Breakthrough Energy Contrails

Transitioning contrail science into practice

National Academy of Sciences

August 19, 2024

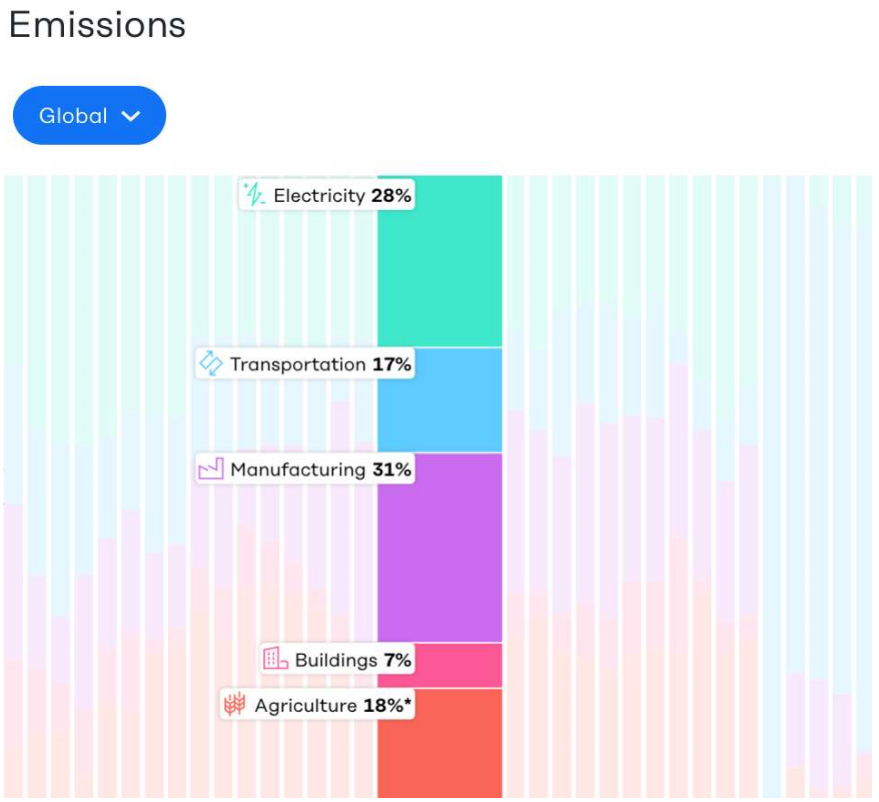
Overview

1. Motivation
2. Contrail avoidance in practice
3. Recent progress
4. Call to action: An ambitious national research agenda on contrails

Breakthrough Energy

Accelerating climate progress across:

- **Technology.** Climate technologies our world will need to meaningfully reduce emissions.
- **Markets.** Bring together public and private sectors to accelerate market formation, spur further innovation, and reduce Green Premiums.
- **Policy.** Advocate public policies that will give new technologies a chance in the marketplace, incentivize investment, and drive down clean technology costs.



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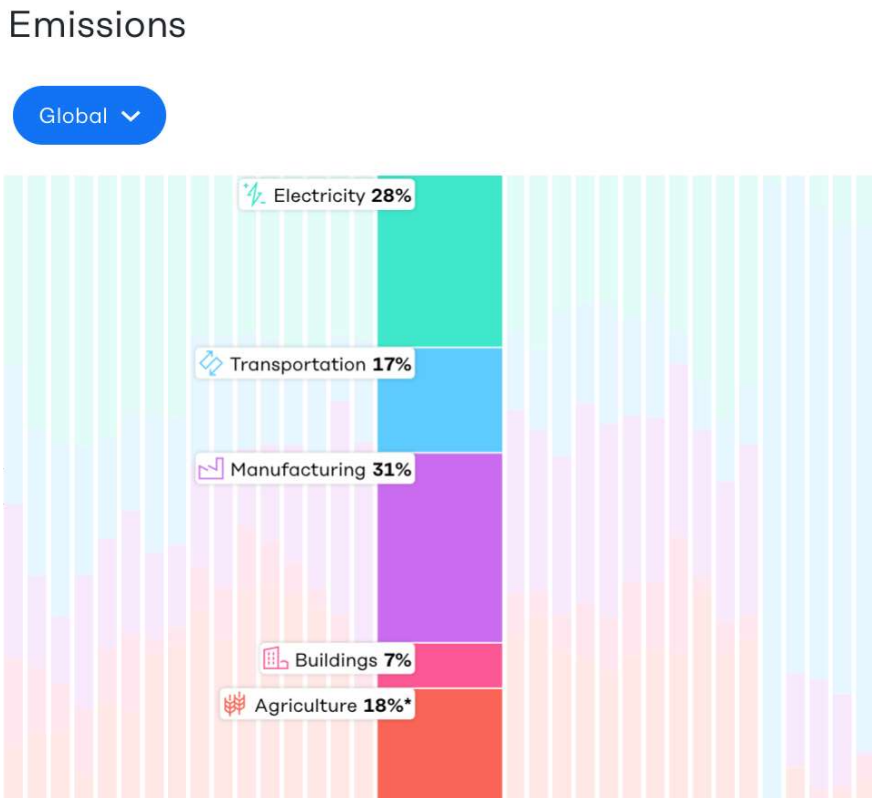
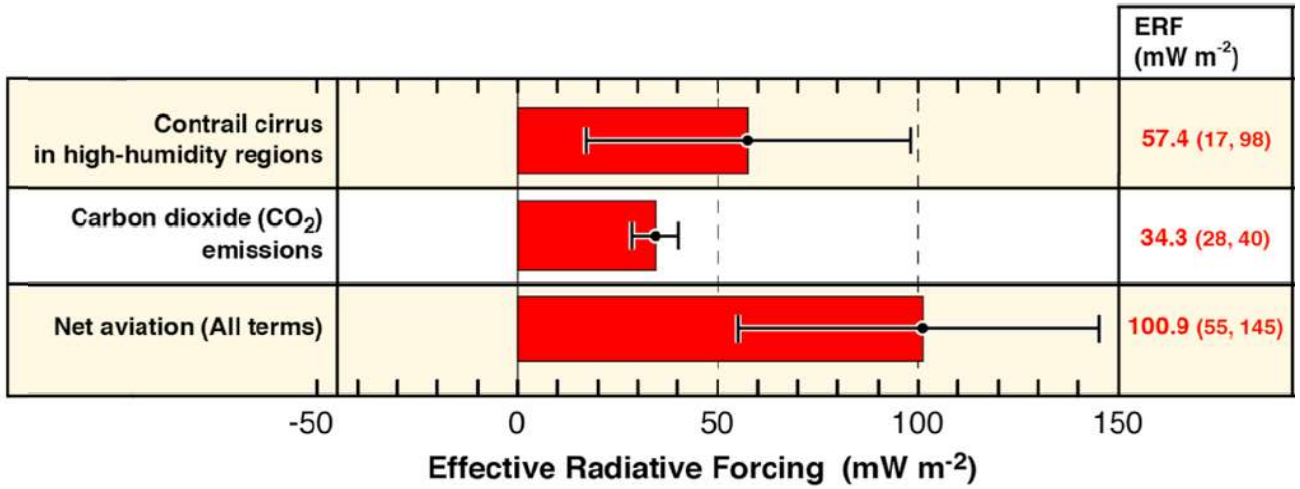
Breakthrough Energy Contrails

BE Contrails established in 2021
to support contrail research and transition



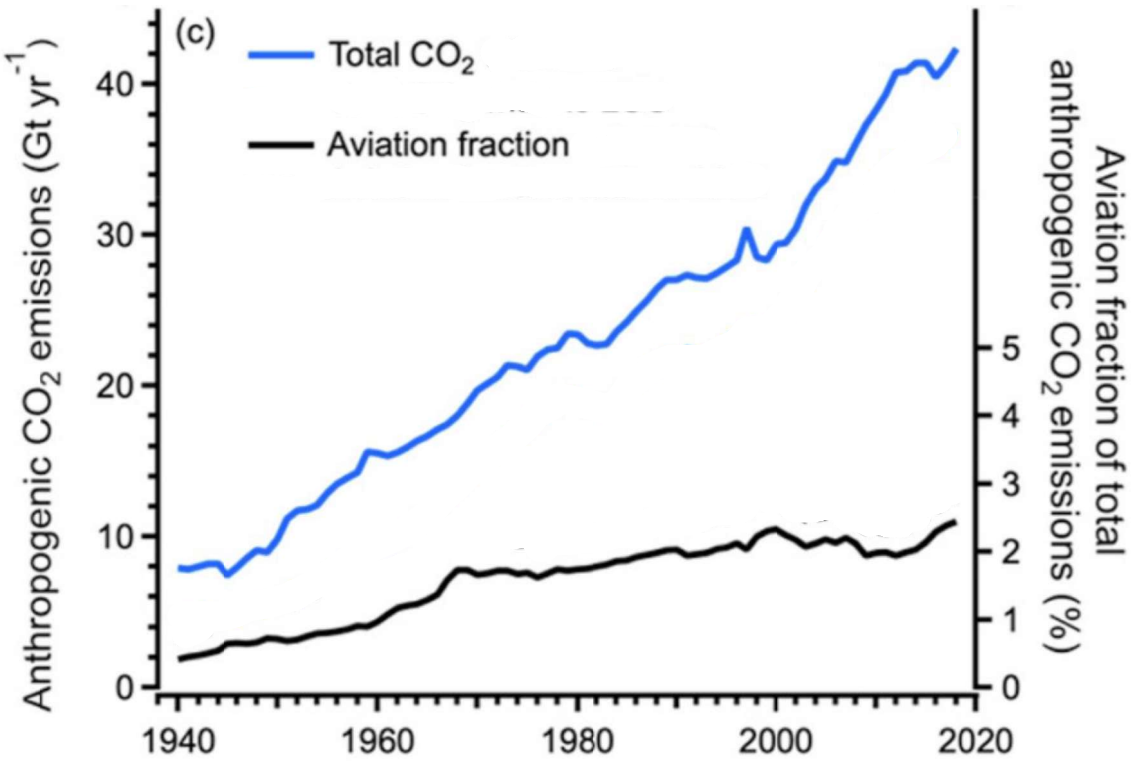
Motivation

Effective radiative forcing from aviation



Lee et al. Atmospheric Environment (2021)

Aviation started emitting CO_2 in the 1940s



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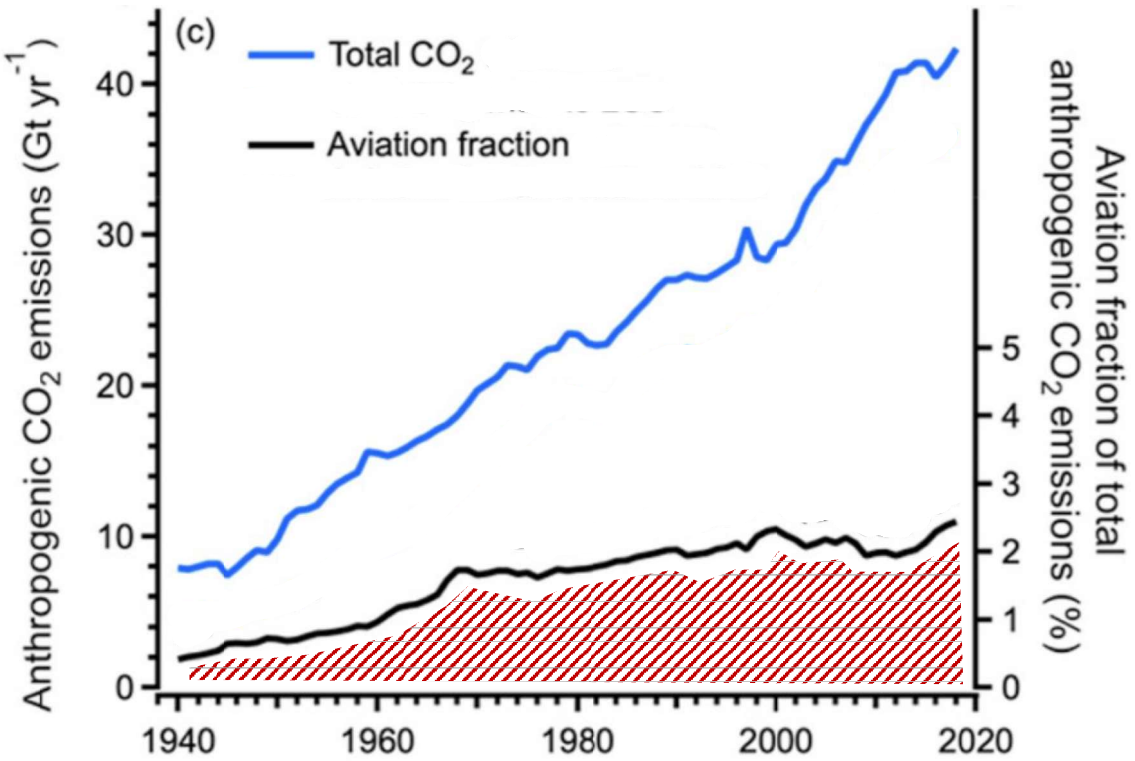


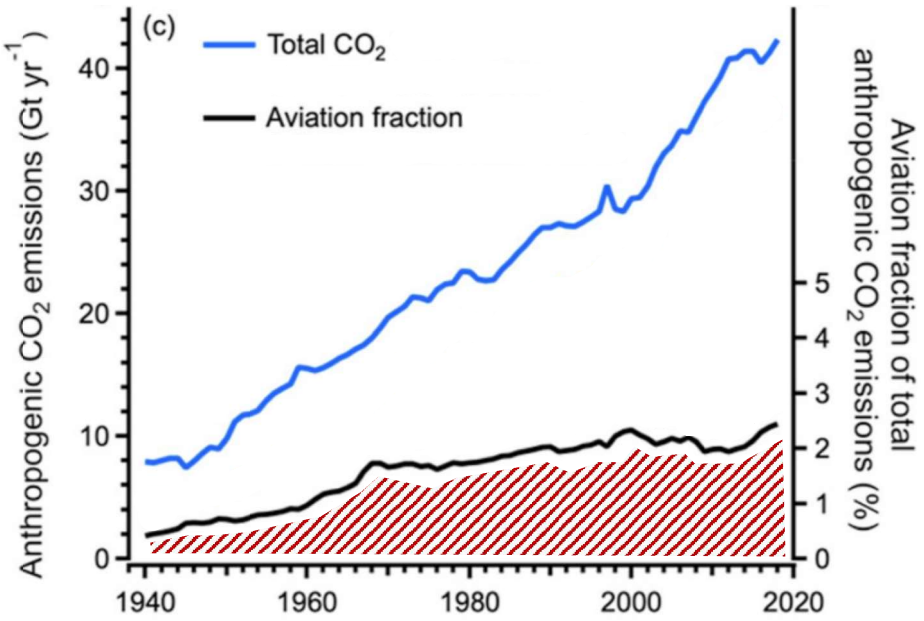
CO_2 emissions
~32 Gtonnes

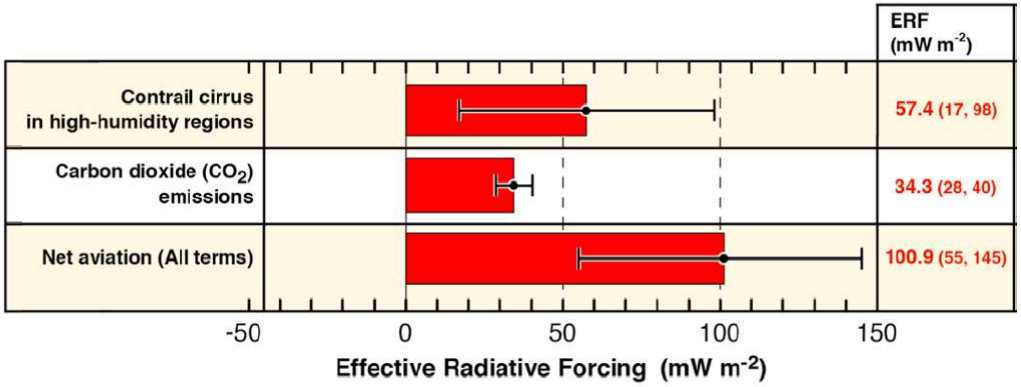
Adapted from Lee et al. Atmospheric Environment (2021)

Effective radiative forcing from aviation

Central estimate for contrail forcing (in 2018): **54.7 mW m^{-2}** [17, 98]

Greater than the 2018 forcing from accumulated aviation emissions





Adapted from Lee et al. Atmospheric Environment (2021)

Quantify by the social cost of additional CO_2

What is the social cost of an additional CO_2 mW m^{-2} forcing?

A constant tonne of CO_2 additional in the atmosphere is worth the same as 1.5 to 2 tonnes of CO_2 emission for a 2 – 3% discount rate

Estimate of radiative forcing per tonne of atmospheric CO_2 =1.6 x 10^{-12} W m^{-2}

For a social cost of carbon is \$190/tCO_2 (EPA)
→ a constant radiative forcing of 1 W m^{-2} is worth ~\$200T in NPV terms.

Each additional CO_2 mW m^{-2} is ~\$200B in NPV → central value for contrails ~ \$11T

If we were willing to spend 1% of this NPV per year on contrail avoidance, we should be willing to spend ~**\$100B per year**

Estimate of radiative forcing per tonne CO2

RF = 5.35 W m^{-2} in (CO_2/CO_{2ref})
CO_{2ref} = 3300 x 10^9 tCO_2
RF per ton = 1.6 x 10^{-12} W m^{-2}

The potential benefits far outweigh the risks

Sources of uncertainty

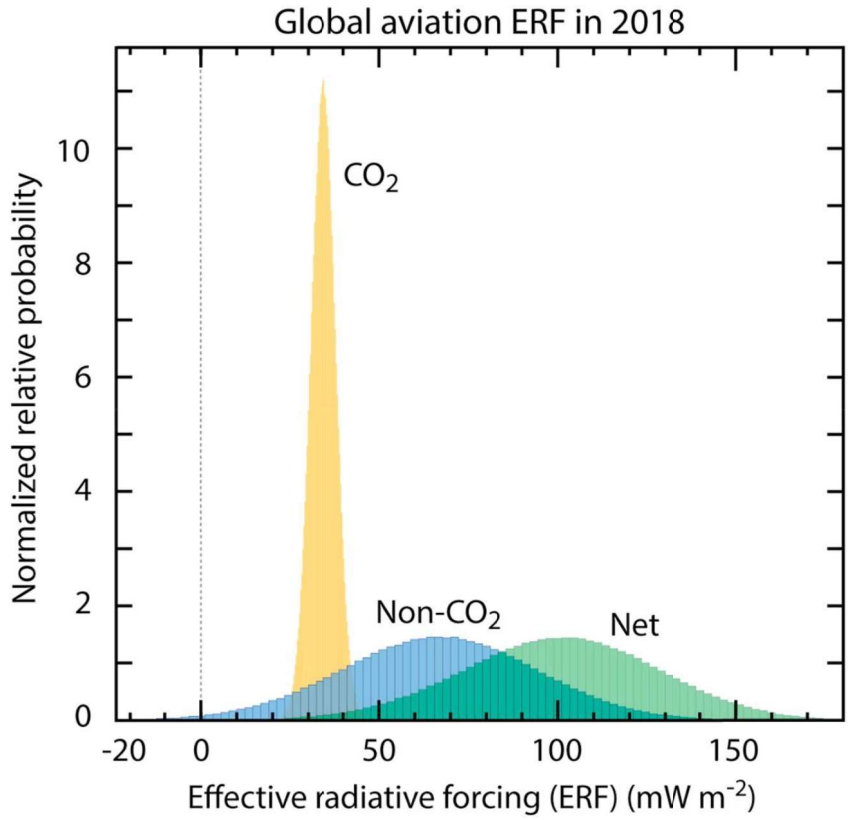
1. Predicting ice-supersaturated regions of the atmosphere
2. Aviation aerosol effects on natural cirrus
3. Forcing efficacy & climate feedback
4. Counterfactuals in mitigation

But even amid mitigation uncertainty, benefits far outweigh the costs

Minimal added fuel (<1%) ~ 0.01 mK / yr

Potential benefit ~ 50 mW m^{-2} ~ 10 mK

~1000 years for cost to outweigh benefits



Adapted from Lee et al. Atmospheric Environment (2021)

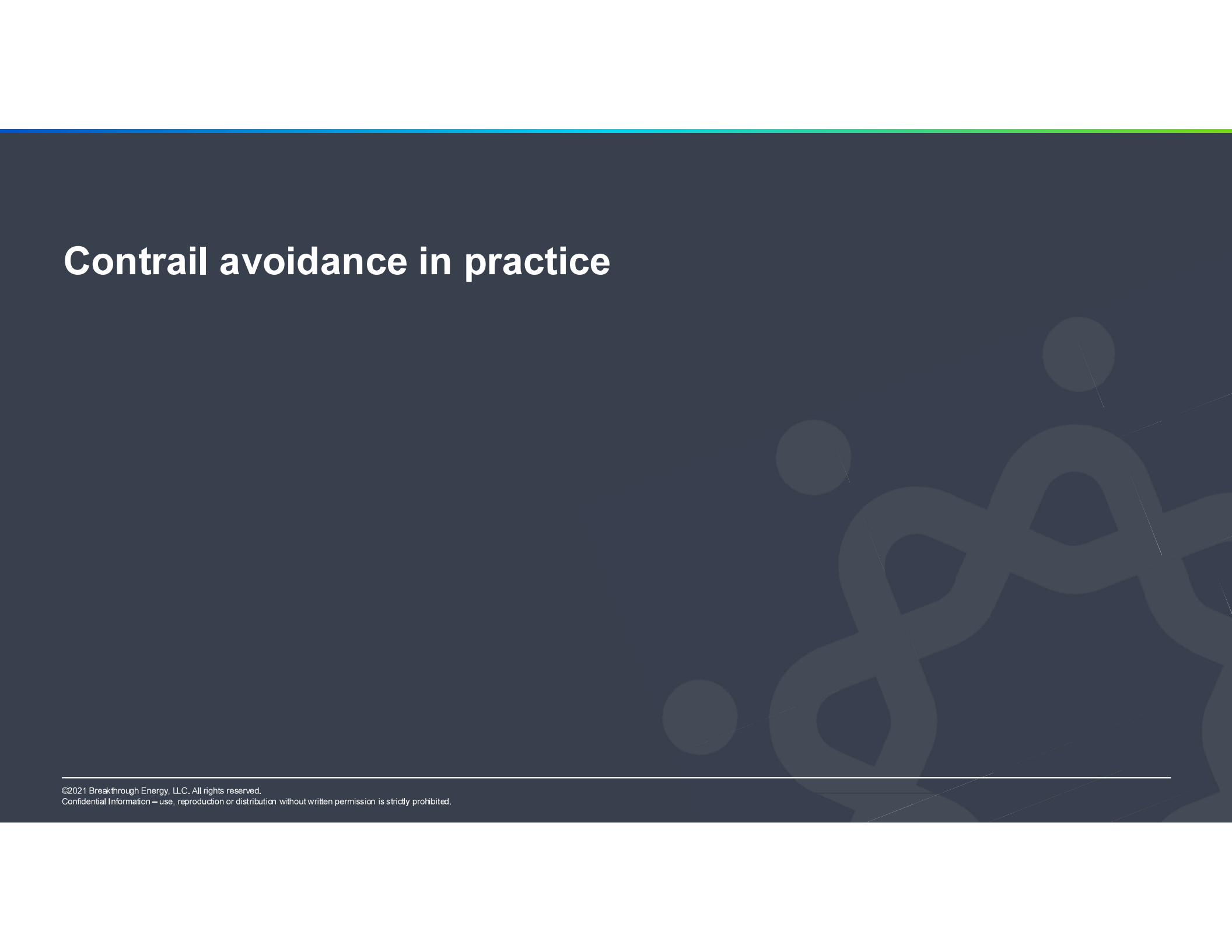
Raising ambition

We can aim to avoid **> 80% of contrail caused warming** by modestly re-routing **< 5% of aircraft** at a fleet-average **cost of < $5 per flight**

Remove 1 – 2% of human caused warming at a cost of < $1 per ton CO2 equivalent in years

But there is a lot of work to do!

Contrail avoidance in practice



Navigational contrail avoidance

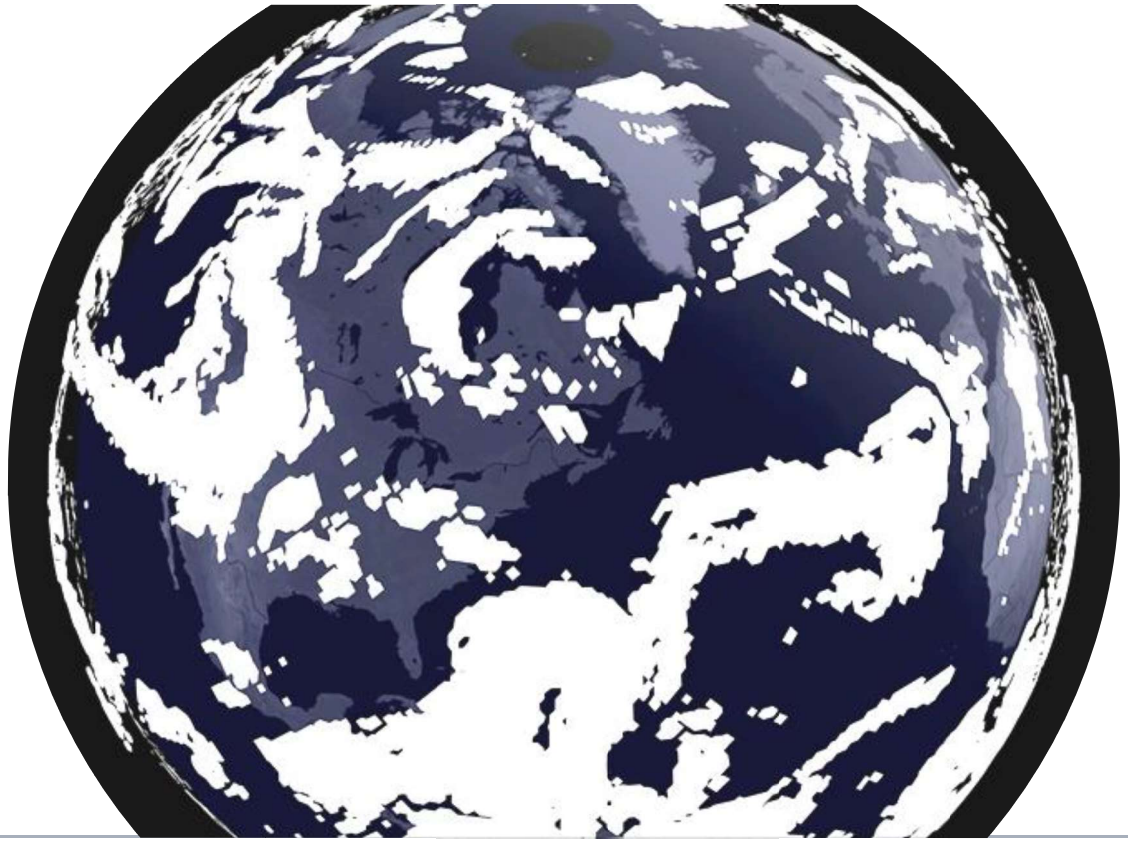
Re-routing to avoid key contrail forming regions at specific times

High level approach

1. Understand where contrail-cirrus will likely form
2. Characterize the expected climate effects
3. Integrate into flight planning and management
4. Verify actual outcomes

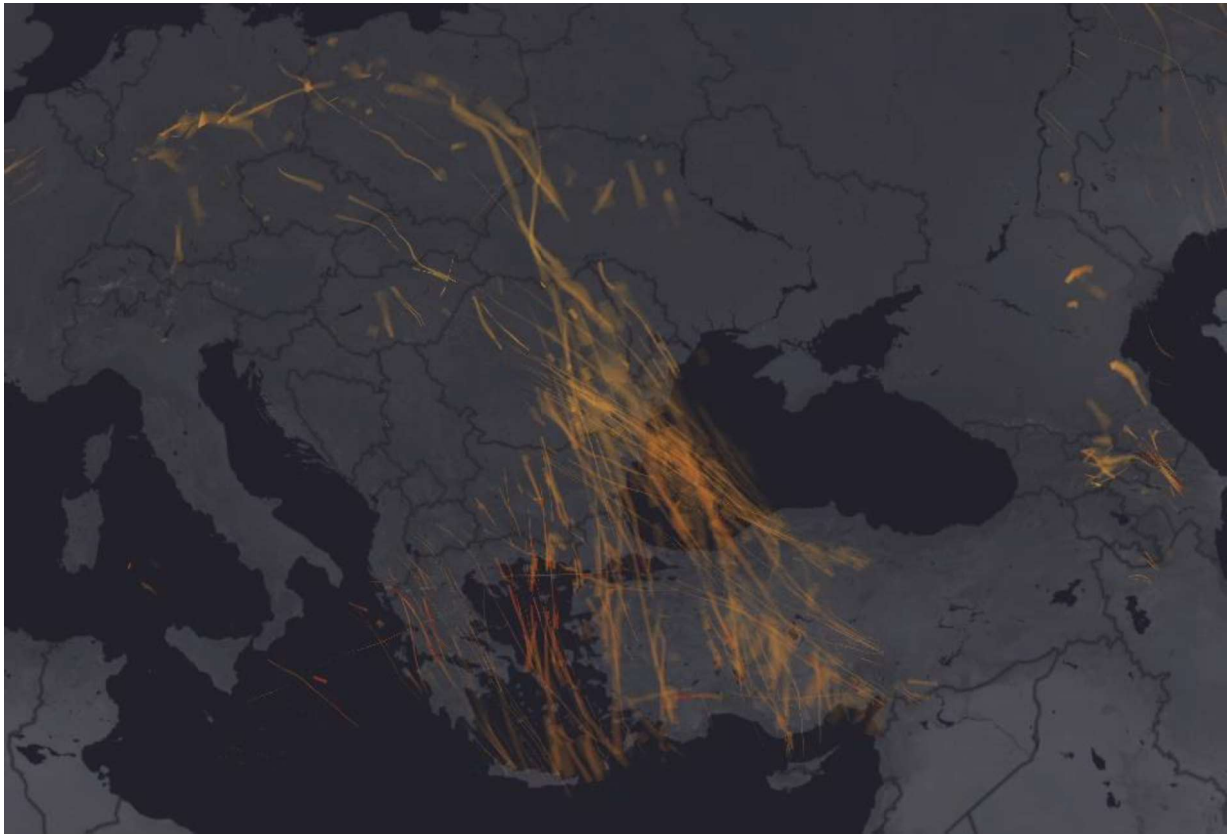
Contrails form in cold, humid regions of the atmosphere

Categorical avoidance would be effective, but completely avoiding persistent contrails regions is impractical to start



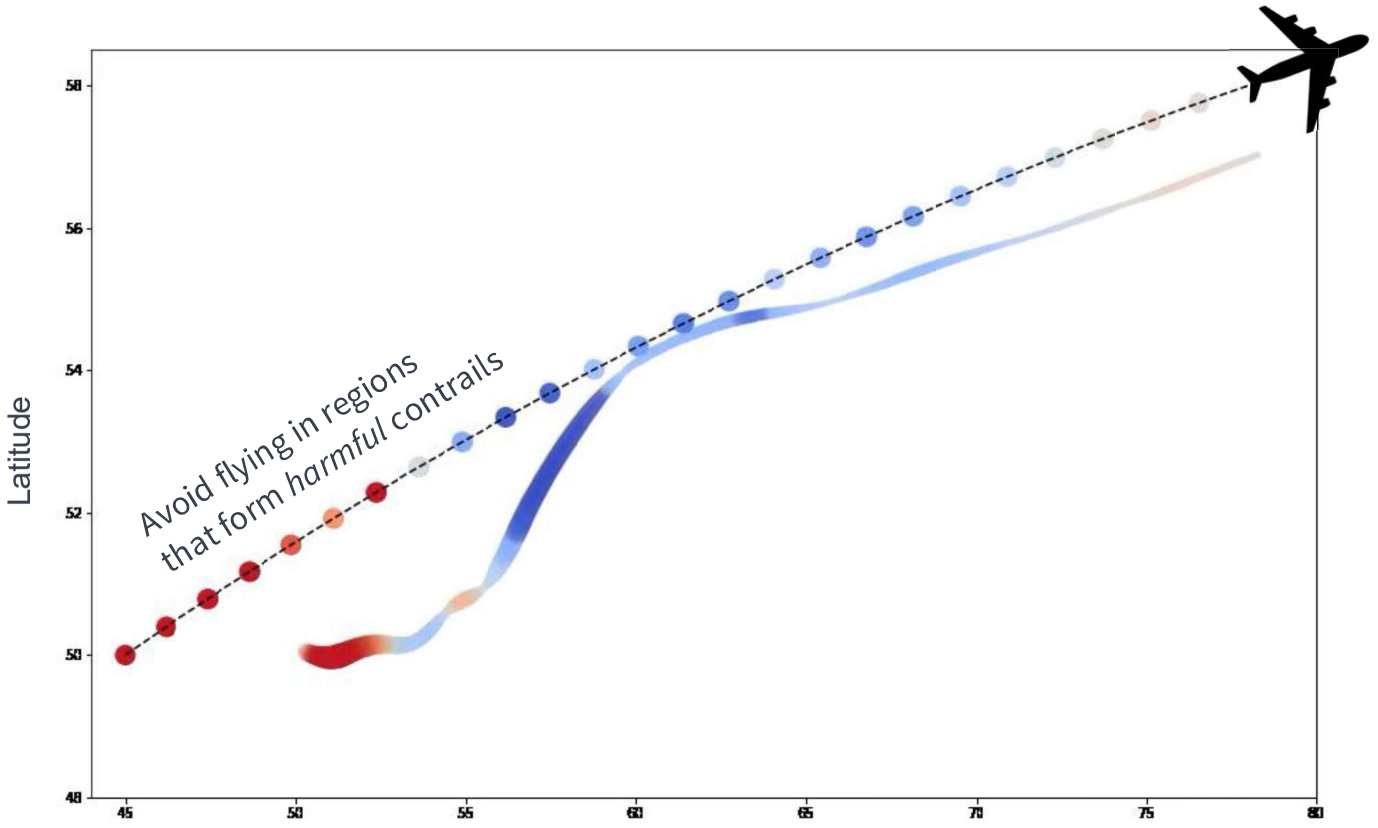
Not all contrail regions are created equal

Meteorology, engine emissions, albedo, diurnal / seasonal cycles – all dramatically affect radiative forcing



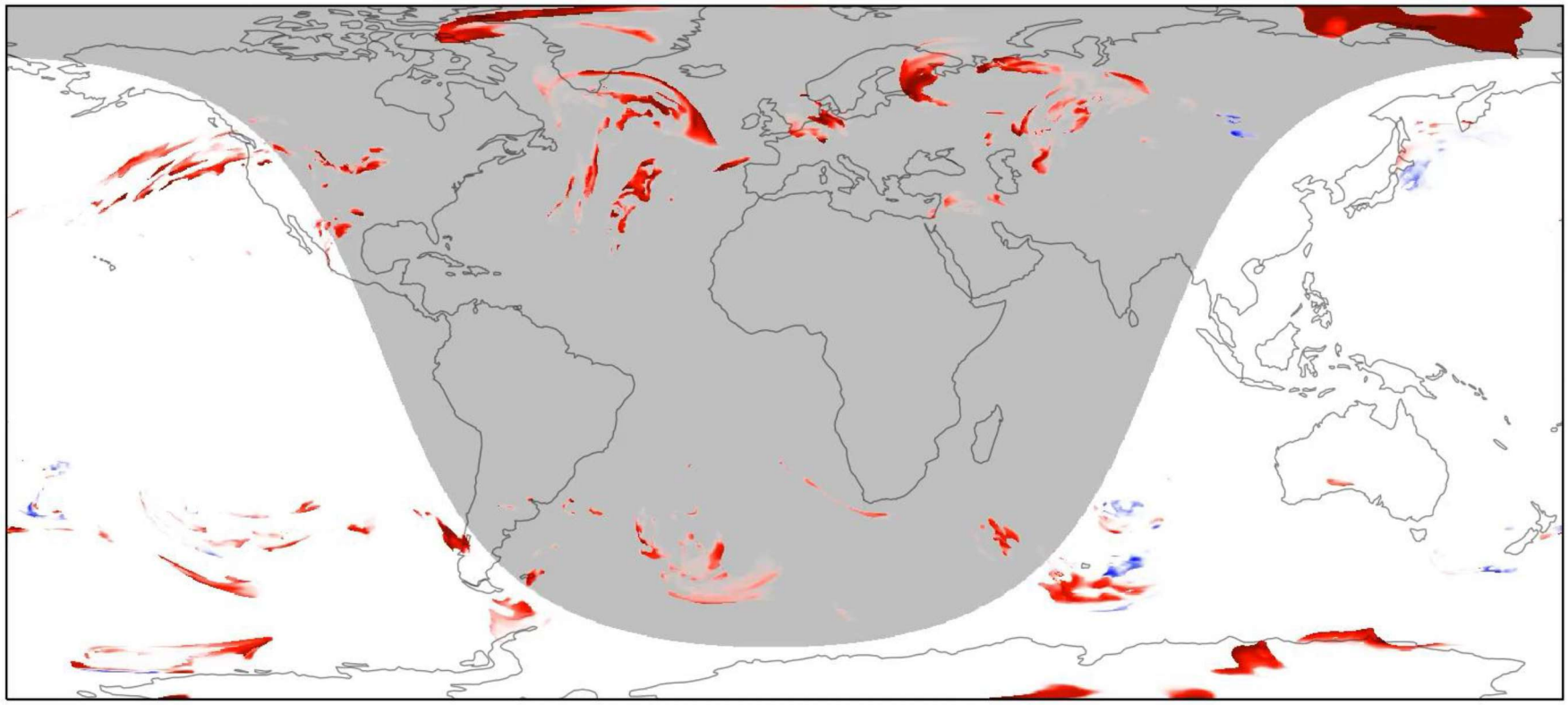
Track contrail evolution to understand climate effects

Avoid harmful regions by understanding persistence and downstream forcing



Contrail forecast + nowcast enables trajectory co-optimization

Planning tools can ingest and analyze contrail climate-forcing as any other “weather-like” data (e.g. icing, turbulence)



Contrail observations inform forecasts, nowcasts

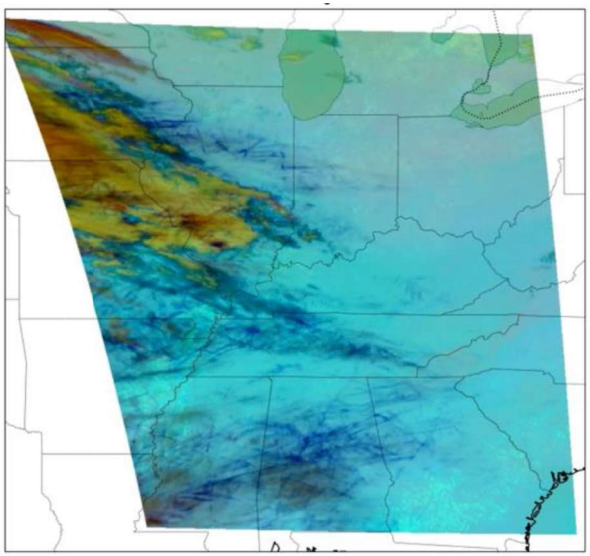
Satellite and ground-based observations improve model accuracy and feed into contrail forecasts / nowcasts

In-situ measurements

Airframe sensors
(IAGOS, WVSS-II)

Ground-based

Fixed sky-observing cameras,
LIDAR (MPLNet)

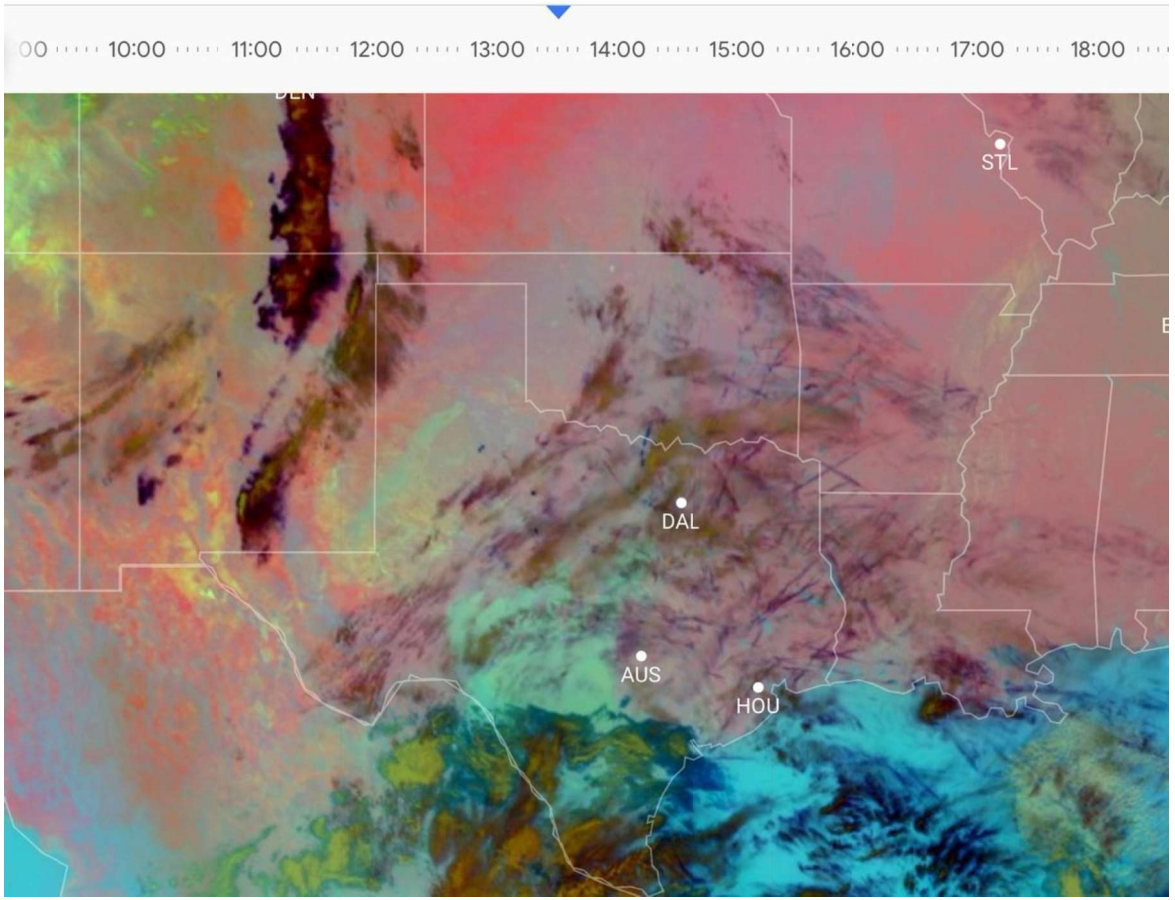


Satellite

Radiometers, LIDAR, Sounders
(GOES, Meteosat, Landsat,
CALIPSO, CLOUDSAT)

https://www.iagos.org/iagos-core-instruments/

Satellites detect contrail outbreaks in real time

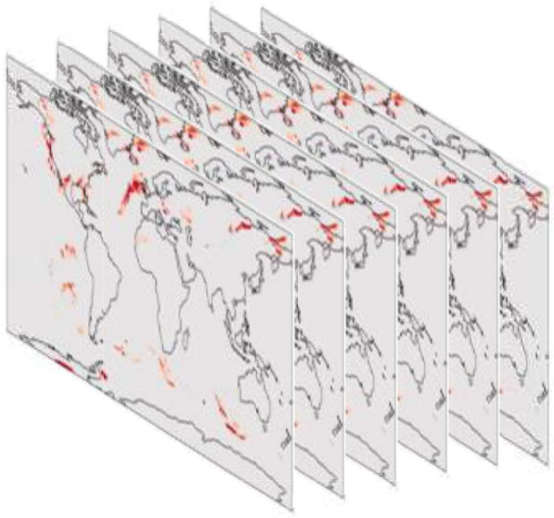


https://contrails.webapps.google.com/main

← back

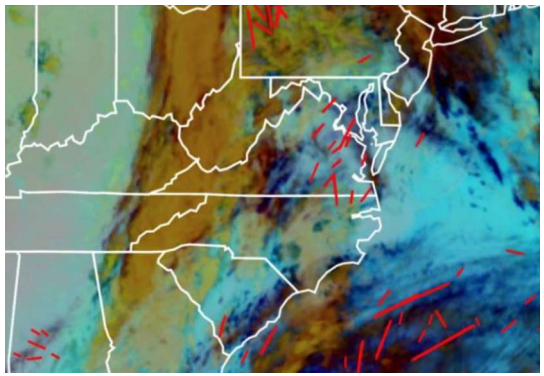
Focus on high-probability high-forcing regions in forecast

Use model ensembles and observations to generate expected values of contrail warming



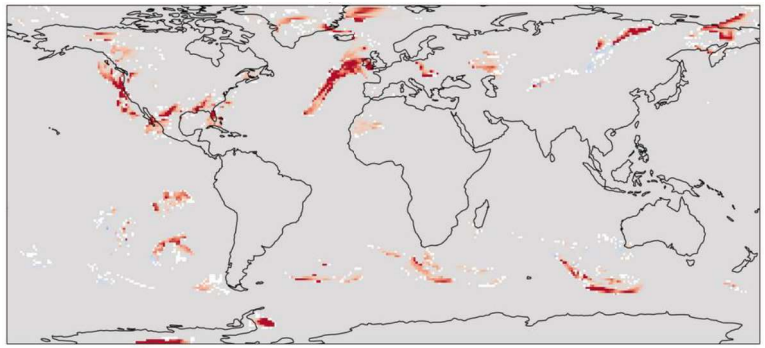
Generate contrail forecast ensembles

+



Assimilate observation sources

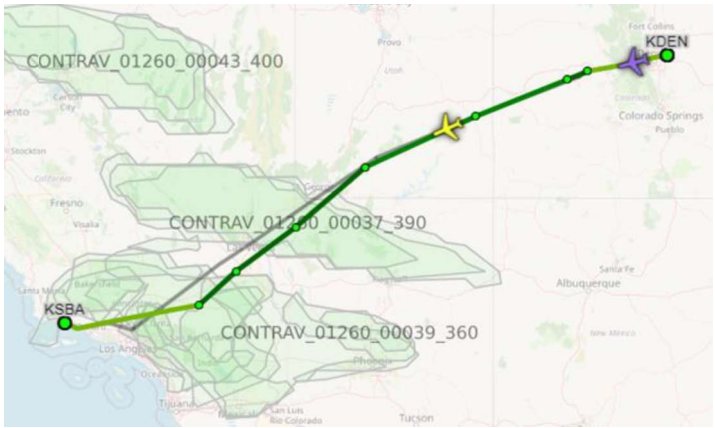
→



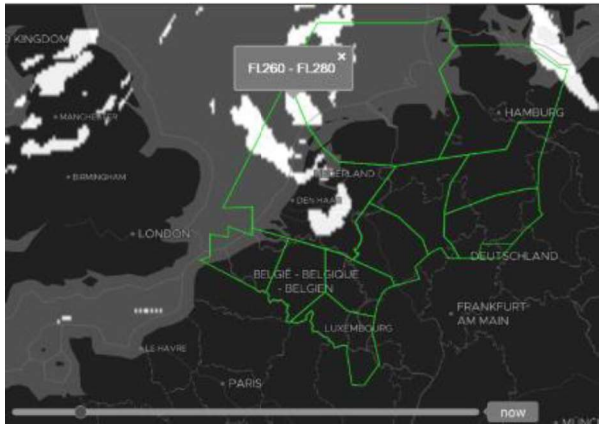
High-probability high impact contrail regions

Distribute at scale with aviation weather

Low overhead, scalable integration into aviation planning cycle



Flight Planning

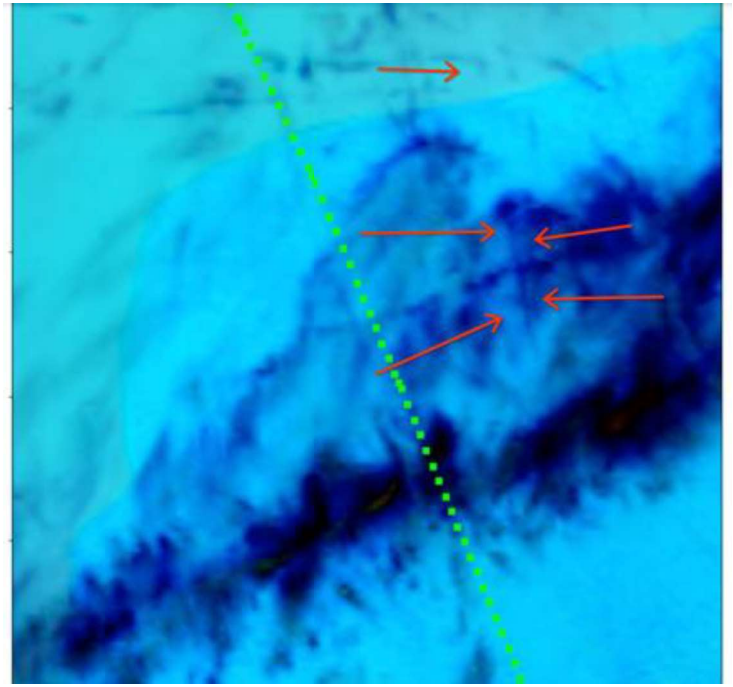


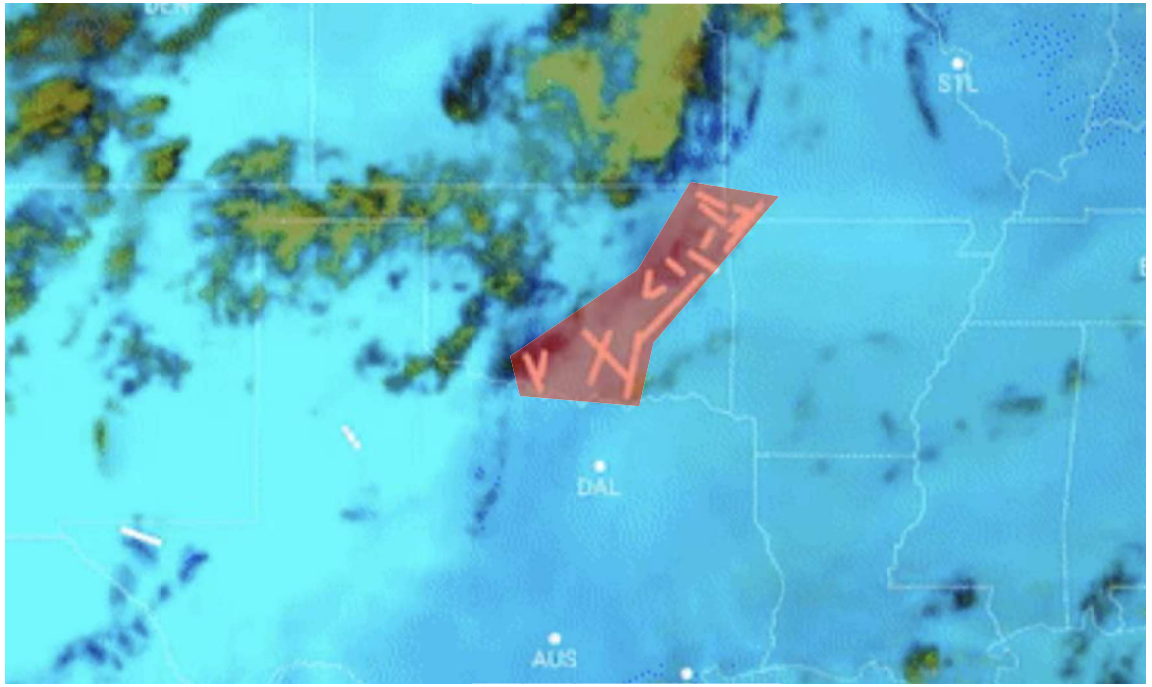
Air Traffic Control

Electronic Flight Bag (Cockpit Tablet)

Verify interventions with observational data

Ensure forecast / nowcast pipelines lead to reduction in contrail formation and contrail outbreaks overall

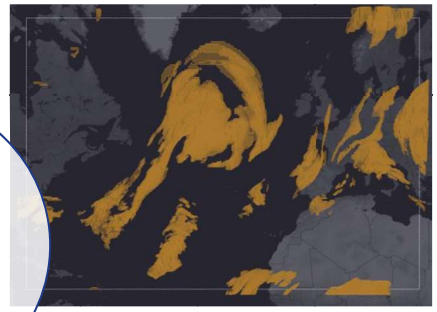




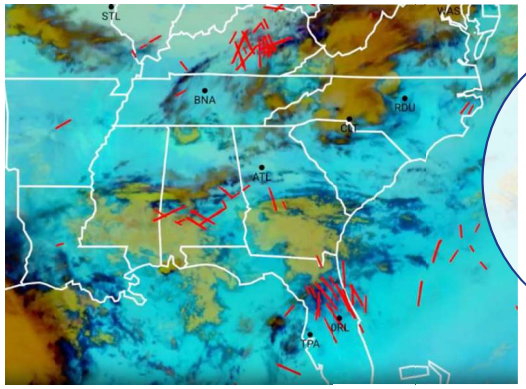
https://sites.research.google/contrails/

Continuously Improved

Observations assimilated in near-real-time

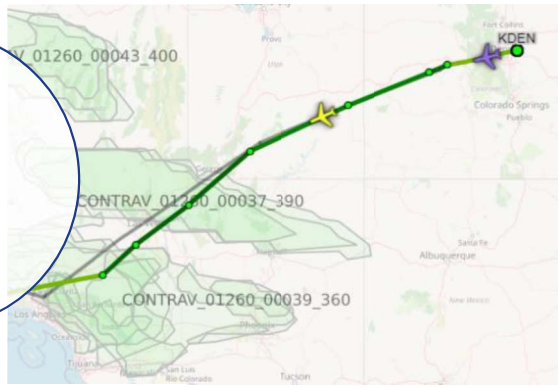


Contrail forecast



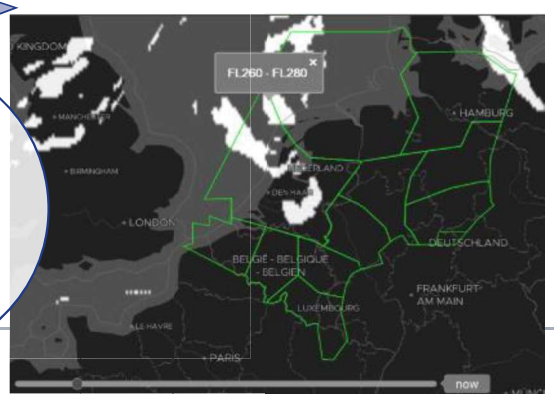
Contrail observations

Flight planning



EFB (Cockpit)

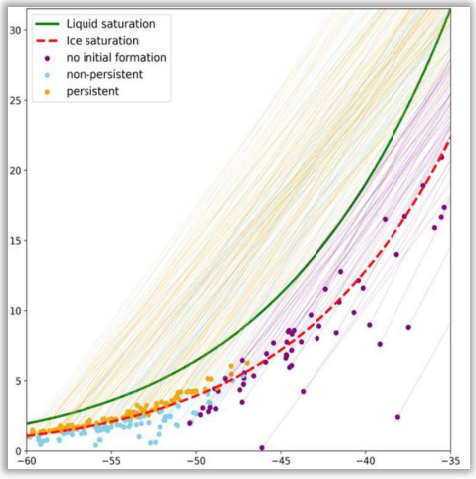
ATC

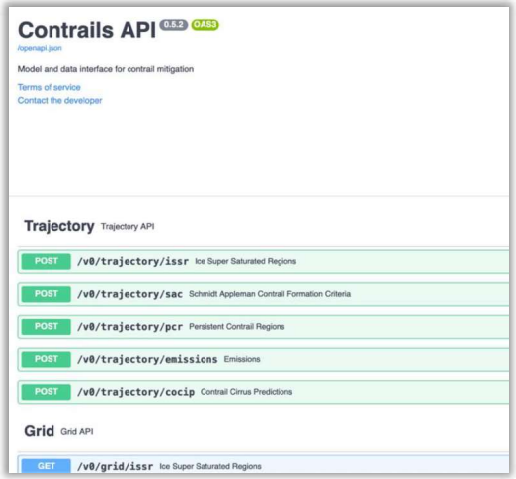


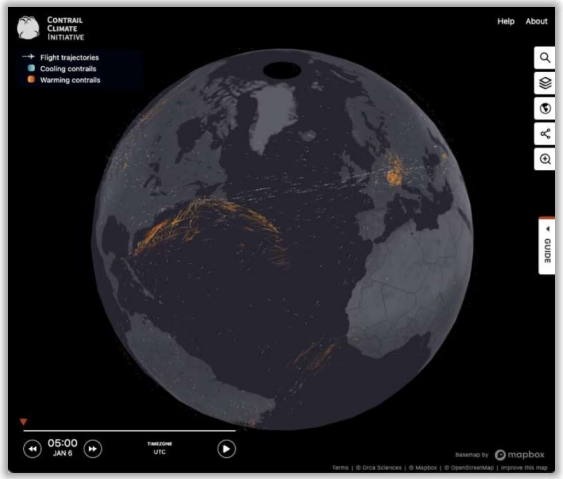
Recent progress

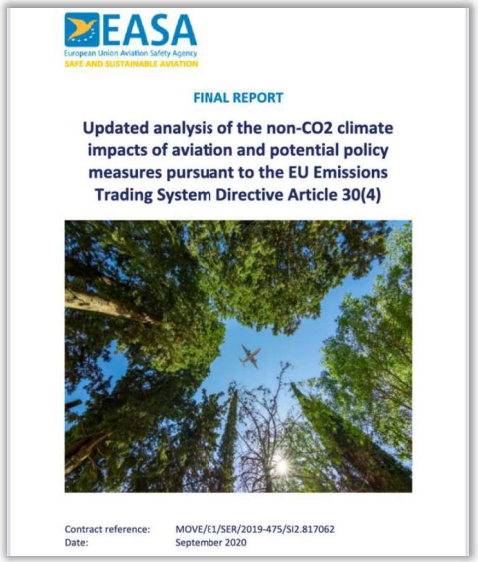
BE Contrails

Accelerating contrail research into action









Science

Advance **understanding** of contrail climate impacts

Open Tools

Build open **standards** and **capability** for avoidance

Outreach

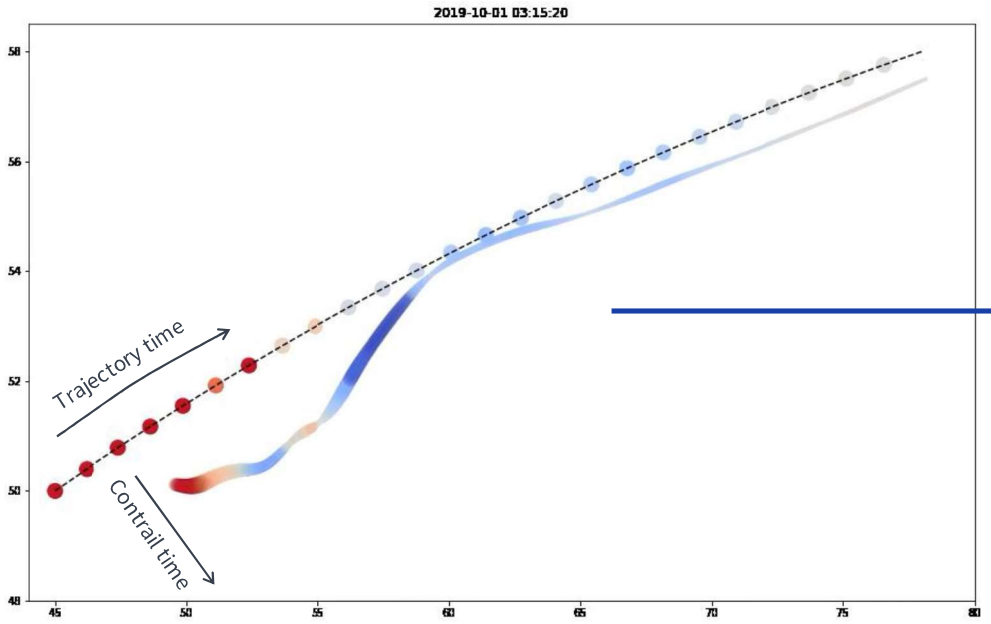
Educate and **engage** the industry and public

Policy

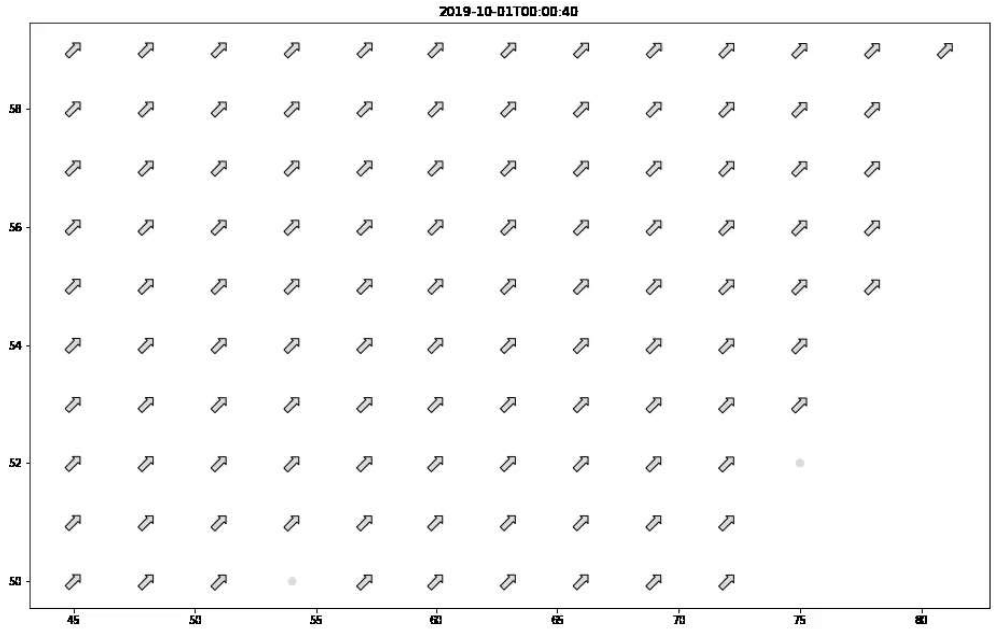
Inform **regulations** and **incentive** development

Establish prototype contrail forecast and implementation

Engberg et al (under review) “Forecasting Contrail Climate Forcing for Flight Planning and Air Traffic Management Applications: The CocipGrid Model in Pycontrails 0.51.0” *Geoscientific Model Development* https://doi.org/10.5194/egusphere-2024-1361



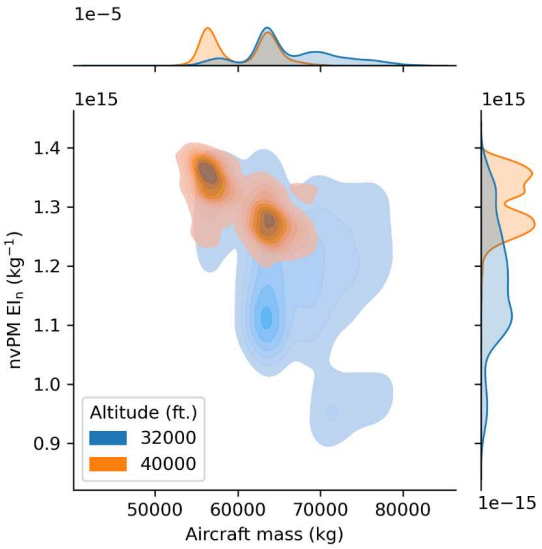
Contrail evolution for flight segments



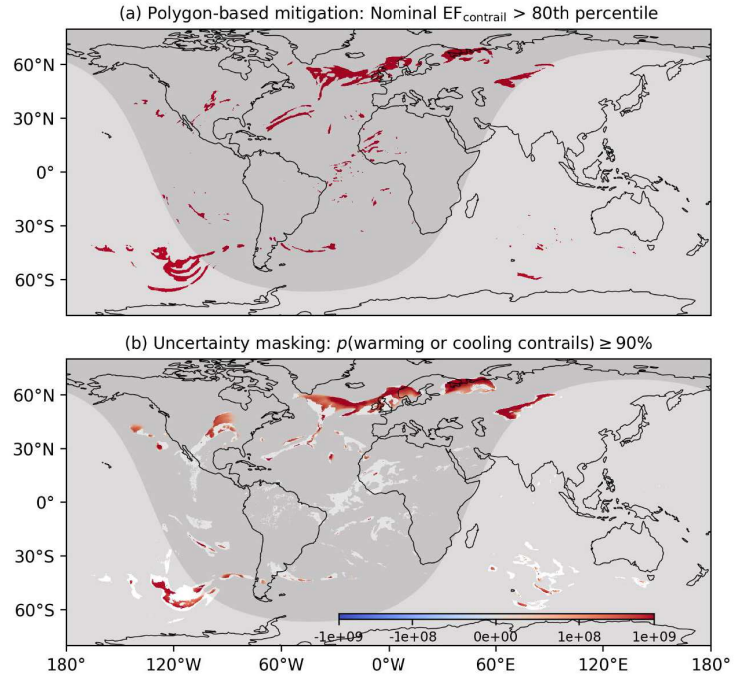
Contrail evolution for grid of infinitesimal segments

Establish prototype contrail forecast and implementation

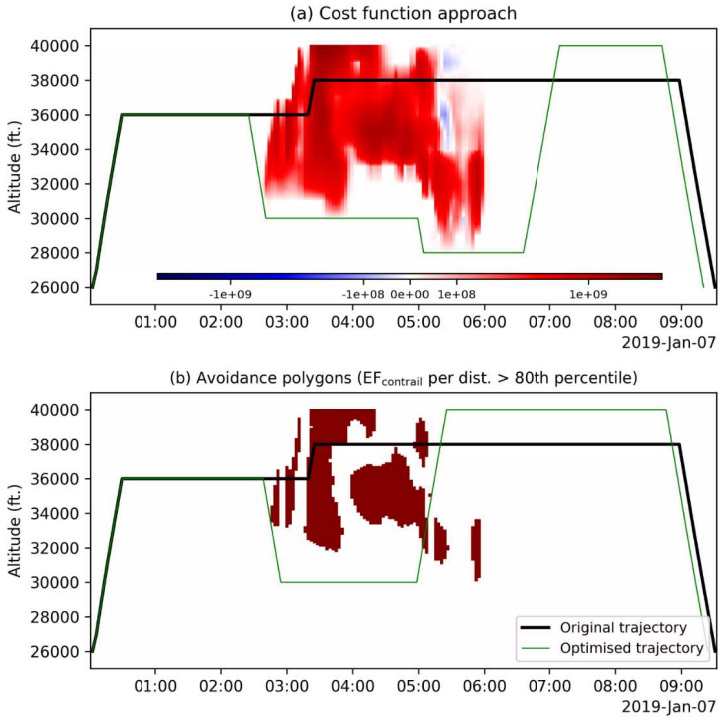
Engberg et al (under review) “Forecasting Contrail Climate Forcing for Flight Planning and Air Traffic Management Applications: The CocipGrid Model in Pycontrails 0.51.0” *Geoscientific Model Development* https://doi.org/10.5194/egusphere-2024-1361



Aircraft classes



Uncertainty masking



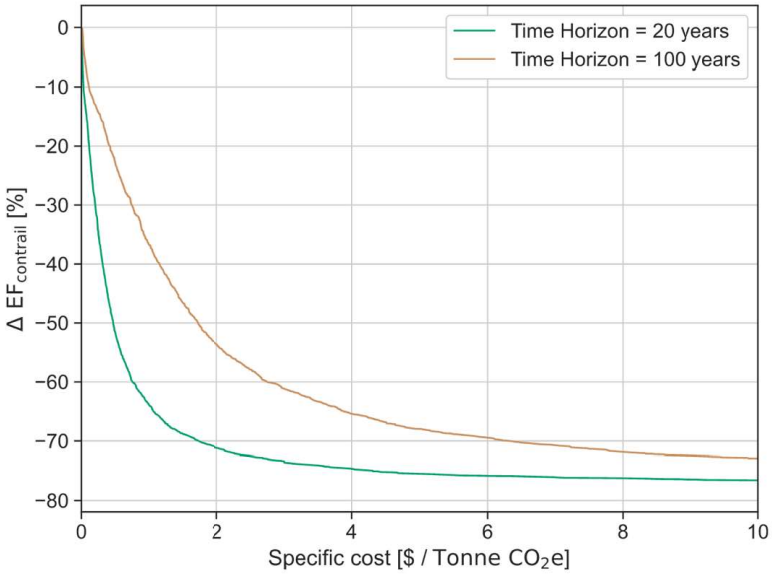
Trajectory optimization

Quantify cost and feasibility in flight planning system

Frias et al (2024) "Feasibility of Contrail Avoidance in a Commercial Flight Planning System: An Operational Analysis." *Environmental Research: Infrastructure and Sustainability* https://doi.org/10.1088/2634-4505/ad310c

High-fidelity contrail avoidance simulation on 84,839 flights in commercial flight planning system

Total cost to the airline **+0.08%** (or +0.11% CO2 emissions)



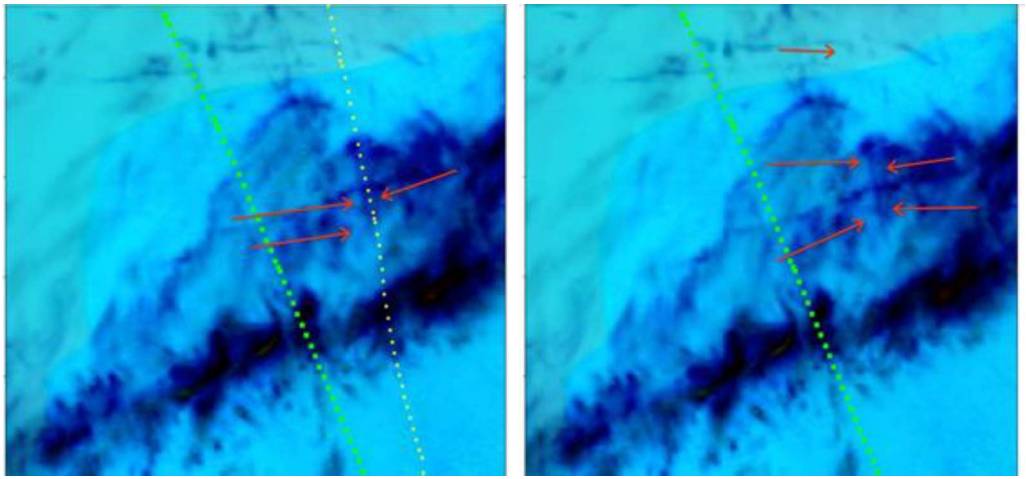
Trial forecast model in live trials

(→ Google presentation to follow)

Contrail forecast on pilot iPad

“Pilot” project w. American Airlines

- Jan – Jun 2023
- Manually communicated flights levels forecast to generate contrails
- Evaluate contrail formation manually from GOES



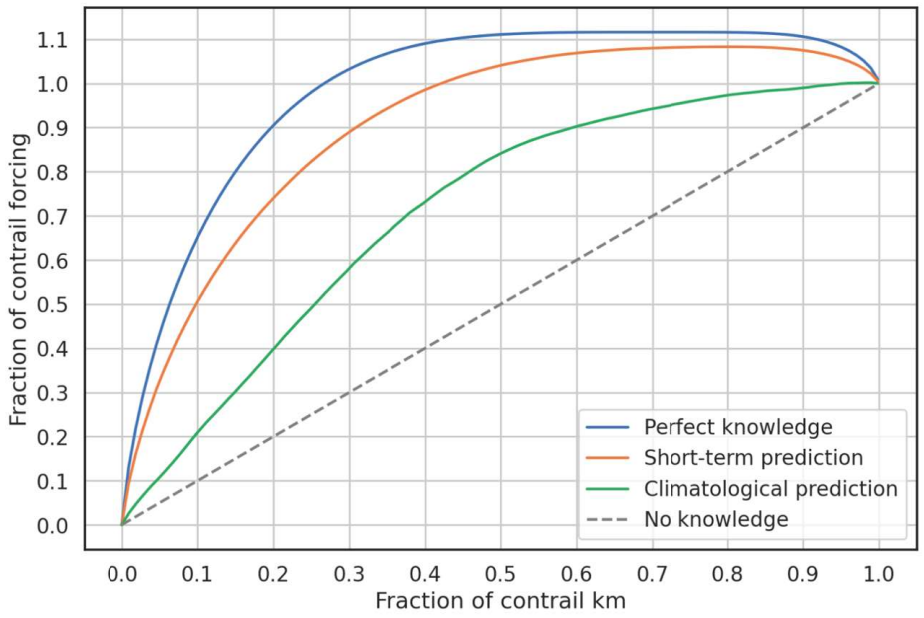
Verification using GOES and advected emissions path

Next step is automated trials via flight planning

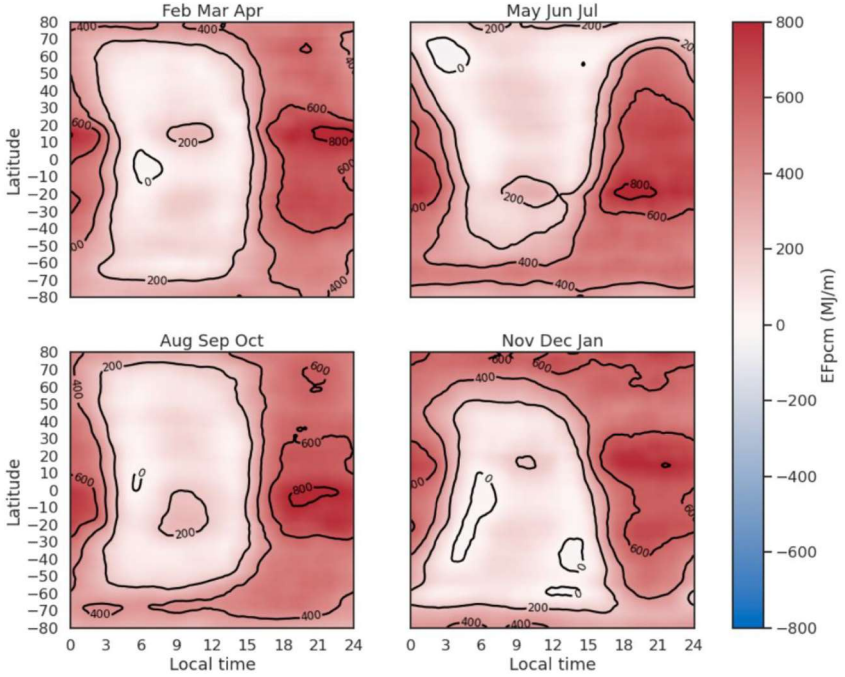
Developing additional trials with multiple other airlines and w. Airbus in the CICONIA project

Evaluate the effect of uncertainty on forecast skill

Platt et al (2024) "The Effect of Uncertainty in Humidity and Model Parameters on the Prediction of Contrail Energy Forcing." *Environmental Research Communications*. https://doi.org/10.1088/2515-7620/ad6ee5



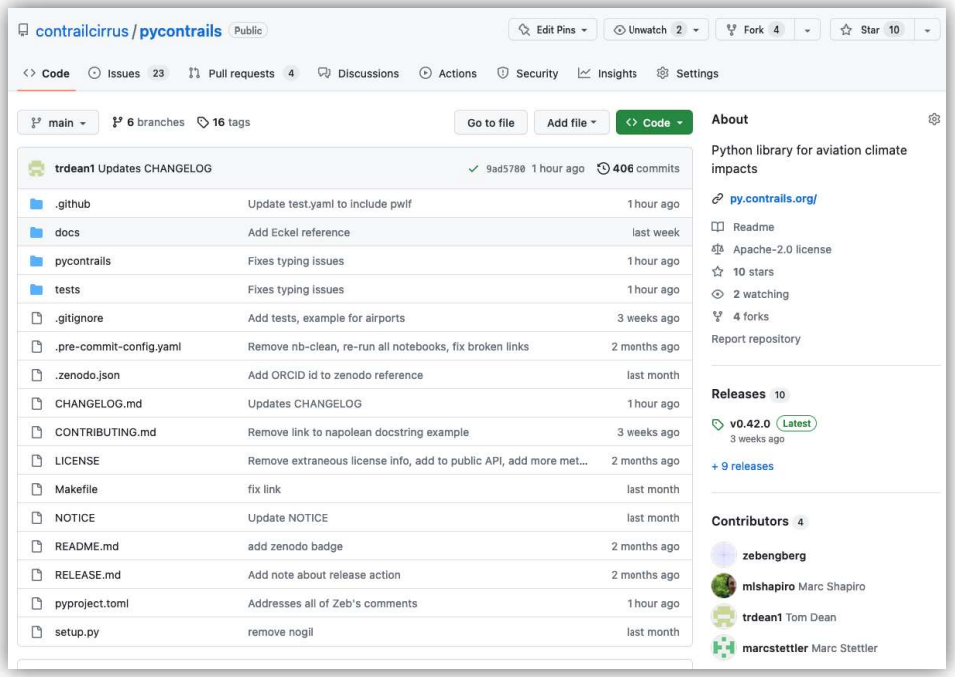
Performance curve



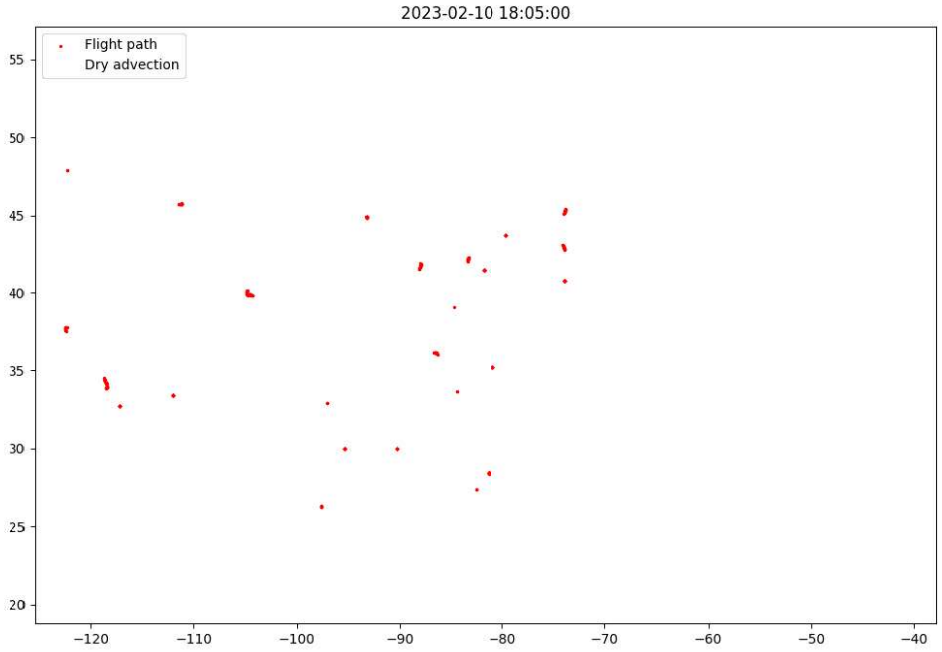
Seasonal maps of contrail climatology

Open-source aviation climate impact models

Contrail model implementations (CoCiP, aCCF), comparison with observations (GOES), integration with climate models, utilities



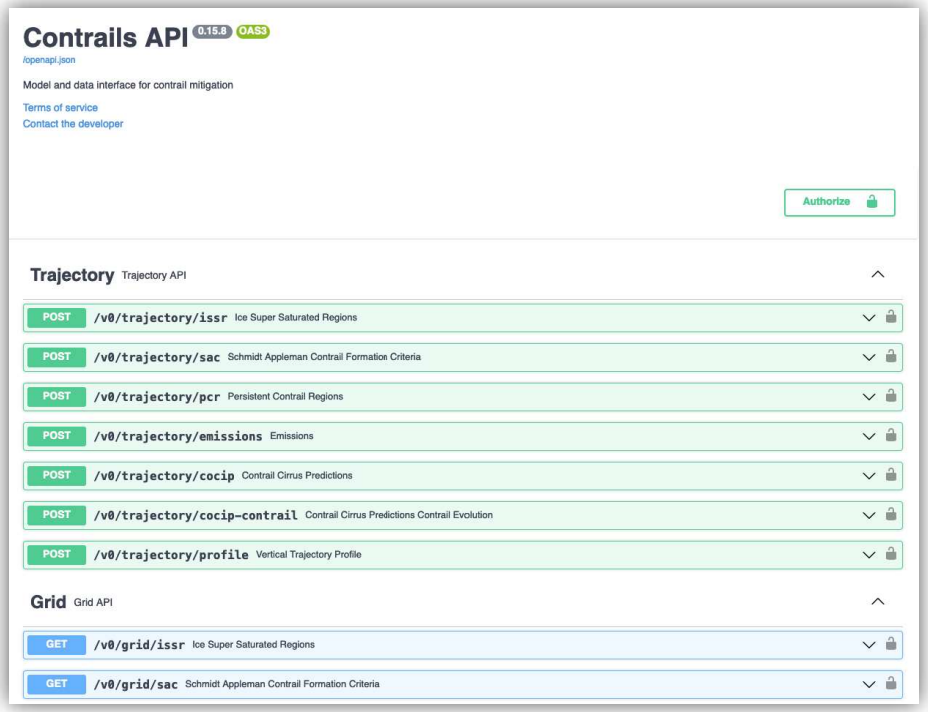
https://py.contrails.org



Dry-advection of aircraft emissions

Develop standard interface for contrail data

API access to forecast data, verification tools, and historical impact data. Dashboard presents data visually.



https://api.contrails.org

https://forecast.contrails.org

Flight Emissions Report

Flight by flight estimates of aircraft emissions, flight length with persistent contrails, climate forcing, satellite verification

icao_address	callsign	tail_number	flight_number	engine_uid	aircraft_type	ef_mj	fuel_burn_kg	co2_kg	total_nox_kg	h2o_kg	so2_kg
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484F73	KLM765	PH-AKD	KL765	01P14RR101	A333	-14101903	43343	136923	578.950543	53313	52.01269047
48436E	KLM706	PH-BQG	KL706	2RR027	B772	5900514	65112	205691	1061.58094	80088	78.13553767
486072	KLM644	PH-BKM	KL644	01P17GE213	B78X	25637975	31810	100490	501.440326	39127	38.17292012
4851B3	KLM168	PH-BVP	KL168	01P21GE217	B77W	136086591	53141	167874	1025.84987	65364	63.77003547
485788	KLM258	PH-BHP	KL258	01P17GE212	B789	33237115	50286	158856	752.126157	61852	60.34422425
484F18	KLM46D	PH-BCB	KL1952	01P11CM116	B738	0	6206	19606	65.9145071	7634	7.447911649
485789	KLM898	PH-BHO	KL898	01P17GE212	B789	-1301477	46719	147587	660.586382	57465	56.06348074
4843F2	KLM896	PH-BQO	KL896	2RR027	B772	237298151	87131	275248	1374.31346	107171	104.5580054
484558	KLM1266	PH-BGA	KL1266	01P11CM116	B738	0	1311	4142	15.1252669	1613	1.573714708
48418D	KLM1248	PH-BXS	KL1248	01P11CM121	B739	0	4230	13362	50.2690645	5203	5.076140307
48455D	KLM1162	PH-BGF	KL1162	01P11CM114	B737	-27856816	1873	5916	19.7887309	2303	2.247645371
3C6D43	KLM1838	D-AKJC	KL1838	8GE116	E190	0	908	2870	9.19735684	1117	1.090534493
485A35	KLM70B	PH-BCL	KL1350	01P11CM116	B738	-75827	1603	5065	17.6494917	1972	1.924242737
484C54	KLM1708	PH-EZP	KL1708	8GE116	E190	0	342	1081	2.97187228	421	0.410958423
3C76EF	KLM1282	D-AMWO	KL1282	8GE116	E190	0	929	2935	9.2662464	1142	1.115118352
484132	KLM90J	PH-BXC	KL1770	01P11CM116	B738	0	1304	4120	14.6392234	1604	1.565154218
484163	KLM92B	PH-BXK	KL1228	01P11CM116	B738	0	1648	5208	18.8749505	2028	1.978692551
484B31	KLM1982	PH-EZD	KL1982	8GE116	E190	0	2529	7990	24.470164	3111	3.035381263
484B30	KLM1150	PH-EZC	KL1150	8GE116	E190	0	2266	7158	22.8454289	2787	2.719442558
484CC3	KLM1184	PH-EZS	KL1184	8GE116	E190	0	1038	3281	10.8770264	1277	1.246366486

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Transition research into industry action

Contrail Science & Technology Network

Global NGO cohering research, standards, and advocacy

https://www.contrails.org

Mission

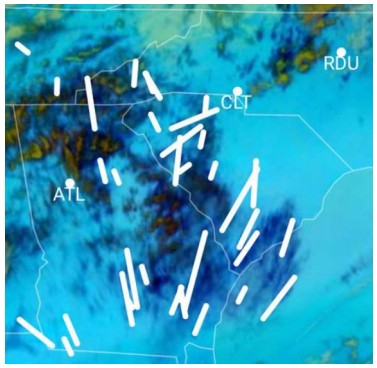
Avoid > 80% of contrail caused warming by modestly re-routing < 5% of aircraft at an average cost of <$5 per flight

Remove 1 – 2% of human caused warming at a cost of < $1 per ton CO_2 equivalent

Call to action

Critical gaps

1) Contrail observations need to be improved to inform and verify avoidance



Geostationary (GEO) too coarse to resolve flights

Low-earth orbit (LEO) too sparse to track evolution

Ground cameras sparse

Very few humidity sensors in service

2) No incentive exists to drive testing and adoption

Submit grant to the EU Innovation Fund (€20M) to fund trials, but not enough to support ongoing mitigation

3) Air Navigational Service Providers (ANSPs) are missing from the development

The need for an ambitious research agenda on contrails

Negative contrail climate effects are avoidable

A major portion of these effects are avoidable in a short timeframe (years)

We have the tools to test and learn how to do this today – and improve over time

The need for an ambitious research agenda on contrails

Negative contrail climate effects are avoidable

A major portion of these effects are avoidable in a short timeframe (years)

We have the tools to test and learn how to do this today – and improve over time

→ Contrail avoidance is likely the cheapest and fastest way to mitigate the climate effects of aviation

“We know of no comparable climate investment with a similarly high likelihood of success.”

— Caldeira & McKay, 2021, *Nature*

The need for an ambitious research agenda on contrails

Researchers, regulators, and industry are lacking the resources to prioritize this today

- We need **airlines** to run trials and build contrail awareness into dispatch and pilot workflows
- We need **meteorologists (NOAA, AWC, WMO) and climate scientists (DoE)** to improve upper-troposphere weather prediction, data assimilation, ice microphysics, atmospheric feedback, and long-term impacts
- We need **regulators** (**FAA, Eurocontrol**) to support airspace-wide trials, and provide historical flight data for climate model testing and emissions assessment
- We need **new sensing platforms (NASA, EUMETSAT)** to improve remote sensing of contrail cover and radiative impacts
- **We need global coordination (particularly N. America and Europe)**
  - **Contrail free zones in N. Atlantic?**

Breakthrough Energy Contrails

More info

contrails.org

Contact

Marc Shapiro: marc.shapiro@breakthroughenergy.org

BE Contrails core team

Accelerating the transition of contrail research into actionable climate solutions

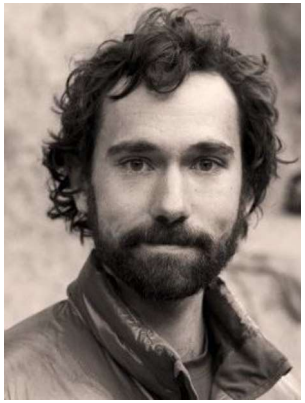
Marc Shapiro

Zeb Engberg

Tom Dean

Tristan Abbott

Science



Nick Masson

Engineering

Matteo Mirolo

Outreach

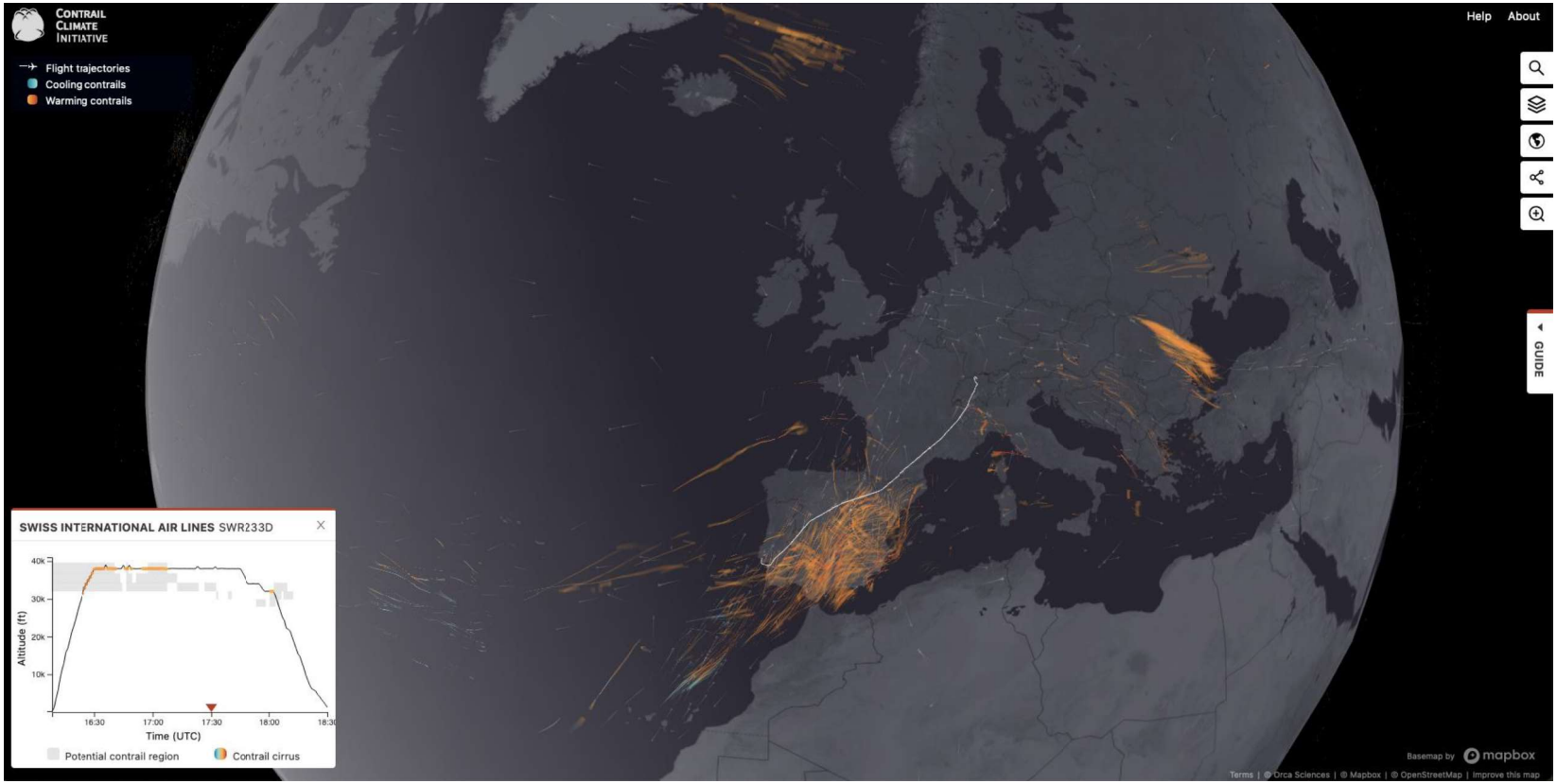
Advisors

— Eric Toone (BE), Ian McKay (Orcas), Ken Caldeira (Carnegie Sciences), Dick Benschop (Mission Possible)

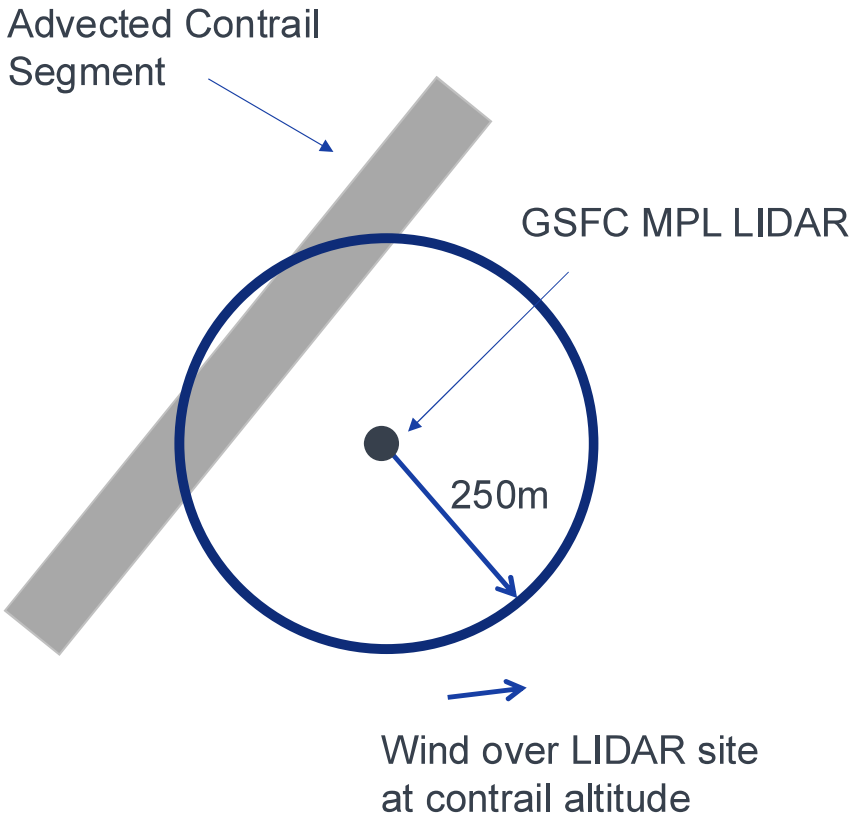
Details

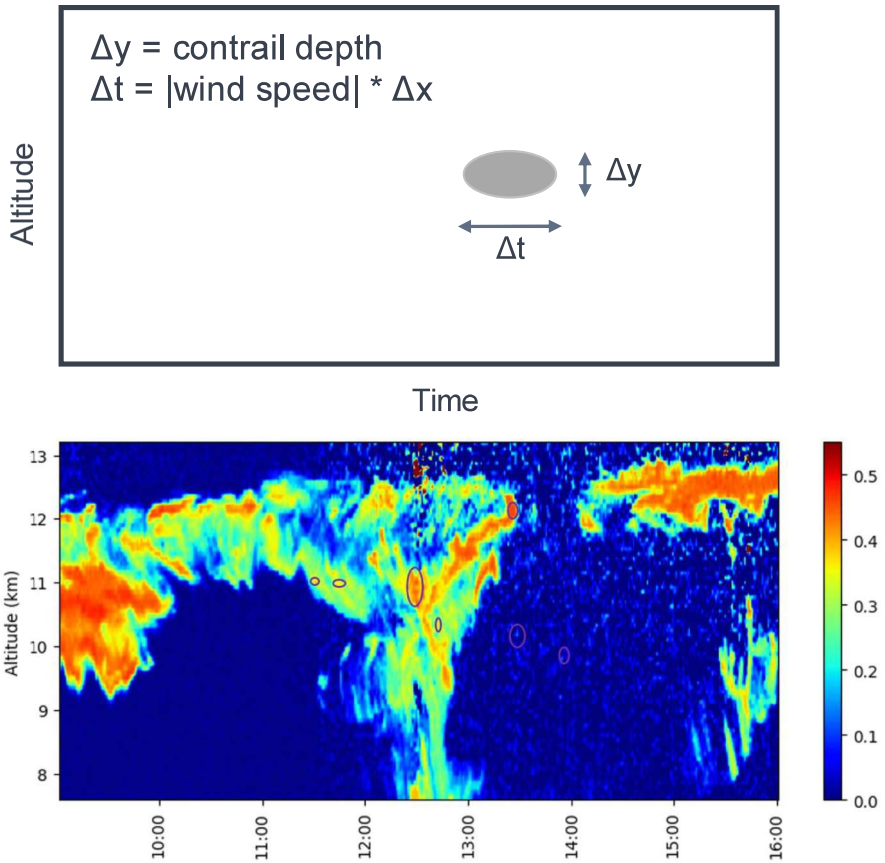
Visualize global contrails on interactive map

https://map.contrails.org



Investigate LIDAR returns for contrail observations

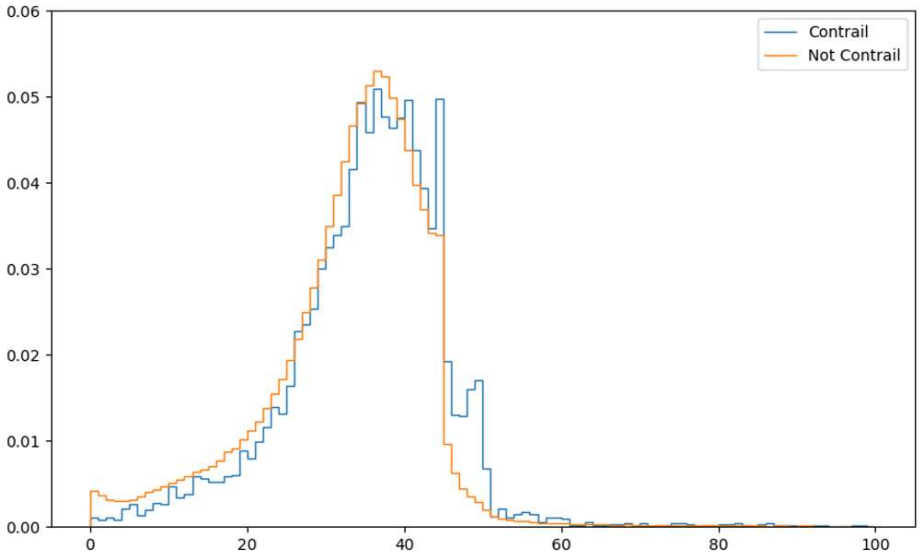




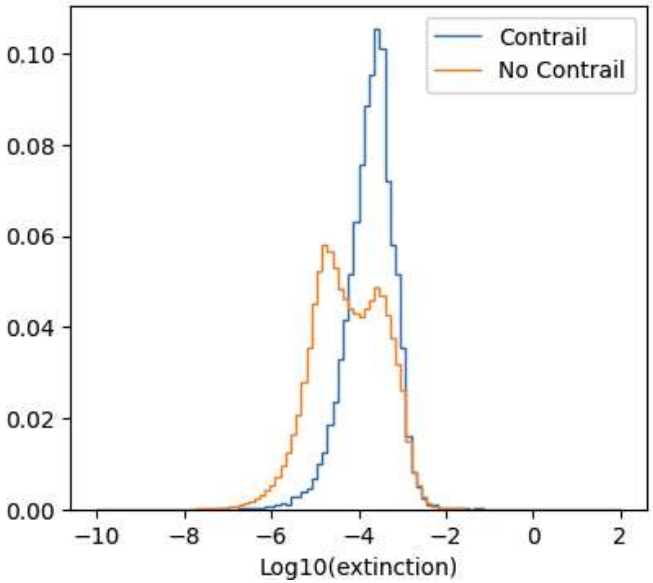
Investigate LIDAR returns for contrail observations

High depolarization ratio and extinction attributed to relatively high optical absorption of contrails

Related to the mechanism of their formation (i.e., nucleation on black carbon).



Empirical PDF estimates of the depolarization ratio



Empirical PDF estimates of extinction from aerosols

AA “pilot” study

Structure

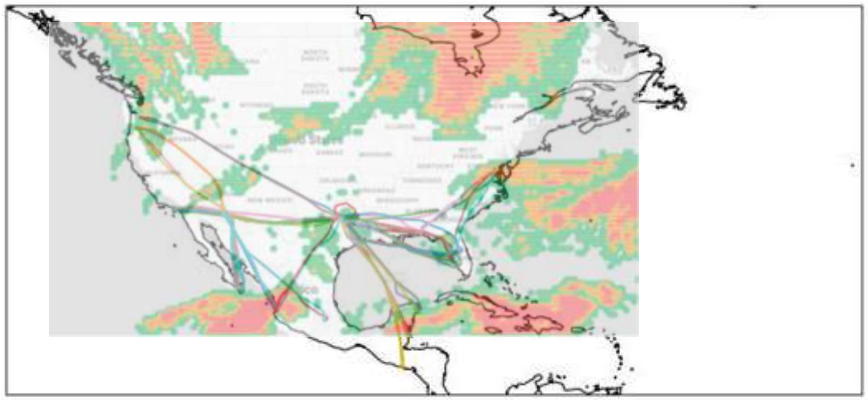
- 10 pilots participated
- Between Jan 1 and early June, 2023

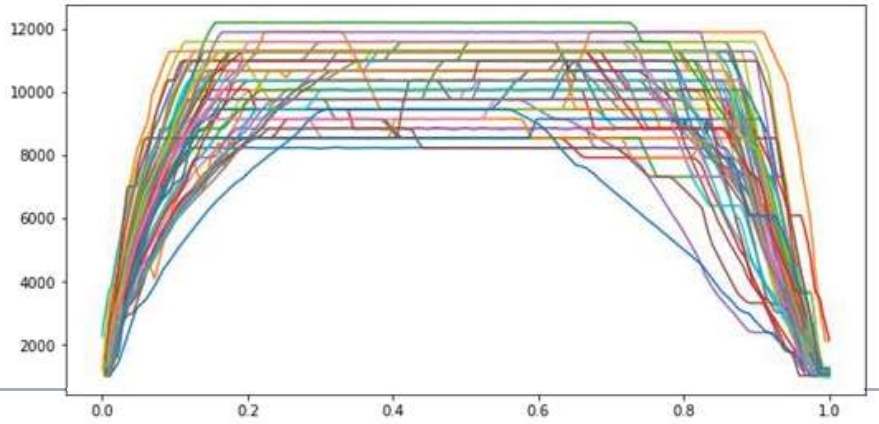
Turns

- City A to City B, back the same day
- Contrail Likely Zone (CLZ) on flightpath in/out of city A or B
- Contrail avoidance on arrival or departure (random choice)
- Avoidance only **early descent or late ascent**

Input

- Manual presentation of Google / BE contrail predictions
- PACE-integrated Google predictions





AA “pilot” study

35 turns, of which 22 included in analysis (44 flight segments)

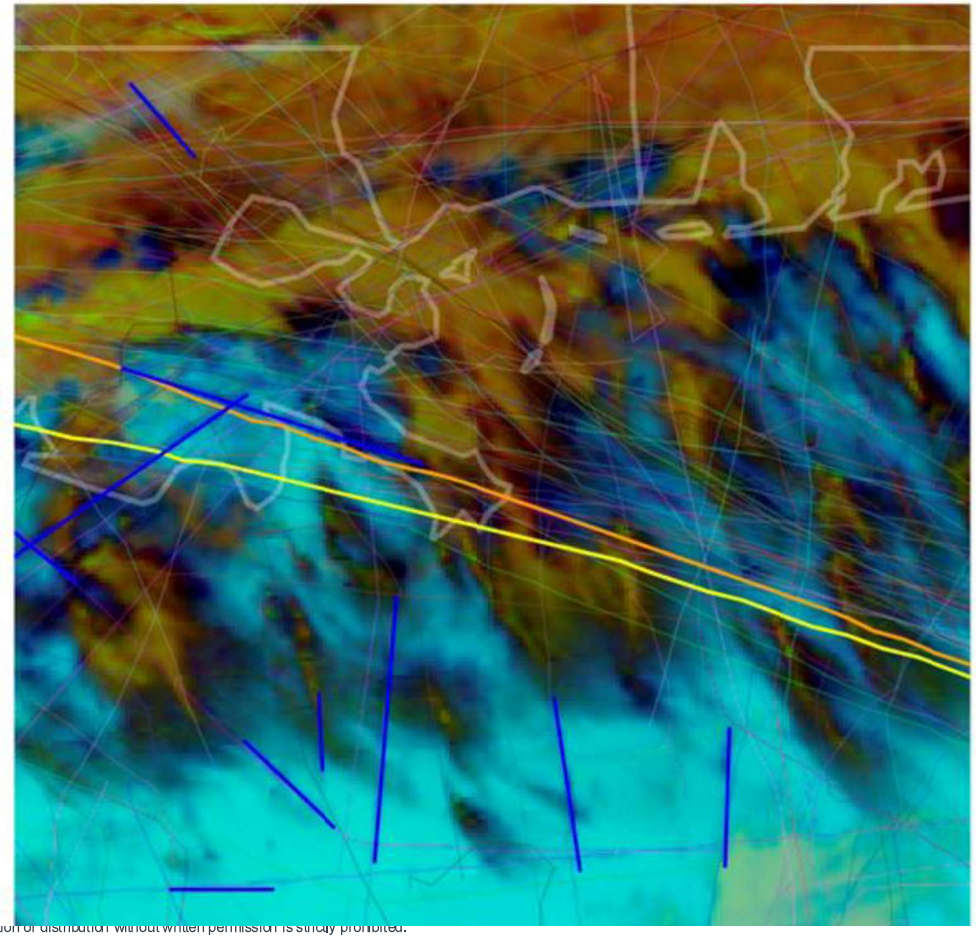
	No detectable contrail created	Detectable contrail created	Contrail length [km]	Total flight length [km]
Control	11	**11**	**726**	36802
Experiment	18	**4**	**321**	35729

64% fewer contrails observed in treatment group

54% reduction in contrail length per flight kilometer

Average of **2% more fuel per adjusted flight** (without using an optimizer)

AA “pilot” study



Geographic Features
Boundaries

Other flights
other flights

AAL189
advected flight path

AAL189
original flight path

Contrails
contrails