Contrail Modeling, Measurements, and Mitigation

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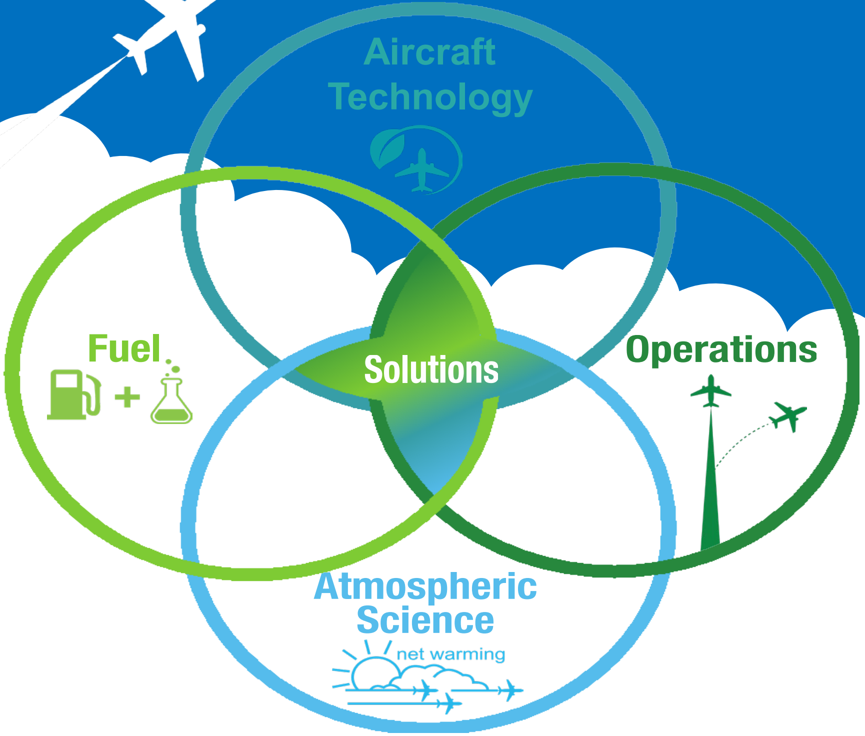
Federal Aviation Administration

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.



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 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

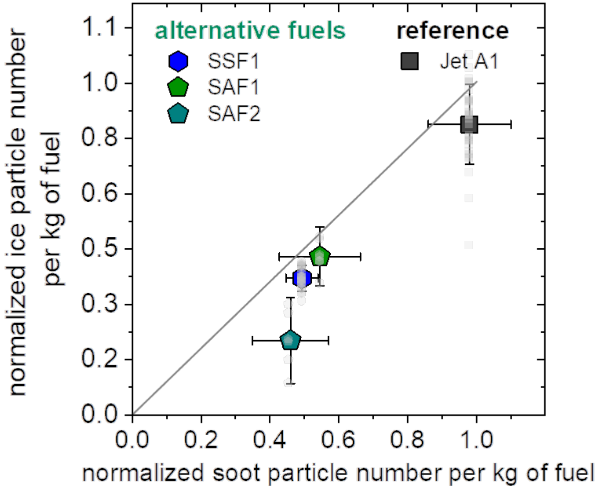
CLEEN Program; ASCENT 74 & 98

Aviation Induced Cloudiness 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%

AEE focuses SAF efforts across four pillars

Testing

Evaluate SAF performance

- Improve testing methods
- Conduct fuel evaluation
- Streamline ASTM Intl. approval

Analysis

Enhance environmental, economic sustainability

- Lifecycle emissions
- Cost reduction
- Production potential
- Supply chain opportunities

Coordination

Enable SAF development, deployment

- Public-private partnership – *CAAFI*
- U.S. interagency cooperation – *SAF GC*
- International cooperation – *ICAO*

• Deployment

•Build production, transportation, blending and storage infrastructure to enable SAF scale-up

•Grants – *FAST*

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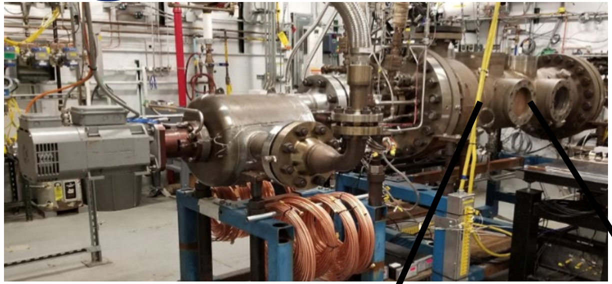
Researching Technologies

CLEEN III Grant Research:

- 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

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

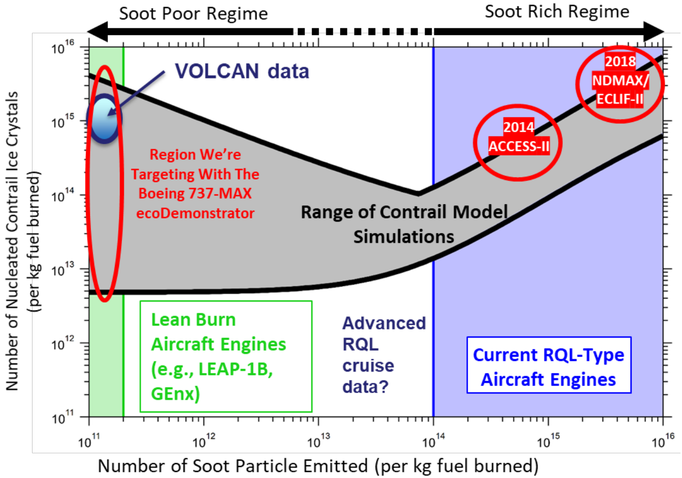
Engine Emission Measurements

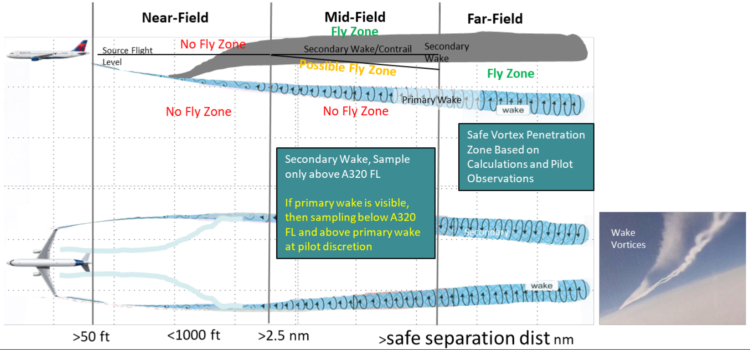
- Combustor and Engine Transfer Functions
- New Technology emission production w/SAF, Low Sulfur, Traditional Jet A
- Lube Oil/nvPM for different engine designs

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

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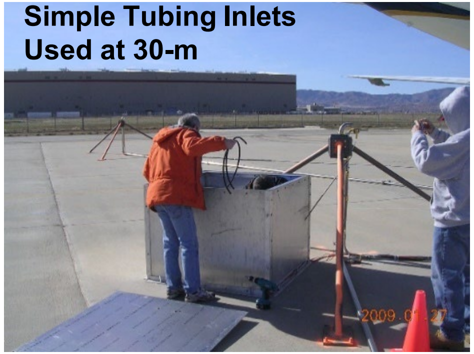
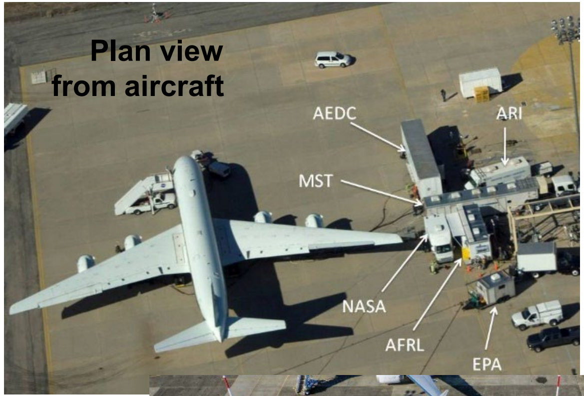
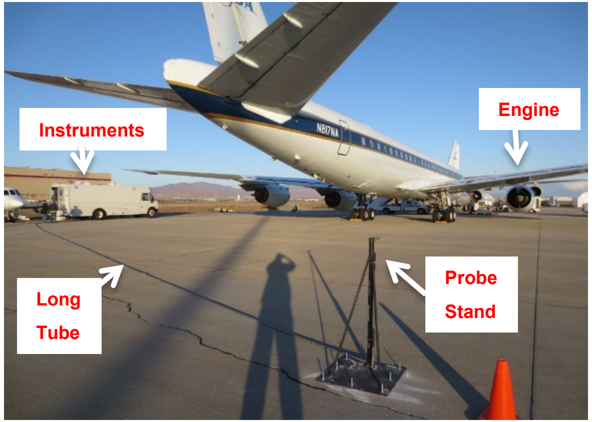
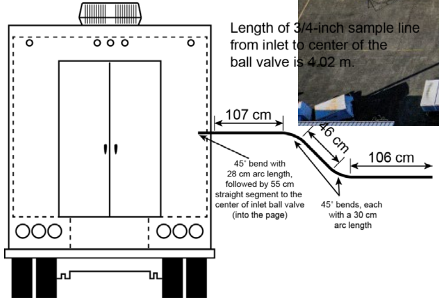
Emissions Measurements
1. Rig & 2. Ground Testing









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***

Contrail formation phases

Jet phase

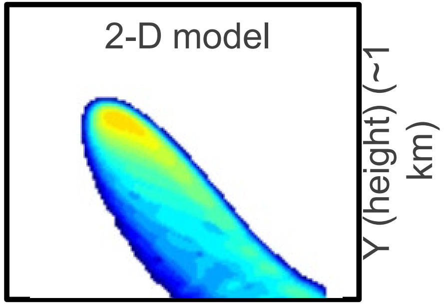
Vortex phase

Dispersion phase

The APCEMM model:

Box model with parametrizations for computational efficiency

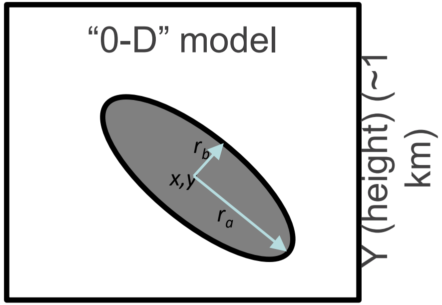
Explicit simulation of the cross-section:



Other models:

Gaussian plume model:

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



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"***

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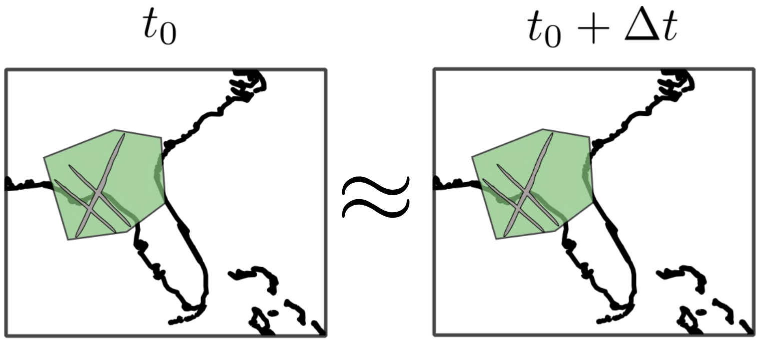
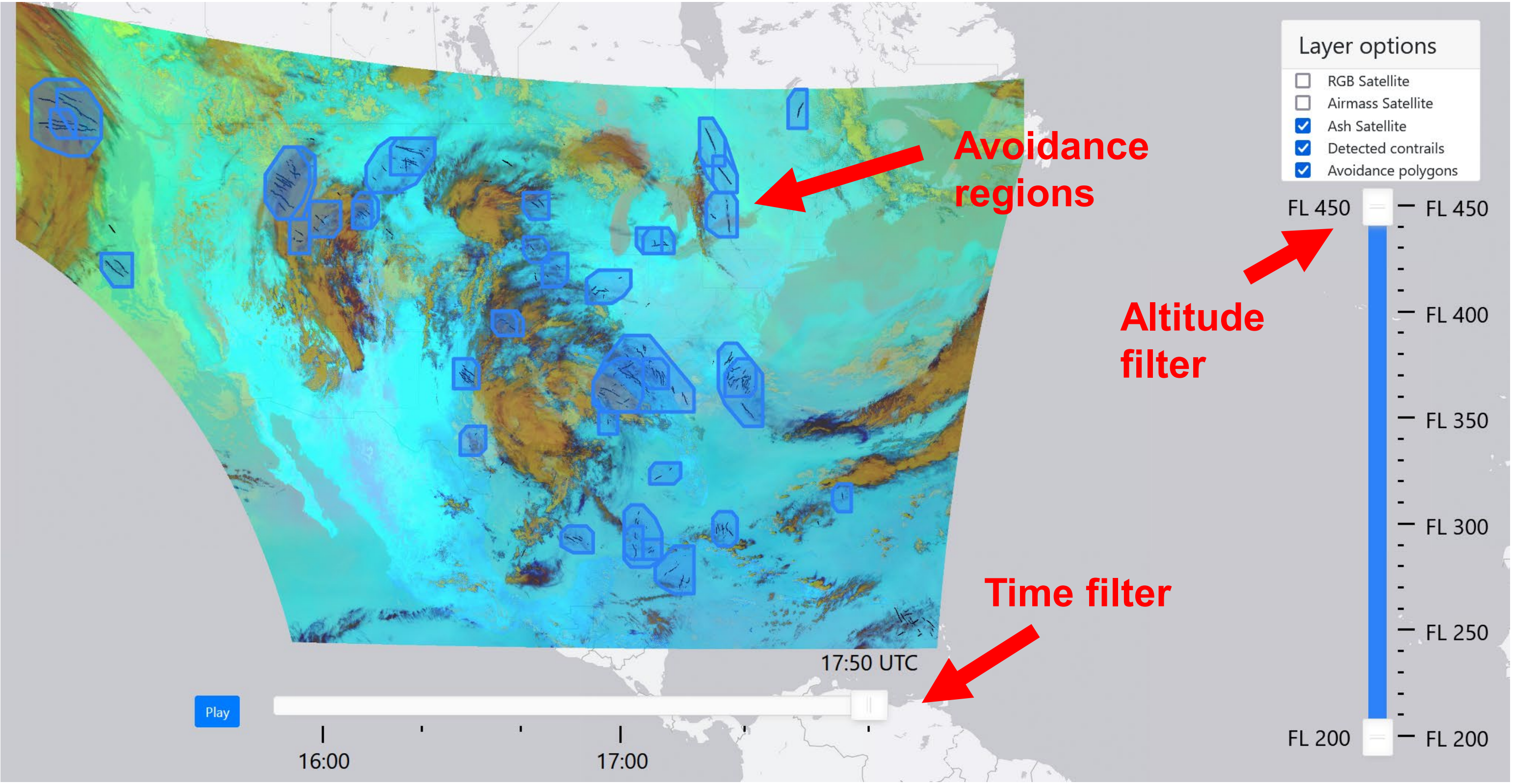
Sample vertical deviation:



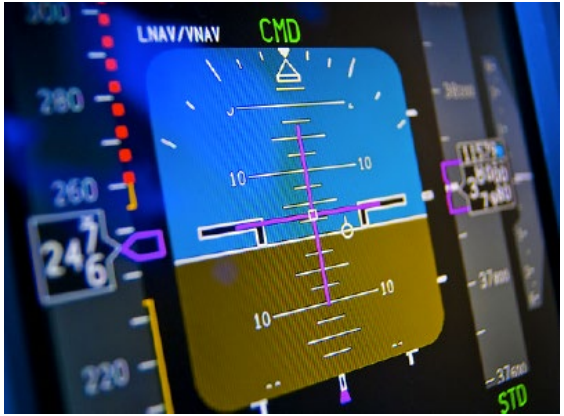
•Example forecast: detected contrail in gray, avoidance region in green. The region is considered stable over the forecast lead time

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

Contrail Avoidance – Operational Implications



- **Various decision-making models under exploration: pre-tactical (flight planning), tactical (in-flight), combination**

- **Participating in multiple groups considering operational implications:**
  - Contrail Impact Task Force (RMI, Breakthrough Energy, Alaska, American, Southwest, United, Virgin Atlantic, Airbus, Boeing, Flightkeys, Google Research, MIT, Imperial College London, and others)
  - CAEP Working Group 2 (Airports and Operations) Task: Operational Opportunities to Reduce Contrails
  - US-Europe ATM R&D Seminar

Considering an AIC – ATC Trail

Stakeholders

ATC – specific enroute facility (maybe Boston Center - ZBW)

Airlines – pick specific airlines (American, United, Delta, and/or SWA)

Tool Development – MIT LL and MIT Campus (maybe Google/Breakthrough Energy if needed)

Scientists – AEE, MIT Campus (Validate APCHEMM and CAST, plus determine RF)

Leadership – present findings, determine follow on or implementation in the NAS

Potential Outcomes

- Controller Workloads: how this differs from Convective Weather and Turbulence
- Safety implications: Sector Loads/Changes – outside of Convective Weather and Turbulence
- Reduction or change in AIC
  - Increase/Change in Fuel Burn
  - Non-CO2 and CO2 implications
  - Radiative Forcing
- Tools Validation and Need updates; integration into facilities
- Coordination with Airlines

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