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Radiative Forcing Response to Reduced Contrail Ice Formation via Controlled Ice Nuclei Seeding: A Global Study with CoCiP

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Abstract:

Contrail cirrus dominates aviation's non-CO₂ climate impacts, contributing substantially to atmospheric warming. Contrail Mitigation By Ice Nuclei Effective Seeding (COMBINES) has been proposed to mitigate contrail warming by reducing the number of ice crystals formed per kg of fuel burned (El_{ice}) by 1–2 orders of magnitude in persistent, warming contrails. Using the grid-based Contrail Cirrus Prediction (CoCiPGrid) model, we simulated for the first time the sensitivity of contrail radiative forcing (RF) to COMBINES-motivated El_{ice} reductions applied only to warming contrails. The global annual mean net RF (56.5 mWm^{-2}) decreased nonlinearly by ~43%, ~78%, and ~94% at 2-, 5-, and 10-fold reductions, and leveled off near zero beyond about 15-fold, set by shortwave cooling of unseeded contrails. Targeting only warming contrails removed more forcing than reducing all contrails (~78% versus ~65% at 5-fold). The required reduction varied regionally and seasonally: at 10-fold, annual net RF became slightly negative over Europe and the USA (-4.2 and -5.0 mWm^{-2}), while the North Atlantic remained positive (33.8 mWm^{-2}) and required 15- to 25-fold reductions (25- to 50-fold in winter). These instantaneous RF estimates suggest that regionally and seasonally optimized COMBINES El_{ice} reductions, if achieved, could substantially mitigate contrail warming.

23

24 **Keywords:** aviation, contrails, climate forcing, ice nuclei seeding, climate mitigation

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26 **Synopsis:** Targeted reductions in contrail ice crystal number could greatly mitigate aviation's
27 contrail warming, but required reductions vary by region and season.

28

29 **1. Introduction:**

30 Research on strategies to mitigate the climate impact of contrails and contrail-induced cirrus
31 clouds has increasingly become a critical priority due to their substantial contribution to
32 aviation-induced radiative forcing (RF) and global warming.^{1–4} Past studies have identified the
33 contrail cirrus as the largest non-CO₂ contributor, accounting for about 57% of aviation's net
34 effective RF (ERF) in 2018, with large uncertainties.² Lee et al. estimate contrail cirrus RF at
35 111.4 mWm⁻² (95% likelihood range: 33–189 mWm⁻²), and total aviation RF, including CO₂
36 and non-CO₂ effects, at 149.1 [70–229] mWm⁻² for 2018.² Recent model studies estimate
37 global mean contrail net RF of 44 to 72 mWm⁻² for traffic years between 2006 and 2019 with
38 substantial uncertainty.^{5–8} This forcing is comparable to, or in some cases exceeds, that of
39 aviation cumulative CO₂ emissions.^{9,10} Projections indicate their impact could potentially triple
40 by 2050, driven by continued air traffic growth and rising non-CO₂ effects.^{11–13} A recent
41 assessment found that a 3% reduction in contrail forcing could offset a 1% increase in CO₂
42 forcing over 100 years, showing that small reductions in contrail forcing can significantly
43 offset CO₂ increases over shorter periods.¹⁴ These findings highlight the need to mitigate non-
44 CO₂ impacts. As contrail cirrus is currently the largest short-lived atmospheric perturbation

45 due to aviation, reducing its occurrence and impact could provide immediate climate
46 benefits.^{14,15}

47 Contrails form behind aircraft when water saturation in the cooling exhaust plume allows water
48 vapor to condense on aerosol particles, including nonvolatile (nvPM), volatile (vPM), and
49 ambient particles.^{16–19} These particles then freeze into ice crystals. The number of ice crystals
50 depends on engine and fuel characteristics, as well as ambient atmospheric conditions.
51 Contrail-induced clouds reflect shortwave (SW) solar radiation during the day, causing
52 cooling, but predominantly trap and re-emit longwave radiation to Earth's surface, resulting in
53 a net warming effect that amplifies the greenhouse effect.^{2,9,20} The climate impact of contrails
54 is determined by their microphysical and optical evolution over their lifetime. Key factors
55 include the number of ice particles formed and their optical properties that affect radiative
56 forcing. Contrail mitigation strategies, such as using sustainable aviation fuels,^{21–23} next-
57 generation engines with lower particle emissions,²⁴ and hydrogen combustion,^{25,26} focus on
58 reducing ice crystal formation in the exhaust plume (EI_{ice} , number of ice crystals formed per
59 kg of fuel burned) or avoiding regions where persistent warming contrails are likely to
60 form.^{27,28}

61 Previous studies show that reducing EI_{ice} increases ice crystal size, which in turn lowers the
62 optical depth, lifetime, ice water content (IWC), and coverage of contrail cirrus and therefore
63 its RF.²⁹ In a global climate model (GCM) with 2002 traffic, 2-, 5-, and 10-fold reductions in
64 EI_{ice} lowered RF by 21%, 50%, and 69%,²⁹ and a 2-fold reduction lowered it by 14% for the
65 projected 2050 traffic.¹¹ When only the radiative effect was considered, a ~6.7-fold (85%)
66 reduction in EI_{ice} lowered linear contrail RF by 35%.³⁰ The response therefore is non-linear:
67 reducing EI_{ice} by 2-fold lowers the RF by only 14–21%, whereas a 10-fold reduction lowers it

by ~70%. With a trajectory-based CoCiP for the 2019 fleet, lowering the nvPM number emission index (EIn) from a constant 10^{15} to 10^{14} kg^{-1} for all flights lowered the global net RF by 82%,⁷ and over Europe 2-, 10-, and 100-fold nvPM reductions lowered the net RF by 20%, 60%, and 88%.³¹ These climate model studies indicate that significantly reducing EI_{ice} can substantially decrease contrail RF.

Most proposed ways to lower EI_{ice} focus on reducing the number of particles on which contrail ice forms. Sustainable aviation fuel (SAF) has been shown to reduce the nvPM emissions and contrail ice numbers by 50-70% in flight measurements.^{8,21} Modeling studies suggest this reduction could achieve a 26–44% decrease in contrail net RF.^{8,21–23} However, real-world deployment of SAF is limited by delivery and supply chain challenges.³² Additionally, below an nvPM EIn of about 10^{14} kg^{-1} (soot-poor regime), droplets formed on volatile particles from sulfur, organics, and lubrication oil vapors can freeze into ice crystals, potentially resulting in ice particle numbers similar to soot-rich regimes.^{18,19,33,34} The role of these particles remains insufficiently understood. For example, behind an A321neo with lean-burn engines, nvPM EIn was about 1000 times lower than in rich-burn mode, yet EI_{ice} was still 1.6×10^{15} kg^{-1} .²⁴ Combining low nvPM with cleaner fuel can further reduce EI_{ice} : a lower-sulfur fuel blend reduced EI_{ice} by ~3-fold, and a model predicts up to ~10-fold reduction with ultralow sulfur fuel.²⁴ However, this route is still limited because organic vapors from unburned fuel and oil are difficult to eliminate, ambient aerosol sets a lower bound on ice particle numbers,^{34,35} and it may take many years for new engines and fuels to be adopted across the fleet, including on flights that produce cooling contrails.

One of the recently proposed mitigation approaches is Contrail Mitigation By Ice Nuclei Effective Seeding (COMBINES), which adds a small, optimized quantity of efficient ice-

91 nucleating particles (INPs), such as silver iodide or bismuth triiodide or other environmentally
92 friend materials, into engine exhaust when persistent, warming contrails are predicted.³⁵ The
93 seeded INPs absorb water vapor and lower the peak relative humidity in the plume, resulting
94 in fewer particles forming droplets and freezing. By acting on contrails formed on both nvPM
95 and volatile particles, COMBINES, through controlled INP seeding, might reduce EI_{ice} in both
96 soot-rich and soot-poor regimes. The extent of EI_{ice} reduction depends on nvPM and volatile
97 particle concentrations which depend on fuel types and compositions, ambient temperature,
98 and the amount of INPs used, allowing for optimization based on specific conditions. Model
99 simulations using the Aerosol and Contrail Microphysics (ACM) plume model predict that
100 optimized seeding can reduce EI_{ice} by up to 1-2 orders of magnitude.³⁵ Specifically, seeding
101 reduced EI_{ice} by up to ~80-fold in soot-poor exhaust when ambient temperature was more than
102 about 5 K below the formation threshold, and in soot-rich exhaust within about 10 K below
103 this threshold. Reductions of up to 100-fold were possible when condensable gas emissions
104 were low. In colder air with soot-rich exhaust, the reduction was about 3-fold or less, while in
105 warm soot-poor exhaust, seeding was not required and could even raise EI_{ice} , and too few or
106 too many INPs led to smaller reductions. Laboratory data indicate that proposed seeding
107 materials, such as silver iodide particles of 40-400 nm, froze at similar temperatures, but fewer
108 than 0.5% of them formed ice below water saturation at 255-262 K in controlled settings.³⁶
109 However, seeding has not yet been tested under the rapid cooling and mixing conditions of an
110 actual jet exhaust plume where exhaust temperature quickly drops below 250 K and humidity
111 approaches or exceeds water saturation. COMBINES, therefore, still remains a model-based
112 proposal; the seeding hardware, environmental fate and effects of the particles, and real-world
113 performance remain to be tested. While significant EI_{ice} reductions predicted by COMBINES

indicate a potential for contrail cirrus mitigation, the potential effectiveness of such reductions on global contrail RF has not yet been assessed.

In this study, we apply the CoCiPGrid³⁷ model (pycontrails version 0.51.0), a grid-based version of the Contrail Cirrus Prediction model (CoCiP),³⁸ to estimate the potential effectiveness of COMBINES in mitigating contrail-induced warming. We conduct a sensitivity analysis of contrail RF in response to EI_{ice} reductions of up to 1-2 orders of magnitude, using idealized scenarios based on COMBINES predictions. Unlike earlier studies, we reduce EI_{ice} only in contrails with a strong warming effect, since COMBINES would seed only when such contrails are expected. We evaluate how these reductions affect contrail properties and RF and analyze regional and seasonal variations in areas with high air traffic density and significant contrail climate forcing—specifically the United States, Europe, and the North Atlantic. These three regions are chosen for their high contrail warming in the 2019 global trajectory-based CoCiP simulation, with annual mean net RF of 414, 876, and 300 mWm^{-2} , respectively, compared with the global mean of 62.1 mWm^{-2} .⁷ Collectively, these regions account for about half of the global contrail energy forcing (20.9%, 18.4% and 10.9%, respectively). Because contrail occurrence, persistence, microphysical evolution, and radiative effects vary substantially across regions and seasons, global annual mean results can obscure the spatial and temporal conditions under which mitigation is most effective.

2. Materials and Methods:

This section describes the data sources and models employed to simulate contrail properties and associated climate forcing. The contrail simulation incorporates the following components: (i) a global aviation emissions inventory (GAIA)³⁹ based on Automatic Dependent Surveillance-Broadcast (ADS-B) data, as detailed in section 2.1; (ii) ERA5 high-resolution

realization (HRES) reanalysis meteorological data from the European Centre for Medium Range Weather Forecast (ECMWF),⁴⁰ as outlined in section 2.2; and (iii) the CoCiPGrid³⁷ model, which is described and summarized in section 2.3.

2.1 Global Aviation Emission Inventory

Emission data for contrail climate forcing simulations were sourced from the gridded GAIA dataset.³⁹ This dataset provides high-resolution global flight distance, fuel consumption, and various pollutant emissions for 2019. Emission parameters were mapped to a four-dimensional spatio-temporal grid with $0.25^\circ \times 0.25^\circ$ horizontal, 1000 ft altitude, and hourly resolution to derive input parameters such as fuel flow, flight segment length, and nvPM EI_n for each grid box. We filter GAIA to include emission only between the cruise altitudes of 6—13 km.

2.2 Meteorology

Global meteorological and radiation data were obtained from the ECMWF ERA5 HRES reanalysis,⁴⁰ accessed through the Copernicus Climate Data Store (CDS), with a spatial resolution of 0.25° longitude $\times$ 0.25° latitude, 37 vertical pressure levels, and hourly intervals. Previous studies report that ERA5 humidity fields are weakly supersaturated, underestimate regions with high supersaturation (relative humidity with respect to ice (RHi) $> 120\%$), and show inconsistencies with situ measurements.^{23,41} Teoh et al.⁷ introduced a global humidity correction method to align ERA5 HRES RHi with in situ observations. This study applies the global RHi correction method to address these limitations.

2.3 Contrail model and contrail simulation

We use the CoCiPGrid model to simulate the contrail lifecycle and identify regions of contrail-induced warming. This model extends the trajectory-based CoCiP, a Lagrangian Gaussian

159 Plume model, to a grid-based approach. It simulates the evolution of contrail segments on a
 160 four-dimensional grid (latitude, longitude, altitude, and time) to estimate gridded contrail
 161 energy forcing across airspace volumes.³⁷ In CoCiPGrid, contrails form when the Schmidt-
 162 Appleman criteria are met,¹⁶ and persist only if ice crystals remain after the wake-vortex phase,
 163 which requires ice-supersaturated air. EI_{ice} is computed as a function of $nvPM EI_n$, and a
 164 temperature-dependent activation fraction ($f_{activation}$) that increases as the air becomes colder
 165 than the formation threshold, with a lower limit of 10^{13} kg^{-1} to represent ice formation on
 166 ambient air and volatile particles when nvPM emissions are low.^{37,38}

$$167 \quad EI_{ice} = nvPM EI_n \times f_{activation} \quad (1)$$

168 Then the number of ice crystals per meter of contrail before the vortex phase ($n_{ice,0}$) depends
 169 on fuel burn per meter ($\dot{m}_{f,dist}$) as;

$$170 \quad n_{ice,0} = EI_{ice} \times \dot{m}_{f,dist} \quad (2)$$

171 The number of ice crystals per meter of contrail after the vortex phase ($n_{ice,1}$) depends on the
 172 fraction of crystals that survive this phase ($f_{survival}$), set by the difference in IWC before and
 173 after the vortex phase (denoted by IWC_0 and IWC_1 , respectively) as the sinking vortices warm
 174 the plume adiabatically; it does not depend on the number or size of the crystals.

$$175 \quad n_{ice,1} = n_{ice,0} \times f_{survival} \quad (3)$$

$$176 \quad f_{survival} = \frac{IWC_1}{IWC_0} \quad (4)$$

177

The plume initially has a width of $\pi/4$ times the wingspan and a depth determined by the downward displacement of vortices.^{37,38} It is then advected by ERA5 wind as a Gaussian plume kept at ice saturation, gaining ice in supersaturated air and losing ice in subsaturated air. Crystals are characterized by one volume-mean radius based on ice mass and number of crystals per meter of contrail. So, for the same ice mass, fewer crystals result in larger sizes. Terminal fall speed increases with radius,⁴² causing the plume to descend, often into drier air, and spread vertically, which shortens lifetime for larger crystals. Crystals are also lost through turbulent mixing and aggregation. The width is computed at each time step from the lateral spread of the plume, which grows by horizontal diffusion and vertical wind shear.^{37,43} A contrail segment ends when its optical depth falls below 10^{-6} , its ice number concentration falls below the background level of 10^3 m^{-3} , it leaves the allowed altitude domain of between 6-13 km, or contrail age exceeds the maximum contrail age that is set to 20 hours.³⁷

CoCIPGrid uses a parametric RF scheme of Schumann et al.,⁴³ fitted to the libRadtran radiative transfer package, to estimate local contrail SW and longwave (LW) RF' (RF', the change in radiative flux over the contrail coverage area). This uses simulated contrail properties and ERA5 meteorological data, including top-of-atmosphere radiative fluxes (outgoing longwave radiation and reflected solar radiation). Contrail energy forcing (EF) is then estimated by integrating the contrail net RF' over its lifetime (T), segment length (L) and width (W), providing the cumulative contrail climate forcing over its lifetime.^{7,37}

$$EF_{contrail}[J] = \int_0^T RF'_{net}(t) \times L(t) \times W(t) dt \quad (5)$$

Then the annual mean contrail RF, which quantifies the radiative flux change over the globe/region at a given time, is estimated from $EF_{contrail}$ following Teoh et al.⁷ as;

$$200 \quad \text{Annual mean contrail net RF } [mW m^{-2}] = \frac{\Sigma EF_{contrail}[J]}{S_{region}[m^2] \times (365 \times 24 \times 60^2 [s])} \quad (6)$$

201 $S_{region}[m^2]$ represents the surface area of the region of interest. We use equation (6) to
 202 estimate the annual, seasonal, and monthly global and regional mean contrail net RF.

203 Unlike the trajectory version, the grid model cannot directly initialize contrail segment
 204 properties based on specific flight and aircraft-engine data. Instead, parameters such as contrail
 205 orientation and aircraft performance are replaced by calibrated constants or estimated using a
 206 grid-adapted Poll-Schumann (PS) aircraft performance model (see Engberg et al.³⁷ for details).
 207 These simplifications affect the spreading rate, ice crystal loss rate, and contrail lifetime. To
 208 reduce computational demands, passenger aircraft-engine types are grouped by similarities in
 209 mass and nvPM emissions, with each group representing combinations that produce similar
 210 climate impacts. Each group is defined by fixed properties, including wingspan, design-
 211 optimum Mach number, aerodynamic coefficients, and nvPM emissions profile, set to those of
 212 the aircraft engine type with the largest market share. Following Engberg et al.³⁷ and Dean et
 213 al.²⁸, we use the three aircraft-engine groups (low-, nominal-, and high-nvPM), defined by
 214 different levels of nvPM emissions (Table 1).

Table 1: Aircraft-engine groups based on nvPM EIn classification, corresponding aircraft engine class/family and representative aircraft-engine type/family

Aircraft-engine group	Aircraft engine family	Representative aircraft engine family
Low-nvPM	CFM LEAP-1A, CFM LEAP-1B, GE GENx	GE GENx
Nominal-nvPM	CFM56, Rolls-Royce RB211, Rolls-Royce Trent 500/700/900/1000/XWB, GE CF6-80, GE90	CFM56

215

216 For each four-dimensional grid, the CoCiPGrid model was initialized with flight segment and
 217 nvPM EIn data from GAIA, assigning each grid to a representative aircraft-engine family
 218 based on its GAIA nvPM EIn. The engine and performance properties for each family (Table
 219 1) were obtained from Engberg et al.³⁷ All grid points are assumed to share the same nominal
 220 aircraft, engine, and performance properties, including aircraft mass, wingspan, efficiency, and
 221 Mach number for the representative combinations. These assumptions introduce input-related
 222 uncertainties in contrail net RF calculations. However, addressing uncertainties related to
 223 aircraft-engine classifications or other input parameters is beyond the scope of this study, which
 224 rather focuses on evaluating the potential efficacy of the COMBINES-motivated large EI_{ice}
 225 reductions in reducing contrail climate impacts. The three group simulations together cover the
 226 entire grid, and all RF values in this paper refer to this combined field.

227 Teoh et al.⁷ used the trajectory-based CoCiP model to simulate contrail lifecycle and properties
 228 along actual flight trajectories using GAIA and ERA5 HRES reanalysis weather data to
 229 estimate a global annual mean contrail net RF of 62.1 mWm⁻² for 2019. Engberg et al.³⁷
 230 evaluate how well grid-based CoCiP reproduces trajectory-based CoCiP with several skill
 231 scores. Grouping the aircraft-engine types changed these scores by an average of 0.6% for 12
 232 groups, 13.1% for the three nvPM-based groups used in this study, and 34.5% for a single
 233 group, relative to a grid-based run with the actual aircraft-engine type of each flight. For the
 234 reference case (REF) of this study, contrail net RF is estimated at 56.5 mWm⁻², about 9% lower

than the 62.1 mWm^{-2} from trajectory-based CoCiP for the same year, inventory, and meteorology, which reflects the grid-based approach and the aircraft-engine grouping.

In the REF simulation, contrail warming regions are defined as high-energy forcing (EF) regions, where contrail EF per unit flight distance exceeds 10^7 J m^{-1} ($\text{EF}_{\text{Threshold}}$), capturing nearly all significant warming contrails (Figure S1). In the reduction scenarios, EI_{ice} is reduced only at grid points and hours where contrail formation exceeds the $\text{EF}_{\text{Threshold}}$. This $\text{EF}_{\text{Threshold}}$ is consistent with values used by Engberg et al.³⁷ and Dean et al.²⁸ in navigational contrail avoidance studies. The global RF response to reduced EI_{ice} at these locations is simulated for idealized reduction scenarios with 2-, 5-, 10-, 15-, 25-, 50-, 75-, and 100-fold reductions in EI_{ice} , within the COMBINES predicted framework. The 10-fold (RED10) and 50-fold (RED50) reduction cases are analyzed in detail. These reduction factors represent reductions in EI_{ice} , not in nvPM emissions, and are applied directly. COMBINES seeding, freezing, and particle competition are not simulated in this study, and the same reduction factor is applied at every seeded grid point, regardless of temperature or nvPM emissions. However, the actual reduction achieved by seeding depends on both and is smaller when too few or too many particles are seeded. These scenarios are used to evaluate the potential efficacy of COMBINES-motivated EI_{ice} reductions. In the COMBINES plume model, controlled INP seeding can reduce EI_{ice} by up to 50-fold in both soot-rich and soot-poor regimes under representative cruise altitude conditions.³⁵ Optimized seeding with INP emission indices of $\sim 5 \times 10^{12} \text{—} 5 \times 10^{13} \text{ kg}^{-1}$ fuel can achieve up to ~ 100 -fold EI_{ice} reductions under favorable conditions, for silver iodide or bismuth triiodide particles of 100nm diameter, these corresponds to $\sim 15\text{--}1500 \text{ mg}$ of material per kg of fuel.³⁵ Therefore, RED10 falls within the range simulated for favorable conditions, while RED50 is near the upper end. The 75- and 100-

fold cases are the upper-bound sensitivity tests consistent with the optimized strong INP seeding under favorable thermodynamic conditions.

3. Results and Discussion:

This section examines changes in simulated contrail properties and global RF sensitivity to reduced EI_{ice} in scenarios motivated by COMBINES, focusing on 2019 aviation emissions. We specifically assess changes resulting from EI_{ice} reductions. The potential effectiveness of COMBINES in mitigating aviation-induced contrail warming is evaluated by comparing simulations with different EI_{ice} reduction factors to a baseline REF simulation.

3.1 Global Spatial and Diurnal Variability

The potential effectiveness of COMBINES in reducing contrail-induced warming is shown by the spatial and temporal distribution of mean net RF in Figure 1, using two EI_{ice} reduction experiments: RED10 and RED50. The corresponding longwave and shortwave components are detailed in Figure S2. In REF, net RF is strongly positive and concentrated over major Northern Hemisphere flight corridors, with the highest annual means (~4-7.5 times the global mean) over Europe, the North Atlantic, and the USA (also see Figure 3b). These regions are highlighted by dashed bounding boxes in Figure 1a. This spatial pattern (Figure 1a) reflects the combined effect of dense air traffic and meteorological conditions that favor frequent ice supersaturated regions (ISSRs) and persistent contrail cirrus.⁷ Using the CoCiPGrid model, the annual global mean contrail net RF in REF is estimated at 56.5 mWm^{-2} . For Europe, North Atlantic, and the USA, annual mean net RF values are 424.7, 350.7, and 208.2 mWm^{-2} , respectively, with local values of several hundred mWm^{-2} . These estimates are lower for Europe and the USA (~52% and 50%, respectively) and higher for the North Atlantic (~17%)

280 compared to trajectory-based CoCiP estimates by Teoh et al.⁷ (876, 414, and 300 mWm⁻²,
281 respectively), attributed to differences in aircraft/engine input parameters and model
282 assumptions. Our focus is to assess contrail RF sensitivity under higher EI_{ice} reduction
283 scenarios. Figure 1b shows that RED10 reduces global mean net RF from 56.5 to 3.4 mWm⁻²,
284 shifting mid-latitude corridors from positive to near-zero net RF. With RED50 (Fig. 1c), annual
285 mean net RF becomes slightly negative globally (−6.1 mWm⁻²), as is the net RF over broad
286 mid-latitude corridors. In the three marked regions, RED10 results in near zero or slightly
287 negative net RF for Europe and the USA, while RED50 yields the largest reduction in Europe
288 followed by the USA and the North Atlantic, respectively (Table 2). Globally, RED10 lowers
289 the annual mean net RF by ~94% and RED50 by ~111%, indicating that with sufficient
290 reduction, the annual mean net RF approaches zero or becomes slightly negative.

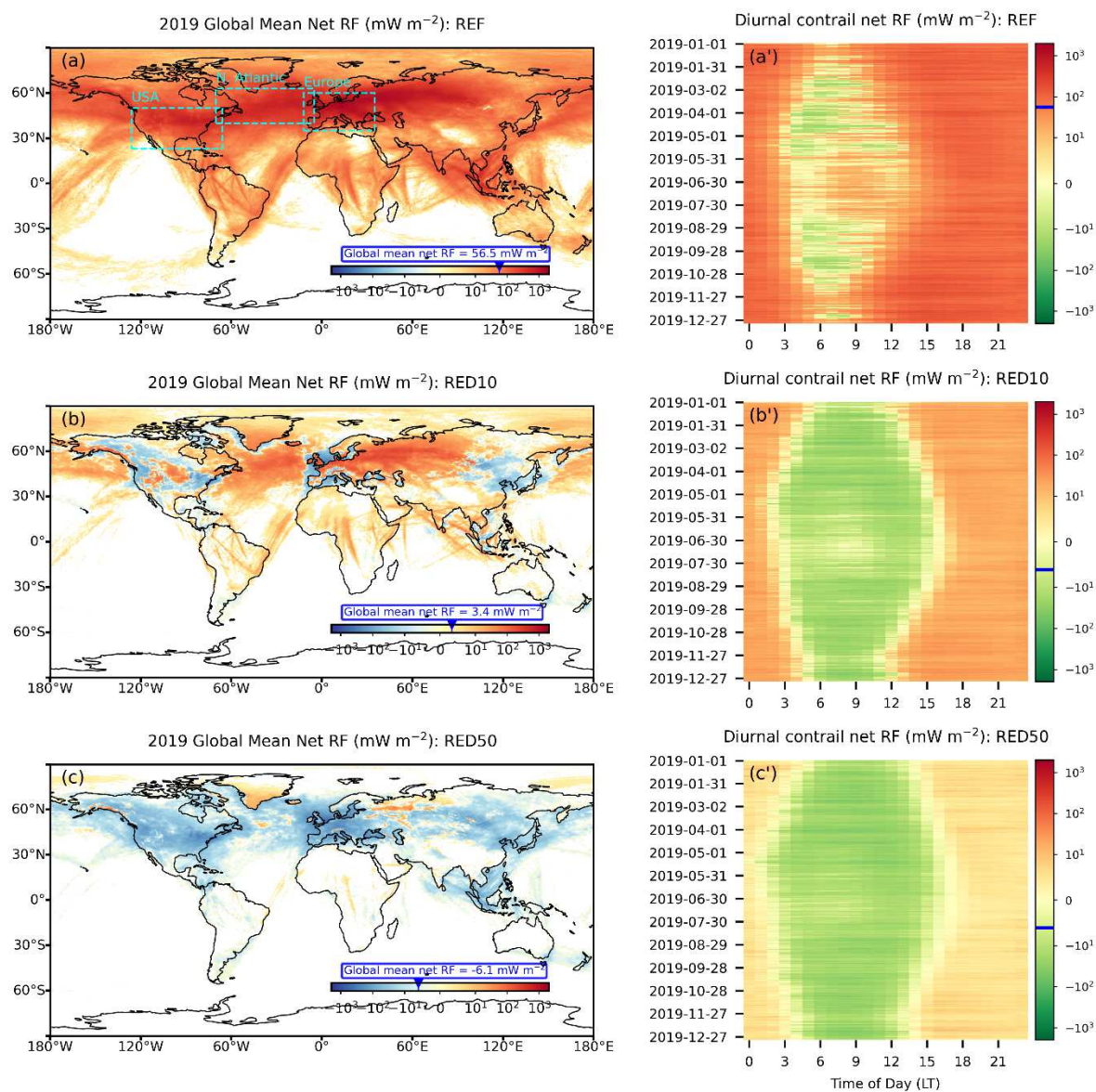
Table 2: Annual mean contrail net RF (mWm⁻²) for REF and different EI_{ice} reduction scenarios applied to warming contrails in 2019 across global, Europe, the USA and N. Atlantic regions. Values in parentheses show changes relative to REF.

	EI _{ice} reduction cases						
Region	REF	RED5	RED10	RED15	RED25	RED50	RED100
Global	56.5	12.4	3.4	-0.2	-3.3	-6.1	-7.6
		(-78.1%)	(-94.0%)	(-100.3%)	(-105.9%)	(-110.7%)	(-113.4%)
Europe	424.7	67.2	-4.2	-32.2	-57.4	-79.0	-91.3
		(-84.2%)	(-101.0%)	(-107.6%)	(-113.5%)	(-118.6%)	(-121.5%)
USA	208.2	30.7	-5.0	-18.9	-31.4	-41.8	-47.6
		(-85.3%)	(-102.4%)	(-109.1%)	(-115.1%)	(-120.1%)	(-122.9%)
N. Atlantic	350.7	89.8	33.8	11.1	-9.6	-27.7	-38.1
		(-74.4%)	(-90.4%)	(-96.8%)	(-102.8%)	(-107.9%)	(-110.9%)

291 The diurnal contrail net RF heatmap (Figure 1a'-c') shows the underlying factors leading to this
292 reduction (the corresponding shortwave and longwave components are shown in Figure S2).

293 In REF, contrails warm at night, when only the longwave term acts, while during the day,
294 shortwave cooling offsets part of the longwave, resulting in a net RF close to zero around 3-9
295 LT (Figure 1a'). Reducing EI_{ice} lowers both longwave and shortwave terms, but not equally.
296 Global longwave RF decreases from 126.2 to 47.3 mWm^{-2} ($\sim -63\%$) with a 10-fold reduction
297 and to 33.2 mWm^{-2} ($\sim -74\%$) at 50-fold, while shortwave RF weakens only from -69.7 to -43.9
298 mWm^{-2} ($\sim -37\%$) and -39.2 mWm^{-2} ($\sim -44\%$), respectively (Figure S3a). As a result, net RF is
299 lower than REF at all hours (also see Figure S4), with the largest reductions in the afternoon
300 and evening from November to February (down to $\sim -200 mWm^{-2}$) and around midnight when
301 only longwave effects are present. The smallest reductions occur at midday in spring and
302 summer, when the lost shortwave cooling offsets more of the lost longwave warming. In
303 RED10 and RED50, the remaining daytime net RF is often negative, and nighttime warming
304 is much weaker than in REF (Figure 1b',c'). Net RF decreases because seeded contrails
305 dissipate sooner and become optically thinner. Fewer ice crystals grow large enough to fall
306 rapidly, reducing contrail age and horizontal extent (mean age and width $\sim 40\%$ and $\sim 44\%$
307 lower in RED50, respectively; Figure 3d). The resulting lower optical depth alters the balance
308 between longwave and shortwave forcing. Larger crystals increase longwave and decrease
309 shortwave forcing per unit optical depth,⁴³ so thinner contrails lose shortwave cooling at least
310 as quickly as longwave warming. The larger drop in the global longwave RF is mainly due to
311 which contrails were reduced. Only warming contrails were seeded, so cooling contrails retain
312 their shortwave cooling. If RED100 is taken as close to the state in which seeded contrails no
313 longer contribute, the unchanged contrails retain $\sim 55\%$ of the REF shortwave RF (-38.5 of -
314 69.7 mWm^{-2}) but only $\sim 25\%$ of the longwave RF (30.9 of 126.2 mWm^{-2}). For the seeded
315 contrails alone, both shortwave and longwave RF decrease by about the same fraction ($\sim 83\%$

316 at 10-fold), consistent with thin contrails⁴³ and as observed by Teoh et al.²³ The shortwave
 317 cooling from unchanged contrails is what makes the global annual mean net RF close to zero
 318 or negative beyond about 15-fold EI_{ice} reduction.



319
 320 **Figure 1.** 2019 global annual mean contrail net RF averaged over the whole year (a), (b), (c)
 321 and diurnal variation of global average contrail net RF for each hour of 2019 (a'), (b') and (c')
 322 for REF, RED10, and RED50 cases, respectively. The REF represents the reference case

simulation with three aircraft-engine categories based on nvPM EIn using the CoCiPGrid model. RED10 and RED50 represent the idealized simulations with E_{ice} reduced by factors of 10 and 50. Spatial bounding box in (a) shows the regions (Europe, USA, and North Atlantic) with high air traffic density as defined by Teoh et al.⁷

3.2 Seasonal and Regional Variability

Figure 2a shows the global monthly mean net RF for REF, RED10, and RED50 scenarios. In REF, mean net RF remains positive throughout the year, ranging from 37.7–40.4 mWm^{-2} in June–July to 77.8–83.9 mWm^{-2} in November–January. It peaks in winter (DJF, 74.8 mWm^{-2}) and is lowest in summer (JJA, 41.2 mWm^{-2} ; Figure 2b), mainly due to the shortwave component. Global longwave RF varies little by season (117.0–132.0 mWm^{-2}), while shortwave RF is weakest in winter (-57.2 mWm^{-2}) and strongest in spring and summer (-83.3 and -75.8 mWm^{-2} , respectively; Figure S5). The largest absolute reduction occurs in winter: at 10-fold reduction, net RF decreases by 66.9 mWm^{-2} in winter, but by 40.0 mWm^{-2} in summer, as more longwave warming is removed (88.6 versus 70.2 mWm^{-2}) and less shortwave cooling is lost (21.7 versus 30.2 mWm^{-2}). With RED50, net RF is negative in all months (-4.1 to -8.8 mWm^{-2} for seasonal means).

However, regional and seasonal analysis (Figure 2c-e) shows that the order of highest reductions in different regions occurs in different seasons. Over Europe, REF net RF is highest in winter and fall (601.8 and 537.8 mWm^{-2}) and lowest in summer (227.8 mWm^{-2}). The shortwave to longwave RF ratio increases from 0.53–0.54 in winter and fall to 0.71–0.76 in spring and summer. As a result, RED10 makes net RF negative in spring and summer (-48.0 and -24.2 mWm^{-2}), but not in winter and fall (21.4 and 35.2 mWm^{-2}), which require 10- to 15-fold and 15- to 25-fold reductions, respectively. Over the USA, net RF is highest in winter and

spring (285.8 and 269.6 mWm^{-2}), and about half as large in summer and fall (139.6 and 138.9 mWm^{-2}). RED10 makes net RF negative in all seasons except summer (2.9 mWm^{-2}), which requires a 10- to 15-fold reduction. Over the North Atlantic, net RF is highest in winter (430.6 mWm^{-2}) and lowest in spring (274.0 mWm^{-2}) and remains positive in RED10 across all seasons (4.7-65.5 mWm^{-2}). It becomes negative with a 10- to 15-fold in spring, 15- to 25-fold in summer and fall, and 25- to 50-fold in winter, which has the smallest ratio of shortwave to longwave RF ratio of all regions and seasons (~ 0.41). Under RED50, all regions exhibit negative net RF across all seasons, with the largest absolute reductions in winter in all three regions (681.8 mWm^{-2} in Europe followed by 437.3 mWm^{-2} in the North Atlantic and 339.1 mWm^{-2} in the USA).

Figure 2f-i presents reduction scenarios based on percentage differences from REF, showing that the order of reduction changes in relative terms. Globally, at 10-fold EI_{ice} reduction, the largest relative reduction occurs in spring ($\sim -101\%$), and the smallest in winter ($\sim -89.5\%$), as spring has the strongest shortwave cooling, much of which remains with the unchanged contrails, while winter has the largest absolute reduction. For the same reduction factor, the relative reduction is largest in spring and smallest in fall over Europe (-114% and -93%), largest in fall and smallest in summer over the USA (-107% and -98%), and largest in spring and smallest in winter over the North Atlantic (-98% and -85%). The EI_{ice} reduction required to eliminate net warming varies by regions and seasons: a 10-fold EI_{ice} reduction is sufficient over Europe in spring and summer and over the USA for most of the year, while the North Atlantic requires a 10- to 25-fold reduction from spring to fall and 25- to 50-fold in winter. This suggests that significant contrail net RF reduction could be achieved with EI_{ice} reduced to these levels, for example by region- and time -dependent INP seeding.

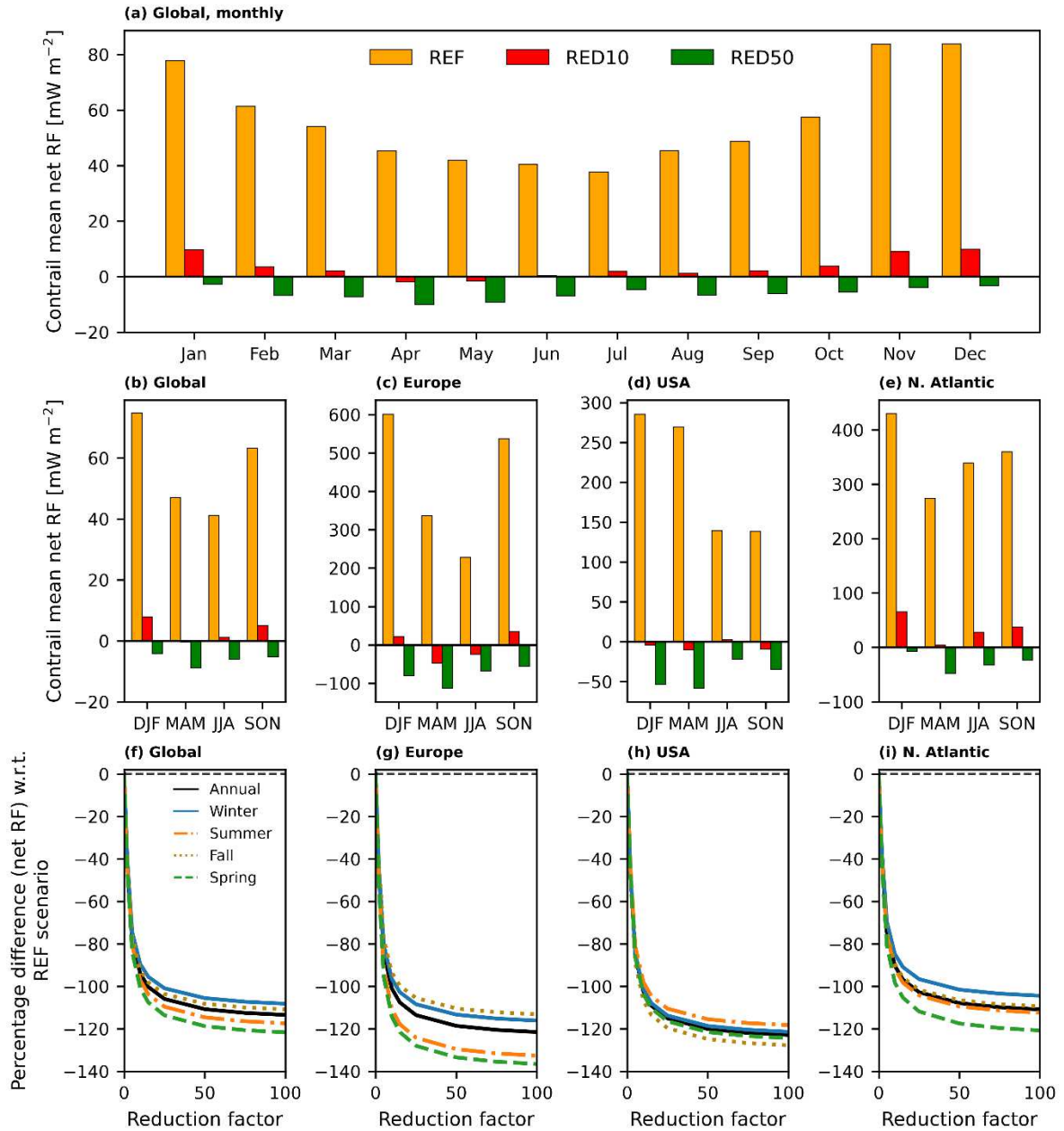


Figure 2. Seasonal and regional variation of mean contrail net RF in 2019. (a) Monthly distribution of global contrail mean net RF for REF, RED10, and RED50 scenarios. (b-e) Seasonal mean net RF (DJF: winter, MAM: spring, JJA: summer, SON: fall) for the global, Europe, the USA, and the North (N.) Atlantic. (f-i) Change in annual and seasonal mean net RF relative to REF (%) as a function of El_{ice} reduction factors for the same regions.

3.3 RF Sensitivity to EI_{ice} Reduction

Sensitivity tests show that contrail net RF decreases nonlinearly with reductions in EI_{ice} (Figure 3a,b). Most of the radiative response occurs with 2- to 10-fold reductions; further reductions yield diminishing returns as the response approaches an asymptote. The global mean net RF drops sharply at the small reduction factors. The global mean net RF drops sharply with small reductions: 2-, 5-, and 10-fold reductions remove ~43%, ~78%, and ~94% of the REF net RF, respectively. Nearly half of the change occurs with the first 2-fold reduction, and most is achieved by 10-fold. Net RF is close to zero (-0.2 mWm^{-2}) at 15-fold and decreases slowly with further reductions; increasing from 10- to 100-fold lowers net RF by only $\sim 11.0 \text{ mWm}^{-2}$. The 10- to 25-fold range adds only $\sim 6.7 \text{ mWm}^{-2}$ (12% of REF), during which global net RF shifts from slightly positive to negative values. These results suggest that most achievable net RF reduction occurs within 2- to 10-fold reductions in EI_{ice} , with further reductions providing smaller incremental benefits (Figure 3a). Physically, this reflects a transition from numerous, optically effective ice particles causing net warming dominated by longwave trapping, to thinner, shorter-lived contrails with less coverage as EI_{ice} decreases. The curve levels off because cooling contrails are not reduced; as seeded contrails lose most of their forcing, the global net RF approaches the small negative value left by unchanged contrails, rather than from seeded contrails that have become cooling. Because no uncertainty analysis was done in this study, we do not attach significance to the sign of this small residual; this should be assessed in future work.

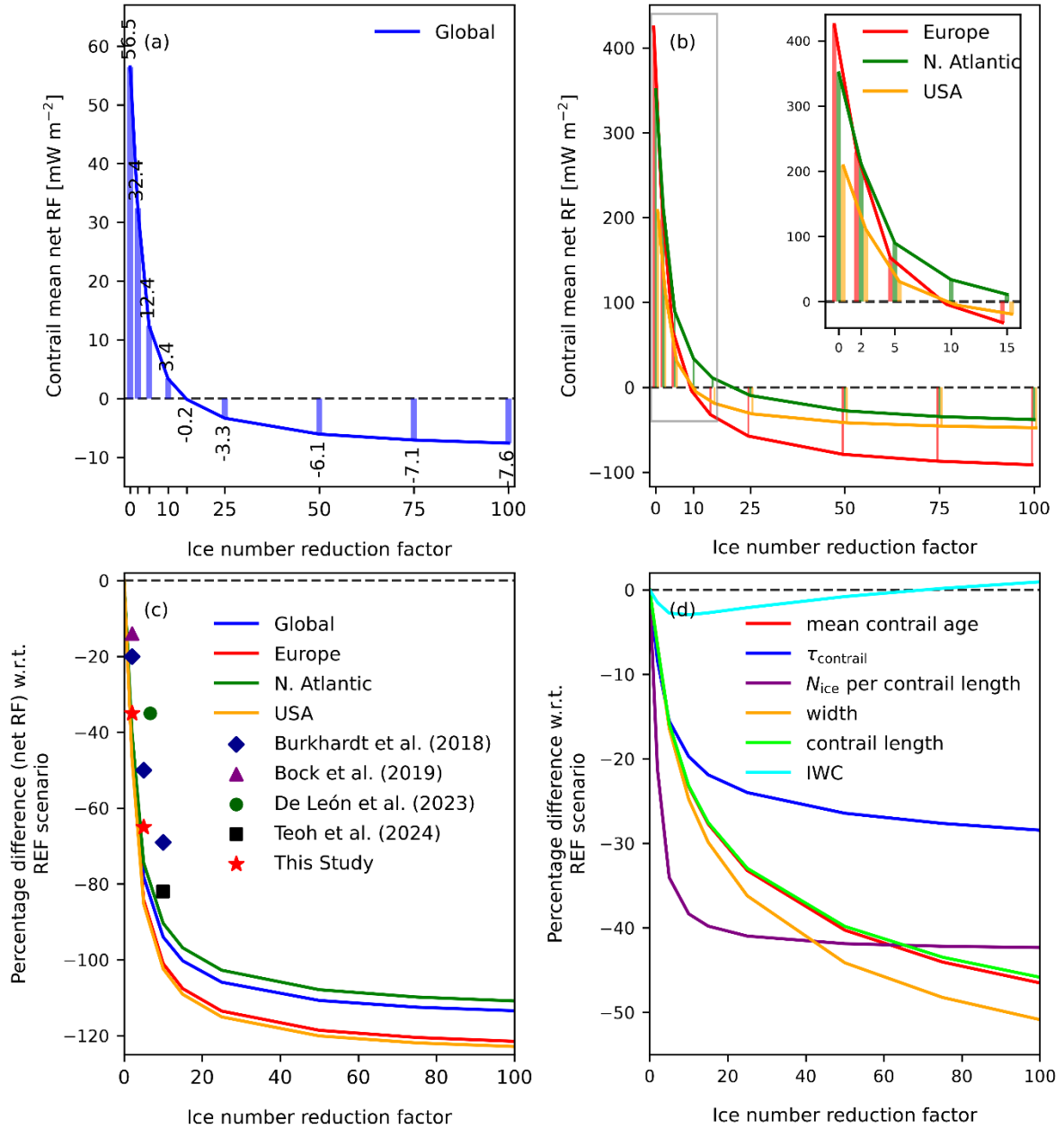


Figure 3. 2019 annual mean contrail net RF as a function of EI_{ice} reduction factor applied to warming (high-EF) contrails; a factor of 1 is REF. (a) Global mean contrail net RF, (b) mean contrail net RF for Europe, USA, and the North Atlantic region; the insets enlarge reductions of 1- to 15-fold, (c) change in net RF relative to REF (%) for global, Europe, USA, and North Atlantic, and (d) change relative to REF (%) in global mean contrail age, length, width, optical depth (τ_{contrail}), number of ice crystals per contrail length and ice water content (IWC). In

(d), mean contrail properties are obtained by averaging lifetime means across all contrails. In (c), the red (star) markers show the percentage difference in net RF with REF for this study when all contrails (warming + cooling) are reduced by a factor of 2 and 5, respectively. Blue markers (diamond) represent the decrease in mean net contrail RF for a 2- and 5-fold reduction in initial ice number using global climate model simulation by Burkhardt et al.²⁹ Similarly, the purple marker (triangle) shows the decrease in RF for a 2-fold reduction from Bock and Burkhardt,¹¹ the green marker (circle) shows for ~6.7-fold reduction from De León and Lee³⁰ and the black square shows for 10-fold reduction from Teoh et al.⁷

This nonlinearity is also observed regionally, though with varying magnitudes (Figure 3b,c). Regional curves display similar nonlinear behavior, but Europe and the USA show greater fractional sensitivity than the North Atlantic, with the global curve falling in between. All three curves follow the same pattern but level off at different values. Europe and the USA drop below zero at 10-fold and change by -121% and -123%, respectively, at 100-fold, while the North Atlantic only drops below zero between 15- and 25-fold and changes by -111% at 100-fold. This difference is due to remaining cooling. At 100-fold, unchanged contrails still provide about 62% of the REF shortwave RF over Europe and the USA, but only 50% over the North Atlantic, leaving less cooling there to offset longwave warming. These results indicate that, while global mean analysis shows negative contrail mean net RF at a reduction factor of 15 and above, regional analysis reveals that Europe and the USA can achieve large reductions (negative annual mean net RF) with a factor of 10. In contrast, for the North Atlantic, net RF remains positive at this level, demonstrating that a single global reduction factor does not eliminate contrail warming equally across all regions.

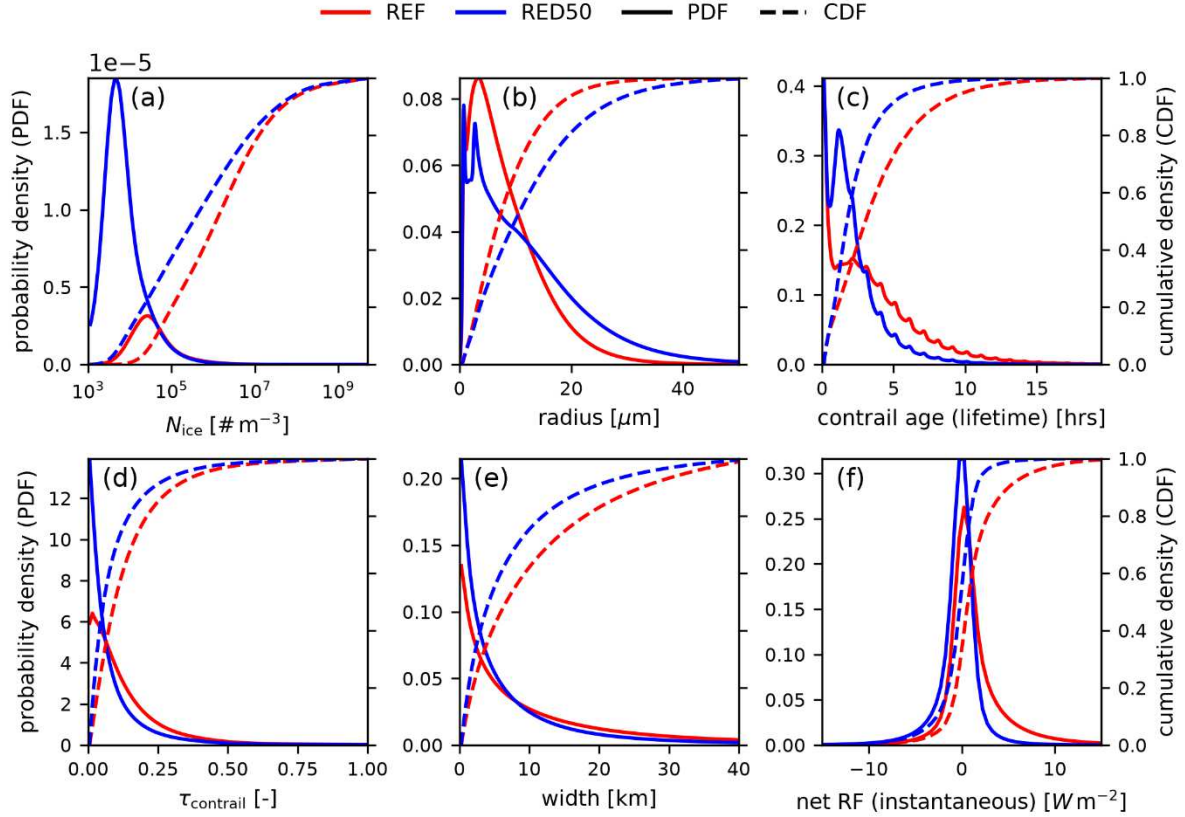
3.4 Contrail Properties and Mechanisms

Figure 3d illustrates how mean contrail properties vary with the EI_{ice} reduction factors. The ice number per contrail length decreases by ~21%, ~38%, and ~42% at 2-, 10-, and 50-fold reductions, then levels off because the seeded contrails carry about ~43% of the REF ice number per length, while other contrails remain unchanged. IWC changes by less than ~3% across all reduction factors because CoCiP keeps the plume at ice saturation, so its ice mass is set by the emitted water vapor and the ambient humidity rather than by the number of ice crystals. As a result, the same ice mass is distributed among fewer crystals, increasing the volume-mean radius by ~42% at 10-fold and ~82% at 50-fold reductions (from 6.5 to 11.7 μm), nearly tripling the fall speed. Seeded contrails dissipate sooner and spread less: mean age decreases by ~23% and ~40%, and width by ~25% and ~44% at 10- and 50-fold reductions, respectively. Consequently, ice mass per contrail length drops by ~36% and ~50%, although IWC remains nearly constant. Optical depth decreases by ~20% and ~26% at 10- and 50-fold reductions, as larger crystals partially offset the lower number. The ~111% decline in net RF at 50-fold is much larger than the drop in optical depth, due to shorter lifetime and smaller area of seeded contrails, as well as unchanged cooling contrails. While contrail properties vary by region and season (Figure S3e–h), the microphysical response to EI_{ice} reduction is largely consistent, with similar decreases in age, width, and optical depth, and similar increases in radius. Apart from a weaker shortening of North Atlantic winter contrails, regional and seasonal RF differences mainly result from the shortwave–longwave balance rather than microphysical variations.

Figure 4 presents probability and cumulative density plots of contrail properties. Figure 4a shows the distribution of ice particle number concentration (N_{ice}) in the contrail plume on a logarithmic scale, indicating probability per decade. In RED50, reducing EI_{ice} results in

448 significantly lower initial ice number concentrations compared to REF. The RED50 curve
449 peaks at lower N_{ice} , indicating a predominance of lower concentrations. As N_{ice} decreases,
450 mean particle size increases (Figure 4b). Larger particles fall nearly three times faster in
451 RED50, resulting in younger contrails on average (mean age 2.1 hours versus 3.5 hours in
452 REF; Figure 4c), with fewer reaching older, wider stages (Figure 4e). The optical depth
453 distribution shifts only slightly (Figure 4d), as larger crystals partially compensate for the lower
454 number. The instantaneous net RF of the contrail segments also shifts toward smaller values
455 (Figure 4f). A similar pattern was observed in a trajectory-based CoCiP study for SAF over the
456 North Atlantic: ~55% lower ice number per contrail length resulted in 25% larger crystals, a
457 15% shorter contrail age, and a 22% lower optical depth.²³ So, at formation, reducing EI_{ice} while
458 conserving IWC produces fewer, larger crystals. These larger crystals scatter more
459 anisotropically and less efficiently per unit mass, reducing contrail optical depth per area,

460 consistent with reduced lifetime and width, and together shift the LW/SW balance to decrease
 461 net RF.²⁹



462

463 **Figure 4.** Probability (solid) and cumulative (dashed) density function of (a) ice crystal number
 464 per contrail plume volume and (b) volume-mean ice crystal radius (c) contrail age (lifetime),
 465 (d) contrail optical depth ($\tau_{contrail}$), (e) contrail width, and (f) instantaneous net RF, for the
 466 REF (red) and RED50 (blue) cases. The distribution includes all contrails. In (a), (b), (d), and
 467 (e), each contrail segment is counted once at each model time step (unweighted); in (c), each
 468 contrail is counted once with its lifetime; and in (f), each segment and time step is weighted
 469 by its area. In panel (a), the left y-axis represents the logarithmic probability density

($dP/d\log_{10}N_{ice}$), indicating probability per decade of ice crystal number and expressed as a dimensionless quantity.

3.5 Comparison with Previous Studies and Limitations

Both GCMs and the CoCiP model have been used to estimate global mean net RF from contrail cirrus due to reductions in El_{ice} or $nvPM\ EIn$. This study finds a stronger net RF response to El_{ice} reduction than previous GCM studies (Figure 3c). Applying 2- and 5-fold reductions to all contrails, net RF decreases by 35% and 65%, compared to 21% and 50% in the ECHAM5-CCMod (ECHAM5 climate model with contrail cirrus module) climate model used by Burkhardt et al.²⁹, 14% for a 2-fold reduction in Bock & Burkhardt¹¹ with projected 2050 traffic, and 35% for a 6.7-fold reduction in De León & Lee.³⁰ These differences result from variations in model physical processes and spatiotemporal resolution, including saturation effects, cloud overlap, environmental interactions, and early contrail formation. A significant portion of the difference is due to how water vapor and ice growth are treated. In the climate model, contrail cirrus competes with natural cirrus for available water vapor, so water not used by fewer contrail crystals remains available to natural cirrus and older contrails. This offset limited RF reduction to less than 40% over Europe and the USA.²⁹ In CoCiPGrid, each contrail segment evolves independently, without exchanging water vapor with its surroundings or other contrails. It also keeps the plume at ice saturation, so fewer crystals absorb the available water at once, leading to faster growth and sedimentation.^{37,38} The climate model shows the same early response, with larger crystals, faster sedimentation, and a 4–5 hour shorter life of contrail cirrus clusters. However, later in the life cycle, the ice mass is limited by the low ice number concentration, and in dense traffic, new contrails add ice crystals to older contrail cirrus. Over the North Atlantic, an 80% reduction lowered contrail cirrus RF by about 70%.²⁹ The baselines

also differ: Burkhardt et al.²⁹ used a single initial ice number ($\sim 5 \times 10^{14} \text{ kg}^{-1}$ fuel) for 2002 traffic and reported stratospheric-adjusted RF, while this study uses gridded nvPM emissions for 2019 and instantaneous RF.

Trajectory-based CoCiP shows a similarly strong response, with an 82% reduction in net RF when nvPM EIn was lowered from 10^{15} to 10^{14} kg^{-1} for all 2019 flights (Figure 3c).⁷ Because the activation fraction in CoCiP depends only on temperature and the lower limit of 10^{13} kg^{-1} is not reached, this scenario is comparable to a 10-fold EI_{ice} reduction for all contrails. The 82% decrease is larger than the 69% observed for the same reduction in ECHAM5-CCMod,²⁹ indicating that both CoCiP versions respond more strongly than the climate model, for the reasons outlined above. Restricting the reduction to warming contrails further increases the benefit. This targeted approach differs from earlier studies, which reduced the ice number of all contrails or the nvPM emissions of all flights. For the same reduction factor, net RF falls by 43% and 78% at 2- and 5-fold when only warming contrails are reduced, but by 35% and 65% when all contrails are reduced, as unseeded contrails retain their shortwave cooling. Burkhardt et al.²⁹ estimated the effect of targeting only from the life cycles of contrail cirrus clusters (about 21% and 35% when the initial ice number is reduced by 80% in the 10% and 25% of synoptic situations with the largest clusters), whereas here it is simulated at each grid point and hour. Existing studies do not show whether the CoCiP or the climate model response is more realistic. Our 65% decrease for a 5-fold reduction of all contrails is close to the climate model decrease over the North Atlantic (about 70%) and for single contrail cirrus clusters (about 65% in lifetime-integrated extinction), where contrails interact little, but is larger than the decrease over Europe and North America (less than 40–50%).²⁹ Comparisons of both model types for

the same targeted scenarios, and observations of contrails with reduced ice number, are needed to resolve this.

Several processes not represented in CoCiPGrid could change the simulated response, either reducing or increasing the benefit of a given reduction factor. First, the lack of water vapor and ice exchange between contrails, older contrail cirrus, and natural cirrus may lead to larger reductions in dense traffic regions than in a model that includes these interactions. Second, vortex-phase survival does not depend on ice number, while large-eddy simulations show that fewer and larger crystals survive the vortex phase more efficiently.^{44,45} For example, a 10-fold reduction in EI_{ice} results in only about a 5.3-fold reduction after the vortex phase, with a stronger effect in warm and dry air.^{44,45} We note that an ice-number-dependent survival fraction⁴⁵ and the extended K15 activation³⁴ scheme for volatile particle activation have been added to later pycontrails releases (v0.63.2). With an ice-number-dependent survival fraction, fewer crystals would survive the vortex phase in nominal- and high-nvPM exhaust, lowering REF net RF, while a larger fraction of remaining crystals would survive in the reduction cases. As a result, net RF in the reduction cases would be higher than simulated here. Volatile particle activation can yield up to $\sim 10^{16} \text{ kg}^{-1}$ in cold air with sulfur-rich exhaust, increasing REF EI_{ice} for the low-nvPM group.³⁴ Because seeded particles also suppress ice formation on volatile particles,³⁵ the reduction factors would then act on a larger REF EI_{ice} , so the absolute benefit of a given reduction could be larger. Additionally, CoCiPGrid gives a lower EI_{ice} than the COMBINES plume model when nvPM emissions are low. For an nvPM EI_n of 10^{12} kg^{-1} , CoCiPGrid uses the lower limit of 10^{13} kg^{-1} , whereas the plume model gives an EI_{ice} without seeding of about 10^{14} to $5 \times 10^{15} \text{ kg}^{-1}$ at 209–220 K, because volatile particles also form ice, and a smallest EI_{ice} of about $2 \times 10^{13} \text{ kg}^{-1}$ with optimized seeding.³⁵ Applying a constant

reduction factor to the lower CoCiPGrid value therefore underestimates the REF RF of these contrails and the absolute benefit, but it also produces reduced El_{ice} values below those reached by seeding, which overstates the reduction. In nvPM-rich exhaust, the reduction achieved by seeding ranges from about 3-fold or less in cold air to about 80-fold closer to the formation threshold,³⁵ so a single factor applied at all seeded grid points can be too small or too large. The reduction is also applied to all warming contrails, which assumes perfect forecasts of warming contrails and overstates the benefit achievable in practice.²⁸ Because the missing processes influence El_{ice} and contrail RF in different directions that were not tested here and large uncertainties in RF based on CoCiP, the simulated net RF presented here should not be interpreted as a definitive upper or lower estimate for any reduction factor. Establishing whether the true response lies above or below our sensitivity results remains a topic for future work.

Two additional factors influence the sign of net RF at large reductions, which is determined by shortwave cooling. First, overlap is only partially represented: natural cirrus above a contrail and clouds below it are included in the RF scheme through cirrus optical depth and ERA5 fluxes,⁴³ but contrail-contrail overlap is not included in CoCiPGrid. Overlap reduces shortwave cooling more than longwave warming (by 66% and 37% for overlap with natural clouds), and contrail-contrail overlap lowers the global net contrail RF by about 3%⁴⁶ or by 4.8% in trajectory-based CoCiP for 2019⁷. Omitting this effect tends to overestimate the negative net RF. A change of 2-3 mWm^{-2} would not eliminate the negative net RF at 50-fold ($-6.1 mWm^{-2}$) but could at about 15-fold ($-0.2 mWm^{-2}$), especially in dense traffic corridors such as the North Atlantic. Contrail cirrus ERF is smaller, less than 50% of the instantaneous or stratosphere-adjusted RF, with a best estimate of about 35% in one climate model study,⁴⁷ and 0.42 (0.21–

0.59) of RF in aviation assessments.^{2,7} However, these ratios were derived for contrail populations with net warming. When the shortwave and longwave terms nearly cancel, their adjustments may not scale similarly, so the negative net RF at large reductions should not be interpreted as a negative ERF.

4. Implications

Results highlight that large EI_{ice} reductions in warming contrails, motivated by COMBINES, could substantially reduce aviation-induced climate warming. Sensitivity experiments extending EI_{ice} reductions beyond the 10-fold limits of earlier studies^{29,30} yield three key findings for contrail mitigation. First, the most benefits occur early and then saturate: 2-, 5-, 10-, and 25-fold reductions in warming contrails decrease global net RF by ~43%, ~78%, ~94%, and ~106%, respectively, with diminishing returns at higher reductions. Second, the saturation point is determined by unseeded contrails, whose shortwave cooling brings global net RF close to zero or slightly negative at about 15-fold reductions and higher. Third, the required reduction varies by region and season: a 10-fold reduction brings annual net RF close to zero or below over Europe and the USA, while the North Atlantic requires 15- to 25-fold reductions, and 25- to 50-fold in winter. Globally and seasonally, most benefits are realized by about a 10-fold reduction, with larger reductions offering minimal additional gains, though requirements differ by region, season, and individual contrail. For COMBINES, a 10- to 25-fold reduction, achievable under favorable conditions, would capture most potential benefits. Since ~ 2.2% of flights account for 80% of total contrail warming, only a small proportion of flight distance requires seeding to reach targeted EI_{ice} levels.^{7,27} This effectiveness is comparable to navigational avoidance, which reduces contrail forcing by 59-73% with only 0.01-0.1% additional fuel by rerouting flights that form warming contrails.^{27,48} A 5-fold EI_{ice}

reduction in this study yields a comparable benefit (~78%), while 10- to 25-fold reductions provide greater benefits of ~94% and ~106%, respectively, when fully achieved. The two approaches differ: avoidance prevents contrails by altering flight paths at the expense of extra fuel burn, while seeding maintains the route and modifies contrail properties, requiring onboard seeding systems and materials. This targeted approach might address challenges related to identifying ISSR, additional fuel use, and operational complexity associated with avoidance.³⁵ In this study, reductions are applied to all contrails with high EF; however, optimal reduction factors depend on aircraft type, flight trajectory, fuel burn, and atmospheric conditions. Customizing INP seeding strategies for specific aircraft, operational profiles, and environmental conditions could further improve COMBINES effectiveness.

Within the constraints of grid-based mean aviation emissions and aircraft properties, the results suggest that reducing EI_{ice} in warming contrails by more than 10- to 15-fold would bring the global annual mean contrail net RF close to zero or slightly negative. These findings are idealized and subject to uncertainties that require further evaluation before interpreting the small net RF at high reduction levels. At a 15-fold reduction, the global net RF (-0.2 mWm^{-2}) is much smaller than the likely uncertainty from model inputs such as humidity, nvPM emissions, and aircraft properties.^{7,37} A comprehensive climate assessment of COMBINES should also consider the direct radiative effect of seeded particles and their potential as ice nuclei for natural cirrus after contrail dissipation. Studies of deliberate cirrus seeding show that added ice nuclei can either thin or thicken cirrus, depending on quantity, so the overall effect remains uncertain.⁴⁹ Future research should evaluate COMBINES for specific aircraft-engine trajectories or fleets with well-defined emission and performance characteristics, test both nvPM/vPM activation microphysics and number- and size-dependent vortex survival, compare

with climate models for the same reduction scenarios, quantify the uncertainty of the small net RF at large reductions, and assess targeted seeding using realistic forecasts of warming contrails.

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Code and Data Availability:

The pycontrails repository that contains the algorithms for trajectory-based CoCiP and grid-based CoCiP (CocipGrid) is publicly available at <https://github.com/contrailcirrus/pycontrails>.

The Global Aviation emissions Inventory-based ADS-B (GAIA) dataset for 2019 was obtained from <https://doi.org/10.5281/zenodo.8369829>.

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Figures

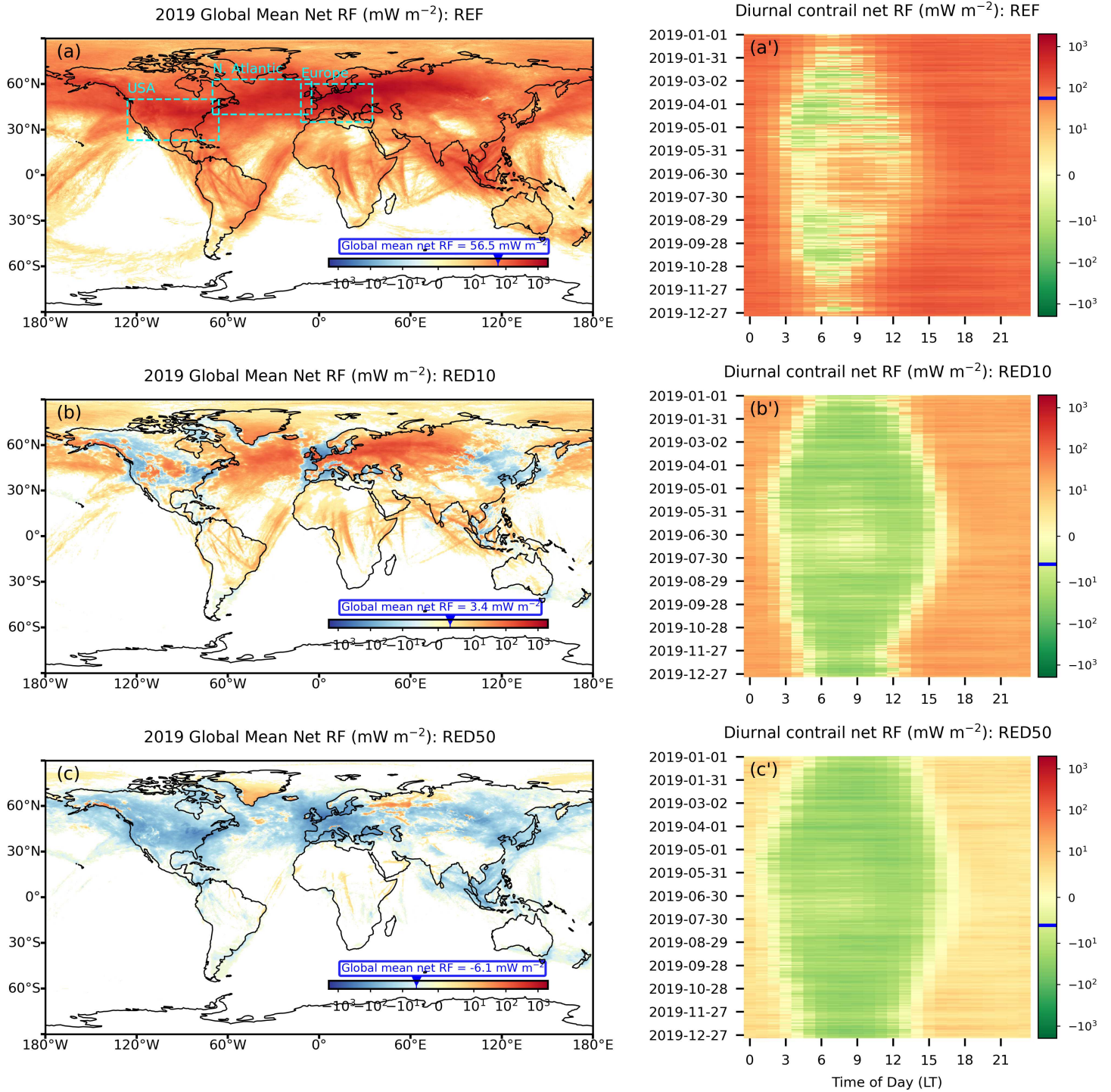


Figure 1

Figure 1. 2019 global annual mean contrail net RF averaged over the whole year (a), (b), (c) and diurnal variation of global average contrail net RF for each hour of 2019 (a'), (b') and (c') for REF, RED10, and RED50 cases, respectively. The REF represents the reference case simulation with three aircraft-engine categories based on nvPM EIn using the CoCiPGrid model. RED10 and RED50 represent the idealized

simulations with El_{ice} reduced by factors of 10 and 50. Spatial bounding box in (a) shows the regions (Europe, USA, and North Atlantic) with high air traffic density as defined by Teoh et al.⁷

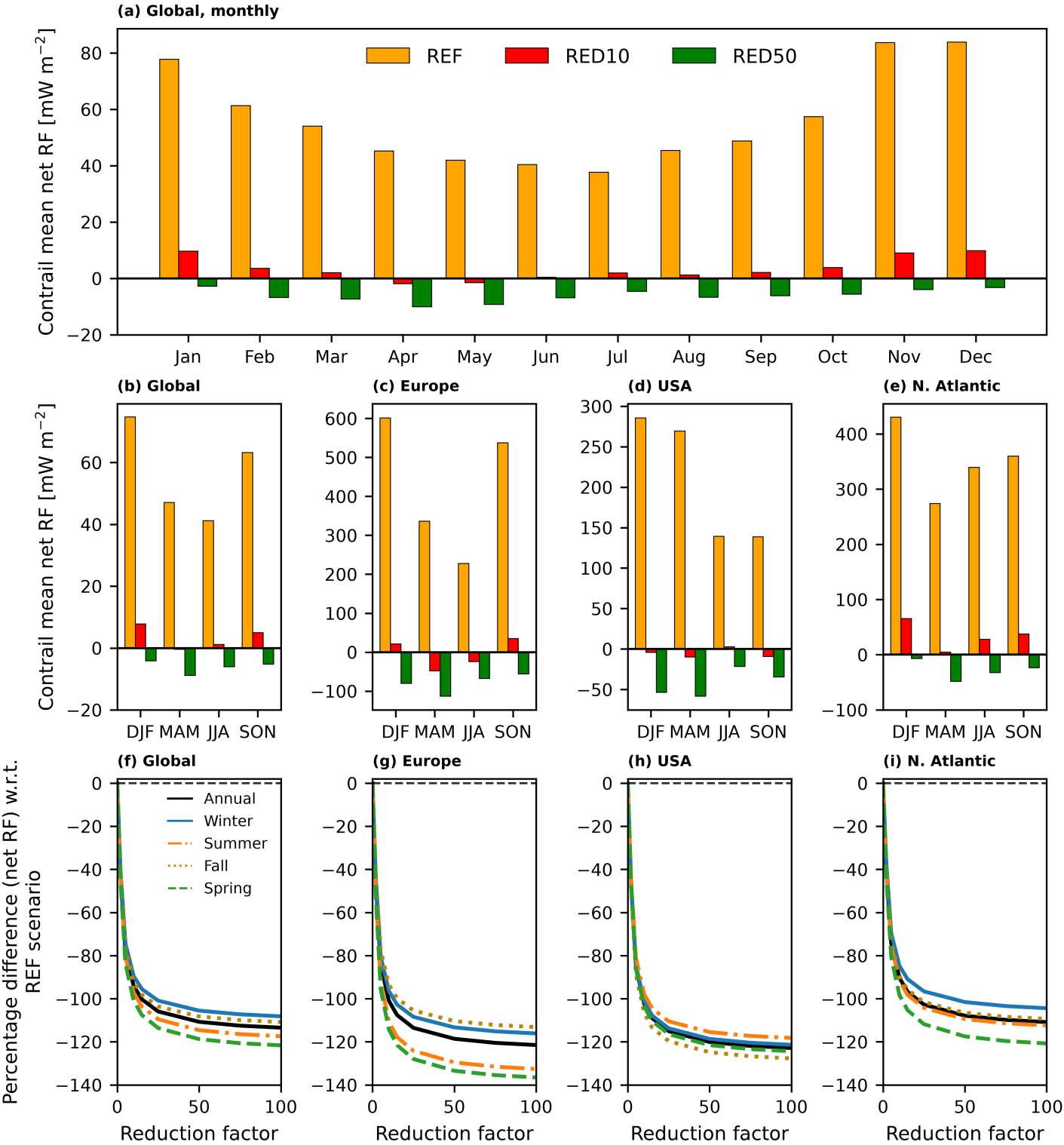


Figure 2

Figure 2. Seasonal and regional variation of mean contrail net RF in 2019. (a) Monthly distribution of global contrail mean net RF for REF, RED10, and RED50 scenarios. (b-e) Seasonal mean net RF (DJF:

winter, MAM: spring, JJA: summer, SON: fall) for the global, Europe, the USA, and the North (N.) Atlantic. (f-i) Change in annual and seasonal mean net RF relative to REF (%) as a function of EI_{ice} reduction factors for the same regions.

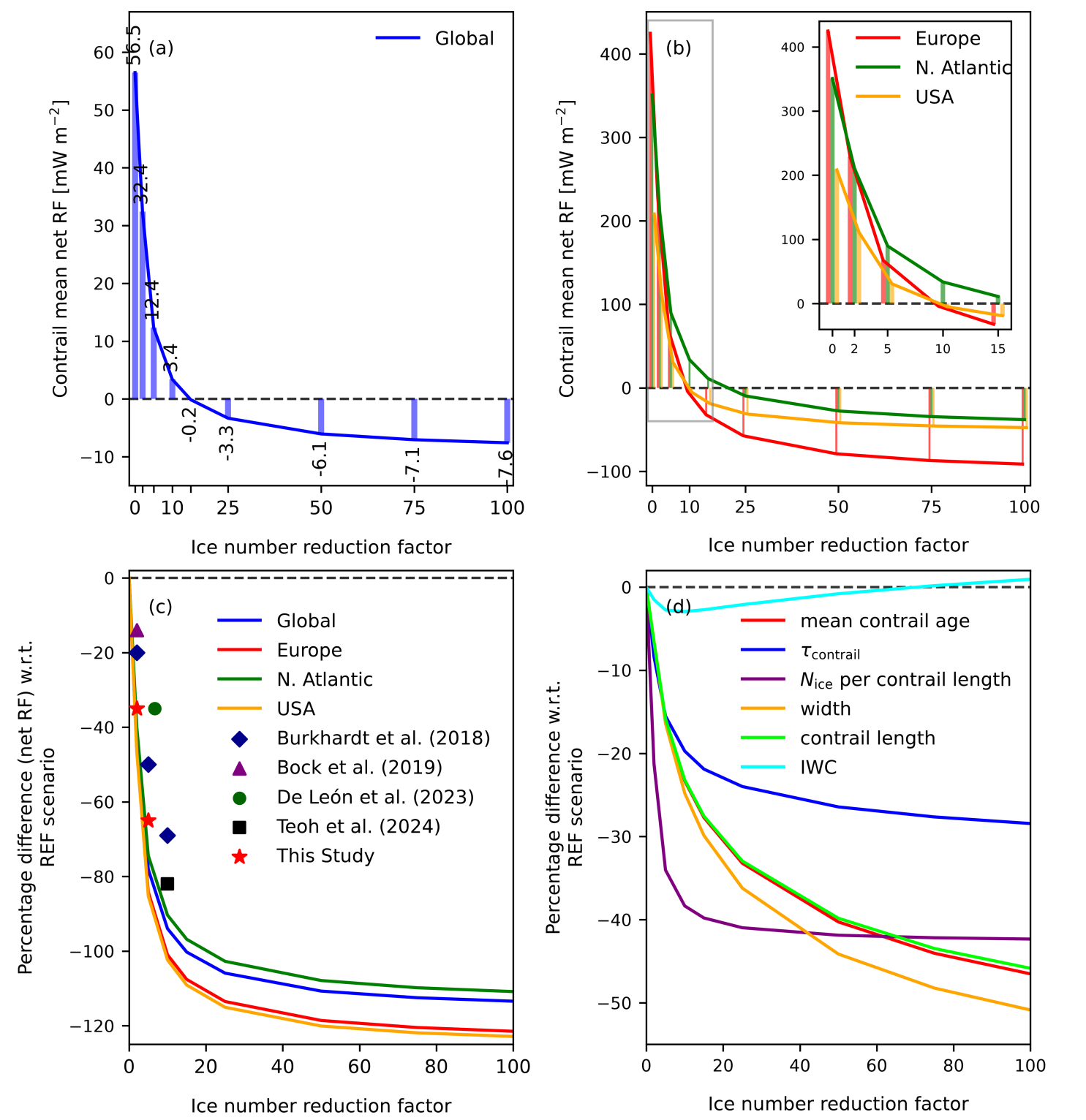


Figure 3

Figure 3. 2019 annual mean contrail net RF as a function of El_{ice} reduction factor applied to warming (high-EF) contrails; a factor of 1 is REF. (a) Global mean contrail net RF, (b) mean contrail net RF for Europe, USA, and the North Atlantic region; the insets enlarge reductions of 1- to 15-fold, (c) change in net RF relative to REF (%) for global, Europe, USA, and North Atlantic, and (d) change relative to REF (%) in global mean contrail age, length, width, optical depth (), number of ice crystals per contrail length and ice water content (IWC). In (d), mean contrail properties are obtained by averaging lifetime means across all contrails. In (c), the red (star) markers show the percentage difference in net RF with REF for this study when all contrails (warming + cooling) are reduced by a factor of 2 and 5, respectively. Blue markers (diamond) represent the decrease in mean net contrail RF for a 2- and 5-fold reduction in initial ice number using global climate model simulation by Burkhardt et al.²⁹ Similarly, the purple marker (triangle) shows the decrease in RF for a 2-fold reduction from Bock and Burkhardt,¹¹ the green marker (circle) shows for ~6.7-fold reduction from De León and Lee³⁰ and the black square shows for 10-fold reduction from Teoh et al.⁷

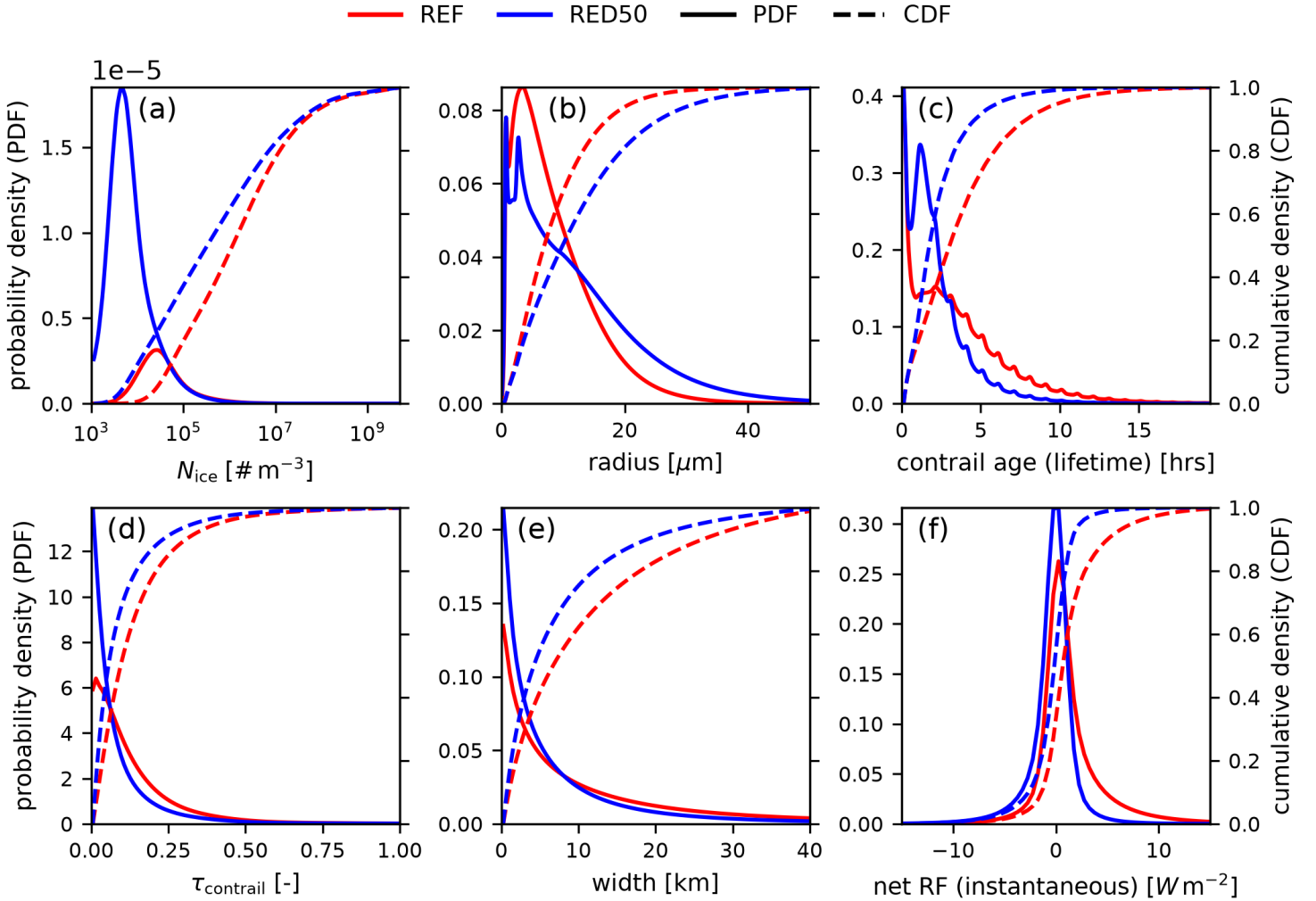


Figure 4

Figure 4. Probability (solid) and cumulative (dashed) density function of (a) ice crystal number per contrail plume volume and (b) volume-mean ice crystal radius (c) contrail age (lifetime), (d) contrail optical depth (), (e) contrail width, and (f) instantaneous net RF, for the REF (red) and RED50 (blue) cases. The distribution includes all contrails. In (a), (b), (d), and (e), each contrail segment is counted once at each model time step (unweighted); in (c), each contrail is counted once with its lifetime; and in (f), each segment and time step is weighted by its area. In panel (a), the left y-axis represents the logarithmic probability density ($dP/d\log_{10}N_{ice}$), indicating probability per decade of ice crystal number and expressed as a dimensionless quantity.

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