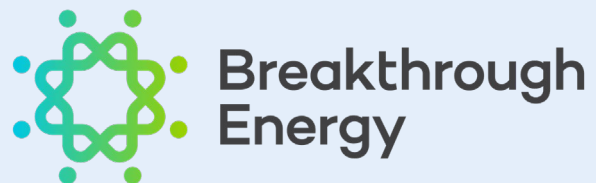


# 2023 Contrail Avoidance Trials

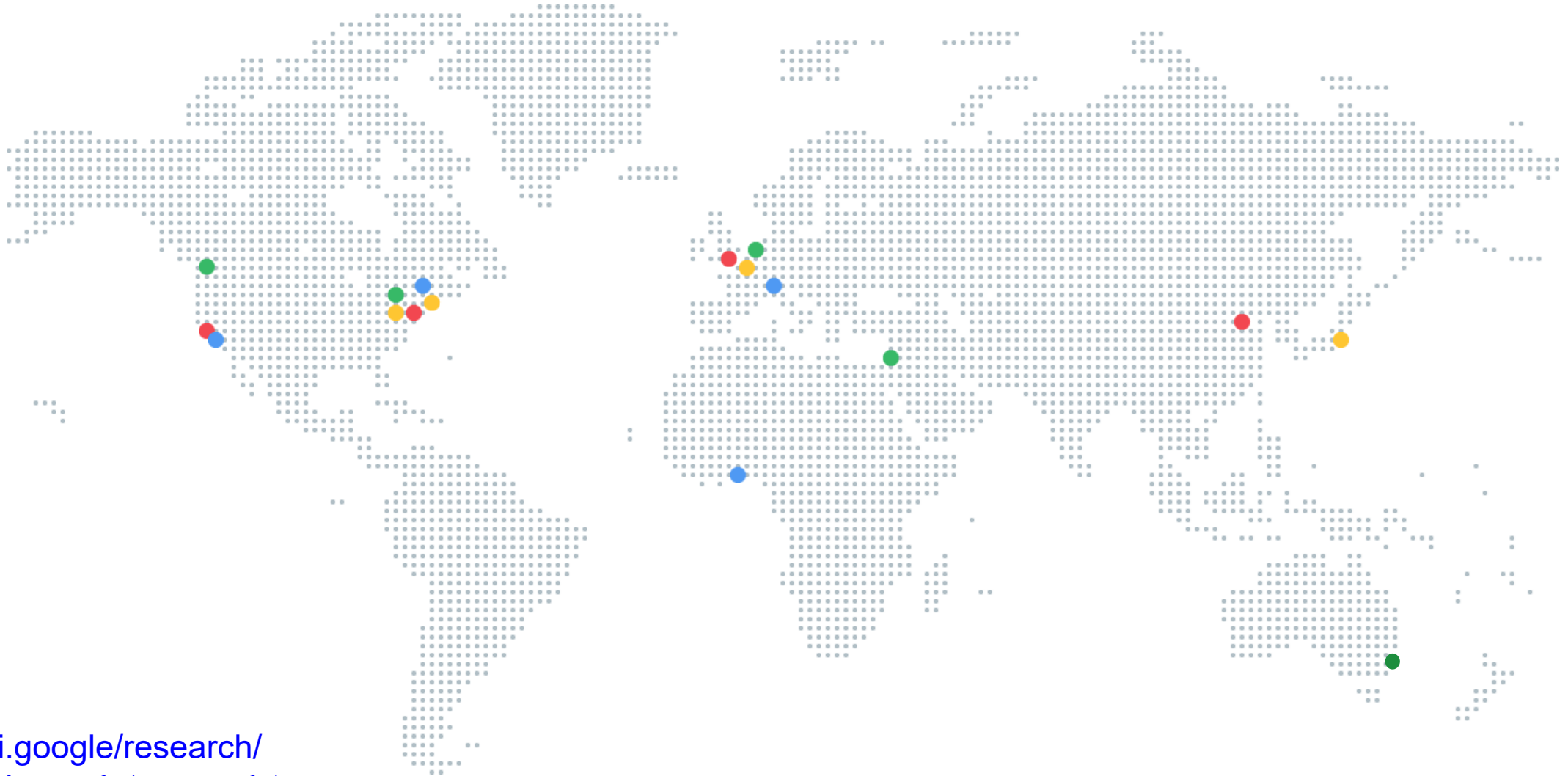
American Airlines 



Google



# GOOGLE RESEARCH IS A GLOBAL TEAM FOCUSED ON AI RESEARCH



<http://ai.google/research/>  
<http://ai.google/research/teams>

# Aviation Emissions

## Aviation's climate impact

CO2 emissions  
**55.9%**

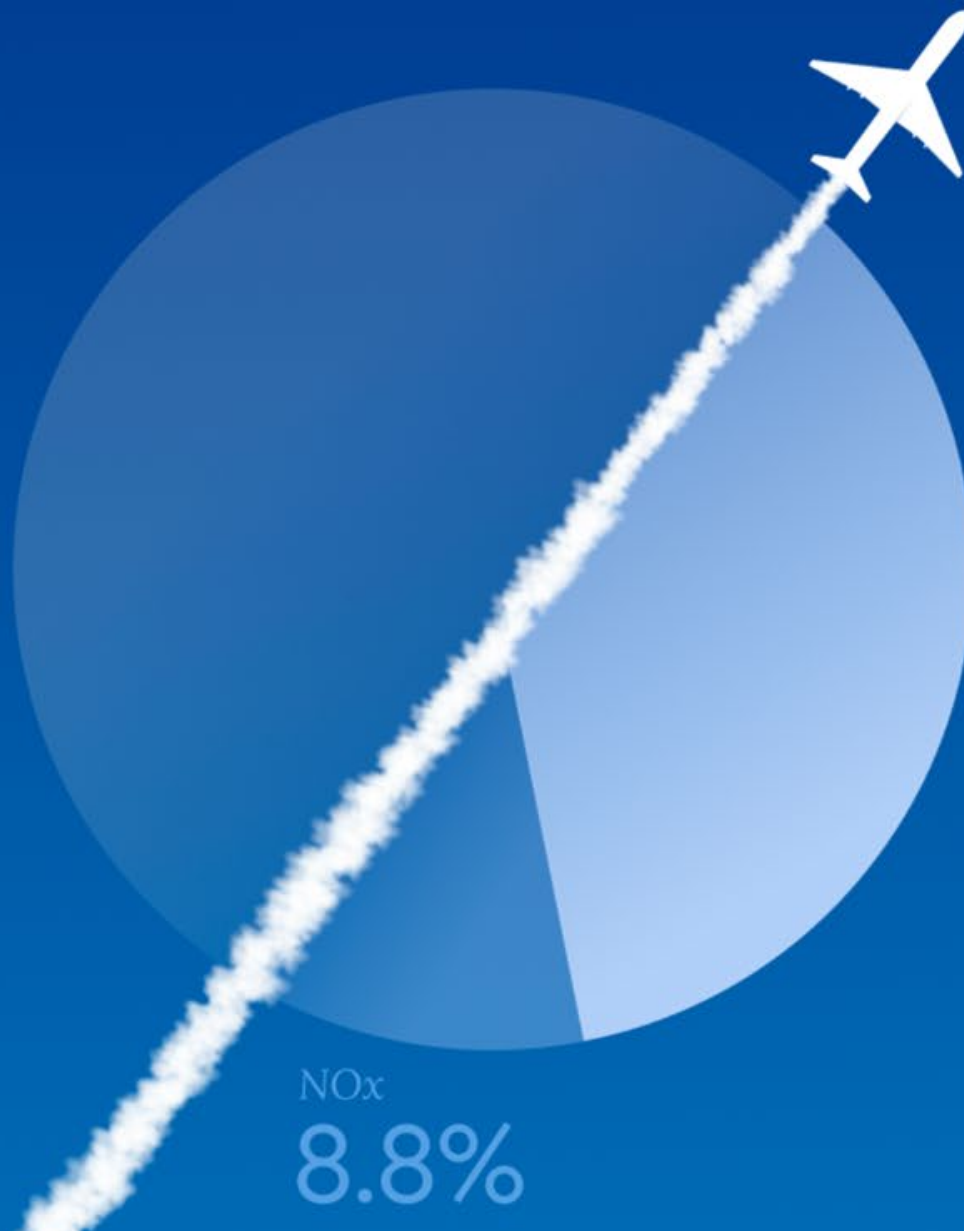
Contrails  
**35.3%**

NOx  
**8.8%**

### 100 year net impact

MTCO2e (GWP100)

Lee et al 2021



## Aviation's climate impact

**Really hard emissions to avoid**

CO<sub>2</sub> emissions  
**55.9%**

Contrails  
**35.3%**

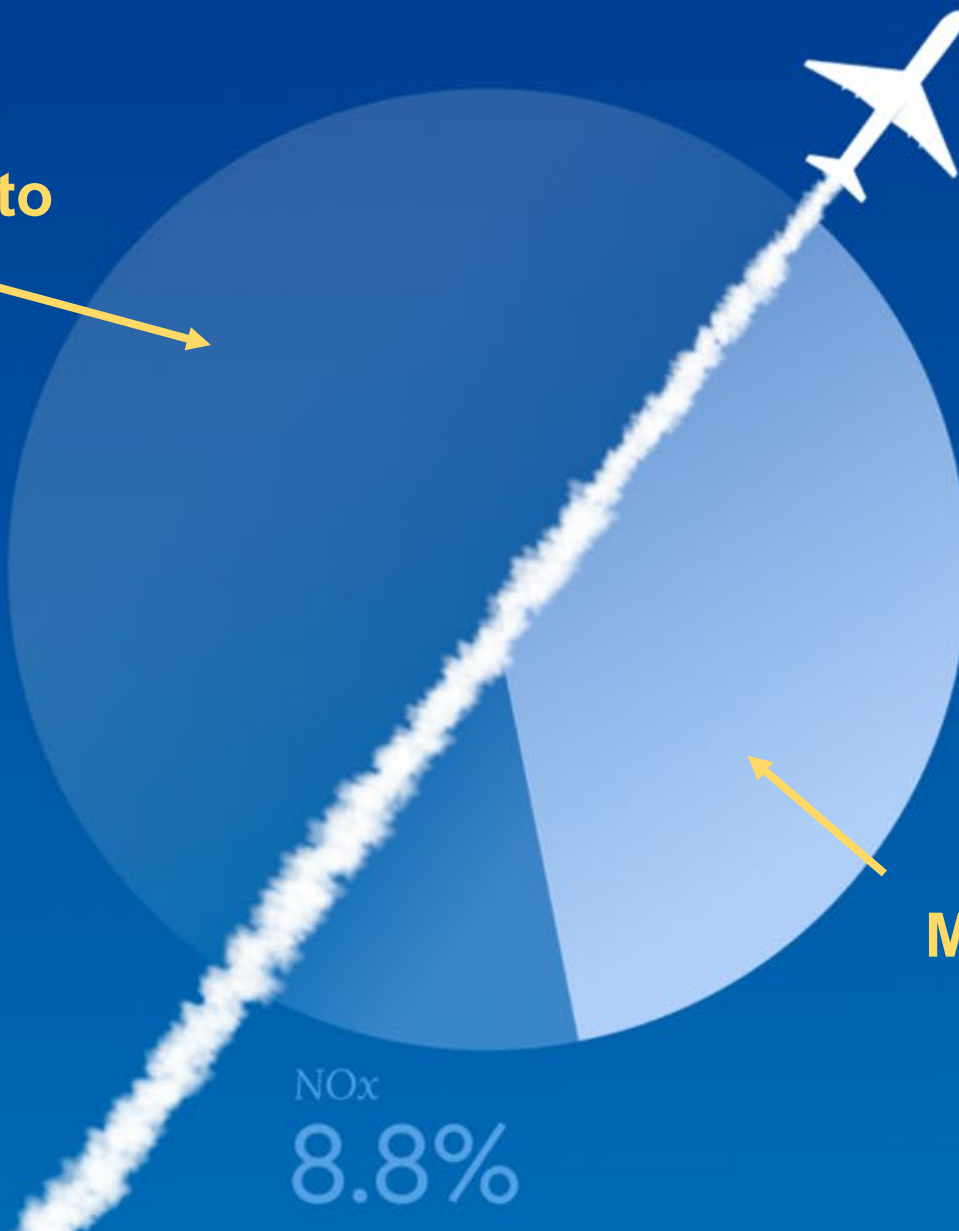
**Much easier to avoid**

NO<sub>x</sub>  
**8.8%**

**100 year net impact**

MTCO<sub>2</sub>e (GWP100)

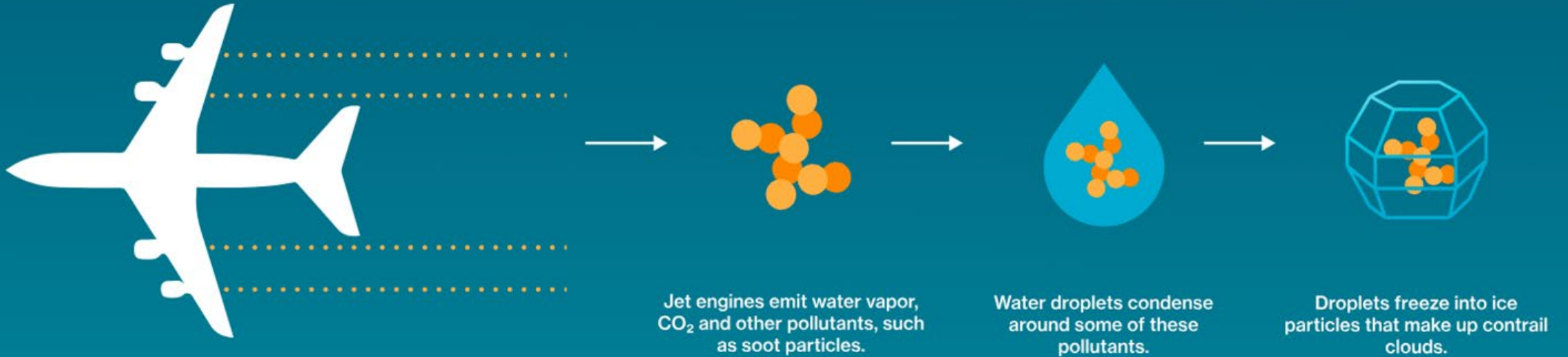
Lee et al 2021



# Backing up: Contrail Review

# CONTRAILS FORM ON ENGINE EXHAUST

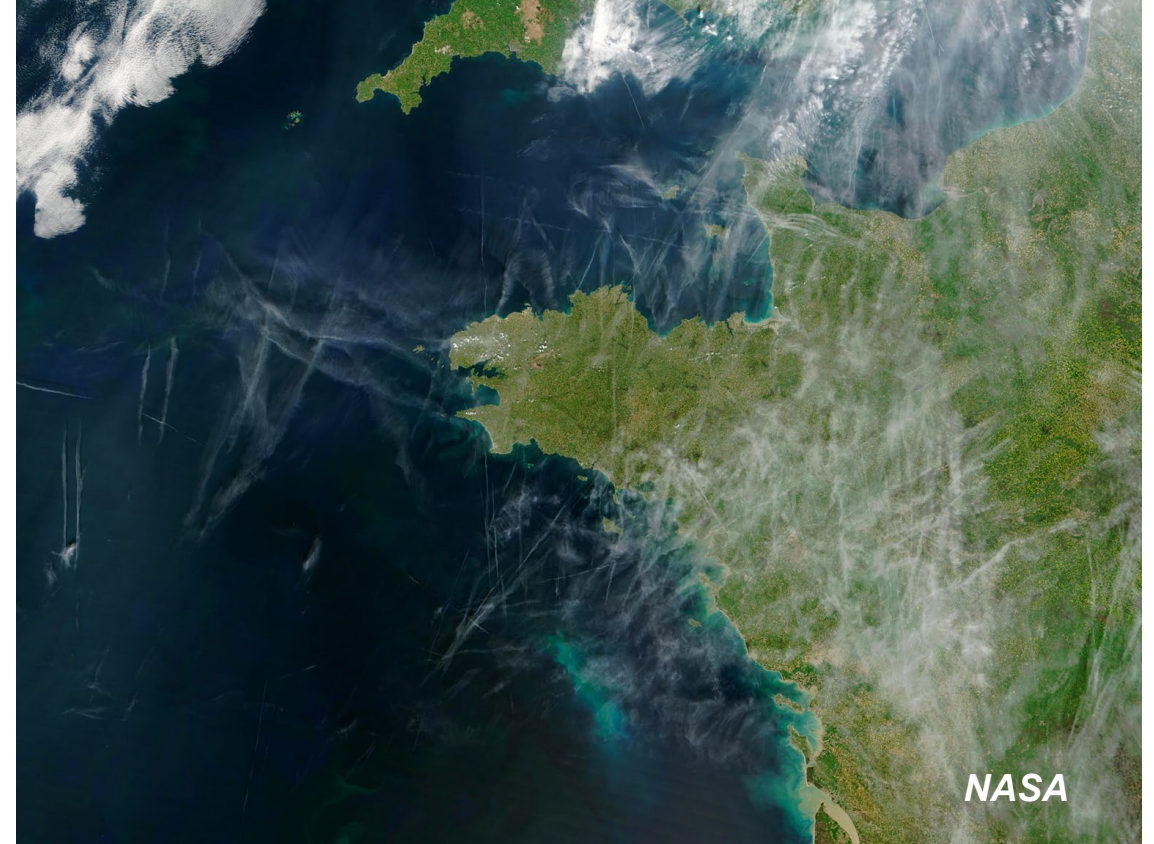
Water droplets condense on aircraft engine soot and other aerosols to form high-altitude ice (cirrus) clouds





# CONTRAILS *SOMETIMES* PERSIST AND SPREAD INTO CIRRUS CLOUDS

Ice particles spread by wind shear and turbulence; particles persist when the **relative humidity** is high





# US Contrails (1 Day)

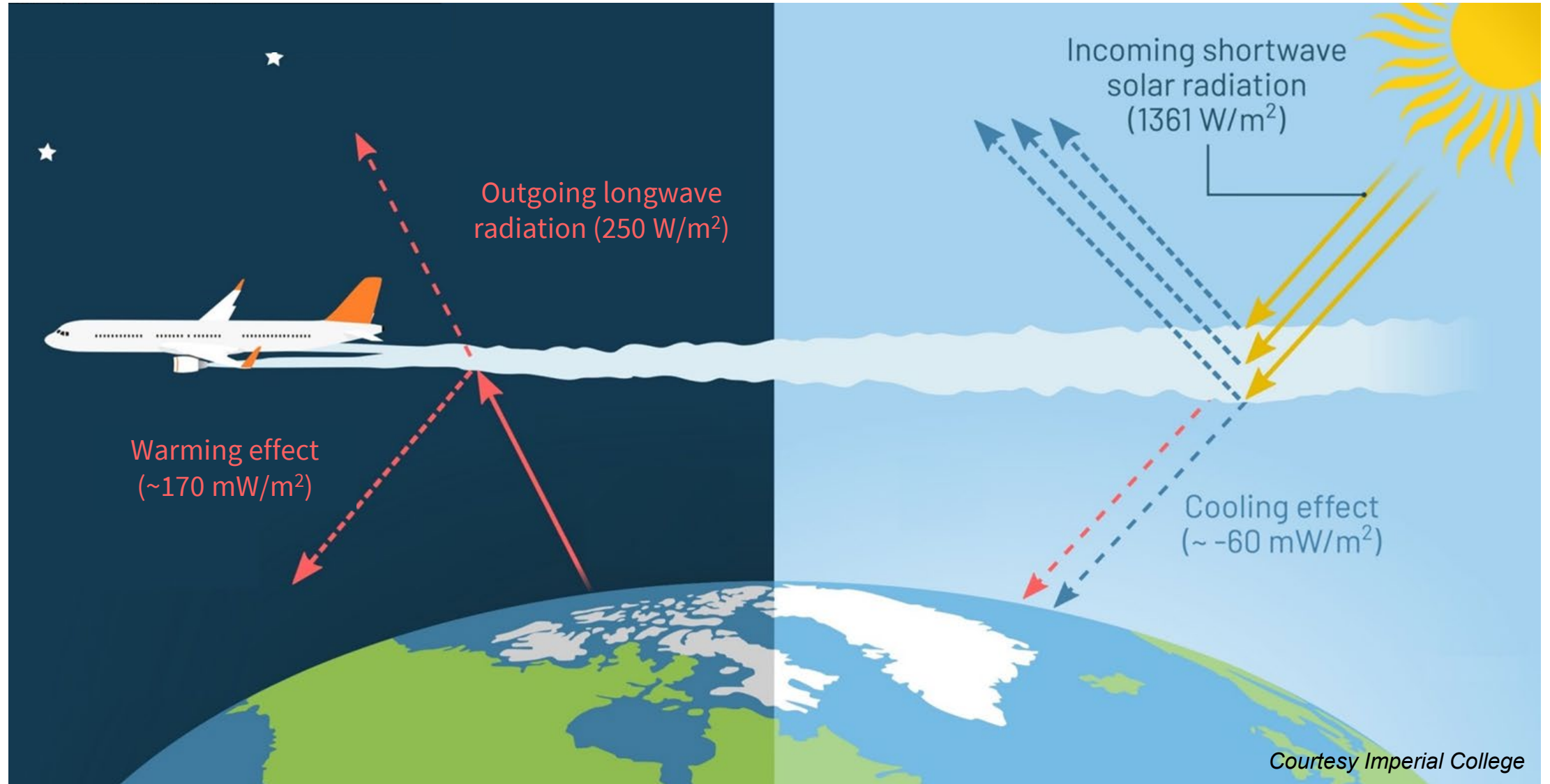
We can use AI to detect contrails being formed in real time, and match them to flights using ADS-B data.



**Why are they warming?**

# CIRRUS CLOUDS TRAP AND REFLECT RADIATION

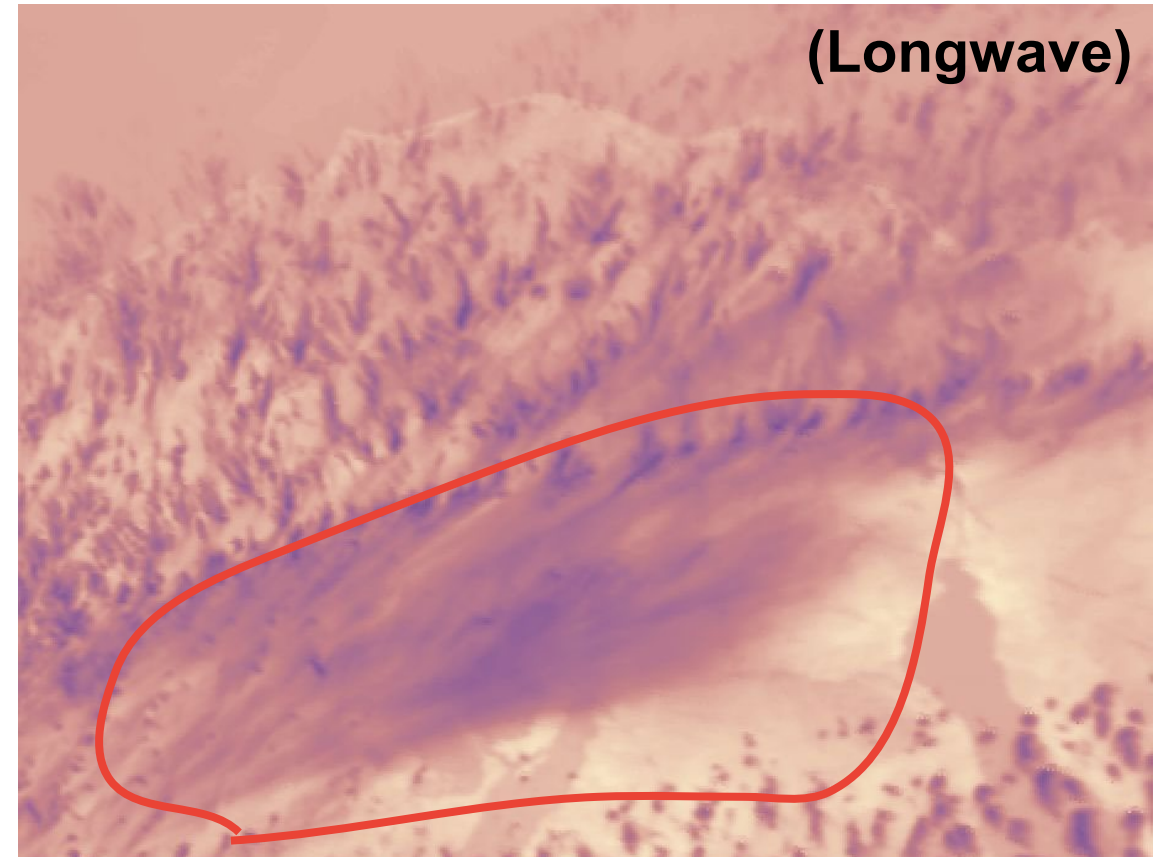
No cooling effect in the nighttime, or when low clouds are already present (~75% of the time)



*Courtesy Imperial College*

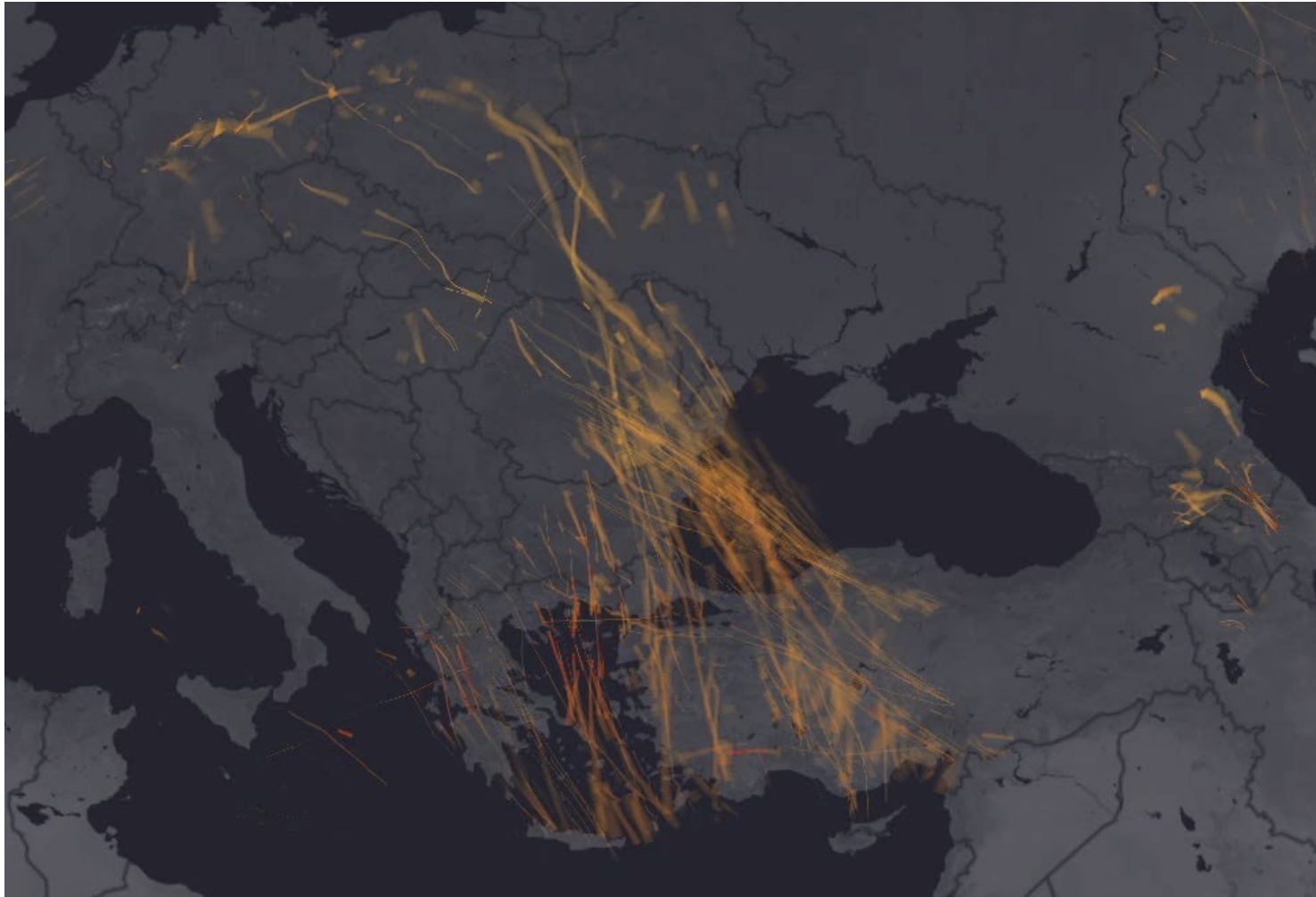
# CONTRAIL-CIRRUS TRAP MORE THERMAL RADIATION THAN THEY REFLECT

Artificial cirrus clouds absorb longwave (thermal) radiation



# NOT ALL CONTRAILS ARE CREATED EQUAL

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





# HOW DO WE KNOW CONTRAILS ARE WARMING?

## *Empirical Observation*



Observe warming  
through satellite  
imagery

## *Physics Estimates*



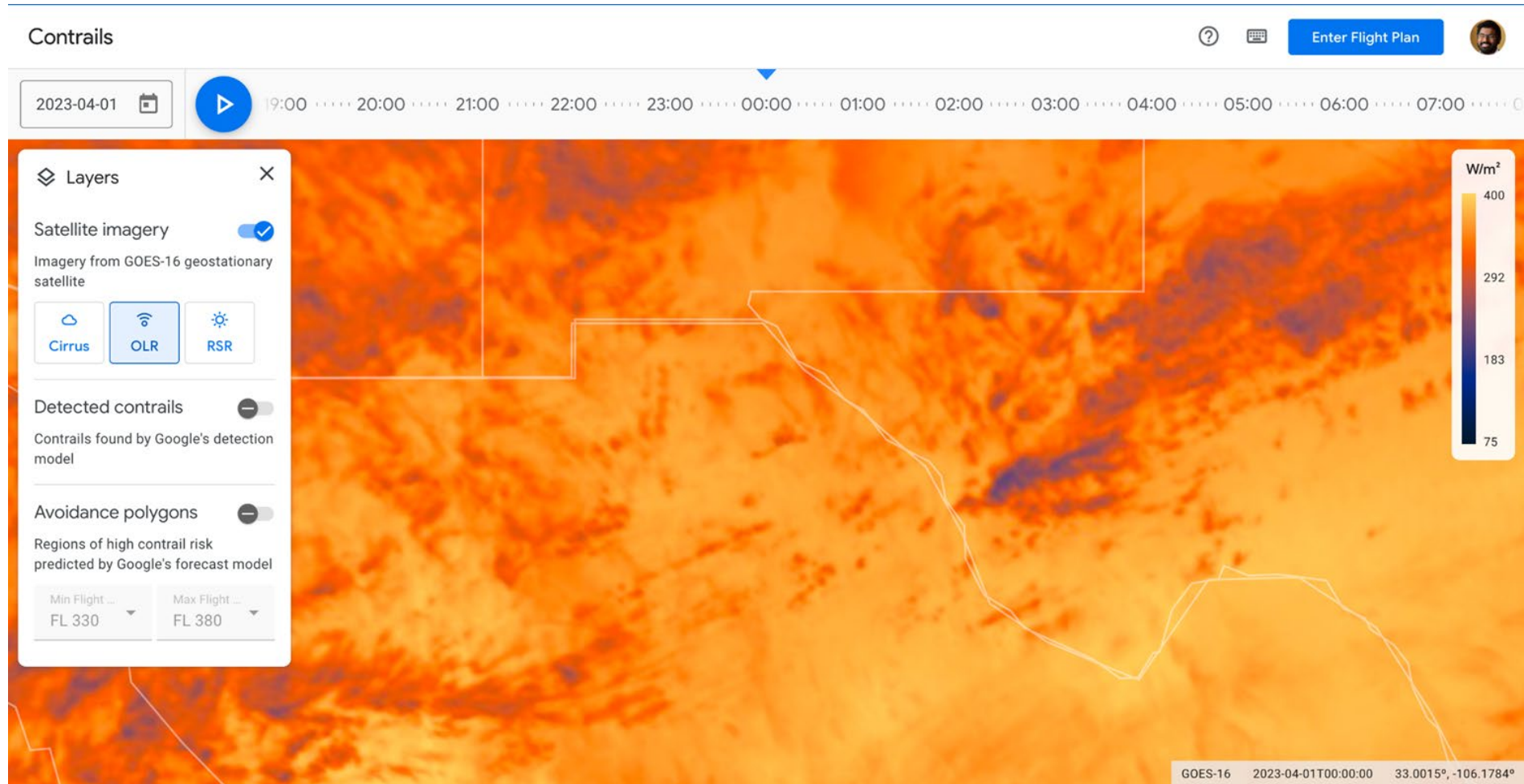
Model contrail ice  
properties

## *Simulations*



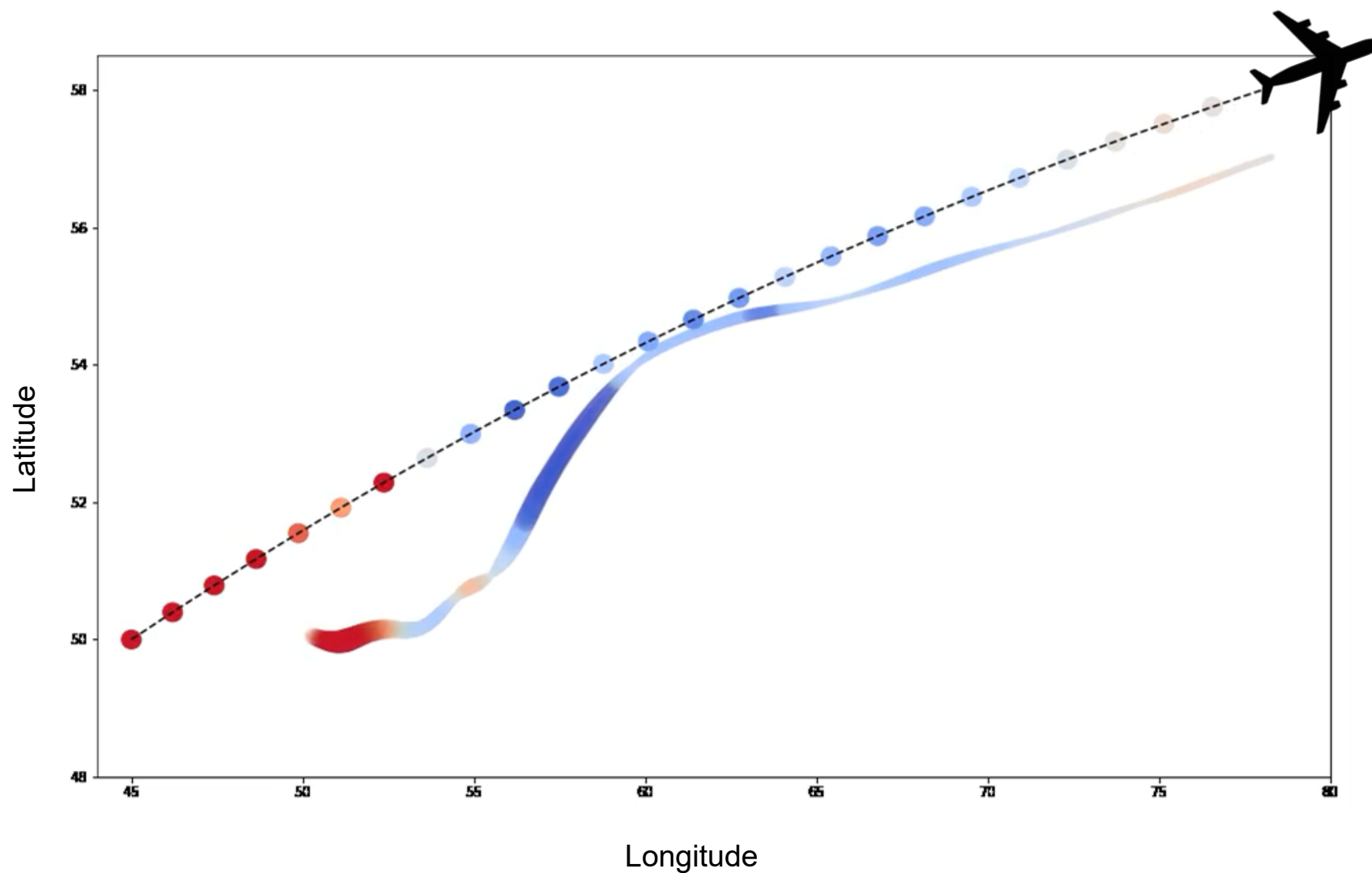
Model the global  
impact of contrails over  
decades

# EMPIRICAL: OBSERVE WARMING VIA SATELLITE IMAGERY (DEMO)



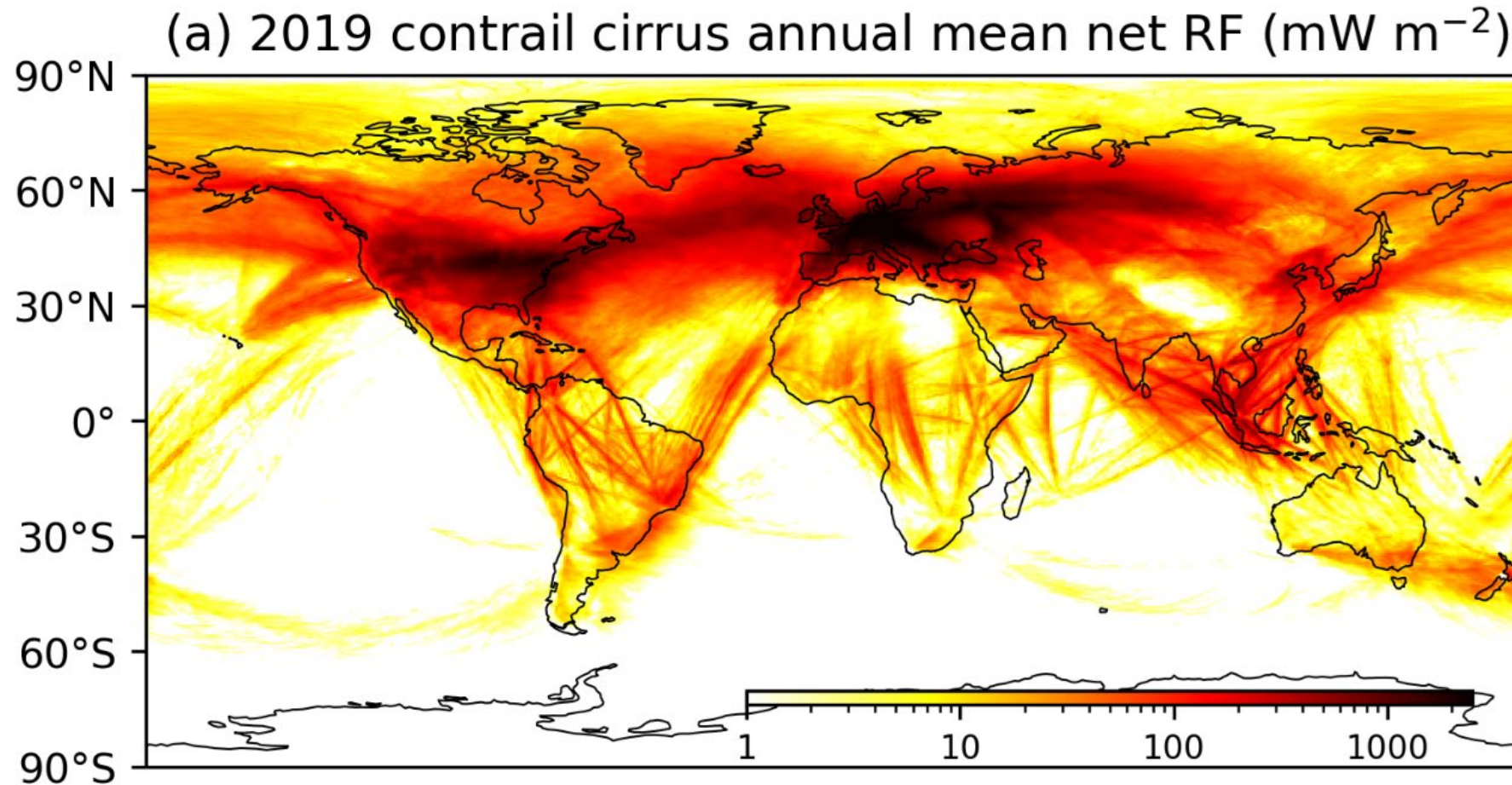
# PHYSICS: PARAMETERIZE CONTRAIL EVOLUTION

Estimate the warming (or cooling) by integrating downstream climate forcing using weather & flight (engine efficiency, fuel burn, etc) data



# SIMULATION: CONTRAIL FORCING FROM GLOBAL FLIGHTS (2019)

Parameterized models can efficiently estimate the spatial distribution of contrail forcing across the globe



**What can aviation do about contrails?**



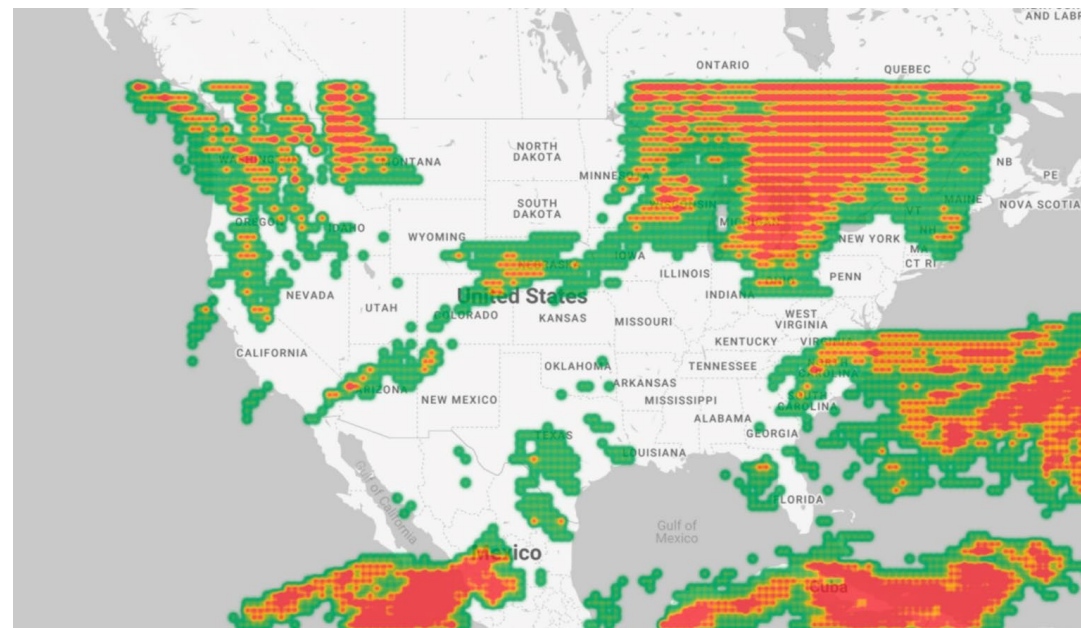
# AVIATION CAN REDUCE ~1.5% OF HUMAN-CAUSED WARMING BY MAKING FLIGHT ADJUSTMENTS

## Contrail Airspace:

- Only ~3% of flight miles make almost all of the warming!!!
- Conditions exist only at **specific altitudes**/temperatures, and high humidity levels

## Observation:

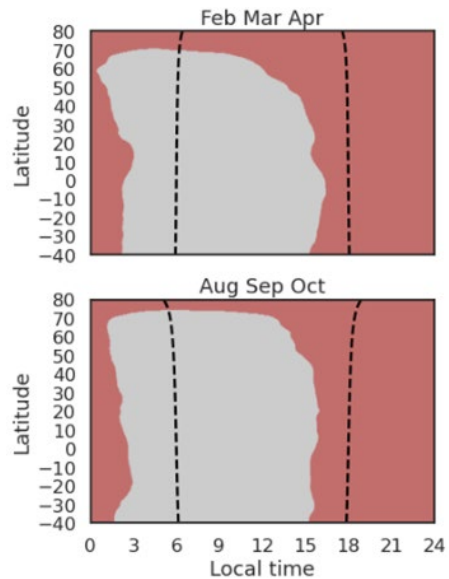
If we could map them out (in advance or in real time), **small adjustments** to the route might avoid the warming entirely.



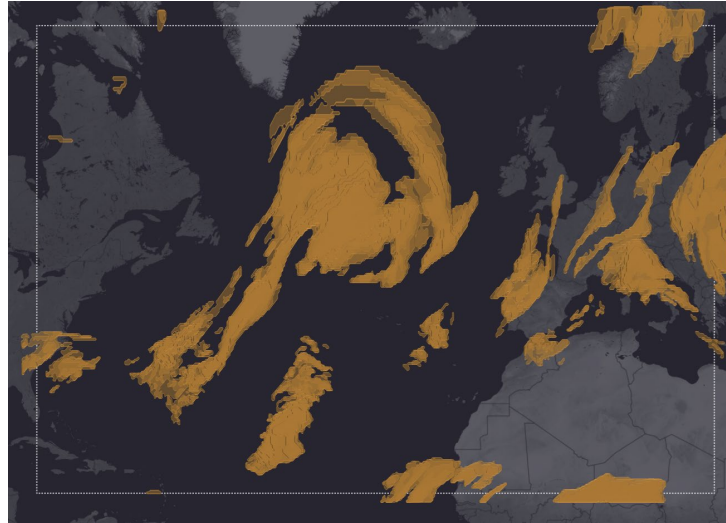
Caldeira & McKay, [Nature 2021](#)

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

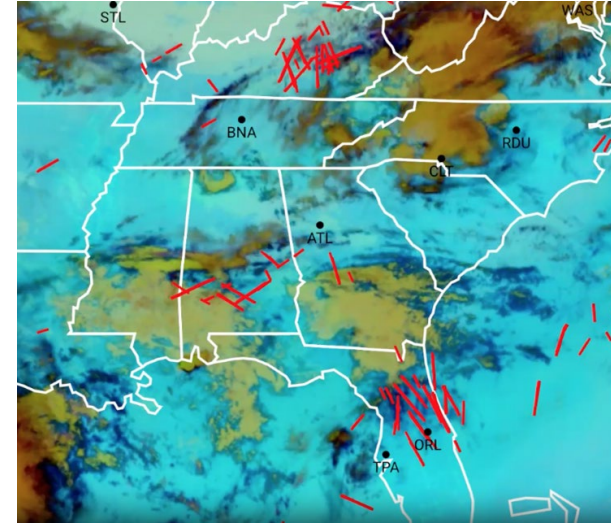
# HOW TO AVOID CONTRAIL INDUCED WARMING



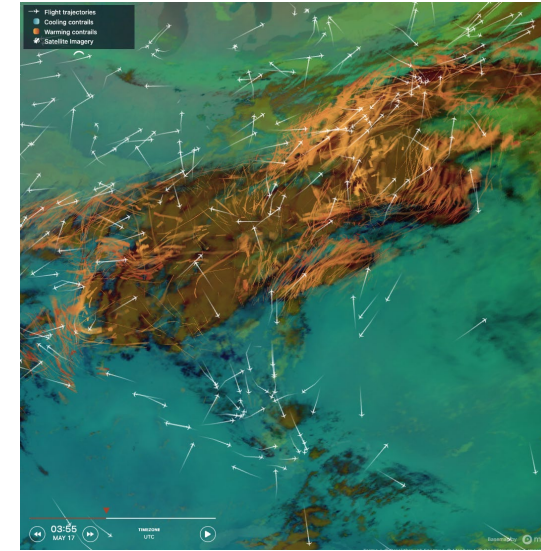
Develop heuristics for climate optimal air traffic



Forecast high-impact contrail regions



Detect contrails in satellites, LIDAR, and pilot observations



Evaluate and improve avoidance strategies

T-6 months

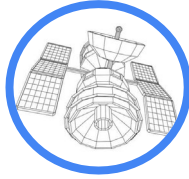
T-24 to T-0 hours

Flight 

T+24 hours

# SKILLFUL CONTRAIL FORECASTS ENABLE CONTRAIL AVOIDANCE

Forecasts need to answer two distinct questions:



## Formation -

If an aircraft flies  
through this space,  
will a persistent  
contrail form?



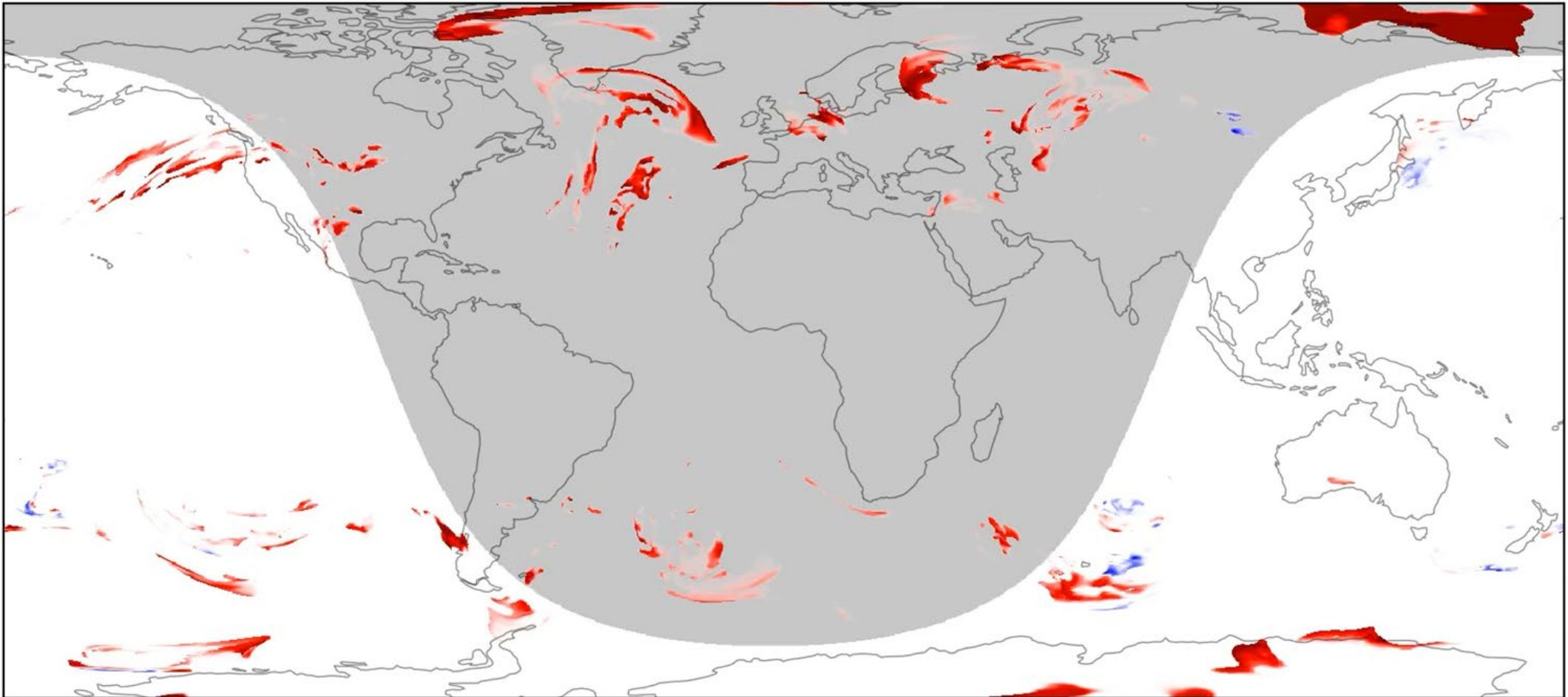
## Climate Impact Estimate -

If a persistent contrail  
forms, what will its  
climate impact be?

# CONTRAIL FORECAST ENABLES TRAJECTORY CO-OPTIMIZATION

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

2021-12-01 00:02



# AA Pilot Study



# AA “PILOT” STUDY: SUCCESSFUL DEMONSTRATION OF CONTRAIL REDUCTION

## Trial Structure

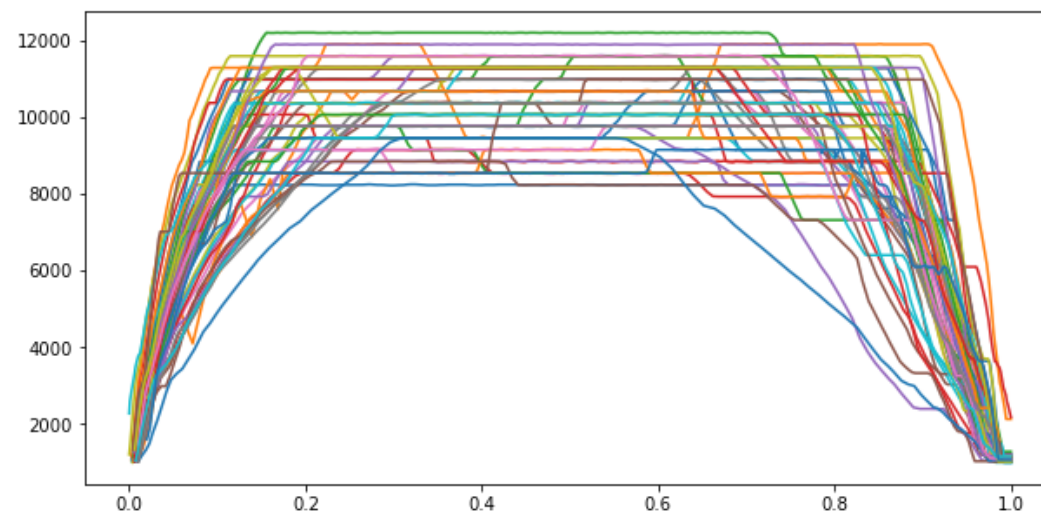
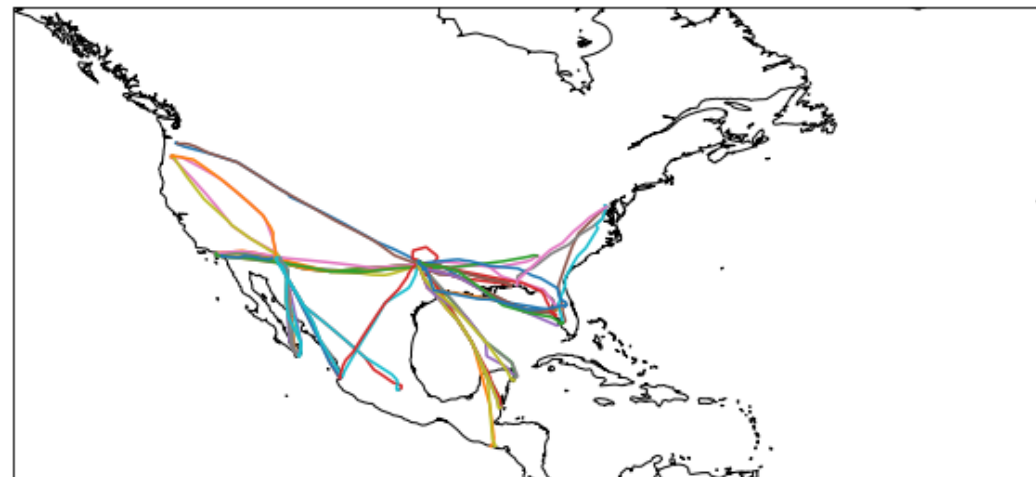
- 10 pilots participated
- Between Jan 1 and early June, 2023
- **Turns.** City A to City B, back the same day.
- Avoidance only **early descent or late ascent**

## Turns

- Contrail Likely Zone (CLZ) on flightpath in/out of city A or B
- Contrail avoidance on arrival or departure (random choice),

## Results

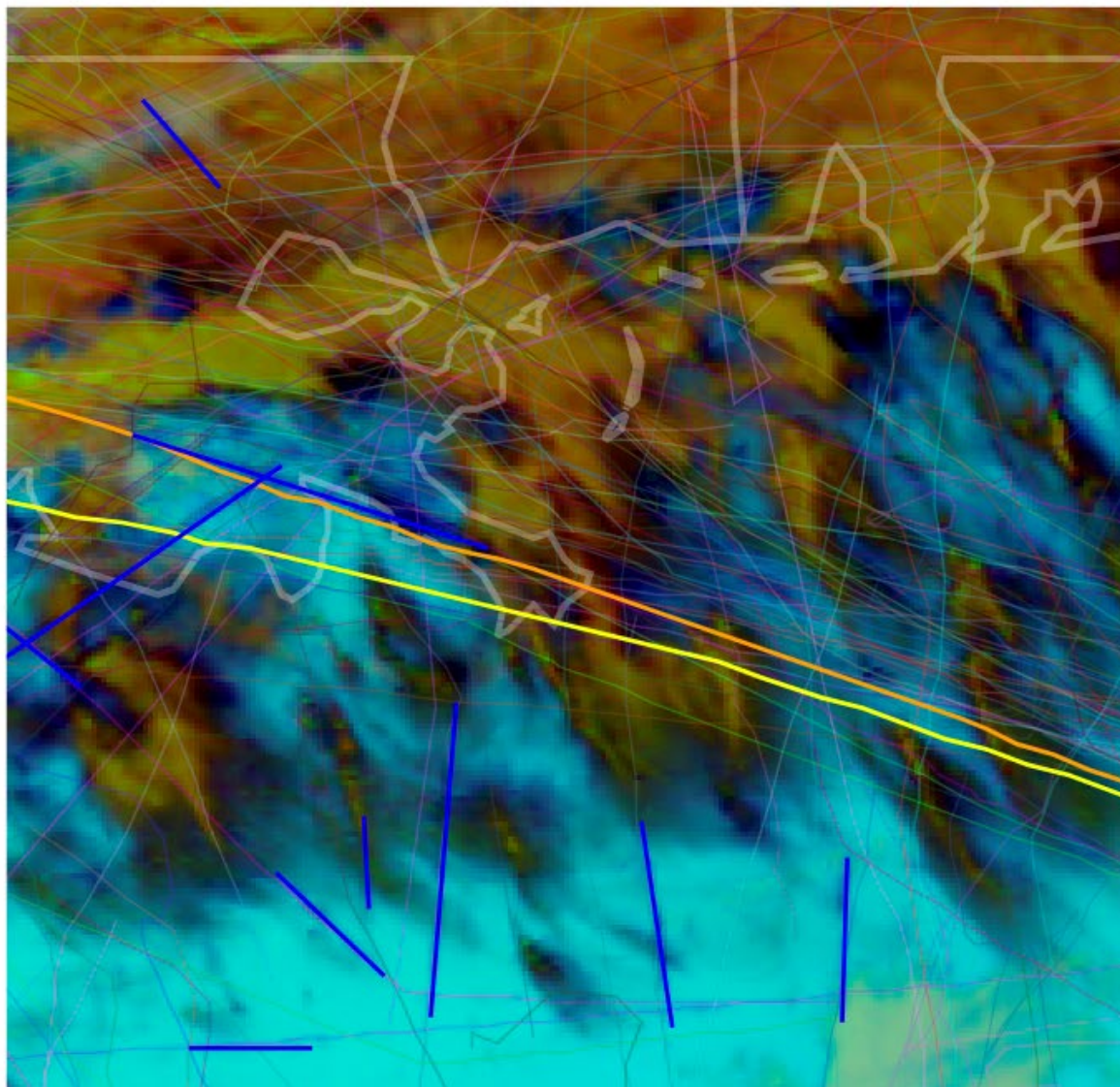
- **35 Turns**, of which
- **22** included in analysis. Met above criteria
- **13** excluded from contrail-formation analysis
  - Most of these were opportunistic flights that didn't intersect with CLZ near target.
  - Exclusions tracked before flight began



## CASE STUDY: EXAMPLE OF SUCCESSFUL AVOIDANCE USING THE EFB



# CASE STUDY: SATELLITE-BASED VERIFICATION OF CONTRAIL FORMATION



Geographic Features

Boundaries

Other flights

— other flights

AAL189

— advected flight path

AAL189

— original flight path

Contrails

— contrails

OUR JOINT STUDY SUCCESSFULLY DEMONSTRATED CONTRAIL REDUCTION WITH OPEN, FUTURE-LOOKING RESEARCH QUESTIONS

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

# NEXT STEPS: DISPATCHER BASED INTERVENTION, SIMULATION, AND TRIALS

## Ascent/Descent vs Cruise

- Trial was small, only ascent/descent
- Contrails  $\geq 25,000$ ft, terminal operations is less interesting than mid-flight.
- Ascent/descent allows for larger altitude changes than mid-flight, in practice.

## Dispatcher Approach

- Integration into flight planning systems is in progress
  - Much lower operational burden
  - Allows lateral diversion
  - We expect a reduced efficacy due to time horizon.
  - ... but, simulations here show relatively high leverage anyway ( $\sim 0.25\%$  fuel burn  $\rightarrow \sim 50\%$  reduction in warming)
- We need more simulations

## ATC Approach?

- Mostly untested
- EUROCONTROL (MUAC) tried this for a small set of flights during the day
  - Airspace was tiny and congested  $\rightarrow$  diversions operationally difficult
  - flights handed off to another zone almost immediately



**Questions?**