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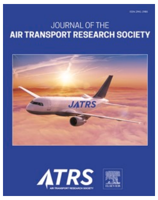

Segregated supply of Sustainable Aviation Fuel to reduce contrail energy forcing – demonstration and potentials

Gunnar Quante [a,*], Benedict Enderle [b], Peter Laybourn [c], Peter W. Holm [d], Lars W. Andersen [e], Christiane Voigt [f,g], Martin Kaltschmitt [b]

[a] *Hamburg University of Technology (TUHH) Institute of Environmental Technology and Energy Economics (IUE), Eißendorfer Straße 40, 21073 Hamburg, Germany*
[b] *German Aerospace Center Institute of Combustion Technology, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany*
[c] *Brændstoflageret Københavns Lufthavn, Hydrantvej 10 2770 Kastrup, Denmark*
[d] *Københavns Lufthavne A/S, Lufthavnsboulevarden 6, 2770 Kastrup, Denmark*
[e] *Scandinavian Airlines System SAS, SE-195 87, Stockholm, Sweden*
[f] *German Aerospace Center Institute of Atmospheric Physics, Münchner Straße 20, Oberpfaffenhofen, 82234 Wessling, Germany*
[g] *Johannes Gutenberg-University Mainz, Institute of Atmospheric Physics, Johann Joachim Becherweg 21, 55099 Mainz, Germany*

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ABSTRACT

Aviation contributes about 4 % to net anthropogenic climate forcing, with contrails being the largest individual contributor to radiative forcing from aviation. One option to mitigate contrail-related climate impacts is using kerosene containing fewer or no aromatic components and thus showing a higher hydrogen content compared to conventional kerosene (i.e., fossil fuel-based). Such “low contrail” kerosene can be provided as a blend of conventional (crude oil-based) and synthetic kerosene or from hydroprocessing conventional kerosene.

Low contrail kerosene reduces contrail lifetime and optical thickness and thus the magnitude of contrail climate forcing. However, market shares of such kerosene are presently very low. Simultaneously, a small fraction (< 10 %) of all flights globally accounts for the majority (> 80 %) of global warming contrail climate forcing. Hence, the targeted use of low contrail kerosene on those flights appears promising. But, such an approach would require additional operational efforts, such as a duplication of supply lines and storage tanks.

This study evaluates the feasibility and operational efforts of a segregated supply of a 35 m-% SAF-blend (14.34 m-% hydrogen content) to 84 winter time demonstration flights to reduce contrail climate forcing. Between 17th January 2023 and 2nd February 2023, low contrail kerosene was supplied to commercial A320 type aircraft flights on the route between Stockholm and Copenhagen in northern Europe. The operational feasibility and related efforts to target flights with the highest contrail energy forcing as well as a large-scale application are described. The evolution of contrails is tracked using data from the Meteosat Second Generation (MSG) satellite. The contrail energy forcing is calculated for the corresponding flight trajectories assuming another, well-validated engine model (CFM56–5B4 for the simulations instead of LEAP1A-26 for the demonstration flights) using the Contrail Cirrus Prediction (CoCiP) model with meteorological input fields from European Reanalysis data (ERA5).

For the first time, the experiment demonstrates the operational feasibility for a segregated supply of low contrail kerosene to medium range aircraft at Stockholm airport. The segregated supply of low contrail kerosene can be realized for short to medium range flights, which can be fueled by a refueller truck. Targeting individual flights via single line hydrant fueling systems seems impractical as of now. Operational efforts to target single flights with highest contrail energy forcing are almost identical to the efforts in this demonstration experiment.

Simulations estimate that the segregated supply of the medium blend kerosene (14.34 m-% hydrogen content) can reduce contrail energy forcing by about 11 % assuming the use of a “Rich-Quench-Lean” (RQL) engine (CFM56–5B4). The contrail climate benefit increases to >20 % for a 50 % blend ratio (14.7 m-% hydrogen content). Also, the location and evolution of the demonstration flights’ 28 contrails calculated with CoCiP was tracked with satellite data.

The uncertainty of absolute contrail climate forcing estimates is mainly limited due to meteorological data input and also by lacking information on fuel composition in terms of cycloalkane, mono- and polycyclic

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* Corresponding author.
E-mail address: gunnar.quante@tuhh.de (G. Quante).

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aromatics content. Contrarily, the uncertainty of relative changes in contrail climate forcing is subject to low uncertainty, since it compares the use of different fuels for an identical fleet and identical weather conditions.

1. Introduction

Aviation contributes about 4 % towards net anthropogenic climate forcing (Lee et al., 2021). Its climate impact can be attributed to contrails, carbon dioxide (CO_2) emissions, effects caused by NO_x emissions, and several other effects. In terms of radiative forcing, contrails are the largest individual contributor to the total radiative forcing from aviation, being even larger than the radiative forcing from historically accumulated aviation carbon dioxide (CO_2) emissions (Lee et al., 2021; R. Teoh et al., 2024). Hence, the mitigation of aviation's climate impact is considered a key challenge in air transportation research (Wandelt et al., 2024a, 2024b; Raman et al., 2024).

One option to mitigate contrail climate impacts is the use of kerosene[1] with a reduced content of aromatic compounds compared to conventional kerosene ("low contrail kerosene"). Such kerosene lowers contrail climate forcing by reducing average contrail lifetime and optical thickness (R. Teoh et al., 2022; Woeldgen, 2023; Quante et al., 2024; Voigt et al., 2021; Moore et al., 2017; Gierens et al., 2024; Burkhardt et al., 2018; Quante & Voigt, 2024). The content of aromatic components within conventional kerosene can be reduced technically by hydroprocessing of the fossil fuel-based kerosene (Voigt et al., 2021; Märkl et al., 2024; Zschocke et al., 2017; Schripp et al., 2022) or by blending conventional (untreated) kerosene with synthetic kerosene (Märkl et al., 2024; Harlass et al., 2024; Dischl et al., 2024) This synthetic kerosene is derived from non-crude oil based sources such as biomass or coal (ASTM, 2024a) and typically does not contain any aromatic compounds. Synthetic kerosene from renewable sources is colloquially referred to as "Sustainable Aviation Fuel" (SAF). Since the renewable origin does not necessarily guarantee compliance with other sustainability aspects (e.g., biodiversity, no child labour), the term renewably sourced kerosene is used here instead of the term "Sustainable Aviation Fuel" (SAF). The use of low contrail kerosene has further environmental impacts than contrail-related climate forcing. The reduced aromatics content of such fuel reduces soot particle emissions and can thus improve the local air quality around airports (Raman et al., 2024; Schripp et al., 2022; Dischl et al., 2024). Kerosene from renewable energy sources can also reduce aviation's carbon dioxide-related climate impact, depending on feedstock and provision pathway being used (Raman et al., 2024; Quante et al., 2023; S. Wandelt et al., 2024). The choice of any renewably sourced feedstock type needs careful consideration, since it might affect land use or could stipulate competition with food and feed markets (Watson et al., 2024; Buchspies & Kaltschmitt, 2018; Buchspies et al., 2020).

Low contrail kerosene is currently scarcely available on the global fuel markets; neither large scale production units are under operation nor the economic environment supports the use of such fuel and additionally the valid fuel standards do not address the use of such fuels. Simultaneously, about 3 % of all flights in 2019 (or 11 % of the contrail-forming flights) are estimated to account for 80 % of the global contrail energy forcing (R. Teoh et al., 2024). For this reason, the targeted use of low contrail kerosene on flights with a substantial probability to cause high contrail climate forcing seems to be a promising way to reduce aviation's climate forcing impact. However, such a concept would imply additional operational efforts, e.g., due to the provision of segregated supply lines, additional storage tanks and specific equipment for a segregated aircraft refueling.

Against this background, this study reports about the operational efforts required for a segregated kerosene supply to 84 demonstration flights between Stockholm airport and Copenhagen airport. These efforts are weighted against the contrail climate benefits of using low contrail kerosene. To reduce uncertainties in the contrail climate forcing for lean burn engine (turbine) technologies, a predecessor of the demonstration flights' aircraft with a rich-quench-lean engine was assumed within this assessment. Additionally, implications for supplying flights based on their climate forcing ("targeted use") are derived and their general applicability at large-scale is discussed.

Initially, contrails are formed when the mixture of ambient air and aircraft engine exhaust cools down and reaches supersaturation against water. The required threshold air temperature and pressure can be determined by the Schmidt-Appleman criterion (Schmidt, 1941; Appleman, 1953; Schumann, 1996). The combustion of kerosene in a jet engine produces water (among others) formed from the hydrogen chemically bound within the aviation fuel and oxygen from the ambient air. This water mainly condenses on soot particles (from incomplete combustion) emitted in parallel from the aircraft engines. The majority of present-day engines (turbines) emit in the so-called "soot-rich" emission regime (10^{14} to 10^{15} particles/kg_{fuel}). If the temperatures of the ambient air masses are sufficiently low, the formed water droplets subsequently freeze into ice crystals. When the humidity of the surrounding air is below ice saturation, the ice crystals will sublime after a short while. Contrarily, in ice-super-saturated regions, the initial ice crystals will trigger the formation of additional ice crystals from the humidity of the ambient air and thus cause a persistent contrail, which can persist for several hours and – depending on vertical wind shear – can spread over large areas (Minnis et al., 1998; Gierens & Vázquez-Navarro, 2017; Schumann et al., 2017). Typically, such persistent contrails exhibit a large climate impact. Finally, the contrail cirrus dissolves because its ice crystals sublimate (Urbanek et al., 2017), e.g., by sedimentation into warmer and / or dryer air masses.

At night, contrails trap outgoing terrestrial radiation in the atmosphere, while during day they also reflect incoming solar radiation (Schumann, 2012). Hence, the climate impact of individual contrails is largely dependent on the solar zenith angle during its life time. Most contrails at night have a warming climate impact, while contrails during the day can also exhibit a cooling climate impact. On the long-term average, the global net climate impact of contrails is clearly warming (R. Teoh et al., 2024).

The sooting tendency of kerosene decreases roughly from poly- to mono-cyclic aromatics via cyclo, iso and n-alkanes (Schripp et al., 2022; Schripp et al., 2018). The reduced soot particle emissions number causes a marginally higher amount of water to condense onto substantially fewer soot particles. As a result, those soot particles covered by more water tend to be heavier and sediment earlier compared to the current situation. The reduced ice particle number also results in a decreased contrail optical thickness. Both, reduced optical thickness and faster sedimentation lower the absolute value of a contrail's climate impact; i.e., it shows either less warming or less cooling effects (Burkhardt et al., 2018; Märkl et al., 2024; Schumann, 2012; Schumann et al., 2012; Teoh et al., 2020; Schumann et al., 2013).

The aromatics content of aviation kerosene can be reduced either by using kerosene produced based on renewable sources (which typically does not contain any aromatics) or based on an additional processing step of crude oil based kerosene (Quante et al., 2024). The targeted supply of such low contrail kerosene to flights with a high contrail climate impact has been studied theoretically in several simulation studies (R. Teoh et al., 2022; Woeldgen, 2023; Quante & Voigt, 2024).

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[1] Typically, kerosene denotes a certain fraction of hydrocarbon molecules containing about eight to 16 carbon atoms. Thus it is not per se compliant with aviation turbine fuel specifications. Note that the term kerosene refers to specification compliant jet fuel here.

The majority of these studies focus on the climate forcing mitigation potential (R. Teoh et al., 2022) or on approaches avoiding infrastructure modifications (Woeldgen, 2023). This investigation adds a weighting of operational efforts and contrail climate benefits to the existing literature, based on a practical application of a segregated low contrail kerosene supply.

From 17th January to 2nd February 2023, 84 demonstration flights between Stockholm airport and Copenhagen airport have been conducted with low contrail kerosene. A blend of 35 % synthetic and 65 % conventional (crude oil based) kerosene was supplied specifically to the demonstration flights segregated from the usual kerosene supply chain. The synthetic blend component was provided based on renewable sources via the Hydroprocessed Esters and Fatty Acids Synthesized Paraffinic Kerosene (HEFA-SPK) pathway (Zemanek et al., 2020; Neuling & Kaltschmitt, 2018a, 2018b). These demonstration flights have been conducted as part of the ALIGHT project (ALIGHT Aviation 2024). Data from the respective measurement campaign are used in this ex-post analysis to study the operational efforts and potential climate benefits of a segregated low contrail kerosene use. First-hand experiences from planning and conducting the demonstration flights are the basis to describe the corresponding operational efforts. The resulting demonstration flight's contrail climate forcing is estimated with a well-validated engine model (CFM56–5B4) for different conventional, crude oil based and low contrail kerosene options using the Contrail-Cirrus Prediction Model (CoCiP).

The remainder of this study is structured as follows: Section 2.1 details methods and Section 2.2 data used to derive the operational efforts and to estimate the contrail climate forcing. Additionally, uncertainties of the contrail modeling and the Contrail Cirrus Prediction Model (CoCiP) are discussed qualitatively in section 2.3. Based on the experiences during these demonstration flights, operational efforts for targeting flights based on their contrail energy forcing and for a large-scale application are discussed (Section 3.1). The satellite detection of individual contrails (Section 3.2) and contrail climate benefits are described (Section 3.3). As such, this study can be seen as an initial experimental demonstration of a segregated low contrail kerosene supply.

2. Methods, data and model uncertainties

2.1. Methods

This section covers the segregated supply of low contrail kerosene as it was realized for the demonstration flights first (Section 2.1.1). Then, the methods to estimate the change in contrail climate forcing are discussed (section 2.1.2).

2.1.1. Segregated supply of low contrail kerosene

The demonstration flights were carried out with the primary objective to measure the local air quality impacts of using a kerosene with a low content of aromatic compounds. To supply this specific kerosene blend to the demonstration aircraft, a segregated supply infrastructure was required. Kerosene handling standards advocate that only kerosene in compliance with the respective applicable kerosene standards (e.g., ASTM D1655, Def Stan 91–091 (ASTM, 2024b; UK Ministry of Defence 2024)) is delivered to an airport (Energy Institute 2024). Since the applicable fuel specification (here: ASTM D7566) presently limits the use of synthetic kerosene to blends with at least 50 % conventional (crude oil based) kerosene and $>$ 8 % aromatic components (ASTM, 2024b), this regulation implies that blending takes place before the blend is supplied to an airport. Up to the point of blending, the supply of neat synthetic kerosene is segregated in any case, since an upstream blending of different synthetic kerosene components is not permitted by the respective standards. Therefore, the current (non-segregated) and the investigated (segregated) supply chains differ only from the point where all kerosene supplies for a particular airport merge and usually commingle. For the demonstration flights, this point is Gävle fuel terminal, located in Sweden north of Stockholm airport.

Overall, 84 demonstration flights with a low contrail kerosene consisting of about 35 m-% HEFA-SPK and 65 m-% conventional (crude oil based) kerosene were conducted between 17th January to 2nd February 2023. The aircraft, a commonly used single-aisle commercial airliner equipped with LEAP1A-26 engines, carried out scheduled passenger services between Stockholm airport and Copenhagen airport. For logistical reasons, fueling took place at Stockholm airport only, where this aircraft was fuelled for both flight legs, to and from Copenhagen airport (Fig. 1).

Kerosene supply to Stockholm airport is realized from Gävle fuel terminal, where kerosene is supplied from a global range of refineries. From Gävle, the kerosene is transferred by train over a distance of about 140 km to a station nearby Stockholm and then supplied by a pipeline to the airport's fuel depot.

The low contrail kerosene was initially stored at Gävle's fuel depot in an individual tank. Usually, kerosene supplies from different tanks commingle in the supply lines for fueling the various train wagons. To avoid this, another outlet directly connected to the respective tank was used for filling a road tanker. This tanker served also as an intermediate storage, carrying the low contrail kerosene to the loading gantry, where it was transferred to another road tanker. Aviation kerosene handling standards require using filter / water separators to be installed at road / rail tank cars, marine vessels or entries into delivery pipelines which directly supply airport service tanks (Energy Institute 2024). With a filter capacity of more than 800 L, residual kerosene in a filter/water separator can substantially alter the properties of the kerosene transported. Hence, the road tankers were drained and cleaned prior to fueling them with low contrail kerosene. Upon arrival at Stockholm airport's fuel depot, the low contrail kerosene was transferred to a segregated refueller truck of Stockholm airport.

Fueling at Stockholm airport is usually performed by the airport's hydrant system. In principle, such systems constitute a closed-loop with hydrants at most aircraft parking positions. Fueling is performed here by dispenser trucks basically connecting the hydrant system with the aircraft's fueling coupling. In a hydrant system, kerosene is continuously circulated to prevent fuel degradation (Hromadka & Ciger, 2017). This inhibits the segregated supply of a particular kerosene blend volume to a specific aircraft. Accordingly, for the measurement campaign, refueling was performed by a refueller truck, equipped with a pump, couplings and filters suitable for an aircraft refueling fulfilling the given legal requirements. Prior to its use, the refueller truck was drained and cleaned to prevent commingling of the low contrail kerosene with former conventional (crude oil based) volumes.

With an approximate capacity of 8000 L, one trip of the refueller truck to the aircraft's position was usually sufficient to supply both flights (i.e., from Stockholm airport to Copenhagen airport and vice versa). Due to their tank volume, refueller trucks require more space than fuel dispensers. As a result, the aircraft was boarded at a remote stand instead of a contact stand during the demonstration flights. Remote stands are distant from the airport terminal and require the transportation of passengers by bus to and from the aircraft. Contact stands are in close proximity to the airport terminal, allowing passengers to board either via a boarding bridge or simply by walking. Additionally, the flights of the demonstration aircraft were scheduled with at least 40 min turnaround time to ensure sufficient time for fueling and boarding. To prevent commingling with residual kerosene in its tanks, the aircraft was defueled the night before the start of the measurement campaign and exclusively fuelled by low contrail kerosene for the entire duration of the measurement campaign.

2.1.2. Contrail climate forcing estimation

The contrail energy forcing of the demonstration flights is estimated using the contrail cirrus prediction model (CoCiP) (Schumann et al., 2012; Shapiro et al., 2023). This model simulates the life cycle of

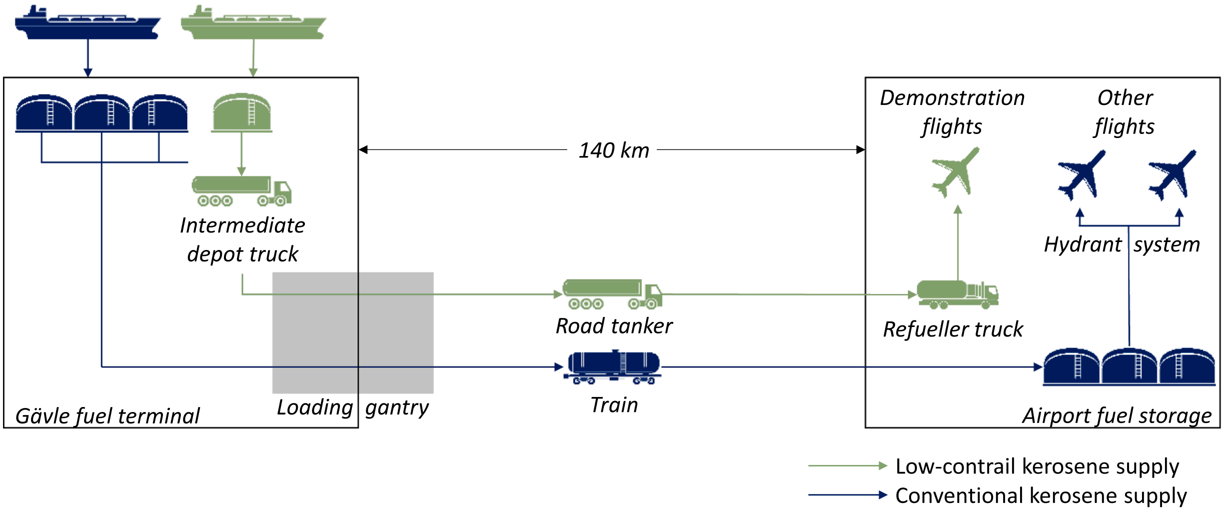

Fig. 1. Schematic overview of the kerosene supply to Stockholm airport.

contrail segments formed along individual flight trajectories and derives the resulting contrail radiative and energy forcing (Schumann, 2012) based on an ex-post weather dataset (Section 2.2). In the following, the basic principles of CoCiP are highlighted (R. Teoh et al., 2024; R. Teoh et al., 2022; Schumann, 2012; Teoh et al., 2020; Shapiro et al., 2023; Kaufmann et al., 2024; Teoh et al., 2022b).

When consecutive waypoints meet conditions for contrail formation (i.e., the Schmidt-Appleman criterion (Schmidt, 1941; Appleman, 1953; Schumann, 2012)) CoCiP assumes that contrails are formed. The soot emissions number being a main criterion for the contrail formation potential is derived from the ICAO's engine emissions database (EASA 2024) for a particular combination of a specific aircraft and its corresponding engine. The soot emissions are subsequently adjusted to the assumed average hydrogen content of the respective kerosene blend and the thrust setting (which is directly correlated with the fuel flow) estimated from aerodynamic data (Shapiro et al., 2023). The higher a fuel's average hydrogen content, the lower it's sooting tendency ceteris paribus. The hydrogen content within the kerosene is mainly influenced by the composition of the kerosene because various component groups are characterized by different average shares of hydrogen; e.g., aromatic compounds show a hydrogen content of typically < 10 m-%, while alkane compounds have a hydrogen content > 15 m-%.

The amount of soot particles (non volatile organic particles) emitted by the airplane's engine due to incomplete combustion serve as condensation nuclei for the formation of ice crystals. A lower limit for the soot emissions number is introduced at 10^{13} particles/$\mathrm{kg}_{\mathrm{fuel}}$ since also ambient aerosols and volatile organic particles emitted by the airplane's engine can serve as ice nuclei (Kärcher, 2018). The ambient temperature at flight attitude, the soot activation rate (T. Bräuer et al., 2021) and the fraction of ice particles surviving the wake vortex phase (Schumann, 2012) affect the initial number of ice crystals. A potentially enhanced activation of ultrafine aqueous particles at temperatures well below the formation threshold temperature (Kärcher, 2018) is not taken into account.

Contrail segments surviving the wake vortex phase are simulated with time steps of 30 min until they reach their end-of-life conditions defined as follows:

- The contrail ice crystal number decreases below the background ice nuclei concentration ($<10^3\ \mathrm{m}^{-3}$);
- The contrail's optical depth $\tau_{contrail}$ is less than 10^{-6}, or
- The lifetime surpasses a maximum of 24 h (Schumann, 2012).

Based on the contrail evolution, the local instantaneous contrail radiative forcing (RF') for each waypoint is calculated based on the change in radiative flux over the contrail area (R. Teoh et al., 2022). This change is affected by the outgoing longwave radiation at the top of the atmosphere and the effective albedo from the atmospheric weather model used (e.g., ECMWF reanalysis 5 (ERA5)) (Schumann, 2012). In this way, the presence of other clouds is taken into account. Subsequently, the contrail energy forcing is calculated by integrating the radiative forcing of each contrail segment (RF') multiplied by its length and width over the contrail segment's lifetime (Teoh et al., 2020, 2022a, 2022b; Schumann & Heymsfield, 2017). The humidity data of the ECMWF reanalysis 5 (ERA5) data scaling to in-situ measurements (Teoh et al., 2024b) is performed using the "exponential boost with latitude scaling" method (R. Teoh et al., 2024). Furthermore, radiative heating effects (i.e., the influence of radiative heating on the contrail plume and thus contrail lifetime) are taken into account (R. Teoh et al., 2024).

2.2. *Data*

The operational requirements for the segregated supply of low contrail kerosene (section 2.1.1) were gathered by expert interviews as first-hand information from partners involved in the measurement campaign. The general requirements for the segregated supply (section 3.1) were derived based on these interviews and publicly available information on aviation kerosene handling requirements (Energy Institute 2024).

The CoCiP model is used with the aviation's kerosene hydrogen content as free variable and further datasets about the flight trajectories, performance data such as kerosene consumption and weather data (e.g., relative humidity at the aircraft's altitude).

Five different kerosene options are assumed (Table 1). As described in section 2.1.2, the hydrogen content is used as proxy for the respective kerosene composition.

- "Conventional average" denotes a kerosene resembling an average hydrogen content, based on World Fuel Survey Data, summarizing kerosene samples taken until 2013 (Edwards, 2024).
- As the properties and composition of conventional (crude oil based) kerosene differ considerably, a second conventional kerosene option, "conventional low hydrogen" with a relative low hydrogen content is also included. It's hydrogen content corresponds to the conventional kerosene used during the ECLIF-2 flight measurement campaigns (Voigt et al., 2021; Bräuer et al., 2021b).

Table 1
Kerosene types compared against each other.

Name	Hydrogen content [m-%]	Description
"conventional low hydrogen"	13.8	First conventional (crude oil-based) kerosene assuming a comparatively high aromatics content / low hydrogen content. (R. Teoh et al., 2022; Voigt et al., 2021; Märkl et al., 2024; EASA 2024; Bräuer et al., 2021a, 2021b)
"conventional average"	14.10	Second conventional (crude oil-based) kerosene assuming an average aromatics content, based on data of (Edwards, 2024); an evaluation of kerosene certificates at Stockholm airport and Copenhagen airport indicates similar hydrogen contents for the conventional supplied at the time of the demonstration flights.
"blend uniform"	14.13	Kerosene blend based on 2 m-% neat synthetic kerosene and 98 m-% "conventional average" kerosene. 2 m-% corresponds to EU blending mandate in 2025. (EC, 2021)
"blend demo"	14.34	Kerosene blend used in the demonstration flights, hydrogen content measured from kerosene batch.
"blend max"	14.7	Kerosene blend based on 50 m-% neat synthetic kerosene and 50 m-% "conventional average" kerosene. This reflects the current upper blending limit of the ASTM specification. (ASTM, 2024b)

- A blend of 2 m-% synthetic kerosene, corresponding to the EU's blending mandate in 2025 is assumed for "blend uniform". It represents a case where the renewably-sourced kerosene is uniformly distributed among all flights departing at a particular airport.
- The kerosene used during the demonstration flights is "blend demo", its hydrogen content was measured using the ASTM D7171 method.
- To incorporate a kerosene blend at the blending limit of 50 m-%, "blend max" is introduced with an estimated hydrogen content of 14.7 m-%. This hydrogen content is based on a blend of "conventional average" (hydrogen content 14.1 m-%) and neat synthetic kerosene (hydrogen content 15.3 m-% (Voigt et al., 2021; Märkl et al., 2024; Zschocke et al., 2017, T. Bräuer et al., 2021)), but does not take into account the minimum aromatics content of 8 m-% for renewably-sourced kerosene blends.

Flight trajectories of the 84 demonstration flights between Stockholm airport and Copenhagen airport are based on Automatic Dependent Surveillance Broadcast (ADS-B) data from flightradar24 (Flightradar24 AB 2024). They contain temporal, latitudinal, longitudinal and flight altitude information subsequently resampled to a frequency of 1 min. Fig. 2 shows the corresponding flight trajectories.

Performance data are derived from the flight trajectories, using geodesic functions (e.g., to calculate a flight's groundspeed) and the Eurocontrol Base of Aircraft Data (BADA) version 4.2 (EUROCONTROL 2024) (e.g., to calculate a flight's kerosene consumption).

The demonstration aircraft is a relatively new aircraft and its LEAP1A-26 engines were designed with so-called "lean-burn" combustion chambers. This design is expected to substantially lower soot particle emissions (Bräunling, 2015). It is suspected that the emissions of those engines fall in the so-called "soot-poor regime" of $< 10^{13}$ particles/kg_{fuel}, whereas engines with previous designs emit in the so-called "soot-rich regime" ($> 10^{14}$ particles/kg_{fuel}) (Manneville, 2023). According to theory, within the "soot-poor regime" at ambient temperatures considerably below the Schmidt-Appleman temperature, the activation of ultrafine aqueous particles is enhanced (Kärcher, 2018). This would counterbalance the linear relationship between soot particle emissions and nucleated ice crystal numbers assumed in the contrail cirrus prediction model (CoCiP). Thus, the representation of the LEAP1A-26 engine in this model is highly uncertain. For this reason, the simulations were performed assuming a similar aircraft equipped with CFM56–5B4 engines (turbines), a predecessor of the LEAP1A-26 engine. For an average kerosene hydrogen content of 14.1 m-%, the CFM56–5B4 emit about $6.5\cdot 10^{14}$ particles/kg_{fuel} in the simulations for this study. In terms of ground handling and aerodynamical properties, both aircraft are almost identical and most likely also the operational efforts for their segregated supply with low contrail kerosene will be identical.

Weather data from the European Centre for Medium-Range Weather Forecast's fifth generation high-resolution reanalysis (ECWMF ERA5) are utilized (ECMWF 2024), featuring a $0.25^\circ \times 0.25^\circ$ horizontal resolution across 37 pressure levels, with a temporal resolution of 1 h. Meteorological conditions for flights between these pressure levels are interpolated from the two closest pressure levels. Recent studies reveal a slight underestimation of RHI in ERA5 data at cruise altitudes (Wang et al., 2024; Wolf et al., 2024), which needs to be corrected. Therefore the ERA5 humidity fields are adjusted to in-situ observations using an exponential scaling with latitude correction (Teoh et al., 2024b).

2.3. Model uncertainties

The primary goal of the experiment was to demonstrate the

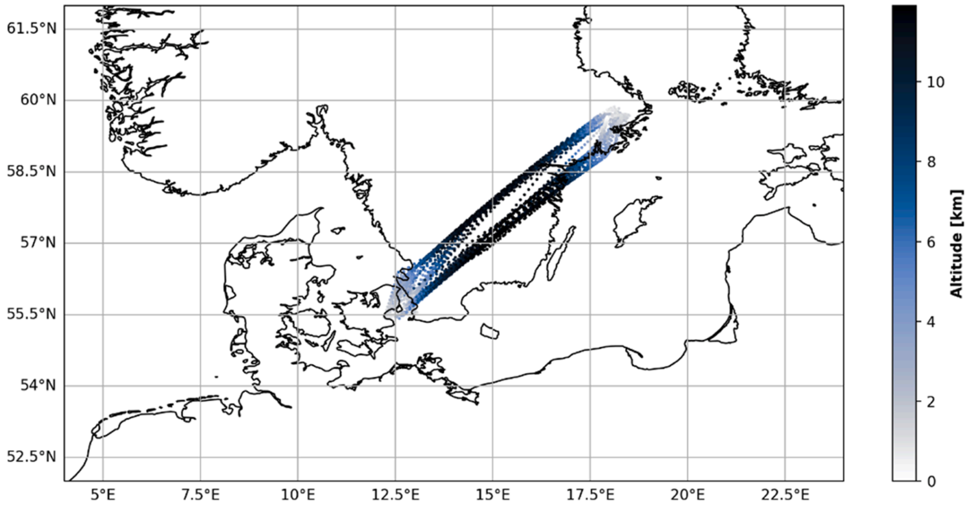

Fig. 2. Flight trajectories of the demonstration flights from 17th January 2023 until 2nd February 2023.

feasibility of the segregated use of SAF on airport level. For this reason, the number of flights evaluated here is small (84 flights) compared to other studies on contrail-related climate forcing. This small sample size motivates a detailed analysis of the uncertainties of the Contrail Cirrus Prediction (CoCiP) model to estimate (a) an individual flight's absolute contrail climate forcing and (b) the effect of differing kerosene compositions on the resulting relative change in contrail climate forcing.

2.3.1. Contrail climate forcing for an individual flight

Uncertainties of the contrail climate forcing estimations have been evaluated in a broad range of studies, e.g., by comparing model results with in-situ measurements or remote sensing data from ground- or space-based cameras (Schumann et al., 2017; Geraedts et al., 2024, Ng et al., 2024; Knollenberg, 1972; Heymsfield, 1975; Schumann & Graf, 2013; Gierens et al., 2020; Heymsfield et al., 1998). In one study, a sample size of about 250,000 flights was evaluated using satellite images of the contiguous US with an automated detection and matching algorithm for a timeframe from 04th April 2019 to 04th April 2020 (62). The algorithm matches flight trajectories from Automatic Dependent Surveillance Broadcast (ADS-B) data with linear-shaped, high-level ice clouds in the satellite image (Ng et al., 2024). The resulting data are compared to CoCiP model results for the same flight dataset using ECMWF's ERA5 meteorological dataset. In this way, each contrail predicted by CoCiP is compared to satellite images. For the investigated weather and contrail model resolution, the study finds, however, a rather low agreement between the contrails predicted by the weather-contrail model and the contrails detected by the satellite-based detection algorithm (62) (about 15 % of the contrails predicted by ERA5 / CoCiP matched a contrail found on a Geostationary Observational Enviromental Satellite (GOES) image and about 30 % of the contrails detected via satellite images matched a contrail predicted by ERA5 / CoCiP). However, it remains unclear, to which extent the detection algorithm for the satellite images or the weather model input or the contrail model lack resolution or accuracy. Thus, a binary (yes / no) predictability of an individual contrail remains challenging. In addition to the validation of the respective climate forcing of individual flights not considered here.

In-situ measurements of contrails have been conducted since 1972 (Knollenberg, 1972; Heymsfield, 1975; Heymsfield et al., 1998). A large comparison study including most in-situ measurements and many remote sensing data indicates a large variation for both, measurement and CoCiP contrail simulation data (Schumann et al., 2017). Contrail evolution from initial formation stages to lifetimes of almost 3 h and a variety of local contrail parameters are assessed (e.g., ice particle numbers, ice water content, optical thickness). In general, a good agreement of the micro- and macro-physical properties of the modeled contrails has been reported over the contrail's lifetime within the measurement range of the various observations (Schumann et al., 2017). The physical processes reflected in the model align with the measurement data, indicating that the CoCiP model reflects the behavior of these processes (Schumann et al., 2017). A similar, earlier study also highlights a generally good agreement between satellite observations and the contrail model CoCiP (Schumann & Graf, 2013).

The outgoing longwave radiation and reflected shortwave radiation used by CoCiP to calculate the radiative forcing of contrails has been compared to remote sensing retrievals by MSG and a general agreement has been found within the uncertainties during times of normal and reduced air traffic (e.g. the COVID pandemic) (Schumann & Heymsfield, 2017; Schumann et al., 2021a, 2021b; Voigt et al., 2022).

With respect to the weather model input, many simulations use ERA5 weather data as input for contrail simulations. While the ERA5 weather data set is more accurate than many other weather model predictions, recent studies have demonstrated a humidity bias in the ERA5 data set particularly for high humidity in cirrus regions at cruise altitudes (Gierens et al., 2020; Kaufmann et al., 2018; Li et al., 2023). Measurement data by the In-flight service Aircraft for a Global Observation System (IAGOS) were also used to evaluate uncertainties of the weather input to the contrail simulations (Gierens et al., 2020) and to develop correction functions for relative humidity (Wolf et al., 2024) or AI based optimizations (Wang et al., 2024) with specific correction functions used in CoCiP (Teoh et al., 2024b; R. Teoh et al., 2022). The general prediction quality of the integrated forecast system (IFS) of the ECMWF is supported by experiences in using the IFS based CoCiP simulations for planning of contrail measurement campaigns (Voigt et al., 2021; Märkl et al., 2024; T. Bräuer et al., 2021; Voigt et al., 2017; Voigt et al., 2010). Still, the persistence of contrails (and thus their overall life cycle) is subject to uncertainties often related to the representation of relative humidity and ice supersaturation in weather models (Wang et al., 2024; Gierens et al., 2020).

Concluding, estimating the absolute contrail energy forcing especially for individual flights is still subject to relevant uncertainties, to a large extent due to uncertainties of the model input data (e.g., weather data) as well as caused by uncertainties in the contrail cirrus micro- and macro-physical as well as radiative properties (Lee et al., 2021). For the relative change in contrail energy forcing, e.g., when comparing the contrail forcing of different kerosene options, weather and aircraft data are not varied and thus the uncertainties in weather and aircraft data are of minor importance. Instead, the effect of fuel composition in terms of aromatic and hydrogen content (R. Teoh et al., 2022) plays a role for the contrail properties and radiative effect.

2.3.2. Contrail climate impact for different kerosene compositions

The effect of different kerosene compositions on the resulting contrail climate forcing is reflected in CoCiP by using the kerosene's hydrogen content. The various chemical component groups contained within kerosene being mainly n- and isoalkanes, cycloalkanes and aromatic components vary characteristically in their hydrogen content (e.g., a typical hydrogen content of an alkane is ca. 15.3 m-%, of a cycloalkane about 14.3 m-% and of an aromatic component about 10.1 m-%) (Quante et al., 2024). Thus, using the hydrogen content of a kerosene can serve as a proxy for its composition related to the various chemical component groups. However, such an approach might underestimate the case when certain components (e.g., polyaromatic molecules) are over-proportionally responsible for a kerosene's sooting tendency.

Soot particle emissions are modelled by CoCiP using data from the ICAO Aircraft Emissions Database (EASA 2024), which provides soot particle emission values depending on the engine's thrust setting for 47 different engines (turbines), including the reference aircraft's engines. These data are based on engine manufacturer's reports during engine certification. While the emissions are calculated for changes in engine thrust settings, increasing soot particle emissions due to engine aging are not taken into account (EASA 2024). Subsequently, the emissions number is calculated for the respective kerosene hydrogen content with a thrust-setting dependent empirical relationship (R. Teoh et al., 2022; Schripp et al., 2022; Schripp et al., 2018; Brem et al., 2015; Schripp et al., 2021).

The number of initial ice crystals formed is modelled as a function of soot particle emissions, with a lower boundary of 10^{13} particles/kg_{fuel} considering the activation of organic volatile particles and ambient naturally occurring aerosols. Additionally, partial activation of soot particles for temperatures close to the Schmidt-Appleman threshold temperature is taken into account (Teoh et al., 2022b). These interrelations are based on data from in-situ measurements comparing renewably-sourced and conventional (crude oil based) kerosene (Voigt et al., 2021; Märkl et al., 2024; Dischl et al., 2024; Bräuer et al., 2021b; Kleine et al., 2018). The physical relations after initial ice crystals have been formed are independent of the kerosene used.

Overall, the effects of differing kerosene compositions are depicted at great detail in the model and largely based on measurement data, at least for the engine models studied in ground- and flight experiments (e.g., CFM56–5B4). For this reason, a well validated engine is used in the simulations (CFM56–5B4) instead of the comparatively new LEAP1A-26 engines used for the demonstration flights. The omission of engine aging affecting soot emissions most likely increases the overall uncertainty. Again, the primary interest here is the relative change of contrail climate forcing for different kerosene options within an identical set of flights and meteorological data. As a result, it can be assumed that the engine aging of these flights is identical and thus the associated uncertainty does not affect the relative mitigation potentials. Overall, the absolute contrail climate impact for a single flight has substantial uncertainties, but relative changes in contrail energy forcing for different fuels – which are the focus of this study – are calculated with reasonable certainty.

3. Results and discussion

This section qualitatively weights the operational efforts for a segregated kerosene supply with its potential climate benefits. First, operational efforts for targeting flights with the highest climate forcing and the general applicability of a targeted use concept are discussed (section 3.1). Then, the satellite detection of individual contrails is described (section 3.2) and associated potential contrail climate benefits are detailed for five different kerosene options (section 3.3).

3.1. Operational efforts

The segregated supply of low contrail kerosene requires modifications of the fuel supply infrastructure and alterations to the current fueling operations at airports. The respective efforts to realize a segregated fuel supply are discussed below based on the experiences made by conducting the demonstration flights. The implications derived from the demonstration flights are transferred to an approach where flights with the highest climate forcing (instead of flights for a particular route) would be targeted (section 3.1.1) and the general applicability of such a targeted use concept is discussed in terms of operational and economic efforts (section 3.1.2).

3.1.1. Targeting flights with the highest climate forcing

While the segregated supply of the measurement campaign aimed at flights for an individual aircraft flying a specific route (“segregated use”), the largest climate benefits from using low contrail kerosene could be achieved by targeting the flights with the highest contrail energy forcing first (“targeted use”). This approach would most likely require the fueling of various aircraft flying on different routes and thus might incur additional operational efforts.

First, a model to provide a list with the highest climate forcing flights to be targeted is required, in order to allocate the available volumes of low contrail kerosene to the respective individual flights. This would require the use of ex-ante weather data. Once the data on the most climate relevant flights are available, basically the requirements of the segregated use concept would apply. Presumably, several aircraft would need to be fuelled by refueller trucks at a remote stand and the segregated refueller trucks should be compatible to those aircraft types (e.g., in terms of fuel panel height).

The requirement to use refueller trucks creates further implications concerning space requirements for refueling and fueling times. In general, the fueling time is a crucial factor for airline operation, since airlines aim at minimizing the time on ground to save cost and increase an aircraft’s economic productivity (Belobaba, 2009). While a typical short- to medium-range aircraft like the demonstration aircraft has a tank capacity of about 21 t (Airbus 2024a), large long-range aircraft have a tank capacity of up to 250 t (Airbus 2024b). At an approximate capacity of 6.4 to 8 t, more than 30 trucks would be required for fueling such a long-range aircraft. Assuming a typical turnaround time of about 90 min (Belobaba, 2009), in the short-term it seems practically unfeasible to fuel long-range aircraft by refueller trucks in due time.

For short to medium range flights, in terms of the fuel supply system, no major obstacles would result when changing from the segregated supply of an individual route towards a targeted supply of the flights with the highest contrail energy forcing.

3.1.2. Applicability of a targeted use concept

Table 2 summarizes additional efforts for the demonstration flights (chapter 2.1.1), their rationale,to which extent they would be required in general and lists potential economic implications. The fuel supply systems of individual airports differ considerably; e.g., some are supplied by various means of transport from different refineries across the globe while others are more or less directly connected to a specific refinery (Zschocke et al., 2017). Thus, implications for a particular airport might differ to some extent from the general points described below.

Almost all of the additional efforts within the measurement campaign would also be required for the general application of a segregated supply for individual flights. This particularly holds for the segregated storage and supply lines at Gävle, the transport from Gävle to Stockholm airport, and also the use of segregated refueller trucks instead of the airport’s hydrant system.

Fuel supply standards advocate that only specification-compliant kerosene is delivered to an airport (Energy Institute 2024). Since this has historically always been one fuel type, supply lines from the land-side storage to an airport’s fuel storage will generally not be capable for a segregated supply of two different kerosene options; e.g., in the case of Stockholm airport a large portion of the transport is realized by tank wagon, which could physically segregate two different kerosene options, but the last part is realized by a pipeline where kerosene options would necessarily commingle. As a result, the construction of a second supply line would most likely be required to realize a segregated supply at most airports. Since 3 % of all flights are estimated to cause about 80

Table 2
Additional efforts during the measurement campaign, their rationale and general necessity as well as potential cost implications for a segregated supply with low contrail kerosene.

Additional Effort for demonstration flights	**Rationale**	Generally required for segregated supply	**Potential cost implication**
Segregated storage and supply lines at Gävle	Avoid commingling when transferring kerosene from tank to loading bridge	A segregated tank in any case, most likely also supply lines	+10 % land-side storage capacity
Transport from Gävle to Stockholm airport by road tanker	Segregated supply via pipeline to Stockholm airport’s fuel depot not feasible without construction of a second pipeline	Individual supply line from land-side fuel storage to air-side fuel storage	10 % of annual fuel consumption supplied by road tanker
Fueling by refueller trucks instead of hydrant system and dispenser	Enable segregated supply	Required, provided that airport has single hydrant system	Modification of supply lines, designated fleet of refueller trucks
Draining and cleaning of road tankers and refueller trucks	Avoid commingling with residual kerosene volumes	Required due to comparatively large filter capacity (>800 L)	No additional cost, due to designated fleet of low-contrail kerosene refueller trucks
Draining of demonstration aircraft	Avoid commingling with residual kerosene volumes	Required in case of large volumes of kerosene remaining on board	Assumed to be negligible
Aircraft fueling at remote stand	Provide sufficient space for refueller truck	Depending on available space at contact stands	Assumed to be negligible

% of the contrail climate forcing (R. Teoh et al., 2024), it is assumed that about 10 % (considering a safety margin) of the airport's fuel use would need to be provided by such an additional supply line. Presumably, these amounts are too small to justify the construction of a pipeline and would rather be transported by road tanker.

Typically, an airport's fuel storage contains several individual tanks. In principle, a subset of those tanks could be used for low contrail kerosene, provided that their supply lines allow the targeted supply of a kerosene batch to a specific tank and also supply of e.g., a refueller truck by a specific tank. Thus, at least the modification of supply lines at an airport's fuel storage would be required in general.

The closed-loop single line structure of most hydrant systems prevents the segregated supply of a particular kerosene to a specific flight via hydrant systems. In principle, a segregated supply of different kerosene types could be realized at airports where the hydrant system is composed of multiple supply lines. However, this is rarely the case (Hromadka & Ciger, 2017) and thus the use of a refueller truck is typically required. Presumably, a designated fleet of refueller trucks for low-contrail kerosene would be required to prevent commingling with conventional kerosene. At space-constrained airports, fueling at remote stands would be additionally required.

In principle, a hydrant system could be sequentially fuelled by different kerosene options (e.g., at day vs. at night or during different seasons). In this case, the segregated supply would be less specific; i.e., also flights without large contrail energy forcing would receive low contrail kerosene. The mitigation potential of such strategies is subject of ongoing studies (Woeldgen, 2023). Additionally, the restriction to refueller trucks would constrain the targeted use concept to short and medium range aircraft (chapter 3.1.1).

Some other additional efforts of the demonstration flights might not be strictly necessary for a general application of a segregated low contrail kerosene supply, but rather prevent commingling with smaller volumes of conventional (crude oil based) kerosene. This mainly relates to draining and cleaning of the road tanker, the refueller trucks and the demonstration aircraft itself. Provided that the remaining kerosene volume in each of them is small compared to the new load of low contrail kerosene, a certain extent of commingling with conventional (crude oil based) kerosene might be acceptable. Most likely, this would come at the cost of a slightly reduced kerosene hydrogen content and thus reduced climate benefits.

As a result, the economic implications for a segregated fuel supply are comprised of adding 10 % additional fuel storage at the airport's land-side, additionally supplying 10 % of the airport's fuel consumption by road tanker and procurement and operation of a dedicated fleet of refueller trucks. Since such infrastructure is usually commonly owned by the airport and fuel suppliers (at least for most European airports) (Buse, 2024), these changes would most likely increase the handling fees charged by the airports. Typically, such fees amount to less than 5 % of an airline's cost (Belobaba, 2009). As a result, the segregated supply with low-contrail kerosene would most likely increase cost from an airline perspective by less than a few %-points. This increase seems rather small compared to current estimates for mitigating carbon dioxide-related climate impacts either by using renewably sourced kerosene (Quante et al., 2023; U. Neuling & Kaltschmitt, 2018; Jong et al., 2015) or liquefied hydrogen (Hoelzen et al., 2022a, 2022b). However, a comprehensive economic analysis would be required for a sound comparison among the marginal abatement cost for reducing contrail-related climate impacts by a segregated fuel supply and the marginal abatement cost for reducing carbon dioxide-related climate impacts by renewably sourced kerosene or hydrogen. Such an investigation – while being beyond the scope of this study – is clearly an interesting area for further research. The implementation of a targeted use of low-contrail kerosene could be stipulated by economic incentives. As of now, only the carbon dioxide-related climate impact of aviation is considered in most mitigation policies (Quante and Voigt, 2024), the European Union presently introduces a monitoring, reporting and verification scheme for aviation's non carbon dioxide-related climate impacts by 2025 (Niklaß et al., 2019). Assuming that future mitigation policies will also aim at aviation's contrail-related climate impact and a broadly accepted methodology to determine the contrail climate forcing of individual flights will be implemented, also different economic approaches such as the inclusion in emissions trading schemes, subsidies or penalties for contrail-related climate impacts could be developed.

3.2. Satellite detection of individual contrails

For this study, the evolution of all 28 contrails simulated by CoCiP (out of 84 demonstration flights) were visually assessed and tracked during their evolution with corresponding images of the second generation EUMETSAT satellite. To investigate the uncertainty in the ERA5 weather data input (mainly humidity and 3-dimensional wind velocities at cruise) the "Volcanic Ash RGB" color scheme (EUMETSAT. EUMETSAT User Portal 2024; Piontek et al., 2021a, 2021b) was applied. Most of the contrails on the satellite images ($n = 21$) were at least partially covered by other clouds, impeding a visual detection of the potential contrails. The remaining contrails ($n = 7$) are too few for a detailed statistical analysis. Thus, a thorough validation of contrail mitigation strategies by satellite data would require substantially larger sample sizes and ideally also a multi-seasonal timespan. Such studies are part of current research projects (e.g., D-KULT) Deutscher Wetterdienst, 2024). Video files of all demonstration flights are available in the digital supplement (Fig. 3).

3.3. Contrail climate benefits

Fig. 4 shows the resulting contrail energy forcing assuming the kerosene options described in section 2.3.2. The energy forcing of warming contrails is indicated by positive values (light orange) and cooling contrails are depicted as negative value (light blue). The net energy forcing (black) is clearly positive and decreases by increasing kerosene hydrogen content. In comparison to "conventional average", the contrail energy forcing of "conventional low hydrogen" increases by almost 13 m-%. The 2 m-% blend of "blend uniform" alters the contrail energy forcing only marginally (less than 2 -%), while the 35 m-% blend labelled "blend demo" (Table 1) and the 50 m-% blend named "blend max" (Table 1) lowers the energy forcing by about 10 % and 23 %, respectively.

The comparison of the two conventional (crude oil based) options highlights the uncertainty resulting from the conventional kerosene

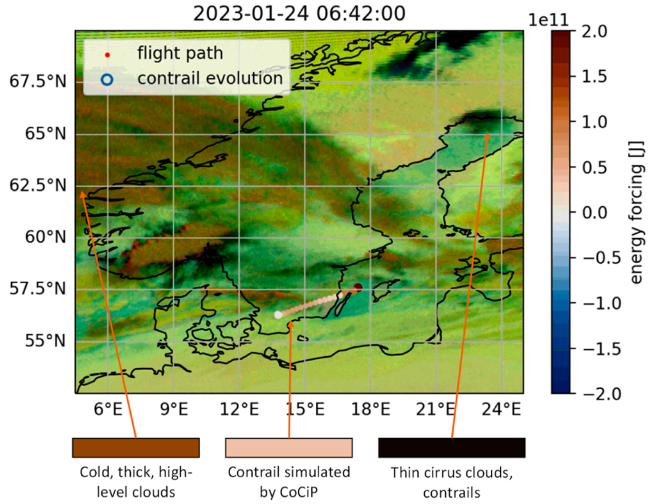

Fig. 3. Contrail simulated by CoCiP and corresponding Volcanic Ash RGB image from EUMETSAT 2G satellite images for 24th January 06:42 UTC (all demonstration flights are available as videos via the digital supplement).

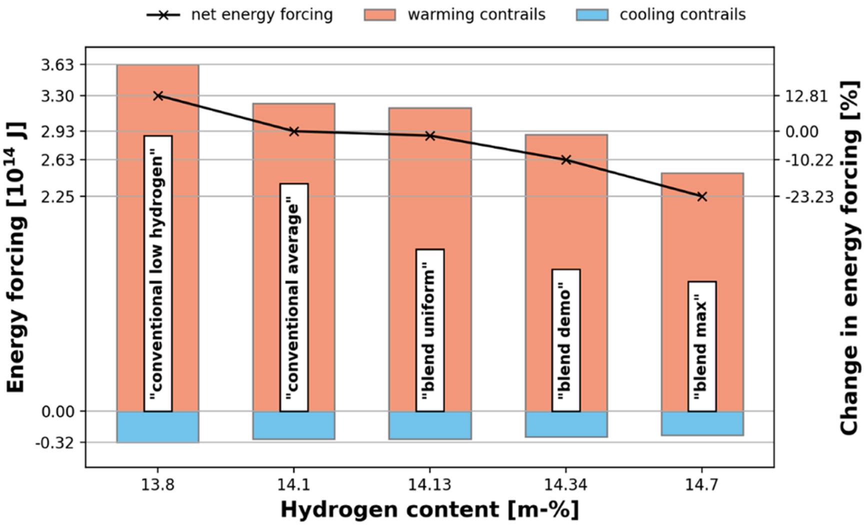

Fig. 4. Contrail energy forcing of the simulated flights ($n = 84$) in absolute terms (left ordinate) and relative change (right ordinate) compared to the "conventional average" kerosene (Table 1).

composition being here in the order of magnitude of 10 %. As a result, the difference between "conventional average" and "blend uniform" (Table 1) can hardly be considered significant. Despite the large effect of the conventional kerosene's hydrogen content, only very limited data is publicly available (Edwards, 2024). Measuring or estimating the hydrogen content of the kerosene used for individual flights would substantially improve the estimation of their contrail energy forcing.

Overall, for the aircraft-engine combination used in these simulations, the segregated use of low contrail kerosene reduced the associated contrail energy forcing by more than 10 %, compared to the "conventional average" kerosene (Table 1). This is broadly in line with previous mitigation potential estimates for this hydrogen content (Quante et al., 2024). For the theoretically maximum blend share of 50 m-%, the mitigation potential would increase to about 20 %. These values are roughly in accordance with other investigations (Quante et al., 2024). Simultaneously, kerosene specifications require certain amounts of aromatic molecules in a low contrail kerosene blend, while renewably-sourced kerosene typically do not contain any aromatic compounds. Hence, the conventional kerosene for such blends would require a comparatively high amount of aromatics (Zschocke et al., 2017). This effect might in turn slightly reduce the mitigation potential of the 50 m-% blend.

In absolute terms, warming contrails largely outweigh cooling contrails for any of the fuels investigated. This can be explained by daily and seasonal variation. In theory, during daytime contrails typically exhibit a cooling climate forcing by reflecting incoming shortwave (solar) radiation to a larger degree than they absorb outgoing longwave (terrestrial) heat radiation. At night a contrail only absorbs outgoing longwave radiation and thus causes warming climate forcing. Despite that, most demonstration flights take place between 06:00 am and 22:00 pm local time. Therefore, the fraction of cooling contrails has been small (cf. Fig. 4). At Stockholm airport the difference between sunrise and sunset is only about 7.5 h in January, which is more than 10 h less than on 21st June. Since the demonstration flights took place in January and February, most likely their contrail climate forcing was substantially higher compared to a situation if they would have been realized in June or July. This effect will be less pronounced for regions at lower latitude, since the seasonal variation of sunrise and sunset times is lower for lower latitudes.

4. Conclusion

The targeted use of low contrail kerosene on particularly climate relevant flights has previously been discussed in various, simulation-based studies. This investigation derives the operational efforts for such a concept based on the segregated supply of low contrail kerosene to 84 flights between Stockholm airport and Copenhagen airport. The operational efforts are weighted against a simulation-based estimate of the demonstration flights' contrail climate benefits, assuming an experimentally validated aircraft-engine combination. Beyond the operational efforts for supplying the demonstration flights, implications for targeting flights based on their climate forcing are derived and a targeted use at large-scale is discussed.

The main results can be summarized as follows.

- For the current infrastructure, a segregated supply of low contrail kerosene can be realized for short to medium range flights, or in other terms any flight which can be fuelled by refueller trucks at an outside position. To realize such a concept, large parts of the supply chain (e.g., supply lines to and at airports) would need to be duplicated, incurring additional efforts and of course further costs. Targeting long-range flights with low-contrail kerosene would most likely require a multiple line hydrant fueling system at airports, which would need to be constructed at most airports and thus incur additional cost and be available in the medium to long term only.
- A segregated supply of e.g., a particular flight route (as employed during the demonstration flights) and targeting flights with highest contrail energy forcing first are almost identical in terms of operational efforts. Primarily, it might be necessary to allocate several remote stands for a targeted use concept (instead of one). The general applicability of a targeted use concept, however, is highly airport specific; nevertheless, it is most likely that in most cases large sections of the kerosene supply infrastructure would need to be duplicated and / or an additional other fuel supply system would need to be installed.
- In terms of contrail climate benefits, the segregated supply of low contrail kerosene reduces the contrail energy forcing for the aircraft-engine combination with the 35 % blend assumed here by about 11 %. A higher blend share could increase these benefits towards a reduction of more than 20 %, specifically targeting flights with the highest contrail energy forcing could allow for even greater contrail climate benefits (R. Teoh et al., 2022). Additionally, the mitigation potentials for flights conducted at other latitudes will be altered by a different ratio of day- and night-time for different seasons.
- The coarse estimation of the cost implications for a segregated fuel supply indicates a cost increase due to the abovementioned

infrastructure modifications. These cost seem to be smaller than the marginal abatement cost of e.g., renewably sourced kerosene or the direct use of hydrogen. For the development of incentive schemes to facilitate a targeted low-contrail kerosene supply, several pre-requisites exist, such as the inclusion of aviation's contrail-related climate impacts in mitigation targets or an accepted and validated approach to determine the contrail climate forcing of an individual flight.

Estimating the absolute contrail energy forcing of individual flights is still strongly affected by the available input data (e.g., meteorological data), but these uncertainties do not affect the relative changes given here. Uncertainties in fuel composition data increase towards the highest hydrogen content fuels. Further uncertainties exist for new engine (turbine) models (e.g., lean-burn combustors), when ice activation on soot particles might be replaced by other processes. When comparing the use of different kerosene options for an identical set of flights, the meteorological uncertainties do not play a role for the relative changes in contrail forcing. As a result, the relative contrail benefits are subject to smaller uncertainties than the absolute values of the demonstration flights contrail energy forcing.

The study of those uncertainties highlights important areas of further research: Increasing the accuracy of atmospheric weather data at aircraft cruise altitude (especially humidity data) would allow for more reliable estimations of contrail evolution and associated contrail energy forcing. Also, more detailed information about kerosene properties (e.g., by using sensors during refueling) would improve the reliability of current models. The same holds for experimental data about modern engines and the implementation of engine aging in current contrail climate impact models.

Solutions for the infrastructure modifications are technologically and organizationally available. The primary barrier are the efforts and thus the costs for their implementation. Considering that several companies are aiming to develop a hydrogen fueled aircraft within the next decade (Quante et al., 2023; Airbus. ZEROe 2024), cost due to infrastructure modifications for a targeted use concept appear comparatively small. Estimating the investment and operational costs of the discussed efforts would be an important step towards calculating the marginal abatement cost of a targeted use concept and thus to compare it against other mitigation strategies, which is partially envisioned as future work of the ALIGHT research project (Quante et al., 2023; Airbus. ZEROe 2024)

Overall, by conducting the demonstration flights, a segregated supply of low contrail kerosene was successfully demonstrated in an experimental setting. Contrail climate benefits were quantified based on simulations. An insightful next step would be to compare the weighting between operational efforts and contrail climate benefits described here against other climate mitigation options for aviation.

Data availability

Data can be made available by the corresponding author upon request.

CRediT authorship contribution statement

Gunnar Quante: Writing – original draft, Methodology, Investigation, Conceptualization. **Benedict Enderle:** Writing – review & editing, Methodology, Investigation. **Peter Laybourn:** Investigation. **Peter W. Holm:** Investigation. **Lars W. Andersen:** Investigation. **Christiane Voigt:** Writing – review & editing, Supervision, Methodology. **Martin Kaltschmitt:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Gunnar Quante reports financial support was provided by EU Horizon 2020 research and innovation program under grant agreement No 957,824. Peter Laybourn reports a relationship with Brændstoflageret Københavns Lufthavn (BKL) that includes: employment. Peter W. Holm reports a relationship with Københavns Lufthavn (BKL) that includes: employment. Lars W. Andersen reports a relationship with Scandinavian Airlines (SAS) that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jatrs.2024.100049.

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