

Contrail Detection and Coverage Estimation across Air Route Traffic Control Centers from Satellite Observations

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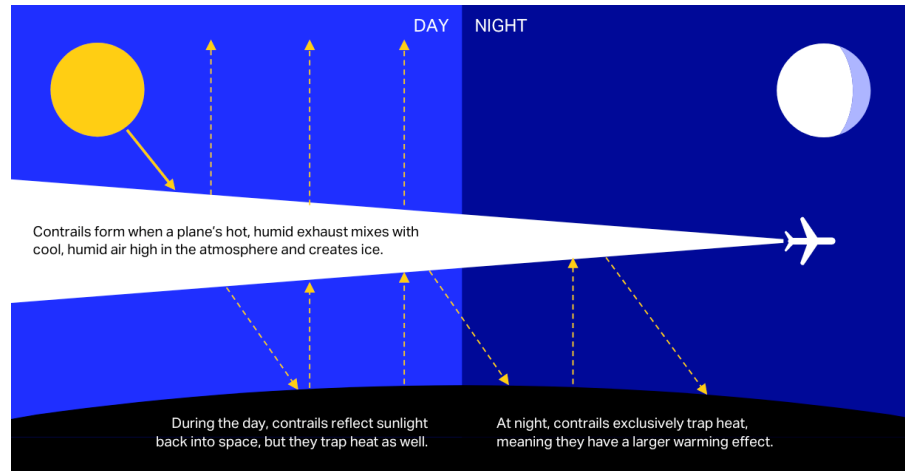
Introduction

Condensation trails



<https://www.youtube.com/watch?v=xBkK7olwix0>

(The future of flight: Can AI make flying sustainable? | Google AI)



IATA: Aviation contrails and their climate effect: Tackling uncertainties and enabling solutions

Schmidt-Appleman Criteria (Appleman, 1953)

Temperature (below ~ 235 K ≈ -38 °C);

Relative humidity (≥ 100 % over ice);

Water vapour, Pressure, Emission index of aircraft engine, ...

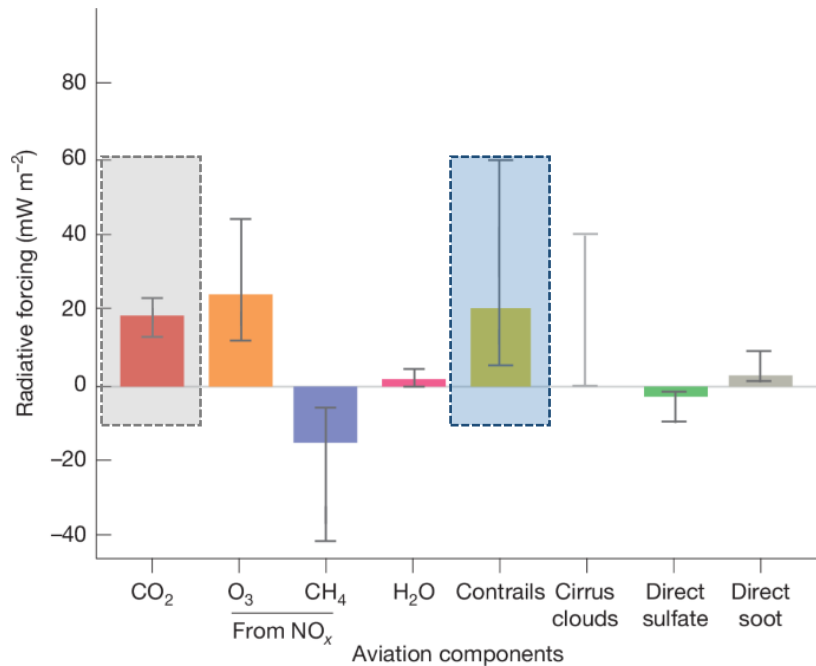
Reflecting solar radiation (cooling)

Trapping thermal-infrared radiation (warming)

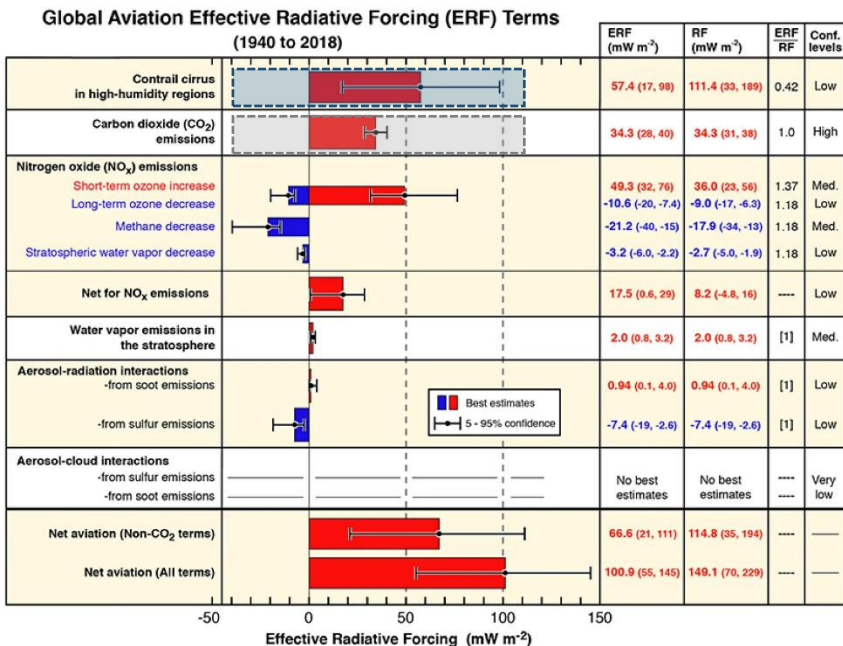
Daytime: warming & cooling effect

Nighttime: only warming (no solar radiation)

Contrails-Induced Climate Impact



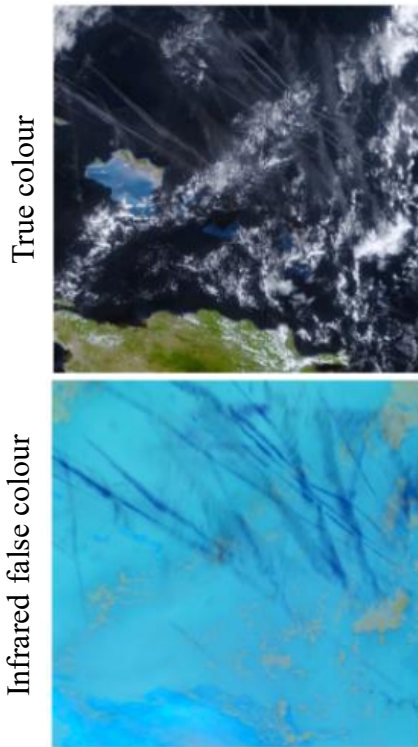
RF (W m^{-2}) in 1992, caused by the accumulated effects of civil aviation (Prather et al., 2025).



ERF (W m^{-2}) from 1940 to 2018 (Lee et al., 2021).

Introduction

Satellite Observations



GOES-16 (GEO)

Human-labelled Dataset

	OpenContrails (GOES-16)	Landsat-8
Distribution	Pixel-wise	Polygon
Strength	high temporal resolution (10 min)	high spatial resolution (300 m)
Region	North and South American	in viewable extent of GOES-16
Period	April 2019 - April 2020	from 2018
Size	22410 scenes, 9283 contain more than one contrail	4289 scenes, 47% contain at least one contrail
Authority	Google, MIT	

(McCloskey et al., 2021; Ng et al., 2023)

Contrail detection algorithm (CDA)

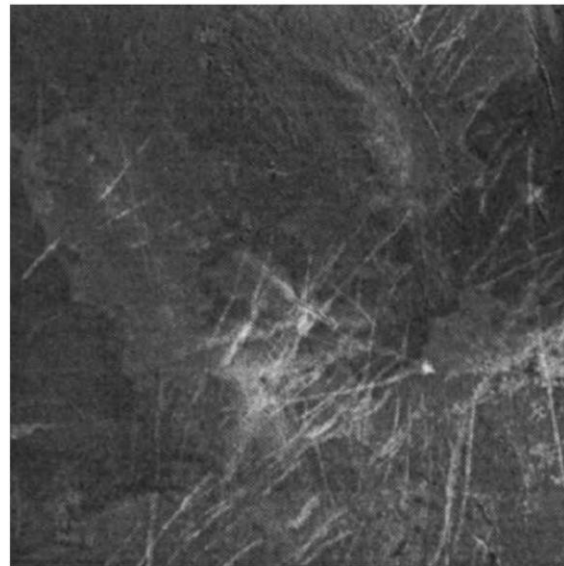
Brightness Temperature Difference (BTD, 1-channel)

- Consisting of a series of filters and empirical thresholds to detect contrails (Mannstein et al., 1999).
- Widely utilised in contrail lifespan estimation and analysis of contrail properties and coverage over the years (e.g., Duda et al., 2013; Vázquez-Navarro et al., 2015).

Deep Semantic Segmentation

Infrared false colour (RGB, 3-channel)

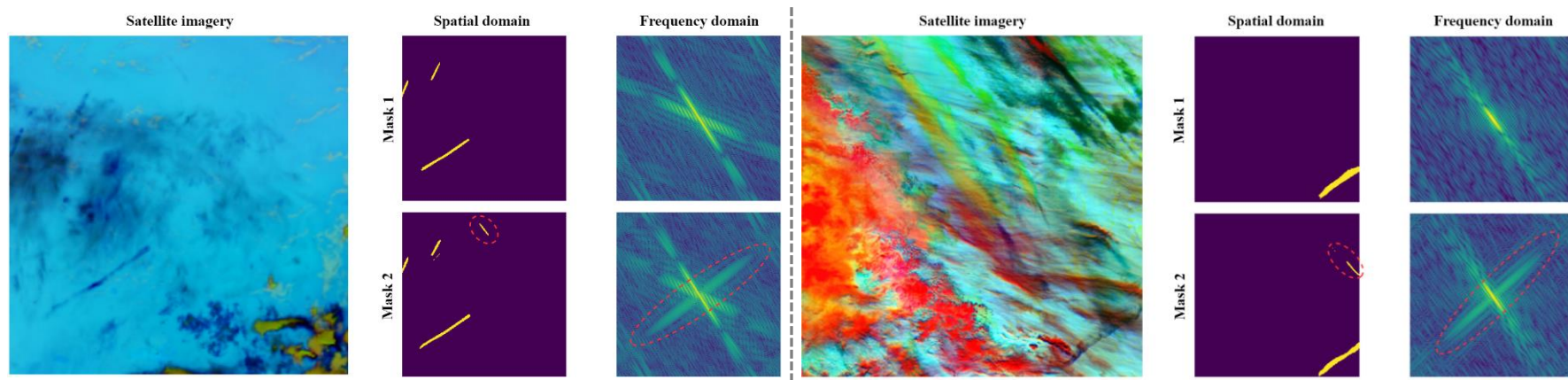
- Transferring segmentation models developed for medical images and satellite imagery of rivers and roads into contrails detection (e.g., Riggi-Carolo et al., 2023; Ng et al., 2024; Jarry et al., 2024).
- Utilising Hough Transform to regularise the contrail detection in both spatial and Hough spaces (Sun and Roosenbrand, 2025).



The BTD between channels 4 and 5 of the NOAA-12 satellite (Mannstein et al., 1999)

Frequency Distance

- Discrepant **orientations** in the spatial domain could lead to a significant discrepancy in frequency components.



- Given Y_i and $\hat{Y}_i$ are the ground truth and detected contrail probability maps, respectively, the L1-based **frequency distance (FD)** over n samples is defined as:

$$\mathcal{L}_{FD}(Y, \hat{Y}) = \frac{1}{n} \sum_{i=1}^n \left\| \mathcal{F}(Y_i) - \mathcal{F}(\hat{Y}_i) \right\|_1$$

where $\mathcal{F}(\ast)$ is a 2D discrete Fourier transform (DFT).

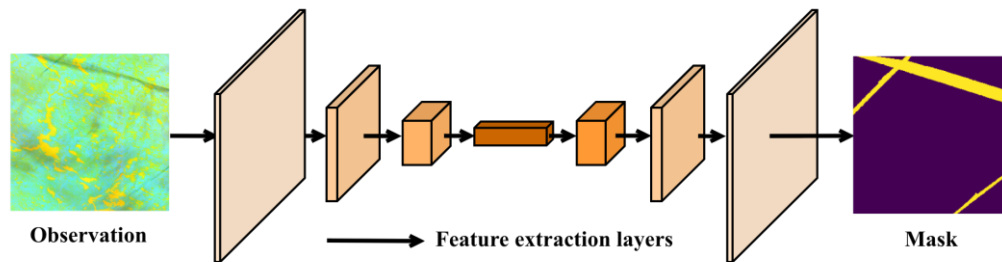
Joint Spatial-Frequency Loss

Combined with the conventional spatial loss $\mathcal{L}_{\text{base}}$ (e.g., binary cross-entropy (BCE)), the joint spatial-frequency loss is defined as:

$$\mathcal{L}_{\text{joint}}(Y, \hat{Y}) = (1 - \lambda)\mathcal{L}_{\text{base}}(Y, \hat{Y}) + \lambda\mathcal{L}_{FD}(Y, \hat{Y})$$

where the weight λ is used to adjust the relative contributions of the two loss components, and is set as 0.9 for better performance.

Model Architecture: U-Net



Encoder: MaxViT-tiny; $\mathcal{L}_{\text{base}} = \text{BCE (pixel shift)}$ (Ng et al., 2023).

Contrail Detection

Experiment

Metric:

- Dice and IoU: quantifying the overlap;
- Precision and Recall: showing the proportion of missed and falsely detected contrail pixels.

$$\text{Dice} = \frac{2 \times (Y \cap \hat{Y})}{|Y| + |\hat{Y}|} = \frac{2 \times \text{TP}}{2 \times \text{TP} + \text{FP} + \text{FN}}$$

$$\text{IoU} = \frac{Y \cap \hat{Y}}{|Y \cup \hat{Y}|} = \frac{\text{TP}}{\text{TP} + \text{FP} + \text{FN}}$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

Results:

Loss	Threshold	Dice (%)	IoU (%)	Recall (%)	Precision (%)
$\mathcal{L}_{\text{bce}}$	0.05	57.18	40.01	89.36	42.02
	0.30	69.62	53.39	70.19	69.05
	0.95	25.11	14.36	14.42	96.90
$\mathcal{L}_{\text{joint}}$	0.05	57.50	40.35	89.85	42.27
	0.30	70.23	54.12	70.58	69.89
	0.95	23.18	13.11	13.16	97.13

Table 1. 4-fold ensemble quantification of contrail detection on the OpenContrails dataset, expressed as percentages, for different binarization thresholds.

Contrail Coverage Estimation

Averaged Contrail Coverage Ratio (ACCR)

Contrail Coverage Count (C^3): the pixel-wise accumulation of contrail detections over an observation time window.

$$C^3 := (c_{i,j}^3)_{M \times N} \quad c_{i,j}^3 = \begin{cases} 0, & \text{contrail-free,} \\ c_{i,j}, & \text{otherwise, } 1 \leq c_{i,j} \leq C, \end{cases}$$

where $M \times N$ denotes the spatial dimensions of each satellite frame, and $c_{i,j}^3$ is the number of contrail-covered frames at pixel (i, j) .

ACCR: the geo-spatial occurrence of contrails across a region over a certain period:

$$ACCR = \frac{\sum \mathbb{I}(C^3 \geq 1)}{M \times N} \times 100\%$$

where $\mathbb{I} (*)$ is the indicator function.

Contrail Coverage Estimation

Multi-level Estimations across CONUS

Case: across CONUS and each ARTCC over 60 days in 2024, with 15 consecutive days (1st–15th) selected from Jan, Apr, Jul, and Oct.

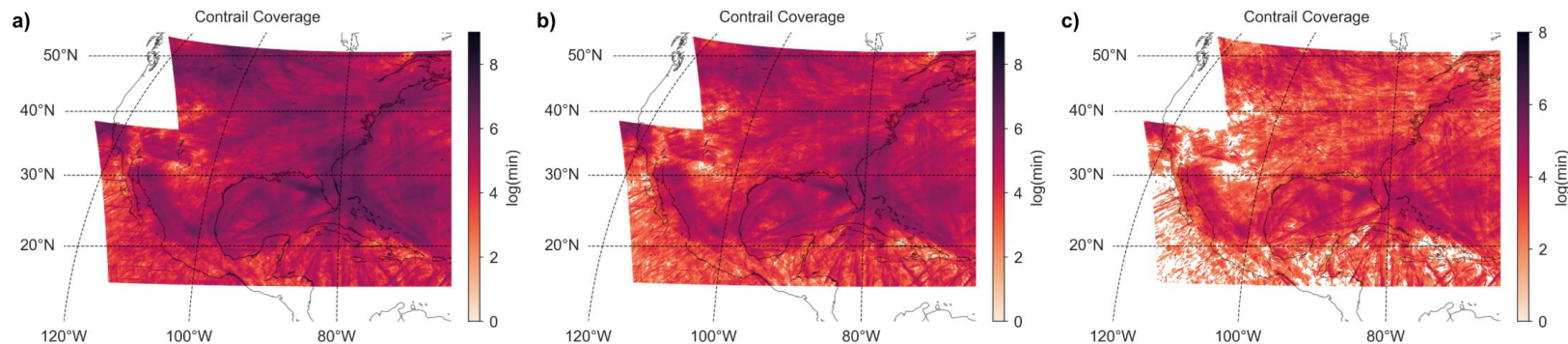


Figure 1. Contrail coverage over CONUS, estimated using thresholds of **0.05 (a)**, **0.30 (b)**, and **0.95 (c)**, with colours representing the logarithm of the accumulated contrail covering time over 60 days. To avoid large viewing-angle distortion and incomplete patches, the upper-left region of the GOES-16 CONUS frame is excluded. ($\exp(8) \approx 2980 \approx 3.45\%$ of 60 days.)

Table 2. Comparison of day-averaged contrail coverage, estimated in ACCR (%), across CONUS over 60 days in 2024 under different thresholds.

Threshold	0th	25th	50th	75th	100th
0.05	0.051	0.117	0.254	0.301	1.017
0.30	0.022	0.055	0.115	0.146	0.471
0.95	0.003	0.008	0.015	0.021	0.058

Contrail Coverage Estimation

Seasonal Patterns across Air Route Traffic Control Centers (ARTCC)

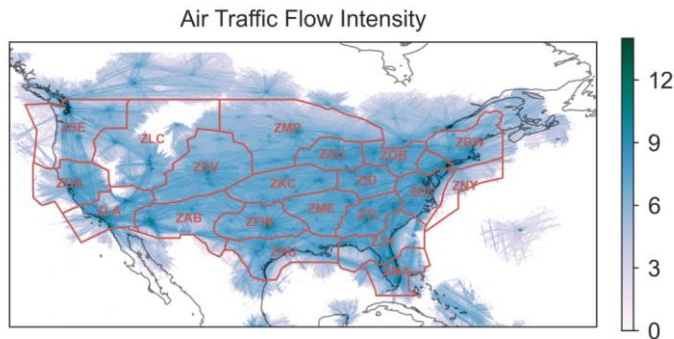


Figure 2. Air traffic flow intensity across CONUS for **daytime (07:00-18:00 CST) over 2 days per season in 2024**, with colours representing the logarithm of the gridded waypoint (**above 7200 m**) histogram at 0.1-degree resolution. (ADS-B data from OpenSky (Schäfer et al., 2014; Olive, 2019)).

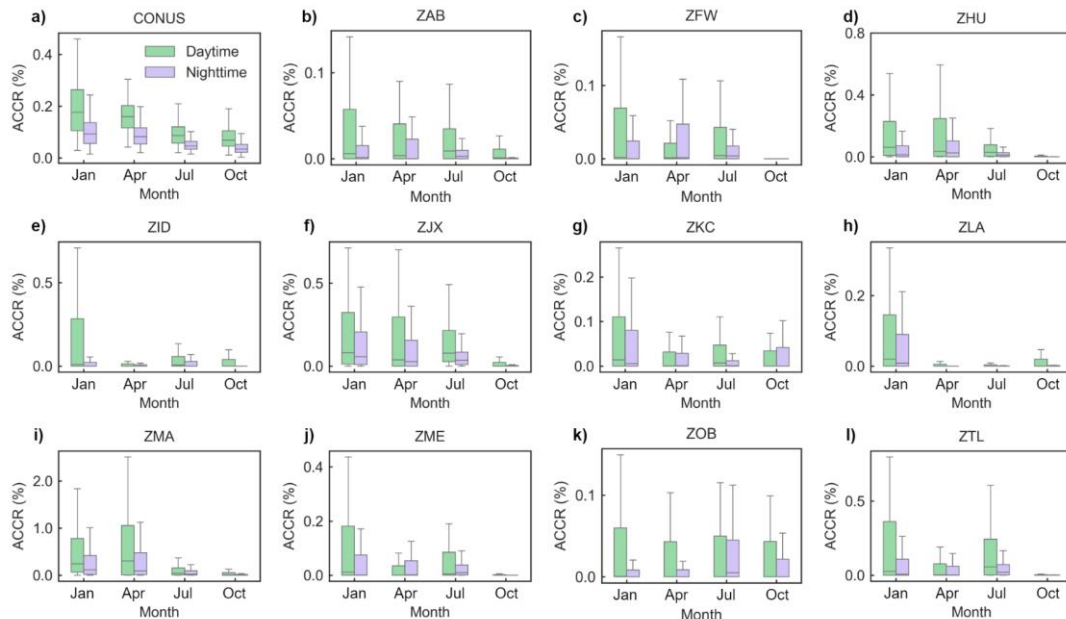


Figure 3. Seasonal ACCR over CONUS and the ARTCCs exhibiting similar patterns in 2024.

- ZSE, ZOA, and ZLC are excluded due to excessive filtered-out pixels.

➤ A **decreasing trend** from colder to warmer seasons is evident.

Contrail Coverage Estimation

Extremes in Regions

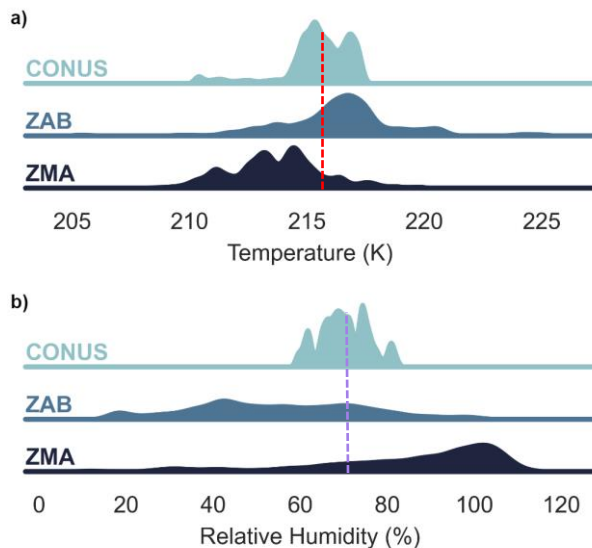
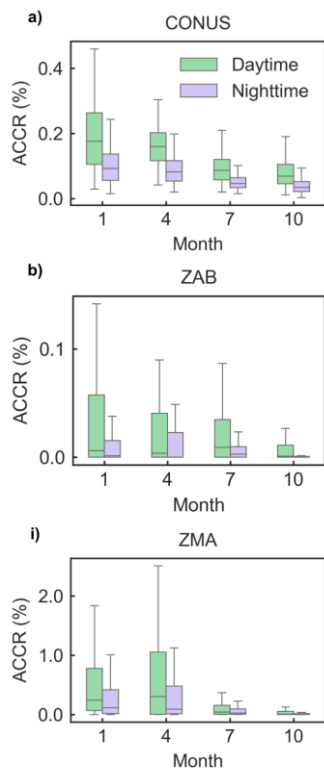


Figure 4. Distributions of spatially averaged temperature (a) and relative humidity (b) in three zones (CONUS, ZAB, and ZMA) over 60 days in 2024.

Findings: Uneven Meteorology

- ZAB experienced *warmer and drier* UTLS conditions (high temperature and lower humidity), to some extent suppressing contrail formation;
- ZMA was marked by *cooler and more humid* conditions conducive to contrail formation.

Contrail Coverage Estimation

Anomalies in Seasons

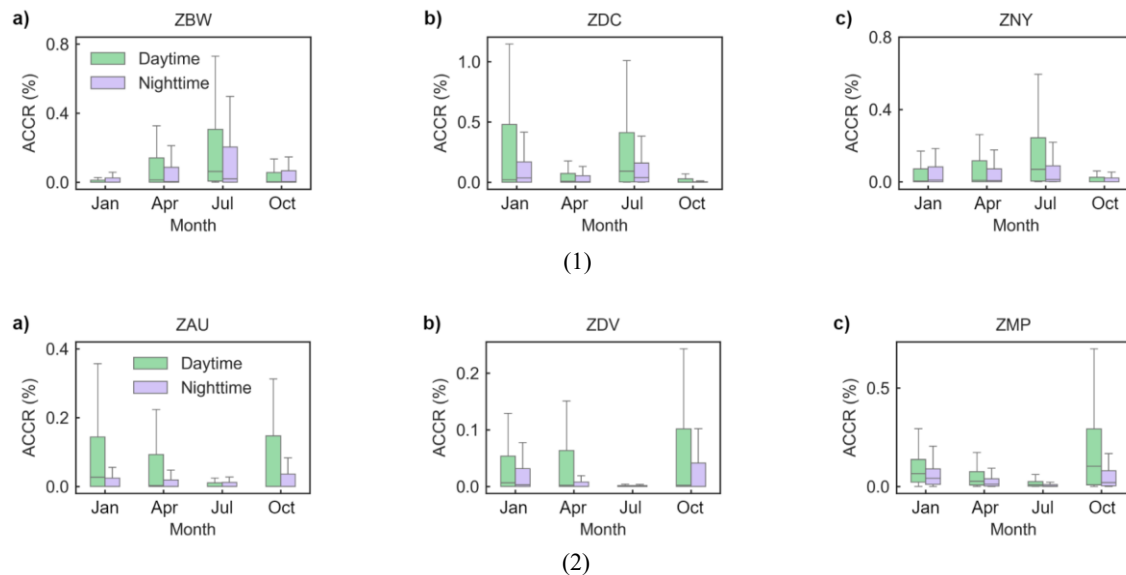


Figure 5. Representatives exhibiting **anomalously high contrail coverage** in July (1) and October (2).

Location:

Jul: northeastern coast;
Oct: high-altitude, landlocked areas.

Causes:

Lower temperature;
Higher relative humidity.

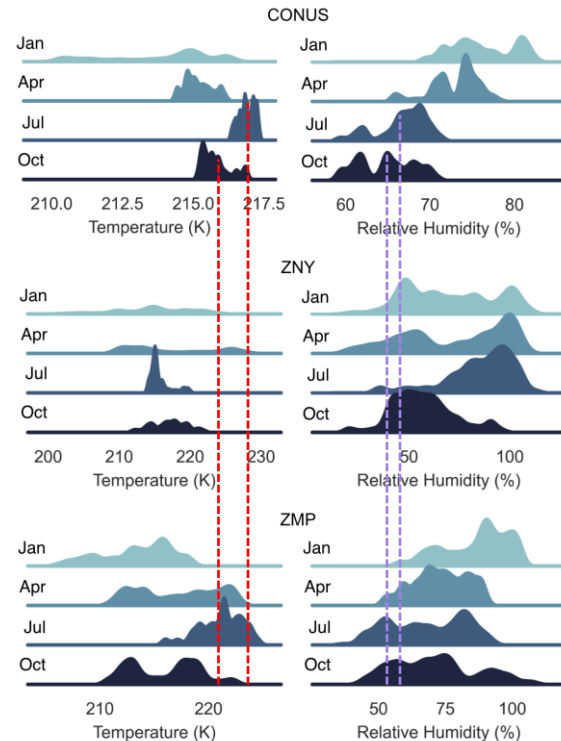


Figure 6. The spatially averaged temperature and relative humidity over months in CONUS, ZNY, and ZMP.

Contrail Coverage Estimation

Diurnal Patterns across CONUS

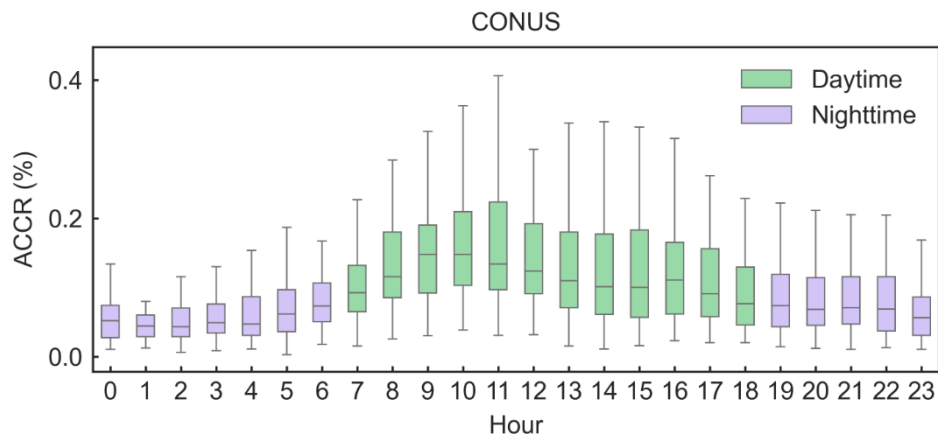


Figure 7. Hourly ACCR distribution over CONUS in CST time, averaged across 60 days in 2024.

Findings: Diurnal Cycle

- Reaching a **peak of 0.164% on average around 10 a.m.** in local time (CST), attributed to the bilateral actions of meteorology and air traffic flow.
- **Dropping to 0.052% at midnight.**

The diurnal cycle is consistent with previous studies (Schumann and Graf, 2013; Meijer et al., 2022; Duda et al., 2023), and our forthcoming 9-year analysis.

Limitations

- *Contrail detection uncertainty*: propagating to coverage estimates and causing bias in climate impact assessment and rerouting decisions. It underscores:
 - **larger and more diverse label datasets; stronger segmentation models; formal uncertainty quantification.**

- *Cirrus Contamination*: possibly underestimating contrails in dense cloud regimes. It is expected to:
 - Integrating **optical depth retrievals**;
 - Aligning with **cruise-level meteorological fields**;
 - Improving **cross-sensor (GEO & LEO) calibration.**

- *One-year Scope*: only exploring a single year (sampling 60 days). A multi-year extension is required to:
 - Capturing **interannual weather variability**;
 - Strengthening **regional climatology robustness.**

Conclusion

Contributions

- The proposed **joint spatial–frequency loss** can effectively capture line-shaped structures of contrails, seamlessly integrated into gradient-based frameworks and with negligible computation cost.
- Clear Spatiotemporal Patterns (**seasonal and diurnal**) indicate when/where mitigation may be more effective.
- Joint analysis with meteorological fields reveals **contrail-intense zones and corridors** and substantial **inter-ARTCC variability**, implying **uneven potential for region-specific mitigation**.

Future Work

- Future efforts target global application (contrail lifetime and radiative forcing) and refined rerouting strategies (region and enroute), which will hinge on contrail forecast quality and air traffic complexity.

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Thank you!

We welcome you to join this adventure of flying ☺