Overview of non-CO_2 emissions from aircraft and fuel composition effects

Aviation's climate impact extends beyond CO_2. Non-CO_2 effects, especially contrails and contrail cirrus, are contributors to aviation radiative forcing, though uncertainties remain high. This article outlines the main non-CO_2 emissions from aircraft and explains contrail formation. It also reviews how fuel composition can affect particulate emissions and contrail properties, with a focus on sustainable aviation fuel (SAF) and the trade-offs of further hydroprocessing in existing European refineries.

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Introduction

Aviation is one of the most important global economic activities in the modern world, with an extremely high increasing activity trend over the past 50 years.[1] Aviation emissions can have an impact on surface air quality[2,3] as well as on climate change via a complex set of processes.[4] From a climate perspective, the most important radiative forcing components of aviation are carbon dioxide (CO_2), oxides of nitrogen (NO_x), water vapour (H_2O), aerosol (soot, sulphates, nitrates), and condensation trails (contrails). The latter in particular, based on an evaluation of global aviation activity in 2018, was estimated to be among the largest contributors to annual mean radiative forcing due to aviation, albeit subject to a high degree of uncertainty, followed by aviation's cumulative CO_2 and annual NO_x emissions.[1] This article provides an overview of non-CO_2 emissions from aircraft and fuel composition effects based on recent studies conducted by Concawe.

Non-CO_2 emissions from aircraft

Aircraft emit several non-CO_2 species that influence climate and, in the landing and take-off regime, local air quality.[5,6] Beyond CO_2, the most consequential climate impact is the formation of contrails and contrail cirrus from exhaust water vapour interacting with ambient cold, humid air; their radiative impact depends on the initial ice crystal number, size, optical depth and lifetime. Combustion also releases: NO_x, which perturbs upper tropospheric ozone (warming) and methane (cooling) with a net positive effect on most decadal timescales; SO_x that oxidises to sulphuric acid; non-volatile particulate matter (nvPM, soot) that seeds droplet/ice formation; volatile PM (vPM) that forms as sulphuric acid and organics that condense in the cooling plume; and small amounts of CO and unburned hydrocarbons. Together, these species and the meteorology at cruise altitudes determine whether contrails form and persist. Near airports, the same emissions—especially nvPM and NO_x—drive air quality concerns, motivating tighter certification and operational controls.[5]

The different gases and particulate matter emitted by aircraft engines remain in the atmosphere for different lengths of time. Consequently, their radiative forcing and the subsequent climate impacts also occur on different timescales. CO_2 is removed slowly, so it accumulates in the atmosphere over periods ranging from decades to millennia. During that time, it exerts a radiative forcing on the climate system. Therefore, a substantial fraction of past aviation CO_2 emissions continues to exert a radiative forcing today and will continue to do so in the future. The residence time of non-CO_2 emissions is much shorter, so non-CO_2 radiative forcing is exerted by recent emissions. In particular:

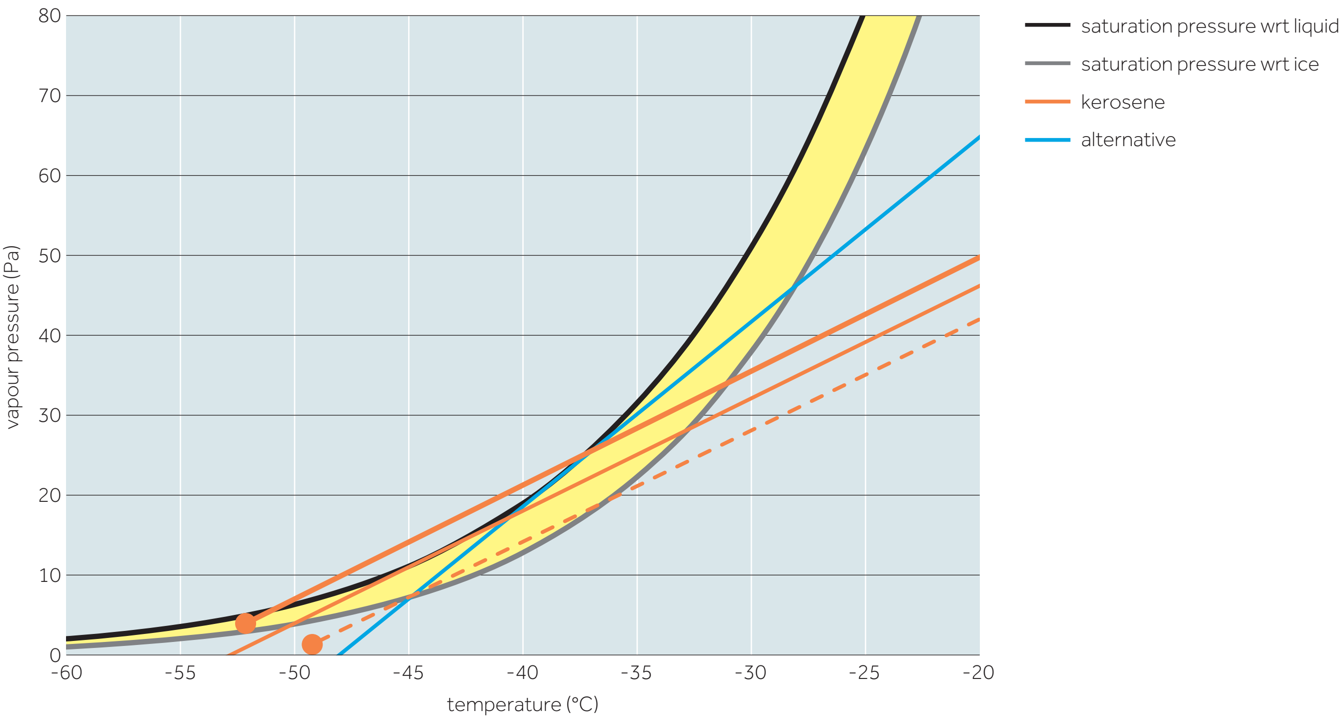
- Aviation PM can be involved in forming contrails, which last up to several hours. During that time, contrails exert a radiative forcing through both their own greenhouse effect (warming), and by reflecting sunlight (cooling), with the net effect depending on atmospheric conditions.
- Aviation PM remains in the atmosphere for days to weeks. During that time, it exerts a radiative forcing by interacting with sunlight and terrestrial radiation, and in some cases by interacting with clouds.
- Aviation NO_x remains in the atmosphere for several weeks. It triggers perturbations to ozone and methane concentrations that last for months to decades, during which they exert a radiative forcing.

The influence of aviation on climate is shown to be greater than that from its CO_2 emissions alone, but with large uncertainties on the non-CO_2 effects.[1,6,7] The aviation non-CO_2 effects comprise: changes in the atmospheric concentrations of O_3, CH_4 and H_2O resulting from NO_x emissions; the formation of contrails and contrail cirrus; the direct emission of H_2O; the emission of aerosols and aerosol precursors with their direct radiative effects; and the indirect cloud effects resulting from aviation-induced aerosols.[1,6,7,8] Recent studies have shown that non-CO_2 effects contributed two thirds of total aviation effective radiative forcing (ERF) between 1940 and 2018, with CO_2 contributing the remaining third. From all non-CO_2 components, contrails and contrail cirrus were found to be the largest contributors.

What are contrails and why do they form?

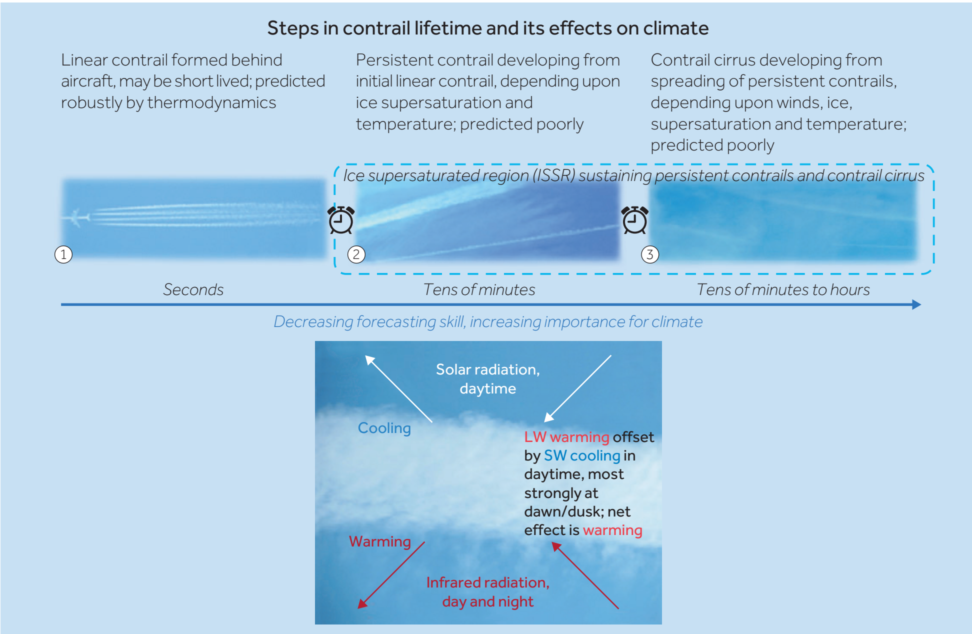
Contrails are line-shaped ice clouds triggered by the emission of water vapour by aircraft engines under specific atmospheric conditions within the atmosphere, in particular in sufficiently cold air (specified in the so-called Schmidt-Appleman criterion—see Figure 1). Persistent contrails can spread horizontally in the air, such that they no longer appear line-shaped after a short while. These clouds are termed contrail cirrus.

Figure 1: Typical T-e (temperature vs. vapour pressure) diagram of water showing fuel-specific contrail thresholds



The principle behind contrail formation is that the mixing of two air masses that are both subsaturated (i.e. their relative humidity is below 100%) can result in a supersaturated state (i.e. the relative humidity of the mixture exceeds 100%) (Figure 2). In the case of contrail formation, the two air masses are the exhaust gases, which are emitted hot and with high vapour pressure, and the ambient air, which is cold and has low vapour pressure. After emission, the mixture immediately attains ambient pressure, so the mixing and contrail formation process is isobaric. Mixing more and more ambient air into the exhaust gases allows them to cool down, and lets the vapour pressure approach the ambient value. If, during this process, the vapour pressure transiently reaches values above the saturation vapour pressure, condensation sets in and liquid droplets form that freeze instantaneously in the cold ambient air. Hence, a contrail forms. A contrail does not form if the mixture never becomes supersaturated (i.e. if the vapour pressure of the mixture remains below the saturation pressure).

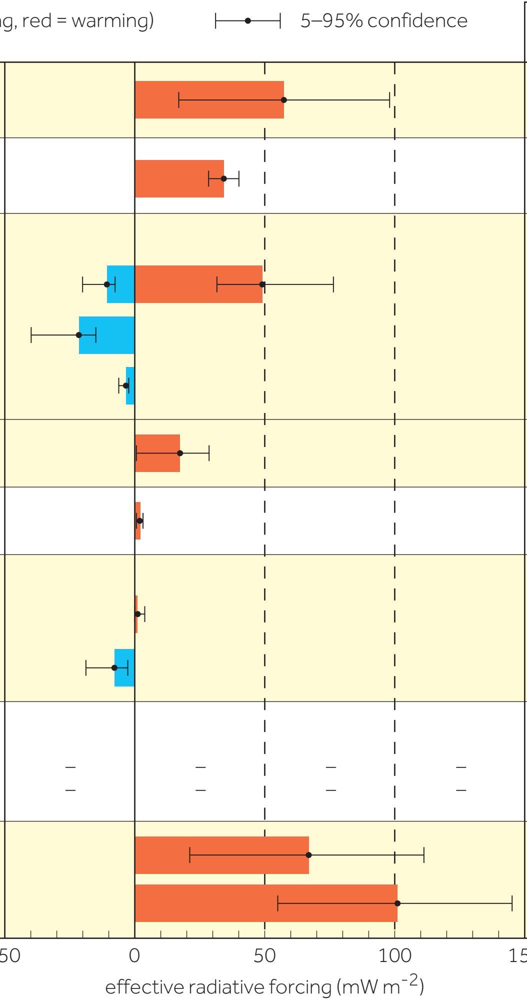
Figure 2: Illustration of the formation and evolution of contrails, and their impact on radiative fluxes[9]



Climate impact of contrails

Figure 3 on page 33 shows the various contributions of aviation to climate change in terms of ERF as presented in a recent paper by Lee *et al.*[1] The results show that contrails and contrail cirrus, while short-lived relative to CO_2, are currently among the largest contributors to total radiative forcing (RF) and ERF, respectively, from aviation if the best estimates are considered. Nevertheless, the uncertainty of the magnitude of the contrail- (and contrail cirrus-) induced RF and ERF is large in comparison to CO_2. The uncertainty further increases if RF or ERF are to be transferred into climate change effects, e.g. in terms of global mean temperature change due to the associated efficacy. Note that the efficacy of contrails and contrail cirrus is significantly smaller than 1, i.e. the temperature response is smaller than would be expected from RF or ERF.[10,11,12,13]

Figure 3: Best-estimates for climate forcing terms from global aviation from 1940 to 2018



	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Confidence 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 (23, 56)	1.37	Medium
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	Medium
Stratospheric water vapour 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 vapour emissions in the stratosphere	2.0 (0.8, 3.2)	2.8 (0.8, 3.2)	[1]	Medium
Aerosol-radiation interactions				
From soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
From sulphur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
From sulphur emissions From soot emissions	No best estimates	No best estimates	– –	Very low
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)	–	–

Contrails interact with both solar (short-wave) and terrestrial (long-wave) radiation. They generally cool in sunlight by reflecting solar radiation, but warm during both day and night by trapping outgoing long-wave radiation; on average the long-wave effect dominates, yielding a net warming. The magnitude depends on optical depth, ice crystal size, and lifetime—all of which are influenced by initial ice number and ambient supersaturation and dynamics. In addition to the impact of atmospheric conditions, the magnitude of the RF and ERF from contrails and contrail cirrus depends on fuel composition, engine type, and consequential soot emissions—effects which require improved quantification.[14] The following sections provide further insights into these aspects.

Notes on Figure 3:

- The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively.
- Red bars indicate warming terms and blue bars indicate cooling terms.
- Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels.
- RF values are multiplied by the respective ERF/RF ratio to yield ERF values.
- ERF/RF values designated as '[1]' indicate that no estimate is currently available.[1]

Effects of changes in fuel composition on non-CO_2 emissions from aviation

Fuel composition and fuel source

One proposed way to achieve a reduction in non-CO_2 emissions is by changing the composition of aviation fuel. Sustainable aviation fuel (SAF) has been the primary focus of recent discussions on the impact of fuel composition on non-CO_2 emissions for two reasons:

- First, because SAF plays a central role in aviation decarbonisation plans. The production process for SAF, when using CO_2 taken directly from the atmosphere or by using various bio or waste feedstocks, can provide reductions in net CO_2 emissions from aviation, depending on the feedstock and production process used. Hence, the possibility of decreasing both CO_2 and non-CO_2 emissions with the same fuel change is worthy of consideration.
- Second, because flight tests have to date focused on one of the SAF types, HEFA-SPK.[1] Hence, scientific evidence is most extensive for this fuel source.

Recent research suggests that some of the non-CO_2 emissions of aircraft engines can be reduced by increasing the hydrogen content of the fuel. The hydrogen content is increased by saturating aromatic molecules, and decreasing total aromatic and naphthalene content. In a conventional refinery, this could be done by hydrotreating which will also decrease the sulphur content of the fuel.[15] This processing is, however, expensive and CO_2 intensive, but SAF blending with conventional jet fuel would provide these benefits as SAF, including HEFA-SPK, naturally has very low sulphur, aromatic and naphthalene content, and therefore a high hydrogen content. Other fuel sources (fossil, bio-co-processing, etc.)[15] could also have high hydrogen content and ultra-low sulphur, aromatic and naphthalene content, although these would require severe hydrotreatment in the refinery, which is not possible with most current refinery configurations, hence this would require additional capital investment. It would also require additional hydrogen production and more energy, with the associated higher GHG costs. Some refineries are not able to hydrotreat jet fuel but only use a sweetening process, transforming mercaptans in disulphides, which has no impact on sulphur or aromatics content. Typical kerosene hydrotreating units, when available, are designed for sulphur removal, with little aromatics saturation. As such, most refineries would require substantial capital investment for significant aromatic reduction. However, the economic impact on resources for such units could reduce the funds available for refiners to invest in the development of SAF production, or accelerate refinery shut-down and reduce jet fuel supply.

[1] HEFA-SPK = hydroprocessed esters and fatty acids-synthetic paraffinic kerosene (straight paraffinic jet fuel)

What are the impacts of fuel composition on non-CO_2 emissions of aircraft engines?

Different categories of non-CO_2 emissions respond differently to changes in fuel composition, and are discussed in turn below.

Nitrogen oxides (NO_x): Fuel composition has minimal impact on ground-based and cruise NO_x emission indices,[16] which primarily depend on engine and combustor design, and on operating conditions.

Water vapour (H_2O): The use of fuels with high hydrogen content increases water vapour emissions. Flight tests powered by 100% HEFA-SPK SAF measured an increase in the water vapour emission index by about 10%.[17] This could increase the number of ice crystals in contrails.

Non-volatile particulate matter (nvPM, also called soot): Petroleum-based Jet A / A-1 fuels have a hydrogen content range of around 13.5–14.5% by mass, depending on the crude oil origin and the degree of hydrotreatment. The use of fuels with higher hydrogen content, up to around 15% by mass, including fully paraffinic SAF, leads to reductions in nvPM emissions in certain engine types and operating points. That reduction is expected because a high hydrogen content is associated with the saturation of aromatic molecules and desulphurised fuel, which in turn reduces nvPM formation in the primary zone of the combustor where the fuel-to-air ratio is high to ensure a stable combustion. As a general principle, paraffinic molecules will combust more readily than aromatic molecules, thereby reducing the chance of soot formation caused by incomplete combustion. The hydrogen content of the fuel is, therefore, a simplified directional predictor of nvPM emissions. Individual fuel properties such as sulphur, aromatics and napthalenes content, carbon number distribution and the distillation curve will each affect nvPM emissions to varying degrees. Reduced soot emissions from combustion of 100% SAF (HEFA-SPK) and different blends of fossil-based Jet A-1 and HEFA-SPK or FT-SPK[2] have been confirmed by ground and airborne measurements, with a reduction in soot particle number of 20% to 80%, depending on the fuel tested, engine type, combustor design and engine power settings.[18,19,20,21,22,23] The highest reductions appear at engine idle, at the lowest combustion temperatures, however this is not relevant to the operating conditions of aircraft in flight. In high-thrust conditions, fuel effects are generally less apparent.

Lean-burn combustion technology, which is used on most modern narrow body aircraft representing approximately 16% of the total fleet and growing with aircraft renewal, substantially reduces soot emissions when engines run between medium to high thrust. Recent in-flight soot measurements have indicated very low (near-ambient) levels of soot emissions when burning Jet A / A-1.[24] A combination of high hydrogen content fuels and lean-burn combustion technology will minimise soot particle number emissions at the lower thrust range (idle and taxi), and have a small effect on already very low emissions at higher thrust ranges (take-off and flight). This result is a logical consequence of the combined effects of fuel and engine technology, although the low thrust range has a negligible impact on non-CO_2 emissions as this operating point is seldom used in flight. At medium to high thrust, lean burn systems are combusting lean, with close to zero nvPM formation even with low-hydrogen content jet fuels. It would therefore be expected that fuel hydrogen content will have little effect on nvPM in lean burn engines when operating at altitude cruising conditions, where contrails are formed.

[2] FT-SPK = Fischer-Tropsch straight paraffinic jet fuel

Volatile particulate matter (vPM): The impact of fuel composition on the number of emitted vPM particles is more complex. vPM form from precursor gaseous emissions from the aircraft engines, in amounts that also depend on external factors such as weather conditions, or from lubricating oil emissions. The sulphur content of the fuel is important because sulphur oxidises into sulphur dioxide, one of the precursor gases for vPM. Petroleum-based Jet A/A-1 typically contains a range from fifty to several hundred parts per million of sulphur by mass. In contrast, HEFA-SPK does not contain sulphur. The number of formed vPM particles also depends on nvPM (soot) number[25] because soot scavenges the volatile molecules from the engine plume, especially organics, including oil vapours and sulphur oxides, thus preventing them from forming vPM. Therefore, when nvPM numbers remain relatively large, in the so-called 'soot-rich regime' associated with rich-burn, quick-mix, lean-burn (RQL)[3] combustion, sulphur has a limited impact on vPM number but might play a role in 'activating' the hydrophobic nvPM particles to allow water to condense on them,[26] leading to the formation of ice crystals, contrails and cirrus clouds. Conversely, in the so-called 'soot-poor regime', achieved by some advanced RQL and lean-burn combustors, theoretical calculations predict that the lack of nvPM limits the scavenging of vPM precursors and opens previously suppressed pathways of volatile particle formation.[25,27,28] Flight tests in the soot-rich regime using fuels with different sulphur contents confirmed the expected reduction in vPM with decreasing fuel sulphur content.[29] The extent to which oil droplets, nitric acid or organic compounds would drive volatile particle formation in soot-poor, ultra-low sulphur conditions remains an open question.

Note that hydrogen content is not currently measured or reported in commercial aviation fuel specifications, nor are there any limits on hydrogen content. This is because aromatics, naphthalenes and sulphur are individually measured and each have their associated limits. It follows that lower levels of these three properties would result in higher hydrogen content. Hydrogen content is a useful indicator for research purposes and can be easily calculated from the current Jet A/A-1 certificate of analysis (COA) using the method ASTM D3343 (Standard Test Method for Estimation of Hydrogen Content of Aviation Fuels).

What does the use of SAF or fuels of similar composition mean for contrail formation and the climate impact of contrails?

The previous section concluded that fuels with high hydrogen content and low sulphur content, such as, but not limited to, SAF, can reduce the number of particles generated by aircraft engines. This number of particles is one of the factors, along with, more significantly, atmospheric conditions, that determines the initial number of ice crystals in contrails. Contrail ice crystals form when water vapour condenses onto the particles emitted or formed in the aircraft engine exhaust plume, forming liquid water droplets that quickly freeze. It is expected that the emission of fewer particles will lead to the formation of fewer ice crystals.[25] Recent research stresses that the reduction should be in total particle emissions, not just nvPM emissions, because from a thermodynamics perspective, ice crystals will form if there are particles available.

[3] RQL = Rich-burn, quick-quench, lean burn combustion technology

Several in-flight measurements taken behind aircraft burning fuels with varying hydrogen and sulphur contents confirm the formation of fewer ice crystals from reduced soot particle numbers and/or reduced volatile particle numbers.[24] Most recently, reduced ice crystal numbers have been observed in the case of SAF and desulphurised Jet A / A-1.[29]

Climate modelling suggests that a reduced ice crystal number translates into reduced radiative forcing by contrails and contrail cirrus, thanks to smaller contrail optical depths and shorter lifetimes.[4] [14] Simulations using the Schmidt-Appleman criterion to determine conditions favourable to contrail formation find that the use of SAF slightly increases the extent of the regions of formation of persistent contrails because of its higher water vapour emission index compared to Jet A-1. However, this effect is small and, consequently, models still find a net reduction in contrail-cirrus radiative effect, driven by decreases in contrail optical properties and lifetime.[17,30] There is however more uncertainty as to the extent that radiative forcing causes climate temperature variations.

It should also be taken into account that increasing hydrogen content will first remove sulphur from jet fuel. Reducing sulphur in jet fuel will reduce the sulphate emissions which slowly form sulphuric acid in the atmosphere. The interaction between sulphuric acid and low-level clouds has the effect of cloud brightening, which is known to have a significant atmospheric cooling effect. Hence, there is a trade-off between increasing hydrogen content which may reduce contrails, and losing the sulphur which provides this cooling effect.[31,32] The net effect on global cooling/warming could well be unchanged compared to current aviation fuel composition; however, the scientific literature currently lacks the confidence level to draw net temperature conclusions. For this reason, a production process that emits large additional amounts of CO_2 to achieve higher hydrogen content would be unlikely to yield a net benefit; however, SAF blending would be a more neutral way to achieve higher hydrogen content.

A change to current Jet A / A-1 aviation fuel specifications would require additional hydroprocessing at existing refineries, which will come at a substantial cost in terms of invested capital, hydrogen consumption and additional CO_2 emissions from production. Furthermore, over 30% of European refineries do not have any installed hydrotreating capacity for jet fuel. The business case required to fund large capital investments would be unlikely in an environment of overall demand reduction for petroleum products, so tighter specifications would most likely accelerate refinery closure rather than improve jet fuel quality. Security of supply is a concern in this scenario as Europe is already a net jet fuel importer for 40% of its needs. Imported products are also less likely to comply with tighter European specifications at competitive pricing.The quantification of European refinery impacts is the subject of a Concawe study entitled *Aviation fuel composition effects on non-CO_2 emissions: European refinery impacts & effects on fuel quality*.

[4] Note that Bier, A. *et al.* (2017) shows that this reduction in climate impact is due to the reduction in the radiative forcing of long-lived contrails. The reduction in ice crystal numbers is negligible for short-lived contrails.

It is therefore an open question whether the net effect of the various fuel property-related trade-offs on non-CO_2 emissions would be enough to justify the additional GHG emissions required to further hydroprocess conventional jet fuel. However, if SAF mandates are achieved in the coming years, the hydrogen content will naturally increase proportionally in the final fuel blends used in the market.

References

1. 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., De León, 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. (2021). 'The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018.' In *Atmospheric Environment*, Vol. 244, pp. 1-29. https://doi.org/10.1016/j.atmosenv.2020.117834
2. Barrett, S. R. H., Britter, R. E. and Waitz, I. A. (2010). 'Global Mortality Attributable to Aircraft Cruise Emissions.' In *Environmental Science and Technology*, Vol. 44, No. 19, pp 7736-7742. https://doi.org/10.1021/es101325r
3. Eastham, S. D. and Barrett, S. R. H. (2016). 'Aviation-attributable ozone as a driver for changes in mortality related to air quality and skin Cancer.' In *Atmospheric Environment*, Vol. 144, pp 17-23. https://doi.org/10.1016/j.atmosenv.2016.08.040
4. Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M., Schumann, U., Bais, A., Berntsen, T., Iachetti, D., Lim, L. L. and Sausen, R. (2010). 'Transport impacts on atmosphere and climate: Aviation.' In *Atmospheric Environment*, Vol. 44, pp. 4678-4734. https://doi.org/10.1016/j.atmosenv.2009.06.005
5. Concawe (2023). *The impact of aviation emissions to urban air quality in Europe – Detailed airport-city analysis*. Concawe report no. 10/23. https://www.concawe.eu/publication/the-impact-of-aviation-emissions-to-urban-air-quality-in-europe-detailed-airport-city-analysis/
6. Sausen, R., Isaksen, I., Grewe, V., Hauglustaine, D., Lee, D. S., Myhre, G., Köhler, M. O., Pitari, G., Schumann, U., Stordal, F. and Zerefos, C. (2005). 'Aviation radiative forcing in 2000: An update on IPCC (1999).' In *Meteorologische Zeitschrift*, Vol. 14, pp 555-561. https://www.schweizerbart.de/papers/metz/detail/14/54291/Aviation_radiative_forcing_in_2000_An_update_on_IPCC_1999
7. Lee, D. S., Fahey, D. W., Forster, P. M., Newton, P. J., Wit, R. C. N., Lim, L. L., Owen, B. and Sausen, R. (2009). 'Aviation and global climate change in the 21st century.' In *Atmospheric Environment*, Vol. 43, Issues 22-23, pp. 3520–3537. https://www.sciencedirect.com/science/article/pii/S1352231009003574
8. Prather, M., Sausen, R., Grossman, A. S., Haywood, J. M., Rind, D. and Subbaraya, B. H. (1999). 'Potential Climate Change from Aviation.' In J. E. Penner, D. H. Lister, D. J. Griggs, D. J. Dokken and M. McFarland (eds.): *Aviation and the Global Atmosphere. A Special Report of IPCC Working Groups I and III*, pp. 185-215. Cambridge University Press, Cambridge, UK. https://www.researchgate.net/publication/224795891_Potential_Climate_Change_from_Aviation
9. Lee, D. S., Allen, M. R., Cumpsty, N., Owen, B., Shine, K. P. and Skowron, A. (2023). 'Uncertainties in mitigating aviation non-CO_2 emissions for climate and air quality using hydrocarbon fuels.' In *Environmental Science: Atmospheres*. Vol. 3, Issue 12, pp. 1693–1740. https://doi.org/10.1039/D3EA00091E
10. Ponater, M., Marquart, S., Sausen, R. and Schumann, U. (2005). 'On contrail climate sensitivity.' In *Geophysical Research Letters*, Vol. 32, Issue 10, L10706, 5 pp. https://doi.org/10.1029/2005GL022580
11. Rap, A., Forster, P. M., Haywood, J. M., Jones, A. and Boucher, O. (2010). 'Estimating the climate impact of linear contrails using the UK Met Office climate model.' In *Geophysical Research Letters*. Vol. 37, Issue 20, L20703, 6 pp. https://doi.org/10.1029/2010GL045161

12. Bickel, M., Ponater, M., Bock, L., Burkhardt, U. and Reineke, S. (2020). 'Estimating the Effective Radiative Forcing of Contrail Cirrus.' In *Journal of Climate*, Vol. 33, Issue 5, pp. 1991-2005. https://doi.org/10.1175/JCLI-D-19-0467.1
13. Bickel, M. (2023). *Climate Impact of Contrail Cirrus*. Research report 2023-14. Dissertation at the Faculty of Physics, Ludwig Maximilian University, Munich, Germany. Deutsches Zentrum für Luft- und Raumfahrt (DLR). 135 pp, ISSN 1434-8454, ISRN DLR-FB-2023-14. https://doi.org/10.57676/mzmg-r403
14. Burkhardt, U., Bock, L. and Bier, A. (2018). 'Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions.' In *npj Climate and Atmospheric Science*, Vol. 1, Article no. 37, 7 pp. https://doi.org/10.1038/s41612-018-0046-4
15. Schripp, T., Anderson, B. E., Bauder, U., Rauch, B., Corbin, J. C., Smallwood, G. J., Lobo, P., Crosbie, E. C., Shook, M. A., Miake-Lye, R. C., Yu, Z., Freedman, A., Whitefield, P. D., Robinson, C. E., Achterberg, S. L., Köhler, M., Oßwald, P., Grein, T., Sauer, D., Voigt, C., Schlager, H. and Le Clercq, P. (2022). 'Aircraft engine particulate matter emissions from sustainable aviation fuels: Results from ground-based measurements during the NASA/DLR campaign ECLIF2/ND-MAX.' In *Fuel*, Vol. 325. (European Union Aviation Safety Agency (EASA) initial findings on lower compositional limits; part of 'WP2 Short Term Use Case – Preparatory work to develop fuel standard to lower non-CO_2 climate impacts', Specific Contract No. SC06, Final Report 2025-06-04.) https://doi.org/10.1016/j.fuel.2022.124764
16. Harlass, T., Dischl, R., Kaufmann, S., Märkl, R., Sauer, D., Scheibe, M., Stock, P., Bräuer, T., Dörnbrack, A., Roiger, A., Schlager, H., Schumann, U., Pühl, M., Schripp, T., Grein, T., Bondorf, L., Renard, C., Gauthier, M., Johnson, M., Luff, D., Madden, P., Swann, P., Ahrens, D., Sallinen, R. and Voigt, C. (2024). 'Measurement report: In-flight and ground-based measurements of nitrogen oxide emissions from latest-generation jet engines and 100 % sustainable aviation fuel.' In *Atmospheric Chemistry and Physics*, Vol. 24, Issue 20, pp. 11807-11822. https://doi.org/10.5194/acp-24-11807-2024
17. Märkl, R. S., Voigt, C., Sauer, D., Dischl, R. K., Kaufmann, S., Harlaß, T., Hahn, V., Roiger, A., Weiß-Rehm, C., Burkhardt, U., Schumann, U., Marsing, A., Scheibe, M., Dörnbrack, A., Renard, C., Gauthier, M., Swann, P., Madden, P., Luff, D., Sallinen, R., Schripp, T. and Le Clercq, P. (2024). 'Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails.' In *Atmospheric Chemistry and Physics*, Vol. 24, Issue 6, pp. 3813-3837. https://doi.org/10.5194/acp-24-3813-2024
18. Moore, R. H., Shook, M., Beyersdorf, A., Corr, C., Herndon, S., Knighton, W. B., Miake-Lye, R., Thornhill, K. L., Winstead, E. L., Yu, Z., Ziemba, L. D. and Anderson, B. E. (2015). 'Influence of Jet Fuel Composition on Aircraft Engine Emissions: A Synthesis of Aerosol Emissions Data from the NASA APEX, AAFEX, and ACCESS Missions.' In *Energy & Fuels*, Vol. 29, Issue 4, pp. 2591-2600. https://doi.org/10.1021/ef502618w
19. Moore, R. H., Thornhill, K. L., Weinzierl, B., Sauer, D., D'Ascoli, E., Kim, J., Lichtenstern, M., Scheibe, M., Beaton, B., Beyersdorf, A. J., Barrick, J., Bulzan, D., Corr, C. A., Crosbie, E., Jurkat, T., Martin, R., Riddick, D., Shook, M., Slover, G., Voigt, C., White, R., Winstead, E., Yasky, R., Ziemba, L. D., Brown, A., Schlager, H. and Anderson, B. E. (2017). 'Biofuel blending reduces particle emissions from aircraft engines at cruise conditions.' In *Nature*, Vol. 543, pp. 411-415. https://doi.org/10.1038/nature21420
20. Voigt, C., Kleine, J., Sauer, D., Moore, R. H., Bräuer, T., Le Clercq, P., Kaufmann, S., Scheibe, M., Jurkat-Witschas, T., Aigner, M., Bauder, U., Boose, Y., Borrmann, S., Crosbie, E., Diskin, G. S., DiGangi, J., Hahn, V., Heckl, C., Huber, F., Nowak, J. B., Rapp, M., Rauch, B., Robinson, C., Schripp, T., Shook, M., Winstead, E., Ziemba, L., Schlager, H. and Anderson, B. E. (2021). 'Cleaner burning aviation fuels can reduce contrail cloudiness.' In *Communications Earth & Environment*, Vol. 2, Article no. 114. https://doi.org/10.1038/s43247-021-00174-y
21. Dischl, R., Sauer, D., Voigt, C., Harlaß, T., Sakellariou, F., Märkl, R., Schumann, U., Scheibe, M., Kaufmann, S., Roiger, A., Dörnbrack, A., Renard, C., Gauthier, M., Swann, P., Madden, P., Luff, D., Johnson, M., Ahrens, D., Sallinen, R., Schripp, T., Eckel, G., Bauder, U. and Le Clercq, P. (2024). 'Measurements of particle emissions of an A350-941 burning 100 % sustainable aviation fuels in cruise.' In *Atmospheric Chemistry and Physics*, Vol. 24, Issue 19, pp. 11255-11273. https://doi.org/10.5194/acp-24-11255-2024
22. Brem, B. T., Durdina, L., Siegerist, F., Beyerle, P., Bruderer, K., Rindlisbacher, T., Rocci-Denis, S., Andac, M. G., Zelina, J., Penanhoat, O. and Wang, J. (2015). 'Effects of Fuel Aromatic Content on Nonvolatile Particulate Emissions of an In-Production Aircraft Gas Turbine.' In *Environmental Science and Technology*, Vol. 49, No. 22, pp. 13149-13157. https://pubs.acs.org/doi/10.1021/acs.est.5b04167

23. Durdina, L., Brem, B. T., Elser, M., Schönenberger, D., Siegerist, F. and Anet, J. G. (2021). 'Reduction of Nonvolatile Particulate Matter Emissions of a Commercial Turbofan Engine at the Ground Level from the Use of a Sustainable Aviation Fuel Blend.' In *Environmental Science and Technology*, Vol. 55, No. 21, pp. 14576-14585. https://pubs.acs.org/doi/10.1021/acs.est.1c04744
24. Voigt, C., Märkl, R., Sauer, D., Dischl, R., Kaufmann, S., Bräuer, T., Jurkat, T., Renard, C., Seeliger, K., Le Chenadec, G., Moreau, J., Yu, F., Bonne, N., Roche, A., Zelina, J., Dörnbrack, A., Eirenschmalz, L., Heckl, C., Horst, E., Lichtenstern, M., Marsing, A., Roiger, A., Scheibe, M., Stock, P., Giez, A., Eckel, G., Neumann, G., Vals, M., Requena-Esteban, E. and Le Clercq, P. (2025). *Substantial aircraft contrail formation at low soot emission levels*. Preprint: https://doi.org/10.21203/rs.3.rs-6559440/v1. Licensed under a Creative Commons Attribution 4.0 International Licence.
25. Yu, F., Kärcher, B. and Anderson, B. E. (2024). 'Revisiting Contrail Ice Formation: Impact of Primary Soot Particle Sizes and Contribution of Volatile Particles.' In *Environmental Science & Technology*, Vol. 58, Issue 40, pp. 17650-17660. https://doi.org/10.1021/acs.est.4c04340
26. Kärcher, B., Burkhardt, U., Bier, A., Bock, L. and Ford, I. J. (2015). 'The microphysical pathway to contrail formation.' In *Journal of Geophysical Research: Atmospheres*, Vol. 120, Issue 15, pp. 7893-7927. https://doi.org/10.1002/2015JD023491
27. Kärcher, B. and Yu, F. (2009). 'Role of aircraft soot emissions in contrail formation.' In *Geophysical Research Letters*, Vol. 36, Issue 1, 5 pp. https://doi.org/10.1029/2008GL036649
28. Rojo, C., Vancassel, X., Mirabel, P., Ponche, J.-L. and Garnier, F. (2015). 'Impact of alternative jet fuels on aircraft-induced aerosols.' In *Fuel*, Vol. 144, pp. 335-341. https://doi.org/10.1016/j.fuel.2014.12.021
29. Dischl, R., Märkl, R., Sauer, D., Voigt, C., Harlaß, T., Scheibe, M., Hahn, V., Kaufmann, S., Marsing, A., Dörnbrack, A., Roiger, A., Yu, F., Gauthier, M., Renard, C., Swann, P., Johnson, M., Ahrens, D., Sallinen, R., Eckel, E. and Le Clercq, P. (2025). *Fuel sulfur content can modulate contrail ice crystal numbers*. Preprint: https://doi.org/10.21203/rs.3.rs-6566706/v1. Licensed under a Creative Commons Attribution 4.0 International Licence.
30. Teoh, R., Schumann, U., Voigt, C., Schripp, T., Shapiro, M., Engberg, Z., Molloy, J., Koudis, G. and Stettler, M. E. J. (2022). 'Targeted Use of Sustainable Aviation Fuel to Maximize Climate Benefits.' In *Environmental Science & Technology*, Vol. 56, Issue 23, pp. 17246-17255. https://doi.org/10.1021/acs.est.2c05781
31. CarbonBrief (2023). 'Analysis: How low-sulphur shipping rules are affecting global warming' (online). Authors: Dr Zeke Hausfather, climate science contributor for Carbon Brief; and Prof. Piers Forster, professor of climate physics at the University of Leeds and director of the Priestley International Centre for Climate. https://www.carbonbrief.org/analysis-how-low-sulphur-shipping-rules-are-affecting-global-warming/
32. Szopa, S., Naik, V., Adhikary, B., Artaxo, P., Berntsen, T., Collins, W. D., Fuzzi, S., Gallardo, L., Kiendler-Scharr, A., Klimont, Z., Liao, H., Unger, N., Zanis, P., *et al.* (2021). 'Short-lived Climate Forcers.' Chapter 6 in *Climate Change 2021: The Physical Science Basis*. Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/9781009157896.008