



Altitude-Dependent Climate Effects of Hydrogen Combustion in Turbofan Aircraft: A Comparative Literature Synthesis

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Submitted: 2026-09-27 · Accepted: 2026-10-13 · Published: 2026-10-13

DOI: 10.26417/1lfzg4nz

Abstract

Liquid hydrogen combustion eliminates direct carbon dioxide emissions from turbofan aircraft but releases roughly 2.6 times more water vapour per unit of released combustion energy than conventional Jet-A fuel, raising the question of whether the resulting non-CO₂ effects offset the carbon benefit. This study addresses that question through a comparative literature synthesis of 24 peer-reviewed sources, asking under what flight altitudes and atmospheric conditions hydrogen combustion yields a net climate benefit relative to kerosene. A two-stage search protocol combined a date-restricted systematic screen with a targeted search for foundational work published under earlier terminology. Nine standardised variables were extracted from the primary studies and the supplementary evidence was tabulated separately. Altitude was treated as a categorical variable across three bands, with ambient temperature and relative humidity with respect to ice recorded as the underlying mechanism. Hydrogen contrails form at threshold temperatures approximately 10 K higher than kerosene contrails while containing more than 80 to 90 percent fewer ice crystals, which reduces their optical thickness. The altitude dependence is established but is jointly determined by latitude, season and aircraft design, and the direction of the contrail-frequency response reverses between equatorial and non-equatorial regions. The principal gap is not an absence of altitude-resolved evidence but an absence of harmonised comparison under common metrics.

Keywords: hydrogen aviation, contrail cirrus, radiative forcing, flight altitude, non-CO₂ effects, literature synthesis, climate assessment horizon

Introduction

Commercial aviation contributes significantly to global anthropogenic climate forcing through direct carbon dioxide emissions and non-CO₂ atmospheric effects, such as water vapour accumulation and contrail cirrus formation (Lee et al., 2021). Liquid hydrogen combustion in turbofan engines is a promising decarbonisation pathway because it completely eliminates direct CO₂ emissions (Adler & Martins, 2023). However, LH₂ combustion releases roughly 2.6 times more water vapour per unit of released combustion energy into the atmosphere than conventional Jet-A fuel, raising questions about its overall net climate impact (Bier et al., 2024). A separate mission-level estimate reports a larger factor of roughly 4.3 times more water vapour (Khan et al., 2022); this figure is expressed on a total mission basis, where aircraft mass and fuel burn differ from the per-unit energy comparison above, rather than representing a contradiction between the two sources.

Evaluating the atmospheric impact of LH₂ therefore requires considering both the elimination of direct CO₂ emissions and the changes in non-CO₂ effects associated with hydrogen combustion. The formation and persistence of contrails depend on atmospheric temperature, pressure, humidity, and aircraft exhaust properties (Schumann, 1996; Megill & Grewe, 2025).

This study conducts a comparative literature synthesis to answer the following research question: Under what flight altitudes and atmospheric conditions does hydrogen combustion yield a net climate benefit relative to conventional Jet-A fuel, once the non-CO₂ forcing of its water vapour emissions is weighed against its elimination of direct CO₂ emissions?

Literature Review

Two Pathways with Different Timescales

Aviation forces the climate through carbon dioxide emissions that accumulate over centuries and through non-CO₂ effects, principally contrail cirrus, that act over hours to days. Lee et al. (2021) quantified both for the 2018 global fleet, reporting a contrail-cirrus effective radiative forcing of +57.4 mW m⁻² against a CO₂ effective radiative forcing of +34.3 mW m⁻². These figures are not directly commensurable, since the contrail term arises from a single year of traffic while the CO₂ term reflects emissions accumulated over decades. Grewe et al. (2026) address this problem directly, reviewing the methods and metrics used to convert aviation non-CO₂ effects into CO₂-equivalent terms and recommending the Average Temperature Response and the efficacy-weighted Global Warming Potential, both over 100 years. Their recommendation motivates the assessment horizons adopted in the present synthesis.

Conditions for Contrail Formation and Persistence

Schumann (1996) generalised and quantified the Schmidt-Appleman criterion, which relates contrail formation to ambient temperature and pressure, to the water vapour and heat released per unit of fuel burned, and to the overall propulsion efficiency of the engine. Propulsion efficiency governs the slope of the mixing line and therefore differs between propulsion types burning the same fuel. Persistence is a separate condition requiring air that is supersaturated with respect to ice. Megill and Grewe (2025) confirmed from a decade of reanalysis data that ice supersaturation, rather than aircraft design, is the limiting factor for all designs considered, which explains why altitude operates as a proxy for contrail behaviour rather than as its cause. Dischl et al. (2022) quantified the resulting variability over Europe, where potential contrail cirrus cover near 300 hPa swings from 20 percent in winter to 2 percent in summer.

Ice Crystal Number as the Controlling Variable

A second body of work locates the controlling variable in ice crystal number rather than contrail frequency. Burkhardt et al. (2018) showed that initial crystal number governs optical depth, lifetime and coverage, and that the relationship is nonlinear: an 80 percent reduction lowers contrail cirrus radiative forcing by approximately 50 percent, whereas a twofold reduction lowers it by only about 20 percent. Teoh et al. (2020b) reached a consistent conclusion from a flight-track model of Japanese airspace, finding that diverting 1.7 percent of flights could lower contrail energy forcing by 59.3 percent, that combustor technology reducing black carbon emissions could lower it by 68.8 percent, and that the two together could lower it by 91.8 percent. The two agree on sign and mechanism but use different metrics and models, so their sensitivity slopes are not directly comparable. Märkl et al. (2024) provided the corresponding measurement evidence, recording a 56 percent reduction in ice particle numbers per mass of fuel burned for a 100 percent synthetic paraffinic kerosene relative to Jet A-1 in a single in-flight comparison, which supports the modelled link between reduced particle emissions and reduced contrail forcing.

Hydrogen Propulsion: Convergent Mechanisms, Divergent Net Estimates

Hydrogen combustion produces no soot and substantially more water vapour, shifting both terms at once. Bier et al. (2024) reported a formation threshold temperature approximately 10 K higher than for kerosene together with a reduction in ice crystal number of more than 80 to 90 percent, since ice must form on entrained ambient aerosol rather than on soot. Lottermoser and Unterstrasser (2025) extended this to the vortex phase at high resolution and found that vortex-phase processes compress a four order of magnitude difference in initial crystal number to two orders of magnitude, so the microphysical advantage of hydrogen is real but smaller than the initial numbers suggest. Gierens (2021) reached a compatible conclusion for fuel-cell propulsion, although that scope limits its direct

applicability to turbofan combustion. Khan et al. (2022) quantified the emissions side, reporting a 4.3-fold increase in mission water vapour alongside an 86 percent reduction in nitrogen oxides.

The mechanisms converge but the net estimates do not. Megill and Grewe (2025) found that hydrogen combustion could increase globally averaged persistent contrail formation by 46.5 percent relative to a conventional reference, and fuel-cell propulsion by 54.7 percent, while noting that translating these frequency changes into climate impacts requires further work. Miller et al. (2023) reached a different emphasis, finding that contrail cirrus accounts for approximately 81 percent of the combustion climate impact of liquid hydrogen against 32 percent for conventional jet fuel, which makes the hydrogen case considerably more sensitive to contrail uncertainty than the kerosene case. The disagreement is not contradictory so much as unresolved: the same physical mechanisms support different conclusions depending on the metric, the traffic scenario and the atmospheric conditions assumed.

A further tension sits inside these estimates and is rarely stated. Miller et al. (2023) obtain their result by modelling the contrail cirrus impact of liquid hydrogen as only modestly lower than that of conventional fuel, whereas the microphysical literature reports a reduction in ice crystal number of more than 80 to 90 percent (Bier et al., 2024) together with a strongly nonlinear relationship between crystal number and forcing (Burkhardt et al., 2018). Reconciling the fleet-level assessments with the microphysical results is itself an open problem, and the present synthesis does not resolve it.

This indeterminacy is longstanding. Marquart et al. (2005), writing when the technology was termed the cryoplane, modelled radiative forcing for a hypothetical hydrogen fleet and found it could be approximately 30 percent lower or 30 percent higher than a conventional fleet, concluding that available knowledge did not permit a conclusive assessment. The terminology has changed and the microphysics is far better understood, but the direction of the net effect remains open.

Altitude, Latitude and Season

Fichter et al. (2005) established the baseline relationship for conventional fleets, finding that lowering cruise altitude by 2000 to 6000 ft reduces global annual mean contrail coverage approximately linearly, by up to 45 percent at the largest downshift. Kaufmann et al. (2024) extended the question to hydrogen, using twelve years of reanalysis data to show that the difference between kerosene and hydrogen scenarios depends systematically on season, altitude and latitude, and that it cannot be represented by a single multiplicative factor. Sanogo et al. (2024) found from in-service aircraft observations between 325 and 175 hPa that the increase in contrail frequency under a switch to liquid hydrogen decreases with decreasing pressure and increases toward the tropics.

Two studies approach altitude from the design side and reach opposite operational conclusions. Barton et al. (2023) noted that the lighter fuel and reduced seating capacity of a hydrogen aircraft raise its optimal cruise altitude by roughly 2 km, lifting the cruise point in non-equatorial regions above the layer where contrails persist and giving less than a 1 percent probability of long-lived contrails at 14 km beyond 35 degrees of latitude. Proesmans and Vos (2024) found the opposite solution for a medium-range hydrogen aircraft, with climate impact minimised at 6.0 km where contrails are eliminated altogether and the average temperature response reduced by 73 to 99 percent relative to a cost-optimal kerosene aircraft, at an 11 percent lower lift-to-drag ratio and a 10 percent lower engine efficiency. Both routes avoid the persistent contrail layer, one from above and one from below, which indicates that the intermediate band rather than altitude as such carries the problem.

Mourouzidis et al. (2024) reported that contrails could be largely avoided at fuel penalties of a few percent regardless of the fuel, with mitigation required for only a small fraction of flights. At the upper extreme, Pletzer et al. (2022) showed for hydrogen-powered hypersonic transport that the radiative impact of emitted water vapour strengthens with altitude, a direction that transfers to the subsonic case even though the magnitudes do not.

The Gap Addressed Here

The literature therefore does not lack altitude-resolved evidence. What it lacks is a harmonised comparison in which hydrogen and kerosene forcing are evaluated under matched atmospheric conditions, a common traffic scenario and a stated assessment horizon. The present synthesis organises the evidence by altitude band and records the assumptions that prevent such a comparison, so that the limits of what can be concluded are explicit. Because the design is a synthesis rather than an empirical test, the study is guided by a research question rather than by hypotheses.

Methodology

Study Design

This study presents a comparative literature synthesis to evaluate the net climate forcing of liquid hydrogen (LH2) combustion relative to conventional Jet-A aviation fuel. The synthesis focuses on the direct climate benefit of eliminating CO₂ emissions from hydrogen combustion and the associated non-CO₂ effects, particularly increased water vapour emissions and changes in contrail formation and contrail-cirrus properties.

Because CO₂ is long lived whereas contrail-related effects are comparatively short-lived, two assessment horizons are considered: 20 years and 100 years. These horizons follow the metric recommendations of Grewe et al. (2026) and are treated as assessment periods rather than as lifetimes of individual atmospheric effects.

Data Extraction Protocol and Inclusion Criteria

Literature retrieval was conducted in two stages. The first stage applied a systematic screen across Google Scholar, ScienceDirect and Copernicus Atmospheric Chemistry and Physics. The primary search strings were “hydrogen combustion”, “LH2”, “contrail cirrus”, “radiative forcing”, “ERF”, “aviation” and “turbofan”, with the publication period restricted to 2018 to 2026 in order to capture recent atmospheric modelling studies. This stage identified 38 records. After title and abstract screening, 14 full-text studies were evaluated against the inclusion criteria and 5 primary studies were retained: Lee et al. (2021), Teoh et al. (2020b), Gierens (2021), Bier et al. (2024) and Khan et al. (2022).

The second stage was a targeted, citation-led search conducted without the date restriction. It was prompted by the observation that the initial window excluded foundational work published under the earlier term cryoplane, and that altitude-resolved evidence for hydrogen propulsion existed outside the sources retrieved in the first stage. This stage was not an exhaustive database screen, and its yield is therefore reported separately rather than combined arithmetically with the first-stage screening funnel. It added 19 peer-reviewed sources. The final evidence base contains 24 peer-reviewed sources.

Studies were included when they provided peer-reviewed atmospheric chemistry, atmospheric physics, or aviation climate evidence relevant to hydrogen or kerosene combustion, including radiative forcing (RF), effective radiative forcing (ERF), contrail formation thresholds, water vapour emissions, or contrail microphysical properties. Studies reporting atmospheric conditions such as altitude, temperature or relative humidity were prioritised for the altitude-based comparison. Industry publications describing technology status were excluded from the evidence base.

Nine standardised variables were recorded for each of the five primary studies: source, fuel type (LH2 vs Jet-A), metric (RF, ERF or microphysical), altitude band, atmospheric assumptions (T and RH_i), reported value and units, traffic scenario and reference year, time horizon, and source type. These appear in Table 1. Because the supplementary sources are more numerous and report a wider variety of metrics, the eleven that report altitude- or metric-resolved values are summarised in Table 2 using a reduced set of fields. The remaining eight supplementary sources are cited in the text for methodological or contextual points and are not entered into the extraction tables.

Table 1. Data extraction summary for the five primary studies.

Source (Author, Year)	Lee et al. (2021)	Bier et al. (2024)	Gierens (2021)	Teoh et al. (2020b)	Khan et al. (2022)
Fuel type (H2 vs Jet-A)	Jet-A (kerosene)	H2 vs Jet-A	Fuel-cell propulsion	Jet-A	H2 vs Jet- A

Metric	ERF and RF	Process metrics	Formation threshold physics	Contrail energy forcing (EF)	H2O and NOx emissions
Reported value and units	Contrail cirrus +57.4 mW m-2 ERF; CO2 +34.3 mW m-2 ERF	T threshold ~10 K higher; ice crystals reduced by more than 80 to 90%; optical thickness significantly reduced	No forcing value reported; contrail factor (G) much larger than for jet engines	Contrail EF reduced 59.3% by diverting 1.7% of flights at +0.014% fuel; 68.8% from reduced black carbon particle emissions; 91.8% combined	H2O 4.3x; NOx reduction 86%
Altitude band	Mid band (9-11 km); global cruising fleet	Broad tropospheric range; spans all three bands	Extended vertical range, from the lower troposphere to the stratosphere	Mid band (9-11 km); cruise altitudes in the study airspace	Mid band (9-11 km); constant cruise at 32,000 ft
Temperature and RH _i assumptions	Globally averaged meteorology; varied T and RH _i	Schmidt-Appleman driven; T threshold elevated by 10 K	Schmidt-Appleman variant for fuel cells; formation possible even near the surface in cold weather; persistence requires RH _i >100%	T, pressure and RH _i from ECMWF	Model specific; not reported in terms of T and RH _i
Traffic scenario and reference year	Global aviation fleet, 2018	Microphysical trajectory box-model simulations	Theoretical thermodynamic derivation	Japanese airspace flight-track dataset; CoCiP contrail model	A320-like aircraft; 3000 nmi mission
Assessment horizon stated by source	Not specified	Not specified	Not specified	Not specified	Not specified

Source type Peer-reviewed Peer-reviewed Peer-reviewed Peer-reviewed Peer-reviewed

Note. "Not specified" in the horizon row indicates that the study states no assessment horizon of its own. Gierens (2021) addresses fuel-cell propulsion rather than hydrogen combustion in turbofan engines and is used here primarily for the general contrail-formation mechanism.

Table 2. Quantitative results of the eleven supplementary studies that report altitude- or metric-resolved values.

Source (Author, Year)	Fuel	Metric	Reported value	Altitude context
Fichter et al. (2005)	Jet-A	Contrail coverage vs cruise altitude	Lowering cruise altitude by 2000 to 6000 ft reduces global contrail coverage approximately linearly, by up to 45%	2000 to 6000 ft downshift
Marquart et al. (2005)	H2 (cryoplane) vs Jet-A	Global mean RF	Cryoplane contrail RF between about 30% lower and 30% higher than conventional contrails	Global fleet mean; not altitude resolved
Burkhardt et al. (2018)	Jet-A (reduced soot)	Contrail cirrus RF sensitivity	80% fewer initial ice crystals gives ~50% lower RF; a twofold reduction gives ~20% lower RF	Global fleet cruise altitudes
Teoh et al. (2020a)	Jet-A	Contrail energy forcing	Rerouting 15.3% of flights reduced contrail energy forcing by 105% at a 0.70% fuel penalty, that is, the sign of the fleet contrail effect reversed	Flight level changes across cruise altitudes
Dischl et al. (2022)	Jet-A	Potential contrail cirrus cover	10 to 20% at 200 and 250 hPa; 20% near 300 hPa in winter falling to 2% in summer	200 to 300 hPa over Europe
Barton et al. (2023)	H2	Persistent contrail probability	Optimal cruise altitude raised by ~2 km; <1% probability of long-lived contrails beyond 35 degrees latitude	14 km
Miller et al. (2023)	LH2 vs Jet-A	Share of combustion climate impact	Contrail cirrus 81 +/- 31% for LH2 against 32 +/- 7% for Jet-A	Reference aircraft cruise
Kaufmann et al. (2024)	H2 vs Jet-A	Potential contrail cirrus cover	Difference depends systematically on season, altitude and latitude; not reducible to a single factor	Reanalysis across cruise levels

Sanogo et al. (2024)	LH2 vs Jet-A	Contrail formation frequency	LH2 increases frequency; effect decreases with decreasing pressure and increases toward the tropics	325 to 175 hPa
Proesmans and Vos (2024)	H2	Average temperature response	Climate impact minimised at 6.0 km where contrails are eliminated; ATR reduced 73 to 99%, at an 11% lower lift-to-drag ratio and 10% lower engine overall efficiency	6.0 km
Megill and Grewe (2025)	H2 vs Jet-A	Persistent contrail formation	H2 combustion +46.5% and fuel cell +54.7% globally averaged; design influence decreases with altitude	Global, pressure-level resolved

Note. Table 2 records a reduced set of fields because the supplementary studies report a wider variety of metrics than the primary studies. Eleven of the nineteen supplementary sources report values suitable for tabulation; the remaining eight are cited in the text for methodological or contextual points and are not entered into the extraction tables. All entries are peer-reviewed.

Variables and Altitude Categorisation

Altitude serves as the operational variable, while ambient temperature (T), pressure and propulsion efficiency determine whether contrails form according to the Schmidt-Appleman criterion (Schumann, 1996) and RH_i determines whether the resulting ice crystals persist (Megill & Grewe, 2025). Data points were categorised into three altitude regimes: low altitude below 9 km, generally associated with warmer conditions and less favourable conditions for persistent contrail formation (Schumann, 1996; Bier et al., 2024); mid altitude between 9 and 11 km, characterised by variable supersaturation (Dischl et al., 2022); and high altitude above 11 km, where temperatures are lower but ice supersaturated regions become progressively rarer, since the relative humidity distribution in the lower stratosphere falls off steeply with increasing supersaturation (Sanogo et al., 2024) and ice supersaturation is the factor that most limits persistent contrail formation (Megill & Grewe, 2025).

Data and Results

Tables 1 and 2 summarise the extracted values and assumptions. Table 1 covers the five primary studies from the systematic screen and Table 2 the quantitative results of the supplementary evidence.

The extracted literature shows that hydrogen combustion changes both the frequency of contrail formation and the microphysical properties of the resulting contrails. Bier et al. (2024) reported that the formation threshold temperature for hydrogen contrails is approximately 10 K higher than for conventional kerosene

contrails, consistent with the thermodynamic criterion of Schumann (1996). The absence of soot produced a reduction in ice-crystal number of more than 80 to 90 percent, and Bier et al. (2024) report a correspondingly reduced contrail optical thickness. Because the formation threshold temperature is higher, hydrogen contrails can also form at lower flight altitudes than conventional contrails under otherwise comparable conditions. Lottermoser and Unterstrasser (2025) qualified this result, finding that vortex-phase processes reduce a four order of magnitude spread in initial crystal number to two orders of magnitude. Gierens (2021) reported a formation threshold shifted in the same direction but by a considerably larger margin, since the contrail factor for fuel cells is much greater than for jet engines; that analysis concerns fuel-cell propulsion rather than hydrogen combustion in turbofan engines. It is therefore used here for the general formation mechanism, while Bier et al. (2024) provides the combustion-specific evidence.

For the band below 9 km, the primary studies provided evidence on the increased temperature range over which hydrogen contrails can form rather than altitude-specific forcing values. The supplementary evidence is more informative. Proesmans and Vos (2024) found that the climate impact of a medium-range hydrogen aircraft is minimised at 6.0 km, an altitude at which contrails are eliminated entirely, with the average temperature response reduced by 73 to 99 percent relative to a cost-optimal kerosene aircraft. The reduction is obtained at the cost of an 11 percent lower lift-to-drag ratio and a 10 percent lower engine overall efficiency, so the benefit is operational rather than free.

For the 9 to 11 km band, the literature includes both global forcing estimates and hydrogen-specific microphysical results. Lee et al. (2021) reported a global aviation contrail-cirrus ERF of +57.4 mW m⁻² and a CO₂ ERF of +34.3 mW m⁻² for 2018 aviation emissions, while Bier et al. (2024) reported the higher hydrogen formation threshold and reduced ice-crystal number. The Lee et al. (2021) values should not be interpreted as directly comparable measures of the relative importance of contrail cirrus and CO₂. The contrail-cirrus ERF is associated with the effects of a particular year of aviation traffic, whereas CO₂ forcing reflects the accumulated atmospheric effect of aviation emissions over a much longer period. The two therefore cannot be compared as if they represented equivalent time-integrated climate effects.

Within this band the supplementary evidence indicates the direction of the hydrogen effect without resolving its magnitude. Megill and Grewe (2025) reported that hydrogen combustion could increase globally averaged persistent contrail formation by 46.5 percent, while Miller et al. (2023) reported that contrail cirrus accounts for 81 +/- 31 percent of the combustion climate impact of liquid hydrogen against 32 +/- 7 percent for conventional jet fuel. The wide uncertainty band on the hydrogen figure is itself part of the finding. The first result concerns frequency and the second concerns the share of total impact, so they are complementary rather than contradictory, but neither yields a net figure for the band.

For the band above 11 km, the retained studies again provided primarily process-based rather than directly comparable hydrogen versus Jet-A forcing values. Sanogo et al. (2024) found that the increase in contrail frequency under a switch to liquid hydrogen decreases with decreasing pressure, which implies a weaker hydrogen penalty at the top of the band than within it. Barton et al. (2023) reported that the lighter fuel and reduced seating capacity of a hydrogen aircraft raise its optimal cruise altitude by approximately 2 km, and that in non-equatorial regions this lifts the cruise point above the layer in which contrails persist, giving less than a 1 percent probability of long-lived contrails at 14 km beyond 35 degrees of latitude.

Khan et al. (2022) supported the emissions component of the synthesis rather than the altitude comparison, reporting 4.3 times more water vapour on a total mission basis and 86 percent lower NO_x emissions for a modelled A320-like hydrogen aircraft.

Discussion

The net climate impact of LH₂ combustion varies with flight altitude and with the atmospheric conditions encountered during flight. The shifts in formation threshold temperature reported by Bier et al. (2024) and Gierens (2021) indicate that contrail frequency alone is an insufficient basis for evaluation. Hydrogen engines trigger contrails more frequently across expanding flight envelopes, yet the accompanying reduction in ice crystal number of more than 80 to 90 percent (Bier et al., 2024) produces optically thinner clouds, and on the nonlinear relationship established for kerosene by Burkhardt et al. (2018) a reduction of this size implies a substantially lower forcing per contrail. Evaluation therefore requires frequency, optical depth and persistence to be considered together.

The assessment horizon also affects how these effects are weighed, although the argument that follows is a general consequence of the metric literature rather than a finding of this synthesis, since none of the primary studies reports horizon-resolved values. Over a 20-year horizon short-lived contrail effects weigh heavily because they act immediately, whereas the benefit of eliminating CO₂ accumulates over a longer period. Extending the horizon to 100 years therefore shifts the relative contribution toward the long-lived CO₂ effect. Grewe et al. (2026) recommend the Average Temperature Response and the efficacy-weighted Global Warming Potential over 100 years for precisely this reason. None of the five primary studies in Table 1 states an assessment horizon of its own, so the horizons adopted here frame the interpretation rather than the extracted values.

Read band by band, the evidence points in different directions. Below 9 km, hydrogen's higher formation threshold permits contrail formation where kerosene contrails would not form, yet Proesmans and Vos (2024) show that descending to 6.0 km eliminates contrails altogether and minimises the climate impact of a hydrogen aircraft. The penalty is aerodynamic and economic rather than climatic.

Between 9 and 11 km, where conventional aviation commonly cruises, the reduced ice crystal number and optical thickness reported for hydrogen suggest a lower forcing per contrail while direct CO₂ emissions are eliminated, but the higher formation frequency reported by Megill and Grewe (2025) works in the opposite direction and the net magnitude is not established. Above 11 km, Barton et al. (2023) indicate that a hydrogen aircraft may climb clear of the persistent contrail layer in non-equatorial regions, while Sanogo et al. (2024) show the opposite tendency in the tropics. The direction of the contrail-frequency response therefore reverses with latitude within the same altitude band, while the sign of the net climate effect remains undetermined in both cases.

Two implications follow. First, the intermediate band rather than altitude as such carries the problem, since both the descent strategy of Proesmans and Vos (2024) and the climb strategy of Barton et al. (2023) work by avoiding the same layer from opposite directions. Second, altitude management appears viable as an operational lever. Teoh et al. (2020a) demonstrated a 105 percent reduction in contrail energy forcing for conventional fleets by rerouting 15.3 percent of flights at a 0.70 percent fuel penalty. A reduction exceeding 100 percent is a change of sign rather than an arithmetic error: the strategy avoids long-lived warming contrails while permitting cooling ones, so the fleet contrail energy forcing becomes slightly negative. Mourouzidis et al. (2024) reported that contrails could be largely avoided at fuel penalties of a few percent regardless of the fuel, with mitigation required for only a small fraction of flights. For hydrogen aircraft the penalty is paid in additional water vapour rather than additional CO₂, which changes the character of the trade-off but does not remove it.

Limitations

Several limitations affect the interpretation of this synthesis. First, the RF and ERF values reported in the literature derive from different traffic scenarios, atmospheric assumptions and modelling approaches, and none of the five primary studies in Table 1 states an explicit assessment horizon. They are therefore indicative rather than strictly commensurable, and no consistent altitude-resolved dataset of hydrogen versus Jet-A net forcing exists for both the 20-year and 100-year horizons.

Second, the two-stage search protocol is not a systematic review in the formal sense. The supplementary stage was targeted and citation-led rather than exhaustive, so the evidence base should be read as a structured synthesis of the relevant literature rather than as a complete enumeration of it.

Third, this study focuses on water vapour emissions and contrail cirrus. It assesses neither NO_x forcing, which hydrogen combustion still produces because of high flame temperatures, nor the well-to-wake impacts of hydrogen production. Miller et al. (2023) found that the life cycle impacts of the two dominant commercial LH₂ pathways average 8 and 121 percent larger than conventional jet fuel, and Rostami

et al. (2025) project that 7.3 to 12.2 Mt of unburned hydrogen will reach the atmosphere in 2050 depending on the demand scenario, with indirect climate effects of its own. The present synthesis is therefore not a complete life cycle climate assessment.

Fourth, the three-band altitude scheme approximates a relationship that is jointly determined by altitude, latitude, season and aircraft design. Kaufmann et al. (2024) demonstrate that the hydrogen and kerosene difference cannot be represented by a single multiplicative factor, which places a ceiling on what any fixed vertical partition can resolve.

Conclusions

The literature provides a conditional and partial answer to the research question. Between 9 and 11 km, the evidence indicates that hydrogen combustion eliminates direct CO₂ emissions while raising the contrail formation threshold and substantially reducing ice crystal number. The direction of the microphysical evidence points toward reduced contrail-cirrus forcing per contrail, although its magnitude, and therefore whether it outweighs the higher formation frequency reported by Megill and Grewe (2025), is not established.

Below 9 km and above 11 km the picture is better developed in operational and design terms than a reading confined to recent microphysical studies would suggest, although comparable forcing values for hydrogen and kerosene are still unavailable for either band. A hydrogen aircraft optimised for minimal warming settles at 6.0 km, below the contrail-forming layer (Proesmans & Vos, 2024), while one optimised for zero persistent contrails climbs to 14 km, above it (Barton et al., 2023). The hydrogen and kerosene difference also varies systematically with season and latitude, differing in direction between high latitudes and the tropics (Kaufmann et al., 2024; Sanogo et al., 2024). A fixed three-band comparison therefore approximates a relationship determined jointly by altitude, latitude, season and aircraft design.

The gap is accordingly not an absence of altitude-resolved evidence but an absence of harmonisation. Existing studies use different traffic scenarios, metrics and atmospheric assumptions, and the primary studies state no assessment horizon at all, which prevents their results from being combined into a single net comparison. Closing this gap requires hydrogen and kerosene forcing to be evaluated under matched atmospheric conditions and a common metric, with latitude and season treated as explicit variables rather than as sources of scatter. On present evidence, and on contrail-formation grounds alone rather than on a completed net forcing comparison, the more defensible operational conclusion is that hydrogen aviation should be designed and flown to avoid the intermediate altitude band rather than to optimise within it.

Declarations

Conflict of Interest

The authors declare no conflict of interest regarding the research, authorship, or publication of this article.

Data Availability Statement

All relevant data generated or analysed during this study are included within this published article.

Declaration of Generative AI in Writing

During the preparation of this work, the authors used generative AI tools in order to assist with language editing and proofreading. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the final publication content.

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