Aviation climate impact and mitigation

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I. Climate impact

The likely range of human-caused global surface temperature increase from 1850–1900 to 2010–2019 is 0.8°C to 1.3°C, with a best estimate of 1.07°C. (IPCC, 2021). Commercial aviation (passengers and goods) has up to 2019 been responsible for about 4% of this increase (Klöwer *et al*., 2021). Global aviation impacts Earth's climate through emissions of carbon dioxide (CO_2) and through non-CO_2 effects that are unique to this sector of transportation — predominantly changes in high-level ice clouds (cirrus) and the oxidative capacity of the atmosphere (IPCC, 1999). Without countermeasures, aviation is projected to cause about 0.1°C of additional warming by 2050. The following emissions from aircraft engines give rise to the majority of the aviation climate forcing: CO_2, nitrogen oxides (NO_x), and aircraft-induced clouds (AIC) generated from emitted water vapor (H_2O) and carbonaceous soot particles.

CO_2 is a major fossil fuel combustion product, but also occurs naturally in the atmosphere as the most significant long-lived greenhouse gas. Isotope studies show that CO_2 from burning of fossil fuel is released into the atmosphere faster than it is removed. Aviation CO_2 emissions are directly related to fuel consumption. NO_x emissions from aircraft engines occur in the form of NO and NO_2 and alter the concentration of atmospheric trace gases, most importantly ozone (O_3), a greenhouse gas in its own right and key player in atmospheric chemistry, and methane (CH_4), another potent greenhouse gas. The fuel combustion products H_2O and soot lead to the formation of ice crystals in persistent contrails and contrail cirrus evolving from them—AIC (Kärcher, 2018). Sulfur (S) species, emitted as SO_2 and SO_3 and oxidized to H_2SO_4 forming particulate sulfate, derive from the S content of fossil-based fuels. Aviation sulfate particles alter physical properties and chemical composition of the atmospheric aerosol; similar to contrail cirrus, they participate in heterogeneous chemical reactions.

Emissions of greenhouse-active water vapor (H_2O) and light-absorbing soot particles from subsonic aviation have little direct warming impact by themselves due to their limited tropospheric residence time (weeks, except for the highest flight levels) and small mass, respectively. The direct cooling effect of sulfate aerosols from aircraft S emissions is small (Lee *et al*., 2021). Part of aircraft NO_x emissions form tropospheric nitrate aerosols; likewise, they induce only a small cooling effect (Brasseur *et al*., 2016). Additional aircraft emissions of carbon monoxide (CO) and unburnt hydrocarbons (UHC) play a minor role in atmospheric chemistry, but low-volatile, water soluble UHC participate in chemi-ion-mediated nucleation of ultrafine (sizes < 10 nm) aqueous plume particles (UAP) contributing to contrail formation for sufficiently low soot emissions (Kärcher, 2018). The forcing from aircraft soot-cirrus interactions has been suggested to be a relatively large negative number, however, recent work implies that this forcing is much smaller and may be insignificant (Kärcher *et al*., 2021). Process-based studies are needed to better understand the forcing due to aerosol-liquid cloud interactions from aircraft S emissions.

I.1 Contribution of aviation to climate change

Biogeochemical sinks of emitted CO_2 operate on widely disparate timescales; a significant fraction, around 20%, remains in the atmosphere for millennia. CO_2 mixes within and across the hemispheres within one year inducing sustained global warming irrespective of the location of emission. Therefore, the temporal history of CO_2 emissions must be known to estimate their effect on climate. How much warming occurs is proportional to atmospheric levels of CO_2. Further global warming produced by cumulative CO_2 emissions would cease when the *net* anthropogenic CO_2 emissions reach zero (‘net zero’) (Fankhauser *et al*., 2021). That said, reaching net zero does not negate emissions reductions. Non-CO_2 effects are much shorter-lived than CO_2, making them amenable for mitigation in the near term, and are therefore better described by present-day emissions.

Climate change is often measured by an increase in the global mean near-surface temperature relative to pre-industrial values. The global effective radiative forcing (ERF, in units of W/m^2), adopted by the Intergovernmental Panel on Climate Change (IPCC) in its 5^{th} assessment report, correlates better with changes in temperature response than the traditional global RF metric that quantifies the imbalance of radiative fluxes at the top of the atmosphere (without adjusting surface and tropospheric conditions) caused by an external climate forcing agent. ERF allows for the comparison of climate effects caused by gaseous or particulate emissions with different atmospheric residence times on a common scale. ERF and RF values are very similar in the case of CO_2. ERF values differ from associated RF values for non-CO_2 forcings due to rapid tropospheric adjustments to climate forcing perturbations (e.g., cloud changes). Rapid adjustments are separated from much slower adjustments developing on multi-decadal timescales up to 200 years with changes sea ice and the deep ocean; they either amplify or diminish the effect of a given forcing.

A number of physical metrics other than ERF have been introduced to compare CO_2 emissions with non-CO_2 effects and their climate impacts on the same scale (Wuebbles *et al*., 2010). They can be used to formulate CO_2-equivalent emission metrics, e.g., the Global Warming Potential, widely adopted in climate policy. Each metric addresses different targets (e.g., emission reduction, temperature change) over different periods of time (e.g., decades, centuries). It is not possible to define a metric independently of time horizon and emission scenario (Shine *et al*., 2007). Thus, no universally ‘correct’ metric exists. Regardless of this issue, the longer the time horizon, the more warming due to cumulative CO_2 emissions is emphasized over non-CO_2 effects. Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 RF would halt anthropogenic global warming on multi-decadal timescales (IPCC, 2018).

Global aviation contributed 2.4% to the total anthropogenic CO_2 emissions up to the year 2018, equivalent to an ERF of 34.3 (29–40 as 5–95% percentiles) mW/m^2 (Lee *et al*., 2021). Aviation’s cumulative CO_2 emissions and transient non-CO_2 effects together contributed 3.5% to anthropogenic climate change in 2018, corresponding to a net aviation ERF of 100.9 (55–145) mW/m^2. Remarkably, about 2/3, or 66.6 mW/m^2, were due to the non-CO_2 forcing terms, which, however, contribute about 8 times more than CO_2 to the uncertainty in the aviation net ERF.

The effects of aviation’s non-CO_2 forcings depend on altitude and emission region, and have compensating warming and cooling contributions. Contrary to CO_2, they diminish soon after the respective emissions stop, making them amenable for mitigation in the near term as long as the associated mitigation strategy does not inadvertently increase CO_2 emissions. The total warming footprint of aviation is at least two times higher than its carbon footprint (caused by its CO_2 emissions) (Klöwer *et al*. 2021), pointing to the relevance currently attributed to aviation’s non-CO_2 effects; AIC and NO_x emissions add more warming than the CO_2 emissions alone. Zero CO_2 emissions *and* a significant decrease in non-CO_2 forcings are needed in order to stop aviation-induced global warming (Lee *et al*., 2021).

I.2 Major aviation non-CO_2 effects

The scientific understanding of the main aviation non-CO_2 forcings has grown considerably in recent years and has led to best ERF estimates of 57.4 mW m^2 due to AIC and 17.5 mW m^2 due to NO_x in 2018, albeit with low confidence levels (Lee *et al*., 2021). Forcings with positive ERF lead to a warmer mean climate state, hence, the non-CO_2 effects of aviation add to the greenhouse effect of its CO_2 emissions. Studies suggest that the ERF/RF-ratio is larger than unity for NO_x and smaller than unity for AIC, implying a lower efficacy of AIC to force surface temperatures compared to NO_x emissions.

I.2 *a* *Aircraft-induced clouds*

Soot particles are produced by burning liquid hydrocarbon fuels. Understanding soot formation processes is an active area of research and its modeling involves coupling of a plethora of gas phase chemical reactions among hundreds of precursor species with models describing the complex dynamics of soot particle formation. In particular, polycyclic aromatic hydrocarbons (PAH), natural components of crude oil and coal, play an important role in soot formation. After fuel break-up, mainly in fuel-rich conditions with less available O_2, PAH covering a wide range of masses condense on incipient soot nuclei which in turn stabilize and evolve due to coagulation growth. A fraction of those newly formed particles is oxidized in fuel-poor conditions by hydroxyl radicals (OH) and atomic oxygen (O).

Within a second past emission from jet engines, soot particles activate into strongly supercooled water droplets in cooling jet engine exhaust plumes. The droplets freeze within tenths of seconds to form contrail ice crystals and in descending aircraft wake vortices a fraction of them sublimate. This short (10 min), aircraft-dominated formation stage is followed by the atmospheric spreading stage, wherein the newly formed line-shaped contrails evolve into irregular contrail cirrus in ice-supersaturated areas, i.e., regions of low air temperatures (below –40°C) and elevated moisture levels (Kärcher, 2018). Over congested airspace, many individual AIC form vast ice cloud layers that are visible in satellite imagery. These areas presumably include regions with cirrus formed unaffected by aircraft emissions. AIC and natural cirrus have different evolution pathways and radiative effects, because for at least a portion of their lifespan, AIC are characterized by higher concentrations of smaller ice crystals.

Following IPCC (1999), AIC research did not include contrail cirrus and estimating RF from persistent contrails alone relied on upscaling observed regional contrail or cirrus coverage based on assumed mean optical depths. The first process-based, full AIC climate model study was carried out in 2011, showed that the RF of contrail cirrus by far exceeds that of persistent contrails, and provided the basis to develop mitigation strategies aiming at reducing the aviation climate impact (Burkhardt & Kärcher, 2011). This study also suggested that AIC forming in cloud-free air reduce spatial coverage and optical depth of natural cirrus primarily by lowering the moisture content of the air. This leads to a cooling partly offsetting the direct warming due to AIC and is one of the rapid adjustments responsible for the low ERF/RF ratio of AIC (Bickel *et al*., 2020). The currently predicted effectiveness of AIC to induce surface temperature changes and associated ERF estimates remain uncertain as long as direct simulations based on coupled atmosphere/ocean models (capturing slow adjustments affecting climate sensitivity) become available (Ponater *et al*., 2021).

AIC results in a net positive RF at altitude with significant geographical and seasonal variations. The RF is a result of a fine balance between positive longwave (near infrared wavelengths) and negative shortwave (visible) contributions. AIC RF may increase three-fold from 2006 to 2050 (Bock &

Burkhardt, 2019). Uncertainties remain in validating simulated radiative flux imbalance and translating it to a temperature response due in part to an incomplete understanding of associated climate feedbacks. An improvement of the representation of natural cirrus in global models is also needed to simulate AIC-related processes and forcing with greater confidence (Kärcher, 2017).

I.2 *b* *Emissions of nitrogen oxides*

Emissions of NO (nitric oxide) and NO_2 (nitrogen dioxide) are caused by chemical reactions in gas turbine combustion chambers through (i) direct decomposition of O_2 molecules into O atoms and subsequent reaction with N_2 producing N that in turn reacts with N_2 to recycle O; (ii) reactions of fuel hydrocarbon radicals with N_2; (iii) breakdown of fuel nitrogen compounds that are present in crude oil; and (iv) the reaction of N_2 with O forming nitrous oxide (N_2O) in a three-body reaction, which further reacts with O to produce NO. Mechanism (i) produces NO very efficiently at temperatures around 1700 K; in fuel-rich conditions, NO is produced by the reaction of N with OH. The NO_x formation pathways (ii)-(iv) are less efficient when burning kerosene in gas turbines. In all cases, the resulting NO molecules are oxidized to NO_2 at declining temperatures, mainly via reactions with hydroperoxide (HO_2) radicals. NO_2 contributes about 10% to total aircraft NO_x emissions; effects of NO_x emissions on O_3 are not sensitive to this partitioning. For a given fuel, the major factors influencing NO_x emissions from gas turbines are the combustion temperature, the residence time of the combusted air/fuel mixture, and the fuel-to-air ratio or equivalent measures. It is a major engineering challenge to design combustors with minimal NO_x emissions, given the inhomogeneous spatio-temporal distribution of temperature and the fuel/air mixture.

The principal sources of tropospheric O_3 are photooxidation chains involving CH_4 and CO in which HO_2 is transformed into OH by reacting with NO, thereby slowly enhancing O_3 concentrations (Atkinson, 2000). The most important tropospheric O_3 destruction path is the reaction of O_3 with HO_2. The HO_x (=OH+HO_2) radicals originate from photolysis of O_3. There exists a critical value for ambient NO concentrations below which O_3 is destroyed and above which O_3 is produced.

The chemical source of stratospheric O_3 is photolysis of O_2. Odd oxygen species (O_3 and O) are interconverted by solar photolysis and O atom reactions with O_2, converting UV radiation into thermal energy. Radical species such as HO_x, NO_x and those derived from halogens catalytically destroy O_3 in a number of reaction cycles (Solomon, 1999). These cycles are coupled to each other and repartition the radicals from their chemical families. The efficiencies of the catalytic cycles depend on altitude, latitude, season and the presence of stratospheric aerosol and cloud particles, among other factors.

Since the 1970s, global chemical effects of aviation emissions have been studied with chemical transport and more recently coupled chemistry-climate models based on ever increasing spatial and temporal resolution and sophisticated representations of atmospheric circulation and chemical processes. According to the above, NO_x emissions have different effects on atmospheric O_3 depending on emission altitude. The response of net O_3 removal rates to changes in aircraft NO_x emissions is highly nonlinear, depending on the local O_3 concentration and other factors. Typically, below (above) about 18 km altitude, increasing NO_x concentrations produce (deplete) O_3.

Aircraft NO_x emissions in the upper troposphere across the tropopause (flight altitudes 7–13 km) lead to a direct short-term O_3 production (positive RF). The associated increase in OH levels leads to a reduction in the lifetime and concentration of CH_4 and resulting reductions in tropospheric O_3 and stratospheric H_2O levels on longer timescales (all negative RF). Therefore, as in the case of AIC, the positive net-NO_x forcing arises from offsetting contributions that are strongly emission-dependent. All studies agree that subsonic air traffic produces O_3 and have little impact on tropospheric H_2O levels (Brasseur et al., 2016).

Aircraft emissions of H_2O in the lower stratosphere (flight altitudes 13–23 km) are a source of O_3-depleting HO_x radicals, exert a direct warming effect, and may additionally affect aerosol composition and high latitude, polar stratospheric cloud formation. Any increase in sulfate particle surface area enhances O_3 losses through heterogeneous chemical reactions. Depending on the balance between emissions of NO_x and H_2O, a supersonic aircraft fleet may increase or decrease lower stratospheric O_3, depending on altitude, when sulfate particle emissions are ignored (Zhang *et al*., 2021).

I.2 *c* *Observational evidence and pending uncertainties*

AIC in clear air are the most easily perceived evidence of aviation's impact on climate. Aircraft measurements and process models describe the physical and optical characteristics of contrails in the formation stage quite well. This includes the thermodynamic formation conditions, and total ice crystal number and size up to aircraft vortex break-up (Kärcher, 2018). In-situ observations confirmed the expected, close to linear relationship between the number of emitted soot particles and the number of nucleated contrail ice crystals (Kleine *et al.*, 2018), providing a physical basis for mitigation of the contrail climate impact through the use of alternative aviation fuels. More systematic observations are needed linking contrail ice crystal properties to fuel composition and to investigate contrail formation from different propulsion technologies. The role of UAP in ice formation from fuels with low soot emissions has not been investigated observationally.

Numerous in-flight measurements since the 1990s have probed emissions in young aircraft exhaust plumes and contrails. A few case studies and large-scale surveys of persistent contrail evolution during the first few hours after formation are available based on aircraft measurements, active (ground-based lidar) and passive (space-borne, using solar reflection and IR absorption channels) remote sensing methods (see Kärcher, 2018 for further references). Older contrail cirrus can hardly, if at all, be distinguished visually from other cirrus owing to their irregular shape or be detected with upwelling radiance measurements owing to their low optical depth. Therefore, it would be particularly valuable to combine high-resolution models with airborne and satellite measurements to analyze large atmospheric regions and better judge RF from AIC. More studies need to investigate contrail formation within pre-existing cirrus clouds. This would help advance regional and global models with regard to their representation of AIC, the upper tropospheric moisture field, and cloud radiative flux changes.

Aircraft NO_x emissions in the upper troposphere compete with stratospheric and lightning sources, and precursors from ground-based sources (such as peroxyacetylnitrate). The general direction of O_3 changes due to aircraft NO_x emissions is predicted by models with reasonable confidence (IPCC, 1999). While observational evidence for enhancements in NO_x due to aircraft activity may be found in meteorological situations where emissions accumulate over several days, observational evidence for an effect on O_3 may be obtained only with the help of models due to the small magnitude of the initial perturbation and the large interannual variability of O_3. ERF depends on surface emissions of tropospheric O_3 precursors and aircraft NO_x emissions. The confidence of net RF and ERF due to aircraft NO_x emissions is low (Lee *et al*., 2021).

The database of atmospheric observations has greatly expanded since the last two decades. Such data may be used to evaluate the chemical background states simulated by global models. However, it is important that remaining uncertainties in tropospheric NO_x sources, discrepancies between modeled and measured upper tropospheric NO_x and HO_x concentrations, and the partitioning between NO_x and nitric acid (HNO_3, a temporary NO_x reservoir) be resolved. The latter involves scavenging of HNO_3 in ice clouds. Further research is needed to better quantify the chemical response to NO_x perturbations and to characterize stratosphere-troposphere exchange (mixing) processes. The roles of reactions on stratospheric background aerosols and in AIC, affecting the activation of halogen species and the partitioning of HNO_3 and NO_x, have not been fully scrutinized.

II. Mitigation

With 3.16 kg CO_2 emitted with each kg of fuel burnt and global annual emissions amounting to hundreds of millions of kg of fuel in recent years (Lee *et al*., 2021), aviation is a carbon-intensive mode of transportation. Flying may well nullify efforts of an average person to shrink a major portion of their annual carbon emissions. A round-trip from Munich to Washington D.C. with an average airline leads to about 1.3 tons of CO_2 emissions per person (https://www.atmosfair.de), while an average German person's CO_2 emissions is about 8.5 tons (in 2019, https://ourworldindata.org/co2).

No sector — industry, public or private — is exempt from reducing its climate footprint significantly by the mid-century to avoid dangerous climate change. Decarbonization of aviation is part of this quest by way of mitigating its impact on global climate. Mitigation of aviation emissions is scientifically challenging and technologically complex; atmospheric and technological tradeoffs exist that affect policy decisions and demand careful consideration. With regard to the latter, a fundamental issue is encapsulated in the question of how to balance the long-term warming from CO_2 emissions against short-lived AIC and NO_x effects.

With high likelihood, the climate impact of aviation will not meet the overall goal of the 2015 Paris agreement, if non-CO_2 effects are not accounted for in setting aviation's climate targets (Grewe *et al*., 2021). Under a sustained pre-pandemic air traffic growth path ('Back-to-normal' scenario with 3% annual growth that includes efficiency improvements in technology and operations based on historical trends), global aviation contributes up to 17% of the global warming budget left in 2050 to stay within the 1.5°C limit (Klöwer *et al*., 2021). The reduction of air traffic volume due to COVID-19 merely delays this contribution for a few years due to the cumulative nature of CO_2 emissions.

Discussing mitigation options must observe that state-of-the-art global modeling of the AIC climate impact does not cover all effects such as contrail formation within cirrus and from UAP, that the skill of predicting ice supersaturation on the scale of individual contrails is poor, that RF estimates are uncertain in part due to incomplete radiation parameterizations and sparse data on spreading contrails, and that direct simulations of the global temperature response due to AIC are not yet available.

A number of potential scientific solutions operating on different time horizons have been suggested to reduce or eliminate aviation CO_2 emissions and/or reduce or eliminate its non-CO_2 climate effects, each with specific challenges to realization and barriers to implementation. Mitigation options relating to the decades beyond 2050 come too late, if at all, to prevent humanity from overstepping further planetary boundaries crucial for the existence of life as we know it (Rockström *et al*., 2009). These long-term options include radically new aircraft designs, electric flight based on renewable electricity including hybrid-electric propulsion technologies, and liquid hydrogen fuel (LH_2) produced from renewable energy sources.

Design variants such as blended wing body aircraft and hydrogen-fueled aircraft require new aircraft and airport infrastructures that can only be implemented gradually. Electric flight would lead to zero CO_2 emissions and non-CO_2 effects, but the use of electrified propulsion systems (and fuel cells, for that matter) is realistic only for small aircraft and short-haul flights and thus, the impact on total emissions is minimal. Technological challenges associated with all-electric aircraft are well-known (Schäfer *et al*., 2019); likewise, fuel cells suffer from energy storage (battery) issues.

Green LH_2 propulsion is considered a viable long-term mitigation strategy free of CO_2 and soot emissions, but with 2–3-fold increased H_2O emissions. The latter enhances the contrail formation frequency and the absence of soot means that contrails form on ambient particles with altered microphysical and optical properties. Redesigning combustors could potentially lower NO_x emissions. The overall climate impact is not known and there are no measurements available. These modifications and the resulting AIC RF is subject to ongoing research. Previous research into `cryoplanes´ suggested significant reductions in RF and surface temperature response due to aviation, depending on a delicate balance between a number of contributing effects beyond changes in simulated linear contrail coverage (Ponater *et al*., 2006). More experimental and modeling studies are needed to test prediction of climate effects from LH_2-fueled aircraft, especially with regard to contrail cirrus.

Together with offsetting schemes that merely trade, but not reduce carbon emissions, and fiscal measures, these long-term mitigation options are not discussed any further. More details are discussed in IPCC (2022).

The jet fuel market is large, with a global demand on the order of 400 billion liters per year. Therefore, providing environmentally sustainable aviation fuels (SAF) in sufficient quantities is a huge challenge. Moreover, the price of SAF today is higher than that of petroleum-based jet fuel. If SAF become economically viable and their production can be scaled in the near term, they have the potential to make an important contribution to achieving net zero CO_2 emissions in aviation by 2050 (EASA, 2019). SAF are drop-in capable, meaning that existing distribution and fueling infrastructures can be used. The use of SAF addresses both AIC and CO_2 emissions, in contrast to an operational mitigation option related to air traffic management (ATM)—navigational avoidance of persistent contrail formation—which, in addition, has several confounding factors warranting consideration.

Mitigating the atmospheric effects of NOx emissions addresses the chemistry of its formation in aircraft engine combustors. Since most NO_x is still produced thermally during combustion of SAF, aircraft NO_x emissions are not affected or only slightly reduced inasmuch as fuel nitrogen components are missing in SAF relative to conventional kerosene (in which case the nitrogen mass fraction is very small). With regard to mitigation, in the case aircraft NO_x-induced O_3 change is a significant contributor to future ERF, a recent study concluded that further efforts leading to lower fuel efficiency and hence, CO_2 emissions, may actually be preferable to reducing NO_x emissions (Skowron *et al*., 2021). In addition, as ERF due to aircraft NO_x emissions may change over time, for instance due to changing surface emissions of NO_x, formulating NO_x mitigation policies based on current conditions is problematic.

II.1 Sustainable aviation fuels

SAF are high energy density liquid hydrocarbons with reduced aromatic and S content and may be divided into two broad categories: biofuels based on processing and refining of feedstocks/organic wastes/biomass and power-to-liquid (PtL) fuels based on renewable electricity. While the production of biofuels rests on a safe and maturing technology, PtL technology is in development. SAF can be viable kerosene substitutes only if their lifecycle emissions of CO_2 are ideally zero (zero carbon fuels). This section focusses on subsonic aircraft, as environmental effects of recently proposed supersonic transport aircraft with and without SAF require further study.

Jet fuels are composed of various alkanes (paraffines) and aromatic hydrocarbons in a mix that guarantees strict energy and stability requirements. Approval by the American Society of Testing and Materials (ASTM) is required to ensure technical compatibility and safety standards of both, conventional Jet A fuel and SAF. The reduced aromatic content in SAF makes blending with kerosene necessary. Biofuels from hydro-processed esters and fatty acids (HEFA) have been certified with a 50% blending limit. From a cloud physics viewpoint, SAF appear to be useful for mitigation, because they reduce the number of ice crystals in the contrail formation stage.

II.1 *a* *Reduction of warming due to CO_2 emissions and AIC*

The Back-to-normal aviation emissions scenario (growth rates predicted prior to the pandemic) leads to a global warming of 0.09 K by 2050 (Klöwer *et al*., 2021). When this scenario is combined with a 90% use of zero carbon fuels from 2024 onwards, aviation-induced warming reaches a constant level of 0.04 K by 2050, resulting in no further warming than aviation has already caused up to 2019.

We know with reasonable confidence from a combination of measurements and models that replacing kerosene with SAF lowers AIC RF by reducing the number of emitted soot particles and therefore, ice crystal numbers in AIC, a link predicted by numerical simulations and seen in airborne observations.

Reductions in soot particle number at emission substantially lowers the optical depth of young contrails, thereby working towards decreasing the climate impact of AIC according to a process model study (Kärcher, 2016). In-situ measurements demonstrated that a 50% blend of low-S Jet A fuel and HEFA biofuel reduces total volatile (UAP) and non-volatile (soot) particle number and mass emissions by 50–70% relative to pure Jet A fuel across a range of engine thrust conditions (Moore *et al*., 2017). Recent airborne measurements employed blended fuels to investigate the effects of aromatics on contrail ice formation (Voigt *et al.*, 2021), confirming that burning low-aromatic SAF can reduce soot *and* contrail ice crystal number concentrations by 50–70% along with an increase in mean ice crystal size. In these measurements, the HEFA fuel blend with the lowest naphthalene (a bicyclic aromatic hydrocarbon) content caused the largest reduction in contrail ice numbers. Other hydrocarbons with significant sooting propensity are known to be present in jet fuel.

A global climate model study suggests that AIC RF is nonlinearly dependent on the reduction of initial contrail ice crystal number: reducing the latter by 50% (80%) from current values leads to a decrease in AIC RF by (20%) 50% (Burkhardt *et al*., 2018). In combination with the experimental results, this means that the use of fuel blends alone will not decrease the aviation climate impact sufficiently enough. The three-fold increase in AIC RF in the year 2050 due to the projected increase in fuel use in a Back-to-normal-type scenario and changes in the geographical and vertical distribution of air traffic cannot be compensated for by an assumed decrease in initial contrail ice crystal numbers by 50% due to the use of a 50% fuel blend (Bock & Burkhardt, 2019). The simulations include improvements in engine propulsion efficiency and increases in the H_2O emission index connected to alternative fuel use, leaving soot number reduction as the most important factor controlling future AIC RF.

Biofuels have lower levels of S (and PtL fuels none) compared to conventional aviation fuel. Since UAP formed in jet aircraft exhaust plumes contain sulfate and produce sulfate via photooxidation of SO_2, the use of alternative fuels would reduce both, the weak cooling effect of aircraft-induced sulfate aerosol particles (associated with an ERF of –7.4 mW/m^2, Lee *et al*., 2021) and their interaction with liquid clouds, for which no best ERF estimate is available.

II.1 *b* *Future research topics*

Measuring emission indices of aircraft-emitted soot particles with sizes well below 100 nm, let alone UAP with sizes below 10 nm, is a tall order. The likelihood of particles to be detected throughout the sampling lines of aerosol measurement systems diminishes with decreasing particle size due to diffusion. Particle sampling losses must be accounted for to accurately determine particle number emission indices, especially the relative contributions of carbonaceous soot and aqueous UAP around 10 nm, a size range above which exhaust particles may contribute to contrail ice formation.

To achieve zero soot emissions, all gaseous soot precursors present in jet fuel must be eliminated. Measurements are underway to quantify particle emissions behind aircraft with engines operating fully on SAF. Current soot emission indices lie around or above 10^{15} particles per kg-fuel burnt, so a reduction by 90% — not achievable with current fuel blending mandates — still results in soot-controlled contrail formation ('soot-rich' regime). A process model study suggests that, depending on ambient temperature and other factors, it may be counterproductive to reduce soot emissions to levels below 10^{14}/kg-fuel ('soot-poor') (Kärcher, 2016). A corresponding contrail parameterization scheme developed for use in climate models *assumes* negligible UAP effects in desulfurized fuel and therefore predicts that soot-poor contrails form on ambient aerosol particles entrained into the young exhaust plumes, leading to relatively low apparent contrail ice emission indices in the range 10^{12}–10^{13}/kg-fuel.

Large reductions in soot emissions result in similar reductions in contrail ice crystal numbers only if UAP do not grow to sizes large enough to contribute significantly to contrail ice formation. For soot-rich kerosene and low-S HEFA blends, in-situ measurements point to a 50% contribution of volatile UAP to the total exhaust particle emissions (Moore *et al*., 2017). The current scientific understanding is that most UAP stay too small to form contrail ice if enough soot particles are co-emitted (> 10^{14}/kg-fuel), except for kerosene with very high S content (Kärcher, 2018). The UAP contribution in the case of soot-poor and S-free SAF is not known and depends on the amount and hygroscopicity of water-soluble UHC (such as aldehydes and alkenes) in these fuels. While contrail ice crystal formation from SAF can be maximally reduced (down to the levels of ambient particles) only with sufficiently low soot particle emissions and no UAP formation, efforts to reduce soot numbers in SAF may be supported by technological improvements.

More research is needed to better understand and quantify UAP and their gaseous precursors in future SAF, including airborne near-field plume measurements and systematic model studies of UAP and resulting contrail ice formation in competition with different levels of soot particle numbers. Besides studying the contribution of UAP in contrail formation with variable S and UHC emissions, apparent contrail ice crystal number emission indices should be quantified across a range of contrail ages in the same measurement behind a single aircraft in order to validate the relative contributions of ice nucleation and sublimation processes predicted by models. This is relevant, since losses of freshly nucleated contrail ice crystals due to sublimation depend on the amount of emitted soot particles, preventing a 1:1 scaling of ice crystal number concentrations in AIC with soot emissions from different fuels (Kärcher, 2018).

II.2 Navigational contrail avoidance

The climate impact of AIC in the atmospheric spreading stage depends on altitude, geographical location and local meteorological conditions. AIC that affect climate most strongly develop in regional-scale, long-lived, ice-supersaturated areas ('outbreak' regions) and global climate modeling suggests that only a few such areas are responsible for a large part of AIC RF (Burkhardt *et al*., 2018). The use of a potential ATM strategy that aims to avoid contrail formation in synoptic conditions that support AIC outbreaks via vertical or horizontal flight diversions ('re-routing') has been suggested as an immediate option to mitigate aviation's climate impact.

Fuel price amounts to about a quarter of the operating cost of airlines. ATM optimizes the fuel efficiency of aircraft operations with next-to-no room left for further reducing fuel consumption. As a result of re-routing, travel times and fuel burn increase. It is an appealing aspect of navigational avoidance that it can be based on the present aircraft fleet and that only the subset of flights impacting AIC outbreaks may have to be targeted. Besides operational and governance challenges, determining suitable detours for specific routes and aircraft necessitates the application of meteorological forecast models with high temporal and spatial resolution.

A theoretical model study of contrail development over Japanese airspace was conducted based on European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data and targeted only those contrails associated by the model with the most potential warming impact (Teoh et al., 2020). The study concluded that contrail RF there could be reduced by 80% by diverting about 2% of the flights with little fuel penalty, while in a flight diversion scenario not permitting additional CO_2 emissions, the reduction in contrail RF decreases only by 20%. In view of the strong sensitivity of potential RF reductions on the chosen scenario, it is unclear how these results translate to outbreak regions such as the more crowded airspace over central Europe and how the use of forecast data (as needed for the implemented avoidance strategy) instead of reanalysis data might affect the results.

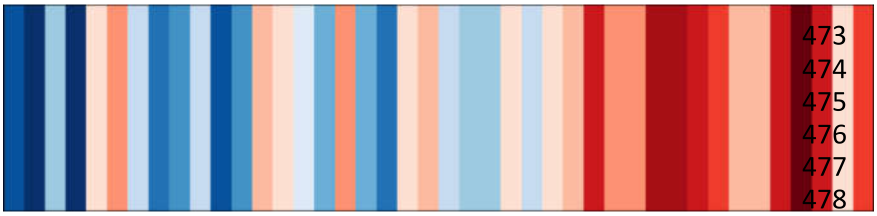
While low resolution climate models are designed to predict the aggregate effects on climate of AIC from all flights together, high resolution numerical weather prediction (NWP) models are needed to estimate the properties and radiative impact of contrail segments for single flights. In particular, the requirements for accurate NWP predictions of time, duration, location, and spatial extent of, as well as magnitude of temperature and moisture fields in, ice-supersaturated areas are much stricter for use in navigational avoidance strategies than in climate prediction. Upper tropospheric ice supersaturation and ice cloud properties are not conventionally analyzed or benchmarked in NWP models. Thus, any implementation of AIC formation for the purpose of navigational contrail avoidance must be carefully documented and validated.

For navigational avoidance to ensure a long-term climate benefit (depending on choice of metric and time horizon), the tradeoff from increased CO_2 emissions against possible reductions in AIC RF needs to be well understood (IPCC, 2022). While thermodynamic contrail formation conditions can be predicted fairly well, significant scientific uncertainties remain regarding the development of contrail cirrus and the forecasting, on a flight-by-flight basis, the vertical and horizontal extent of ice-supersaturated areas and degree of supersaturation along the contrail path. A study analyzing ECMWF model predictions found that predicting individual contrail persistence is problematic due mainly to poorly simulated ice supersaturation (Gierens *et al*., 2020). When used in navigational avoidance, inaccuracies in predictions of ice-supersaturated areas along individual flight routes may even risk increasing CO_2 emissions with no reduction in AIC RF whatsoever (Shine & Lee, 2021). In addition to the poor skill and low confidence in quantifying and attributing a climate effect to individual flight detours, metric-related value judgments are raised, e.g., regarding how much extra fuel burn is justified to avoid a specific contrail (Shine & Lee, 2021).

Uncertainties in global model predictions connected with ice cloud processes are large, with uncertainties mostly related to radiative transfer parameterizations and the upper tropospheric water budget (Lee *et al*., 2021). In particular, the scientific basis to reliably evaluate atmospheric and climate effects of single flights needs to mature before re-routing can be reliably determined and no-regret solutions can be ensured (Shine & Lee, 2021). With dedicated scientific research over the next years, improvements in weather forecasting systems may allow navigational contrail avoidance to be established as a viable mitigation option, perhaps specifically targeting outbreak regions in conjunction with an increasing use of green aviation fuels.

III. Epilogue

To prevent increasing human suffering and loss of biodiversity beyond 2100 requires reaching and sustaining net zero anthropogenic CO_2 emissions, including those from global air traffic, as soon as possible in order to meet the 1.5°C guard-rail temperature target. Much of this increase in global mean surface temperature has already occurred, so every tenth of a degree of less warming matters. Aviation non-CO_2 climate forcings — mainly contrail cirrus clouds and to a lesser degree emissions of nitrogen oxides — cause a short-term warming currently believed to dominate today's overall aviation-induced warming because of the historical growth rates of aviation. Reducing the CO_2 emissions produced by aviation decreases the importance of most of its less well understood non-CO_2 effects and moving to sustainable aviation fuels directly reduces the global warming contribution from contrail cirrus.



Warming stripes of aviation: percentage contribution to global warming 1980–2021. Retrieved: January 19, 2022.

Credit: https://www.eurekalert.org/news-releases/933729

On average, more than 100,000 flights depart from airports daily. With a moderate reduction of air traffic emissions of 2.5% per year — less than required by other sectors to meet their climate targets — aviation's contribution to global warming is projected to reach a constant level in 2050, a situation where the remaining CO_2 forcing balances the diminishing non-CO_2 forcings. Replacing fossil aviation fuels by 2050 with a 90% mix of zero-carbon fuels can be as effective in limiting aviation-induced warming. In such a world, 'climate-friendly flying' may no longer be considered an oxymoron.

Meeting the aviation climate target requires a sea change in technology *and* lifestyle (from those who can afford to fly, a small fraction of the world population). The expected degree of the benefit for climate depends on the knowledge of atmospheric processes and effects along with the accuracy with which climate models predict the associated temperature response, so any such transition must be carefully managed.

IV. References

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V. Glossary

AIC	aircraft-induced clouds: persistent contrails and contrail cirrus
ASTM	American Society of Testing and Materials
ATM	air traffic management
ECMWF	European Centre for Medium-Range Weather Forecasts
ERF	effective radiative forcing
HEFA	hydroprocessed esters and fatty acids: fuel or fuel production path
IPCC	International Panel on Climate Change
LH2	liquid hydrogen fuel
NWP	numerical weather prediction
PAH	polycyclic aromatic hydrocarbons
PtL	power-to-liquid production pathway
RF	radiative forcing
SAF	sustainable aviation fuels: biofuels and PtL
UAP	ultrafine aqueous particles