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Targeted use of paraffinic kerosene: Potentials and implications

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ABSTRACT

Aviation contributes to anthropogenic climate change mainly by contrails, CO_2 and NO_x emissions, whereof contrails are considered the largest single contributor to the radiative forcing from aviation. Powering aircraft with kerosene containing fewer or no-aromatics, i.e., “Sustainable Aviation Fuels” (SAF) or hydroprocessed, fossil-based kerosene, can significantly reduce contrail climate forcing. However, such kerosene is currently scarcely available. Moreover, less than 10 % of the flights worldwide cause more than 80 % of the contrail climate forcing. Hence, this study investigates a targeted allocation of paraffinic, i.e., aromatics-free kerosene to flights and flight segments with the highest contrail climate forcing, by calculating the resulting contrail energy forcing (in J) on 844 364 flight trajectories worldwide departing from five large European airports in 2019.

The contrail radiative forcing integrated over contrail evolution (i.e., contrail energy forcing [J]) is simulated for a reference fleet powered with conventional kerosene of 14.1 m - % hydrogen content. 5 % of overall kerosene demand assumed to be paraffinic kerosene with 15.3 m - % hydrogen content is allocated via a uniform, a flight-specific and a segment-specific approach. The uniform allocation assumes that all flights receive the same blend of 5 % paraffinic kerosene. The other cases target 100 % paraffinic kerosene either to flights or segments with highest contrail energy forcing. Compared to the reference, the results indicate a reduction on contrail energy forcing by 4 %, 36 % and 55 %, respectively. For market shares of paraffinic kerosene up to 30 %, a segment specific allocation appears advantageous compared to a flight specific allocation. However, they might require airport and aircraft modifications. Uncertainties in contrail climate benefits can be reduced by providing additional information on kerosene properties and accurate meteorological data. Overall, this study highlights robust potentials of paraffinic kerosene to significantly reduce the climate forcing from aviation.

1. Introduction

The air transport sector contributes with 3.5–4 % to global anthropogenic climate forcing [1]. The release of greenhouse gases (GHG), mainly CO_2, and several other emission effects (“non-CO_2“ effects) are the primary causes of air transport’s climate impact. While CO_2 presently accounts for roughly one third of aviation’s effective radiative forcing (ERF) (Lee et al., 2021, 2009), the other two thirds are comprised of contrail effects, indirect effects of NO_x emissions, and direct and indirect aerosol effects (in decreasing order of magnitude) (Lee et al., 2021). The effective radiative forcing (ERF) of contrails has been estimated as 58 mW per m^2 (variation: 17–98 mW per m^2) corresponding to about 57 % of the overall aviation-related ERF until 2018 (Lee et al., 2021, 2009).

Historic air traffic volume growth rates have been around 3–4 % per year. After a disruption by the COVID-19 pandemic (Schumann et al., 2021a; Voigt et al., 2022), growth rates currently return to pre-pandemic levels (IATA, 2023; ICAO, 2024). Simultaneously, passenger/freight-specific fuel consumption has been reduced by about 1.3 % per year due to numerous technical and organisational measures (Grewe et al., 2021). Thus, as long as growth rates remain higher than fuel efficiency improvements, aviation kerosene consumption on a global scale and as a result also the climate impact of air transport will increase. Based on these assumptions, it is expected that the global air transport system’s CO_2 emissions might more than double within the next 20 years to values clearly above 2 Gt of CO_2 in the year 2050 (Grewe et al., 2021). Since non-CO_2 effects are an indirect result of fuel combustion, it is also most likely that they also increase in the future; however, it is expected that they increase slightly slower due to the different lifetimes of both effects (Grewe et al., 2021). Accordingly, an

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effective reduction of both, CO_2 and non-CO_2 effects, is required to swiftly reduce the overall climate impact of the global air transport sector.

The use of kerosene with a reduced aromatics content may provide an option to lower the climate impacts of contrail formation (Burkhardt et al., 2018; Teoh et al., 2022a; Bräuer et al., 2021a; Voigt et al., 2021; Gierens et al., 2024.). However, such fuels are currently available at small volumes (Quante et al., 2023). Bearing in mind that a few (2–10 %) of all flights account for the majority of the contrail energy forcing (Teoh et al., 2020a; Teoh et al., 2020b; Teoh et al., 2022b; Teoh et al., 2023a; Ng et al., 2023; Geraedts et al., 2023), it seems promising to allocate currently small amounts of such kerosene to the flights or segments producing those contrails. Thus, this study aims to analyze the targeted use of paraffinic kerosene. Paraffins are saturated, acyclic hydrocarbons (Latscha, 2016) and therefore paraffinic kerosene refers to kerosene free of aromatics and cycloalkanes.

Four different allocation cases are investigated; i.e., the contrail climate forcing of allocating a given market share of paraffinic kerosene uniformly, for individual flights and for segments of flights is compared to a base case where only conventional kerosene is used. Flight trajectories of departing flights from the years 2017–2019 of the five largest European airports (by passenger number) are considered.

Contrails form when water vapor emitted by fuel combustion condensates on aerosol particles and subsequently freezes into ice crystals due to the low temperatures at typical flight levels. Depending on temperature and humidity of the surrounding atmosphere, contrails can be short lived, but in ice supersaturated air they can also persist for several hours (Vázquez-Navarro et al., 2015; Schumann et al., 2017). Persistent contrails can spread over large areas, potentially lose their linear shape and develop into so-called contrail cirrus (Schumann et al., 2017; Wang et al., 2023). Finally, the ice crystals of the contrail (cirrus) sublimate, e.g., caused by sedimentation into warmer and dryer air masses/atmospheric layers.

Aerosol particles originate from the combustion of kerosene and from the surrounding air (Teoh et al., 2022a; Kärcher, 2018; Märkl et al., 2023). Aircraft engines with differing combustor designs, e.g., shifting from presently used "Rich-Quench-Lean" (RQL) combustion chambers to "Twin Annular Premixing Swirler" (TAPS) lean burn combustors can reduce soot particle emission numbers by several orders of magnitude (Teoh et al., 2022a; EASA, 2017; Lee et al., 2023). The majority of engines presently used in commercial aviation typically operate in the so-called soot-rich regime (10^{14} to 10^{16} particles per kg_{fuel}), while a few new engines equipped with lean-burn combustors emit substantially fewer particles ("soot-poor" regime, $<10^{13}$ particles per kg_{fuel}). In the soot-rich regime, ice nucleation on soot particles from fuel combustion is the dominant process, while for the soot-poor regime, ice nucleation on volatile particles emitted by the engine or on aerosols of the ambient air become the dominant cause for ice nucleation (Kärcher, 2018).

The use of aviation kerosene with a reduced sooting tendency could also reduce particle emission numbers. The use of neat renewably-sourced kerosene has been found to reduce soot particle emission numbers by up to 60 % compared against neat conventional kerosene (Märkl et al., 2023; Schripp et al., 2022). Soot forming aviation kerosene components are poly- and mono-cyclic aromatics, cyclo-, iso- and n-alkanes (by decreasing order of magnitude) (Schripp et al., 2018, 2022). The hydrogen content of these components decreases in the same order. Therefore, the average hydrogen content of a kerosene is often used as proxy for its sooting tendency (Teoh et al., 2022a; Märkl et al., 2023; Schripp et al., 2022; Quante et al., 2024). Additionally, the fuel sulfur content is another cause for soot particle activation (Voigt et al., 2021; Märkl et al., 2023; Moore et al., 2015; Miake-Lye et al., 1998; Schumann et al., 2002; Petzold et al., 2005). Fuel lubricant oil is considered a further source of contrail-ice nucleation (Ponsonby et al., 2024). For modern jet turbines with soot emissions in the low-soot regime, these effects might gain importance for contrail formation (Märkl et al., 2023). In addition to using neat renewably-sourced kerosene as paraffinic kerosene, hydroprocessing of crude oil-based kerosene allows to (partially) transform aromatic components to alkanes. This provides a technical option to adjust the composition of kerosene to reduce the sooting tendency of fossil-based kerosene.

Reducing soot emission numbers leads to the formation of fewer but larger initial ice crystals (Voigt et al., 2021). Due to the reduced particle number, the optical thickness and thus the resulting contrail climate forcing is reduced (Burkhardt et al., 2018; Teoh et al., 2022a; Schumann, 2012; Bier and Burkhardt, 2022). Due to the increased ice crystal weight, ice crystals sediment faster into warmer and/or drier air layers (Kärcher, 2018). This results in faster sublimation, a shorter contrail lifetime, and hence also a reduced climate forcing (Burkhardt et al., 2018; Teoh et al., 2022a; Schumann, 2012; Bier and Burkhardt, 2022).

The climate impact of contrails is distributed strongly heterogeneously among flights; about 3 % of all flights globally within a year (or 11 % of the contrail-forming flights) accounted for 80 % of the global contrail energy forcing in 2019 (Teoh et al., 2023a). While the net climate impact of contrails is positive (i.e., warming), the climate impact of individual contrails varies by several orders of magnitude. During the night contrails have a warming climate impact, but during the day contrails can also have a cooling impact due to the reflection of solar radiation and less solar energy input at the surface. (Teoh et al., 2023a, 2024a; Wang et al., 2023).

More than 99 % of the global kerosene supply is presently produced from fossil fuel sources (i.e., crude oil). Roughly 310 Mt per year of such conventional kerosene are consumed. Compared to that, the production volumes of renewably sourced kerosene[1] are estimated at around 200 kt per year, i.e. more than three orders of magnitude smaller compared to conventional kerosene (IEA, 2022; WEF and CST, 2020). Most studies indicate significant market shares of renewably sourced kerosene (>10 %) not before 2030 (IEA, 2021; Staples et al., 2018; Kieckhäfer et al., 2018). Simultaneously, hydroprocessing of conventional kerosene to increase the content of acyclic alkanes (i.e. paraffins) is technically possible but not realized on a large scale. In this study, 5 % of overall kerosene demand are assumed to be available as paraffinic kerosene at all aiports considered.

This work adds to the previous analysis by Teoh et al. by additionally evaluating a segment specific allocation (Teoh et al., 2022a). The study by Woeldgen et al. focusses on allocation strategies which avoid large infrastructure modifications, e.g., by allocating kerosene based on season or time of the day (Woeldgen, 2023). The allocation cases in this study would require infrastructure and in the case of the segment specific allocation even aircraft modifications. Thus, both studies complement each other indicating a broad range of options for the targeted use of paraffinic kerosene.

The remainder of this study is structured as follows: Section 2 details methods and data used for both fuel options, their allocation cases and the contrail cirrus prediction (CoCiP) model to estimate the different climate impacts. In section 3, the climate impact reduction potential is analyzed and discussed for increasing market shares of paraffinic kerosene, changes in the weather data used for fuel allocation and influential factors for a flight's contrail climate forcing. Finally, the results are summarized and discussed.

2. Methods and data

This study evaluates the targeted use of paraffinic kerosene via different allocation strategies (Fig. 1). The main criterion for the assessment is the relative change in contrail energy forcing compared to the exclusive use of conventional kerosene ("base case"). The contrail

[1] Colloquially, such fuels are often referred to as "Sustainable Aviation Fuel" (SAF). However, this term is not used here, because renewable origin does not guarantee compliance with other sustainability aspects (e.g., biodiversity or social criteria).

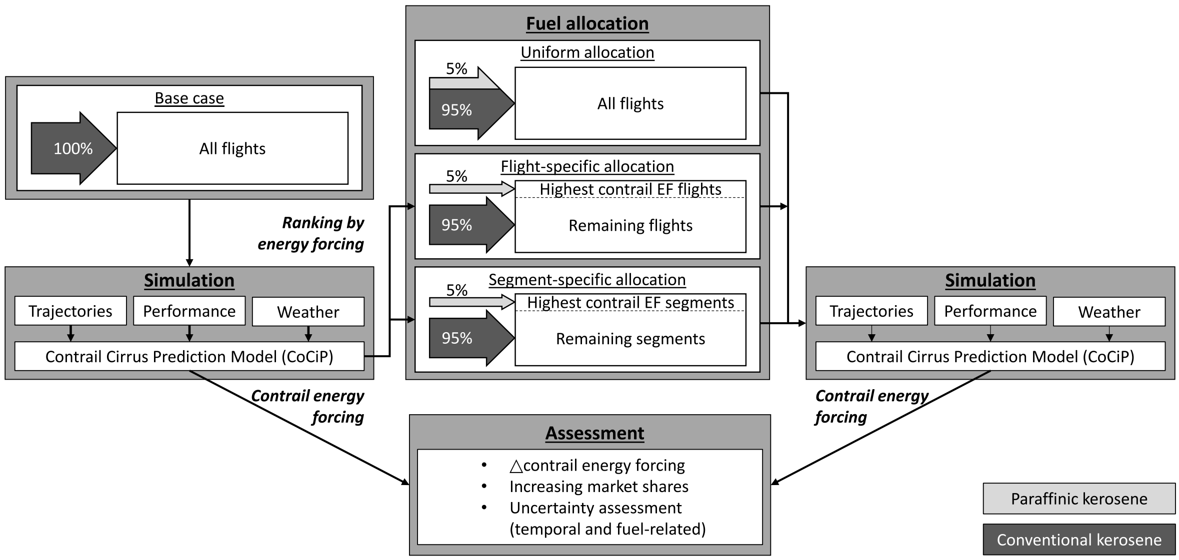

Fig. 1. Methodological approach: For each of the allocation cases (uniform allocation, flight specific allocation, segment specific allocation) the contrail energy forcing is calculated and its relative change compared to the base case is used for the assessments (**EF** energy forcing).

energy forcing is chosen as a metric to assess the climate impacts of each allocation case (Teoh et al., 2020a, 2022a). It is defined as the amount of energy added to the earth-atmosphere system, calculated as the instantaneous radiative forcing of contrails integrated over their individual lifetime (section 2.1.2). The different cases are simulated using the Contrail Cirrus Prediction model (CoCiP) (Shapiro et al., 2023).

2.1. Methods

2.1.1. Allocation cases

Paraffinic kerosene is allocated in three different ways being

- a uniform,
- a flight specific and
- a segment specific

allocation case. Fuel allocation is based on the results of a base case simulation, assuming the exclusive use of conventional kerosene. The amount of paraffinic kerosene available equals the fuel consumption of the flights in the dataset multiplied by an assumed market share of 5 %, corresponding to about 200 kt for the entire year 2019 and the flights selected (cf. 2.2.1).

The **base case** constitutes of an initial simulation where only conventional kerosene is used. The resulting contrail energy forcing is used as reference for the mitigation potentials of each allocation cases. The results from this simulation are used to derive the ranking of flights and segments for the flight and segment specific allocation cases.

The **uniform allocation** case distributes the paraffinic kerosene uniformly among all flights considered. It corresponds to a situation, where each flight receives a conventional/paraffinic kerosene blend with a blend share of 5 %.

The **flight specific allocation** distributes the paraffinic kerosene available on a flight by flight basis. Individual flights are prioritized on a daily basis by their overall contrail energy forcing; the flight with the highest overall contrail energy forcing receives paraffinic kerosene first until the remaining paraffinic kerosene is insufficient to cover the fuel consumption of the next flight. The remaining paraffinic kerosene is discarded from the analysis. In reality, this remainder would rather be blended with conventional kerosene to fuel the remaining flight(s) or added to the next day's paraffinic kerosene volume. However, discarded amount is small (on average < 1.7 % of all paraffinic kerosene) and thus the error induced by omitting these options is negligibly small compared to other uncertainties (cf. 3.1.3.).

Currently, large international airports typically supply fuel from their fuel storage towards individual aircraft via a pressurized hydrant system. Special vehicles provide a tube connection between the underground hydrant system at the aircraft's parking positionand the aircraft tank inlets. Typically, the system's main pipeline constitutes a closed loop around the terminal, allowing to circulate the fuel within the system to prevent fuel degradation due to aging (Hromadka and Ciger, 2017). Such a circular system impedes the targeted supply of various fuel types to specific aircraft. Accordingly, targeting a certain share of flights with paraffinic kerosene would require additional infrastructure to store and supply two different fuel types.

For the **segment specific** allocation, flight trajectories are split into segments of three categories, namely segments causing warming contrails, segments without contrail formation and segments causing cooling contrails. Segments are prioritized based on their contrail energy forcing. Since typically only a fraction of each flight causes a contrail, for the segment specific allocation less paraffinic kerosene is required to provide fuel for all warming contrails than in the flight specific allocation.

In this case, a real-world application would not only require additional infrastructure at airports, but also aircraft modifications. These could be the addition of a monitoring system for contrail formation and a control system for in-flight fuel switching, among others. Despite the fact that most commercial aircraft have several fuel tanks and a switching between different tanks during a flight has been demonstrated in flight experiments (Voigt et al., 2021; Märkl et al., 2023), it is not yet clear to which extent this can be realized during regular airline operations (IEA, 2021).

2.1.2. Contrail cirrus prediction (CoCiP) model

The contrail climate forcing of all flights and segments in the dataset is estimated using the contrail cirrus prediction model (CoCiP) (Shapiro et al., 2023; Schumann et al., 2012). The life cycle of contrail segments formed along individual flight trajectories is simulated and used to estimate the resulting contrail radiative and energy forcing (Schumann, 2012). Since CoCiP is well documented (Teoh et al., 2020a, 2022a, 2022b, 2023a; Schumann, 2012; Shapiro et al., 2023), only the basic principles and the particularities of this study are outlined below.

When consecutive waypoints meet conditions for contrail formation, i.e., the Schmidt-Appleman criterion (Schumann, 2012; Appleman, 1953; Schmidt, 1941), contrail formation is assumed in CoCiP. The soot emissions number of the respective engine-airplane combination determines the initial number of formed ice crystals within the contrail. However, a lower limit of 10^{13} particles per kg_{fuel} is introduced to consider ambient aerosols and organic particles as ice nuclei (Kärcher, 2018). Additionally, the ambient temperature affects the initial number of ice crystals, as well as the soot activation rate (Bräuer et al., 2021b) and the fraction of ice particles which survive the wake vortex phase (Schumann, 2012). The simulations do not account for changes in fuel sulfur content. However, a decreasing fuel sulfur content could potentially lower the ice nucleation efficiency of soot particles (Voigt et al., 2021; Märkl et al., 2023; Moore et al., 2015; Miake-Lye et al., 1998; Schumann et al., 2002; Petzold et al., 2005).

Contrail segments enduring the wake vortex phase are simulated in the model using time steps of 30 min until they reach their end-of-life conditions; i.e., the contrail ice crystal number decreases below the background ice nuclei concentration ($<10^3$ 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). The CoCiP model calculates the local instantaneous contrail radiative forcing (RF') for each waypoint representing the change in radiative flux over the contrail area (Teoh et al., 2022a). The contrail energy forcing is calculated as the product of the contrail segment RF', length, and width integrated over the contrail segment's lifetime (Teoh et al., 2020a, 2022b; Schumann and Heymsfield, 2017). The default settings of the CoCiP model are applied with two exceptions. On the one hand, the humidity data of the ECMWF, 2024 reanalysis 5 (ERA5) data scaling to in-situ measurements (Teoh et al., 2023b) is performed using the "exponential boost with latitude scaling" method (Teoh et al., 2023a) (cf. Supporting Info). On the other, radiative heating effects, i.e., the influence of radiative heating on the contrail plume and thus contrail lifetime are taken into account (Teoh et al., 2023a). A comparison of this CoCiP configuration with previous studies can be found in the Supporting Info of Quante et al. (Quante et al., 2024).

2.1.3. Assessment

First, the contrail energy forcing for each allocation case is compared to the base case, where no paraffinic kerosene is used. Then, increasing market shares of paraffinic kerosene are studied and the temporal and fuel-related sensitivity is assessed.

The European Union (EU) recently introduced a blending mandate for renewably sourced kerosene (EC, 2021), requiring kerosene suppliers to supply e.g., 6 % renewably sourced kerosene in the year 2030, 20 % in the year 2035 and 34 % in the year 2040. Hence, increasing market shares are investigated in the first sensitivity study. For the uniform allocation, a paraffinic kerosene market share of 5 % is assumed, which roughly matches the European Union's (EU) blending quota of 6 % by the year 2030 (European Council, 2023). To study the effects of increasing market shares of paraffinic kerosene, assumed market shares are gradually increased between 1 and 100 %. To reduce computation time, the simulations are performed for each third day in 2019, starting January 1st.

Second, the temporal variability of the base case's contrail energy forcing is studied. In addition to the year 2019, simulations are also performed for the years 2017 and 2018. The results are used to compare the day-to-day variability of the contrail energy forcing and also the variability of the annual mean energy forcing for different years. Additionally, the mitigation potentials for each allocation case and year are discussed.

Uncertainties by fuel composition are assessed in another sensitivity study. Because only few data on the hydrogen content of conventional kerosene are publicly available, the fuel properties assumed in the main study may be different from the fuel being used at the airports studied. Thus, three different hydrogen contents corresponding to the mean and the single standard deviation of publicly available datasets (13.9 m-%, 14.1 m-% and 14.3 m-%) (Zschocke et al., 2017; Edwards, 2020; PQIS, 2011). Petroleum Quality Information System) are used for the simulations. Again, each third day in the year 2019 is considered to reduce computation time, starting January 1st.

2.2. Data

2.2.1. Fuel

The composition of **conventional kerosene** might vary depending on the crude oil's respective reservoir and refinery operations. The components typically contained in conventional kerosene, e.g., paraffins or aromatics differ by hydrogen content. Thus, the hydrogen content of conventional and paraffinic kerosene are used as proxies for the detailed fuel composition. The potential impact of fuel sulfur on emissions and contrails is not considered due to the lack of data (Teoh et al., 2022a; Märkl et al., 2023). For conventional kerosene, the hydrogen content is distributed around a mean hydrogen content of 14.1 m-% with a standard deviation $\sigma = 0.2$ m-%-points and based on a sample size of $n = 57$ (Zschocke et al., 2017; Edwards, 2020; PQIS, 2011). Petroleum Quality Information System). Most of the analyzed samples originate from Europe and North America, where a large fraction of aviation kerosene is consumed (Edwards, 2020). Against the large volumes of conventional kerosene in use, this sample size is rather small. However, as of now no larger fuel sample is publicly available.

The properties of **renewably sourced kerosene** are derived from the US Federal Aviation Administration's (FAA) National Alternative Jet Fuels Test Database (Lee, 2024; Blakey et al., 2022) including about 400 alternative fuels/fuel blends from which 21 samples of neat, renewably sourced kerosene options were selected. Only samples for which the hydrogen content was determined by ASTM D7171 or inferred from GC × GC measurements were selected here; other testing methods were excluded due to the expected measurement uncertainty (Gierens et al., 2024.).

The selected samples have a mean of about 15.3 m-% ($\sigma = 0.1$ m-%-points, $n = 21$) and the distribution is shown in Fig. 2. Other fuel properties, e.g., heating value and water emissions, are adopted using a linear relationship with increasing aviation kerosene hydrogen content (Teoh et al., 2022a).

Typical soot precursors (e.g., aromatics) can also be reduced/removed from conventional kerosene, e.g., by hydroprocessing or extractive distillation (Weibel, 2018). So far, it is uncertain how much technological efforts are needed to provide a purely paraffinic kerosene with a similar hydrogen content as renewably sourced kerosene. For this study, the hydrogen content of neat renewably sourced kerosene (15.3 m-%) is assumed for the paraffinic kerosene. Note that this implies the use of unblended, almost aromatics free kerosene which is not compliant with current kerosene specifications (ASTM, 2024). Thus, it rather indicates the theoretical maximum potential of a targeted use concept.

2.2.2. Flight trajectories

The simulations cover 844 364 departing flights from the five largest European airports by passenger numbers (Airports Council International, 2022) (i.e., London-Heathrow, Paris Charles-de-Gaulle, Amsterdam Schiphol, Frankfurt International, Madrid-Barajas) during the year 2019. In the base case, their fuel burn is estimated at about 3 908 t (about 1.4 % of the global fuel burn (Teoh et al., 2024b)) and their contrail energy forcing amounts to about 1.47×10^{19} J (about 1.5 % of the global contrail energy forcing (Teoh et al., 2024b)). To study the interannual variability of meteorological conditions and traffic volume fluctuations, the years 2017 and 2018 are compared against the results for 2019. Flight trajectories are provided from the OpenSky Automatic Dependent Surveillance Broadcast (ADS-B) database (Schäfer et al., 2014) (cf. Fig. 3, Supporting Info).

As shown by Fig. 3, the focus on European airports results in a higher flight density above Europe and the North Atlantic compared to other regions, e.g., Southeast Asia. Therefore, the meteorological conditions above Europe and the North Atlantic play an important role for the overall results. Due to the strong temporary effect of the COVID-19 pandemic (Schumann et al., 2021a), the years after 2019 are not

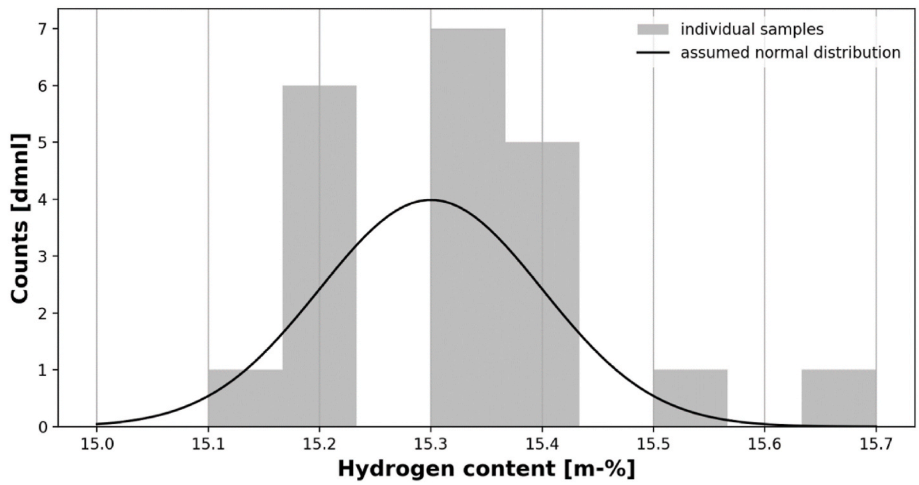

Fig. 2. Frequency distribution (grey bars) and assumed density function (black line) for the hydrogen content of neat, renewably sourced kerosene (data source (Lee, 2024; Blakey et al., 2022)), the abscissa shows the frequency and the ordinate the associated hydrogen content.

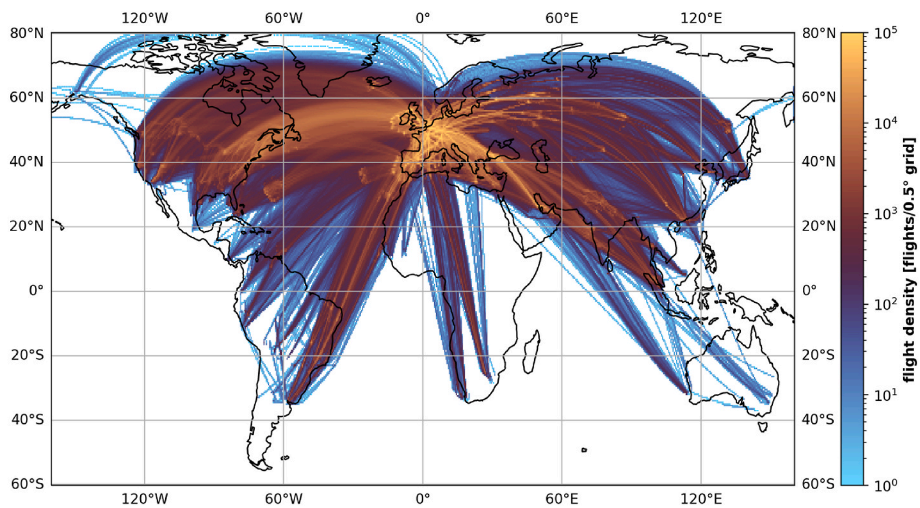

Fig. 3. Number of flights per 0.5° × 0.5° latitude/longitude grid cell for the year 2019, note the logarithmic scaling of the colorbar. Basemap plotted using Cartopy 0.21.1 © Natural Earth; license: public domain.

considered. The use of ex-post data reduces influences of potential future developments, such as the use of less soot emitting engines or different air traffic growth scenarios.

2.2.3. Performance

The performance data used to simulate aviation kerosene consumption and emissions of each flight is calculated using the Eurocontrol Base of Aircraft Data (BADA) version 3.15 (EUROCONTROL, 2023). This data base covers 1409 aircraft types, of which 250 aircraft types are directly supported and the remaining aircraft types are matched with a directly supported aircraft type considered to be equivalent (EUROCONTROL, 2023). The assignment of engine types to specific aircraft is also based on BADA, which assumes a "typical" engine model for a specific aircraft. In reality, however, most aircraft can be equipped with different engine models (e.g., the CFM56-5 or the IAE V2500 engine for the A320 aircraft). In case the emissions of both engine models differ significantly, the use of a "typical" engine model by BADA incurs a bias for e.g., soot or NO_x emissions. A recent study on global contrail climate effects finds an increase of 18 % in contrail radiative forcing for a BADA-based aircraft-engine assignment compared with an assignment on the individual aircraft level from commercially available data (Teoh et al., 2024b). For this study, the bias would primarily affect the absolute values of the contrail energy forcing estimates, but to a lower degree the relative mitigation potentials where identical aircraft fleet are compared against each other.

2.2.4. Weather data

Weather data are used from the European Centre for Medium-Range Weather Forecast fifth generation high-resolution reanalysis (ECWMF ERA5) (ECMWF, 2024) (0.25° × 0.25° horizontal resolution for 37 pressure levels and at a temporal resolution of 1 h). Meteorological conditions for flights between those pressure levels are interpolated from the two nearest pressure levels (Teoh et al., 2023b). The ERA5 humidity fields are adjusted to in-situ observations using the so-called method of exponential scaling with latitude correction (Teoh et al., 2023a) (cf. Supporting Info). This dataset is an ex-post analysis and as such it would not be available for flight planning purposes.

3. Results and discussion

3.1. Results

3.1.1. Allocation cases

Fig. 4 shows the change in median contrail energy forcing for all

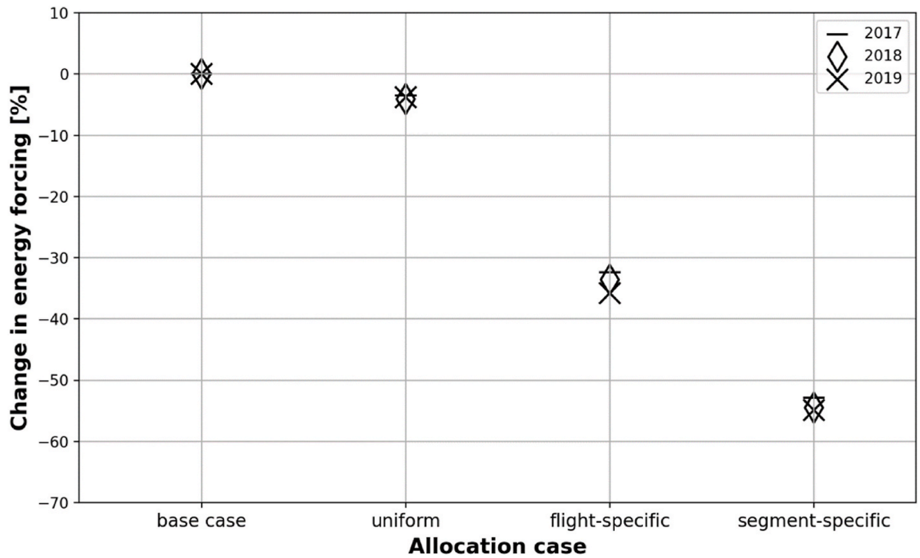

Fig. 4. Relative change of the median contrail energy forcing [%] for all allocation cases and the years 2017, 2018 and 2019.

allocation cases and the years 2017, 2018 and 2019 compared the base case, which assumes conventional kerosene only.

A uniform allocation reduces median contrail energy forcing by less than 5 %, while a flight- and segment specific allocation would reduce median contrail energy forcing by about 36 % and 55 % respectively. The variation among the three years evaluated is clearly smaller compared to the differences among the allocation cases.

Fig. 5 shows the simulation results in the year 2019 on a daily basis for the base case and each of the allocation strategies. Each data point (●) represents the contrail energy forcing for one day. The data mean is indicated as blue data point and the median as orange data point. The grey shaded areas indicate the frequency distribution of the data points. With increasing allocation precision (from a uniform allocation to a segment-specific approach), arithmetic mean and median of the data points move to smaller values, even though this is barely visible due to the large spread of the data points. the value range decreases and the distribution becomes more narrow and moves closer to lower energy forcing values. In all cases, the values range from high positive values (2.7×10^{17} J, base case) to small negative values (e.g., -0.78×10^{16} J, base case). The large majority (almost 98 % for the base case) of the data points is positive, indicating a warming climate impact for most of the days in 2019. Additionally, the flight- and segment specific allocation strategies yield some days with substantially lower energy forcing values (-2.2×10^{16} J, segment specific allocation).

As indicated by the decreasing mean and median, the more precisely the paraffinic kerosene is allocated, the lower the resulting contrail energy forcing. The large variability can be explained by the influence of the strong daily variation of meteorological conditions (cf. Fig. 8).

Most of the days in the dataset indicate a net warming contrail energy forcing. The more precisely the paraffinic kerosene is allocated, the more contrails originate from paraffinic kerosene. The associated reduction in contrail lifetime and optical thickness yields a decrease in contrail energy forcing. Days with a net cooling energy forcing become more cooling, since the few warming contrails during these days receive paraffinic kerosene.

Fig. 6 provides more details concerning the daily energy forcing for

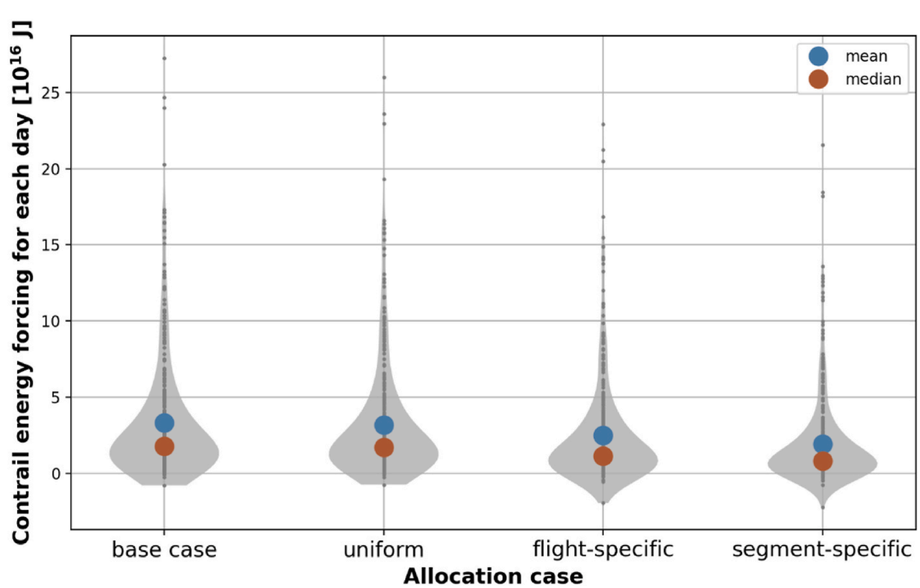

Fig. 5. Contrail energy forcing (ordinate) for each day (●) and frequency distribution of the data points (grey shaded areas) for the base case and each allocation case (abscissa).

values between -1×10^{16} J and $+5 \times 10^{16}$ J. This includes about 80.3 % of all data points for the year 2019. The reduction potential of each option becomes more visible in Fig. 6: While the median contrail energy forcing of the base case is at 1.8×10^{16} J, it decreases by about 4 % for a uniform allocation, by about 36 % for the flight specific allocation and by 55 % for the segment specific allocation. As already indicated by Fig. 5, the frequency distributions of the data points shift towards lower contrail energy forcing values, while some data points show a stronger cooling climate impact.

If the paraffinic kerosene is allocated uniformly, the used kerosene's hydrogen content increases by about 0.4 % from 14.10 m- % to 14.16 m-%. As a result, the reduction in contrail energy forcing is clearly limited. A flight specific allocation strategy uses the limited amount of paraffinic kerosene more effectively, since only flights which form warming contrails (about 25 % of all flights considered) are assumed to receive neat paraffinic kerosene (15.3 m-% hydrogen content) and accordingly, the median contrail energy forcing decreases by about 36 %. For low paraffinic kerosene market shares (including the 5 % market share studied here), some flights with a lower, but still warming contrail energy forcing will not receive paraffinic kerosene. In contrast, a segment specific allocation strategy targets a greater fraction of flights, since the paraffinic kerosene is assumed to be used only on those segments of flights where a warming contrail is formed. Thus, this allocation strategy lowers the median contrail energy forcing even by 55 % for the same amount of paraffinic kerosene.

3.1.2. *Increasing market shares*

Fig. 7 shows the relative mitigation potentials for each allocation case by increasing paraffinic kerosene market shares. Data points represent the results for each third day related to the year 2019 and lines correspond to resulting arithmetic means for each allocation case. While the mean mitigation potential for the uniform allocation (solid line) decreases slowly monotonically with increasing market shares, the average mitigation potential of the flight specific allocation (dashed line) declines steeply and reaches a reduction of >60 % for a paraffinic kerosene market share of about 25 % and remains constant up to market shares of around 75 %. This effect is even more pronounced for the segment specific allocation strategy (dash-dotted line), reaching a mitigation potential of >60 % at a market share of about 10 %. Again, at very high market shares, the reduction in contrail energy forcing decreases until all allocation strategies converge at a mitigation potential of about 40 % for a market share of 100 %.

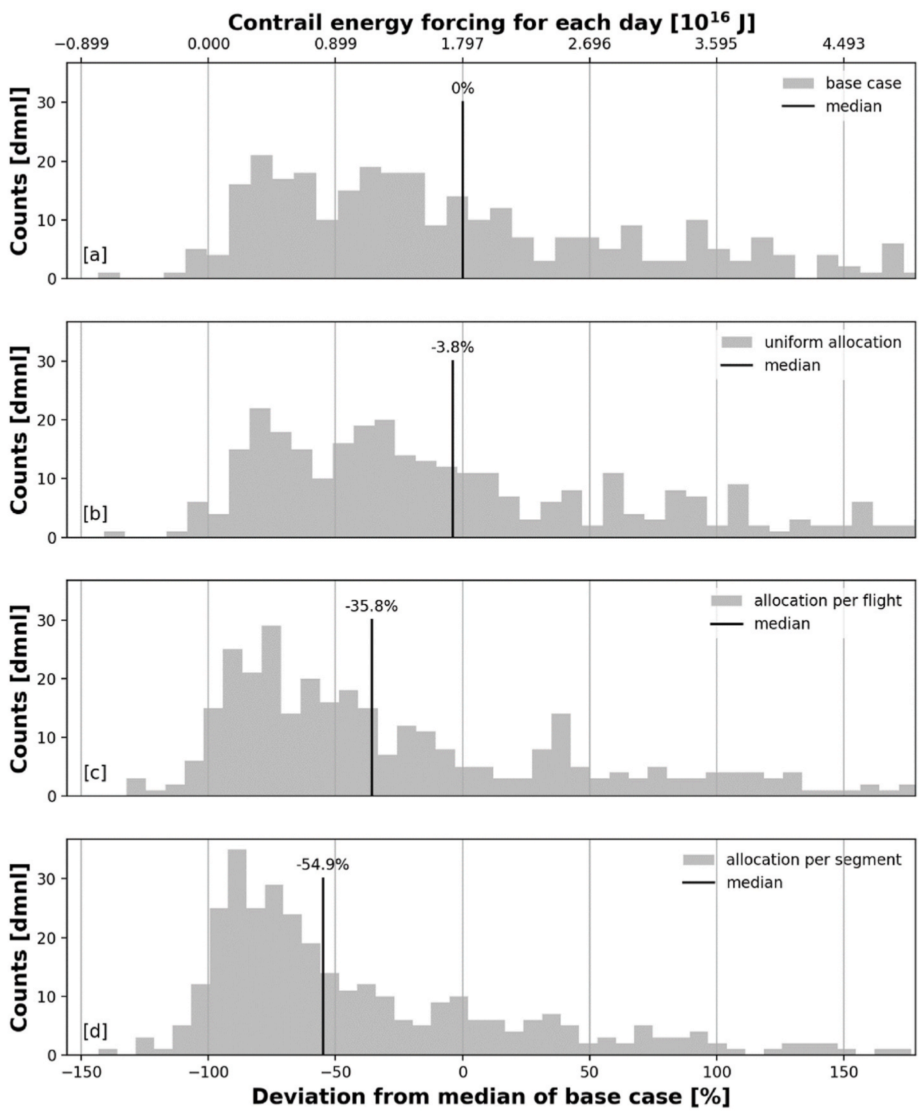

Fig. 6. Histograms for the daily energy forcing for 2019 conditions for the base case [a], a uniform allocation [b], a flight specific allocation [c] and a segment specific allocation strategy [d] (**dmnl** dimensionless), the ordinate shows the frequency of the data points, the top abscissa the absolute energy forcing and the bottom abscissa the relative change compared to the median of the base case.

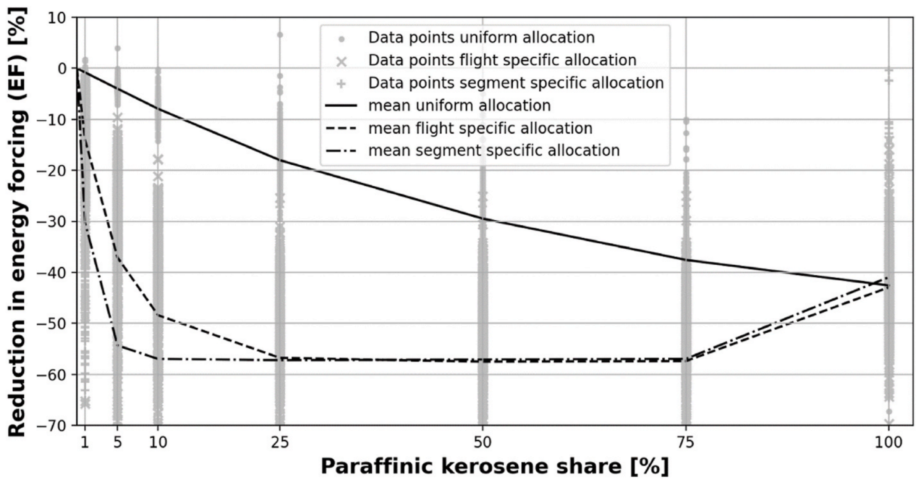

Fig. 7. Change in contrail energy forcing (ordinate) for increasing paraffinic kerosene shares (abscissa) for each third day in the year 2019. Grey data points show individual days, and the black lines connect the mean for each market share and allocation strategy.

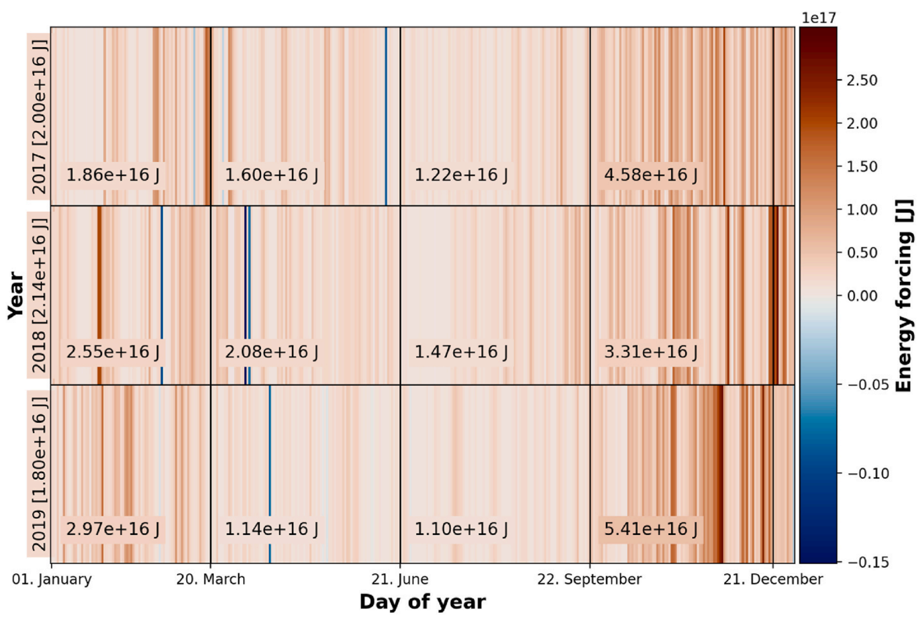

Fig. 8. Contrail energy forcing by day of year (abscissa) for 2017, 2018 and 2019 (ordinate) (figures in each box show the median for the corresponding timeframe; medians of each year are shown in brackets on the ordinate; to increase the visibility of changes for negative (cooling) energy forcing values, a non-linear scaling is applied).

For a uniform allocation, energy forcing decreases almost linearly by increasing paraffinic kerosene market shares. For market shares >50 % the curve flattens slightly. This can be explained by the assumed non-linear relationship between kerosene hydrogen content and soot emission number (nvPM EI_n) (Teoh et al., 2022a), which comes into effect at an increase in hydrogen content >0.5 m. p.p. (corresponding to a hydrogen content of 14.6 m - % or a uniformly allocated market share of about 42 %).

In terms of the flight specific allocation strategy, the steep reduction in energy forcing at market shares up to 25 % is the result of targeting the flights with the highest contrail energy forcing first. As market shares for paraffinic kerosene increase (e.g., from 5 to 10 %), an increasing share of flights with warming contrail energy forcing receive paraffinic kerosene. At a market share of around 25 %, all flights causing warming contrails receive paraffinic kerosene. Thus, the maximum reduction in energy forcing (about 60 %) is achieved. For market shares between 25 and 75 %, flights with a warming contrail climate forcing and an increasing amount of flights without contrail formation receive the paraffinic kerosene, while flights with a cooling contrail climate forcing still receive the conventional kerosene.

The segment-specific allocation strategy targets only segments of flights with a warming contrail energy forcing and accordingly, lower market shares of paraffinic kerosene achieve larger mitigation potentials compared with the other strategies. In this case, the maximum reduction of about 60 % is already achieved at a market share of about 10 %. Again, if market shares increase further, also segments without contrail formation receive paraffinic kerosene.

For both strategies, flight- and segment specific allocation, the mitigation potential decreases once also flights/segments with a cooling energy forcing receive paraffinic kerosene (market shares >75 %). The reason behind this counter-intuitive result is the contrail lifetime reduction. If the lifetime of a cooling contrail is reduced, the absolute value of its energy forcing is reduced, but its sign remains negative (i.e., cooling). Thus, the cooling effect of such contrails decreases, and in relative terms the mitigation potential of the respective allocation strategy decreases. As a result, all curves converge for a paraffinic kerosene market share of 100 % at a reduction in contrail energy forcing of about 40 %.

3.1.3. Uncertainty assessment

3.1.3.1. Temporal variability. Due to different weather patterns, daily and seasonal variations in energy forcing from contrails can be large (Teoh et al., 2022b), and only a few studies investigate interannual variations in contrail forcing (Teoh et al., 2022a, 2022b, 2023a). A larger effect has been observed during the COVID-19 pandemic, when contrail occurrence was significantly reduced due to restrictions in air traffic (Voigt et al., 2022; Schumann et al., 2021b; Gettelman et al., 2021; Groβ et al., 2023). Therefore, the temporal variability of the contrail energy forcing for different days and years is investigated by comparing the resulting contrail energy forcing from respective flight trajectories and weather data of the years 2017, 2018 and 2019 (Fig. 8).

The color of each bar corresponds to the energy forcing of the entire dataset for each day. The large majority of the days has a warming energy forcing with most of the days ranging between 0 and 10^{17} J. Even as sum for all departing flights at the five airports chosen, a few days exhibit a net cooling climate impact, but with a substantially smaller magnitude (about 10^{16} J) compared to the strongly warming days (about 2×10^{17} J). Fig. 8 also shows a seasonal pattern. From autumn equinox to winter solstice the median contrail energy forcing is highest (between 3.3×10^{16} J and 5.4×10^{16} J), while from summer solstice to autumn equinox days show a small to moderate contrail energy forcing (median $<1.5 \times 10^{16}$ J). The median contrail energy forcing for 2017, 2018 and 2019 amounts to 2.00×10^{16} J, 2.09×10^{16} J and 1.80×10^{16} J, respectively. For the three years evaluated here, the inter-annual variation is small (about 10 %) when compared to the seasonal variation (up to five-fold) and even more the daily variation (-10^{16} J up to 3×10^{17} J), indicating a strong influence of daily and seasonal changes.

Two effects are probable causes for this temporal variability, namely variations in meteorological conditions and the traffic volume. The vast daily variation can most likely be explained by short-term changes of meteorological conditions such as the movement of ice-supersaturated regions in the atmosphere. Also, the solar cycle during day and night plays an important role for contrail energy forcing. The seasonal variation can be explained by longer nights in the winter months of the Northern hemisphere resulting in a higher probability of contrails with a warming climate impact. For the dataset used here, more flights (on average + 11 %) travel greater distances per flight (on average + 5 %) during autumn and winter (cf. Supporting Info) than during the other seasons, which also increases the probability for contrail formation.

Table 1 shows the relative change in median energy forcing compared to the base case where no paraffinic kerosene is used for the entire years 2019, 2018 and 2017 and for each season. The annual values for 2017 and 2018 are in line with the results for 2019 discussed above. In general, the mitigation potentials appear highest in spring and lowest in winter. The variation among seasons is substantially larger than the variation among different years, e.g., about 14 %-points between spring 2019 and winter 2019, but only up to 6 %-points among winter months in 2017, 2018 and 2019.

Table 1
Change in median energy forcing relative to the base case by year and season.

Timeframe	Uniform [%]	Flight specific [%]	Segment specific [%]
2019 [2017; 2018]	−3.8 [-3.5; −4.1]	−35.8 [-32.4; −33.6]	−54.9 [-52.9; −54.5]
Spring[a]	−5.5 [-1.2; −3.3]	−44.1 [-44.4; −42.7]	−62.9 [-61.3; −64.7]
Summer[a]	−4.0 [-3.4; −4.2]	−36.7 [-32.4; −38.3]	−59.6 [-52.0; −56.3]
Autumn[a]	−3.6 [-4.0; −4.6]	−26.7 [-24.4; −30.1]	−43.2 [-44.5; −48.6]
Winter[a]	−4.1 [-3.7; −4.3]	−27.8 [-32.6; −29.9]	−48.4 [-55.0; −52.6]

[a] Based on astronomic seasons (i.e., Spring – March 21st to June 21st; Summer – June 22nd to September 22nd; Autumn – September 23rd to December 22nd; Winter – December 23rd to March 20th).

3.1.3.2. Kerosene composition. The effect of the kerosene composition for conventional aviation kerosene is shown in Fig. 9. It shows the distribution of the contrail energy forcing for each third day in 2019 for the base case (top), a uniform allocation (second from top), a flight specific (second from bottom) and a segment specific allocation strategy (bottom). Based on the hydrogen content distribution of the World Fuel Survey (Edwards), the hydrogen content is varied between 13.9 m-%, 14.1 m-%, and 14.3 m-%. These values correspond to the mean (14.1 m-%) and a single standard deviation of the distribution of kerosene samples described in the World Fuel Survey (Edwards, 2020).

Since the base case does not use any paraffinic kerosene, it allows for an estimate of the uncertainty in contrail energy forcing due to kerosene composition changes. Assuming a comparatively low hydrogen content (13.9 m-%), the median contrail energy forcing is about 12 % higher than for the medium hydrogen content (14.1 m-%). For a high hydrogen content (14.3 m-%), the contrail energy forcing decreases by about 16 %. This corresponds to a sensitivity of a 6–8 % change in contrail energy forcing per 0.1 m-% change in kerosene hydrogen content. This roughly corresponds to the inter-annual variability estimated in 3.1.3.1. Due to the non-linear relationship between kerosene hydrogen content and resulting contrail energy forcing (cf. Fig. 7, (Quante et al., 2024)) this approximation is only valid for the hydrogen content of conventional kerosene.

A uniform allocation of paraffinic kerosene yields a small increase of the hydrogen content of all used kerosene for the market share of 5 % assumed here (14.1 m-% to 14.16 m-%). In essence, this results in a slight reduction of the absolute contrail energy forcing (-4 %), but the variability due to kerosene changes (-16/+ 12 %) is barely affected.

For a flight specific allocation, the conventional aviation kerosene with a high hydrogen content reaches the greatest reduction (-37 % compared to the base case and a hydrogen content of 14.1 m-%), while the smallest reduction is achieved by the conventional aviation kerosene with a low hydrogen content (-30 %). The variability due to the changing kerosene hydrogen content is lower than in the base case (-4/+ 3 % compared to - 16/+ 12 %). A similar variability can be observed for the segment specific allocation strategy (-3/+ 3 %). Additionally, for a segment specific allocation, conventional aviation kerosene with a low hydrogen content results in the largest contrail energy forcing reduction (-56 %) and a high hydrogen content (-50 %).

For both targeted allocation cases (flight and segment specific) the variability is reduced because the influence of the conventional aviation kerosene on contrail energy forcing decreases. This is due to the effect that the specific allocation strategies allocate paraffinic kerosene to flights/segments with a warming energy forcing first. As the hydrogen content of this kerosene is not varied, the climate impact of such flights segments is not affected by changes in the conventional aviation kerosene's hydrogen content. For the market share assumed here (5 %), the most impactful flights and almost all segments are fueled with paraffinic kerosene. Thus, changes in conventional aviation kerosene hydrogen content primarily alter the energy forcing of cooling flights/segments. For the large majority of the days and flight trajectories evaluated, the energy forcing of warming flights/segments outweighs the energy forcing of cooling flights/segments (Fig. 8) and thus variations in paraffinic kerosene properties outweigh variations in conventional kerosene hydrogen content. Since paraffinic kerosene properties are not varied, the overall variability decreases.

A similar behavior explains that a flight specific allocation for a

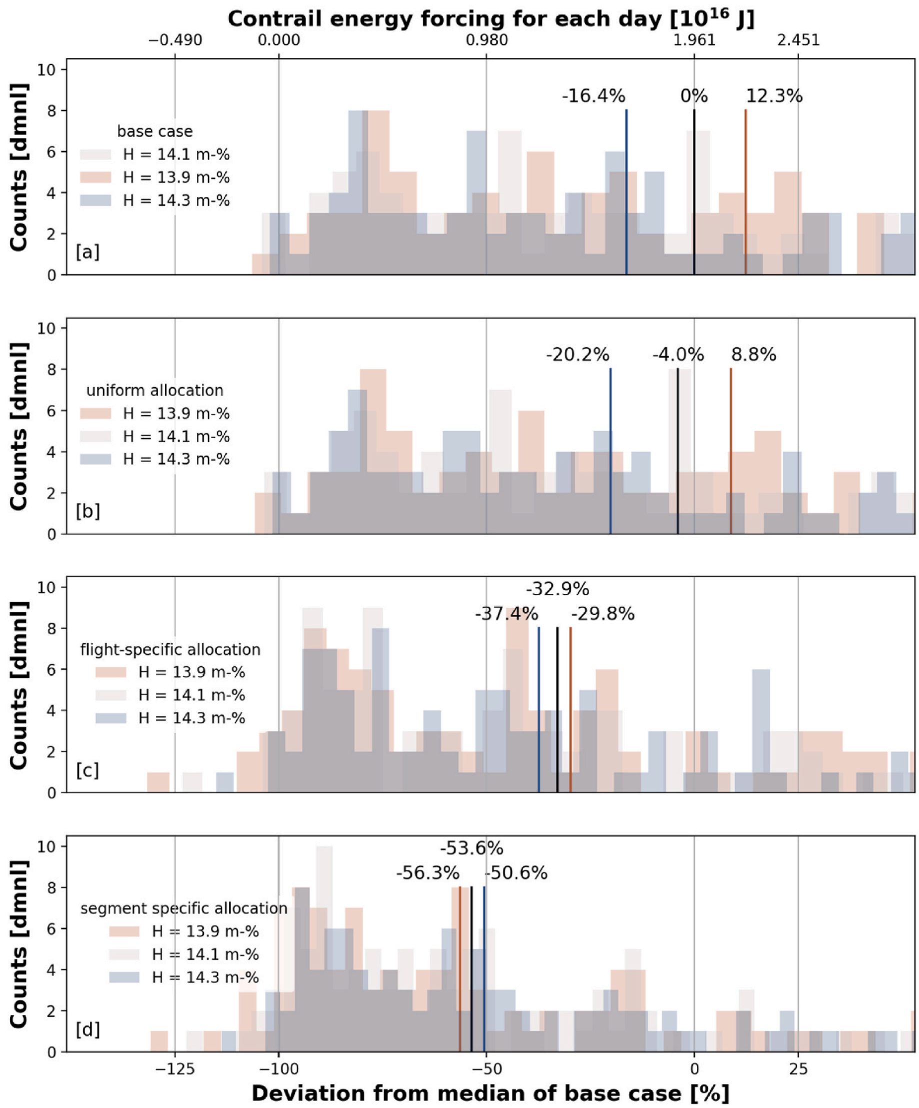

Fig. 9. Distribution of contrail energy forcing for each third day in the year 2019 and the respective medians for a conventional kerosene hydrogen content of 13.9 m-%, 14.1 m-% and 14.3 m-% for the base case [a], a uniform allocation [b], a flight specific allocation [c] and a segment specific allocation strategy [d], the ordinate shows the frequency of the data points, the top abscissa the absolute energy forcing and the bottom abscissa the relative change compared to the median of the base case.

conventional aviation kerosene with a *high* hydrogen content achieves the largest mitigation potential while for a segment specific allocation a conventional aviation kerosene with a *low* hydrogen content achieves the largest mitigation potential. If the kerosene is allocated on a per flight basis, a paraffinic kerosene market share of 5 % is not sufficient to fuel all flights with a warming contrail energy forcing, only about 10 % of the net warming flights receive paraffinic kerosene. The energy forcing of these flights decreases for high hydrogen contents of the conventional kerosene and thus also the net energy forcing of all flights decreases. Since the segment specific allocation is more specific, about 62 % of the net warming flights receive paraffinic kerosene. Thus, variations of the conventional kerosene's hydrogen content mostly affect the energy forcing of cooling segments. Here is the effect opposite: An increasing hydrogen content results in a shorter contrail lifetime and thus a reduced (cooling) energy forcing. As a result, a higher conventional kerosene hydrogen content results in less cooling segments and thus a higher overall energy forcing. If higher paraffinic kerosene market shares (e.g., 25 %) were assumed, also for a flight specific allocation all warming flights would receive paraffinic kerosene and the same effect could be observed.

In general, the variability due to kerosene composition changes has an important effect on the resulting contrail energy forcing. For the overall contrail energy forcing of a representative fleet, such variations average each other out and the use of average values seems appropriate. But for the contrail energy forcing of individual flights the hydrogen content or ideally the composition (i.e., cycloalkanes, aromatics and naphthalene content) needs to be known more precisely.

3.2. Discussion

The results presented allow for distinct conclusions about (1) mitigation potentials of allocating 5 % of overall kerosene demand as paraffinic kerosene in a uniform, flight- or segement specific manner and (2) the temporal development of those potentials assuming increasing market shares of paraffinic kerosene. These conclusions are discussed in the following.

(1) For any of the allocation strategies investigated, paraffinic kerosene reduces the contrail energy forcing. Even without a targeted use, low or paraffinic kerosene can reduce contrail climate

forcing considerably. The relative reduction in contrail energy forcing ranges from 4 % for a uniform allocation, about 36 % for a flight specific allocation (10 % of net warming flights would receive paraffinic kerosene) and around 55 % for a segment specific allocation, (62 % of net warming flights would receive paraffinic kerosene). For the flight and segment specific allocation strategies, these reductions are significant and appear robust against most uncertainties studied.

(2) Assuming an increase in renewably sourced (and thus paraffinic) kerosene market shares also affects the mitigation potential of the different allocation cases. A segment specific allocation shows higher mitigation potentials than a flight specific allocation up to market shares of about 25 % (cf. Fig. 7). Provided that the market shares foreseen by the EU's blending mandate materialize in time (20 % in the year 2035 and 34 % in the year 2040), a segment specific allocation strategy would be beneficial for a bit more than a decade. It appears questionable to which extent this timeframe is sufficient to develop and roll-out the required airport and aircraft modifications. Another option might be the implementation of a flight specific allocation strategy at scale and the use of a segment specific allocation only on newly produced aircraft.

The absolute energy forcing values are largely affected by meteorological conditions (by orders of magnitude) and to a smaller extent seasonal effects, such as the day-night duration (up to five-fold), while the inter-annual variability is <10 %. The conventional kerosene properties play another important role for the absolute contrail energy forcing (6–8 % change per 0.1 m-% change in conventional kerosene hydrogen content). Thus, to determine the contrail energy forcing of individual flights, more detailed information about each flight's kerosene composition would be required.

A segment specific allocation strategy would require substantial infrastructure and aircraft modifications, which would result in substantial cost and delays for the implementation of this strategy. A flight specific allocation strategy would require a segregated infrastructure to supply paraffinic kerosene in a targeted manner to flights with a high contrail energy forcing. Both allocation strategies strongly depend on how reliable the expected contrail climate forcing of individual flights can be estimated. All these factors, limitations from meteorological data, the magnitude of necessary infrastructure changes and aircraft modifications are beyond the scope of this investigation. Such efforts (cost- and time-wise) should be evaluated carefully to ensure that effective allocation strategies can be implemented.

Instead of all flights globally, this study uses departing flights from the five large European airports. This most likely induces two systematic errors, i.e., an increased relevance of weather conditions in Europe and the North Atlantic region and a high share of long-range flights. Thus, the results rather indicate the general mitigation potential of a targeted use concept, but exact airport-specific values may vary depending on its region and size. In particular, for airports located in other climate zones, such as the tropics, the mitigation potentials may vary.

Previous studies to mitigate the climate impact of contrails typically focus on route modifications to avoid ice-supersaturated regions (Teoh et al., 2020a, 2020b; Niklaβ et al., 2017), while the targeted use of paraffinic kerosene has been studied less often (Teoh et al., 2022a; Woeldgen, 2023). In 2022, Teoh et al. reported a 10% reduction in contrail energy forcing for a paraffinic kerosene market share of 1 % for a flight specific allocation strategy. This value is slightly lower than the result for 1 % market share shown here in Fig. 7, because Teoh et al. (2022) assume a 50 % blend of renewably sourced and conventional kerosene, while this study assumes neat paraffinic kerosene on the flights targeted. Woeldgen et al. recently published results for supplying flights with renewably sourced kerosene using strategies which avoid large infrastructure modifications (Woeldgen, 2023). The paraffinic kerosene is allocated either during contrail-sensitive seasons (October to February), between 16:00 and 03:00 UTC and with a combination of days and aircraft-engine combinations for the highest warming contrail formation. They assume an overall paraffinic kerosene market share of 2 % and estimate a reduction in annual contrail energy forcing between 1.4 % and 2.6 % (Woeldgen, 2023). Their allocation strategies are not based on meteorological data but rather fixed external factors and thus their mitigation potential estimate is far lower than the values of Teoh et al. (2022) (Teoh et al., 2022a) and this study. Finding an allocation strategy which optimizes the trade-off between required infrastructure modifications and contrail climate mitigation potential could be an interesting area for further research.

Current kerosene specifications require a minimum aromatics content of 8 m-% for renewably sourced kerosene (ASTM, 2024), while specifications for conventional kerosene do not include a minimum aromatics content (ASTM, 2024). This study assumes the use of neat, i.e., aromatics-free kerosene on a fraction of all flights (<2 % for the flight-specific allocation). Further investigations are necessary to ensure compatibility with current aircraft systems, such as the sealing of fuel systems and fuel quantity measurements. Further research could be conducted about the mitigation potential of the targeted use of specification compliant kerosene (i.e., with a minimum aromatics content of 8 %).

The effectiveness of any targeted use strategy depends on the reliability of estimating an individual flight's contrail climate forcing, most significantly for the segment specific allocation. This study uses an ex-post meteorological dataset (ERA5) which would not be available at the flight planning stage. Different data options are considered for the fuel allocation, e.g., ex-ante datasets (forecasts) and also observation based strategies, such as satellite remote sensing or on-board tracking of contrail formation and evolution conditions (Teoh et al., 2022a; Ng et al., 2023.; Geraedts et al., 2023; Schumann et al., 2017). Further research could be conducted to assess their potential and implications for flight operations.

Both, flight and segment specific allocation achieve their highest mitigation potentials up to paraffinic kerosene market shares of about 75 %. For higher market shares, also the remaining contrails with a cooling climate forcing would be affected. The extent to which the cooling impact of such flights could be maintained once market shares of renewably sourced kerosene increase beyond 75 % is another area for further research. One option might be the admixture of specific molecules, such as renewably sourced aromatics or cycloalkanes. However, further investigations are required to reduce uncertainties and potentially prevent adverse outcomes.

Concluding, this study quantifies the climate benefits of different paraffinic kerosene allocation strategies. For paraffinic kerosene market shares up to 25 %, a segment specific kerosene allocation would be more effective than a flight specific kerosene allocation. However, potential infrastructure and aircraft modification efforts need to be carefully considered. Meteorological and kerosene-related uncertainties as well as economic implications of these strategies remain areas for further research. Further investigations could allow for a derivation of specific marginal abatement cost and thus the comparison of this mitigation option with other strategies to reduce the climate impacts of aviation.

CRediT authorship contribution statement

Gunnar Quante: Writing – original draft, Methodology, Investigation, Conceptualization. **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 a relationship with EU Horizon 2020 research and innovation that includes: funding grants. 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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2024.100279.

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