reduces demand and hence also CO_2 and other emissions
  - Legislative framework already in place
- Disadvantages:
  - Could incentivise technological development that leads to increased CO_2 emissions
  - Uncertainty about direction of climate impact of NO_X in the future
    - Warming/cooling is dependent on background concentrations of other pollutants

11

3. Reduction in maximum limit of aromatics within fuel specifications

- The EU could promote a change in fuel standards to lower the maximum aromatics limit in ASTM and/or DEF STAN specifications
  - Slow process and uncertain outcome
  - Globally applicable
- The EU could develop a new standard with a lower maximum aromatics content
  - Risky to undermine ASTM and/or DEF STAN
- The EU could incentivise the sales of fuels with a lower aromatics content
  - As long as fuel complies with ASTM/DEF STAN, no problems are foreseen
  - Size of financial incentive? Other ways to incentivise?

12

3. Reduction in maximum limit of aromatics within fuel specifications

- In any case, it would be useful to have more information on the aromatics content of jetfuel used in the market today
  - Estimates range from 11% - 20%
- With new standard: consider effects on safety and the military?

13

3. Reduction in maximum limit of aromatics within fuel specifications

- Advantages:
  - Reduction in contrail formation
  - If ASTM/DEF STAN standards are adjusted then the measure has a global impact
  - Lower PM emissions, which lead to a positive impact on local air quality and climate change
- Disadvantages:
  - Uncertain what the current aromatics content is and hence what the new standard should be to have an effect
  - Changing fuel standards: long process and uncertain outcome
  - Legality of EU incentive for the sale of low-aromatics fuels next to existing fuel standards is unclear

14

4. Mandatory use of sustainable aviation fuels

- The EU could adopt legislation that requires fuel suppliers to blend a certain share of sustainable aviation fuels
  - A monitoring and reporting system would need to be set up
  - The aromatics content of the blended fuels should also be monitored. The content should be reduced for the measure to have an effect on nvPM emissions
  - Possibly be incorporated in the RED Directive
- Blending percentage could be increased over time
- National initiatives already in place in Norway and Sweden

15

4. Mandatory use of sustainable aviation fuels

- Advantages:
  - Reduction in contrail formation and SO_x emissions
  - Reduction in fuel lifecycle CO_2 emissions
  - Reduction in nvPM emissions
  - Potential increase in aircraft fuel efficiency
- Disadvantages:
  - Geographical scope is smaller than for the measure on maximum aromatics content
    - Limited to fuel uplifted in Europe vs. potential adjustment of global standard

16

5. Avoidance of ice-supersaturated areas

- Air navigation service provides would route aircraft to avoid ice-supersaturated areas
  - Horizontal or vertical deviation
  - Based on weather forecasts that are available up to 3 days in advance
- Not possible in busy airspaces (e.g. mainland Europe) but possible over Atlantic
  - NATS, NAV Canada and Eurocontrol
- A maximum detour should be determined to manage the trade-off with increased CO_2 emissions.

17

5. Avoidance of ice-supersaturated areas

- Advantages:
  - Reduction in contrail formation
- Disadvantages:
  - Trade-offs in detour (extra CO_2) versus reduced contrail effect
  - Limited scope because the measure cannot be implemented in crowded airspace

18

6. A climate charge

- Member States would task Eurocontrol to levy a charge based on the climate costs of each individual flight.
  - Climate costs are determined by flown route, latitude, height and weather conditions
- Climate cost functions exist, but there is no consensus about the right form of the function or the value of its parameters
  - Trade-off between administrative burden of calculating climate impact and accuracy of calculation
  - E.g. distance dependent charge (simple), 3D charge (more complex), 4D charge (even more complex)

19

6. A climate charge

- The level of the charge would be set by multiplying the climate impact of an individual flight, expressed in tonnes of CO_2-equivalents, by the social cost of carbon
- Eurocontrol's tasks would include:
  - registration and calculation of emissions in EU airspace;
  - operation of the charging and invoicing procedure; and
  - collection and disbursement of revenues.

20

6. A climate charge

- Advantages:
  - Internalises the costs of all the CO_2 and non-CO_2 emissions from aviation

- Disadvantages:
  - No scientific consensus on the cost function
  - Involves weighing impacts of different pollutants that are active across different time periods

21

DG MOVE-DG CLIMA study on the effects of non-CO_2 aviation emissions on climate change

EASA, Brussels
12 March 2020

Summary Record of Meeting

1. Welcome and Introductions

Participation: Rob Gemmill, Jarlath Molloy, Lisanne van Wijngaarden, Jasper Faber, Philippe Lenne, Rik Brouwer, Peter Vis, Chris Lewis, Stephen Arrowsmith, Joonas Laukia.

Remotely: David Lee, Andreas Busa, Stefan Ebert, Cheryl Micallef-Borg.

2. Summary of study ToR and confidentiality

Stephen provided some background to the project, and the meeting objectives. EASA is currently managing the project on behalf of the European Commission to examine the most recent knowledge on the climate change effects of non-CO_2 emissions from aviation, and potential policy options to reduce these impacts. The project arises from the EU ETS Directive Article 30(4), which requests for an analysis on the effects of non-CO_2 aviation emissions on climate change.

The project team contains task focal points for science, existing mitigation measures and trade-offs, and further potential policy action. Stephen clarified that the purpose of the workshop was to discuss the initial findings on the potential policy options to reduce the impact of non-CO_2 emissions. He also highlighted that the report, and recommendations included therein, is still work in progress, and should be treated on a confidential basis.

3. Summary of most recent knowledge on the climate change effects of non-CO_2 from aviation activities

David presented the summary of most recent knowledge on the climate change effects of non-CO_2 from aviation activities. He summarised that:

- Significant uncertainties still remain on non-CO_2 issues;
- The main quantifiable non-CO_2 effects are from NOx and contrail cirrus;
- The general climate science move from RF to ERF affects both the above terms significantly

- There are large uncertainties on aerosol-cloud interactions, and a best estimate[1] for these is not available;
- A number of emission equivalence metrics exist, e.g. GWP, GTP, GWP*, ATR with a range of time horizons (TH) - none can be recommended over the other, since usage depends on concern and user choices such as TH;
- 'Trades' of non-CO_2 against CO_2 need to be considered carefully to ensure no-regrets policies;
- Future impacts of NOx effects may change in sign, depending on background conditions for the same emission (non-linear chemistry);
- Reducing NOx by technological means needs careful consideration:
    - Tradeoffs vs CO_2
    - Technology lock-in
    - Uncertain future outcomes
- Operational mitigation of contrail cirrus could be possible and may be beneficial;
- Tradeoffs vs CO_2 (metrics, assumptions):
    - Only in oceanic airspace
    - Better quantification of uncertainties
    - Fit for purpose meteorological forecasting

The presentation was welcomed by the group. Questions were raised on the relationship between NOx emissions and formation of ice crystals. It was noted that the reduction of aromatics contained in jet fuel is a potential mitigation measure as it would reduce nvPM (mass and number) leading to a reduction in the formation of ice-crystals. On the other hand, it was noted that producing cleaner fuels would incur additional costs (including increased use of energy, hydrogen and consequential impact on price/yield of final fuel) for the fuel producer and operators.

4. Overview of potential policy options to reduce non-CO2 emissions and their feasibility of implementation

Jasper presented the potential policy options to reduce non-CO_2 emissions and their feasibility of implementation as included in the initial draft report. Regarding the scope of the study, it was noted that this study was limited to subsonic aircraft only.

The group reviewed each policy option contained in the draft report, and concluded the following:

1. *NOx charge*
    - A question was raised on the impact of N_2O emissions from aviation. *Post Meeting Note: Aviation emissions contain NO and NO_2 , and it is these species that are regulated within ICAO Annex 16 Volume II engine emissions certification requirements. N_2O is a potent long-lived GHG with GWP100 of around 300 arising principally from agricultural emissions, but also from fossil fuel combustion and*

[1] IPCC terminology: Estimates are available, but they cannot be synthesised because of uncertainties to give a mean/median number (with uncertainty range). The uncertainties may arise because of wildly disparate results (as is the case of aviation aerosol-ice-cloud interactions of soot), or there are considered to be too few results to give it a 'reliable' mean number (as is the case for aviation aerosol-cloud interactions of S with low-level warm clouds).

industrial processes. However, the emission factor is very small for aviation and usually ignored.

- Regarding Article 24 of the Chicago Convention, it was noted that previous research and experience suggests that internalization of environmental cost would be allowed under ICAO rules.
- The geographical scope could be a sensitive issue in a similar manner to the EU ETS.
- Eurocontrol access to accurate engine type data on a tailnumber basis still needs to be clarified.
- The roles and responsibilities between airlines, member states, ANSPs and international organizations was identified as important for the implementation of the NOx charge. We must also be careful with regard to the language used to describe these roles (e.g. MS mandate ECTL to collect charges in line with an agreed charging scheme).
- A legal review would be needed to identify the legislative process through which a NOx charge would be proposed.
- ANSPs highly likely not to favour adding a NOx charge to ATC fees for airlines (passengers) as it would add complexity to a relatively simple cost recovery mechanism, as well as blur the objectives of the CRCO.
- CRCO scheme now based on actual flightpath rather than filed flightpath. Need to ensure policy options do not create perverse incentives.

2. *Inclusion of aircraft NOx into the EU ETS*
    - It was noted that there is greater uncertainty in the climate impact and quantification of NOx compared to CO2, and therefore the CO2eq metric that would permit trading of 1 tonne of CO2 for an equivalent tonnage of NOx could undermine the confidence of the EU ETS.
    - The uncertainty, and potential unintended consequences, has a higher political risk in the ETS option compared to the NOx charge option. People pay real money for real emissions reductions, and a potential repeat of the issues with CDM offsets should be avoided in order to ensure the credibility of the ETS.

3. *Reduction in maximum limit of aromatics within fuel specifications*
    - It was noted that, if taken forward, this option would need to include a robust study to look at the benefits and costs (including environmental impact of increased refinery processing etc.) of changes to the DEF STAN/ASTM fuel specifications.
    - Data on the current specifications of fuel being used in the aviation sector is being collected (e.g. PQIS, JET SCREEN project, US Military), but access to this data is unclear due to there being several different sources.
    - Regarding the governance of the option, it was noted that the existing standardisation schemes use a consensus-driven, technical approach, and it could be challenging to impose actual legal requirements for the specifications of jet fuel which operate in a global commodity regime.
    - A holistic approach (e.g. use of SAF) to justifying proposed changes in fuel specs is likely to be more successful than focusing on a single species (more likely to have a

favourable benefit vs cost balance). For example, car Denox catalytic convertors were introduced to reduce NOx emissions, but needed lower sulphur fuel to work properly leading to changes in fuel specs.

4. *Mandatory use of SAF*
   - In general, the group saw this measure as very promising. It was highlighted that, if taken forward, the SAF mandate would need to take into account the level of current SAF production, and that a gradual increase in the mandate could be considered as production increases. The current major challenge is availability of SAF at commercially viable volume and cost.
   - Regarding the sustainability criteria for the SAF, it was agreed that this would need to refer to the existing criteria included in the EU Renewable Energy Directive (RED) in order to be consistent across EU policies.
   - Chris and Rik to provide a reference study investigating the benefits of SAF (approx. 1%) in terms of aircraft fuel efficiency due to lower mass with same energy content.
   - It was noted that an impact assessment on implementing this measure should consider its potential impact of penalizing regional operators compared to long-haul operators.

5. *Avoidance of ice-supersaturated areas (ISSR)*
   - NATS confirmed that implementation over mainland Europe would be difficult due to congestion
   - NATS was supporting a feasibility study led by the UK Royal Aeronautical Society and including Imperial College London, DLR and IATA on contrail avoidance over the North Atlantic.
   - Further information was also provided on route-planning. The Air Navigation Service Provider (ANSP) provide a pre-designed route track structure for the Airline Operators to choose from, based on where the Operators indicate they wish to fly and the most recent met forecast. Adjusting the track structure pre-tactically to avoid ISSRs would be possible, subject to various conditions and assumptions.
   - Despite the challenges in practical application, it was recognized that there could be some value in a pilot project investigating risks, opportunities, benefits and unintended consequences from avoiding ISSRs.
   - Regarding air navigation charges, it was noted that currently a flat charge is collected for crossing the Atlantic. Compensation may be needed if an airline was asked to detour an ISSR leading to a fuel burn penalty.
   - The additional complexity of contrails having a warming or cooling effect during day and a warming effect during the night would also need to be taken into account.

6. *A Climate Charge*
   - Similar considerations were raised to that of the NOx charge, especially related to the geographical scope, roles and responsibilities, legal issues involved in applying a climate charge and use of revenue raised.

- The complexity of such an option would only be justified if it was also considered more accurate. This is not the case at the moment, and so a more workable and defendable option may be optimum.

5. Summary of key points from discussions

The Project Team will consider the key points per agenda item captured above when finalizing the draft report.

6. AOB

Stephen presented the timeline for finalising the report. Final draft needs to be completed by Friday 4 April. A quick review of the meeting notes would be appreciated to help integrate feedback from the workshop in the report.

APPENDIX 5 – Updated aviation radiative forcing components in 2020

Selected content from Lee et al. (2020, in press), Figure and Table numbers refer to this paper and the legends are reproduced verbatim.

Lee D. S., Fahey D. W., Skowron A., Allen M. R., Burkhardt U., Chen Q., Doherty S. J., Freeman S., Forster P. M., Fuglestvedt J., Gettelman A., DeLeon R. R., Lim L. L., Lund M. T., Millar R. J., Owen B., Penner J. E., Pitari G., Prather M. J., Sausen R. and Wilcox L. J. (2020) The contribution of global aviation to anthropogenic climate forcing in 2018. *Atmospheric Environment* (https://doi.org/10.1016/j.atmosenv.2020.117834).

Abstract
Global aviation operations contribute to anthropogenic climate change via a complex set of processes that lead to a net surface warming. Of importance are aviation emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), water vapor, soot and sulfate aerosols, and increased cloudiness due to contrail formation. Aviation grew strongly over the past decades (1960–2018) in terms of activity, with revenue passenger kilometers increasing from 109 to 8269 billion km yr^{-1}, and in terms of climate change impacts, with CO_2 emissions increasing by a factor of 6.8 to 1034 Tg CO_2 yr^{-1}. Over the period 2013–2018, the growth rates in both terms show a marked increase. Here, we present a new comprehensive and quantitative approach for evaluating aviation climate forcing terms. Both radiative forcing (RF) and effective radiative forcing (ERF) terms and their sums are calculated for the years 2000–2018. Contrail cirrus, consisting of linear contrails and the cirrus cloudiness arising from them, yields the largest positive net (warming) ERF term followed by CO_2 and NO_x emissions. The formation and emission of sulfate aerosol yields a negative (cooling) term. The mean contrail cirrus ERF/RF ratio of 0.42 indicates that contrail cirrus is less effective in surface warming than other terms. For 2018 the net aviation ERF is +100.9 milliwatts (mW) m^{-2} (5–95% likelihood range of (55, 145)) with major contributions from contrail cirrus (57.4 mW m^{-2}), CO_2 (34.3 mW m^{-2}), and NO_x (17.5 mW m^{-2}). Non-CO_2 terms sum to yield a net positive (warming) ERF that accounts for more than half (66%) of the aviation net ERF in 2018. Using normalization to aviation fuel use, the contribution of global aviation in 2011 was calculated to be 3.5 (4.0, 3.4) % of the net anthropogenic ERF of 2290 (1130, 3330) mW m^{-2}. Uncertainty distributions (5%, 95%) show that non-CO_2 forcing terms contribute about 8 times more than CO_2 to the uncertainty in the aviation net ERF in 2018. The best estimates of the ERFs from aviation aerosol-cloud interactions for soot and sulfate remain undetermined. CO_2-warming-equivalent emissions based on global warming potentials (GWP* method) indicate that aviation emissions are currently warming the climate at approximately three times the rate of that associated with aviation CO_2 emissions alone. CO_2 and NO_x aviation emissions and cloud effects remain a continued focus of anthropogenic climate change research and policy discussions.

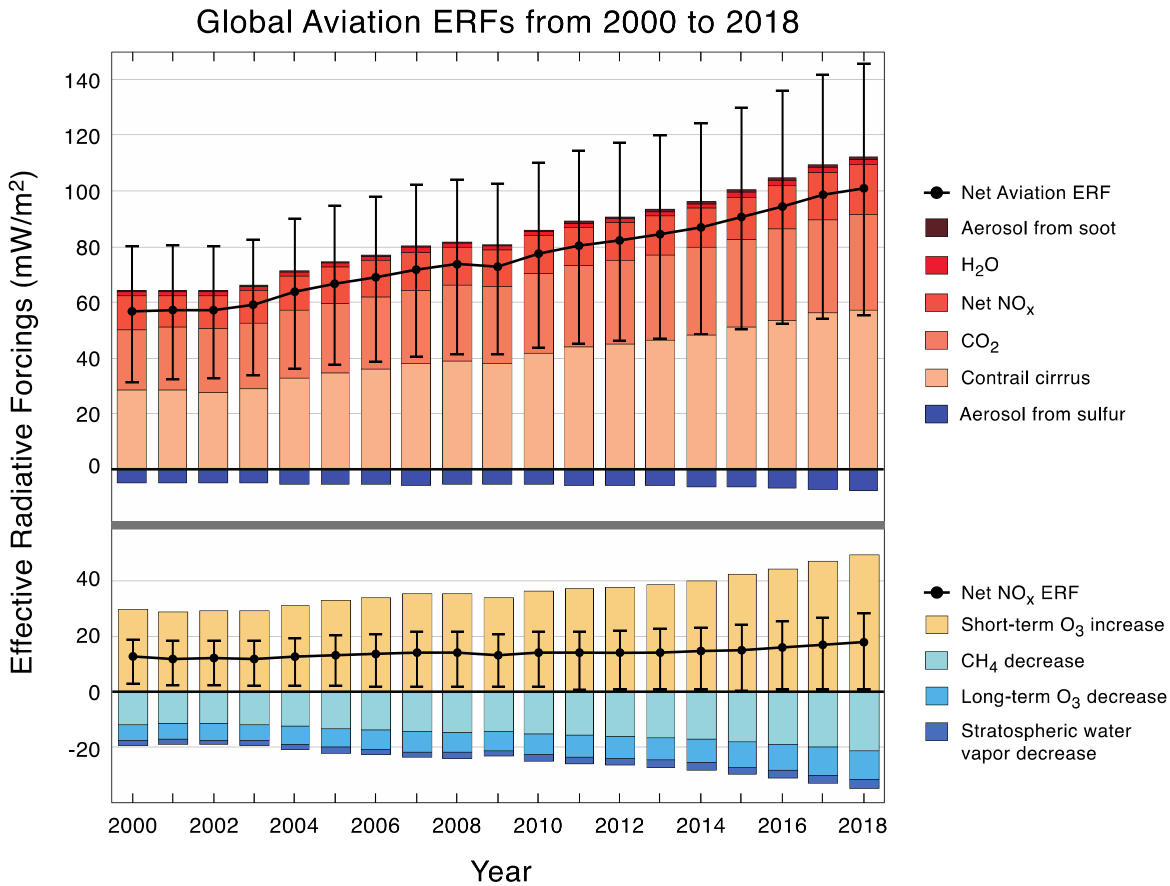

Figure 6. Timeseries of calculated ERF values and confidence intervals for annual aviation forcing terms from 2000 to 2018. The top panel shows all ERF terms and the bottom panel shows only the NO_x terms and net NO_x ERF. All values are available in the SD spreadsheet, in Tables 2 and 3, and in Figure 3 for 2018 values. The net values are not arithmetic sums of the annual values because the net ERF, as shown in Figure 3 for 2018, requires a Monte Carlo analysis that properly includes uncertainty distributions and correlations.

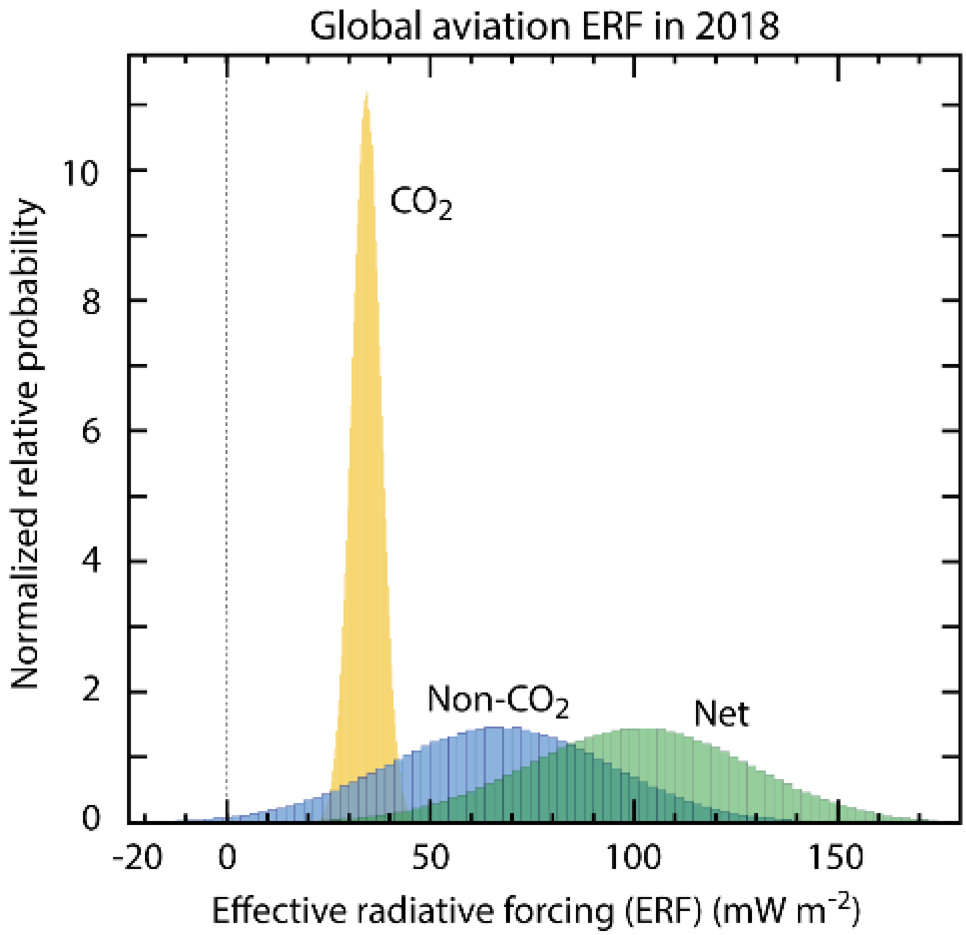

Figure 7. Probability distribution functions (PDFs) for aviation ERFs in 2018 based on the results in Figure 3 and Table 2. PDFs are shown for separately for CO_2, the sum of non-CO_2 terms, and the net aviation ERF. Since the area of each distribution is normalized to the same value, relative probabilities can be intercompared. Uncertainties are expressed by a distribution about the best-estimate value that is normal for CO_2 and contrail cirrus, and lognormal for all other components. A one-million-point Monte Carlo simulation run was used to calculate all PDFs.

Table 2. Best estimates and high/low limits of the 90% likelihood ranges for aviation ERF components derived in this study

ERF ($mW\ m^{-2}$)	2018 [a]	2011 [a]	2005 [a]	Sensitivity to emissions	ERF/RF
Contrail cirrus	57.4 (17, 98)	44.1 (13, 75)	34.8 (10, 59)	9.36×10^{-10} $mW\ m^{-2}\ km^{-1}$	0.42
CO_2	34.3 (28, 40)	29.0 (24, 34)	25.0 (21, 29)		1.0
Short-term O_3 increase	49.3 (32, 76)	37.3 (24, 58)	33.0 (21, 51)	34.4 ± 9.9 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$	1.37
Long-term O_3 decrease	-10.6 (-20, -7.4)	-7.9 (-15, -5.5)	-6.7 (-13, -4.7)	-9.3 ± 3.4 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$	1.18
CH_4 decrease	-21.2 (-40, -15)	-15.8 (-30, -11)	-13.4 (-25, -9.4)	-18.7 ± 6.9 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$	1.18
Stratospheric water vapor decrease	-3.2 (-6.0 -2.2)	-2.4 (-4.4, -1.7)	-2.0 (-3.8, -1.4)	-2.8 ± 1.0 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$	1.18
Net NO_x	17.5 (0.6, 29)	13.6 (0.9, 22)	12.9 (1.9, 20)	5.5 ± 8.1 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$	
Stratospheric H_2O increase	2.0 (0.8, 3.2)	1.5 (0.6, 2.4)	1.4 (0.6, 2.3)	0.0052 ± 0.0026 $mW\ m^{-2}$ (Tg (H_2O) $yr^{-1})^{-1}$	---
Soot (aerosol-radiation)	0.94 (0.1, 4.0)	0.71 (0.1, 3.0)	0.67 (0.1, 2.8)	100.7 ± 165.5 $mW\ m^{-2}$ (Tg (BC) $yr^{-1})^{-1}$	---
Sulfate (aerosol-radiation)	-7.4 (-19, -2.6)	-5.6 (-14, -1.9)	-5.3 (-13, -1.8)	-19.9 ± 16.0 $mW\ m^{-2}$ (Tg (SO_2) $yr^{-1})^{-1}$	---
Sulfate and soot (aerosol-cloud)	----	----	----	----	---
Net ERF (only non-CO_2 terms)	66.6 (21, 111)	51.4 (16, 85)	41.9 (14, 69)	----	---
Net aviation ERF	100.9 (55, 145)	80.4 (45, 114)	66.9 (38, 95)	----	---
Net anthropogenic ERF in 2011	----	2290 (1130, 3330) [b]	----	----	---

[a] The uncertainty distributions for all forcing terms are lognormal except for CO_2 and contrail cirrus (normal) and Net NO_x (discrete pdf).

[b] Boucher et al., 2013. IPCC also separately estimated the contrail cirrus term for 2011 as 50 (20, 150) $mW\ m^{-2}$.

Table 5. Emission metrics and corresponding CO_2-equivalent emissions for the ERF components of 2018 aviation emissions and cloudiness

Metrics

ERF term	GWP_{20}	GWP_{50}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}
CO_2	1	1	1	1	1	1
Contrail cirrus ($Tg\ CO_2$ basis)	2.32	1.09	0.63	0.67	0.11	0.09
Contrail cirrus (km basis)	39	18	11	11	1.8	1.5
Net NO_x	619	205	114	-222	-69	13
Aerosol-radiation						
Soot emissions	4288	2018	1166	1245	195	161
SO_2 emissions	-832	-392	-226	-241	-38	-31
Water vapor emissions	0.22	0.10	0.06	0.07	0.01	0.008

CO_2-eq emissions ($Tg\ CO_2\ yr^{-1}$) for 2018

ERF term	GWP_{20}	GWP_{50}	GWP_{100}	GTP_{20}	GTP_{50}	GTP_{100}	GWP^*_{100} (E^*_{CO2e})
CO_2	1034	1034	1034	1034	1034	1034	1034
Contrail cirrus ($Tg\ CO_2$ basis)	2399	1129	652	695	109	90	1834
Contrail cirrus (km basis)	2395	1127	651	694	109	90	1834
Net NO_x	887	293	163	-318	-99	19	339
Aerosol-radiation							
Soot emissions	40	19	11	12	2	2	20
SO_2 emissions	-310	-146	-84	-90	-14	-12	-158
Water vapor emissions	83	39	23	27	4	3	42
Total CO_2-eq (using km basis)	4128	2366	1797	1358	1035	1135	3111
Total CO_2-eq / CO_2	4.0	2.3	1.7	1.3	1.0	1.1	3.0

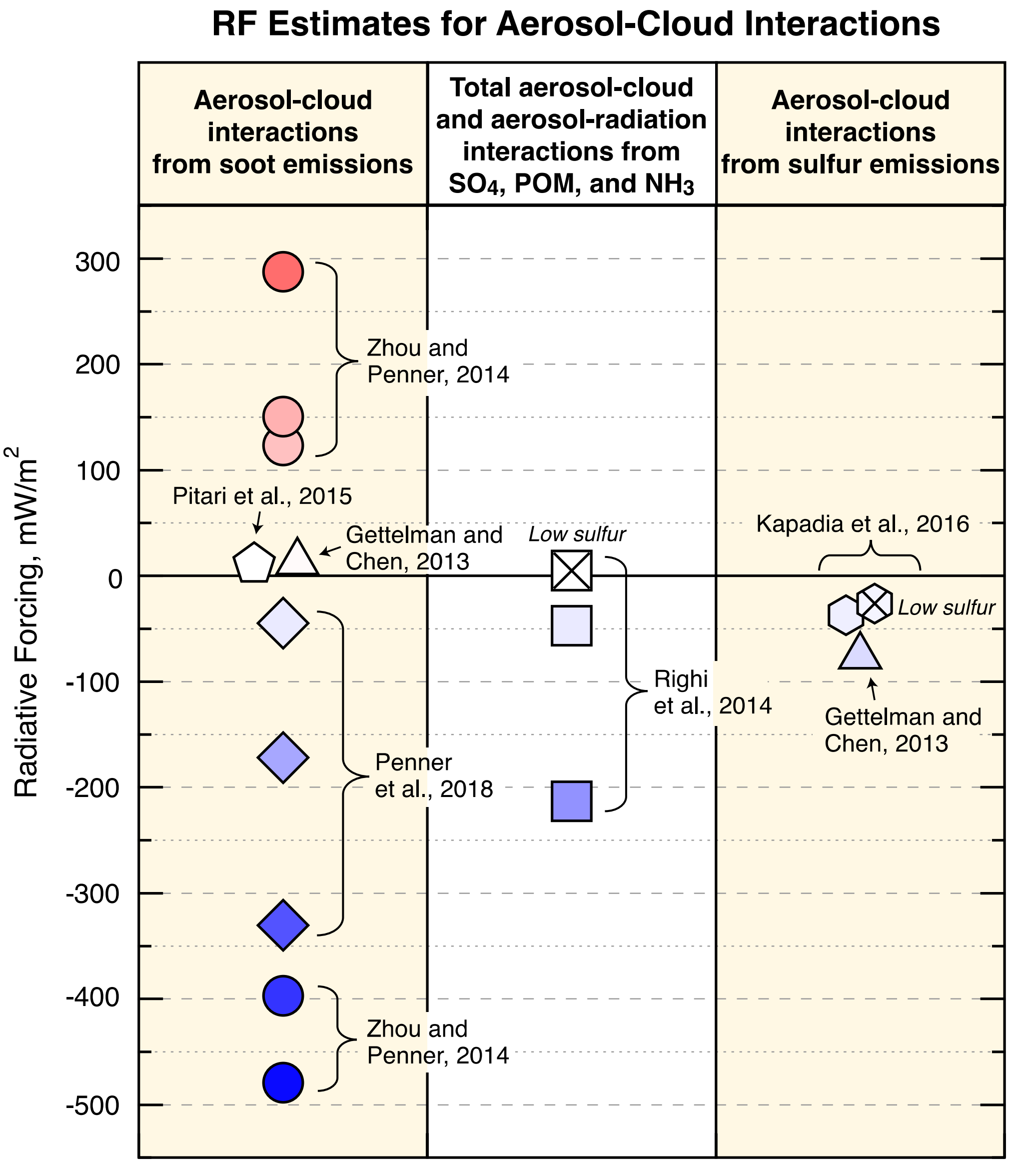

Figure 5. Summary of RF estimates for aerosol-cloud interactions for aviation aerosol as calculated in the SD spreadsheet for a variety of published results normalized to 2018 air traffic and 600 ppm fuel sulfur. The results are shown for soot; total particulate organic matter (POM), sulfate and ammonia (NH_3); and sulfate aerosol from the indicated studies. The color shading gradient in the symbols indicates increasing positive or negative magnitudes. No best estimate was derived in the present study for any aerosol-cloud effect due to the large uncertainties. In previous studies, the estimates for the soot aerosol-cloud effect are associated with particularly large uncertainty in magnitude and uncertainty in the sign of the effect (Penner et al., 2009; Zhou and Penner, 2014; Penner et al., 2018). As part of the present study, an author (JEP) re-evaluated these earlier studies and concluded that the Penner et al. (2018) results supersede the earlier Penner et al. (2009) and Zhou and Penner (2014) results because of assumptions regarding updraft velocities during cloud formation. In addition, a bounding sensitivity case in which all aviation soot acts as an IN in Penner et al. (2018) is not included here.

Table 4a. Confidence levels for the ERF estimates in **Figure 3**

Terms	Evidence	Agree-ment	Conf. level	Basis for uncertainty estimates	Understanding change since L09
Contrail cirrus formation in high-humidity regions	Limited	Medium	Low*	Robust evidence for the phenomenon. Large remaining uncertainties in magnitude in part due to incomplete representation of key processes	The inclusion of contrail cirrus processes in global climate models.
Carbon dioxide (CO_2) emissions	Robust	Medium	High**	Trends in aviation CO_2 emissions and differences between simplified C-cycle models	Better assessment of uncertainties from multiple models
Short-term ozone increase	Medium	Medium	Medium*	Observed trends of tropospheric ozone and laboratory studies of chemical kinetics, reliance on a large number of model results for aviation emissions	Elevated owing to many more studies
Long-term ozone decrease	Limited	Medium	Low*	Reliance on chemical modelling studies	Not provided previously
Methane decrease	Medium	Medium	Medium*	Observed trends of tropospheric methane and laboratory studies of chemical kinetics, reliance on a large number of model results for aviation emissions	Elevated owing to many more studies
Stratospheric water vapour decrease	Limited	Medium	Low*	Reliance on chemical modelling studies	Not provided previously
Net NO_x	Medium	Limited	Low*	Associated uncertainties with combining above effects	Elevated owing to more studies but lowered in total owing to additional terms and methodological constraints
Water vapor emissions in the stratosphere	Medium	Medium	Medium	Limited studies of perturbation of water vapor budget of UT/LS	Elevated owing to more studies
Aerosol-radiation interactions					
From soot emissions	Limited	Medium	Low	Limited studies and uncertain emission index	More studies
From sulfur emissions	Limited	Medium	Low	Limited studies and uncertain emission index	More studies
Aerosol-cloud interactions					
From sulfur emissions	Limited	Low	Very low	None available; few studies, probably a negative ERF	Not provided previously
From soot emissions	Limited	Low	Very low	None available; few studies, varying in sign and magnitude of ERF constrained by poor understanding of processes	Not provided previously

* This term has the additional uncertainty of the derivation of an effective radiative forcing from a radiative forcing.

** This term differs from 'Very High' level in IPCC (2013) because additional uncertainties are introduced by the assessment of marginal aviation CO_2 emissions and their resultant concentrations in the atmosphere from simplified carbon cycle models.

Table 3. Best estimates and low/high limits of the 95% likelihood ranges for aviation RF components derived in this study [a]

RF ($mW\ m^{-2}$)	2018 [b]	2011 [b]	2005 [b]	L09 2005 values	Sensitivity to emissions (this work)
Contrail cirrus	111.4 (33, 189)	85.6 (25, 146)	67.5 (20, 115)	(11.8 [c])	1.82×10^{-9} $mW\ m^{-2}\ km^{-1}$
CO_2	34.3 (31, 38)	29.0 (26, 32)	25.0 (23, 27)	28.0	
Short-term O_3 increase	36.0 (23, 56)	27.3 (17, 42)	24.0 (15, 37)	26.3	25.1 ± 7.3 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$
Long-term O_3 decrease	-9.0 (-17, -6.3)	-6.7 (-13, -4.7)	-5.7 (-11, -4.0)	----	-7.9 ± 2.9 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$
CH_4 decrease	-17.9 (-34, -13)	-13.4 (-25, -9.3)	-11.4 (-21, -7.9)	-12.5	-15.8 ± 5.9 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$
Stratospheric water vapor decrease	-2.7 (-5.0 -1.9)	-2.0 (-3.8, -1.4)	-1.7 (-3.2, -1.2)	----	-2.4 ± 0.9 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$
Net NO_x	8.2 (-4.8, 16)	6.5 (-3.3, 12)	6.6 (1.9, 12)	13.8 [d]	1.0 ± 6.6 $mW\ m^{-2}$ (Tg (N) $yr^{-1})^{-1}$
Stratospheric H_2O increase	2.0 (0.8, 3.2)	1.5 (0.6, 2.4)	1.4 (0.6, 2.3)	2.8	0.0052 ± 0.0026 $mW\ m^{-2}$ (Tg (H_2O) $yr^{-1})^{-1}$
Soot (aerosol-radiation)	0.94 (0.1, 4.0)	0.71 (0.1, 3.0)	0.67 (0.1, 2.8)	3.4	100.7 ± 165.5 $mW\ m^{-2}$ (Tg (BC) $yr^{-1})^{-1}$
Sulfate (aerosol-radiation)	-7.4 (-19, -2.6)	-5.6 (-14, -1.9)	-5.3 (-13, -1.8)	-4.8	-19.9 ± 16.0 $mW\ m^{-2}$ (Tg (SO_2) $yr^{-1})^{-1}$
Sulfate and soot (aerosol-cloud)	----	----	----	----	----
Net RF (only non-CO_2 terms)	114.8 (35, 194)	88.4 (27, 149)	70.3 (22, 119)	----	----
Net aviation RF	149.1 (70, 229)	117.4 (56, 179)	95.2 (47, 144)	78.0	----

[a] ERF values are shown in **Table 2**.

[b] The uncertainty distributions for all forcing terms are lognormal except for CO_2 and contrail cirrus (normal) and Net NO_x (discrete pdf).

[c] Linear contrails only; excludes the increase in cirrus cloudiness due to aged spreading contrails.

[d] Excludes updated CH_4 RF evaluation of Etminan et al. (2016) and equilibrium-to-transient correction.

APPENDIX 6 – List of Resources

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