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

Presented to: REDAC EE Subcommittee Summer/Fall Meeting

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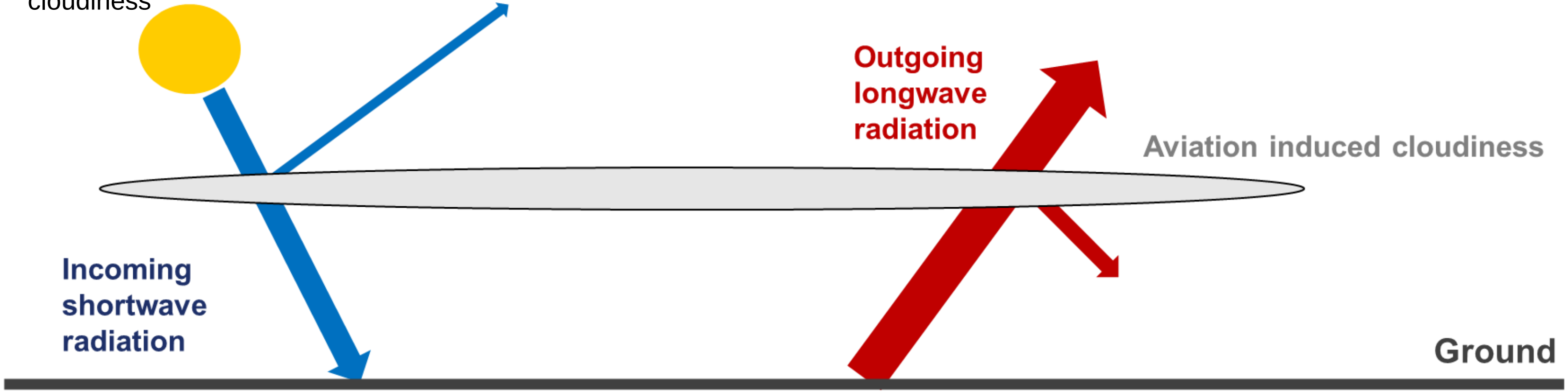
Federal Aviation Administration

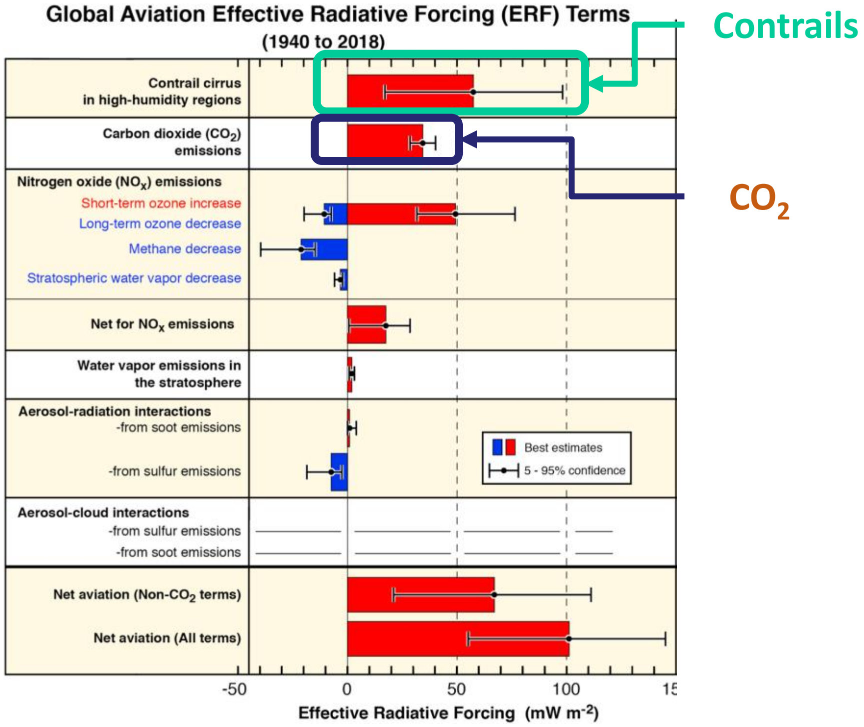
Aviation Induced Cloudiness – Some Basics

- Condensation trails (contrails) are tracks of ice that form as hot water from jet exhaust cools off in the upper atmosphere
- Long-lasting persistent contrails spread and create “Aviation Induced Cloudiness” (AIC)
- Contrail formation and aviation induced cloudiness determined by atmospheric conditions – contrails can form and disappear, or can form and persist, depending on temperature and humidity where the aircraft is flying
- Climate impact of aviation induced cloudiness is due to small differences in the amount of incident solar radiation and outgoing heat from the planet
- Magnitude and sign of climate impact is determined by season, time of day, and presence of other clouds underneath the aviation induced cloudiness



Why do we care?

- Non-CO2 terms (mostly from contrails) potentially significant in aviation climate forcing
- High uncertainty, but impacts are measured in minutes to hours – if aviation activity were to stop, the impact of aviation induced cloudiness would cease within a day
    - Furthermore, small fraction of contrails cause the majority of contrail warming



Lee et al., Atmospheric Environment 244 (2021)

Primary Challenges

Prediction — Where and when will the contrail form

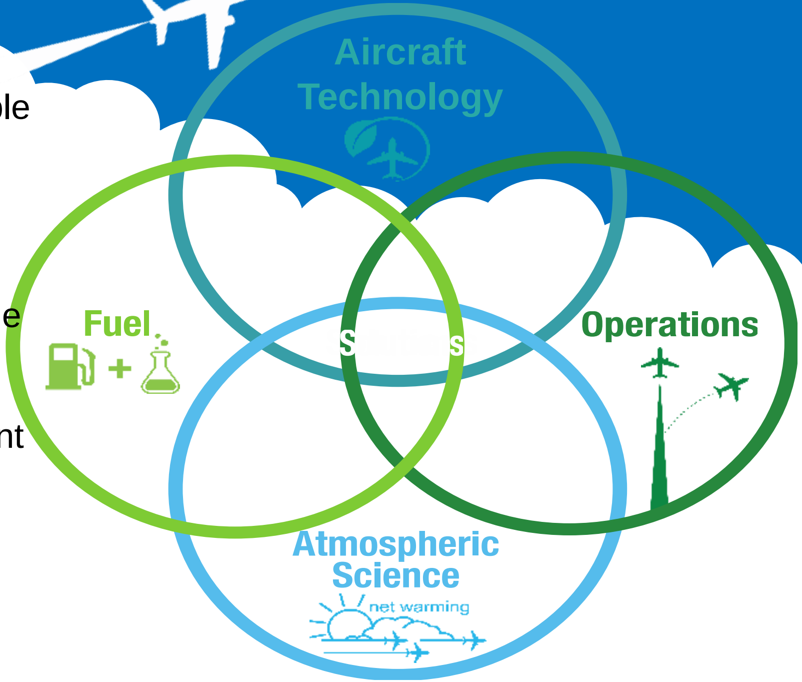
Confidence — Sufficient confidence/reduce uncertainty → decisions on avoidance/ mitigations whilst considering trade-offs (fuel/CO_2, cost, safety/capacity…)

Avoidance/ Mitigation — Ability to predict w/confidence → develop quality strategies for contrail avoidance (informed by technologies, fuel, & operational)

Impacts/ Benefits — Ability to determine the Impacts and the benefits of mitigation

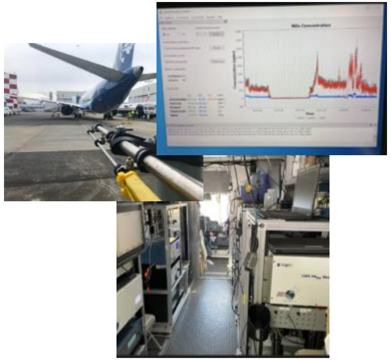
Contrail Impacts Focus Areas

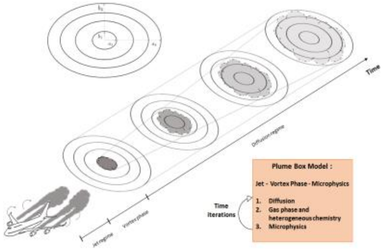
- Aviation-induced cloudiness comes from the formation and **persistence of contrails**, which in turn, are impacted by multiple factors:
  - Atmospheric Science – Meteorology & the local radiation budget determine the sign of the contrail climate impact (warming or cooling).
  - Fuels – Chemical composition drives gaseous and particle emissions.
  - Technologies – Aircraft and engine technology effects on gaseous and particle emissions, including release of spent lube oil.
- Strategies for contrail avoidance also need to be informed by operational considerations
- Focused research in these 4 areas provide the basis for developing a strategy to address the impacts of contrails on climate

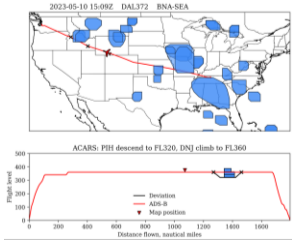


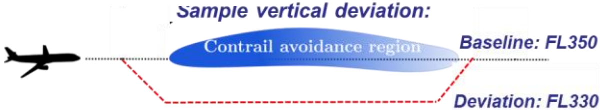
FAA's Connected Contrail Research

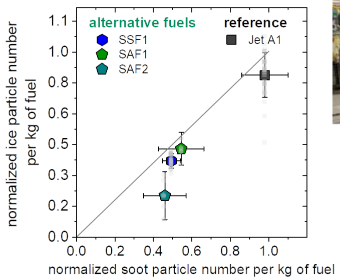
Emission Measurements	Prediction & Modeling	Operations	Fuels	Technology
• Non-CO2 measurements (nvPM, NOx, etc) • Different Fuels • Rig, Wing, In flight • vPM – connect to tech	• APCEMM • Validation with CoCIP • Avoidance Tool	• Airline Trials • ATC (planning) • Like Turbulence? Utilize similar policy/procedures	• Traditional Jet A & Low S • Drop in vs 100% SAF • Production Plus Up to meet demand (FAST)	• ASCENT & CLEEN • Humidity Sensor • Engine advancements to reduce PM

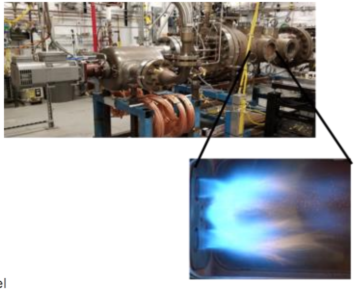












Novel lean premixed prevaporized combustor for CST, has been build, tested, and characterized at engine-relevant conditions

ASCENT 02/Eco Demonstrator Goals

Goal 1

- ✓ Quantify engine emissions burning SAF and Low-Sulfur Jet A

Goal 2

- ✓ Quantify contrail properties associated with varying engine soot and volatile particle emissions
- ✓ Determine how contrail cirrus respond to particle emissions in the “soot-poor regime”

Goal 3

- ✓ Demonstrate capabilities of water vapor lidar and in situ sensors measuring humidity
- ✓ Evaluate contrail prediction forecasts (predict ice supersaturation regions)
- ✓ Evaluate prediction capabilities for contrail formation and persistence

Video credit: NASA and Boeing
Used with permission

EcoD – Preliminary Findings (1)

Goal 1

✓ Aerosol measurements

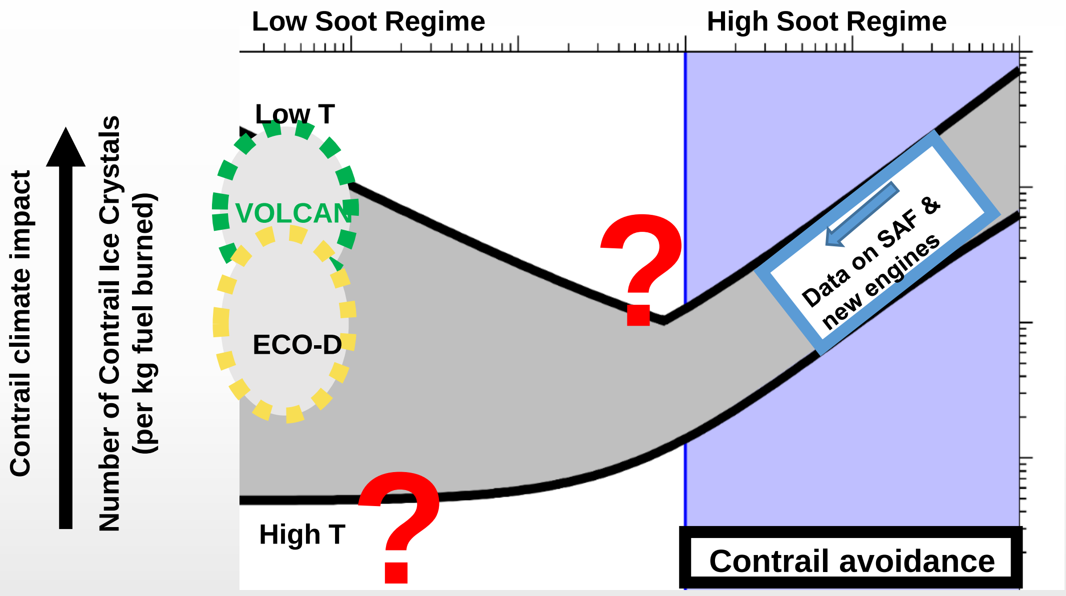
- Small particles: negligible presence of particles with SAF and Jet A (DLR)
- Large particles: showed a higher concentration with SAF (NASA)

Goal 2

✓ Lean burn mode provided up to two order of magnitude reduction in soot particles

✓ Cloud Aerosol Spectrometer (CAS) ice measurements

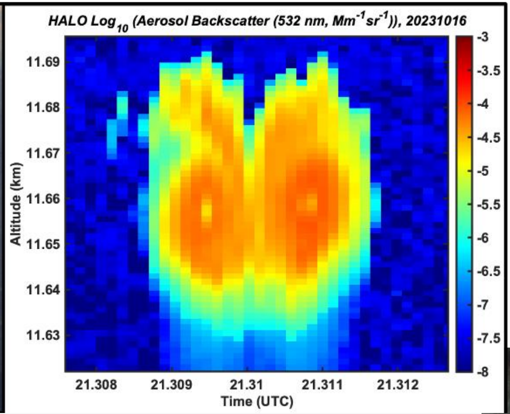
- Measure ice concentration and ice particle size
- Able to quantify the time it took for a plume to dissipate
- Calculate ice emissions index



Number of Soot Particles Emitted (per kg fuel burned)

Moore et al., Nature, 2017
Kärcher, Nature Comm, 2018
Voigt et al., CEE, 2021
Schripp et al., Fuels, 2021
Bräuer et al., GRL, 2021, ACP, 2021
Märkl et al., ACP, 2024,
Harlass et al., EGUspheres, 2024
Dischl et al., EGUspheres, 2024

EcoD – Preliminary Findings (2)



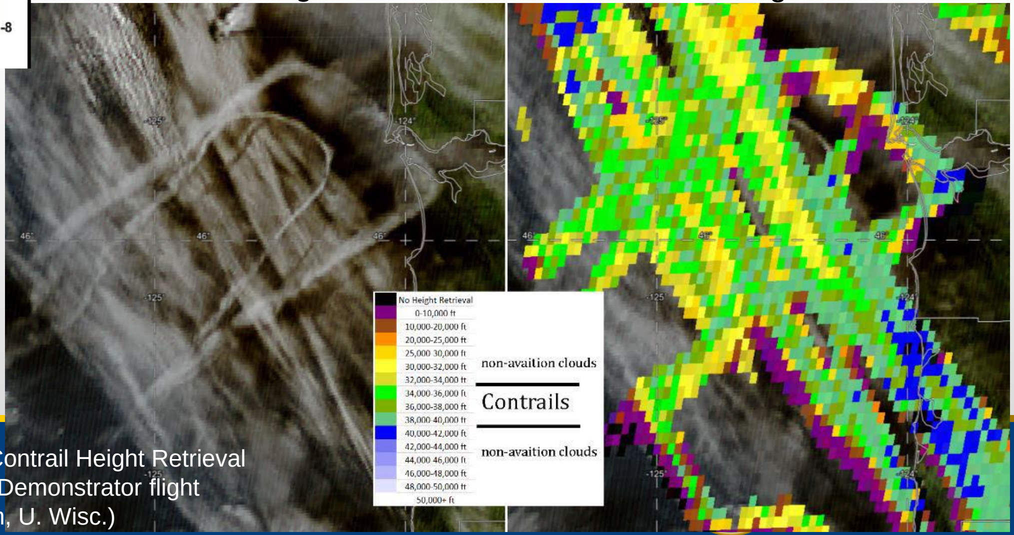
Goal 3

✓First of its kind High Spectral Resolution Lidar (HSRL) measurements reveal contrail cross-section

- Revealing more information about the size(s) of contrails

Visible Image

Contrail Height Retrieval

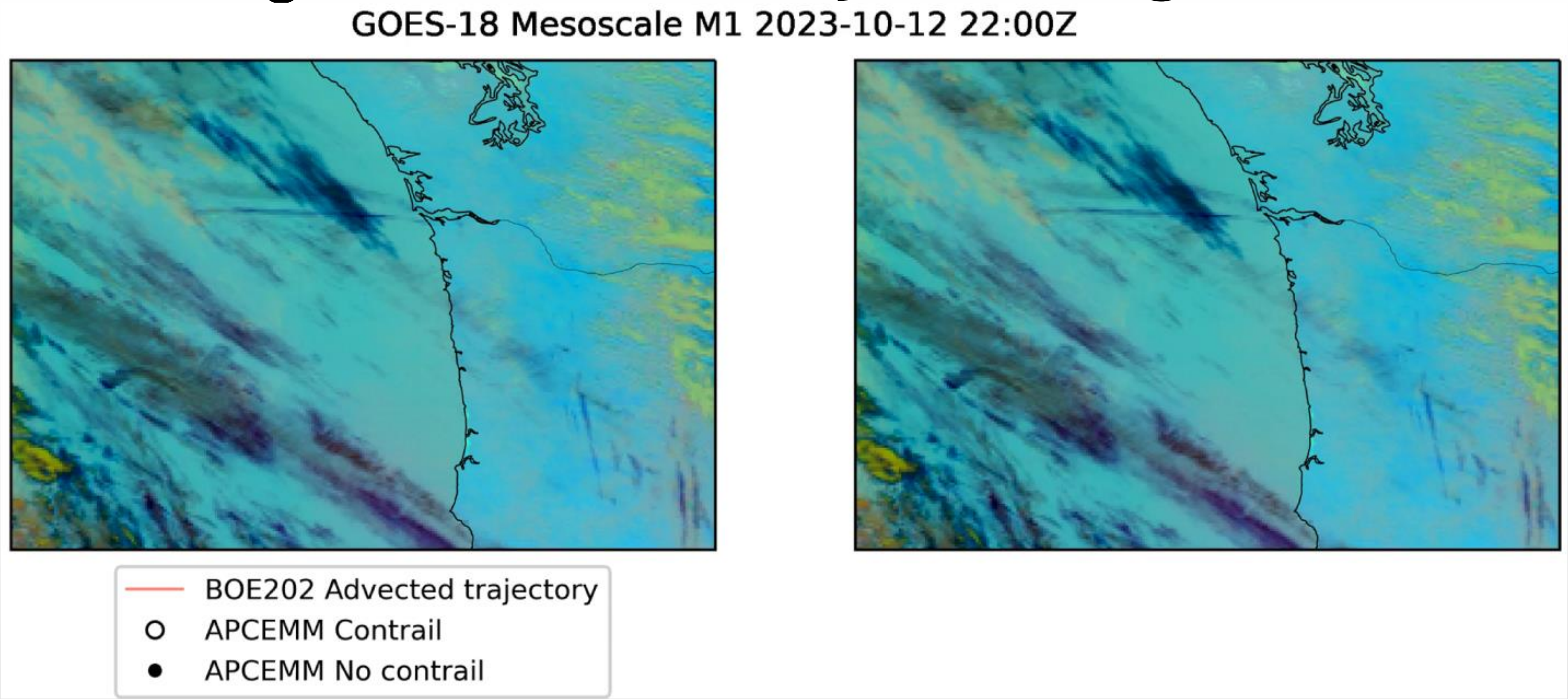


✓Satellite data

- Evaluating how good satellite data and model prediction works on temperature, water vapor and wind compared to observations
- Compared hourly satellite data with collected data – good match

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

EcoD Flight #1: Preliminary Modeling Review



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Lessons Learned

Goal 1

- ✓ Fuel Contamination Focus
  - Careful attention needs to be made to storage of fuels to prevent mixing and maintain purity
  - Properties were still consistent during tests
  - On-site procedures worked – flushing of tanks and using dedicated fuel trucks
- ✓ Fuel Sulfur Content (FSC) - SAF essentially FSC=0; Very difficult get low S Jet A and measure below 10ppm

Goal 2

- ✓ Need to fully understand effect of organics – ultrafine jet lubrication oil droplets – on contrail ice crystal formation – Engine Lube Oil isolation for next tests
- ✓ Volcan/EcoD comparison not 1-1: Engine age, Sulfur content, contamination, oil venting, and engine specification considerations

Goal 3

- ✓ More need on modeling of atmospheric conditions – forecasting Ice Super Saturated Region (ISSR) instead of operational changes
- ✓ Need more humidity and HSRL to provide a more detailed view of the size of contrails

Next Steps (EcoD and Research)

1. **EcoD Data Review**
   - Continued evaluation of data collected
   - Comparison against other campaigns
2. **Improve contrail modeling**
   - 2nd ISSR forecast model (validate DLR)
   - Aerosol modeling and measurements
   - Reduce uncertainties & validate models
3. **Organic effects on Contrails Formation**
   - Add low S jet a to all campaigns; find way to measure low S values
   - Isolate Lube Oil in future rig and on-wing campaigns
4. **Next Campaigns**
   - New fuels & aromatic (besides World Energy/Virent/Neste)
   - Campaigns on Advanced RQL & Rich burn engines, double aisle and biz jets
5. **Connect Climate and Contrail Research Roadmap**
   - Look at ISG report and National Academies (NASA) study
6. **International Partner Connections**

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Currently Identified Research Gaps & Priorities

Gaps

- Improve Understanding ISSR
- Modeling Uncertainty
- Aerosol-Cloud Interactions
- Cruise-2-Ground & LTO Cycle
- Species interdependencies
- e Contrail impacts w/o negative CO_2 impacts

Priorities

- ✓ Improve background models (weather; satellites)
- ✓ Compare Contrail Prediction/RF models as well as avoidance tools and impacts/challenges for ATC
- ✓ Continue Contrails/Contrail Cirrus Prediction/Avoidance Modeling,
- ✓ Improve Aerosol–Cloud interactions for soot & sulfur,
- ✓ Global understanding of Source attribution for LTO cycle & cruise-to-ground
- ✓ Quantification of cruise particulate emissions (Measurement campaigns/SAF/Lube Oil/Sulfur),
- ✓ Improvements to mitigation options and estimated benefits.

Develop the U.S. Contrails Research Roadmap (CRR)

- **Harmonize USG efforts**
  - Work with Government partners to identify ongoing and future USG research efforts
  - Develop shared objective/vision
- **Identify gaps and additional research/modeling needs**
  - Need to methodically answer questions related to mitigating persistent contrails
  - Identify focus of research and leverage other institution research
  - Establish a manageable timeline
- **Hire contractor assistance to assemble CRR in a timely manner**

Discussion of CRR

and

Questions on Research Plan, Priorities, and Gaps

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Next Steps

- Establish contractor support
- Engage interagency partners and determine roles and responsibilities
- Provide progress updates to leadership
- Targeting November 2024 publication

What is FAA doing to understand & mitigate the impact of aviation contrails on climate?

FAA supporting research on multiple fronts to examine measures that *could* mitigate aviation's impact on climate change through modification to contrails and aviation induced cloudiness

Potential means of modifying aviation induced cloudiness

- Modify current jet fuel specification
- Sustainable Aviation Fuels (SAF)
- New engines and combustor technology
- Change lateral flight path or flight altitude

Sensor Development

DOE ARPA-E

Operational Implications

Contrail Impact Task Force, CAEP WG2, etc.

Decision Support Tools

Contrail Avoidance Decision Support and Evaluation (ASCENT Project 78)

Cost Benefit Analyses of Changing Fuel Composition (ASCENT Project 39 and PARTNER Project 27)

Fuel Composition Impacts on nvPM and Contrails

In-flight Measurement Campaigns (NASA, DLR, NRC-Canada, NCAR, & FAA efforts)

Ground and Flight Measurement Campaigns (ASCENT Projects 2 and 69)

Analyses on nvPM (Aerodyne Research Inc. efforts and ASCENT Projects 24, 39, 48/83, 70, 71)

Improved Climate Knowledge and Modeling Capabilities

ASCENT Projects 21, 22, and 58

Combustor Technology Development

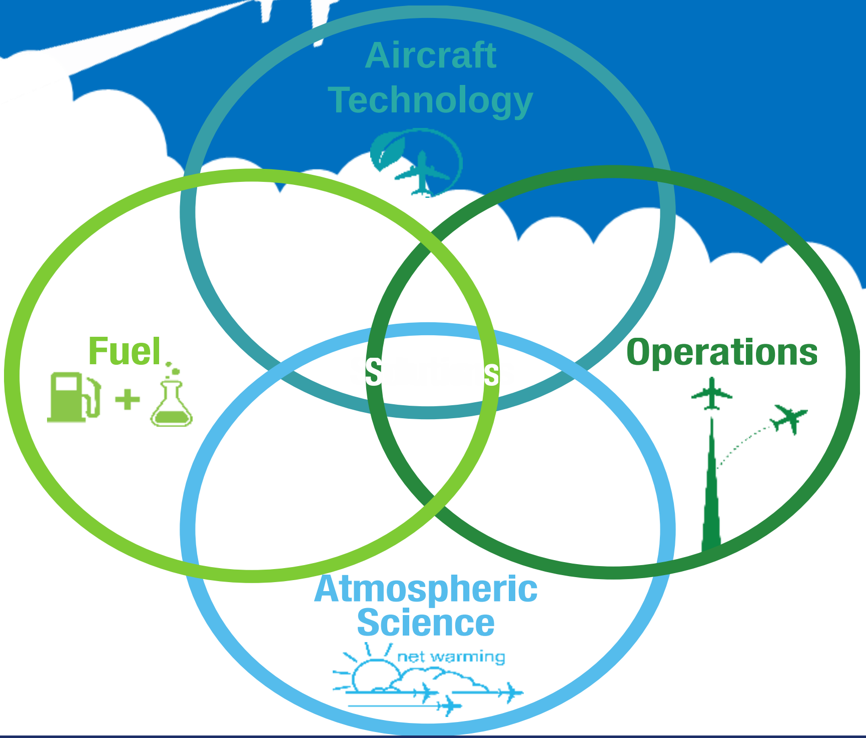
CLEEN Program; ASCENT 74 & 98

Aviation-Induced Cloudiness (AIC)

- Models tell us that **aviation-induced cloudiness** today has a climate warming impact comparable to a century of aviation CO2 emissions

- Aviation-induced cloudiness comes from the formation and **persistence of contrails**, which in turn, are impacted by multiple factors:
  - Fuel – Chemical composition drives particle emissions.
  - Technology – aircraft and engine technology effects on emissions.
  - Atmosphere – Meteorology & the local radiation budget determine the sign of the contrail climate impact (warming or cooling)

- Then we have the scientific knowledge to make operational decisions about whether to avoid (or not) forming the contrail in the first place.

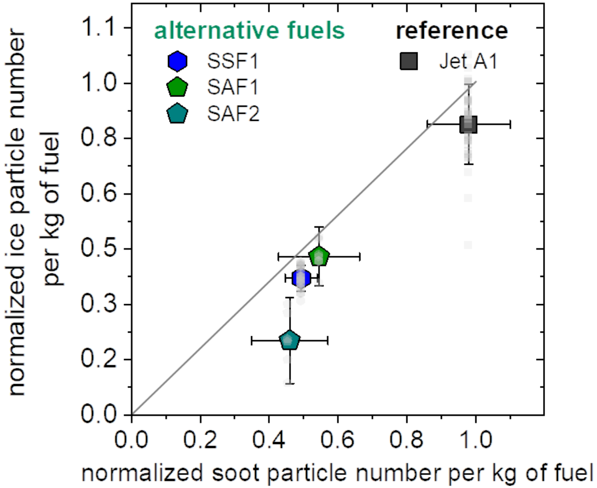


Aviation Induced Cloudiness and SAF

SAF use will result in contrails that are different from those produced from the combustion of conventional jet fuel

- More water vapor → greater contrail frequency (radiative forcing increased)
- Lower nvPM, i.e., fewer particles for ice nucleation → shorter contrail lifetimes (radiative forcing decreased) and thinner clouds (effect varies)
- No sulfur → potentially less particle activation (effect unclear)

Effect of SAF on warming from aviation induced cloudiness depends on the balance of these competing effects (while accounting for uncertainties of each effect)



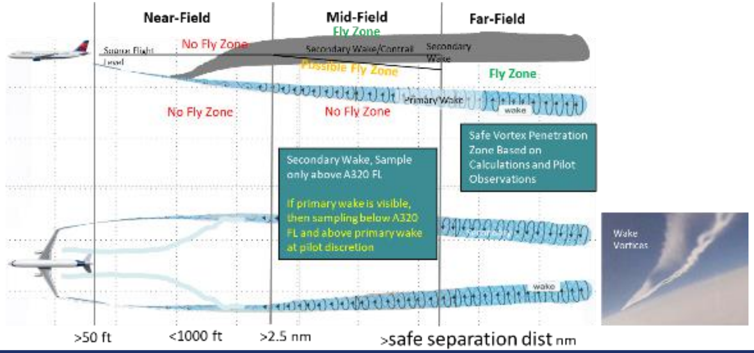
Fuel	Aromatic (vol%)	Naphthalenes (vol%)	Hydrogen (mass%)	Fuel Sulfur Content
Jet A1	17.2%	1.83%	13.7%	0.135%
SSF1	11.4%	0.82%	14.4%	0.057%
SAF1	8.5%	0.61%	14.4%	0.007%
SAF2	9.5%	0.05%	14.5%	<0.001%

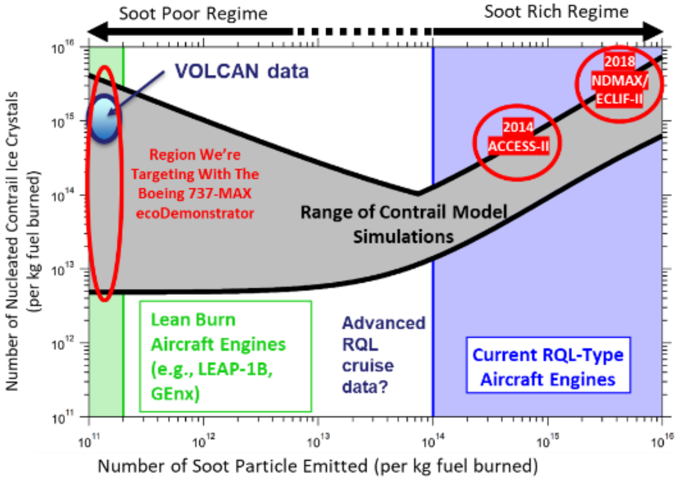
Voigt et al., Communications Earth & Environment, 2021
https://doi.org/10.1038/s43247-021-00174-y.

A02: Contrail/Emission Measurements

Objective:

1. Evaluating engine technology impacts on NOx Cruise and nvPM (advanced RQL, Lean Burn, etc)
2. Quantify the influence of fuel composition on the emissions characteristics of the component combustor (SAF vs JetA);
3. Characterize engine emission for cruise/full flight NOx
4. Evaluation, verification and validation of cruise and performance based NOx and nvPM emissions modeling methodologies
5. Measure Water Vapor, Temperature, & Humidity for Contrails to inform Contrail Modeling including varying fuels.





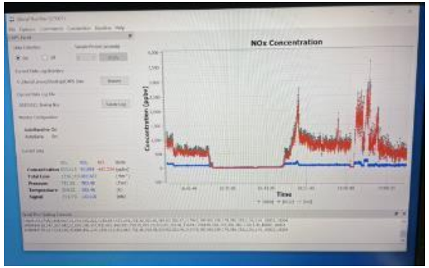
Challenges/Future

- Lube Oil emitted from oil system vent: Not combustion; Not regulated and Manufacturers have different venting strategies and levels (oil separator upstream of vent)
- Fuel Sulfur Content (FSC) - SAF essentially FSC=0; Very difficult to avoid contamination with Jet A

Emission/Contrail Campaign – Oct 2023

eco Demonstrator PROGRAM

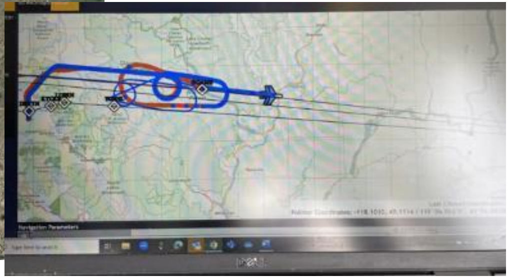
- Past Boeing 787 and 777 (GE and RR engines) – 2022; 737 (Leap) - 2021
- Goal to quantify on-wing emissions relevant for contrails & air quality
- Ultra-low-emitting CFM LEAP-1B engines on a Boeing aircraft
- Four fuels: 100% SAF, Jet A, 2 blends
- Test covers the range of engine thrust conditions from engine idle to takeoff
- Burning 100% SAF in the LEAP-1B engines should give us the lowest possible emissions achievable with in-service technology!
- New Humidity Sensor, NOx, nvPM, and Contrail measurements

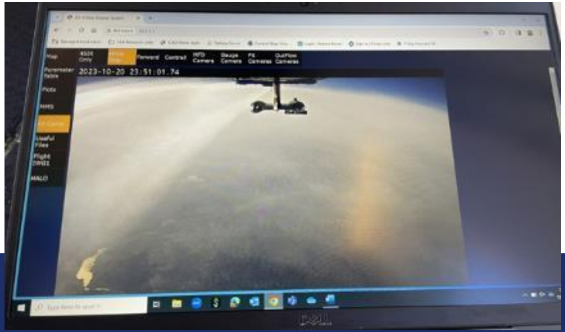


Aerodyne Research, Inc. Canada NRC·CNRC Missouri S&T DLR Deutsches Zentrum für Luft- und Raumfahrt Massachusetts Institute of Technology Transports Canada U.S. Department of Energy NASA Federal Aviation Administration

Emission/Contrail Campaign – Oct 2023

- **11 science flights, 9 of them are considered for the rest of the analysis**
  - 6 flights over the red route (Montana)
  - 3 flights over the blue route (coast)
  - In 6 cases, background cloud cover makes analysis using geostationary imagery only difficult
- **We cannot separate the 737 contrail from the DC-8 contrail**



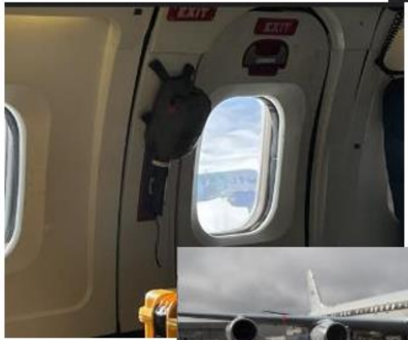


Emission/Contrail Campaign – Oct 2023









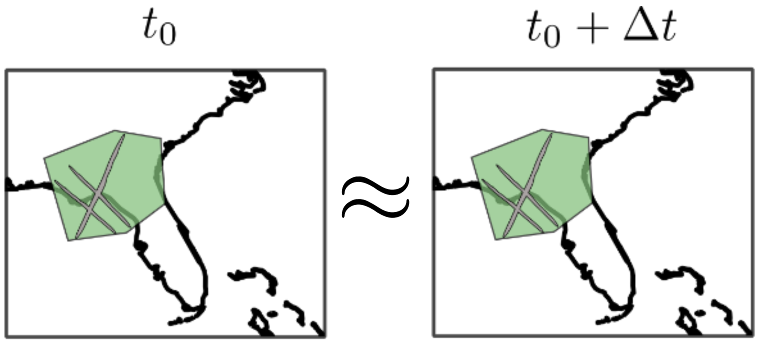


Contrail Avoidance Support Tool (CAST)

- **CAST provides an observation-based near real-time forecast of contrail forming regions**
- **It relies on geostationary satellite imagery (available every 5 minutes) to identify current contrail coverage both horizontally and vertically**
- **The forecast is valid at short lead times:**
- ***"where we currently see persisting contrails, we expect that another flight flying through the same region would also form a persistent contrail"***

MIT LABORATORY FOR AVIATION AND THE ENVIRONMENT

Sample vertical deviation:



•Example forecast: detected contrail in gray, avoidance region in green. The region is considered stable over the forecast lead time

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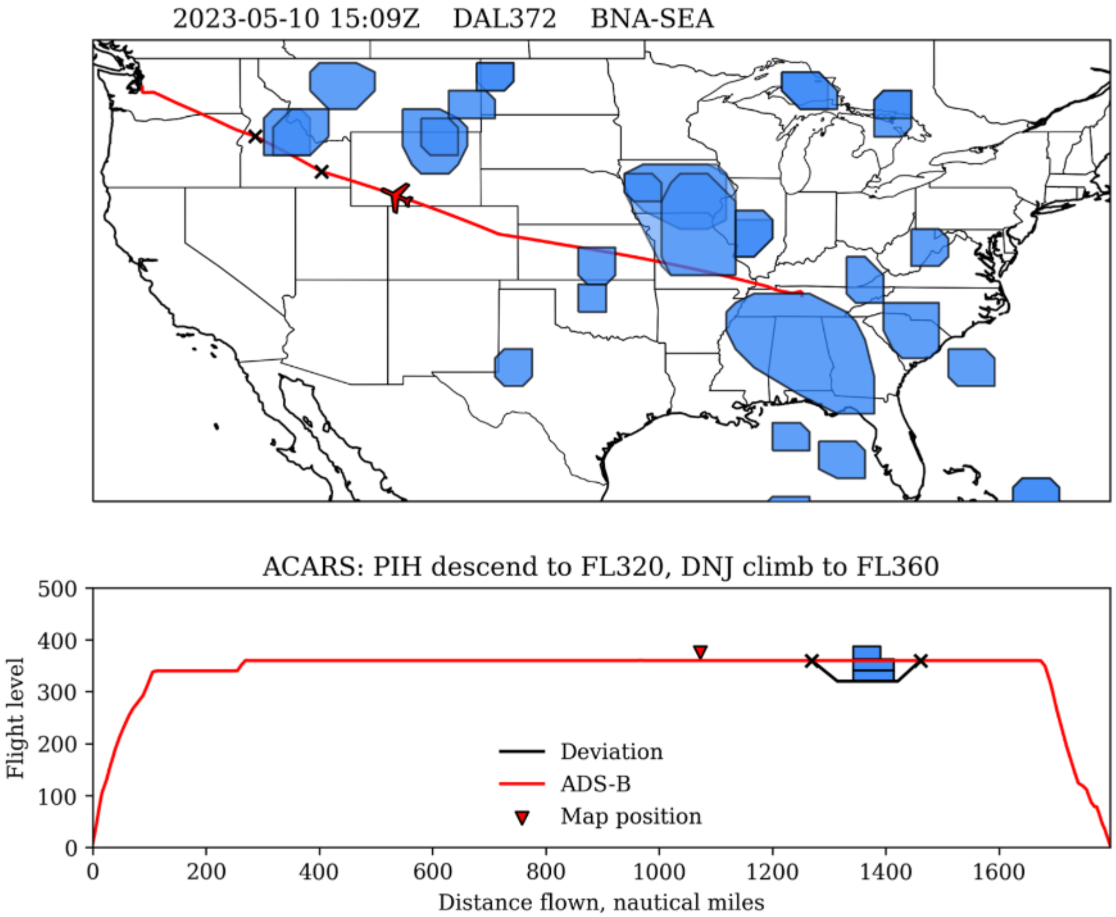
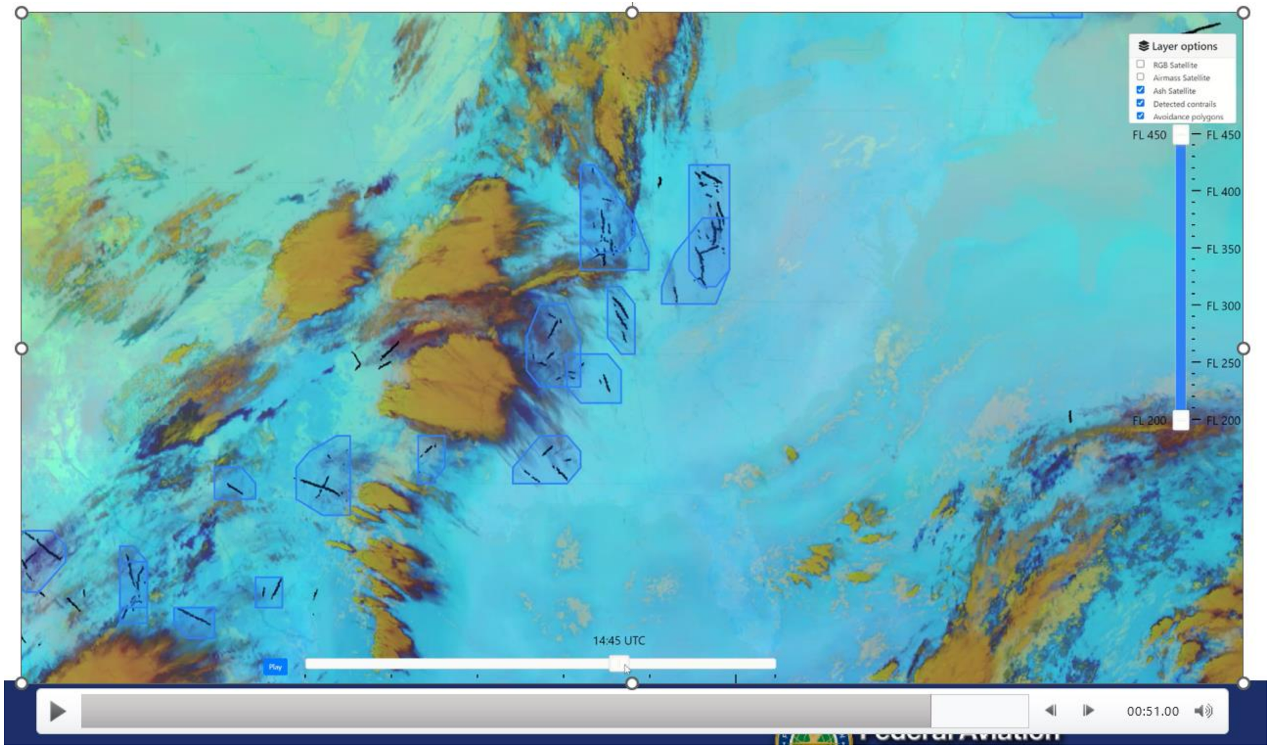
Tool integration: prediction step

Opportunity identified with
30 mins lead time



Contrail Avoidance Support Tool (CAST)



Flight #1: Preliminary modeling

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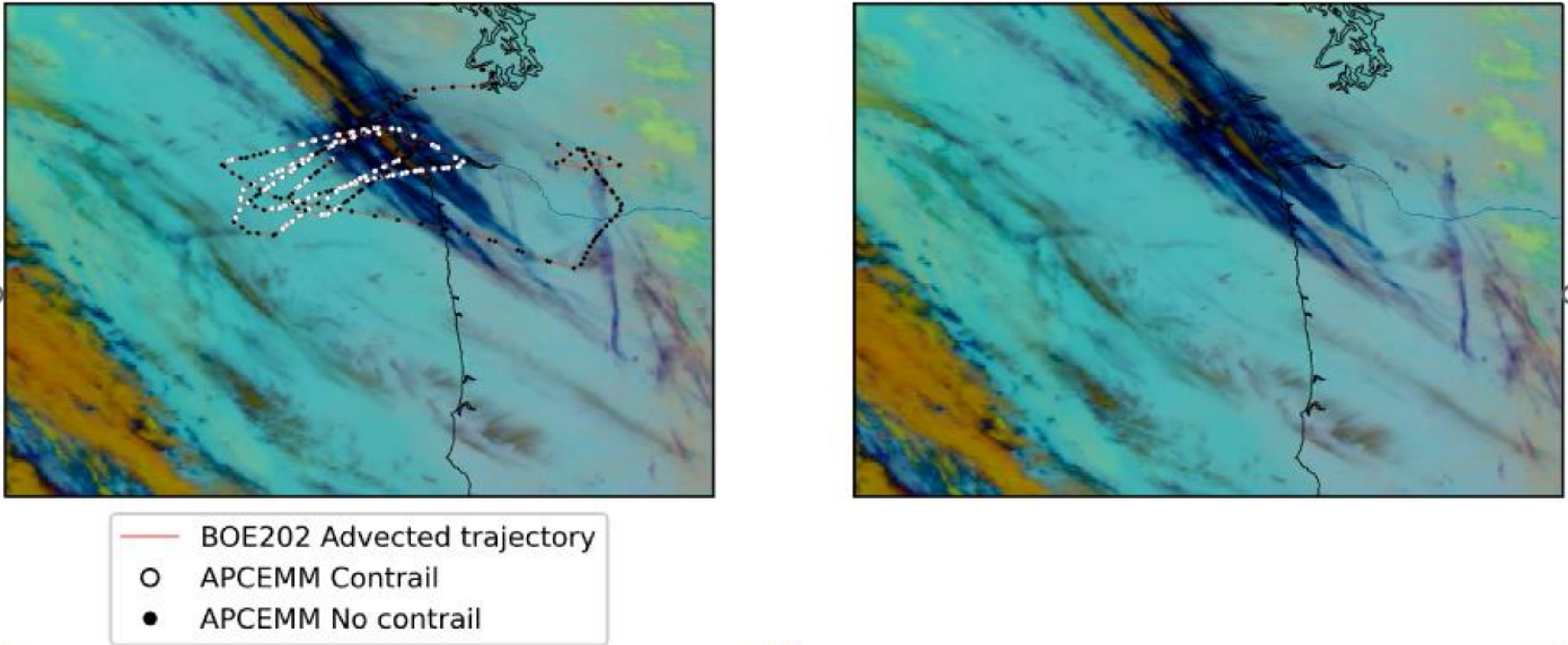

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Researching Technologies

CLEEN Program:

- Low-Emissions Combustor Technology Development for direct nvPM/NOx reduction
- Aircraft technologies for overall fuel burn/CO2 reduction:
- Engine core, nacelle, fan and bypass technologies
- Airframe and aircraft systems technologies

ASCENT Grant Research:

- Fuel injector design to reduce nvPM
- Low Emissions Pre-Mixed Combustion Technology
- Combustion concepts for next gen engines to reduce fuel burn & emissions
- Other research focused on overall fuel burn / efficiency of aircraft

Engine Emission Measurements

- Combustor and Engine Transfer Functions
- New Technology emission production w/SAF, Low Sulfur, Traditional Jet A
- Lube Oil/nvPM for different engine designs

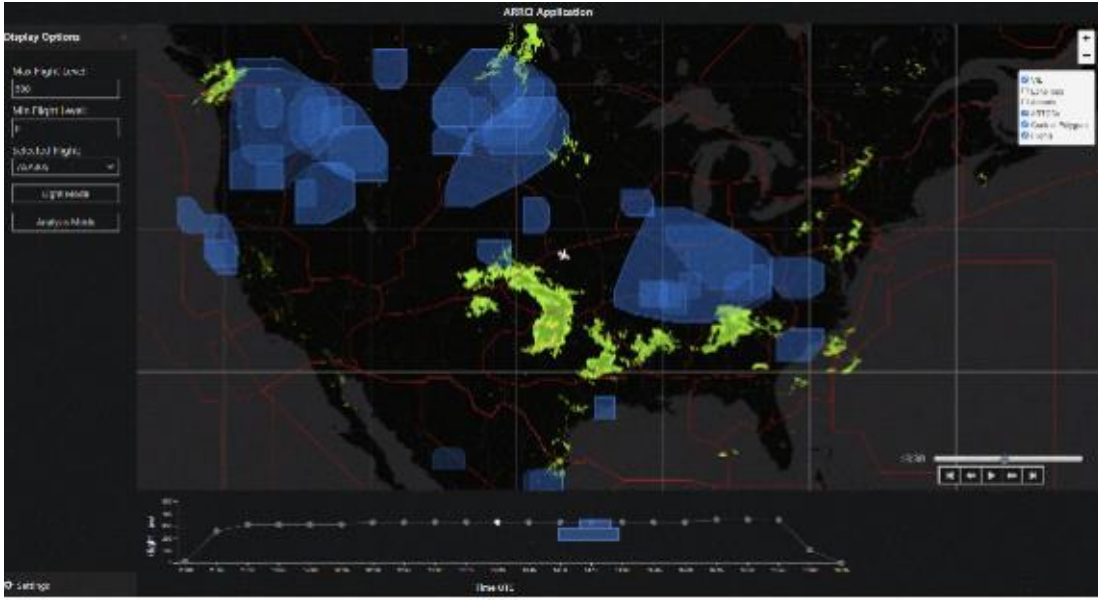
Novel lean premixed prevaporized combustor for CST, has been build, tested, and characterized at engine-relevant conditions

Contrail Avoidance – Operational Implications

- **Various decision-making models under exploration: pre-tactical (flight planning), tactical (in-flight), combination**
- **Airline-centric**
  - Airline tools identify contrail forming regions and route adjustments
  - Allows for optimization in consideration of airline business objectives
  - Narrow, single flight perspective and decision-making
- **Air Traffic Control-centric**
  - System-wide perspective and control
  - Limited airline data visibility

- **How do these operating models impact ATC procedures, workload, safety, etc.?**
- **What protocols or decision support tools would need to be designed and implemented?**

Stakeholder Engagement / Operational Trial



- Engagement is needed with FAA operational stakeholders (ATO/ANG) to identify operational gaps & user needs and explore potential for operational trial
- MIT Lincoln Lab and MIT campus are developing a prototype ATC/airline decision support tool for contrail avoidance
  - Experienced in contrail sensing, forecasting & ATC decision support prototyping
- AEE is working with MIT LL to conduct air traffic stakeholder outreach and identify next steps

Continued FAA Activities

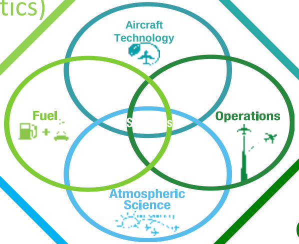
- **Continuing to connect FAA program outcomes** (CLEEN, ASCENT, and FAST)
- **Validating contrail models** (with DLR = need data use agreement)
- **Monitor international research & regulatory initiatives** (MRV, etc)
- **Interagency collaboration – DOE & NASA** (bring in NOAA, DOD & create contrail roadmap)

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

Phases of contrail formation

Jet phase (~1 s)

- Start of ice nucleation on soot particles due to excess water introduced by the engine exhaust

Vortex phase (~100 s)

- Mixing of ambient air with the plume wake
- Ice particles persist if ambient air is sufficiently humid (RH_i >100%)
- Growth of ice particles in the wake

Dispersion phase (~minutes to hours):

- Ice particles growth
- Wind-shear driven growth of the contrail
- Ice particles settling and evaporation
- ***This is where most of the radiative forcing impacts happen***

Weather Forecast Models Predict Contrail Conditions

Common to express contrail forming conditions in terms of temperature:

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

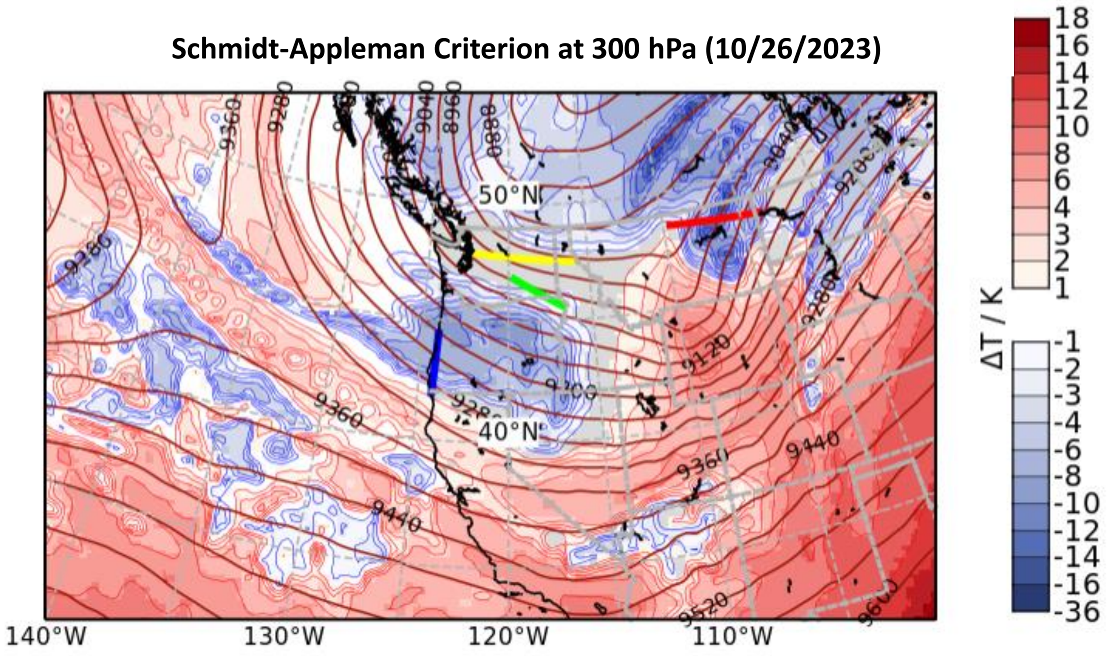
where $T_{ambient}$ = ambient temperature
and T_{SAC} = warmest contrail temp.

$\Delta T > 0$ indicates no contrails

$\Delta T < 0$ indicates contrail formation

Gap: T, RH Accuracy

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



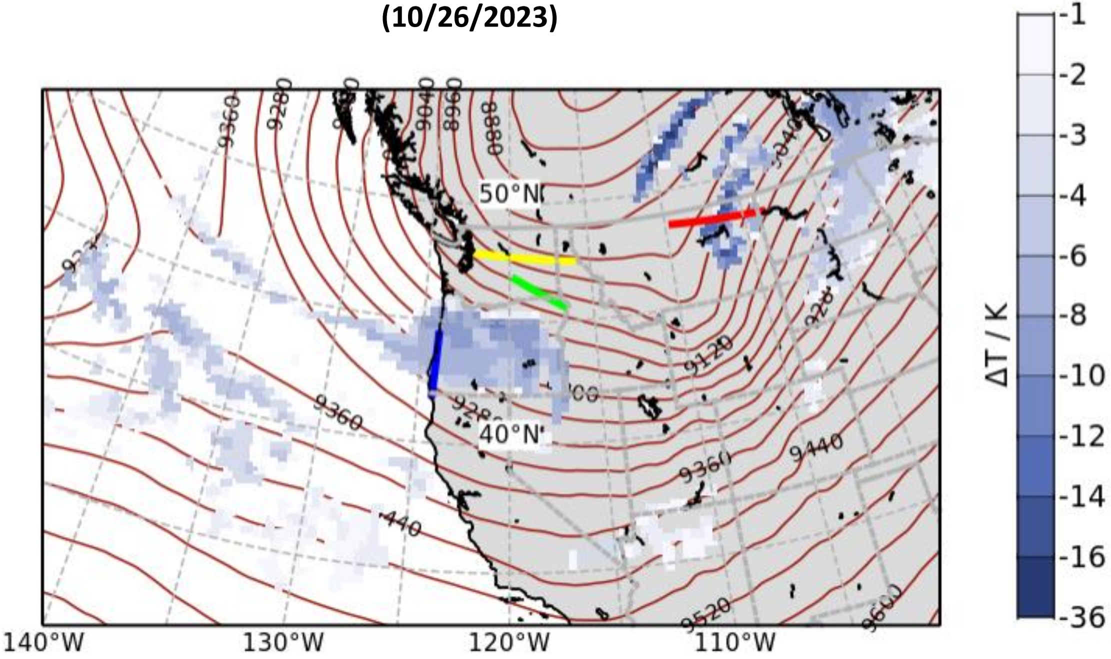
ECMWF Forecast of Schmidt-Appleman Criterion Courtesy of DLR

Weather Forecast Models Predict Contrail Conditions

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

Gap: T, RH Accuracy

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



ECMWF Forecast of Schmidt-Appleman Criterion Courtesy of DLR

Contrail formation phases

Jet phase

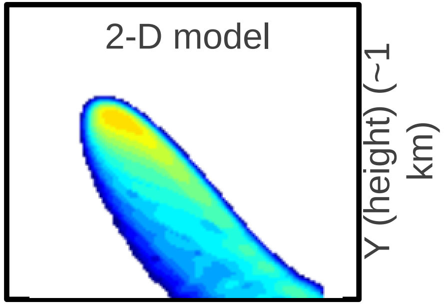
Vortex phase

Dispersion phase

The APCEMM model:

Box model with parametrizations for computational efficiency

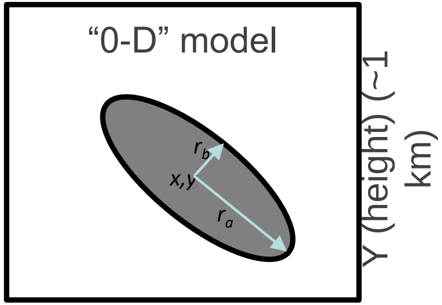
Explicit simulation of the cross-section:



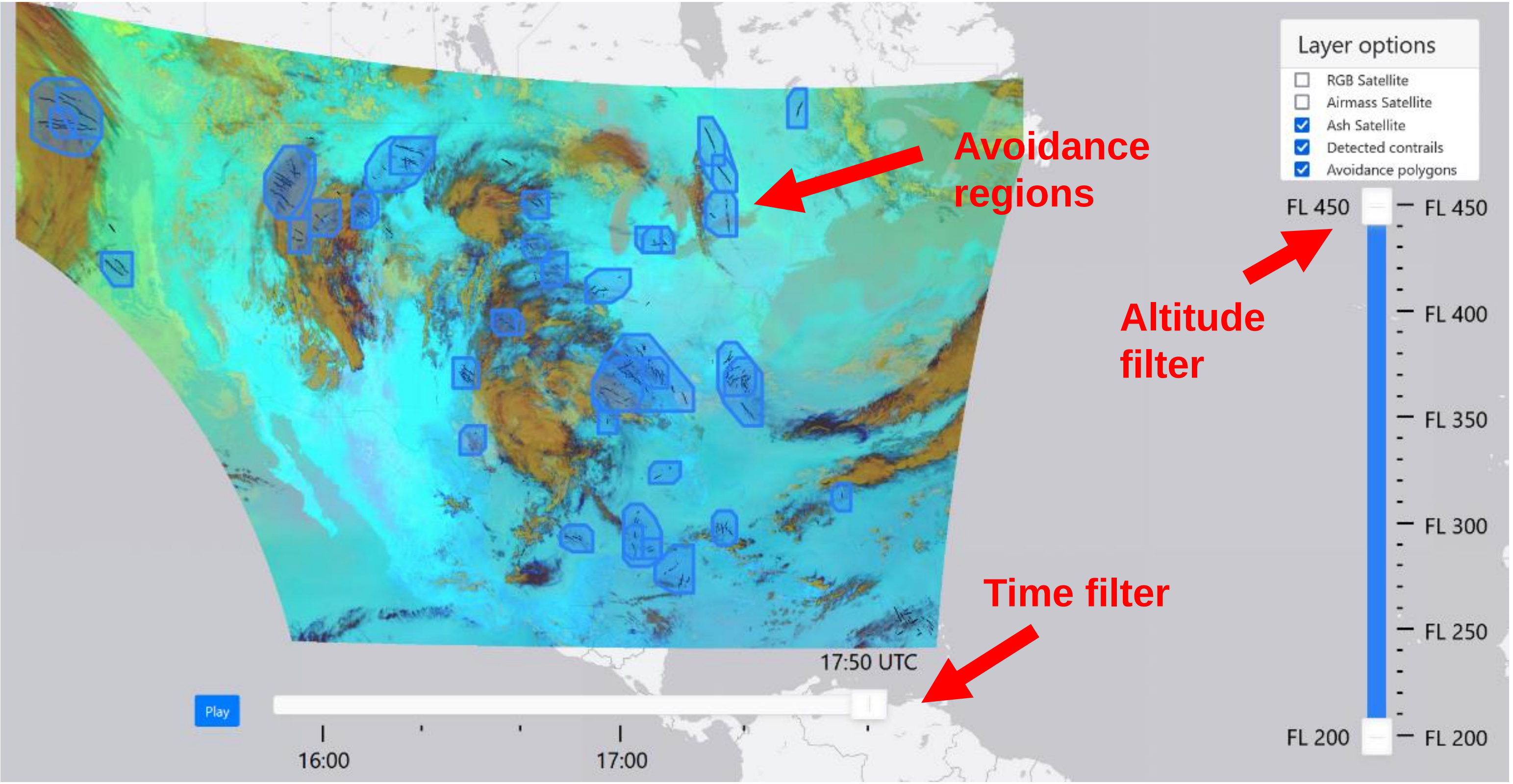
Other models:

Gaussian plume model:

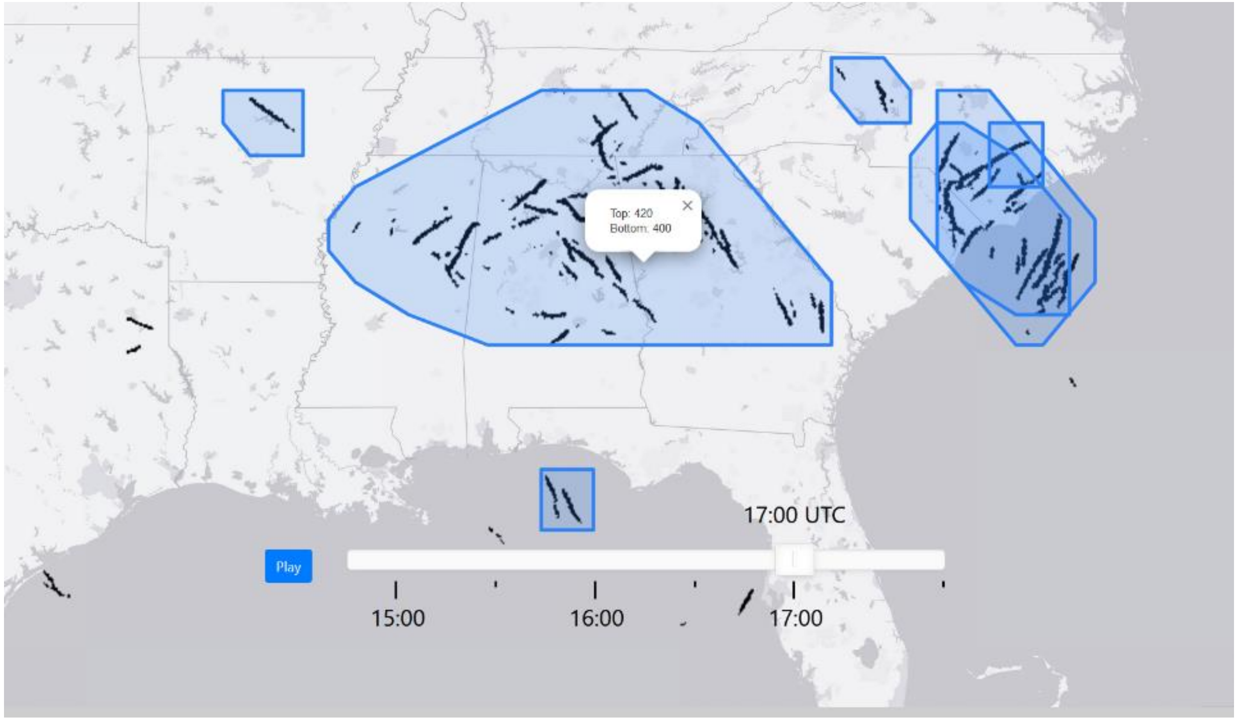
- Shape is assumed to be controlled by a centroid and 2 radii



Tool Layout


Layout options
RGB Satellite
Airmass Satellite
Ash Satellite
Detected contrails
Avoidance polygons
Avoidance regions
Altitude filter
FL 450
FL 400
FL 350
FL 300
FL 250
FL 200
Time filter
17:50 UTC
Play
16:00
17:00

Observational 3D identification of contrail forming regions



Making the CFR forecast robust

- Increasing robustness at the contrail detection level can be achieved through Kalman filtering of individual contrails
- CFR recommendations can be restricted to those which are high-confidence and stable over time