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Observation-Based Assessment of Contrail Climate Effects across the Euro-Atlantic Region in 2023

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Abstract

Aviation’s climate impact is dominated by non-CO₂ effects—primarily contrails—yet their magnitude remains poorly constrained due to reliance on model-based estimates. Here, we present a year-long assessment across the Euro–Atlantic region using a novel, observation-based framework that combines geostationary satellite data, neural-network detection, and rapid radiative forcing estimation. We find that contrail occurrence is highly concentrated over the North Atlantic and adjacent coasts (**75%** of detections), where transatlantic flight corridors intersect the jet stream. This spatial concentration translates into a strong imbalance in climate impact: North Atlantic traffic accounts for only $\sim$ **6%** of flights but contributes $\sim$ **60%** (potentially up to **85%**) of annual contrail-induced warming in this region. This extreme concentration highlights a high-leverage mitigation opportunity: targeting the most influential subset of flights—particularly transatlantic routes, focusing on nocturnal and late-afternoon operations, with stronger constraints in autumn and winter—could deliver substantial near-term reductions in aviation climate forcing.

Keywords: Aviation, Contrails, Satellite Observations, Climate Mitigation

Global mean surface temperature reached a record high in 2024, approximately 1.55°C ($\pm$ 0.13°C) above 1850–1900 levels, marking the first calendar year in which warming exceeded the 1.5°C threshold relative to pre-industrial levels [1] and breaking the limit established under the Paris Agreement [2]. This milestone represents a critical escalation of climate risk, increasing the likelihood of longer-term, potentially irreversible impacts, including accelerated sea-level rise and permanent vegetation change [3, 4]. Despite mitigation efforts, global temperatures are projected to rise by approximately 2.3–2.5°C by 2100 [5]. Identifying and targeting key anthropogenic climate drivers is therefore essential for limiting this expected warming. One such driver is aviation, a hard-to-abate sector that accounts for approximately 5% of total global anthropogenic radiative forcing [6], with this contribution expected to increase given the projected twofold rise in global passenger and cargo traffic growth rates by 2050, according to the International Civil Aviation Organization (ICAO) [7]. The sector has a technical mitigation roadmap in place, which includes the adoption of sustainable aviation fuels (SAFs) [8], the development of advanced engine technologies [9], and the design of hybrid-electric or hydrogen-powered aircraft [10]. However, these measures and regulatory frameworks, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [11], are primarily CO₂-focused and require medium to long-term developments. Also, while such initiatives address the carbon component, they overlook non-CO₂ effects, which have been recognized to contribute approximately two-thirds of aviation’s total anthropogenic radiative forcing [6], albeit with large uncertainties. These non-CO₂ forcing agents include nitrogen oxides (NO_x), aviation-induced ozone (O₃) formation, methane (CH₄) reduction, water vapour emissions (H₂O) at cruise altitudes, and aviation-induced contrails and contrail–cirrus clouds.

Among them, contrail-related effects represent both the largest individual non-CO₂ contributor to aviation’s radiative forcing [12] yet the most uncertain [13], largely due to limited understanding of cirrus cloud properties, geographical distribution, and lifetime, with most evidence derived from modeling studies [14]. Contrails form in the upper troposphere when hot, moist aircraft exhaust mixes with the ambient atmosphere [15]. These ice clouds alter Earth’s radiation budget by reflecting incoming shortwave solar radiation and trapping outgoing longwave terrestrial radiation; a positive (negative) balance results in net warming (cooling). Across a wide range of modelling studies [16–21], the net global annual effect of contrails is consistently estimated to be positive [22]. Young, linear contrails (≤ 5 h) exert an estimated net radiative forcing of 2–12 mWm^{-2} [17, 18, 21, 23], increasing to 50–280 mWm^{-2} when their evolution into long-lived contrail–cirrus clouds is considered [19, 20]. This combined effect is often comparable to, or exceeds, that of CO₂ over short time horizons [14], though reported magnitudes vary due to differences in methodology and spatial and temporal coverage.

Targeted contrail mitigation offers a significant opportunity for near-term climate benefits. By using flight planning to reroute aircraft away from atmospheric regions most prone to contrail warming, such strategies can achieve substantial climate gains at relatively low operational cost [24, 25], thereby driving growing regulatory interest. Indeed, the European Union has become the first jurisdiction to mandate the monitoring, reporting, and verification (MRV) of aviation non-CO₂ effects from January 2025 onward for an initial two-year period, after which the European Commission will assess the findings and propose appropriate regulatory measures [26]. Despite these advances, significant uncertainties remain in contrail identification and in the quantification of their radiative forcing. Observational evidence is therefore critical to validating existing contrail climate models and enabling robust monitoring and verification of their climate impacts.

The use of observation-based methods for studying contrails has gained prominence in recent years [27, 30–35], driven by the growing availability of data from ground-based imagers, low-Earth-orbiting satellites, and geostationary satellites. Ground-based instruments provide high spatial and temporal resolution, enabling detailed assessments of contrail formation and attribution to individual aircraft [30, 31], but their limited spatial coverage restricts large-scale monitoring. Low-Earth-orbiting satellites offer a balance between spatial resolution and coverage [32, 33], although revisit times can extend to several days. In contrast, geostationary satellites enable quasi-continuous monitoring (every 10–15 minutes) over a fixed domain covering much of the Earth-facing hemisphere centered on the sub-satellite point. Despite being 4–5 times coarser than low-Earth-orbiting imagers, their resolution remains sufficient to observe large numbers of contrails [27, 34, 35].

Early automated contrail detection relied on a multispectral line-detection method known as the Contrail Detection Algorithm (CDA) [36], where mean contrail cover distributions were typically determined with an error of order 50-100% [37], limiting its reliability. The availability of human-labeled datasets [32, 38] enabled supervised neural-network approaches, substantially improving detection performance [27]. Meijer et al. [39] produced the first continental-scale observational estimates of contrail coverage using neural networks, though associated radiative forcing was not quantified. Estimating climate impacts from satellite observations requires radiative transfer simulations [40], following pixel-level retrieval of cloud properties. These are typically derived using bi-spectral methods estimating optical depth and effective diameter under an assumed contrail temperature, or uni-spectral approaches assuming fixed effective diameter when infrared data are insufficient [41]. Radiative transfer simulations based on these retrievals have been used to estimate contrail forcing identified with CDA [23].

Recently developed cloud retrieval use full spectral information and optimal estimation to retrieve optical depth, phase, effective radius, and cloud-top pressure [28]. These products, available for some European satellites, were used by Wang et al. [42] to estimate radiative forcing for two contrail outbreak events. However, scaling such analyses is computationally expensive when radiative transfer simulations are performed per pixel. To address this, Dimitropoulou et al. [29] developed extensive look-up tables, producing radiative forcing estimates comparable to those from the CERES polar-orbiting instrument, enabling rapid and reliable pixel-level estimation.

Together, advances in neural-network contrail detection and rapid satellite-based radiative forcing estimation using look-up tables make large-scale observational assessments feasible and reliable. However, these

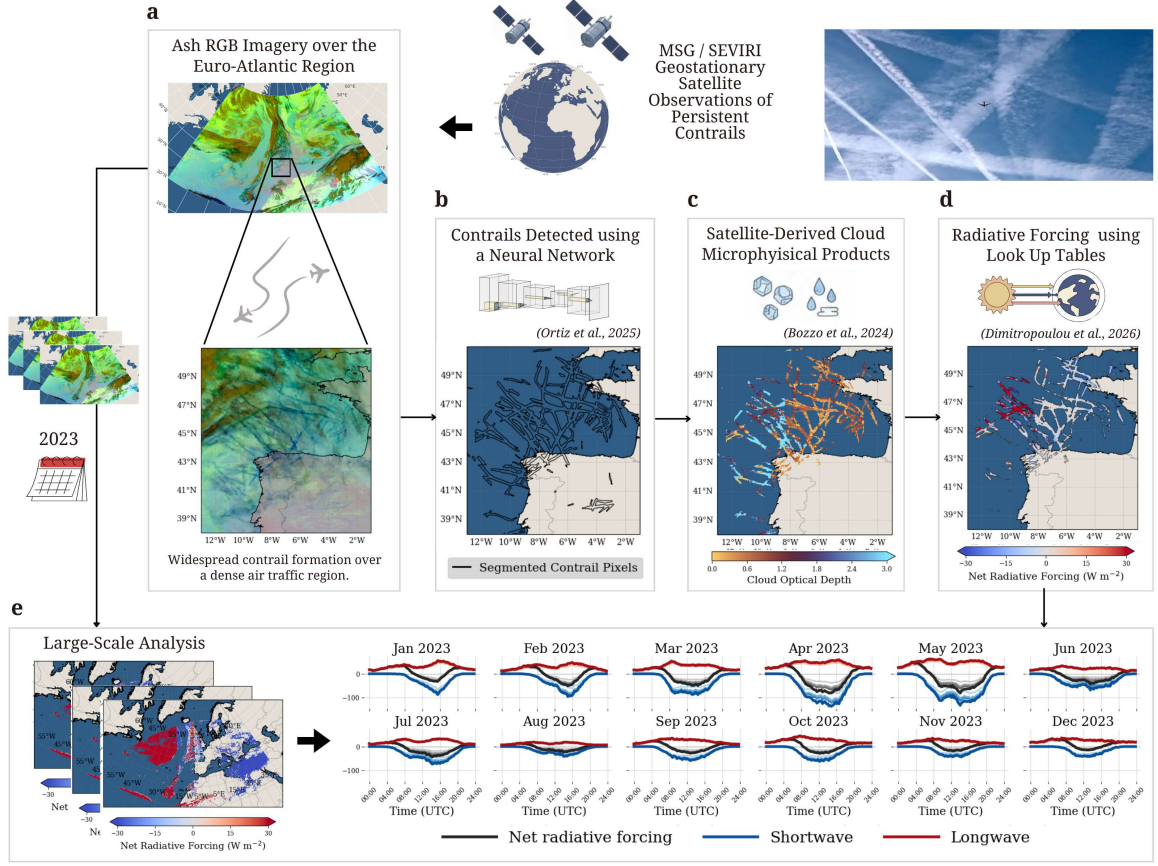


Fig. 1 Schematic overview of the methodology used to derive the year-long study. Observations from MSG/SEVIRI are used to construct Ash RGB imagery over the Euro-Atlantic region (60°W–40°E, 20°N–70°N). Contrails are detected and segmented using a neural-network-based algorithm [27]. Detected contrail pixels are subsequently characterized using cloud properties from the Optimal Cloud Analysis (OCA) products [28], including cloud phase, cloud top pressure, cloud optical depth and cloud effective radius. Shortwave and longwave radiative forcing are then estimated using pre-computed look-up tables derived from radiative-transfer simulations [29]. This framework is applied to the full year 2023 to quantify seasonal, diurnal, and regional variations in contrail coverage and radiative forcing.

capabilities have not yet been used to quantify observational trends in contrail climate impacts. Here, we address this gap by integrating these approaches to estimate contrail coverage and associated radiative forcing across Europe and the North Atlantic for 2023. A schematic overview of the framework is shown in Fig. 1.

1 Results

1.1 Contrail Coverage

The most radiatively relevant contrails are expected to be observable in geostationary satellite imagery for part of their lifetime [43], typically becoming visible once they reach the satellite pixel scale, approximately 1.1–1.9 h after formation [44]. They remain distinguishable until diffusion or transition into contrail-cirrus clouds reduces their optical depth and alters their linear shape. During this stage, contrails exhibit well-defined morphological characteristics that enable reliable detection [27] and clear discrimination from natural clouds in Ash RGB imagery. Consequently, geographical, diurnal, and seasonal trends are derived from all contrails detected by the neural-network-based method [27] (Section 3.2) using the satellite imagery described in Section 3.1.

1.1.1 Geographical Patterns

The results show that 75% of all contrails detected in 2023 occur over the North Atlantic Ocean and the coastal Atlantic region (Supplementary Fig. 1; Supplementary Table 1), as seen in the probability maps in Fig. 2. In the coastal Atlantic, high contrail coverage reflects dense air traffic, yielding relatively low coverage per unit distance flown of $\sim 30 \text{ m}^2\text{m}^{-1}$ (Supplementary Table 2). By contrast, the North Atlantic shows disproportionately high detections relative to traffic density, with values up to $\sim 488 \text{ m}^2\text{m}^{-1}$. Much lower values over other water-covered regions (e.g., the Black Sea, $1.6 \text{ m}^2\text{m}^{-1}$; the Baltic Sea, $8.3 \text{ m}^2\text{m}^{-1}$; and the Mediterranean, $9 \text{ m}^2\text{m}^{-1}$) indicate that enhanced occurrence over the North Atlantic is driven primarily by favorable atmospheric conditions, rather than increased detectability over darker and more homogeneous ocean surfaces.

In particular, contrails cluster near the jet stream, as eastbound nighttime flights along the North Atlantic track system are routed within it to reduce fuel consumption and flight time [45], while the jet stream regulates upper-level moisture, creating conditions favorable for persistent contrail formation, especially along its southern flank [46] (Supplementary Fig. 2). Consequently, spatial shifts in contrail occurrence (Fig. 2) largely reflect day-to-day jet-stream variability, more evident on weekly timescales (Supplementary Fig. 3) and mostly obscured in seasonal means, aside from a weak northward summer shift (Supplementary Fig. 4) consistent with seasonal jet migration.

In central and eastern Europe (excluding coastal Atlantic longitudes; Supplementary Fig. 1), contrail detections account for only 14% of total annual coverage, despite $\sim 70\%$ of aircraft crossings occurring there. As a result, coverage per distance flown is among the lowest in the domain ($5.4 \text{ m}^2\text{m}^{-1}$). This likely

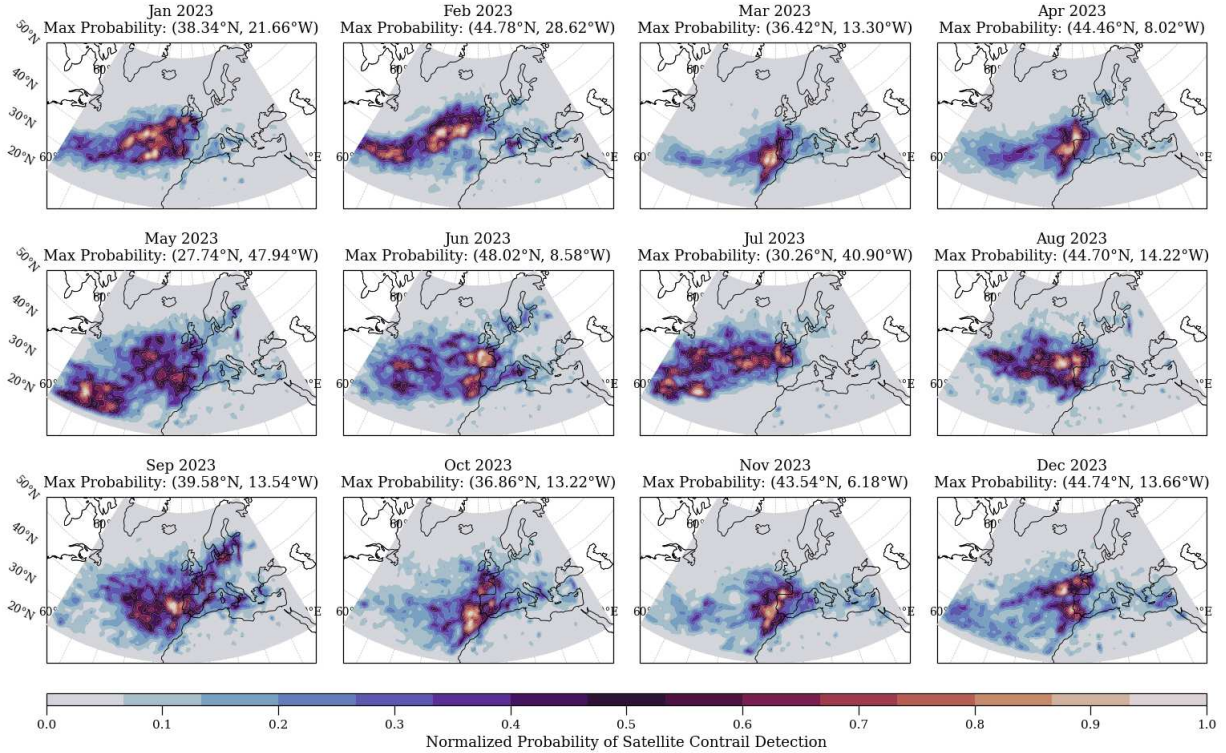


Fig. 2 Monthly distributions of contrail detection probability over the Euro-Atlantic region (60°W – 40°E , 20°N – 70°N) for 2023, inferred from neural-network detections applied to MSG/SEVIRI Ash RGB geostationary satellite imagery, where the mean annual contrail coverage amount to 0.18%. The monthly maps reveal persistent regions of enhanced contrail probability over the North Atlantic coastal sector (15°W – 0° , 20°N – 60°N), including the Iberian Peninsula, the French Atlantic coast, and the British Isles, which together yield the highest annual mean contrail coverage (0.48%). High probabilities, consistent across months, are also evident over the North Atlantic Ocean, corresponding to an annual mean coverage of 0.25%. In contrast, Central-Eastern Europe, the Mediterranean, and North Africa exhibit weaker and more intermittent monthly probabilities, resulting in lower annual mean values (~ 0.10 – 0.12%). High-latitude regions show consistently low monthly probabilities and negligible annual mean coverage ($\sim 0.01\%$) due to reduced spatial resolution at large satellite viewing angles, which makes linear contrails difficult to resolve. Variations in the spatial distribution occur primarily on daily timescales, reflecting meteorological conditions conducive to contrail formation and persistence. Monthly maps therefore depict aggregated patterns representative of regions with higher contrail detectability.

reflects less favorable conditions for persistence over land, such as enhanced vertical mixing or more extensive low-level cloud cover limiting satellite detectability, though these mechanisms require quantitative assessment. Notably, despite substantial Asian connections ($\sim 20\%$; Supplementary Table 3), detections over eastern Europe remain limited year-round (Fig. 2), with footprints at these longitudes mainly over the Mediterranean.

1.1.2 Diurnal Patterns

The diurnal cycle of detected contrail coverage closely follows air-traffic patterns [47], with a 35% nighttime reduction reflecting an approximately 15-fold decrease in traffic. Because nighttime contrail formation is limited and afternoon contrails rarely persist into the following day [48] (mean lifetime ~ 4 h [49]), the atmosphere is largely cleared by early morning. Enhanced moisture and lower temperatures after nighttime cooling favor early-morning formation, explaining the 06:00–08:00 UTC peak (Fig. 3), consistent with observations over the continental United States [39, 48].

Despite peak flight activity around 10:00–11:00 UTC (Supplementary Fig. 5), contrail coverage typically declines after the morning maximum. The causes remain uncertain but may include dehydration of ice-supersaturated regions by existing contrails [50] or reduced detectability due to increasing contrail-induced cloudiness. Months without a post-morning decline coincide with a broader latitudinal extent of detections (September–December; Fig. 2), indicating more extensive ice-supersaturated regions that limit rapid moisture depletion, supporting the dehydration hypothesis. A secondary afternoon peak (14:00–17:00 UTC), intermittent across months and sometimes exceeding the morning maximum, is linked to differences in transatlantic departure times.

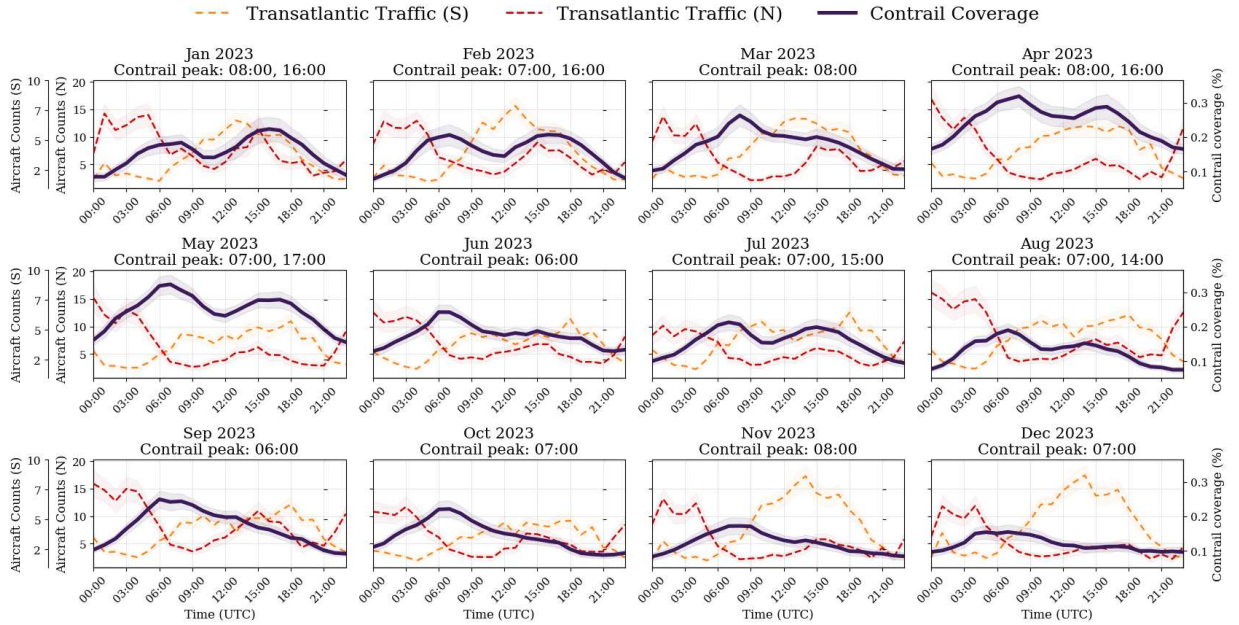


Fig. 3 Diurnal cycle of contrail coverage and aircraft counts over the North Atlantic Ocean (North Atlantic) at satellite image times. Solid lines show monthly mean contrail coverage, and dashed lines show mean transatlantic traffic on northern ($40 - 60^\circ$ N; red) and southern ($20 - 40^\circ$ N; orange) routes; shaded regions indicate 95% confidence intervals. Across all seasons, contrail coverage shows a pronounced morning maximum (06:00–08:00 UTC). This peak coincides with the onset of departures over continental regions and with peak traffic over the high-latitude North Atlantic, driven primarily by eastbound flights departing overnight from the western side of the Atlantic. These flights typically overfly the North Atlantic between approximately 03:00 and 05:00 UTC and arrive in Europe during the early morning hours. In some months, this morning maximum is followed by a secondary afternoon peak (14:00–17:00 UTC), arising mainly and associated with enhanced contrail formation over the southwestern part of the domain following westbound traffic schedules. In both cases, the observed contrail maxima occur approximately 2–3 h after the onset of increased transatlantic traffic over the North Atlantic, consistent with the timescale required for contrails to evolve to spatial scales detectable by satellite sensors.

1.1.3 Seasonal Patterns

Detected coverage exhibits pronounced seasonality (Supplementary Fig. 6), peaking in April–May (0.25%) and reaching a minimum in August (0.13%), nearly half the spring maximum. This pattern contrasts with air-traffic activity, which peaks in summer, indicating that monthly variability is primarily governed by meteorological and synoptic conditions affecting contrail formation, persistence, and detectability rather than aircraft activity alone. Although interpretation from a single year is limited by interannual meteorological variability [20], the observed spring maximum is consistent with previous studies [39, 51].

1.2 Contrail Radiative Forcing

The radiative forcing impact of each detected contrail pixel is computed individually, as described in Section 3.3; however, results are presented as aggregated spatial patterns and analyzed across diurnal and seasonal timescales. To account for potential uncertainty in the derived trends, sensitivity tests (described in Section 3.3.1) are conducted.

1.2.1 Geographical Patterns

The radiative impact of individual contrails depends on local atmospheric conditions, contrail optical properties, and cloud overlap effects [52], leading to strong spatial heterogeneity in the instantaneous radiative forcing magnitude values. When analyzed by season and time of day, however, relevant patterns can be found (Fig. 4). Under sunlit conditions (solar zenith angle $\leq 90^\circ$), the shortwave cooling effect generally outweighs the longwave warming, leading to a net cooling response. Warming contrails during daylight are therefore uncommon and occur mainly at larger solar zenith angles (solar zenith angle $\geq 75^\circ$) or for very optically thin cases (optical depth $\leq 0.1 - 0.5$; Supplementary Fig. 7); with the latter being less likely to be represented in the detections according to typical values retrieved from the cloud products utilized (see Supplementary Fig. 8 for an example). Consequently, the spatial distribution of contrail impacts is primarily determined by latitudinal and longitudinal exposure to solar illumination (Fig. 4). The contrail cooling regime develops first over continental Europe during the morning hours and propagates westward throughout the day, extending toward the North Atlantic. In the afternoon, contrail-induced cooling dominates most of the domain in all seasons, except in winter, when lower solar elevation and shorter daylight lead to an earlier warming regime over eastern Europe and at higher latitudes. As daylight duration shortens in autumn and winter, the magnitude, duration and extent of contrail-induced cooling weakens. During periods of limited or absent sunlight, including nighttime and evening, contrail warming effects dominate across the Euro–Atlantic region; however, in spring and summer, cooling persists longer into the evening over the North Atlantic, particularly at high latitudes (Fig. 4, column 4, rows 2–3), reflecting longer daylight periods relative to mid-latitudes.

1.2.2 Diurnal Patterns

The diurnal evolution of the longwave component (Fig. 5) is largely controlled by contrail extent, as terrestrial infrared emission is continuous and independent of solar illumination. Consequently, longwave forcing closely follows contrail coverage, with coincident timing in peaks (Section 1.1.2). In contrast, shortwave forcing is governed by solar illumination, increasing after sunrise and becoming strongest at low solar zenith angles around midday, where cooling can be one to two orders of magnitude greater than at higher angles (Supplementary Fig. 9). Consequently, despite reduced contrail coverage around midday, shortwave forcing remains substantial and consistently peaks between 12:00 and 15:00 across all months. The interplay between persistent longwave warming and daytime shortwave cooling determines the net forcing pattern, with the strongest contrail warming typically occurring between 05:00–08:00 UTC in winter and shifting earlier, to around 02:30–04:30 UTC, in summer. This is because during spring and summer, the earlier sunrise enhances shortwave cooling during the early-morning contrail peak, shifting the largest warming contribution to the fewer nighttime contrails. Constraining optical depth in the parametric tests does not alter the reported trends (Fig. 5), but it can reverse the sign of the diurnal net forcing in some months (Fig. 6). This sensitivity suggests that optical depth overestimations in the original dataset may bias the monthly radiative forcing estimates toward stronger shortwave cooling, particularly during months with greater solar influence.

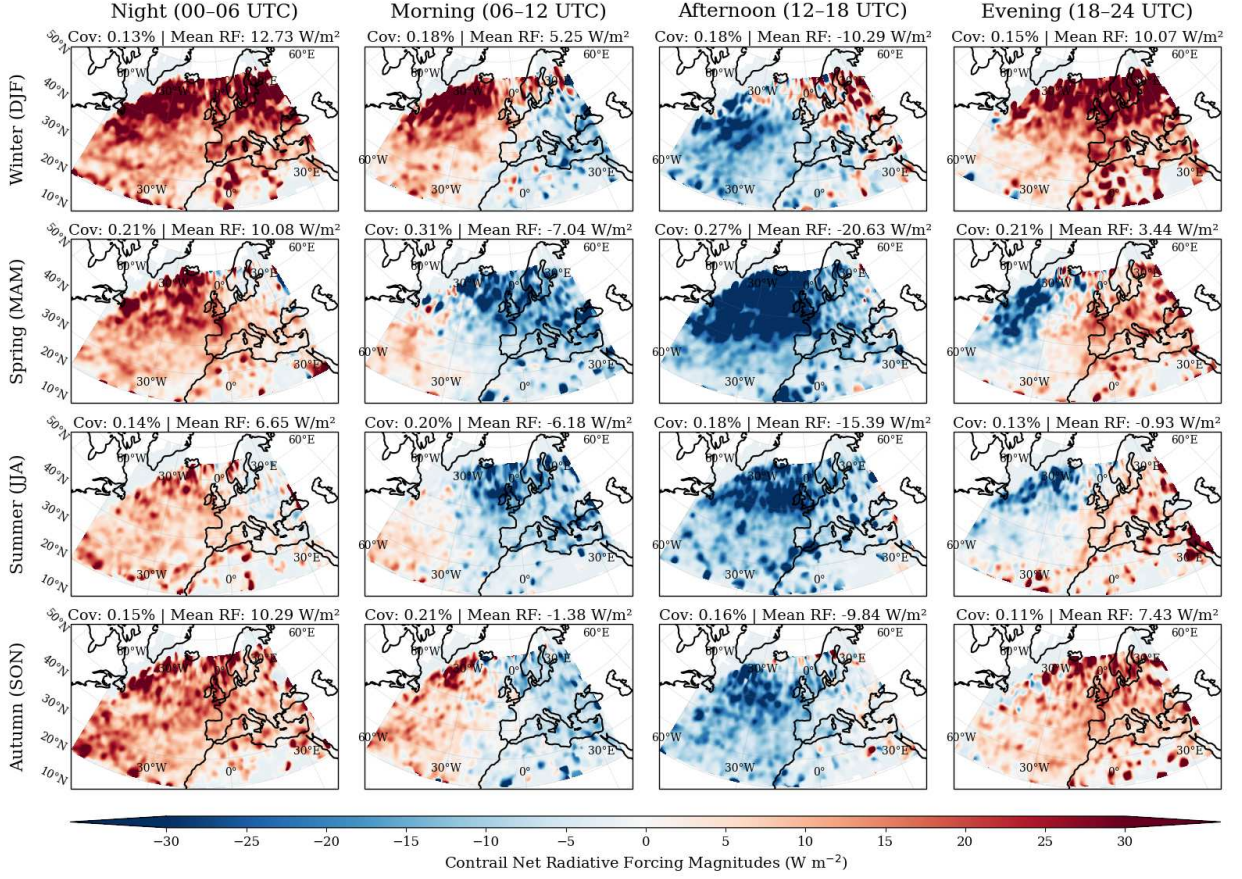


Fig. 4 Monthly geographical distribution of mean contrail radiative forcing magnitude over the Euro–Atlantic region (60°W – 40°E , 20°N – 70°N), averaged by season and 6-hour time-of-day intervals. Seasons follow standard climatological definitions: winter (December–January–February, DJF), spring (March–April–May, MAM), summer (June–July–August, JJA), and autumn (September–October–November, SON). Map colors indicate the pixel-wise mean contrail radiative forcing for each season and time-of-day category, while subpanel titles report the corresponding mean radiative forcing averaged over all detected contrail pixels within the region. Contrail-induced cooling is strongest in the afternoon across all seasons, with peak cooling in spring afternoons reaching -20.63 mW m^{-2} , coinciding with the second highest regional contrail coverage (0.27%) following the spring morning maximum (0.31%). In contrast, the strongest warming occurs at night, peaking in winter with mean values of 12.73 mW m^{-2} , substantially weaker than daytime cooling and associated with roughly half the coverage (0.13%). Together, these opposing effects yield annual mean radiative forcing biased toward net cooling or near-neutral radiative effects.

1.2.3 Seasonal Patterns

Monthly net radiative forcing ranges from a minimum in April of $-14.02, [-15.94, -12.15], \text{mWm}^{-2}$ to a maximum in December of $11.68, [10.92, 12.46], \text{mWm}^{-2}$. From March to August, all months exhibit net cooling, driven by a higher fraction of contrails detected under direct solar illumination, where shortwave effects dominate. In contrast, from September to February, net warming prevails as a larger share of contrails forms outside daylight hours—including early-morning peaks occurring with little or no solar influence (Fig. 6)—resulting in diurnal warming. However, because contrail coverage is substantially lower during these warming-dominated months (Supplementary Fig. 6), the annual mean remains $-1.11, [-2.19, -0.04], \text{mWm}^{-2}$. Accounting for the previously identified parametric uncertainty introduces a potential annual negative bias of $\sim 4, \text{mWm}^{-2}$, yielding an adjusted mean of approximately $+2.89, \text{mWm}^{-2}$ and confirming a net warming effect on an annual basis.

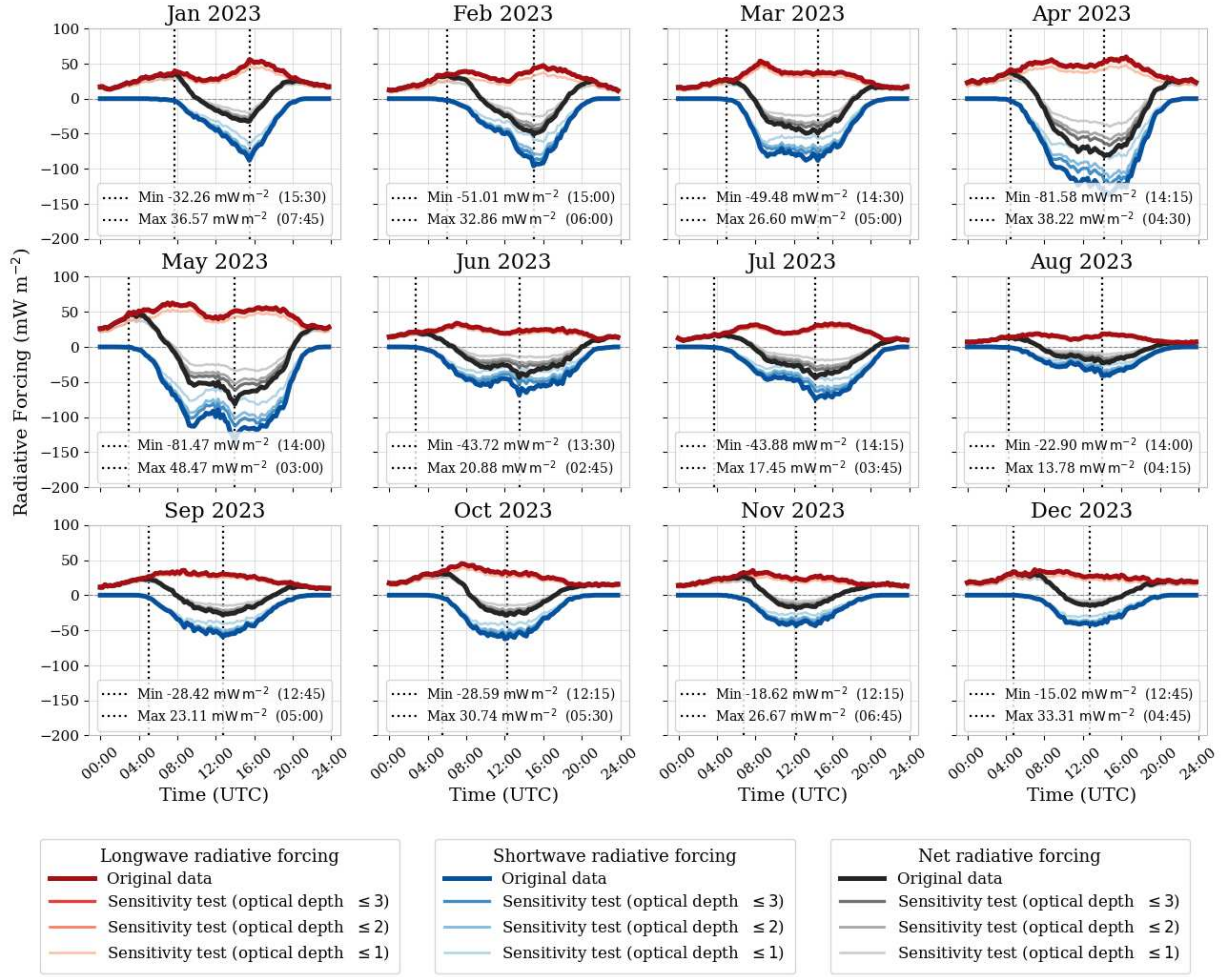


Fig. 5 Diurnal evolution of contrail radiative forcing for each month of 2023, separated into longwave (red), shortwave (blue), and net (longwave plus shortwave; black) components. Months with the largest longwave and shortwave magnitudes (April and May) coincide with periods of enhanced contrail coverage. Net radiative forcing exhibits the strongest cooling during the early afternoon (approximately 12:30–15:30 UTC), while maximum warming occurs during nighttime or early morning contrail peaks. In months with longer daylight periods, the warming peak shifts earlier (approximately 02:00–04:00 UTC), reflecting the absence of shortwave contributions over most or all of the domain during these hours. Shaded curves show radiative forcing estimates modified by applying parametric sensitivity tests to cloud optical depth (upper thresholds of 1, 2, and 3) to assess how uncertainty in this key parameter affects the inferred trends. While the overall diurnal patterns remain robust, uncertainties are largest in spring, when shortwave radiative forcing is highest, and increase with decreasing optical depth upper limits.

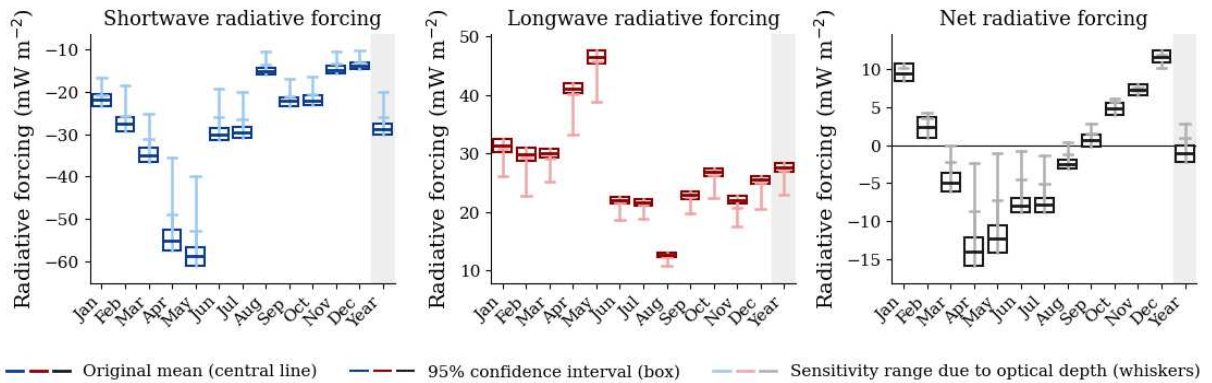


Fig. 6 Monthly and annual mean contrail radiative forcing are shown for the shortwave (left), longwave (center), and net (right) components. Central lines indicate the original mean values, while boxes denote the 95% confidence interval derived from resampling. Whiskers represent the sensitivity range across optical depth thresholds (1, 2, and 3), illustrating parametric uncertainty. Underestimation of optical depth in the cloud products implies a potential negative annual bias of approximately 4 mW m^{-2} , driven primarily by spring and summer months when parameter uncertainty is comparable to the net cooling signal. The largest biases occur in April–May ($\sim 11 \text{ mW m}^{-2}$) and remain substantial in June–July ($\sim 6\text{--}7 \text{ mW m}^{-2}$), as extended daylight enhances the influence of optical depth on shortwave radiative forcing.

2 Discussion

Contrail mitigation is a promising near-term strategy to reduce aviation’s climate impact, but its implementation is limited by highly uncertain, model-dependent estimates. Here, we present a fully observation-based framework that combines neural-network contrail detection with radiative forcing derived from look-up tables, enabling large-scale quantification of contrail impacts. This approach uncovers significant spatial and temporal patterns with reduced uncertainty, thereby reinforcing the empirical basis for mitigation strategies and informing policy decisions.

Satellite observations show that contrail coverage is mostly concentrated over the North Atlantic, despite air traffic densities over continental Europe being an order of magnitude higher. This likely reflects both meteorological factors (e.g., increased upper-tropospheric humidity and atmospheric stability differences) and potential observational biases (e.g., surface contrast, viewing geometry, and cloud cover). While advances in multispectral products could improve detectability over challenging backgrounds such as deserts and cloudy regions, thereby partially reducing the apparent uneven distribution of contrails, fully resolving the drivers of spatial patterns in contrail occurrence—and determining whether their apparent absence in certain regions reflects limitations in remote sensing or genuine differences in their formation and persistence, for example between continental and oceanic environments—will require further work integrating these results with complementary datasets, including meteorological fields and higher-resolution satellite imagery.

Consistent with the observed coverage pattern, contrail impacts are highly skewed: flights over the North Atlantic represent only $\sim 6\%$ of aircraft crossings but account for $\sim 60\%$ of annual net contrail-induced warming (Supplementary Table 1; Supplementary Fig. 12), which could rise to $\sim 85\%$ when accounting for the fact that most coastal Atlantic detections likely originate from transatlantic routes. This pronounced hotspot suggests that targeting a small fraction of flights could substantially reduce annual radiative forcing—potentially even fewer when prioritizing those with the strongest warming based on diurnal variability. This temporal dependence is key: contrails from late-afternoon and night flights, though fewer, contribute disproportionately to warming, suggesting that limiting evening and nocturnal departures from Europe could mitigate this effect. In autumn and winter, early-morning contrails drive the strongest warming, indicating that delaying departures during these periods could further reduce forcing. In these seasons, although afternoon contrails often yield net cooling, shorter daylight increases the likelihood that they persist into nighttime, potentially offsetting this benefit; advancing afternoon departures, particularly on westbound transatlantic routes, may therefore help avoid this effect. Despite the benefits of these temporally targeted strategies, linear contrails often evolve into diffuse contrail-cirrus with impacts not captured here. Realizing the full potential of time-based mitigation—and effectively targeting the most impactful flights based on schedules—therefore requires quantifying radiative effects over the entire contrail life cycle. Future work should develop observational strategies to track contrail evolution, distinguish them from natural cirrus, and quantify their lifetime-integrated forcing.

Sensitivity tests further show that uncertainty in annual mean forcing—driven by uncertain contrail optical properties—is lowest in autumn and winter, when impacts are strongest, indicating that mitigation efforts should prioritize these seasons. By contrast, uncertainty is highest in spring and summer, with a potential underestimation of net warming of up to ~ 11 and $\sim 7 \text{ mWm}^{-2}$, respectively. Nevertheless, uncertainty in the annual net radiative forcing remains limited to $\sim 4 \text{ mWm}^{-2}$, representing a relatively small magnitude compared with values typically reported in the literature.

Collectively, these findings establish a robust observational basis for quantifying contrail impacts at scale, informing mitigation strategies, and guiding future observational efforts. Realizing the full potential of satellite-based contrail impact assessment will require improved retrievals of contrail properties—particularly optical depth—to refine estimates and enable actionable, near-real-time support for aviation climate mitigation.

Author Contributions. IO is the principal author of this work. She implemented the detection algorithm (under the supervision of JGH and MS), carried out the data analysis, and served as the primary writer of the manuscript. ED, PB, and NC developed the radiative forcing look-up tables and actively contributed to the analysis of the results. JGH, HB, and JvG participated in the handling and sharing of the data. HB and JvG also contributed to the development of a dedicated dashboard for the visualization and sharing of

the results presented in this article. MS is the coordinator of the project; he conceived the project idea and designed the experimental setup. All authors reviewed and approved the final manuscript.

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Competing interests. All authors declare no financial or non-financial competing interests.

Data Availability Aircraft trajectory and flight information for the year 2023 were obtained from the OpenSky Network <https://opensky-network.org/>. The look-up tables used in this study are publicly available on Zenodo <https://zenodo.org/records/14859250>. Selected codes related to satellite-based contrail detection are available at <https://github.com/Aircraft-Operations-Lab/ContrAI>. All contrail and radiative forcing data used in this manuscript will be made available for visualization on a dedicated dashboard, similar to <https://econtrail.aeronomie.be/>, upon acceptance.

Supplementary information. The online version contains supplementary material available at the DOI link for this article.

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3 Methods

3.1 MSG/SEVIRI Observations

Satellite scenes are captured by the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the MSG-3 and MSG-4 geostationary satellites of the Meteosat Second Generation (MSG) series [53, 54]. The study domain spans 60°W–40°E and 20°N–70°N, covering Europe, North Africa, and the eastern North Atlantic. The satellite products are obtained from the EUMETSAT data portal [55] and include:

- Level 1.5 (L1.5) geolocated and radiometrically calibrated radiances from three infrared (IR) spectral channels (IR 8.7, IR 10.8, and IR 12.0). These are used to generate brightness temperature scenes for the Ash RGB composite [56], in which contrail visibility is enhanced due to thermal contrast with the surrounding environment and background.
- Level 2 (L2) Optimal Cloud Analysis (OCA) products. From these, cloud phase information is used to filter both ice clouds in single-layer and multi-layer (ice clouds overlying water clouds) conditions. Then, cloud optical depth (COD) and cloud top pressure (CTP) for both layers (where present), and the cloud effective radius (CER) of the upper-layer are also used.

All scenes are reprojected onto an equidistant latitude–longitude coordinate system with a uniform spatial resolution of 0.04°. In total, approximately 35,000 scenes of 1250 × 2500 pixels are collected, representing 96 scenes per day at a 15-minute temporal resolution throughout the entire year 2023.

3.2 Neural Network Detections

A NeXtViT neural network architecture [57] previously trained on the OpenContrails dataset [58] was chosen to automatically segment contrail pixels. Each false-color Ash-RGB image was upsampled to match the pixel scale of the training data and preserve contrail sizes. Detections were then performed using a 256 × 256 sliding window, with a slight overlap between patches to mitigate the effects of partial occlusions. The resulting outputs were merged and then reprojected onto the original image grid to create a single-channel probability mask for the full scene. This mask was then binarized using a fixed threshold of 0.09, empirically determined with visual inspection to balance over- and under-detection in SEVIRI imagery, where ground-truth annotations are not available at the moment. The chosen NeXtViT architecture proved performance comparable to other top-performing models in the literature [34, 59, 60], reaching a $\sim 80\%$ global dice score using the boundary-soft evaluation framework from [27].

Flight data used to compare detected contrail coverage trends with aircraft crossings and schedules were obtained from the OpenSky Network [61] and reconstructed using great-circle interpolation.

3.3 Rapid Radiative Forcing Look-Up Tables

The shortwave and longwave radiative forcing at each pixel i , expressed in W m^{-2} , are computed following [29] as

$$SW_i = F_{i,c}^{\text{sol}} - F_{i,\bar{c}}^{\text{sol}} = [F_{\downarrow}^{\text{sol}} - F_{\uparrow}^{\text{sol}}]_{i,c} - [F_{\downarrow}^{\text{sol}} - F_{\uparrow}^{\text{sol}}]_{i,\bar{c}}, \quad (1)$$

$$LW_i = F_{i,c}^{\text{tir}} - F_{i,\bar{c}}^{\text{tir}} = [F_{\downarrow}^{\text{tir}} - F_{\uparrow}^{\text{tir}}]_{i,c} - [F_{\downarrow}^{\text{tir}} - F_{\uparrow}^{\text{tir}}]_{i,\bar{c}}. \quad (2)$$

where F_i^{sol} and F_i^{tir} denote the solar and thermal infrared fluxes, respectively, and the subscripts c and $\bar{c}$ refer to fluxes computed with and without the contrail. The net radiative forcing at pixel i is then defined as $RF_i = LW_i + SW_i$ with positive (negative) values indicating warming (cooling). The regional mean radiative forcing, expressed in mW m^{-2} , is computed at each time stamp as

$$RF = \frac{\sum_{i \in \mathcal{C}} RF_i A_i}{\sum_{j \in \mathcal{P}} A_j}, \quad (3)$$

where A_i and A_j denote pixel areas in m^2 , $\mathcal{C}$ is the set of contrail pixels detected in the corresponding scene, and $\mathcal{P}$ is the full spatial domain considered. The magnitude of the regional radiative forcing primarily depends on the spatial extent of detected contrails (i.e., the size of $\mathcal{C}$), and the sign of individual pixel RF_i values, which vary with location, season, and time of day.

The radiative forcing look-up tables from which the shortwave and longwave values are derived in each MSG/SEVIRI image pixel were developed in the work of Dimitropoulou et al. [29] for fast estimation of radiative forcing of high-altitude ice clouds, avoiding the high computational cost of running full radiative transfer simulations for large datasets. They achieved correlation coefficients of 0.86 (longwave flux) and 0.99 (shortwave flux) compared with measurements from the CERES polar-orbiting instrument. For their application it is required, in addition to SEVIRI L2 cloud data from the OCA product, information on the solar zenith angle, surface spectral albedos across land types available in the International Geosphere Biosphere Program (IGBP) library, and skin temperature fields from ECMWF Numerical Weather Prediction data [62]. Contrail characterization is achieved by assigning each segmented contrail pixel the corresponding values of cloud optical depth, cloud top pressure, cloud effective radius (all derived from OCA), solar zenith angle, surface albedo, and skin temperature. Contrail shortwave and longwave radiative forcings are derived via multidimensional interpolation of the pixel-level parameters in the look-up tables.

3.3.1 Sensitivity Tests

Given the limitations of the OCA products in correctly characterizing cirrus cloud pixels when they are too optically thin or when there is insufficient optical depth contrast with underlying clouds [28], a parametric sensitivity analysis is performed (Figs. 5–6). Upper optical depth thresholds of 1, 2, and 3 are applied to the observed diurnal and seasonal trends to quantify variability in the reported mean values (Fig. 5). Thresholds of 1 and 2 were chosen as physically realistic based on a compilation of modeling, observational, and in situ evidence [63]; however, optical depths up to 2.3 have been reported for a young (~ 1 h) linear contrail case observed by a spaceborne lidar (and visible in geostationary satellite imagery) [64], motivating the inclusion of a conservative upper threshold of 3. Among cloud parameters influencing radiative forcing, optical depth is considered exclusively in the parametric test due to its dominant influence [65], which can be one to two orders of magnitude greater than that of other cloud parameters (Supplementary Fig. 9).

Supplementary Files

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