



Hydrogen combustion mitigates contrail-induced climate forcing relative to kerosene for 2035-technology A320 aircraft

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Abstract. Global-scale estimates of hydrogen combustion's contrail impact have relied on general circulation models with simplified contrail parameterizations or on gridded lifecycle simulations with generic aircraft, and no study has evaluated hydrogen against kerosene using real-world flight trajectories for a defined aircraft under directly comparable conditions. This study presents a trajectory-based comparison of contrail climate forcing from kerosene and hydrogen combustion for 2035-technology A320 aircraft, applying the Contrail Cirrus Prediction model (CoCiP) to 10,298 flights sampled from 2024 global air traffic, with 2024 ERA5 reanalysis meteorology and fuel-specific baseline aircraft designs simulated along identical routes. Hydrogen's higher water vapor emission expands the contrail formation envelope, more than doubling the persistent contrail fraction from 7.31 % to 15.7 % of fleet distance. Yet under baseline nucleation assumptions, fleet-level energy forcing per kilometer decreases by 86.8 %, because eliminating soot lowers ice crystal numbers by 1 order of magnitude, yielding larger, faster-sedimenting crystals that form shorter-lived, narrower and optically thinner contrails. This reduction depends mainly on the assumed nucleation floor for soot-free hydrogen and on kerosene non-volatile particulate matter (nvPM) emissions: across the plausible hydrogen floor (10^{12} – 10^{14} ice crystals per kilogram of fuel burned) the reduction spans 99.9 % to 86.8 %; even the most conservative hydrogen floor remains 28.7 % below the lowest-nvPM kerosene scenario (10 % nvPM). A complementary surrogate model reproduces the same monotonic decline in forcing with decreasing kerosene nvPM, corroborating the trend. Hydrogen combustion thus offers considerable contrail mitigation potential exceeding that of soot reduction alone.

1 Introduction

Aviation's contribution to anthropogenic climate change extends beyond CO₂ emissions to include significant non-CO₂ effects, with contrail cirrus estimated as the largest single contributor to aviation's effective radiative forcing (*ERF*) (Lee et al., 2021). Condensation trails (contrails) form when hot, humid engine exhaust air mixes with cold ambient air. Under favorable atmospheric conditions, specifically within ice-supersaturated regions (ISSRs), these line-shaped ice clouds can persist for several hours and evolve into extensive contrail cirrus. Their climate impact arises primarily from radiative effects: contrails trap outgoing longwave radiation (OLR) while reflecting incoming solar radiation (ISR), typically resulting in net warming (Meerkötter et al., 1999; Avila et al., 2019). Despite a significant uncertainty range, the estimated *ERF* from contrail

cirrus in 2018 ($57.4 [17, 98] \text{ mW m}^{-2}$) exceeded the forcing of cumulative aviation CO_2 emissions for the 1940–2018 period
 25 ($34.3 [28, 40] \text{ mW m}^{-2}$) (Lee et al., 2021).

Addressing these non- CO_2 effects is increasingly urgent as global air traffic is projected to double or triple by 2050 (Grewe
 et al., 2021). Current mitigation efforts largely focus on near-term solutions, ranging from operational measures, such as
 climate-optimized rerouting to avoid ISSRs (Teoh et al., 2020a), to the deployment of sustainable aviation fuels (SAF) and
 advanced engine technologies designed to reduce particulate emissions (Voigt et al., 2021). Alongside these strategies, liquid
 30 hydrogen (LH_2) has emerged as a potential solution capable of eliminating in-flight CO_2 entirely. Yet, while the industry is
 focused on the engineering challenges of cryogenic storage and propulsion integration, the climate impact of hydrogen-induced
 contrails remains uncertain.

Contrail optical depth and radiative forcing (RF) are governed by the number of ice crystals nucleating at formation, which
 depends on the aerosol particles available in the exhaust plume: non-volatile particulate matter (nvPM), volatile particulate
 35 matter (vPM), or entrained ambient aerosols (Kärcher, 2018). Throughout, ice and nvPM number emission indices are given
 per kilogram of fuel burned and are reported in units of kg^{-1} . Conventional rich-burn kerosene engines operate in a soot-rich
 regime, with nvPM number emission indices of order 10^{15} kg^{-1} (Teoh et al., 2024b; Voigt et al., 2026), in which initial ice crys-
 tal numbers scale approximately linearly with soot particle number (Kärcher, 2018). Modern lean-burn engines and alternative
 fuels shift operation toward a soot-poor regime, in which volatile aerosols can become the dominant nucleation pathway under
 40 representative cruise conditions (Voigt et al., 2026). In-flight measurements from the NEOFUELS/VOLCAN campaign behind
 an Airbus A321neo equipped with CFM LEAP-1A lean-burn engines confirmed a 3-order-of-magnitude reduction in soot num-
 ber emissions relative to forced rich-burn conditions (to a median $EI_{\text{nvPM}} = 1.0 \times 10^{12} \text{ kg}^{-1}$, range $[0.5 \times 10^{12}, 1.9 \times 10^{12}]$),
 yet contrail ice crystal numbers remained at a mean of $1.6 (\pm 0.3) \times 10^{15} \text{ kg}^{-1}$ for the campaign Jet A-1 fuel; simulations with
 an extended Aerosol and Contrail Microphysics (ACM) model (Yu et al., 2024) attribute this persistence to newly formed
 45 sulfate vPM, with minor contributions from organic and lubrication oil aerosols (Voigt et al., 2026). These measurements pro-
 vide the first in-flight characterization of contrails formed behind a lean-burn engine. For an ultralow-sulfur fuel at 3 ppm, the
 ACM model predicts a further 1-order-of-magnitude reduction in ice crystal number relative to the Jet A-1 mean reported
 above, consistent with the lowest ice crystal numbers of the campaign, measured for a synthetic blend containing 2 ppm fuel
 sulfur; under these conditions the fuel sulfur contribution becomes negligible and organic vapor and lubrication oil emissions
 50 are expected to dominate volatile aerosol nucleation and subsequent ice formation (Voigt et al., 2026).

These results progressively narrow the experimental gap toward the hydrogen case but do not close it: hydrogen combustion
 produces neither soot nor sulfur, placing it in a distinct soot-free, sulfur-free regime for which no in-flight contrail observations
 are currently available (Bier et al., 2024). Microphysical modeling for this regime predicts that lubrication oil vented through
 the engine core becomes the primary internal source of ice nuclei (Zink et al., 2025); in scenarios where lubrication oil vPM is
 55 also negligible, entrained ambient aerosol may provide the residual nucleation pathway (Bier et al., 2024). Parameterizations
 of initial ice crystal numbers for the entrained-ambient-aerosol pathway in hydrogen combustion have recently been developed
 for integration into large-scale lifecycle models (Zink et al., 2026a; Zink and Unterstrasser, 2026; Zink et al., 2026b), although
 a comparable parameterization for the lubrication oil vPM pathway is not yet available.



Process-based Lagrangian contrail lifecycle models have been widely applied to fleet-level energy forcing assessments. The Contrail Cirrus Prediction (CoCiP) model tracks individual contrail segments along flight trajectories and resolves ice crystal number evolution through growth, sedimentation, and sublimation (Schumann, 2012). Teoh et al. (2024a) applied CoCiP to real Automatic Dependent Surveillance–Broadcast (ADS-B)-derived flight trajectories from the Global Aviation emissions Inventory based on ADS-B (GAIA) (Teoh et al., 2024b) covering 103.7 million unique flights between 2019 and 2021, producing the most comprehensive trajectory-based estimate of global contrail net RF to date and characterizing its regional and seasonal variability. The sensitivity of global contrail cirrus RF to nvPM emission reductions has been assessed using general circulation models (GCMs) (Burkhardt et al., 2018; Bier and Burkhardt, 2022). Bier and Burkhardt (2022) quantify this response, reporting that an 80 % reduction in soot number emissions decreases contrail cirrus RF by only 41 % because microphysical processing in the jet and vortex phases causes the resulting reduction in initial ice crystal number to be smaller than the reduction in soot number emissions. However, such sensitivity has not yet been quantified using a trajectory-based approach.

For hydrogen aviation, the first global-scale estimates relied on GCMs with simplified line-contrail parameterizations. Marquart et al. (2005) found the cryoplane-driven reduction in optical depth and increase in contrail coverage to be of comparable magnitude, leaving the sign of the net contrail forcing difference unresolved; the reduction reported by Ponater et al. (2006) applies to total aviation forcing, combining this contrail effect with reduced CO_2 and NO_x forcing rather than isolating it. Pettersson et al. (2026) moved beyond these parameterizations and resolved the full hydrogen contrail lifecycle at global scale, applying a modified CoCiP in gridded mode with a generic model aircraft. In place of the scalar nucleation floor used in the standard CoCiP configuration, they applied a physically resolved ice nucleation scheme, adapted from Kärcher et al. (2015), for lubrication oil and entrained ambient aerosols. For their base-case lubrication oil assumptions they report a global average reduction of approximately 70 % in energy forcing per flight meter relative to kerosene, with the corresponding reduction in ice crystal number ranging from a few percent to approximately 99 % across the lubrication oil size distributions and emission indices evaluated. Yet no study has applied CoCiP in trajectory mode to directly compare kerosene and hydrogen contrail climate forcing for a defined aircraft type along identical routes. Furthermore, this study relies on the standard scalar nucleation floor AEI_{min} (the minimum apparent emission index of ice, defined and motivated in Sect. 3.2) rather than a physically resolved scheme, and no trajectory-based comparison has yet quantified its combined sensitivity with kerosene nvPM emission levels for soot-poor and soot-free combustion.

This study evaluates and compares the contrail climate forcing from kerosene and hydrogen combustion for 2035-technology A320 baseline aircraft, using trajectories derived from 2024 global air traffic and ERA5 reanalysis data. Predictions are generated using the pyContrails implementation of CoCiP (Shapiro et al., 2026). Kerosene simulations use nvPM emission index profiles derived from the International Civil Aviation Organization (ICAO) Engine Emissions Databank (EDB) via pyContrails' native engine thrust-dependent interpolation, evaluated across three nvPM scenarios reflecting projected engine technology improvements. For the lowest-emission scenario, sensitivity to the nucleation floor is additionally assessed across $AEI_{min} \in \{10^{13}, 10^{14}, 10^{15}\} \text{ kg}^{-1}$. For hydrogen, which eliminates soot emissions entirely, AEI_{min} alone governs the initial ice crystal number, evaluated across $AEI_{min} \in \{10^{12}, 10^{13}, 10^{14}\} \text{ kg}^{-1}$. The principal sources of uncertainty are the poorly con-



strained value of $AEI_{\min}$ for soot-free combustion and, in the soot-poor nucleation regime, the inability of this floor to capture
the non-monotonic nucleation behavior predicted in the transitional, intermediate regime between soot- and aerosol-dominated
nucleation (Sect. 3.2.1).

2 Theoretical background

Contrail formation and evolution proceeds through four phases (Paoli and Shariff, 2016): the jet phase (~ 0 – 10 s), where ice
crystals nucleate on available aerosol particles; the vortex phase (~ 10 – 100 s), where wake dynamics cause substantial ice
crystal loss through adiabatic heating; the dissipation phase (~ 100 – $1,000$ s), marking the breakup of the wake vortices; and
the diffusion phase ($\gtrsim 1,000$ s), where surviving crystals evolve into contrail cirrus within ISSRs.

As hot moist engine exhaust mixes with cold ambient air, the thermodynamic state of the evolving plume traces a straight
trajectory in the temperature–partial pressure phase space (Schumann, 1996). This mixing line has a slope given by

$$G = \frac{c_p EI_{\text{H}_2\text{O}} p}{\epsilon Q_{\text{fuel}} (1 - \eta)}, \quad (1)$$

where c_p is the specific heat capacity of air at constant pressure, p is the ambient pressure, $EI_{\text{H}_2\text{O}}$ is the water vapor mass
emission index, ϵ is the molecular mass ratio of water to dry air, Q_{fuel} is the lower calorific value of the fuel, and η is the overall
propulsion efficiency.

As the plume cools along this trajectory, it may intersect the liquid water saturation curve. The maximum ambient tem-
perature at which this intersection occurs defines the liquid critical threshold temperature, T_{LC} , which depends on G and on
ambient relative humidity over liquid water (RH_{liq}) (Schumann, 1996). According to the Schmidt–Appleman Criterion (SAC),
a contrail will form if and only if the ambient temperature falls at or below this threshold ($T \leq T_{\text{LC}}$). According to Eq. (1), fuels
with a higher energy-specific water emission ($EI_{\text{H}_2\text{O}}/Q_{\text{fuel}}$) produce a steeper mixing line, raising T_{LC} and permitting contrail
formation at warmer ambient temperatures.

Provided that the SAC is satisfied, the exhaust plume mixture becomes supersaturated with respect to liquid water, enabling
available aerosol particles to activate as cloud condensation nuclei (CCN) in accordance with Köhler theory (Köhler, 1936),
and liquid droplets subsequently form on the activated particles. Once the plume temperature falls below the homogeneous
nucleation temperature (HNT), the resulting supercooled droplets freeze almost instantaneously. This temperature threshold
depends on droplet size, solute concentration, and the thermodynamic water activity of the solution (Koop et al., 2000; Kärcher
et al., 2015). The HNT is approximately 235–239 K for tropospheric cloud droplets but is reduced to around 229–232 K in
contrails due to the rapid cooling rates and small droplet volumes in jet exhaust plumes (Kärcher et al., 2015).

The characteristics of this nucleation process depend heavily on the fuel, since the different particle populations present in
the plume compete for the same limited supersaturation, and the population that activates most readily depletes it before the
others can nucleate. In the soot-rich regime, the abundance and larger size of soot particles allow them to win this competition,
activating at lower supersaturations and preventing vPM from nucleating (Kärcher et al., 2015). As soot particle numbers fall,
soot can no longer deplete the supersaturation on its own, and nucleation in the soot-poor regime is shared between residual



soot and vPM, with entrained ambient aerosol becoming the dominant source in the near-threshold limit where supersaturation is too low to activate either (Kärcher, 2018; Ponsonby et al., 2025). In the soot-free combustion regime, soot is absent from this competition, leaving lubrication oil vPM and entrained ambient aerosol as the sole remaining sources of ice nuclei (Bier et al., 2024; Zink et al., 2025).

130 This nucleation competition therefore governs the initial ice crystal number entering the vortex phase, during which the aircraft's counter-rotating wake vortices descend, adiabatically compressing and warming the entrained air. In the parameterization of Unterstrasser (2016), survival through this phase depends on whether the ice mass supplied by ambient supersaturation and by the aircraft's water vapor emission (EI_{H_2O}) is enough to withstand the sublimation caused by this adiabatic warming. Because the available water vapor is distributed among the initial crystal population, a higher initial ice crystal number yields small-volume crystals that sublimate quickly during the descent, whereas a lower initial number yields larger, more
135 sublimation-resistant crystals and correspondingly higher survival fractions.

For a contrail to persist, the ambient air must be ice-supersaturated: the ambient relative humidity over ice (RH_i) must reach or exceed 100%, the defining condition for an ISSR. Because the saturation vapor pressure over ice falls steeply with decreasing temperature, a given ambient water vapor content more readily yields $RH_i \geq 100\%$ at low temperatures, so ISSRs
140 are statistically concentrated in the colder regions of the upper troposphere (Gierens and Spichtinger, 2000; Petzold et al., 2020). Surviving crystals within ISSRs enter the diffusion phase, where their evolution is governed by the degree of ice supersaturation, vertical wind shear, and gravitational sedimentation (Schumann, 2012). Ice water content (IWC), the mass of ice per unit mass of air, in mature contrails becomes primarily a function of ambient supersaturation rather than initial exhaust water emissions (Schumann, 2012). Crystal size and number influence contrail optical depth both directly and indirectly, since
145 crystal size also determines the sedimentation rate that governs contrail lifetime.

Contrails alter Earth's radiation budget by interacting with both ISR and OLR. They produce a warming effect by absorbing OLR and re-emitting it at lower intensity than the warmer surface below, and a cooling effect by scattering ISR back to space. Contrail opacity is quantified by the optical depth

$$\tau_{\text{contrail}} = c_r Q_{\text{ext}} \pi r_{\text{vol}}^2 N / W, \quad (2)$$

150 where N is the ice crystal number line concentration, r_{vol} is the volume-mean crystal radius, Q_{ext} is the extinction efficiency, $c_r = r_{\text{vol}}/r_{\text{eff}}$ is the crystal shape factor, and W is the contrail width (Schumann, 2012; Shapiro et al., 2026). For optically thin contrails ($\tau_{\text{contrail}} \ll 1$), both RF components scale approximately linearly with τ_{contrail} , and longwave warming typically dominates, yielding a positive net RF (Schumann et al., 2012). As τ_{contrail} increases, the longwave emissivity approaches the blackbody limit more rapidly than the shortwave albedo, so that shortwave cooling keeps growing after longwave warming
155 has saturated, eventually reversing the sign of net RF during daylight hours (Schumann et al., 2012). Because this shortwave cooling requires ISR and is therefore entirely absent at night, night-time contrails contribute only longwave warming regardless of optical depth, reinforcing a positive net RF when integrated over the diurnal cycle.



The cumulative contrail climate impact is quantified using energy forcing (EF), which integrates the net RF over the contrail's dimensions (length L and width W) and lifetime t_{life} :

$$EF = \int_0^{t_{\text{life}}} RF(t) L(t) W(t) dt. \quad (3)$$

EF is normalized by Earth's surface area and the number of seconds per year to yield the global yearly mean RF ($GYMRF$), representing the hypothetical globally averaged RF if the contrail's energy were spread uniformly over the Earth's surface (S_{Earth}) across one year (t_{yr}):

$$GYMRF = \frac{EF}{S_{\text{Earth}} t_{\text{yr}}}. \quad (4)$$

3 Simulation setup

3.1 Flight data and aircraft configurations

Global A320 operations are represented using historical flight trajectories from 2024, obtained from the OpenSky Network, an open-access surveillance infrastructure that aggregates ADS-B position reports from volunteer ground stations worldwide (Schäfer et al., 2014). On the retrieved dataset, proximity validation ensures the aircraft's first and last positions are within 50 km of the assigned airports, and flight length validation excludes missions whose ranges are shorter than the geodesic distance between the two airports or longer than twice that distance, filtering out data anomalies and misassigned airports. From this filtered dataset, a representative random sample of 10,298 flights is selected, a size chosen so that fleet-aggregated energy forcing is dominated by the population statistics rather than by individual high-forcing flights. The geographic distribution of these flights is shown in Fig. 1. Traffic is concentrated in Europe and North America, reflecting both A320 operational patterns and the uneven geographical expansion of the OpenSky sensor network toward densely populated, higher-income regions (Sun et al., 2024; Inauen et al., 2026); operations across Africa, Russia, China, and Southeast Asia are consequently underrepresented, as ADS-B equipage mandates were adopted earliest in European and US airspace (Sun et al., 2021) and receiver density across the global South and sparsely populated areas remains limited (Sun et al., 2025). Because Europe and North America are expected to remain the largest and most established A320 markets through 2035, even as China, India, and the Middle East expand their global share (Prentice et al., 2025), this concentration also supports the use of the 2024 OpenSky dataset as a representative proxy for near-future A320 operations.

Flight performance profiles are generated using the Bauhaus Luftfahrt Aircraft Design Environment (BLADE) with fuel-specific 2035-technology A320 baseline designs developed at Bauhaus Luftfahrt (Türkyilmaz et al., 2025). Each flight is characterized for simulation purposes by a single cruise flight level, extracted from the corresponding OpenSky trajectory by identifying sustained flight-level plateaux within 50 FL of the flight's maximum recorded altitude and computing their duration-weighted mean. This 5,000 ft band is intentionally wide to capture step-climb segments while excluding climb and descent phases entirely. Both fuel configurations are simulated along identical trajectories and altitude profiles, ensuring that

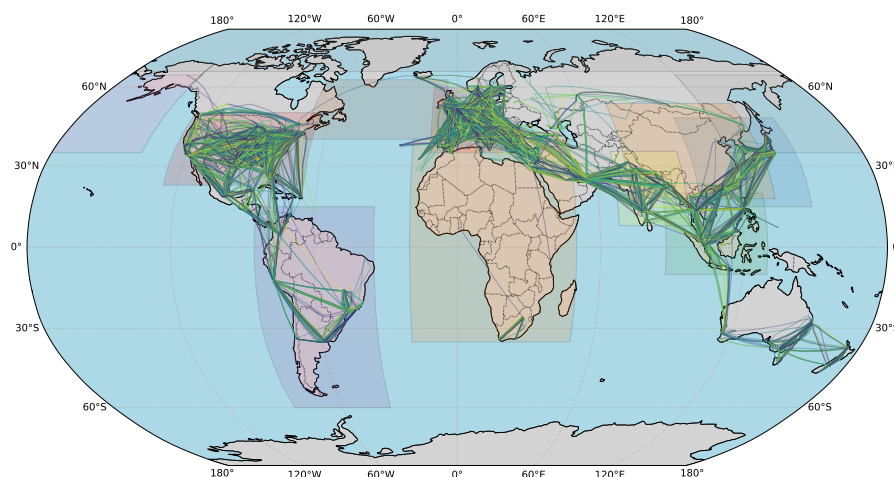


Figure 1. Global distribution of the 10,298 flights randomly sampled from the 2024 A320 OpenSky dataset, with the main geographic regions indicated by boxes. Traffic concentrates in Europe and North America; operations across Africa, Russia, China, and Southeast Asia are underrepresented.

observed differences are exclusively attributable to fuel properties and aircraft performance. The kerosene aircraft (HOPE-BL) has a wingspan of 36.0 m, a fuselage length of 37.57 m, a maximum take-off mass (MTOM) of 69,991 kg, and a design range of 5,556 km (Türkyilmaz et al., 2025). The hydrogen aircraft is derived from the HOPE-BL by converting it to LH₂ propulsion through the integration of two cryogenic fuselage tanks and the adaptation of the remaining aircraft components accordingly, including a 5% mass penalty applied to the dry wing (Kotzem et al., 2024). This conversion requires a 12.8 m fuselage extension, yielding a MTOM of 70,835 kg and a design range of 5,463 km. Both aircraft are powered by ultra-high bypass ratio (UHBR) geared turbofan (GTF) engines adapted for their respective fuels, with design streamtube thrust values of 19.8 kN and 21.4 kN per engine for the kerosene and hydrogen variants, respectively.

The BLADE flight profiles provide the core aircraft parameters along the trajectory: fuel flow, aircraft mass, total thrust, and overall propulsion efficiency. The Pratt & Whitney PW1127GA-JM GTF is used as the representative ICAO EDB entry for the nvPM emission index estimation described in Sect. 3.2.1. This engine is the closest ICAO EDB equivalent to the UHBR GTF engine assumed in the A320 kerosene reference design (Türkyilmaz et al., 2025).

3.2 CoCiP configuration and fuel parameters

Contrail simulations are performed using the CoCiP model as implemented in pyContrails v0.63.1 (Shapiro et al., 2026). Meteorological input is drawn from ERA5 reanalysis data at 0.25° horizontal resolution and hourly temporal resolution for the full year 2024, covering all 12 available pressure levels between 100 and 500 hPa.

The model uses a maximum contrail age of 26 h, an integration time step of 10 min, a maximum segment length of 40 km, and an effective vertical resolution of 1,000 m for the sub-grid wind shear enhancement, half the value derived by Schumann



(2012) from radiosonde comparisons against the ECMWF wind field (Houchi et al., 2010), adopted as a conservative choice that limits the shear enhancement of contrail spreading and is applied identically to both fuels. The methodology from Teoh et al. (2024a), which composes latitude-specific humidity scaling with exponential boosting, is applied to address systematic bias in the ERA5 humidity field. The Unterstrasser (2016) ice survival fraction parameterization, as updated by Lottermoser and Unterstrasser (2025) for low ice crystal numbers and elevated water vapor emissions, is enabled to account for the dependence of crystal loss during wake vortex descent on the initial crystal number and the available water vapor.

The nvPM emission index determines the apparent emission index of ice (AEI), defined as the number of ice crystals formed per kilogram of fuel burned, independent of plume dilution (Kärcher et al., 2015), which sets the initial ice crystal number at contrail formation. Process-based ice nucleation parameterizations, such as the extended Kärcher et al. (2015) parameterization (Ponsonby et al., 2025), explicitly capture the sensitivity of ice formation to ambient conditions and exhaust particle characteristics; however, because AEI predictions from this framework are highly sensitive to plume vPM properties that remain poorly constrained, its application in global simulations is currently limited to sensitivity studies (Ponsonby et al., 2025). Consequently, this study uses the standard simplified bounding approach of the CoCiP framework, where AEI is expressed as $AEI = \max(AEI_{nvPM}, AEI_{\min})$, where AEI_{nvPM} represents the population of emitted nvPM that successfully activates into ice crystals. The term $AEI_{\min}$ provides a lower bound to parameterize alternative nucleation pathways not explicitly resolved by the model, such as nucleation on entrained ambient aerosols or lubrication oil vPM in the case of hydrogen combustion.

In this work, the floor is rescaled by the fuel energy content so that it corresponds to a fixed ice crystal number per unit energy released rather than per unit mass, preventing an artificial underestimation of ice particle formation that would otherwise arise from hydrogen's higher specific energy:

$$AEI = \max\left(AEI_{nvPM}, AEI_{\min} \frac{Q_{\text{fuel}}}{Q_{\text{kero}}}\right). \quad (5)$$

3.2.1 Kerosene scenarios and nucleation floor

The kerosene fuel configuration uses standard Jet A-1 parameters: $EI_{H_2O} = 1.23 \text{ kg kg}^{-1}$ and $Q_{\text{kero}} = 43.13 \text{ MJ kg}^{-1}$ (Shapiro et al., 2026). The nvPM number emission index is obtained from the ICAO EDB entry described in Sect. 3.1 via the T_4/T_2 interpolation methodology implemented in pyContrails (Teoh et al., 2024b), which estimates EI_{nvPM} as a function of engine thrust setting for each flight segment. To assess sensitivity to projected engine technology improvements, three kerosene nvPM scenarios are considered: a baseline using unmodified ICAO EDB nvPM profiles (100 %); a reduced-emission scenario at 80 % of the baseline, representing moderate engine technology improvements; and a low-emission scenario at 10 %, representing a more substantial reduction.

For all three kerosene scenarios, the nvPM emission index is first converted to an activated index, $AEI_{nvPM} = f_{\text{act}} EI_{nvPM}$, where the activation fraction f_{act} follows the pyContrails parameterization (Shapiro et al., 2026), fitted to the airborne measurements of Bräuer et al. (2021), rising from 0.339 at the SAC threshold to unity 5 K below it. This is compared against the $AEI_{\min}$ floor, set in the baseline case to 10^{13} kg^{-1} , representing the ice crystal number expected from background aerosol activating at the SAC threshold itself, where activation efficiency is at its lowest regardless of soot abundance (Kärcher, 2018; Ponsonby et al., 2025).



At every contrail-forming waypoint, AEI_{nvPM} exceeds the baseline floor by factors of 98.4 (100 %), 78.8 (80 %), and 9.84 (10 %). If 10^{13} kg^{-1} were the absolute limit, soot would continue to dictate ice formation even in the lowest-nvPM scenario. However, the literature suggests the actual nucleation transition (i.e. the point where entrained ambient aerosols and vPM outnumber soot to control the ice crystal number) occurs at higher emission indices. Kärcher (2018) identifies 10^{13} – 10^{14} kg^{-1} as the soot emission range where the modeled ice crystal number reaches its minimum, whereas the updated ACM model of Voigt et al. (2026), building on Yu et al. (2024), places this minimum between 10^{13} and $3 \times 10^{14} \text{ kg}^{-1}$. The 10 % scenario's AEI_{nvPM} distribution (2.90 – $6.89 \times 10^{14} \text{ kg}^{-1}$, median $2.91 \times 10^{14} \text{ kg}^{-1}$) therefore lies almost entirely within this range, with 95 % of waypoints below its upper bound. At colder temperatures the range shifts to higher emission indices (Ponsonby et al., 2025), so an even larger share would fall within it in practice.

Two additional floors are consequently evaluated for the 10 % scenario to capture this varying and unresolved transition point. First, $AEI_{\min} = 10^{14} \text{ kg}^{-1}$ matches Voigt et al.'s simulated minimum ice crystal number for Jet A-1 ($2.3 \times 10^{14} \text{ kg}^{-1}$ at 218 K). Second, $AEI_{\min} = 10^{15} \text{ kg}^{-1}$ represents a strict empirical upper bound, matching the mean ice crystal number measured for Jet A-1 under lean-burn operation during the NEOFUELS/VOLCAN campaign (Sect. 1), where volatile particles sustained ice numbers three orders of magnitude above the soot emission index (Voigt et al., 2026). Because this floor exceeds the activated index at every 10 %-scenario waypoint, it is applied uniformly across the fleet rather than as a physically expected case.

The three floors therefore correspond to independent literature constraints on the soot to non-soot crossover: ambient entrainment, modeled particle competition, and vPM-dominated field measurements.

3.2.2 Hydrogen configuration and nucleation floor

For the hydrogen configuration: $EI_{nvPM} = 0$, $EI_{H_2O} = 9.21 \text{ kg kg}^{-1}$, and $Q_{H_2} = 122.8 \text{ MJ kg}^{-1}$ (Khan et al., 2022), as implemented in the pyContrails framework. For hydrogen combustion, $AEI_{\min}$ becomes the primary determinant of initial ice crystal number and its magnitude depends on contributions from lubrication oil vPM and entrained ambient aerosol, both of which remain poorly constrained for hydrogen combustion. Three scenarios are evaluated: 10^{12} , 10^{13} , and 10^{14} kg^{-1} . Because Eq. (5) scales the floor by the fuel energy ratio $Q_{H_2}/Q_{kero} = 2.85$, these nominal, kerosene-referenced values correspond to an effective hydrogen floor of $2.85 \times AEI_{\min}$ crystals per kilogram of hydrogen fuel.

The lower bound (10^{12} kg^{-1}) corresponds to a limiting case where lubrication oil contributions are negligible and ambient aerosol entrainment dominates (Bier et al., 2024). The value of 10^{13} kg^{-1} corresponds to moderate lubrication oil activation. The primary baseline adopts $AEI_{\min} = 10^{14} \text{ kg}^{-1}$, motivated by the NEOFUELS/VOLCAN findings (Voigt et al., 2026) discussed in Sect. 1 and Sect. 3.2.1. As noted in Sect. 1, their ACM simulations, using a fixed lubrication oil emission rate of 120 mg kg^{-1} vented through the hot engine core, reproduce a 1-order-of-magnitude reduction in ice crystal numbers for an ultralow-sulfur fuel at 3 ppm relative to Jet A-1, yielding a floor near $\sim 10^{14} \text{ kg}^{-1}$ (Voigt et al., 2026); this prediction is broadly consistent with the lean-burn measurements for the lowest-sulfur blend, though reproducing absolute ice crystal numbers remains a general limitation of the model (Voigt et al., 2026). For hydrogen combustion, the absence of hydrocarbon fuel further removes the organic aerosol source, suggesting that 10^{14} kg^{-1} constitutes a conservative upper bound rather than a well-constrained value for hydrogen combustion.



Unless stated otherwise, the comparison presented in Sect. 4 refers to the baseline configuration of each fuel: the kerosene
 275 scenario at 100 % of the ICAO EDB nvPM values with $AEI_{\min} = 10^{13} \text{ kg}^{-1}$, and the hydrogen configuration with $AEI_{\min} =$
 10^{14} kg^{-1} ; this combination is referred to throughout as the baseline comparison. The sensitivity to nvPM emissions for
 kerosene and to $AEI_{\min}$ for both kerosene and hydrogen is addressed in Sect. 5.

4 Results

This section presents the baseline comparison (see Sect. 3.2), spanning 10,298 flights covering $1.50 \times 10^7 \text{ km}$, together with
 280 the physical mechanisms governing the inter-fuel differences. Table 1 gives the summary statistics for this comparison.

4.1 Formation and persistence

The SAC is satisfied along 30.5 % of the total fleet distance for kerosene and 62.9 % for hydrogen (+106 %), reflecting a
 substantially wider contrail formation envelope. This expansion results from hydrogen's steeper mixing line slope (Eq. (1)),
 caused by its 2.63-times-greater energy-specific water emission index. This is corroborated by the mean ambient temperature
 285 at waypoints where the SAC is satisfied, which is 224.1 K for hydrogen compared to 218.6 K for kerosene, confirming that
 hydrogen satisfies the SAC in appreciably warmer conditions.

Of the flight distance satisfying the SAC, 23.9 % (kerosene) and 25.0 % (hydrogen) result in persistent contrails after the
 wake vortex phase, which correspond to persistent contrail fractions of 7.31 % and 15.7 % of total fleet distance, respectively.
 The near-equal persistence rates reflect that the initial persistence criterion (i.e. the survival of the initial condensate through
 290 vortex descent, $IWC_1 > 10^{-12} \text{ kg kg}^{-1}$) is governed predominantly by the ambient humidity and temperature at the formation
 location, with only a minor contribution from exhaust water vapor ($EI_{\text{H}_2\text{O}}$) (Schumann, 2012). The marginally higher rate
 for hydrogen is consistent with its greater $EI_{\text{H}_2\text{O}}$ increasing the initial condensate reservoir in near-threshold conditions, as
 well as its broader contrail formation envelope, which encompasses more diverse ambient humidity conditions. Consequently,
 because survival depends predominantly on thermodynamic thresholds rather than aerosol abundance, these persistence rates
 295 show negligible variation across all of the kerosene nvPM scenarios addressed in Sect. 5. Persistent contrails form along
 14.0 % (kerosene) and 25.8 % (hydrogen) of the distance flown over Europe, the region with the largest fleet share at 34 %
 of total distance. Over the United States, which accounts for 20 % of fleet distance, these fractions are 6.9 % and 14.9 %,
 respectively. The prominence of both regions reflects their favorable meteorological conditions, where Northern Hemisphere
 (NH) mid-latitude cruise altitudes lie close to the tropopause and the seasonal expansion of ISSRs promotes persistent contrail
 300 formation (Teoh et al., 2022), as well as the large concentration of fleet operations there.

4.2 Microphysical, geometric, and optical properties

Figure 2 presents kernel density estimates of three microphysical properties of the persistent contrail segments, establishing
 the characteristics of the crystal populations that govern their geometric and optical evolution.



Table 1. Statistics for contrail formation, climate impact, microphysical and geometric quantities for the baseline kerosene (100% ICAO EDB nvPM profile, $AEI_{\min} = 10^{13} \text{ kg}^{-1}$) and hydrogen ($AEI_{\min} = 10^{14} \text{ kg}^{-1}$) configurations. Analysis is based on 10,298 flights covering $1.50 \times 10^7 \text{ km}$. Percentage changes are computed from kerosene to hydrogen. Central statistics for τ_{contrail} and the microphysical variables are evaluated over waypoints with positive values, whereas the radiative forcing means are evaluated over all waypoints with persistent contrails.

Metric	Kerosene	Hydrogen	Rel. change
Formation and persistence			
SAC satisfied (% of fleet distance)	30.5	62.9	+106 %
Post-vortex persistence (of SAC-satisfying distance)	23.9	25.0	+4.48 %
Persistent contrails (% of fleet distance)	7.31	15.7	+115 %
Climate impact per fleet km			
EF (J km^{-1})	1.45×10^{10}	1.91×10^9	−86.8 %
GYMRF ($\text{W m}^{-2} \text{ km}^{-1}$)	9.00×10^{-13}	1.19×10^{-13}	−86.8 %
Climate impact per persistent contrail km			
EF (J km^{-1})	1.98×10^{11}	1.21×10^{10}	−93.9 %
GYMRF ($\text{W m}^{-2} \text{ km}^{-1}$)	1.23×10^{-11}	7.54×10^{-13}	−93.9 %
Mean instantaneous RF (W m^{-2})			
Shortwave	−4.44	−2.84	−36.0 %
Longwave	5.11	3.06	−40.1 %
Net	0.671	0.221	−67.0 %
Concentration of climate impact			
Flight share responsible for 80 % of total positive EF (%)	5.16	7.79	+51.0 %
Optical and microphysical properties of waypoints with persistent contrails [mean (median)]			
τ_{contrail}	0.128 (0.0951)	0.0992 (0.0663)	−22.8 % (−30.3 %)
τ_{cirrus}	0.251 (0.131)	0.658 (0.275)	+162 % (+110 %)
$N \text{ (m}^{-1}\text{)}$	1.77×10^{12} (1.61×10^{12})	1.76×10^{11} (1.72×10^{11})	−90.0 % (−89.3 %)
$r_{\text{vol}} \text{ (}\mu\text{m)}$	7.22 (6.47)	14.0 (13.3)	+93.9 % (+105 %)
IWC (kg kg^{-1})	7.09×10^{-6} (4.92×10^{-6})	1.39×10^{-5} (6.51×10^{-6})	+95.9 % (+32.3 %)
$v_t \text{ (m s}^{-1}\text{)}$	0.0174 (0.0109)	0.0531 (0.0372)	+205 % (+240 %)
Geometry of waypoints with persistent contrails [mean (median)]			
Width (m)	6,680 (4,580)	3,160 (2,300)	−52.7 % (−49.9 %)
Depth (m)	465 (419)	421 (423)	−9.54 % (+0.93 %)
Contrail lifetime [mean (median)]			
Lifetime of persistent contrail segments (h)	2.81 (2.46)	1.10 (0.81)	−60.9 % (−67.0 %)
Atmospheric conditions at waypoints with persistent contrails [mean (median)]			
Altitude (km)	10.7 (10.7)	10.6 (10.7)	−0.94 % (+0.00 %)
Temperature (K)	218 (218)	221 (220)	+1.26 % (+0.69 %)
RH_i	1.09 (1.08)	1.00 (1.03)	−8.24 % (−4.86 %)

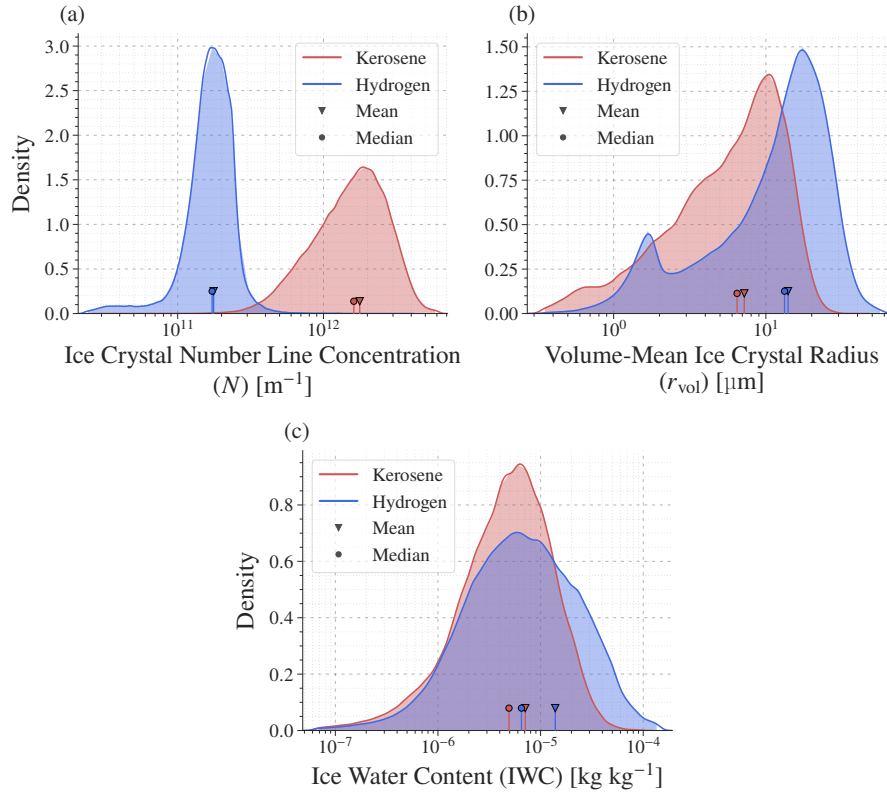


Figure 2. Kernel density estimates of three microphysical properties of persistent contrails. The plot compares baseline kerosene (red) and hydrogen (blue) configurations. (a) Ice crystal number line concentration (N): separated by approximately 1 order of magnitude. (b) Volume-mean crystal radius (r_{vol}): hydrogen shifted toward larger sizes. (c) Ice water content (IWC): distributions exhibit substantial overlap, with similar medians but different means.

The fuels show the greatest separation in post-vortex ice crystal number line concentration (N , in m^{-1}), with each displaying an approximately log-normal distribution (Fig. 2a). Among waypoints with persistent contrails, the mean N for hydrogen is $1.76 \times 10^{11} \text{ m}^{-1}$, which is 90.0% lower than the kerosene value of $1.77 \times 10^{12} \text{ m}^{-1}$. This hydrogen value stems from the assumed nucleation floor AEI_{min} rather than from a resolved microphysical process (see Sect. 3.2.2), so its magnitude carries a parametric uncertainty whose propagation to fleet-level forcing is quantified in Sect. 5; the crystal evolution described below follows the same CoCiP microphysics applied consistently to both fuels.

Kerosene's soot-rich nucleation yields an initial crystal population large enough to remain relatively high despite substantial vortex-phase sublimation, whereas hydrogen's sparser initial population faces less competition for available water vapor, favoring depositional growth to larger sizes and raising the survival fraction toward $f_{\text{surv}} \rightarrow 1.0$ (Lottermoser and Unterstrasser, 2025). This survival advantage does not close the gap: hydrogen's N remains 1 order of magnitude below kerosene's, and its correspondingly larger crystals raise the mean volume-mean radius r_{vol} from $7.22 \mu\text{m}$ (kerosene) to $14.0 \mu\text{m}$ (hydrogen),



315 +93.9%; Fig. 2b). This gap, once established, is largely preserved through the remainder of the contrail lifecycle: turbulent mixing depletes N_1 at a rate proportional to N_1 itself (Schumann, 2012), so it removes the same fraction of both fuels' populations and leaves their ratio unchanged; sedimentation-induced aggregation ($\propto N_1^2$) and mesoscale-fluctuation losses (independent of N_1) would pull the ratio in opposite directions from each other rather than reinforcing one trend (Schumann, 2012); however, both remain minor relative to turbulent losses except at higher temperature and supersaturation.

320 The corresponding IWC distributions (Fig. 2c) exhibit significant overlap, with median values differing by only 32.3% ($4.92 \times 10^{-6} \text{ kg kg}^{-1}$ for kerosene versus $6.51 \times 10^{-6} \text{ kg kg}^{-1}$ for hydrogen), consistent with the dominance of ambient supersaturation over exhaust composition in determining mature contrail IWC (Sect. 2). The larger 95.9% increase in the mean IWC ($7.09 \times 10^{-6} \text{ kg kg}^{-1}$ for kerosene versus $1.39 \times 10^{-5} \text{ kg kg}^{-1}$ for hydrogen) instead reflects an extended upper tail. This is consistent with hydrogen's wider contrail formation envelope (Sect. 4.1), which includes waypoints with unusually strong
 325 or sustained ambient supersaturation.

Larger crystals sediment faster. The mean terminal fall speed (v_t) increases from 0.0174 m s^{-1} (kerosene) to 0.0531 m s^{-1} (hydrogen, +205%). The accelerated sedimentation removes ice from ISSRs before extensive horizontal spreading can occur, shortening the mean lifetime of persistent contrail segments from 2.81 h (kerosene) to 1.10 h (hydrogen, -60.9%) and reducing the mean contrail width (W) from 6,680 m (kerosene) to 3,160 m (hydrogen, -52.7%).

330 Waypoints with persistent contrails separate into those retaining measurable τ_{contrail} and those settling at zero, the latter comprising 15.4% of these waypoints for kerosene versus 33.0% for hydrogen. Among waypoints with non-zero τ_{contrail} (Table 1), the mean decreases by a comparatively modest 22.8%, from 0.128 (kerosene) to 0.099 (hydrogen): despite the 1-

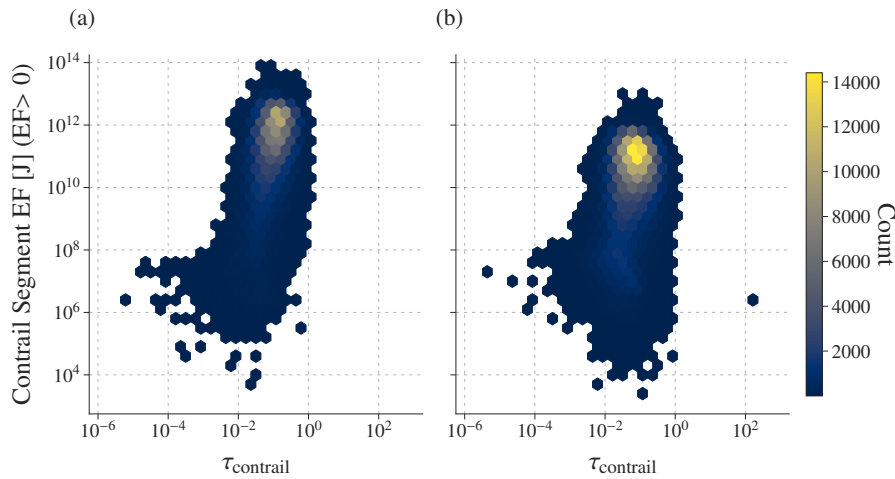


Figure 3. Hexagonal bin density plots of contrail optical depth (τ_{contrail}) versus EF for persistent contrail segments with positive (warming) forcing, for the baseline kerosene and hydrogen configurations, plotted on logarithmic scales. (a) Kerosene population centered near $\tau_{\text{contrail}} \sim 0.1$, with segment forcing spanning approximately 10^{11} – 10^{12} J. (b) hydrogen population at similar optical depths but with forcing approximately 1 order of magnitude lower.



order-of-magnitude reduction in N , the accompanying increase in r_{vol} and decrease in W partially offset its effect on τ_{contrail} (Eq. (2)). Averaged over all waypoints with persistent contrails instead, the mean falls further, by 38.9%, from 0.109 to 0.0664; because a waypoint carrying no optical depth also carries no radiative forcing, it is this zero-inclusive figure that is directly comparable to the RF values below. Both distributions are predominantly optically thin (median non-zero $\tau_{\text{contrail}} = 0.095$ and 0.066 for kerosene and hydrogen, respectively), a regime in which both components scale approximately linearly with τ_{contrail} (Sect. 2), and they accordingly decline by comparable fractions: -40.1% (5.11 W m^{-2} to 3.06 W m^{-2}) for the longwave and -36.0% (-4.44 W m^{-2} to -2.84 W m^{-2}) for the shortwave component. The mean instantaneous net RF nevertheless decreases by 67.0%, from 0.671 W m^{-2} for kerosene to 0.221 W m^{-2} for hydrogen. This reduction exceeds that of either component because the net RF is the residual of two large, opposing fluxes; thus, even a modest divergence in their individual reductions represents a significant fraction of the baseline net RF .

The hexagonal bin density plots in Fig. 3 show the joint distribution of optical depth and warming EF for each persistent contrail segment, for kerosene (left) and hydrogen (right). Consistent with the modest reduction among waypoints with non-zero τ_{contrail} noted above, the two populations occupy largely overlapping τ_{contrail} ranges (interquartile ranges, IQRs, of 0.05–0.17 and 0.03–0.13 for kerosene and hydrogen, respectively). The distributions differ primarily along the EF axis: kerosene segment forcing spans roughly 10^{11} – 10^{12} J at the interquartile level, with a median of $4.33 \times 10^{11} \text{ J}$, while hydrogen spans 10^{10} – 10^{11} J with a median at $4.88 \times 10^{10} \text{ J}$, approximately 1 order of magnitude lower. The wide vertical spread within each distribution at any given τ_{contrail} reflects the influence of additional factors, such as contrail lifetime, meteorological conditions, and the local radiative environment, on segment-level EF .

4.3 Fleet-level energy forcing

For the two baseline configurations, the fleet-level EF/km is $1.45 \times 10^{10} \text{ J km}^{-1}$ for kerosene compared to $1.91 \times 10^9 \text{ J km}^{-1}$ for hydrogen, an 86.8% reduction (Table 1). Applying Eq. (4), the $GYMRF/\text{km}$ is $9.00 \times 10^{-13} \text{ W m}^{-2} \text{ km}^{-1}$ for kerosene and $1.19 \times 10^{-13} \text{ W m}^{-2} \text{ km}^{-1}$ for hydrogen. The kerosene $GYMRF/\text{m}$ of $9.00 \times 10^{-16} \text{ W m}^{-2} \text{ m}^{-1}$ falls below the median of the multi-study distribution of Wiegand et al. (2026b) ($1.71 \times 10^{-15} \text{ W m}^{-2} \text{ m}^{-1}$) but within its 90% confidence interval [7.33×10^{-16} , 4.00×10^{-15}] $\text{W m}^{-2} \text{ m}^{-1}$. This position below the median is consistent with the fleet’s aircraft-class composition: it consists exclusively of A320-class aircraft, whereas the benchmark of Wiegand et al. (2026b) aggregates a mixed global fleet that includes long-haul, wide-body aircraft for which contrail forcing has been shown to be greater (Wiegand et al., 2026a). Its cruise-altitude distribution is correspondingly low: 50.2% of flight distance lies between 7.6 km and 10.7 km (25,000 and 35,000 ft, respectively), exceeding the corresponding values for the mixed global fleet of Teoh et al. (2024b), where this band accounts for 31% of the 2019 global flight distance flown and 44% over Chinese airspace, the region they identify as cruising at lower altitudes than the rest of the fleet. Furthermore, only 29.9% of the present fleet’s distance reaches above 10.7 km (35,000 ft). This low concentration follows from the sample’s short-haul character (median flight distance 1,306 km), meaning most flights are too short to climb to the high cruise altitudes reached more often in mixed global operations. These lower cruise altitudes plausibly contribute to reduced persistent contrail formation (Teoh et al., 2020b; Wiegand et al., 2026a) and thus lower forcing, but this below-median $GYMRF/\text{m}$ cannot be attributed to lower cruise altitudes alone, given other

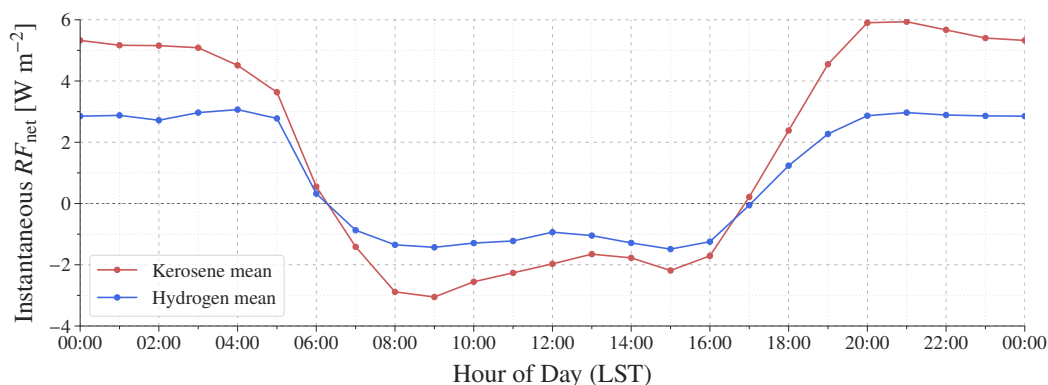


Figure 4. Mean instantaneous net RF (RF_{net}) of existing contrails as a function of the hour of day in local solar time (LST), for the baseline kerosene (red) and hydrogen (blue) configurations. Each point represents the fleet-mean RF averaged over all contrail waypoints whose LST falls within the hour centered on the labeled time, $[(h - 0.5):00, (h + 0.5):00]$, across the full simulation period.

drivers of inter-study variability, including meteorology, model configuration, traffic sample, and analysis year, which also affect the estimate.

The climate impact is concentrated among a small fraction of flights for both fuels: 80 % of the total positive EF arises from just 5.16 % of kerosene flights and 7.79 % of hydrogen flights. These flight shares account for 30.7 % and 26.2 % of all persistent contrail distance, respectively, while covering only 6.04 % and 9.75 % of total fleet distance, reflecting the disproportionate forcing of the small subset of flights that encounter sustained ISSRs.

4.4 Diurnal cycle

Figure 4 shows the mean instantaneous net RF as a function of LST derived from the contrail waypoint longitude. Both fuels exhibit two daytime cooling minima: kerosene reaches $-3.05 W m^{-2}$ at 09:00 LST and $-2.19 W m^{-2}$ at 15:00 LST, while hydrogen reaches $-1.43 W m^{-2}$ and $-1.49 W m^{-2}$ at the same times; these minima correspond to the solar zenith angle range at which shortwave scattering efficiency is maximized while solar direct radiation remains sufficiently intense (Schumann et al., 2012). The smaller magnitude of hydrogen's minima is consistent with its lower optical depth, which reduces interactions with both longwave and shortwave radiation components (Schumann et al., 2012). Both fuels' night-time maxima exceed their daytime minima in magnitude: kerosene reaches $5.94 W m^{-2}$ at 21:00 LST, and hydrogen $3.07 W m^{-2}$ at 04:00 LST, since only longwave warming remains active after sunset.

The net RF turns from warming to cooling between the 06:00 and 07:00 LST points for both fuels, and reverts to warming between the 16:00 and 17:00 LST points for kerosene and between the 17:00 and 18:00 LST points for hydrogen, leaving a cooling regime of roughly ten hours against a warming regime that occupies the remainder of the cycle at the larger magnitudes noted above. Because persistent contrails are short-lived relative to this window (median lifetimes of 2.46 h for kerosene, 0.81 h for hydrogen), most remain within a single regime for their entire lifetime, so the LST of formation largely sets the sign of the



accumulated *RF*: contrails formed within the daytime cooling window contribute negative forcing, whereas those formed after the evening crossing persist entirely under longwave-only conditions and are unambiguously warming. Shifting departures away from the hours immediately following the evening crossing would therefore reduce fleet-level contrail climate impact, a window that is narrower for hydrogen given its shorter lifetime, though operational feasibility is not assessed here.

4.5 Seasonal patterns

Figure 5 shows the monthly mean *EF*/km for both fuels. Both exhibit a NH-winter maximum and a NH-summer minimum—a fleet-level pattern governed by the NH, in which 90.5% of global fleet distance is flown. For kerosene, the fleet-level *EF*/km decreases by 83.9%, from $2.62 \times 10^{10} \text{ J km}^{-1}$ in January to $4.23 \times 10^9 \text{ J km}^{-1}$ in July; for hydrogen, the corresponding decrease is 75.9%, from $3.33 \times 10^9 \text{ J km}^{-1}$ to $8.04 \times 10^8 \text{ J km}^{-1}$. This seasonal reduction is governed by two multiplicative terms: the fraction of flown distance forming persistent contrails, and the *EF* generated per contrail kilometer. Only the first exhibits a coherent seasonal cycle. It decreases from 11.0% in January to 3.18% in July for kerosene (−71.1%), and from 19.9% to 9.21% for hydrogen (−53.7%), reflecting the reduced ISSR frequency and spatial extent in the warmer NH-summer upper troposphere (Teoh et al., 2022, 2024a). The second term oscillates throughout the year, with a peak-to-trough amplitude of 61.9% for kerosene and 65.0% for hydrogen, but without the monotonic winter-to-summer trajectory of the first term. It nonetheless contributes substantially to the January-to-July reduction reported above, declining by 44.4% (kerosene) and 46.7% (hydrogen) over that specific comparison.

Kerosene’s larger seasonal amplitude follows mainly from its steeper winter-to-summer decline in persistent-contrail formation rate reported above: hydrogen’s wider contrail formation envelope (Sect. 4.1) allows it to keep forming contrails under the warmer, less supersaturated summer conditions that increasingly suppress kerosene formation. The *EF* per contrail kilometer,

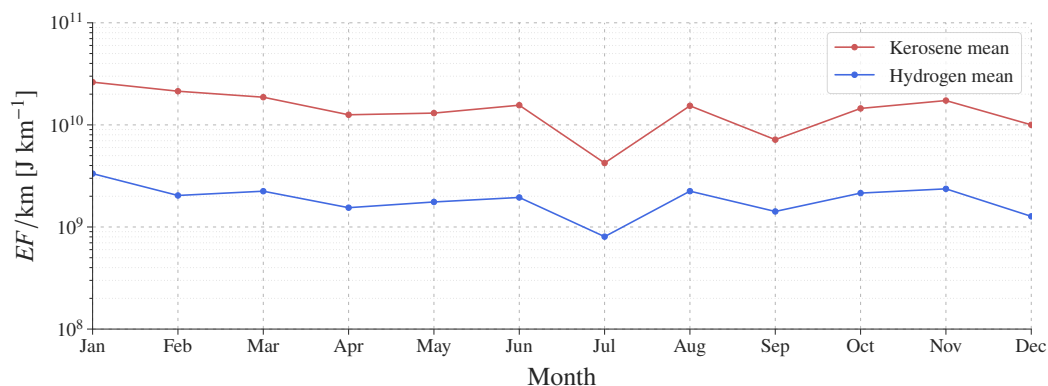


Figure 5. Monthly mean energy forcing per kilometer flown (*EF*/km) for kerosene and hydrogen fleets. Because the flight sample is concentrated in the Northern Hemisphere (NH), the fleet-level trend exhibits a NH-winter maximum and NH-summer minimum, driven primarily by the seasonal decline in persistent-contrail formation rate; the per-contrail-kilometer *EF* varies by a comparable magnitude but without a consistent seasonal signal.



by contrast, varies in close step between the two fuels across the year (Pearson correlation $r = 0.97$) and therefore contributes little to the difference in amplitude between fuels, even though its own seasonal variation is substantial and does not follow a simple winter-to-summer decline; this term peaks in August for both fuels, producing the corresponding departure visible in Fig. 5. Consequently, while the absolute difference in EF/km between the two fuels narrows during the warmer months, hydrogen's fleet-level forcing remains more than 80 % lower than that of kerosene in every month, with the smallest reduction (80.2 %) occurring in September.

5 Sensitivity analysis and limitations

5.1 nvPM emissions

Figure 6 presents the cross-scenario comparison of fleet-level EF/km across the three kerosene nvPM scenarios and the hydrogen configurations, plotting the individual sensitivities to the alternative nucleation floor (AEI_{min}). The median waypoint EI_{nvPM} is 2.91×10^{15} , 2.33×10^{15} , and $2.91 \times 10^{14} \text{ kg}^{-1}$ for the 100 %, 80 %, and 10 % scenarios, respectively, locating the kerosene markers along the EI_{nvPM} axis in Fig. 6. Reducing the nvPM emission index from 100 % to 80 % of ICAO EDB nvPM values decreases EF/km by 13.5 % (from $1.45 \times 10^{10} \text{ J km}^{-1}$ to $1.25 \times 10^{10} \text{ J km}^{-1}$), while a reduction to 10 % yields an 81.5 % decrease to $2.68 \times 10^9 \text{ J km}^{-1}$ (all three at $AEI_{min} = 10^{13} \text{ kg}^{-1}$). Even with this 90 % reduction in soot emissions, the baseline hydrogen configuration reaches $1.91 \times 10^9 \text{ J km}^{-1}$, a further 28.7 % reduction in EF/km relative to this lowest-nvPM kerosene scenario.

As a complementary cross-validation, these results are compared in Fig. 6 against a surrogate contrail prediction model developed by Wiegand et al. (2026a) (overlaid as diamonds). This surrogate operates on precomputed five-dimensional lookup tables trained on CoCiP simulations across aircraft classes, mapping waypoint-level inputs (nvPM emission index, fuel flow, aircraft mass, altitude, and overall propulsion efficiency) to a predicted radiative forcing per unit distance flown for a global traffic scenario in each class, equivalent to the *GYMRF* metric normalized per meter of flight distance. Here, these waypoint-level values are taken from the aircraft performance and emissions data used to run the CoCiP simulations of this study at each cruise waypoint, and the surrogate's cruise-phase *GYMRF*/m output is evaluated on the same 10,298 flights. The fleet-aggregate results are then converted to EF/km through Eq. (4) and compared against the results of this study at $AEI_{min} = 10^{13} \text{ kg}^{-1}$, the configuration closest to the surrogate's own input floor (Table 2).

Table 2 summarizes the comparison. At fleet level, the ratio of this study's EF/km to the surrogate EF/km is 0.60 and 0.64 for the 100 % and 80 % nvPM scenarios, respectively, so the present simulations lie at 40 % and 36 % below the surrogate. For context, the Wiegand et al. (2026b) 90 % confidence interval spans more than a factor of five (Sect. 4.3); against that spread, the surrogate offset found here is comparatively small. The surrogate reflects methodological differences between the separate CoCiP simulations used to build its training data and the specific CoCiP configuration adopted in this study, on top of its own five-dimensional lookup interpolation error; neither factor is quantified here, so the offset cannot by itself be interpreted as a miscalibration of either approach. A more direct check is whether the two approaches agree on the response to a controlled change in nvPM emissions: both reproduce the same monotonic decrease in EF/km with decreasing EI_{nvPM} , differing by only

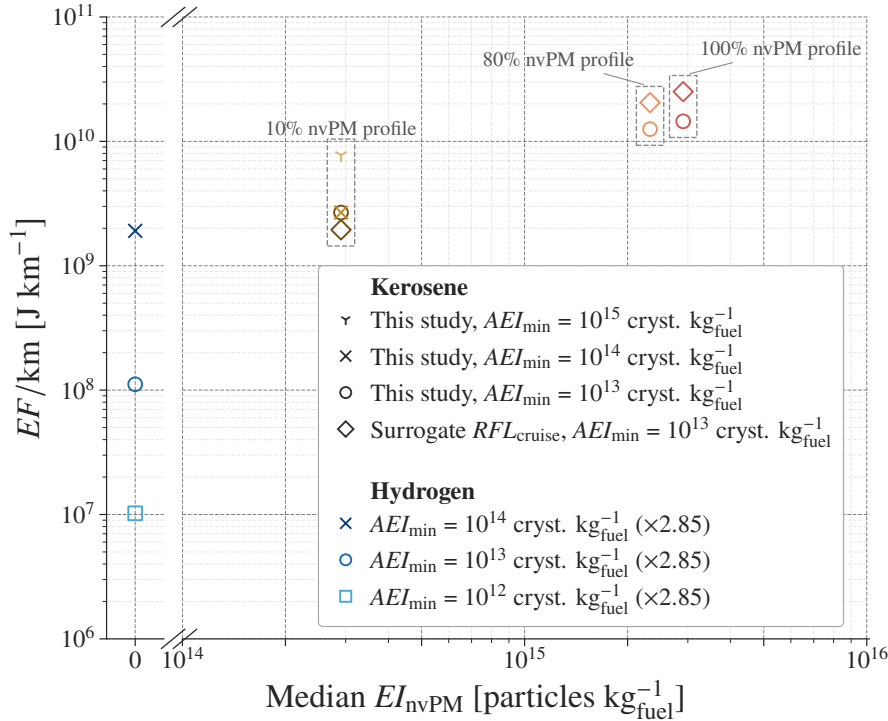


Figure 6. Energy forcing per fleet kilometer (EF/km) versus median nvPM emission index (EI_{nvPM}) for the three kerosene scenarios (100%, 80%, and 10% of ICAO EDB nvPM profiles; colored markers), with the 10% scenario further resolved across the alternative nucleation floors $AEI_{\min}$ considered in this study, alongside the corresponding surrogate model values (Wiegand et al., 2026a) (diamonds; compared against the $AEI_{\min} = 10^{13} \text{ kg}^{-1}$ configuration, the closest match to the surrogate’s own input floor (Table 2)). Since hydrogen combustion produces no nvPM emissions, its three $AEI_{\min}$ configurations (10^{12} , 10^{13} , and 10^{14} kg^{-1} , each scaled by the factor 2.85 of Eq. (5)) are plotted on a detached axis segment at the left of the figure, using the same marker shapes as the corresponding kerosene $AEI_{\min}$ configurations. The nvPM x -axis and the y -axis are both logarithmic. Both this work and the surrogate reproduce the monotonic decrease in climate forcing with decreasing median EI_{nvPM} .

5.1 and 10.8 percentage points (pp) in relative reduction at 80% and 10% nvPM, respectively (Table 2), with closer agreement
 440 at the higher (80%) nvPM level.

When restricted to the flights where both models predict positive forcing (22.6% at 100% and 80% nvPM, 20.3% at 10%), the median per-flight ratio is 0.74 and 0.79 for the 100% and 80% scenarios, respectively, so the present simulations also return somewhat lower forcing on the flights both approaches identify as warming; the wide interquartile ranges ([0.12, 3.62] and [0.12, 3.86]) reflect large per-flight variability, expected because this study’s trajectory-resolved simulations produce non-
 445 zero forcing only where the SAC is satisfied along the specific trajectory, whereas the surrogate returns a response calibrated across a broader range of meteorological conditions (Wiegand et al., 2026a).



Table 2. Fleet-level cross-validation against the surrogate contrail prediction model (Wiegand et al., 2026a) for the three kerosene nvPM scenarios (100 %, 80 %, and 10 % ICAO EDB nvPM profiles). The comparison is performed against the $AEI_{\min} = 10^{13} \text{ kg}^{-1}$ configuration, since this most closely corresponds to the surrogate’s own input floor of 10^{13} kg^{-1} on the raw emission index. The per-flight median ratio and interquartile range (IQR) are computed over flights where both models predict positive forcing. Percentage changes in parentheses are relative to the 100 % baseline of each column.

nvPM scenario	Surrogate ^a EF/km [J km^{-1}]	This work EF/km [J km^{-1}]	Fleet ratio	Median per-flight ratio [IQR]
100 %	2.41×10^{10}	1.45×10^{10}	0.60	0.74 [0.12, 3.62]
80 %	1.96×10^{10} (−18.6 %)	1.25×10^{10} (−13.5 %)	0.64	0.79 [0.12, 3.86]
10 %	1.85×10^9 (−92.3 %)	2.68×10^9 (−81.5 %)	1.45	2.82 [0.49, 12.09]

^aContrail prediction model of Wiegand et al. (2026a).

For the 10 % nvPM scenario, the sign of the discrepancy reverses: this work’s estimate now exceeds the surrogate’s rather than falling below it (fleet ratio 1.45, a 45 % deviation similar in magnitude to the 100 % and 80 % scenarios). The median per-flight ratio is 2.82 (IQR [0.49, 12.1]).

5.2 Initial ice crystal number floor

As shown in Fig. 6, varying $AEI_{\min}$ for the 10 % kerosene nvPM scenario introduces a distinct, nonlinear shift in fleet-level forcing. At the baseline $AEI_{\min} = 10^{13} \text{ kg}^{-1}$, the floor is not triggered at any contrail-forming waypoint (the minimum activated index is a factor of 9.84 above the floor, as noted in Sect. 3.2.1), and the EF/km is $2.68 \times 10^9 \text{ J km}^{-1}$. Raising the floor to 10^{14} kg^{-1} activates it only at the small fraction of waypoints in the extreme lower tail of the AEI_{nvPM} distribution, leaving the EF/km essentially unchanged at $2.68 \times 10^9 \text{ J km}^{-1}$ (+0.03 %). At 10^{15} kg^{-1} , the floor is active at every contrail-forming waypoint of the 10 % scenario, and the EF/km rises to $7.73 \times 10^9 \text{ J km}^{-1}$, a nearly 3-fold increase relative to the baseline. For this scenario, the near-flat response between 10^{13} and 10^{14} kg^{-1} followed by the sharp rise at 10^{15} kg^{-1} reflects the binary, step-function nature of $\max(AEI_{\text{nvPM}}, AEI_{\min})$ rather than a physically resolved transition; a process-based nucleation scheme, such as the one discussed in Sect. 3.2, could instead predict a smoother, and possibly non-monotonic, response across this emission range.

As shown in Fig. 6, the three hydrogen configurations span a wide vertical range relative to the tightly clustered kerosene scenarios, highlighting the high sensitivity of hydrogen forcing to this floor. Evaluating $AEI_{\min}$ at 10^{12} , 10^{13} , and 10^{14} kg^{-1} yields fleet-level EF/km values of 1.02×10^7 , 1.11×10^8 and $1.91 \times 10^9 \text{ J km}^{-1}$, corresponding to reductions of 99.9 %, 99.2 % and 86.8 % relative to the baseline kerosene scenario. This spans more than two orders of magnitude, yet the upper end remains below the lowest-nvPM kerosene scenario (Sect. 5.1). The entrained-ambient-aerosol parameterization introduced in Sect. 1 could resolve $AEI_{\min}$ as a function of ambient and engine conditions rather than as a fixed value (Zink et al., 2026a; Zink and Unterstrasser, 2026; Zink et al., 2026b), though it awaits validation against in-flight measurements for hydrogen combustion.



5.3 CoCiP parameters

A variance-based sensitivity analysis is conducted for the kerosene configuration to quantify the relative contribution of CoCiP
 470 model parameters to the uncertainty in fleet-level climate forcing. Six scalar parameters are varied: the longwave and shortwave
RF enhancement factors, the sedimentation impact factor, the initial wake vortex depth, the wind shear enhancement exponent,
 and the nvPM emission index enhancement factor. Their uncertainty distributions are adopted from the CoCiP uncertainty
 framework in pyContrails (Shapiro et al., 2026). Humidity scaling is the dominant source of uncertainty in CoCiP contrail
 forcing predictions (Teoh et al., 2024a), but the latitude-dependent exponential-boost correction employed here is a spatially
 475 varying transformation of the entire RH_i field whose coefficients are jointly calibrated against in-situ observations rather than
 independent scalars, so it does not admit the mutually independent input distributions that the variance-based framework
 requires; it is therefore excluded from this analysis and deferred to future work.

Sobol indices are estimated using the Saltelli sampling scheme (Saltelli et al., 2010), which generates the input design matrix
 required for the variance decomposition. For $N = 256$ and $k = 6$ parameters, the scheme produces $N(k + 2) = 2,048$ model
 480 evaluations. The analysis is run on the full fleet of 10,298 flights, of which a mean of 4,870 form at least one persistent contrail
 segment across the 2,048 parameter combinations, and the resulting fleet-level *EF*/km values yield a coefficient of variation of
 22.4%, quantifying the spread in fleet-level forcing induced by the combined parameter uncertainty.

The first-order Sobol indices identify the longwave *RF* enhancement factor as the largest single source of output variance
 ($S_1 = 0.473$), followed by the shortwave enhancement factor ($S_1 = 0.282$) and the nvPM emission index enhancement factor
 485 ($S_1 = 0.185$). Together, these three parameters account for approximately 94% of the output variance. The wind shear enhance-
 ment exponent ($S_1 = 0.0403$), the initial wake vortex depth ($S_1 = 0.0269$), and the sedimentation impact factor ($S_1 = 0.00102$)
 contribute the remainder, while the near-equality of the total-order and first-order indices ($S_T \approx S_1$ for every parameter) indi-
 cates negligible parameter interactions.

The Spearman rank correlations between the sampled parameters and the fleet-level *EF*/km (Fig. B1) reproduce the same
 490 ordering as the first-order Sobol indices, with the longwave factor showing the strongest association (correlation coefficient
 $\tilde{r} = 0.67$), followed by the shortwave factor ($\tilde{r} = -0.51$) and the nvPM enhancement factor ($\tilde{r} = 0.42$); the negligible off-
 diagonal correlations between the input parameters confirm the absence of collinearity. This behavior reflects that the *RF*
 enhancement factors are applied as multiplicative output-level scalars whose uncertainty ranges are independent of contrail
 microphysics, so a similarly large contribution is expected for hydrogen. However, this sensitivity analysis is not repeated for
 495 this fuel; microphysical parameters such as the sedimentation impact factor could plausibly carry more relative weight than in
 the kerosene case, given hydrogen's larger, faster-sedimenting ice crystals, though quantifying this is left to future work.

5.4 Model and data limitations

Beyond the modeling uncertainties quantified above, several further constraints limit the precision of the forcing estimates. Co-
 CiP's monodisperse ice crystal size distribution and Gaussian plume geometry cause all crystals within a segment to sediment
 500 at a uniform rate, neglecting the slower-sedimenting smaller crystals that sustain optical depth over time; Akhtar Martínez et al.



(2025) find that this causes CoCiP to underestimate time-integrated extinction relative to a higher-fidelity size-resolving model by a factor of approximately 3.8 for individual contrails under parameterized meteorological conditions. This bias is expected to be asymmetric between the fuels: it acts most strongly on contrails combining high IWC with low ice crystal numbers, precisely the regime occupied by the hydrogen configuration, so the fleet-level reduction reported here is likely an upper bound on hydrogen's advantage (Pettersson et al., 2026). Beyond this microphysical simplification, the $0.25^\circ \times 0.25^\circ$ horizontal resolution of the ERA5 reanalysis smooths sub-grid humidity structures, whereas its discrete vertical pressure levels result in coarse interpolation (Teoh et al., 2024a). Because hydrogen's broader contrail formation envelope extends into conditions closer to the persistence threshold, this smoothing is expected to remove proportionally more contrail-forming waypoints for hydrogen than for kerosene, likely causing greater underestimation of hydrogen contrail formation frequency. Finally, the fleet-level estimates are conditioned by the OpenSky traffic sample, which is heavily concentrated in NH mid-latitudes; consequently, the results may under-represent global operations where meteorological conditions differ significantly from the sampled regions.

6 Conclusions

This study compared the contrail climate forcing of kerosene and hydrogen combustion for fuel-specific 2035-technology A320 baseline aircraft designs, simulating 10,298 flights from 2024 global air traffic with the pyContrails implementation of CoCiP, 2024 ERA5 reanalysis data corrected by the Teoh et al. (2024a) humidity scaling, and identical trajectories for both fuels. Kerosene nvPM emissions were derived from the ICAO EDB at three levels reflecting engine technology improvements in soot reduction. For hydrogen, which produces no soot, the initial ice crystal number is set entirely by $AEI_{\min}$, representing nucleation on entrained ambient aerosols and lubrication oil vPM; lacking in-flight experimental constraints, it was assigned a baseline of 10^{14} kg^{-1} , adopted as a conservative upper bound.

Hydrogen combustion more than doubles the persistent contrail fraction (from 7.31 % to 15.7 % of fleet distance) due to the steeper mixing line caused by its higher water vapor emission index (Eq. (1)), yet reduces the fleet-level EF/km by 86.8 % and the EF per contrail kilometer by 93.9 %. In the absence of soot, ice crystals nucleate only on the less concentrated non-soot particle population, lowering post-vortex crystal numbers by 1 order of magnitude. The resulting larger crystals sediment faster, producing shorter-lived and narrower contrails with lower optical depth. Consequently, the mean instantaneous net RF decreases by 67.0 %, while the reduced lifespan and spatial extent further restrict the total accumulated RF . This reduction gives a definite sign to the net contrail forcing difference that Marquart et al. (2005) left undetermined using simplified line-contrail parameterizations, and exceeds the approximately 70 % reported by Pettersson et al. (2026) for a generic hydrogen aircraft, although the two studies differ in model configuration and nucleation treatment.

Varying the hydrogen nucleation floor $AEI_{\min}$ between 10^{12} and 10^{14} kg^{-1} changes the fleet-level reduction relative to the baseline kerosene scenario (100 % ICAO EDB nvPM values, $AEI_{\min} = 10^{13} \text{ kg}^{-1}$) only from 99.9 % to 86.8 %. Furthermore, even the most conservative hydrogen floor remains 28.7 % below the lowest-nvPM kerosene scenario (10 % ICAO EDB nvPM values). Hence, hydrogen's climate benefit is robust across the configurations evaluated in this study. The kerosene results re-



produce the same monotonic decline with decreasing nvPM emissions as the complementary surrogate model, the two differing by 5.1 and 10.8 pp in relative reduction at the 80 % and 10 % levels, respectively.

535 The main limitation of the present work is the high uncertainty in the contributions from lubrication oil vPM and the entrained ambient aerosol to $AEI_{\min}$ assumed in the adopted nucleation framework, given the lack of in-flight experimental data for hydrogen combustion. For kerosene, the $\max(AEI_{\text{nvPM}}, AEI_{\min})$ formulation is a step function and no choice of $AEI_{\min}$ can capture the non-monotonic AEI response predicted for the intermediate nucleation regime (Kärcher, 2018; Voigt et al., 2026). Process-based nucleation parameterizations that address these limitations offer potential corrections, though neither has
540 yet been validated against in-flight measurements: an entrained-ambient-aerosol scheme for hydrogen nucleation has already been developed (Zink et al., 2026a; Zink and Unterstrasser, 2026; Zink et al., 2026b), while an extended nucleation framework incorporating vPM activation has been developed for kerosene (Ponsonby et al., 2025). Beyond the nucleation representation, meteorological and sampling constraints add further uncertainty: the coarse vertical resolution of the ERA5 humidity fields likely underestimates hydrogen contrail formation in marginal supersaturation zones, and the OpenSky traffic sample's
545 concentration in the NH mid-latitudes limits the extent to which the fleet-level estimates apply to other regions.

Despite these uncertainties, hydrogen combustion offers a contrail mitigation potential exceeding that of nvPM emission reductions alone within all evaluated scenarios, in addition to eliminating in-flight CO₂ emissions. In-flight measurements of hydrogen contrail ice nucleation represent a near-term priority for validating this projected benefit for use in aircraft and infrastructure planning.

550 **Appendix A: Nomenclature**



Table A1. Symbols.

AEI	apparent emission index of ice
c_p	specific heat capacity of air at constant pressure
c_r	crystal shape factor ($= r_{vol}/r_{eff}$)
EF	energy forcing
EI	emission index
ERF	effective radiative forcing
f_{surv}	wake vortex ice crystal survival fraction
G	mixing line slope
$GYMRF$	global yearly mean radiative forcing
IWC	ice water content
L	contrail length
N	post-vortex ice crystal number line concentration
p	ambient pressure
Q_{ext}	extinction efficiency
Q_{fuel}	lower heating value of fuel
$\tilde{r}$	Spearman rank correlation coefficient
r_{eff}	effective crystal radius
r_{vol}	volume-mean crystal radius
RF	radiative forcing
RH_i	relative humidity over ice
S_1	first-order Sobol sensitivity index
S_{Earth}	Earth surface area
S_T	total-order Sobol sensitivity index
t	time
t_{life}	contrail lifetime
T	ambient temperature
T_{LC}	critical threshold temperature (SAC)
t_{yr}	duration of one year
v_t	terminal fall speed
W	contrail width
ϵ	molecular mass ratio of water vapor to dry air
η	overall propulsion efficiency
τ_{cirrus}	optical depth of ambient cirrus above the contrail
$\tau_{contrail}$	contrail optical depth



Table A2. Abbreviations.

ACM	Aerosol and Contrail Microphysics model
ADS-B	Automatic Dependent Surveillance-Broadcast
BLADE	Bauhaus Luftfahrt Aircraft Design Environment
CCN	cloud condensation nuclei
CoCiP	Contrail Cirrus Prediction model
EDB	Aircraft Engine Emissions Databank
GAIA	Global Aviation emissions Inventory based on ADS-B
GCM	general circulation model
GTF	geared turbofan
HNT	homogeneous nucleation temperature
ICAO	International Civil Aviation Organization
IQR	interquartile range
ISR	incoming solar radiation
ISSR	ice-supersaturated region
LH ₂	liquid hydrogen
LST	local solar time
MTOM	maximum take-off mass
NH	Northern Hemisphere
nvPM	non-volatile particulate matter
OLR	outgoing longwave radiation
SAC	Schmidt–Appleman Criterion
SAF	sustainable aviation fuel
UHBR	ultra-high bypass ratio
vPM	volatile particulate matter



Appendix B: Parameter correlation analysis

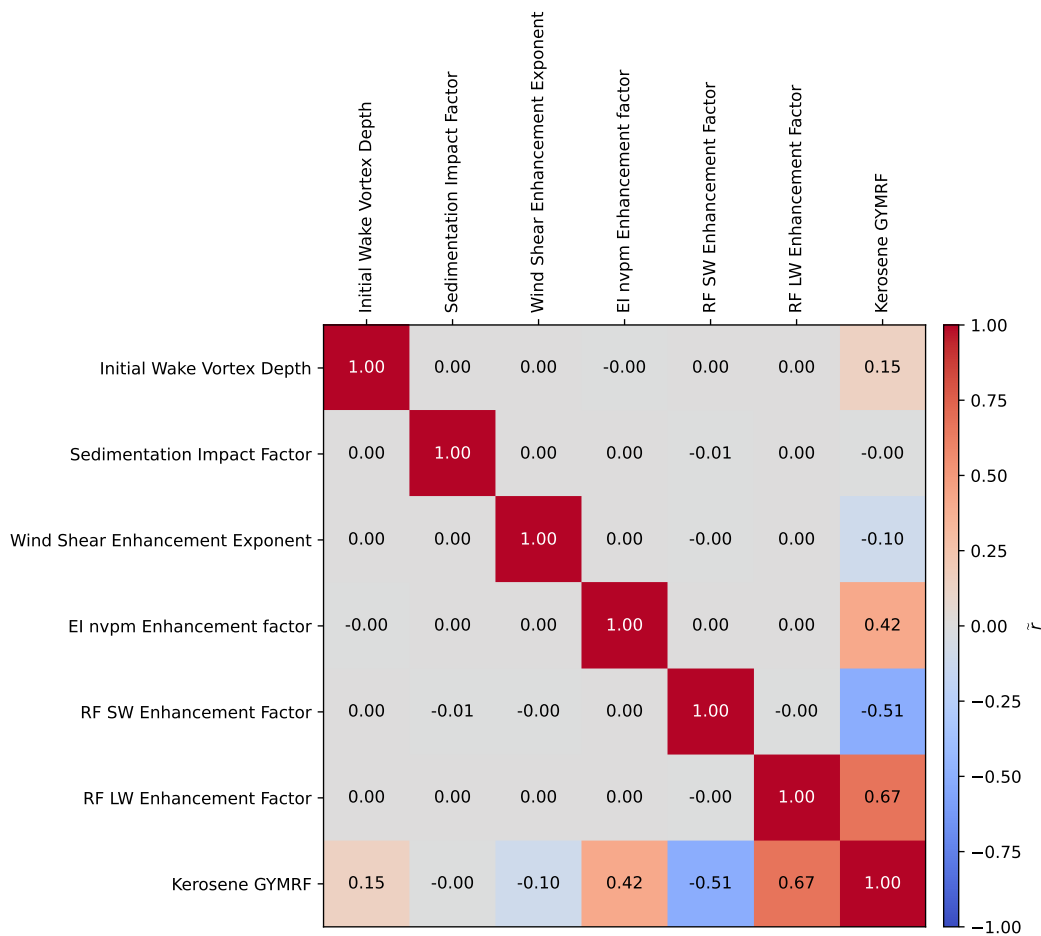


Figure B1. Spearman rank correlation matrix of the six CoCiP model parameters evaluated in the sensitivity analysis and the resulting fleet-level EF/km , for the kerosene configuration. The evaluated parameters include the shortwave and longwave RF enhancement factors, the sedimentation impact factor, the initial wake vortex depth, the wind shear enhancement exponent, and the nvPM emission index enhancement factor.

This appendix provides the Spearman rank correlation matrix of the six CoCiP parameters evaluated in the sensitivity analysis. As discussed in the main text, the matrix confirms the absence of strong collinearity between the selected parameters, which supports the interpretation of the Sobol indices.

555 *Code and data availability.* The pycontrails framework used for contrail simulations (v0.63.1) is archived at Zenodo, <https://doi.org/10.5281/zenodo.20431233> (Shapiro et al., 2026), with development sources at <https://github.com/contrailcirrus/pycontrails>. ERA5 reanalysis data are



560 available from the Copernicus Climate Change Service (<https://cds.climate.copernicus.eu>). OpenSky ADS-B flight data are available from the OpenSky Network (<https://opensky-network.org>). Flight performance data were generated with the Bauhaus Luftfahrt Aircraft Design Environment (BLADE), a proprietary aircraft design environment not publicly available due to intellectual property restrictions. The in-house pipeline used to couple BLADE outputs with pyContrails is likewise not released as open source, as it depends on internal data formats and infrastructure. Data and code are available upon reasonable request, subject to a data-sharing agreement; all modeling steps required for independent reproduction using the open-source components listed above are described in Sect. 3.

Author contributions. M.Conti designed the simulation framework, performed the contrail simulations and analysis, and prepared the manuscript. M. Wiegand developed the surrogate contrail prediction model used for cross-validation, published separately, advised on the pyContrails configuration and nucleation-floor selection, supported its application in this study, and contributed to the manuscript. P. Kiendl contributed to the development of the surrogate model and provided conceptual input throughout the study. R. Balderas-Xicohtencatl conceived and supervised the study and contributed to the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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