National Aeronautics and Space Administration

NASA Contrails Research and Partnerships

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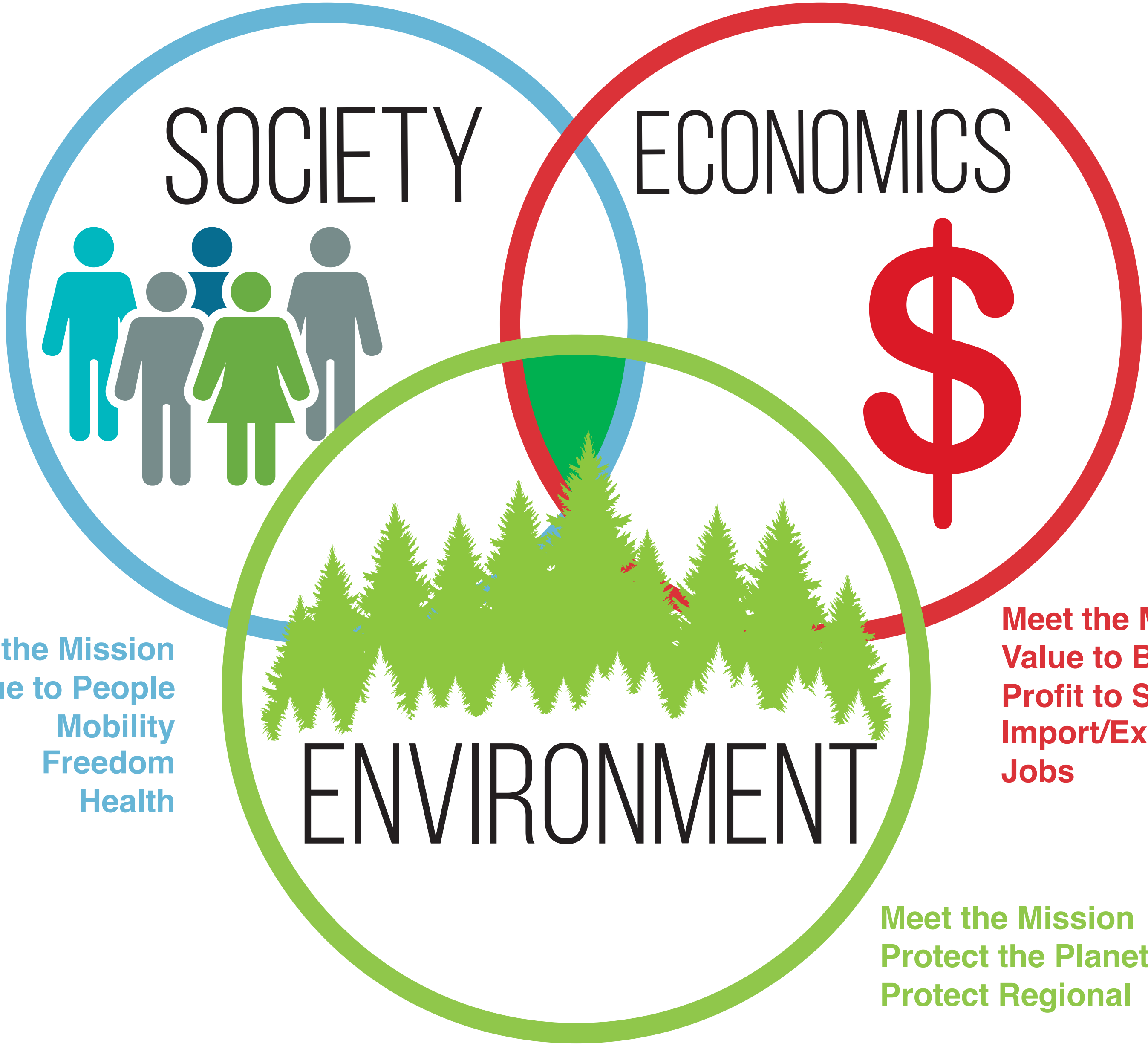
NASEM Aeronautics Research and Technology Roundtable
Washington, DC
February 14, 2024
www.nasa.gov

Topics

- Contrails
  - Contrails in context of Sustainable Aviation
  - Contrail fundamentals
- Research, Planning, and Coordination

Sustainability

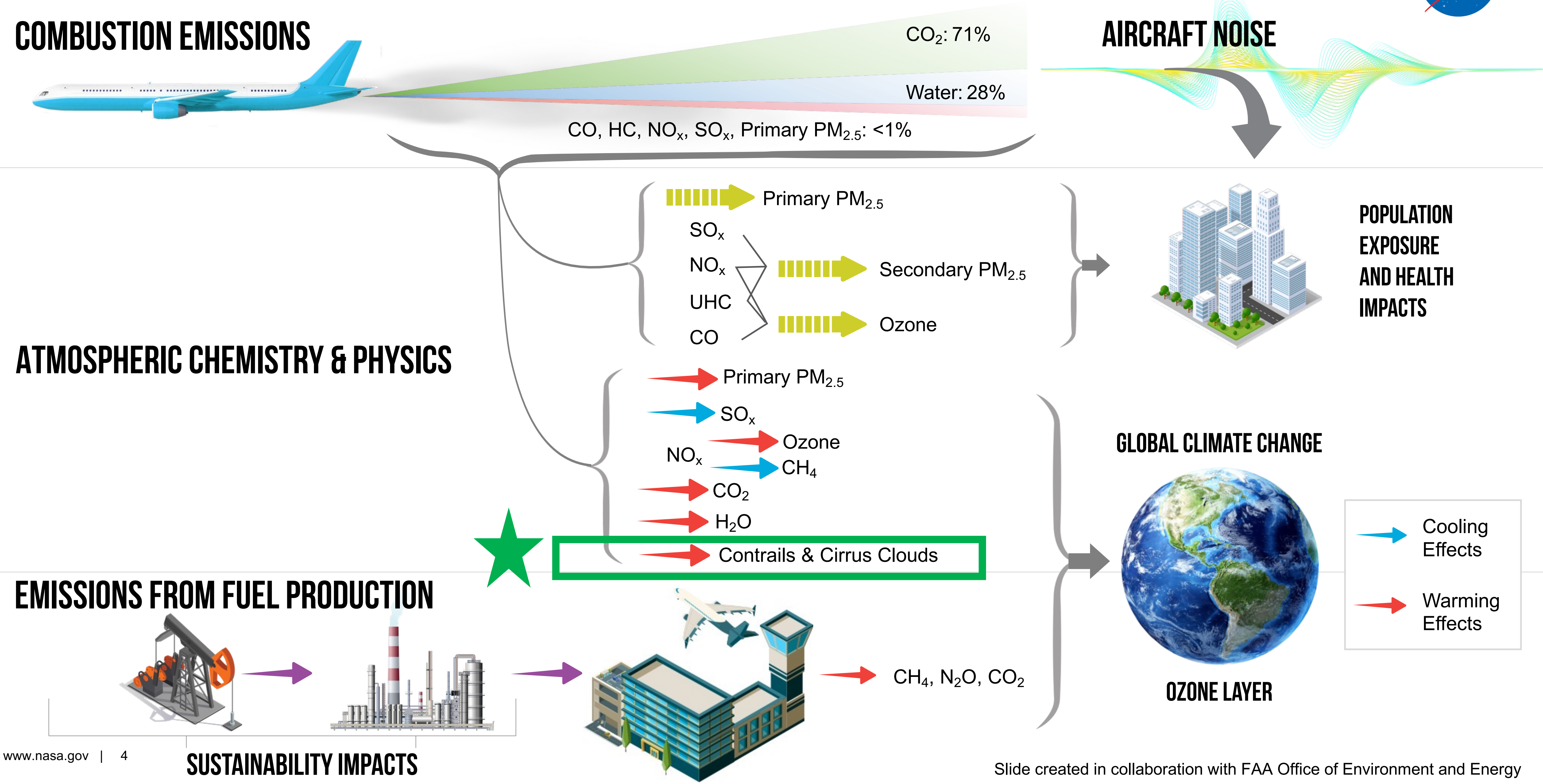


Meet the Mission
Value to People
Mobility
Freedom
Health

Meet the Mission
Value to Business
Profit to Shareholders
Import/Export Trade Balance
Jobs

Meet the Mission
Protect the Planet
Protect Regional & Local Ecosystems

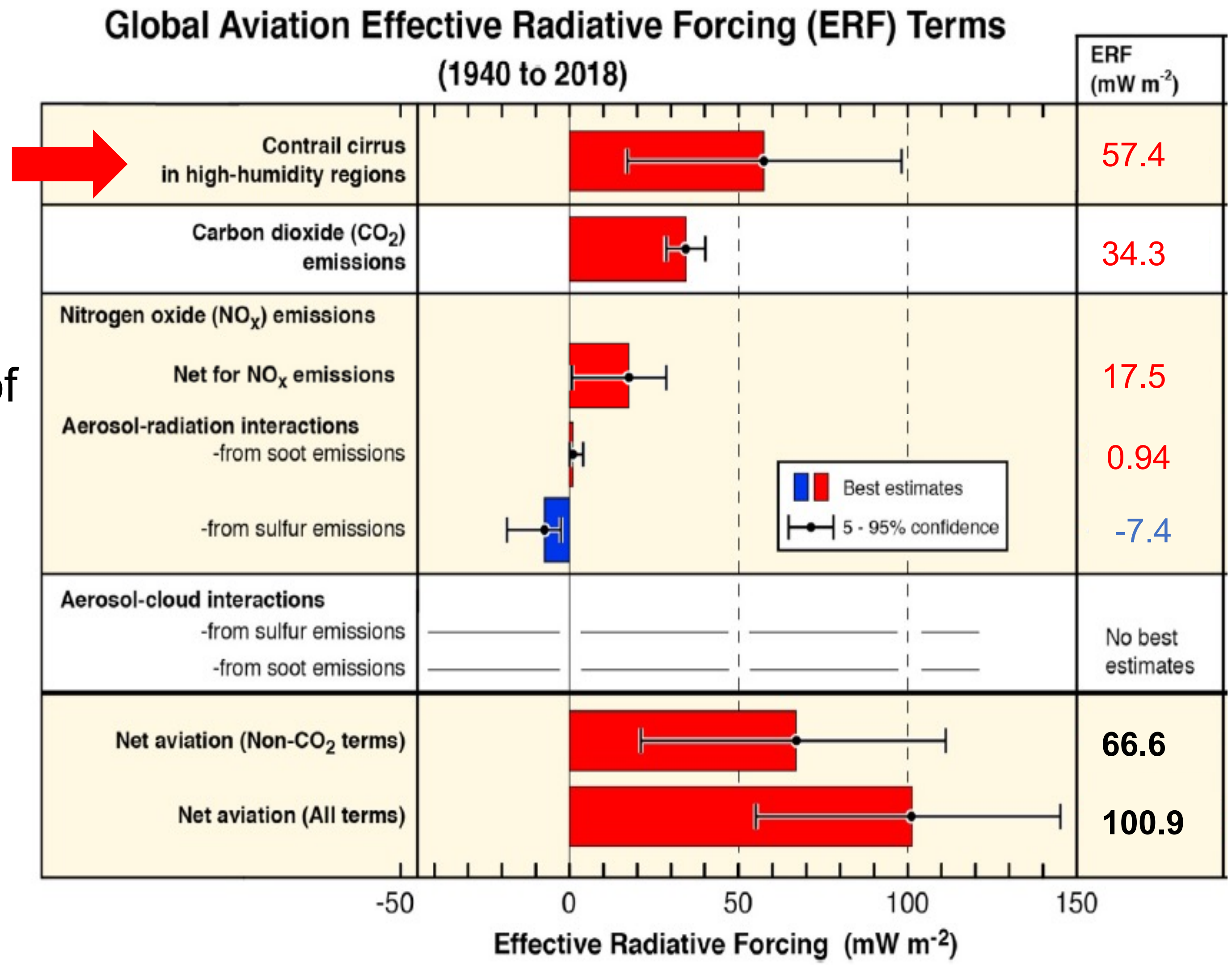
Environmental Impacts of Aviation



Slide created in collaboration with FAA Office of Environment and Energy

Climate Scientists' View of Aviation Impacts on Climate

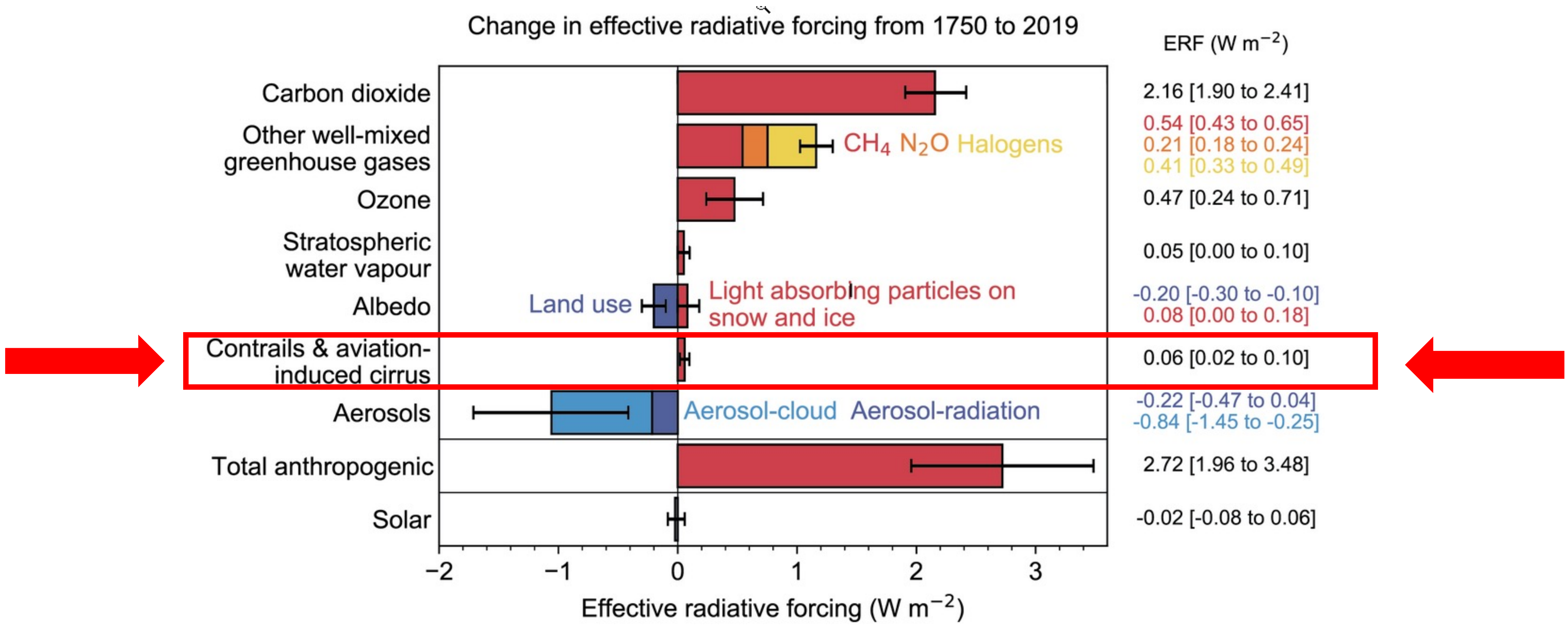
- Lee et al. (2021) represents latest and most comprehensive assessment of aviation's climate impacts
- Non-CO_2 impacts may comprise two-thirds of the net radiative forcing from aviation
- Contrail cirrus has significant uncertainty



Lee et al. (2021) "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018" *Atmospheric Environment*, https://doi.org/10.1016/j.atmosenv.2020.117834

"…to halt aviation's contribution to global warming, the aviation sector would need to achieve net-zero CO_2 emissions and declining non-CO_2 radiative forcing ..: neither condition is sufficient alone." Lee et al. (2021)

Contrail Impact Relative to Other Human-Influenced Climate Drivers



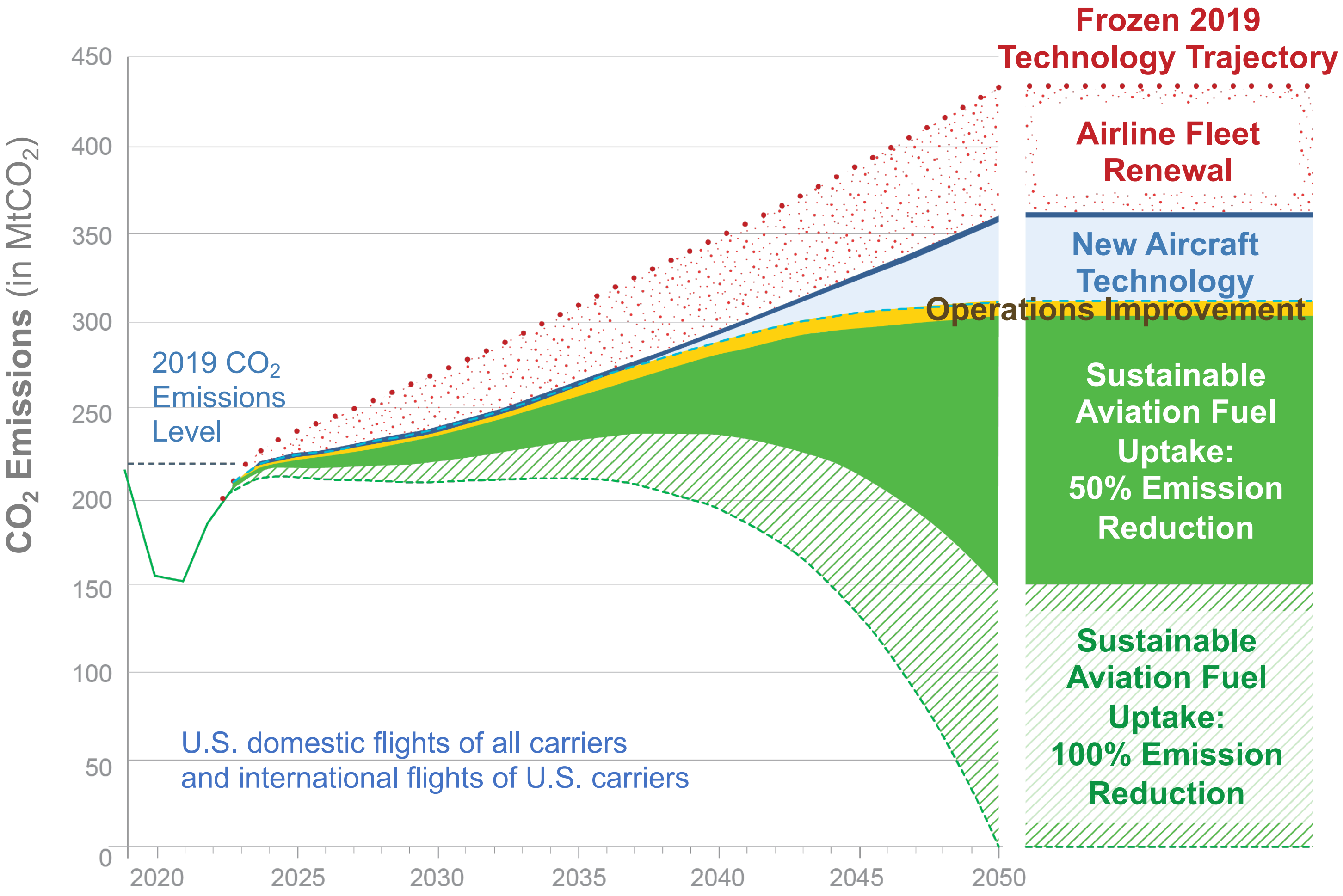
Relatively small overall, but large enough to merit visibility/attention, and an aviation-unique climate impact

U.S. Aviation Climate Action Plan - 2021

Global Context for Sustainable Aviation

U.S. aviation goal is to achieve
net-zero greenhouse gas emissions by 2050.

U.S. Aviation Climate Action Plan is aligned with
- U.S. economy-wide goal
- International Civil Aviation Organization
- Air Transport Action Group



https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

Magnitude and certainty of carbon impact has led to widely established goals
Non-CO_2 impacts widely acknowledged but uncertainties cause goal setting to lag

Sustainable Flight National Partnership

Accelerating Toward Net-Zero Greenhouse Gas Emissions and Reduced Non-CO_2 Climate Impact in the 2030s

Advance engine efficiency and emission reduction

Enable integrated trajectory optimization

Advance airframe efficiency and manufacturing rate

Enable use of 100% sustainable aviation fuels

Next-generation transports using up to 30% less fuel, current and future fleets flying optimal trajectories, engines burning sustainable aviation fuels for greater than 50% reduction in lifecycle greenhouse gas emissions

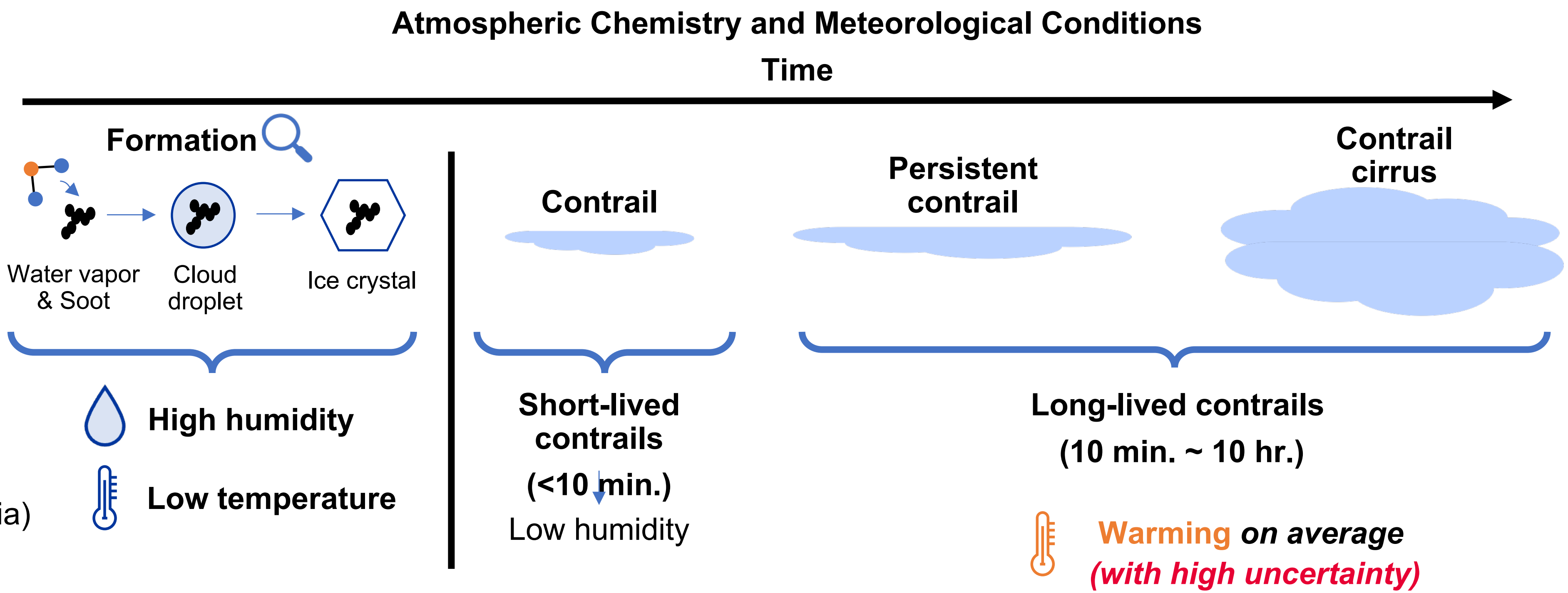
Contrails

persistent contrails and aviation induced cloudiness

Intro to contrails

adapted

Aircraft operations at cruise



Critical Meteorological Conditions
(aka, Schmidt-Appleton Criteria)

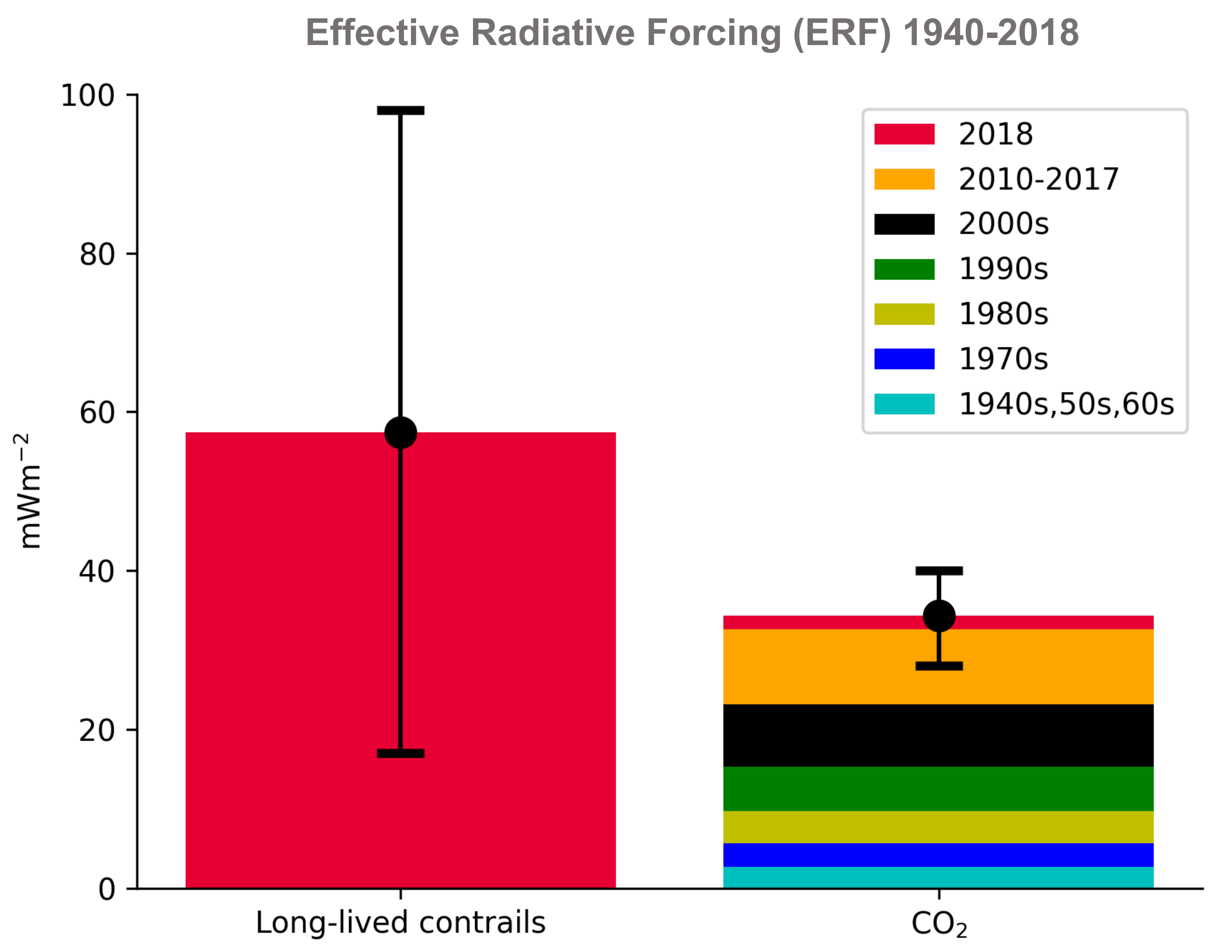
Power Generation (Combustion) Technology

Fuel/Energy Properties

Comparing CO_2 and contrails

lifetime/impact time horizon matters

adapted



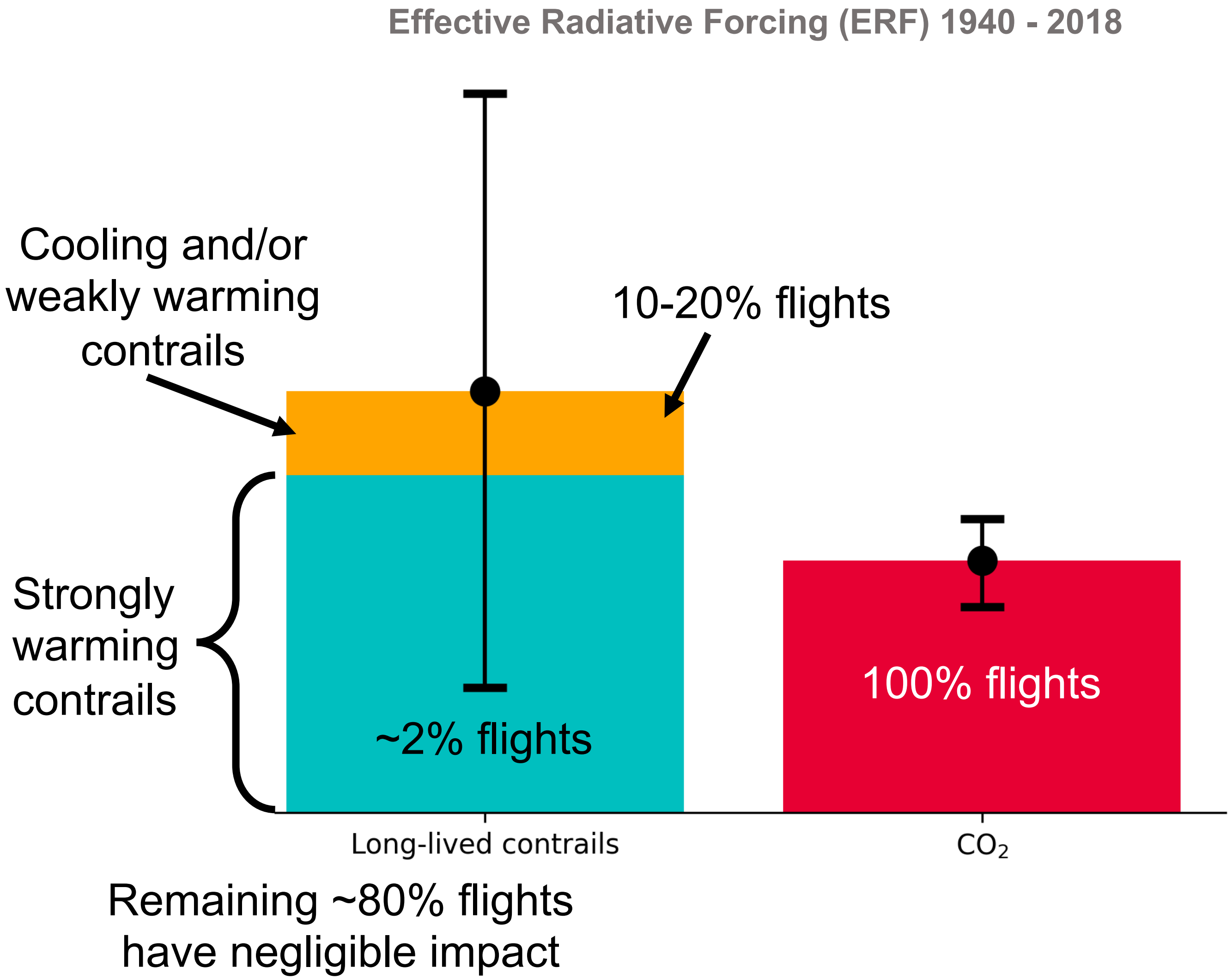
1. Trace amounts of CO_2 emitted during early days of commercial aviation still in the atmosphere
2. Single year of contrail impacts much greater than single year of CO_2
3. Contrail effects are much shorter lived than CO_2

Lee et al., *Atmos. Env.*, 2021

Comparing CO_2 and contrails – continued

contrail impact from small fraction of flights

adapted

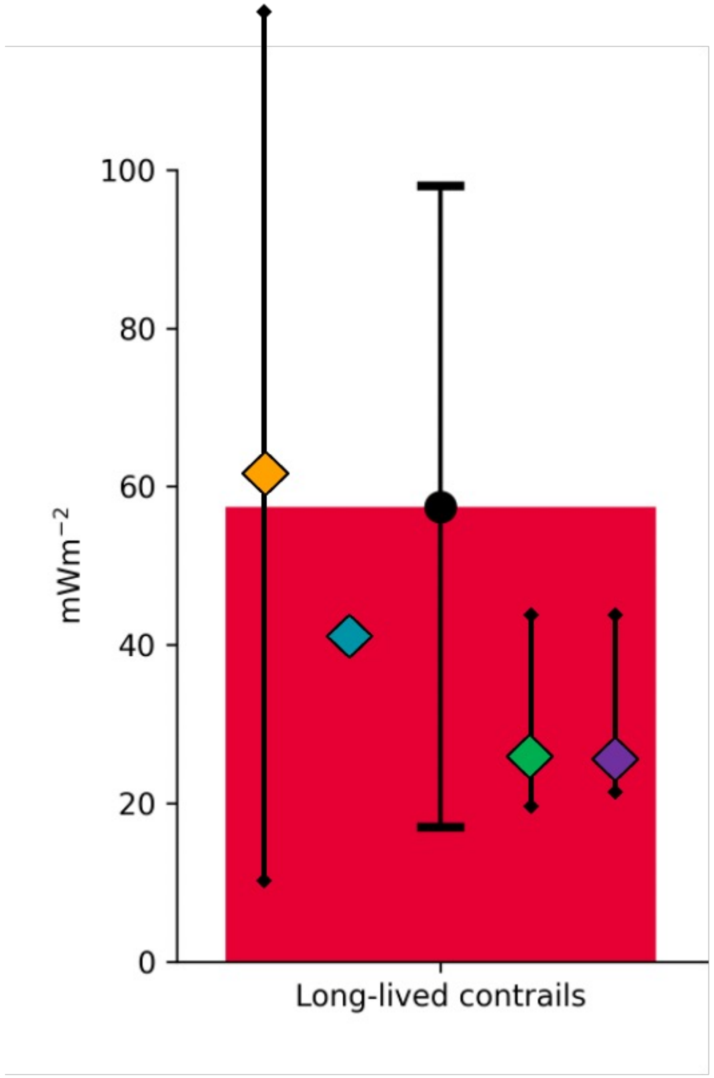


1. CO_2 is well-mixed and produces homogeneous effects
2. Contrail impacts dependent on time of day, season, location, soot emissions, local weather, etc.
3. Majority of contrail impacts from few flights

Lee et al., *Atmos. Env.*, 2021

Global assessment uncertainty

adapted



± 70% around mean

Lee et al., *Atmos. Env.*, 2021

1. Estimate based on average of **three** climate model studies
2. Uncertainty based on expert judgement of model-specific limitations
3. Modeling natural cirrus is already highly uncertain

Additional studies since *Lee et al.* fall mostly within estimated uncertainty
Gettelman & Burkhardt are climate models

Lee et al., *Atmos. Env.*, 2021
Gettelman et al., *ACP*, 2022
Quaas et al., *ERL*, 2021
Teoh et al., *EGUSPHERE*, 2023
Burkhardt and Märkl et al., *in prep*, 2023

Contrail Forecasting
Formation, Persistence, and Modeling

Gaps

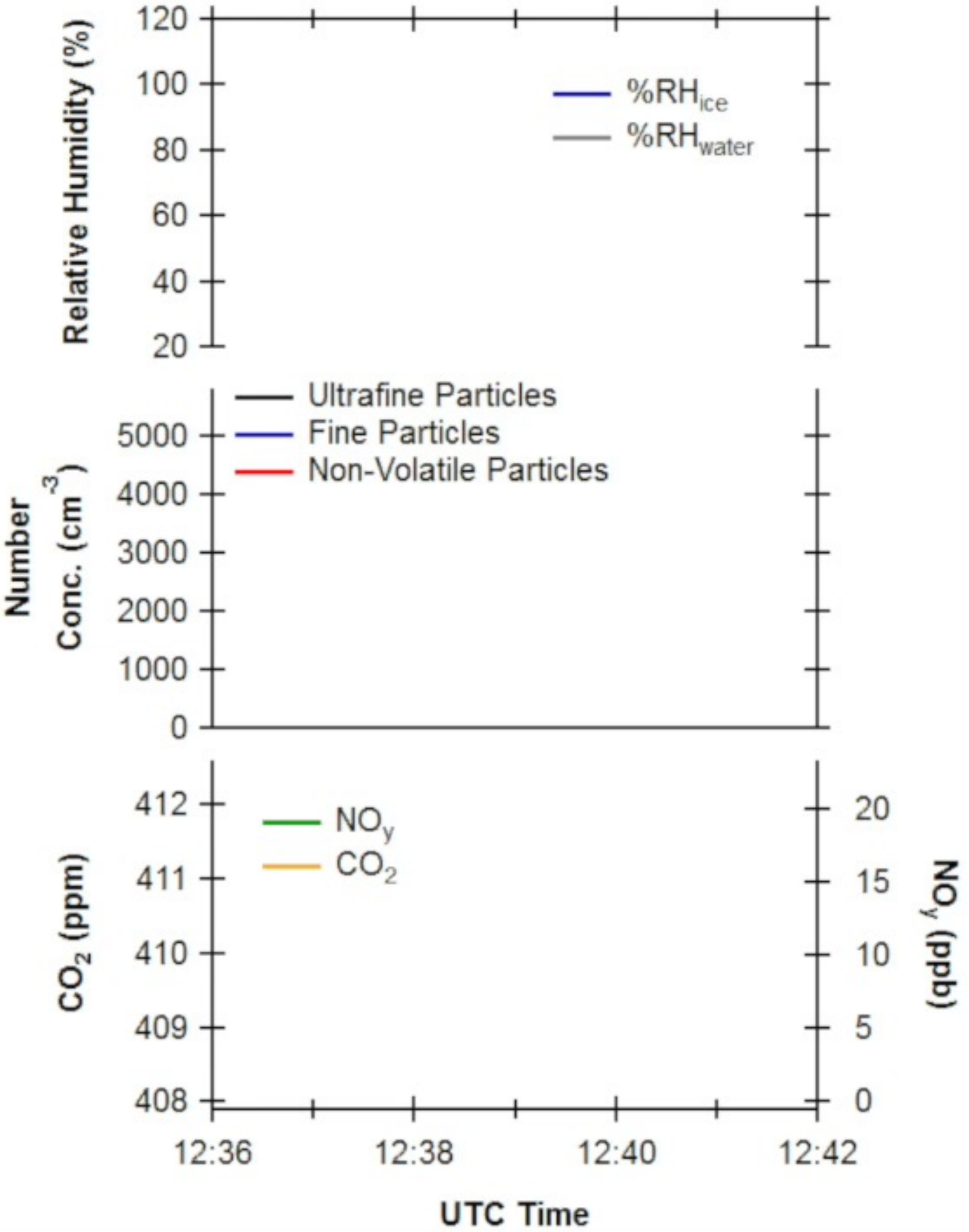
When do contrails form and persist?

Contrails form when the cooling engine exhaust plume becomes supersaturated with respect to liquid water (RH_{water}> 100%), which is often referred to as the Schmidt-Appleman Criterion.

Depends on:

- Atmospheric temperature, pressure, and relative humidity
- Fuel properties (hydrogen content and heat of combustion)
- Engine propulsion efficiency/power generation

Contrails persist when the surrounding atmosphere is supersaturated with respect to ice (RH_{ice} > 100%).


Relative Humidity (%)
120
100
80
60
40
20
%RH$_{ice}$
%RH$_{water}$
Number Conc. (cm^{-3})
5000
4000
3000
2000
1000
0
Ultrafine Particles
Fine Particles
Non-Volatile Particles
CO_2 (ppm)
412
411
410
409
408
NO_y
CO_2
NO_y (ppb)
20
15
10
5
0
12:36
12:38
12:40
12:42
UTC Time

Weather Forecast Models Predict Contrail Conditions

Common to express contrail forming conditions in terms of temperature:

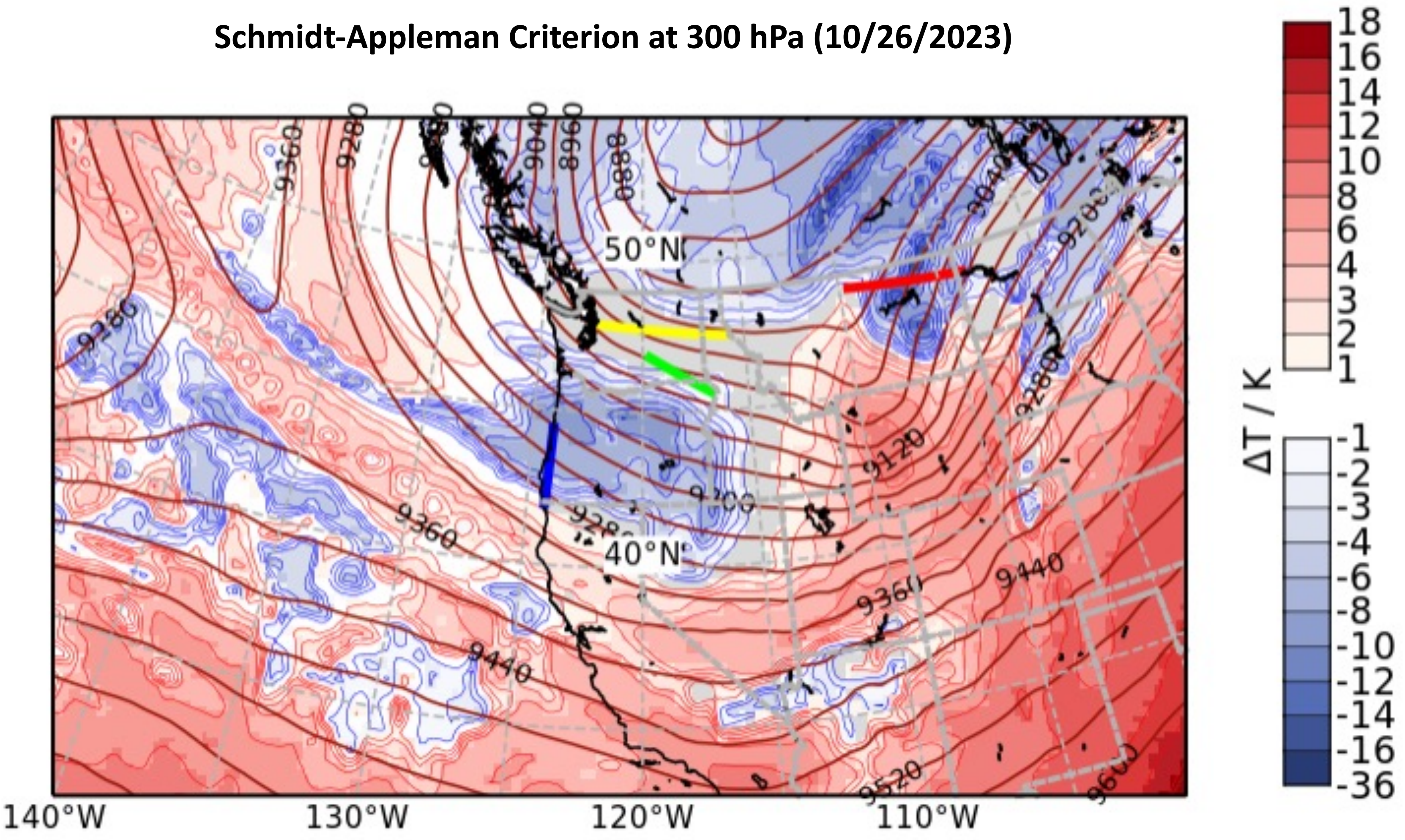
$$\Delta T = T_{ambient} - T_{SAC}$$

where $T_{ambient}$ = ambient temperature
and T_{SAC} = warmest contrail temp.

$\Delta T > 0$ indicates no contrails

$\Delta T < 0$ indicates contrail formation

Schmidt-Appleman Criterion at 300 hPa (10/26/2023)



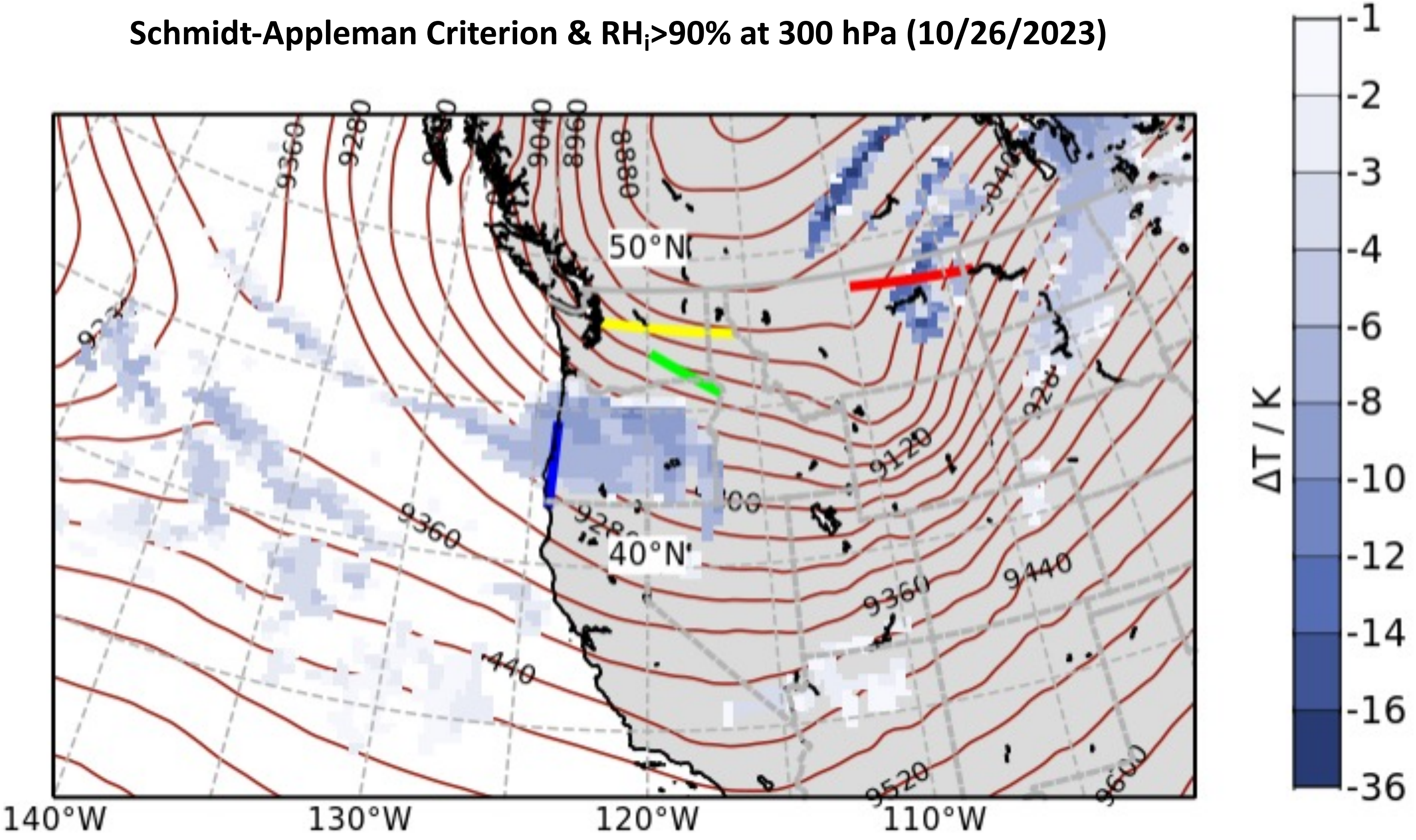
Gap: T, RH Accuracy, timeliness

ECMWF Forecast of Schmidt-Appleman Criterion Courtesy of DLR

Weather Forecast Models Predict Contrail Conditions

Next step is to combine SAC with humidity fields to identify regions of persistent contrail formation.

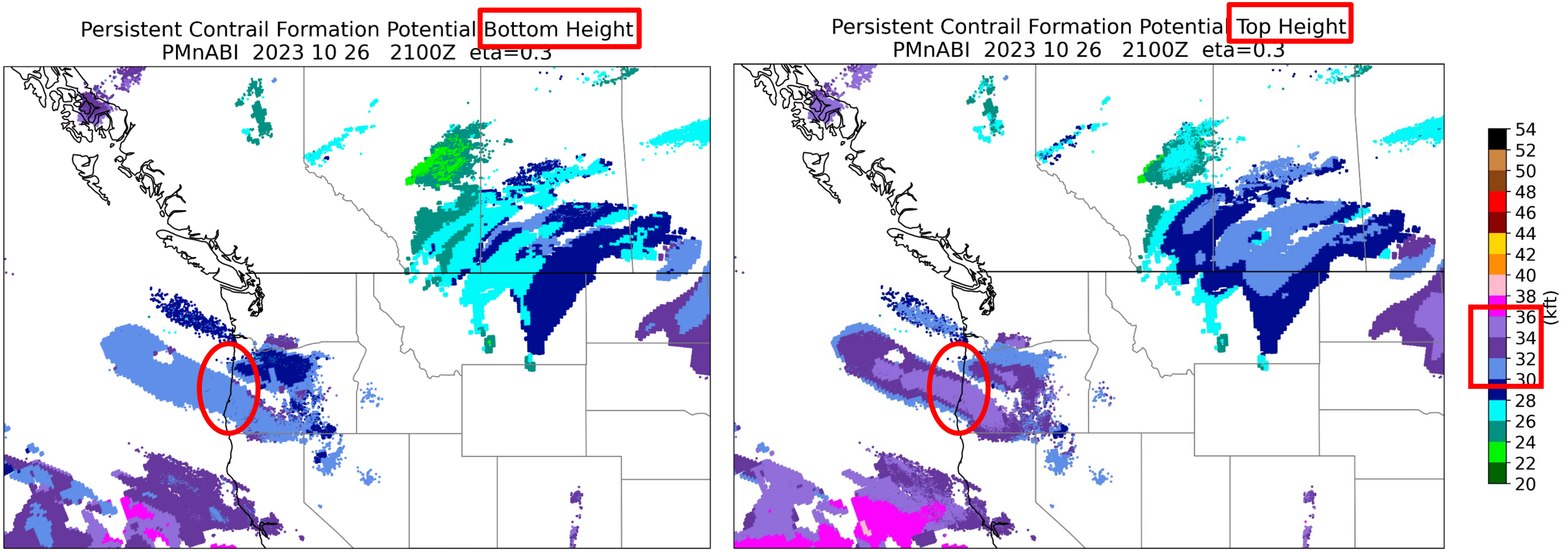
Schmidt-Appleman Criterion & RH_i>90% at 300 hPa (10/26/2023)



Gap: T, RH Accuracy, timeliness

ECMWF Forecast of Schmidt-Appleman Criterion Courtesy of DLR

Near-Real-Time Satellite Information Can Further Improve Contrail Identification



Gap: Satellite Algorithm Development

https://satcorps.larc.nasa.gov/eco-d

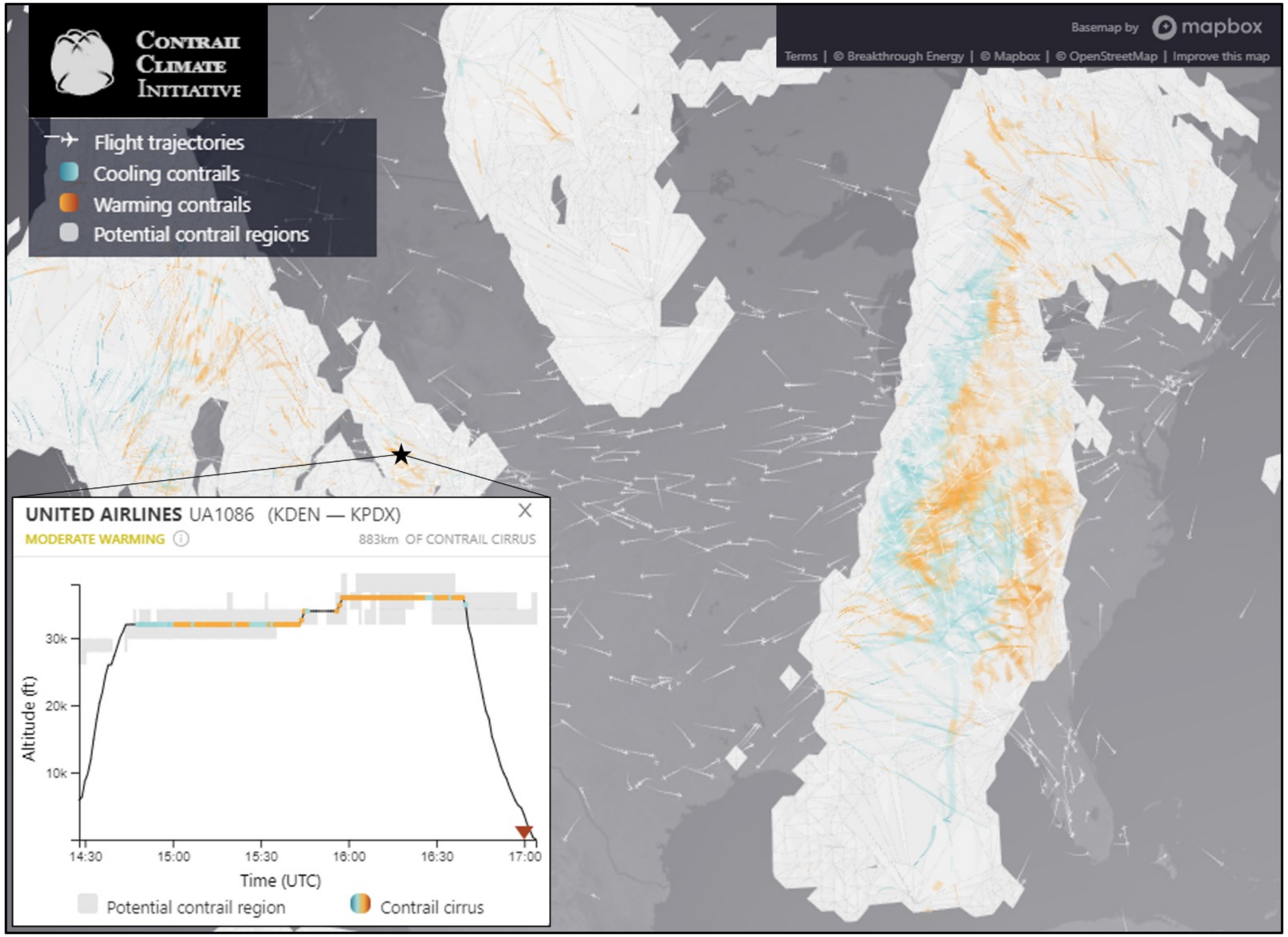
Next step is to simulate the actual flights/contrails and their individual climate impacts

Lagrangian plume models track the formation and evolution of contrails. Two popular ones are:

- CoCip (Schumann, Geosci. Model Dev., 2012)
- APCEMM (Fritz et al., Atmos. Chem. Phys., 2020)

While the global impact of contrails is thought to be warming, individual contrails can be warming or cooling. Depends on many factors, including:

- Day (warming or cooling) / Night (only warming)
- Surface conditions (dark ocean, light sand)
- Existing and/or underlying clouds
- Contrail initial conditions (impacted by engine technology and fuel chemistry)



Gaps: T, RH, + Contrail Input Parameters

Adapted from https://map.contrails.org

Satellite tools can help here, too.

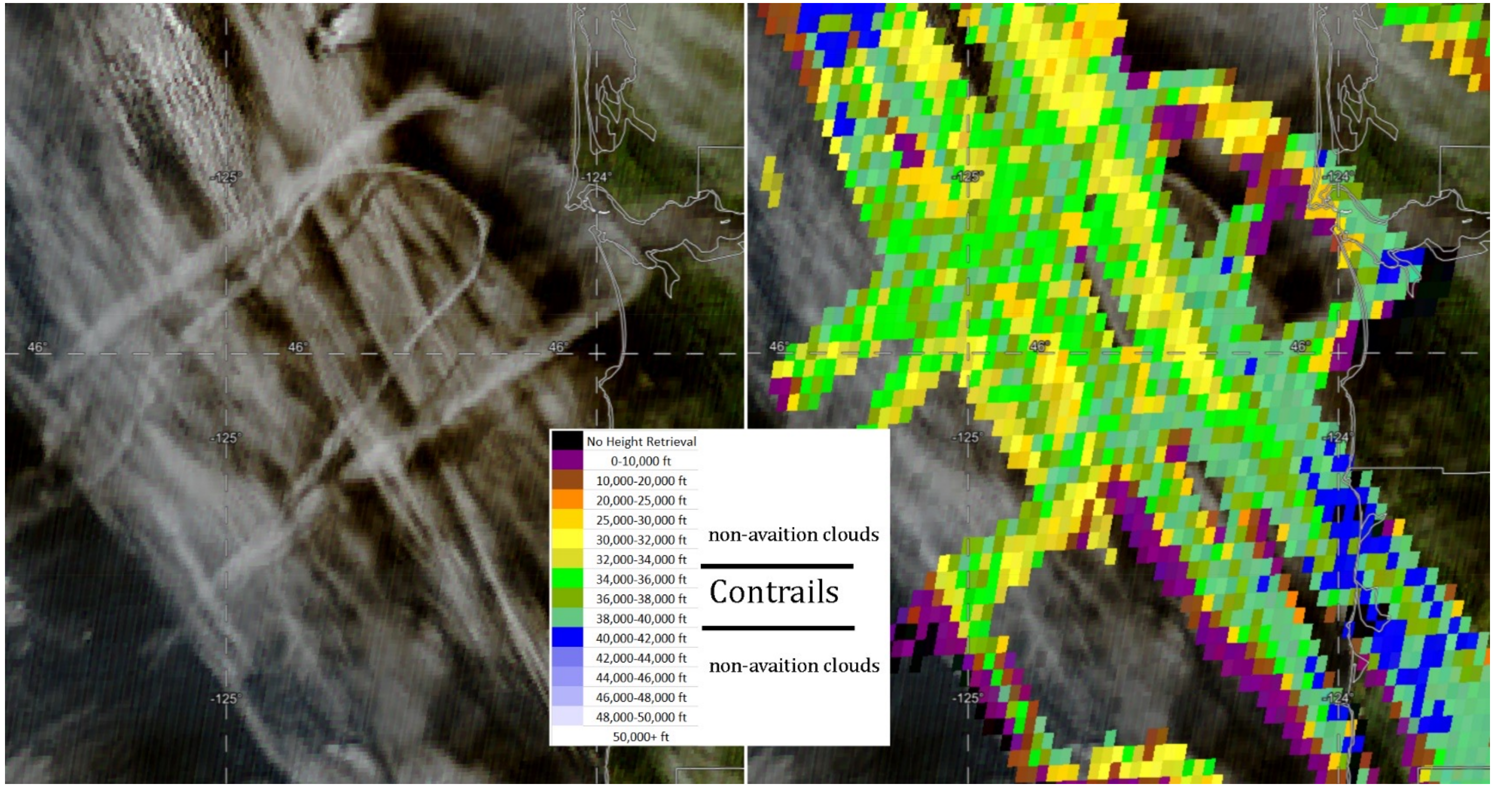
Geostationary satellite imagery can detect contrails if/when they grow larger than satellite pixel scales.

Challenge is distinguishing them from all other line-shaped clouds
(e.g., frontal systems, coastal boundaries)

Opportunity to leverage satellite observations for validating models (did a contrail form or not?) as well as for providing near-real-time decision support.

Visible Image

Contrail Height Retrieval



GOESmeso Image and Contrail Height Retrieval for 12 October 2023 ecoDemonstrator flight (courtesy of Jay Hoffman, U. Wisc.)

Gap: Satellite Algorithm Development

Where are the gaps?

- **Upper tropospheric water vapor and temperature meteorological fields are uncertain**
  - Satellite infrared sounders launching soon in Europe/Asia, expected in the US GeoXO in the 2030s
  - Development/deployment of water vapor sensors on commercial aircraft alongside existing temperature probes

- **Aircraft engine emissions and contrail ice properties vary across aircraft/engine families and fuels**
  - Limited observational data at cruise conditions to inform technology/fuel pathways
  - Sustainable Aviation Fuels (SAF) in rapid development, but **not all have same soot reduction benefits**

- **Predictive models struggle** to identify which flights are the most strongly warming
  - Radiative forcing from individual flights/contrails (not global averages)
  - Limited observational data at cruise to improve predictive models

Gap: T, RH Accuracy, timeliness, satellite algorithms
observational data at cruise

Actions

increasing awareness, coordination, and partnering

advocating for, planning, and executing research

National Academy of Sciences
Aeronautics and Space Engineering Board (ASEB)
National Academies of Sciences, Engineering, and Medicine (NASEM)

Aviation Climate Impact Meeting of Experts

February 13-14, 2023

a two-day meeting of experts to consider the key contributors to climate change arising from commercial aviation, their relative impacts, and what opportunities exist for long-term reductions that are sustainable both from environmental and business perspectives. Emphasis will be placed on full life cycle considerations.

Photo by Rich Moore

Aviation Climate Impacts/Recommendations

- **Combustion CO_2 emissions** – definite contributor with high confidence
    - Recommendation: NASA should keep working energy efficiency/transition to SAF
- **Non-CO_2 effects** – definite contributors with large *uncertainties*
    1. Contrails/Persistent Contrails/Aviation Induced Cloudiness
        - Challenge: Scientific understanding of contrail formation and associated heating is lacking, so predictability is weak
        - Recommendation: NASA should acquire observational data at cruise to improve models
    2. Net NO_X
        - Reduces methane and produces ozone
        - NO_X / Fuel Burn *Trade*: Higher burn temperature yields lower fuel burn but higher NO_X
        - Opportunity: NO_X mitigation – reduce post-combustion emissions with advanced combustors
        - Recommendation: NASA should make cruise NO_X measurements and improve ground to flight emissions predictability
- **Other environmental aviation impacts** not to be forgotten
    - Noise
    - Pollutants affecting local air quality
    - Production and transportation of fuels

Climate Expert on “Contrail Avoidance”

National Academies Meeting of Experts – Feb 2023

“To my mind, there are **3 critical questions** that you have to answer on your way to say should I divert this flight at this moment in time to have a better outcome.”

1

“First…

Can I predict ice supersaturation?

Yes, we’re quite good at predicting ice supersaturation in general.

But can I predict it at say 8:00AM on a Thursday, or a particular Thursday, over Washington DC?

And can I predict it within that 1000-foot flight level?

And can I predict that solidly that I know it would form a contrail?

The absolute answer is no.”

2

“Second…

Let’s say we do cause a contrail.

Under that particular circumstance,
in that particular place,
at that particular time,
how reliable is the question of the forcing that that creates?

That’s a very difficult computation to have with any certainty.”

3

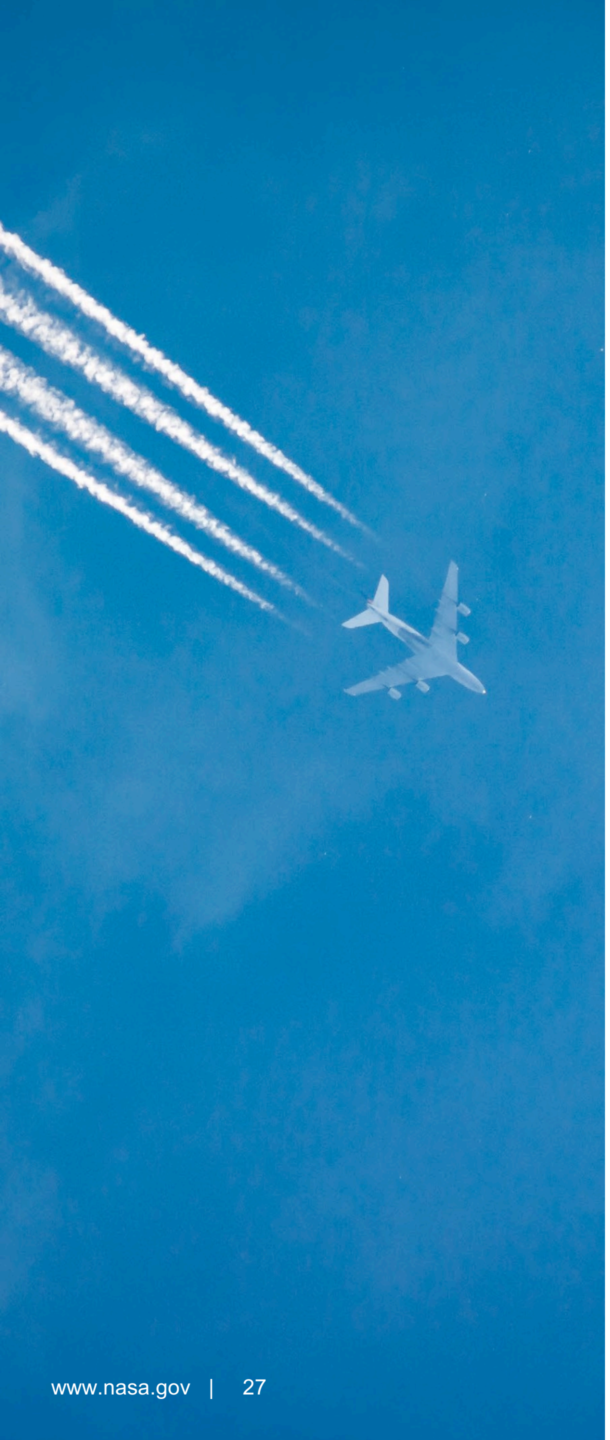
“Third… If…

I’ve predicted ice supersaturation, and I’ve predicted a contrail… and I would say we can’t do either of those things..

Can we then compare it with the CO_2, and to know with reasonable certainty that we’re going to get a good outcome?

Absolutely not.

We cannot do that yet because of those first two conditions.”



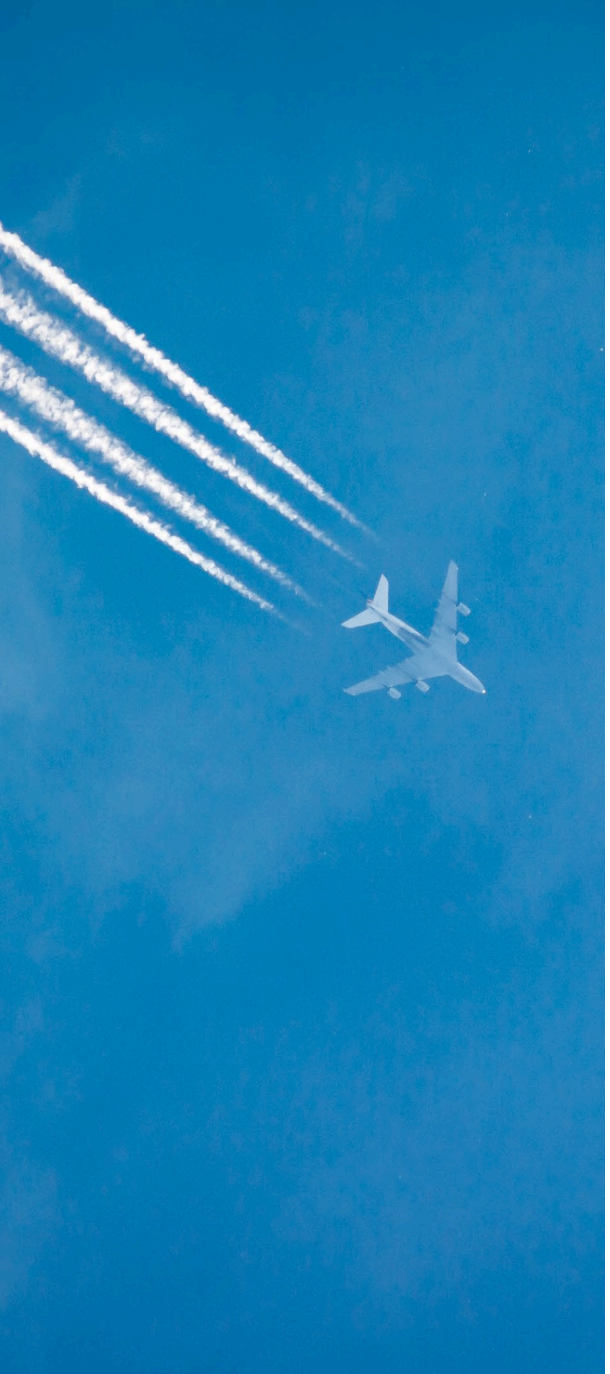
Focus on now… as an Aviation Community

- Focus investments on major aviation sources impacting climate – airliners dominate aviation CO_2 emissions
  – > 92% aviation CO_2 emissions from >125 pax (2018)

- Continue investing in aircraft efficiency technologies
  – use less energy

- Support transition to SAF which will reduce lifecycle CO_2 emissions

- Keep U.S. cautious approach to hydrogen
  – explore, potentially use small aircraft as testbeds/ technology incubators
  – will not help soon enough for significant impact by 2050 but may be used more broadly beyond 2050

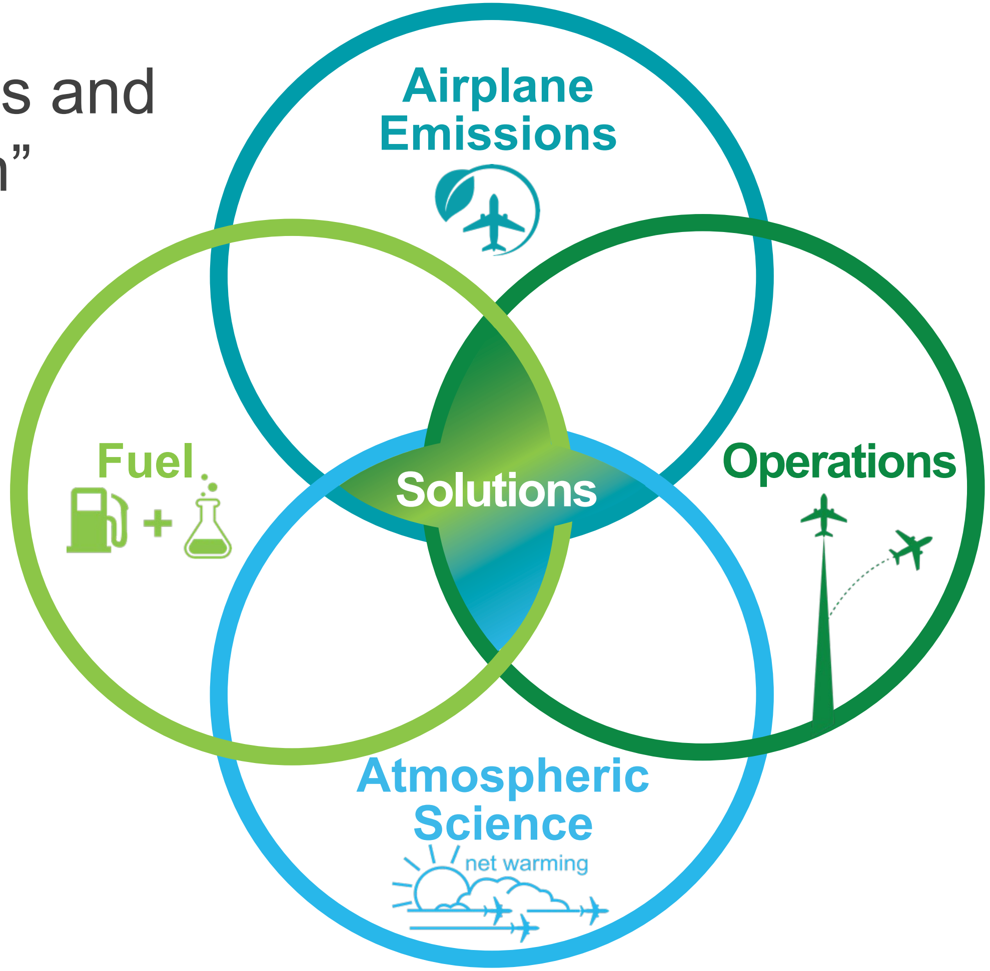


Recommendations to NASA ARMD

- Allocate additional funding to support cruise altitude measurements to constrain models & to quantify benefits of SAF + technology (fill the observational data gap at cruise)
- Commission NAS study on current capabilities and future priorities for “Contrail Management” over the next decade
- Open/continue dialogue with NASA Science Mission Directorate (SMD) on joint measurement & model opportunities
  - Expand beyond characterization to using the data to improve modeling

National Academies Study

- 2024 Jan 23 – Task Order Awarded
  - “Research Agenda for Reducing the Climate Impact of Aviation-Induced Cloudiness and Persistent Contrails from Commercial Aviation”
  - 18 months
  - Jointly funded by ARMD and SMD



NASA Intra Agency Contrails Working Group

sponsored by the SFNP Mission Integration Office

ORG	Team Member	Background
ARMD/AOSP	Doug Christensen (L)	(SFNP Ops, Vehicle Experience)
SMD/Atm Science	Rich Moore	(SMD/AAVP-AATT, POC to Inter-Agency team)
ARMD/AAVP	Jennifer Klettlinger	(AAVP-AATT/CST, POC to SAF Grand Challenge)
ARMD/AAVP	Jesse Quinlan	(Strategic Technical Advisor)
ARMD/AOSP	Swati Saxena	(ATMx/DIP)
ARMD/TACP	Koushik Datta	(TACP/UL, foundational investments)
ARMD/TACP	Naseem Saiyed	(Strategic Advisor)

Contrail Intra-Agency Working Group

Team serves primarily for information exchange and coordination within NASA including across Mission Directorates, programs, and projects regarding aviation-induced cloudiness/persistent contrail research activities. Objective is to ensure coordinated and leveraged efforts to advance the science-based knowledge of contrail formation and persistence, their effect on the climate and potential management/mitigation opportunities. Team would also identify research gaps that could be addressed by NASA or other government agencies.

Contrail Research & Mitigation
USG Interagency Collaboration

Overview of Activities - Executive Meeting

Primary Contributor(s)

Federal Aviation Administration

Nicole Didyk Wells
Prem Lobo
Chris Dorbian

Department of Energy

Kevin Stork
Zia Haq

National Aeronautics and Space Administration

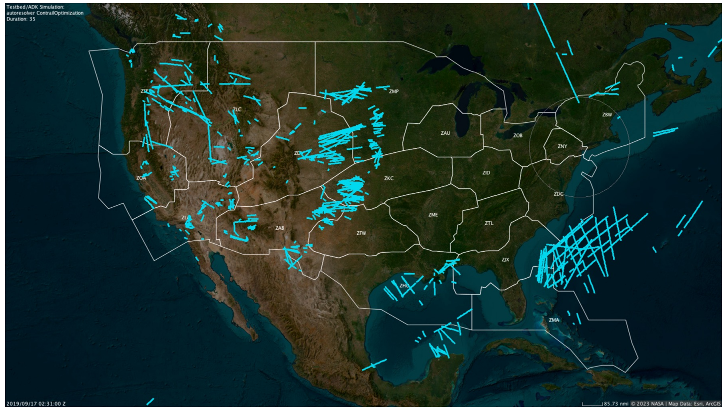
Rich Moore
Doug Christensen
Jennifer Klettlinger

ACCESS II – NASA
Falcon chasing DC-8

NASA Internal Seedling Studies

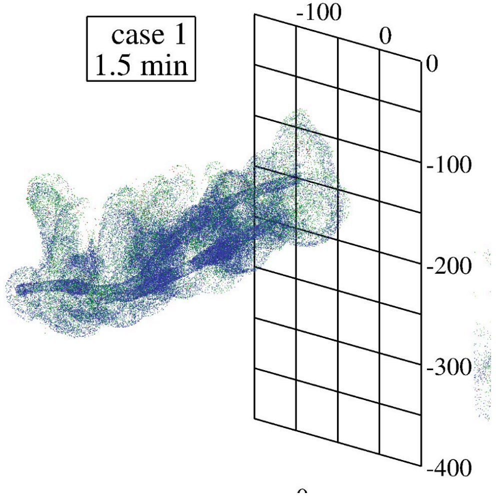
examples

- Macro level
  Persistent Contrail Formation Avoidance Exploratory Study
  NASA Aero Intercenter Systems Analysis Team
  POCs: David Thipphavong (ARC), Todd Lauderdale (ARC)



Snapshot of NAS-Digital Twin simulation
without altitude changes for
persistent contrail formation avoidance

- Micro level
  Contrail Simulation Toward Active Control and Mitigation
  NASA TACP - Transformative Tools and Technology (TTT) Project
  POC: Karim Shariff/ARC



Ice crystal distribution using the
Compact Finite-Difference code,
Picot et al.

Ground and Flight Campaigns

focus on science to improve predictability

opportunities for operational experience / forecasting

fertile ground for partnerships including international

NASA Emissions Research (Ground & Flight)

improve understanding of fuel chemistry & emissions impacts; motivates and advances SAFs

1990s

SNIF, SUCCESS Flight Tests
Concerns about high-sulfur content of petroleum-based jet fuels motivate studies linking fuel chemistry to volatile particles and contrails.

2000s

APEX, AAFEX Ground Tests
First ground tests with SAFs show large soot particle emissions reductions. Tests also inform SAE E-31 regulatory methodology recommendations for ICAO WG3.

2010s

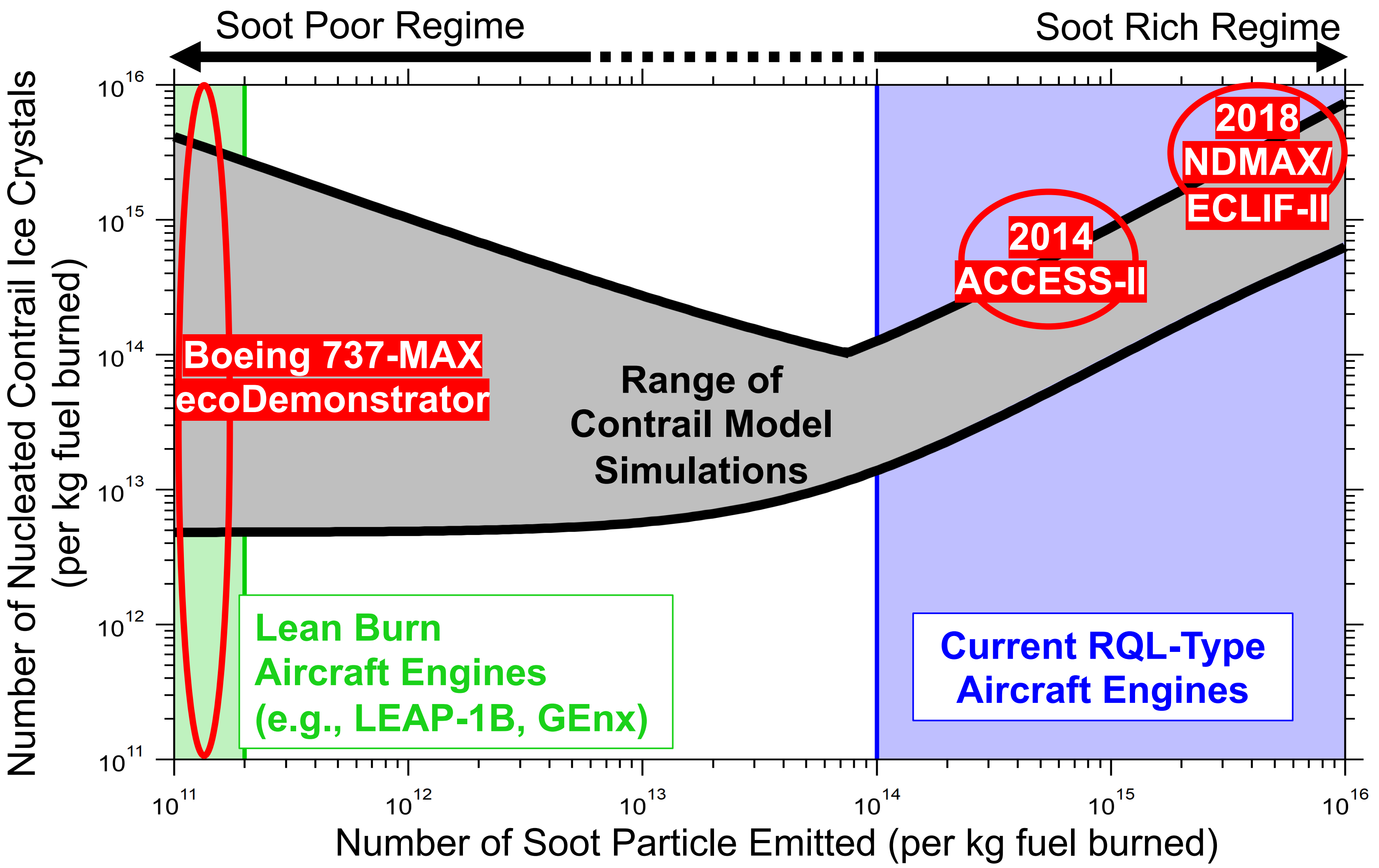
ACCESS, ND-MAX Flight Tests
First, in-flight, chase plane studies with SAF blends show that particle emissions reductions observed during **AAFEX** also translate into lower emissions and fewer contrail ice crystals at cruise altitudes.

2020s

Boeing ecoDemonstrator Ground and Flight Tests
First ground & flight tests with pure SAFs + lean-burn engines will assess “best currently possible” particle & contrail reductions.

Motivation for Flight Campaign

Contrails Potential of SAF and Advanced Combustor Technology



Need to understand the "soot-poor" regime and do it at flight altitude to understand contrails

Figure adapted from Kärcher, *Nature Communications*, 2018.

Moore et al., Nature, 2017; Voigt et al., Nature Comms. Earth & Environ., 2021

Flight Required to Link Emissions to Contrails – Combustor Tech + SAF Important

2021 Ground Tests Demonstrate Lean-Burn Engine Particle Reductions

2021 Boeing ecoDemonstrator 737-9

- CFM LEAP-1B
- 100% Paraffinic SAF Ground Test and Flight Demonstration
- 4 fuels tested (Jet A, 30/70 & 50/50 SAF blends, 100% SAF)
- 1 successful 100% SAF demo flight

NASA
ecoDemonstrator PROGRAM

In-Flight Testing With 100% Sustainable Aviation Fuel Completed In October 2023 In Collaboration With Boeing, US, & International Partners

NASA

eco Demonstrator PROGRAM

Federal Aviation Administration

UNITED

DLR Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center

GE Aerospace

Transport Canada Transports Canada

AERODYNE RESEARCH, Inc.

MIT

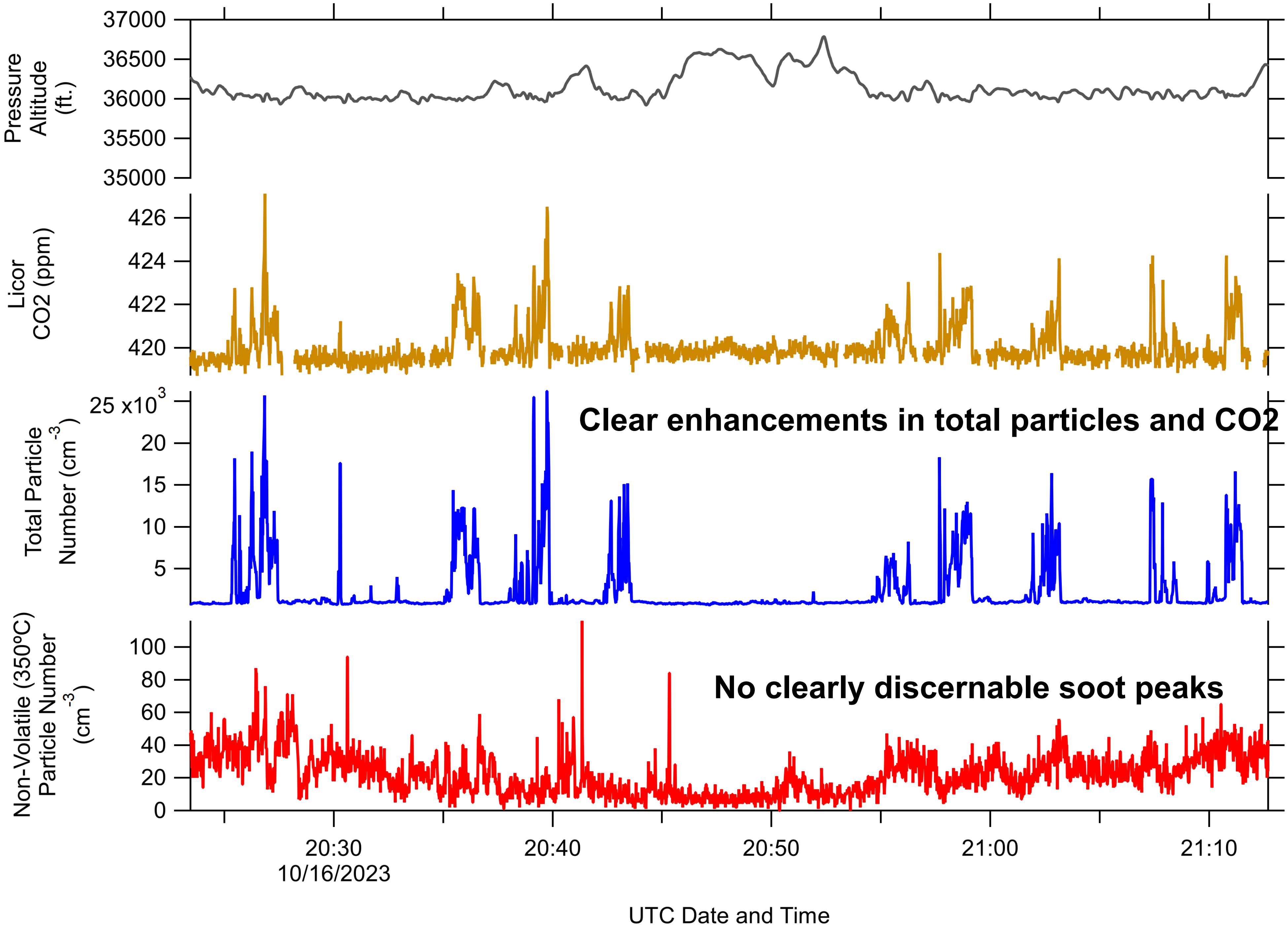
MISSOURI S&T

2023 Emissions Flight Test with the NASA DC8 Chasing the Boeing ecoDemonstrator Explorer 737-10 with LEAP-1B Engines

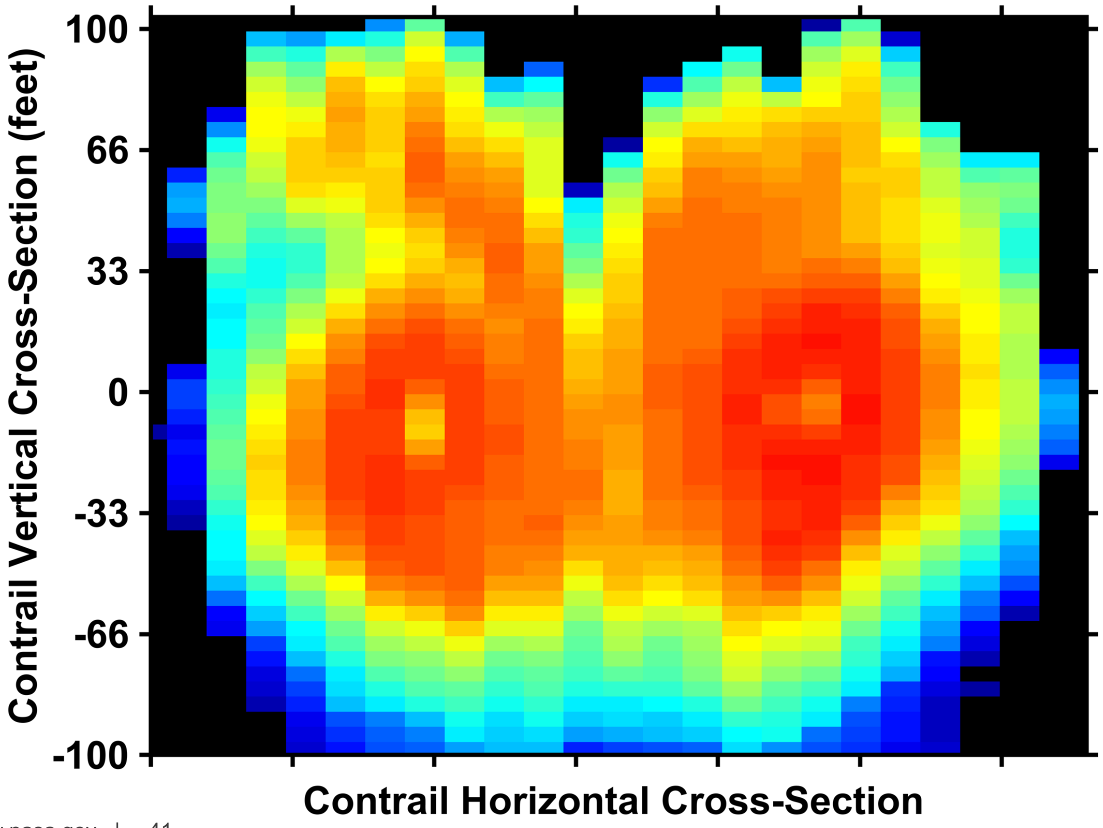
- 11 joint science sorties
- >100 combined DC-8 and 737-10 flight hours
- 3 fuels: 100% SAF and Two Different Jet A Fuels
- Sampling in both contrail & clear air conditions


NASA
←H1
←J

10/16 Quicklook Timeseries Data For 100% SAF



First of Its Kind HSRL Lidar Measurements Reveal Contrail Cross-Section



What's next?

analysis & publish
National Academies study
refine plans & advocate for budget to address non-CO_2
coordination & leverage partnering
stimulate university and small business contributions

What's Next For SAF-Emissions Measurements

Looking beyond the 2021-2023 Test Series

BOEING NASA

adapted

- ***2023 Test Data Reduction & Analysis; Identify gaps***
- ***Explore engine oil handling***
- ***NASA SBIR Water Vapor Sensor Development***
- ***Groundwork for NASA 777 as Chase Plane***
- ***NASA ARMD-SMD Commissioned National Academies Study***

2024

- ***DOE ARPA-E Pre-Trails Testing of Humidity Sensors***
- ***Ground Testing of Novel Fuels***
  - ***HEFA / SAK Fuels***
  - ***Cycloparaffinic Fuels***

2025

Pending NASA Earth Venture Suborbital Proposal (EXCITE-SAF) to Leverage the New NASA 777

2026

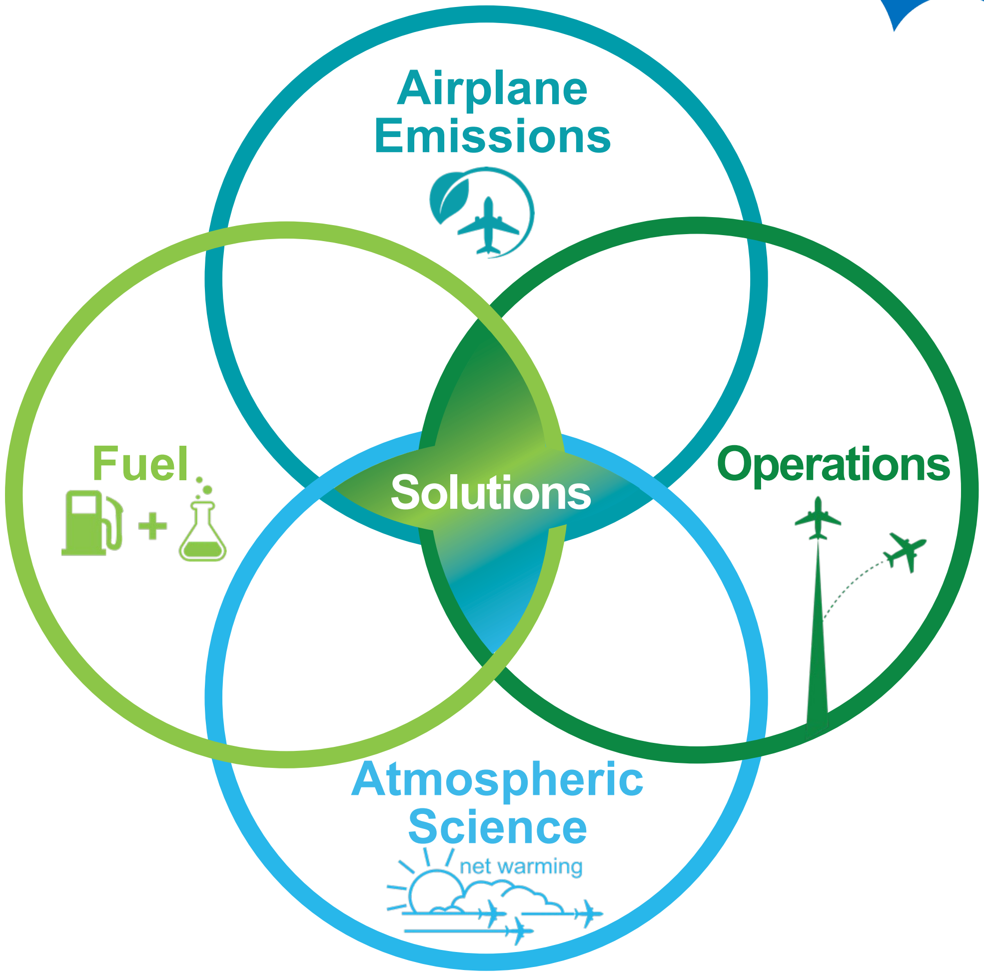
Contrail Forecasting + Rerouting

2027+

decreasing level of funded activity

Contrails

- Climate models tell us that aviation-induced cloudiness has a net warming impact comparable to a century of aviation CO_2 emissions
- Aviation-induced cloudiness comes from the formation of relatively few but long-lasting contrails
- Focused research will give us the scientific basis to inform sustainable flight operations decisions to avoid (or not) contrail formation.



Research Areas

My High-level Take Aways

- Addressing "contrails" feels like low hanging fruit …..
  …but with significant scientific uncertainty at individual contrail level
  …to the point leading climate scientists warn of possible adverse consequences
- Since persistent contrails/aviation induced cloudiness (PC/AIC) have short-lived impact (warming and cooling), the urgency to mitigate is less than that required to reduce carbon impacts,
  …but must be addressed and impact reduced
- Advance science to better inform future policy and operational decisions while preparing for operational management of contrails including the use of advanced technology and alternative energy

Characterize – Understand – Model – Predict → Necessary for Trades → Inform Operational Decisions
Science is the foundation

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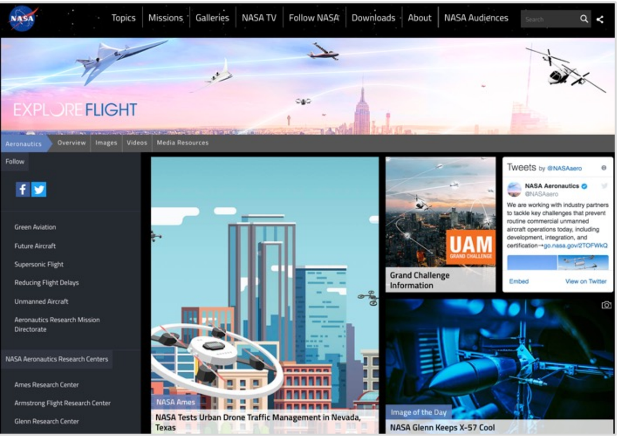
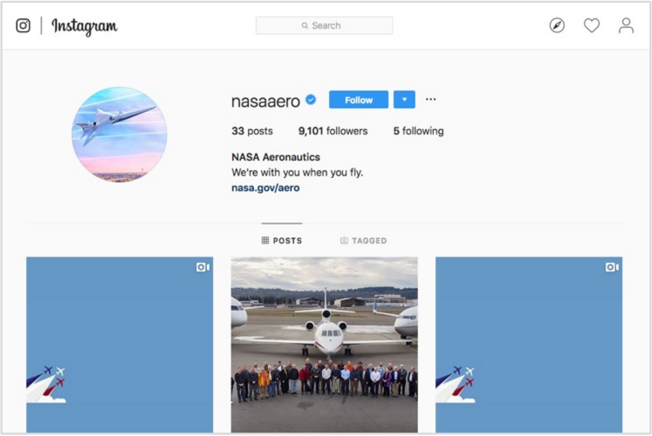




www.nasa.gov/aeroresearch/strategy | www.nasa.gov/aeroresearch/solicitations

Addressing Climate Impacts from Aviation Induced Cloudiness via Operations, Technology and SAF

NASEM Aeronautics Research & Technology Roundtable

Dr. Anna Oldani
Chief Scientific and Technical Advisor for Environment and Energy

February 14, 2024

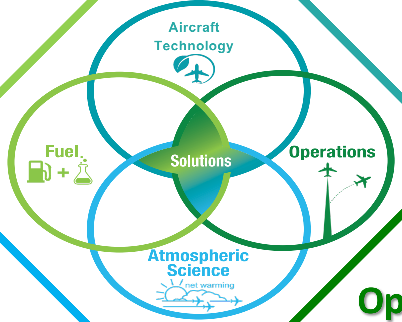
Federal Aviation Administration

Planning and Collaboration

- **Near-term efforts**
  - Coordinate policy direction
  - Enhance interagency collaboration
  - Correlate to other non-CO2 impacts
- **Interagency collaboration – DOE & NASA**
  - Bring in NOAA & DOD
  - Identify research gaps (reduce uncertainty)
  - Connect to international research
- **Contrail Task Force**
  - Airline trials/impacts/concerns

Fuel
- Adjust fuel properties (H_2 content, heat of combustion)
- Reduce use of soot forming fuel compounds (aromatics)
- Reduce fuel impurities
- Hydrogen

Aircraft Technology
- Optimized fuel injectors
- Lean combustors
- Hydrogen combustors
  - Onboard sensors to detect regions of supersaturation



Atmospheric Science
- Predictive identification supersaturation regions
- Improved prediction of ice crystal formation and persistence
- Improved attribution of contrail induced cirrus on radiative forcing

Operations
- Flight path redirection (altitude, course)
- Connected aircraft
- Improved control of fuel impurities

International Partnerships

- **International Standards**
  - ICAO CAEP Working Group 3 - non-CO2 (NOx and nvPM) and CO2 policy
  - Fuels Task Group (FTG)
  - Impacts and Science Group (ISG) - independent experts preparing Contrail Workshop Paper
  - ASTM - sulfur content to reduce nvPM; SAF pathway qualification
- **EU -** Monitoring, reporting, and verifying non-CO_2 effects in aviation (europa.eu)
  - Discussing challenges and industry involvement
- **International research collaboration**
  - DLR contrail model – CoCIP (validation with APCEMM)
  - Modeling/measurement gaps
  - Contrail vs CO2 correlations

Connected Contrail Research

Emission Measurements

- ASCENT 02
- Non-CO2 measurements (nvPM, NOx, etc)
- Different Fuels
- Rig, Wing, In flight
- vPM – connect to tech

Contrail Modeling

- ASCENT 78
- APCEMM
- Validation with CoCIP
- Avoidance Tool

Operations

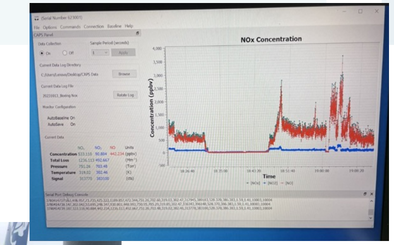
- Airline Trials
- ATC (planning)
- Like Turbulence? Utilize similar policy/procedures

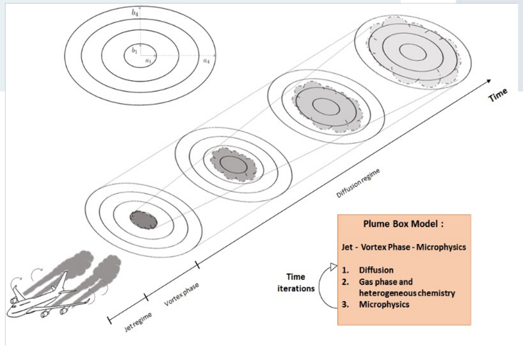
Fuels

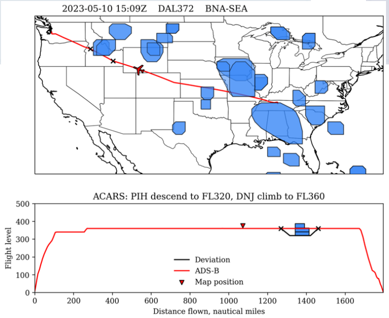
- Traditional Jet A & Low S
- Fully paraffinic vs. drop-in SAF
- Production scale up to meet demand (FAST)

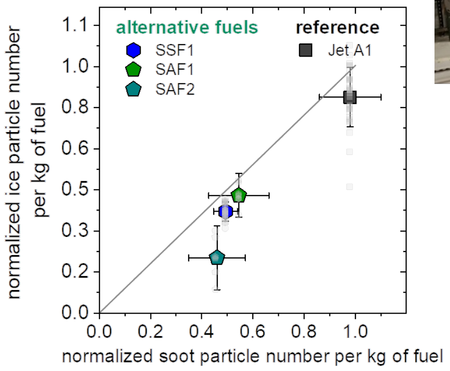
Technology

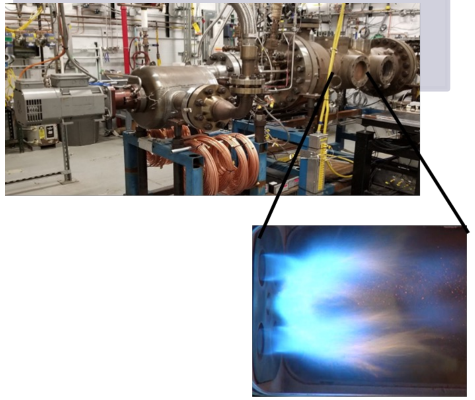
- ASCENT & CLEEN
- Humidity sensor
- Engine advancements to reduce PM











Novel lean premixed prevaporized combustor for CST, has been build, tested, and characterized at engine-relevant conditions

Committed to Contrail Reduction through…

- Contrail Strategic Action Plan
- Domestic & International Partnership
- Fuel, Technology, & Atmospheric Research
- Modeling & Operational Activities