Contrail and Emissions Flight Research with Bio & Petroleum Jet Fuels at the NRC

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Outline

• Description of research, notably
  • PERD AEEM, 2010-2012
  • NASA ACCESS II, also flights before & after, 2014-2015
  • GARDN CAAFCER, 2017
• Experimental method & conditions
• Results & discussion
• Some conclusions
Acknowledgements

- Environment Canada, with sensors (CN7610, Peter Liu, Nox, Jason O’Brien, FSSP, Alexei Korolev, Mohammed Wasey)
- NRCan OERD for PERD AEEM
- NASA for ACCESS II, international collaborative flight research;
- Transport Canada, International Aviation, sponsor for NRC participation in ACCESS;
- NRC for Program support.
- GARDN for CAAFCER, NRC also (APDT program)
- NavCanada as the enabler
Petroleum & Biofuel contrail flight data

Research raison d’etre (evolution)

• Contrail physical processes research:

• PM effects upon GW (ICAO Environmental Report, 2016)
  • direct –
    • black carbon,
    • volatile
  • Indirect (secondary) –
    • RF of spreading contrails (transformation to cirrus; ‘invisible’ ice particles, FAA AEC)
    • Biofuel effects thereupon, NRC flight priority
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NRC CT-133, HAARC research aeroplane

- wing glove on port wing - 600 Hz aerofoil surface pressures at 24 chordal points, measuring unsready air loads in wake vortices

- CO2 (LICOR 840A) plus WVap providing Total Water Content
  - 2 Hz

- airdata 600 Hz

- NRC Particle Detector Probe 600 Hz

- IMU 600 Hz

ice contamination in Great Lakes environment (not in ACCESS II) - forward-facing intake re-designed, provides ice particle separation from LiCor air-stream - enabling water vapour measurement in two-phase atmosphere.

- NII200 (operated with isokinetic)
  - 20 Hz, but sparse data

- FSSP-100
  - >0.5 µm

- isokinetic inlet for 7610 CNC
  - > 10 nm

- gaseous inlet for NOx (1 Hz)

- intake forward-facing, for analyser flow, on ACCESS II (occasional icing) - returned aft-facing

- replaced by LII300 - CW data stream at 20 Hz

- improved HS calibration, simplified plumbing and an airflow meter downstream of the optical cell.

2016ff

- 2016 - new option: ultrafine CPC (>2.5 nm) and denuder for nvPM classification
T-33 Emissions Measurement Projects (to-date)

• 2012
  • **Project AEEM**: Heavy jet transports on Jet A/A1
  • **Biofuel emissions**: 50% HEFA, 60% HEFA, 100% HEFA-SAK

• 2014
  • **NASA ACCESS II**:
    • Pre:- FSSP-100 contrails, B777
    • ACCESS II (DC-8): LS Jet A & HEFA 50%
    • Post:- Jet A / A1 contrails, Heavy jets

• 2015
  • Sensor development
    • LiCor inlet ice particle elimination
    • LII300 advanced BC (soot) sensor
    • NOy performance
  • 50% HEFA blend (GTL, 4 winters outdoors), 100% HEFA-SAK

• 2016 – proposals for 50% HEFA, ATJ, 100% HEFA-SAK

(Courtesy: ACCESS II project)
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PERD AEEM, Jet A/A1 emissions

- Heavy jet transports, Ottawa area (north), NAT & Polar
- CT-133 sensor (u/w pods) development
- Flight technique development
  - Technique development
    - Rested upon wake turbulence flight research
    - Spatial re-construction, regime differentiation
      - Integrate to give EI (autonomous)
- CN data
Petroleum & Biofuel contrail flight data

CN Ein behaviour downstream:—variation if Ein with wake length

ACCESS II DC-8 on low sulphur JP8
Petroleum & Biofuel contrail flight data

NASA ACCESS II, Alternate Fuels Emissions, 2014

- Bruce Anderson, PI;
- International collaborative flight research
  - NASA
    - DC-8 emitter
      - Low sulphur (LS) Jet A
      - 50% blend LS Jet A and hydro-treated ester fatty acids (HEFA) biofuel
    - Guardian, emissions/contrail sampler
  - DLR
    - Falcon 20, emissions/contrail sampler
  - NRC
    - CT-133, emissions/contrail sampler
- Results & discussion
Emissions Plume Dynamics – Three distinct Regions

• Upper Jet Wake: top remains at emitted level, bottom is drawn downwards in a stem, by the TWV (entrainment, then relaxes upwards as vortices decay)
  • region of persistent contrail development
• Trailing Wake Vortex: entrains 25-50% of emissions, which then detrains as the TWV decays downstream
• Lower Viscous Wake: remains low, falls-out eventually; little contrailing

(Courtesy: AEEM project – B&$& contrail)
NRC’s T-33 Contributions to NASA’s ACCESS II

• Measure emissions plumes in climb >10,000 feet, Jet A (low-sulphur, LS)
• At mid-30,000 fest, contrails, T33 measures contrail & emissions:
  • DC-8, Mach 0.8, LS Jet A
  • DC-8, M 0.8, 50% HEFA
  • DC-8, M 0.55, individual inboard engine emissions
    • #2, 50% HEFA
    • #3, Jet A
    • #2, Jet A
    • #3, HEFA
T-33 experimental flight methodology & Cross-Sectional Plume Reconstruction

- Fly horizontal & vertical/oblique traverses across emissions plume
- Group flight-track into sets of 6-8 traverses (2 ~ 3 min). For each, interpolate between traverses (the cross-plane) to construct contours of emissions/contrail species (e.g. re-constructed cross-section of contrail ice particle number density)
- Integrate the contour plot (per meter into the page) to get total no. of particles (or mass) per meter flight-track
Trailing wake vortex dynamics, heavy influence on DC-8 contrails:

Contrails (ice particle number & size distribution >1/2 µm) & wake vortex dynamics:

• **Vortex influence:**
  • Strong entrainment (approximately 50% of emissions at/below trailing vortex pair height)
  • High vortex-induced velocities
  • High vortex suction (gives rise to vortex condensation)
  • Meander together, attract each other, independently have short-wave elliptical instabilities
    • Axial gradients of instabilities strong
    • Taylor vortices of helical, surrounding vorticity likely
      • Therefore, expect over-circulation of vortex strength
  • Then detrains upwards as vortices decay > 20 nautical miles

• **Use for ‘anchoring’ the re-construction of the plume cross-section**
Other contrail characteristics:

- Falcon 20, DC-8 (previous)
- B777 (below left), persistent
- B767 (centre)
- A380 (right)

- All of which:
  - Atmospheric background
  - Jet Types
Trailing Wake Vortex Dynamics

Example of vortex core traverse flight-path

DC-8 trailing wake vortex core radius ($r_C$) vortex-induced air velocity, ($V_T$)

- $r_C$, 0.5 to 2 m radius (varies in funnel-features)
- $V_T$, 15-70 m/s (circumferential vortex elements)
- $P_s$, 0.5 kPa suction
Emissions Plume – Cross-sectional and Axial (near emitter) Plume Reconstruction

Ice particle number density
Cross-plane

Water vapour distribution (scavenged by ice particle formation)

Axial direction (i.e. side-view)

Emissions Plume – Cross-sectional and Axial (near emitter) Plume Reconstruction

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Axial direction (i.e. side-view)

Individual inboard engine, contrails & water vapour plumes (Courtesy: ACCESS II Project)
NRC’s T-33 CN Data Summary

• CN (>10 nano-m aerosol) data
  - Generally, some level of nucleation mode activation (in the plume stem & crown, of which the contrail sublimated by 1 nm– only trailing wake vortex contrail persisted to 15 nm)
  - Mean CN EIn 57% (with σ<13%) lower for 50% HEFA than for LS Jet A

Cross-section of CN plume

Vertical distribution of CN
BC Elm & contrail ice particle EIn relation (now available with LII300 data):

• Generally, increase in ice EIn proportional to BC Eim over a wide range of atmospheric & thrust level conditions
• Use, instead of CN EIn for contrail parametric improvement (previous slide)
• LII300 enough sensitivity to re-construct soot (BC) plumes, cross-sectional plume (which is, also, proportional to fuel-flow)
Parametric influences upon contrail ice particle number density (BC is one)

**Engine thrust influence:**

- CN emissions (left below)
  - Non-linear, but variety of conditions, contrails & non-contrails (latter has many additional particles, e.g. sulphates)
- FSSP ice particle number in contrail (below right)
  - Again, a variety of atmospheric conditions, but more direct association)
Ice particle EIn ~ background RH\textsubscript{ice}
Parametric influences upon contrail ice particle number density, cont.

Ice particle EIn ~ background Ts & RH lapse-rate (vertical gradient)

\[ FSSP-100 \text{ EIn } \sim T_S \]

\[ FSSP-100 \text{ EIn } \sim \frac{\partial RH}{\partial z} \]

\[ FSSP-100 \text{ EIn } \sim \frac{\partial RH}{\partial z} \text{ at survey vortex height (\%)} \]

\[ E_{In, PL} = a_0 T_S^{a_1} (\text{RH}_i)^{2/3} a_2 (\text{RH}_g) E I_{\text{CN}} \]

FA20, JetA1, 7/4/14
JetA, B773, 11/4/14
JetA, ACCESS
HEFA, ACCESS
JetA, B763, 25/6/14
JetA, A343, 27/10/14
JetA, A388, 4/12/14

ONE 4-eng M0.8 contrail survey
Petroleum & Biofuel contrail flight data

- **Contrail ice particle number density data:**
  - e.g. cross-section of contrail centred on TWV region (below right, contours to 1200 ice particles per cc)

- Parametric analysis suggests (below left) mean contrail ice particle EIn 51% lower ($\approx 1.5\sigma$) for 50%HEFA than for LS Jet A (requires confirmation, i.e. reduce data-set error):-

Ice particle size spectrum (below) has MED $\approx 1-3$ µm
Experimental uncertainty:-

Lump all into data-set standard deviations (σ), reasonable overall experimental errors, as no systemic biases (sensitive to ‘signal/noise’, SNR):

- **CN**: extremely high SNR (10^5)
  - EI between fuels, mean difference > 3-5 σ
  - ACCESS, Δ of -57% > 4.5 σ (13%)

- **NO_x**: moderate SNR (5), but sensor installation difficult
  - Maturity in 2015 (data grouping)

- **CO_2**: low SNR (1.02-2)
  - Use known EI of 3.16 kg/kg to iterate plumes (2-4 times)
  - data-set σ reflects experimental variability, ‘differences’ ≥ σ

- **H_2O vapour**: very low SNR (1.003) & ice contamination
  - Ice particles eliminated 2015, ready for future projects

- **BC**: low to moderate SNR (2-5)
  - Sensitivity improved, late 2015

- **Contrail ice particle**: high SNR (3-10^3)
  - Very sound measurement FSSP (Wasey calibrations)
  - Highly sensitive to background atmospheric condition
  - improve parametric grouping as Δ is 1-2 σ only
CONCLUSIONS for ACCESS II, NRC:

- FSSP-100, a valuable installation to the NRC CT-133, and has been used for measuring NRC Falcon 20 contrails, Heavy jet contrails, & NACA DC-8 contrails on NASA ACCESS II.
- NASA ACCESS II data-set, controlled back-to-back, dense ice particle numbers, 4-engine cruise, M0.8, non-persistent contrails
  - Sensitive to background atmospheric conditions
- DC-8 LS Jet A & HEFA-blend contrails, when power-law parameterised, shows 52% reduction in par-mean FSSP-100 ice particle no.; however difference is only 1σ.
- Hence, further flight experiments, back-to-back, Jet A & HEFA, ATF & other biofuels needed to improve the statistics; might be a promising fuel-related reduction in contrails, due to their radiative forcing effect.
GARDN project CAAFCER (2016):
Waterfall Group, Air Canada, Sky NRG, UAlberta, Boeing, NRC

- Motivation – further data, different atmosphere, UJW dominated contrails
- Instrumentation – ultrafine aerosols from UAlberta CPC3776 + denuder (Jason Olfert)
- HEFA/Jet A1 (Alt-Air, cooking oil/tallow)
- Flights conducted, 20th April to 11th May

- Data analysis
  - In-progress
  - Release by Apr 2018
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**CAAFCER flights:**

- CT-133 intercept at TOPC
- CT-133 break-off at TOPD (30-40 nm back)
- typ. prevailing wind

CT-133 break-off after TOPD
### Petroleum & Biofuel contrail flight data

#### CAAFCER flights:

<table>
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<tr>
<th>Date, 2017</th>
<th>Flight, YUL-YYZ (43% HEFA/JetA1)</th>
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Petroleum & Biofuel contrail flight data

CAAFCER flight, contrail example, A320 (stem/crown dominated):
Petroleum & Biofuel contrail flight data

CAAFcer biofuel contrail, A320 (stem/crown dominated): (1) c.15 nm
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CAAFCER biofuel contrail, A320: (2) 20 nm
Petroleum & Biofuel contrail flight data

CAAFCER flight, contrail example, A320: (3) 25 nm, transformation of the crown to cirro-cumulus
Petroleum & Biofuel contrail flight data

CAAFCER flights, preliminary data (subject to change), CN:

![Graph showing data points for different fuel types and flight conditions.](image)

- Falcon, JetA1, flight #8
- "", JetA1, flight #8
- "", 50/50, flight #8
- "", JetA1, flight #6
- "", 60/40, flight #6
- "", JetA1, ARA flt
- "", ReadiJet
- DC8, JetA, ACCESS
- DC8, HEFA, ACCESS
- CAAFCER, JetA1
- CAAFCER, HEFA, 25th April
Petroleum & Biofuel contrail flight data

**CAAFCER flights, preliminary data, FSSP EIn & EIm:**

- Below is one biofuel contrail (5 pts) + three JetA1 contrails (1 pt/each), range of altitudes
- Trend is JetA1 has higher FSSP ice particle # density & spherical ice mass than biofuel
- Both are substantially greater ACCESS II NRC data & other contrails near/North of Ottawa
Petroleum & Biofuel contrail flight data

CAAFCER flights, preliminary data, FSSP MVD size distribution, showing larger UJW growth rates (*left*) & EIn behaviour with age (*right*):

![Graph of contrail age and FSSP-100 EIn](image)

- **FA20, JetA1, 7/4/14**
- **JetA, B773, 11/4/14**
- **JetA, ACCESS**
- **HEFA, ACCESS**
- **JetA, B763, 25/6/14**
- **JetA, A343, 27/10/14**
- **JetA, A388, 4/12/14**
- **CAAFCER, JetA1**
- **CAAFCER, HEFA, 25th April**
Petroleum & Biofuel contrail flight data

CAAFCER flights, preliminary data, FSSP EIn with CN EIn:

![Graph showing FSSP-100 EIn ~ CN_EIn with data points for various flights and dates.]
Petroleum & Biofuel contrail flight data

CAAFCER flights, preliminary data, FSSP EIn with relative humidity (RH) lapse rate:

\[ \text{FSSP-100 EIn} \sim [\partial \text{RH}/\partial z]_{\text{back}} \]

- FA20, JetA1, 7/4/14
- JetA, B773, 11/4/14
- JetA, ACCESS
- HEFA, ACCESS
- JetA, B763, 25/6/14
- JetA, A343, 27/10/14
- JetA, A388, 4/12/14
- CAAFCER, JetA1
- CAAFCER, HEFA, 25th April
**Petroleum & Biofuel contrail flight data**

**CAAFCER flights, preliminary data, CPC (>2.5 nano-m), & non-volatile (nv) (uncorrected):**

- Ultrafine (>2.5 n-m), c.3x CN (>10 nm)
- c.95% ultrafine aerosols were volatile, leaving soot
Soot activation (from previous page)

- EIn ratio (FSSP/nvCPC) implies an average 10% activation, but varies widely, locally
- 10-14 nm (left) contrail length & 20-26 nm (right):
  - Activation values highest in contrail crown
  - Maximum values reduce with increasing contrail length
Petroleum & Biofuel contrail flight data

Future work

• Optical characteristics of contrails
  • Relating to RF (integrates sum of ice particles/shapes), <\sim 0.5\mu m
  • Extinction probe (Alexei Korolev, ECCC)
    • Already on NRC Convair
• 100% biofuel contrails
  • High H\(_2\) (GTL work, Pervez)
• Data analysis
  • Improved atmospheric correlations
Questions?

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