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

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2017 National Colloquium in Sustainable Aviation at UTIAS, June 21-23

Petroleum & Biofuel contrail flight data

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

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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

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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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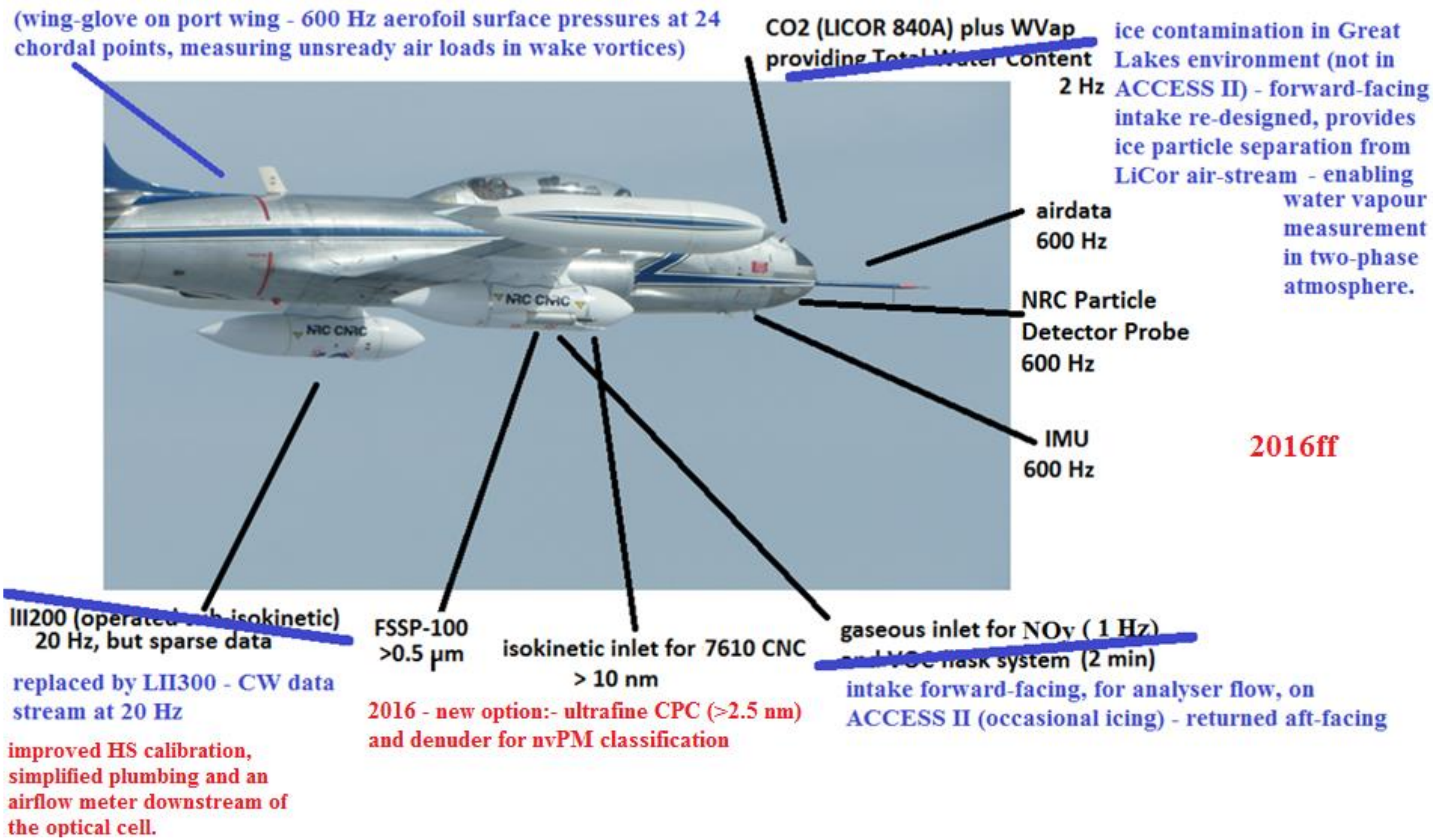
NRC CT-133, HAARC research aeroplane



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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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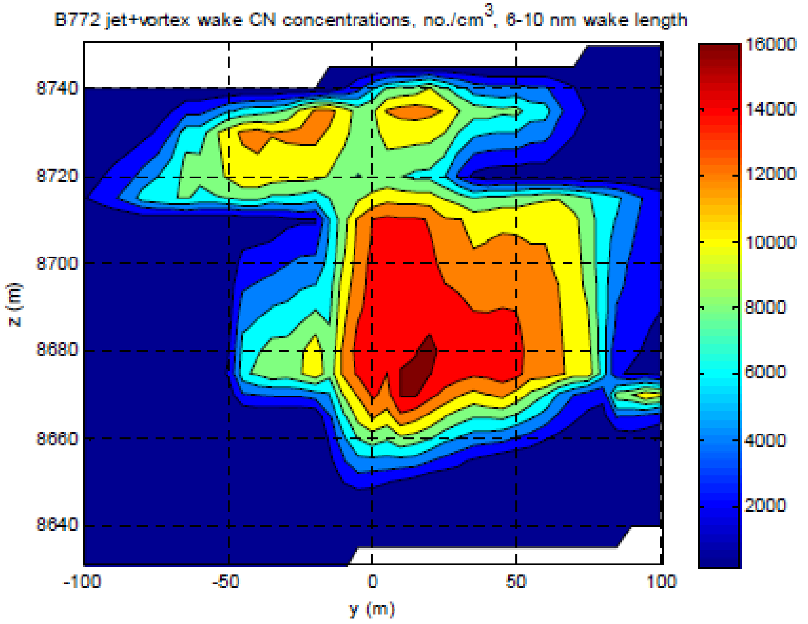
PERD AEEM, Jet A/A1 emissions

- 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



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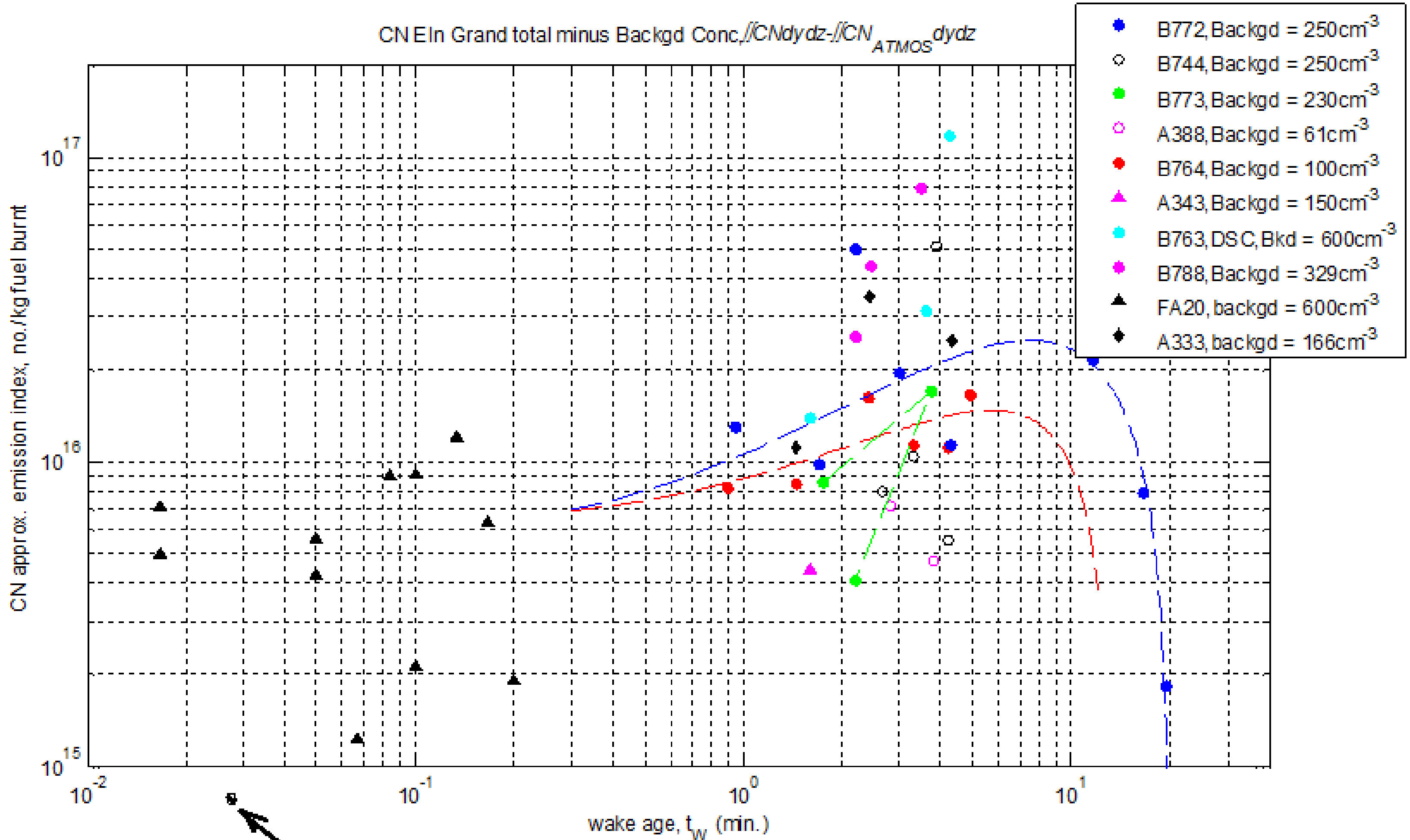
CN Ein behaviour downstream:-

–variation if EIn with wake length



ACCESS II DC-8 on low sulphur JP8

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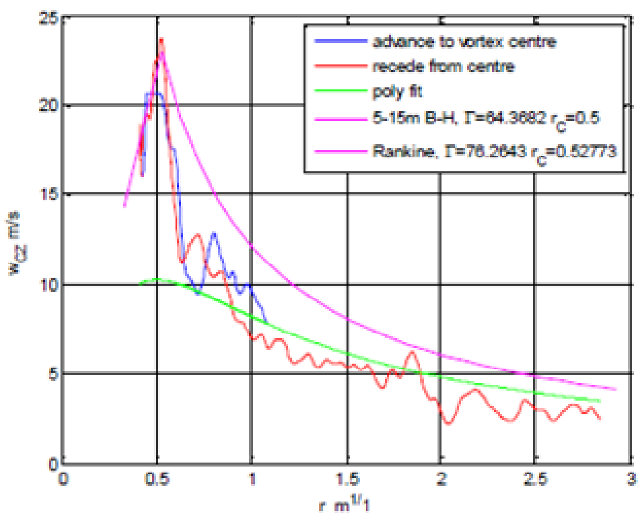
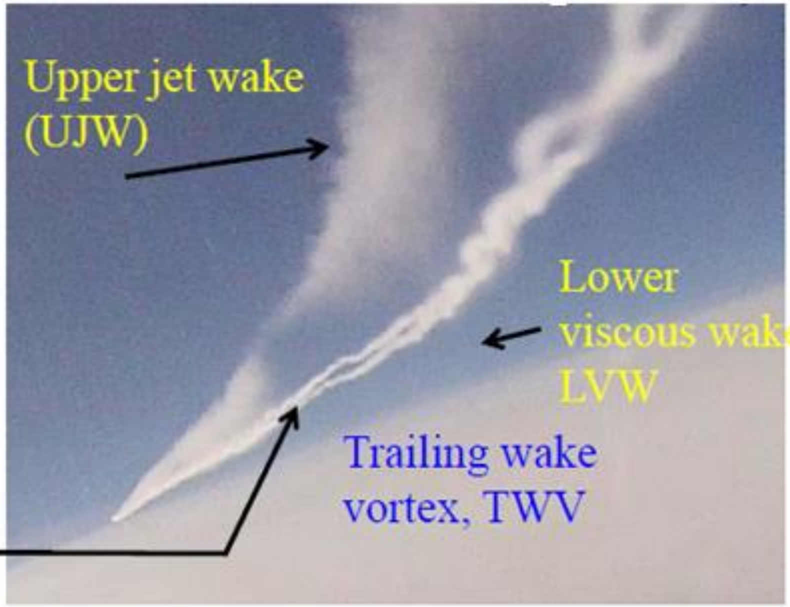
NASA ACCESS II, Alternate Fuels Emissions, 2014

- 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)

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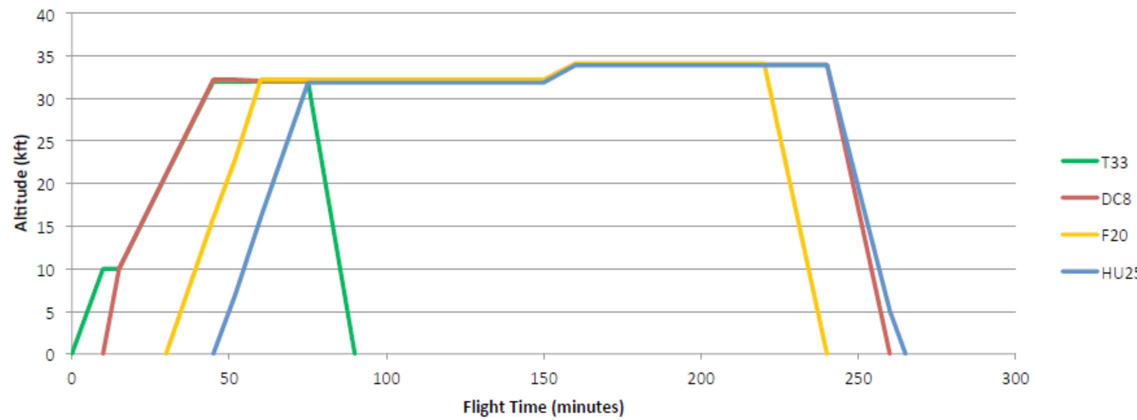
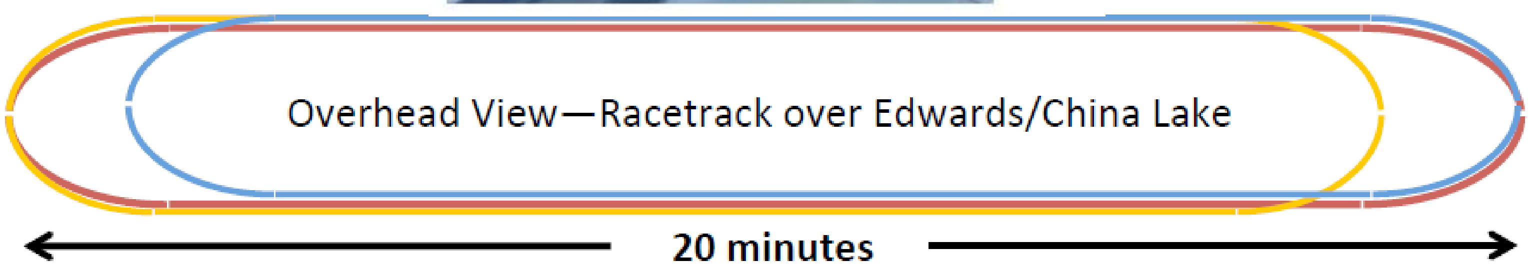
NRC's T-33 Contributions to NASA's ACCESS II

- **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**





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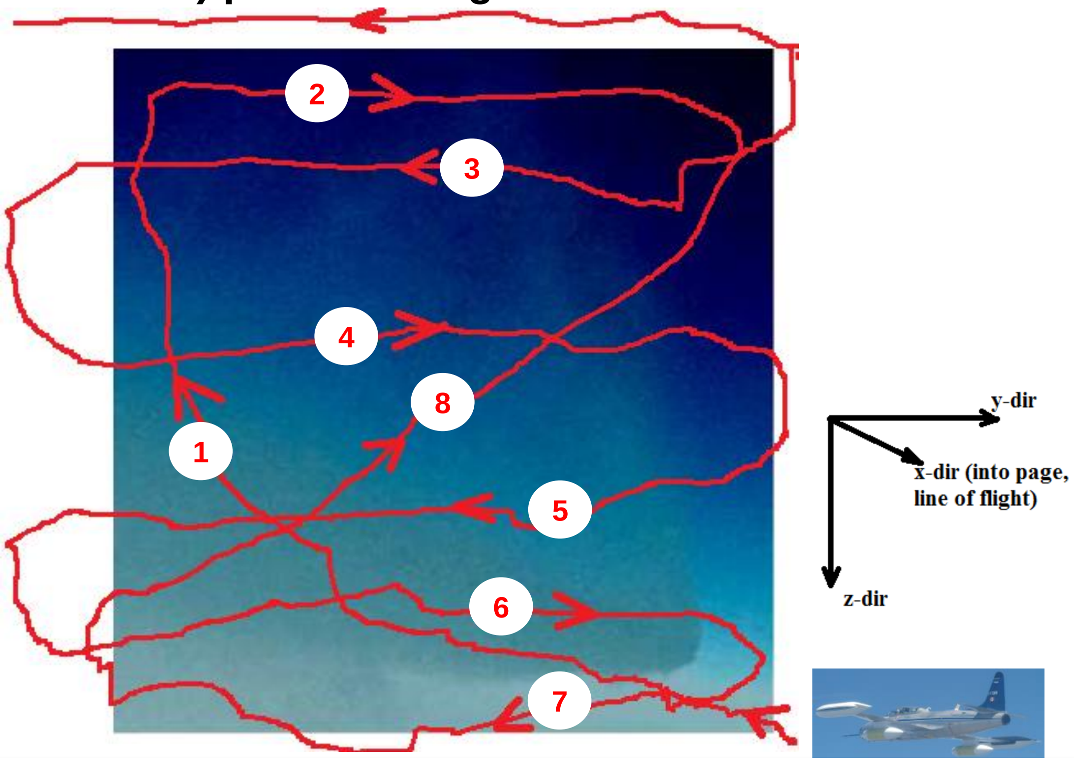
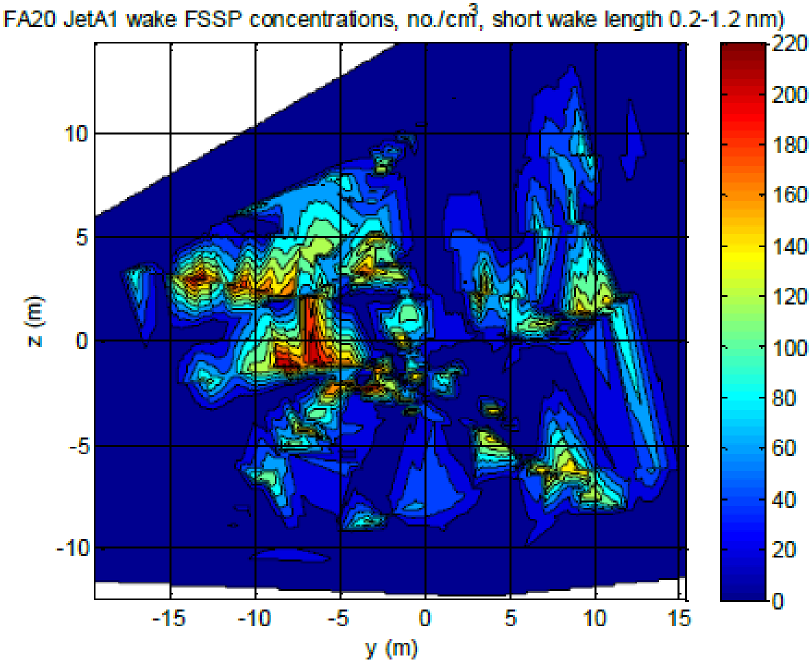
T-33 experimental flight methodology & Cross-Sectional Plume Reconstruction

- 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





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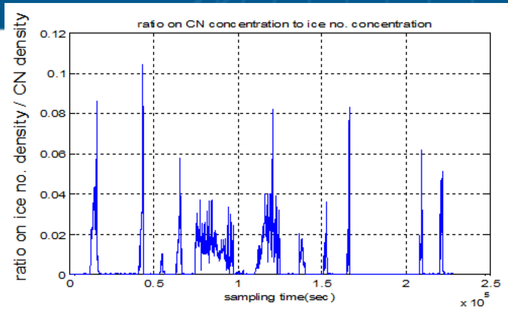
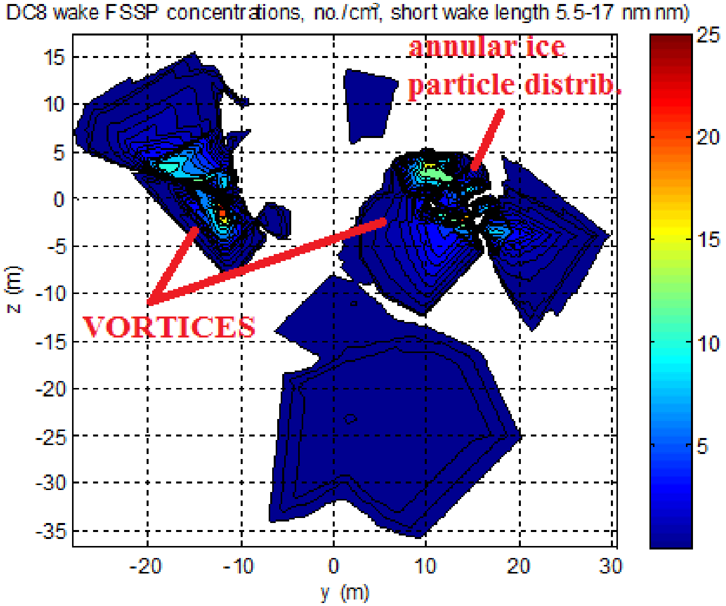
Trailing wake vortex dynamics, heavy influence on DC-8 contrails:-

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**





DC-8 contrail ice particle distribution dominated by TWV, trailing wake vortex pair of vortices

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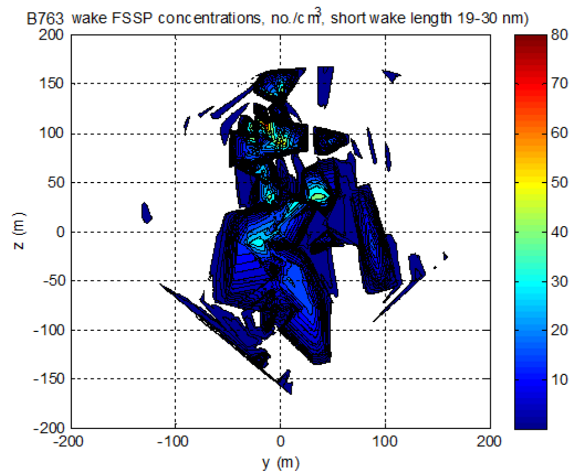
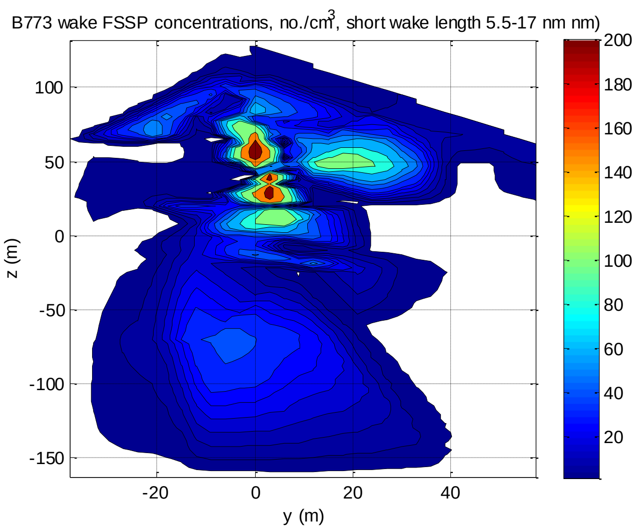
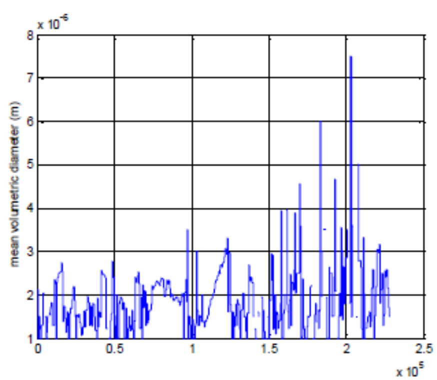
Other contrail characteristics:

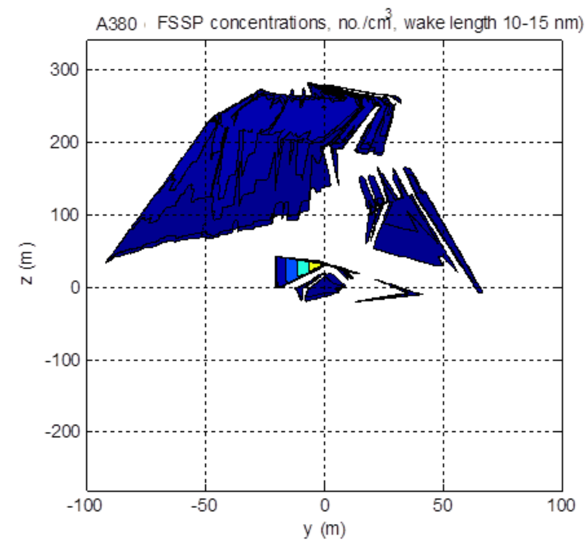
- Falcon 20, DC-8 (previous)
- B777 (below left), persistent
- B767 (centre)
- A380 (right)

- All of which:
  - Atmospheric background
  - Jet Types

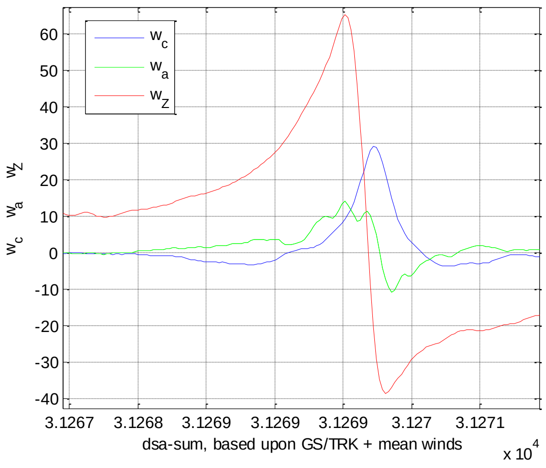


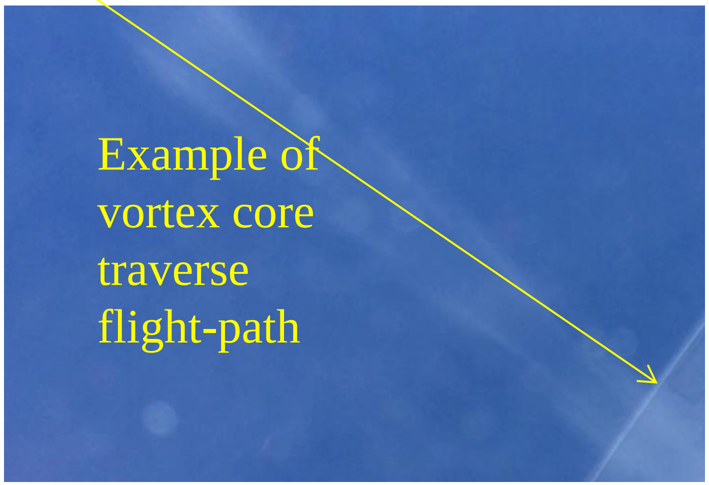


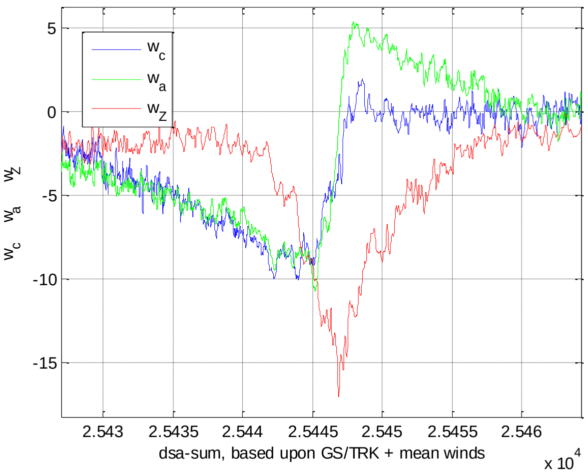




Trailing Wake Vortex Dynamics

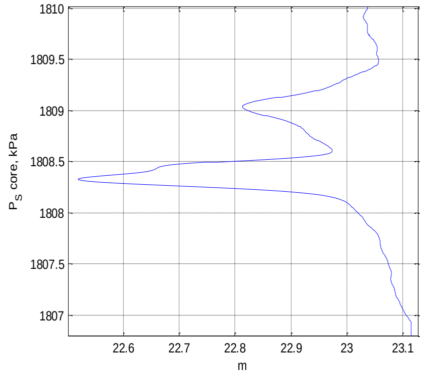


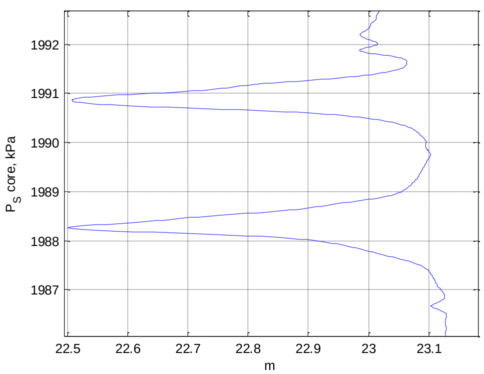


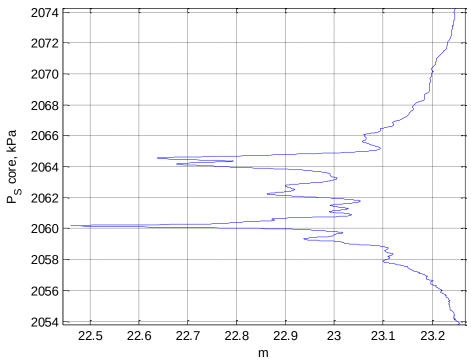


DC-8 trailing wake vortex core radius (r_C) vortex-induced air velocity, (V_T)

- **r_C, 0.5 to 2 m radius (varies in funnel-features)**
- **V_T, 15-70 m/s (circumferential vortex elements)**
- **Ps, 0.5 kPa suction**







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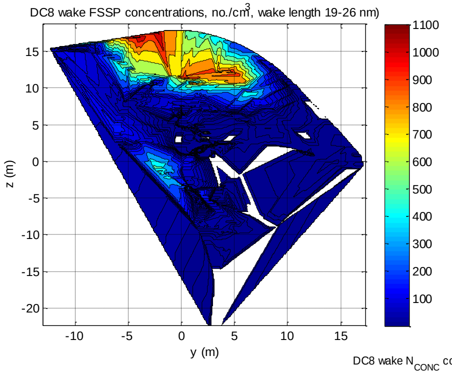
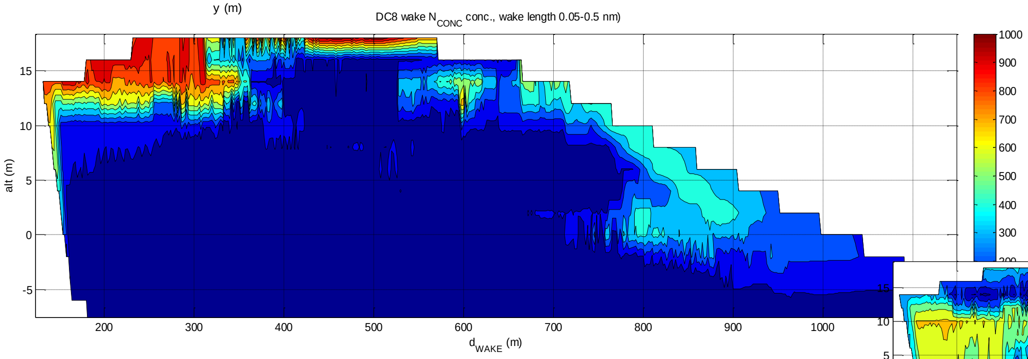
Emissions Plume – Cross-sectional and Axial (near emitter) Plume Reconstruction

Ice particle number density Cross-plane

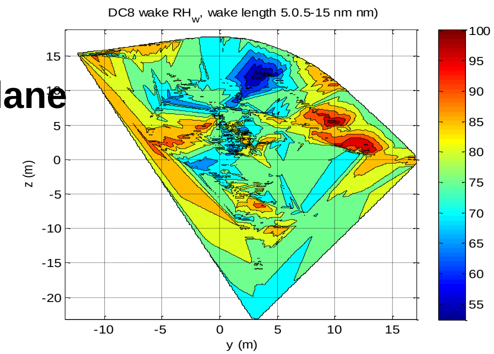


Axial direction (i.e. side-view)



Water vapour distribution (scavenged by ice particle formation

Cross-plane



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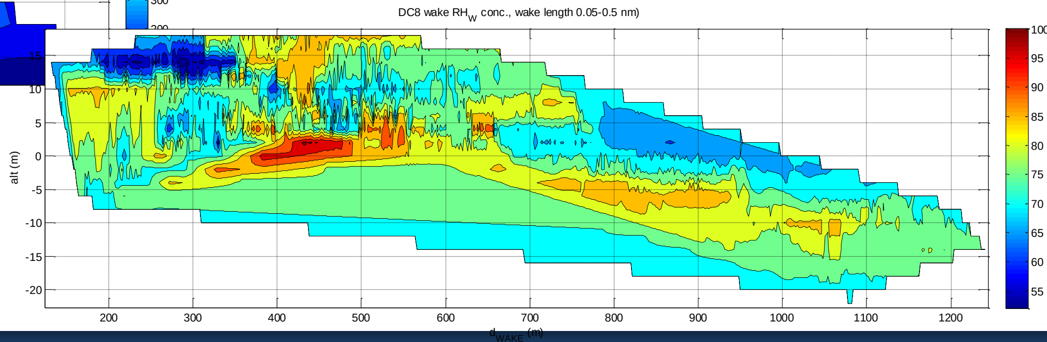
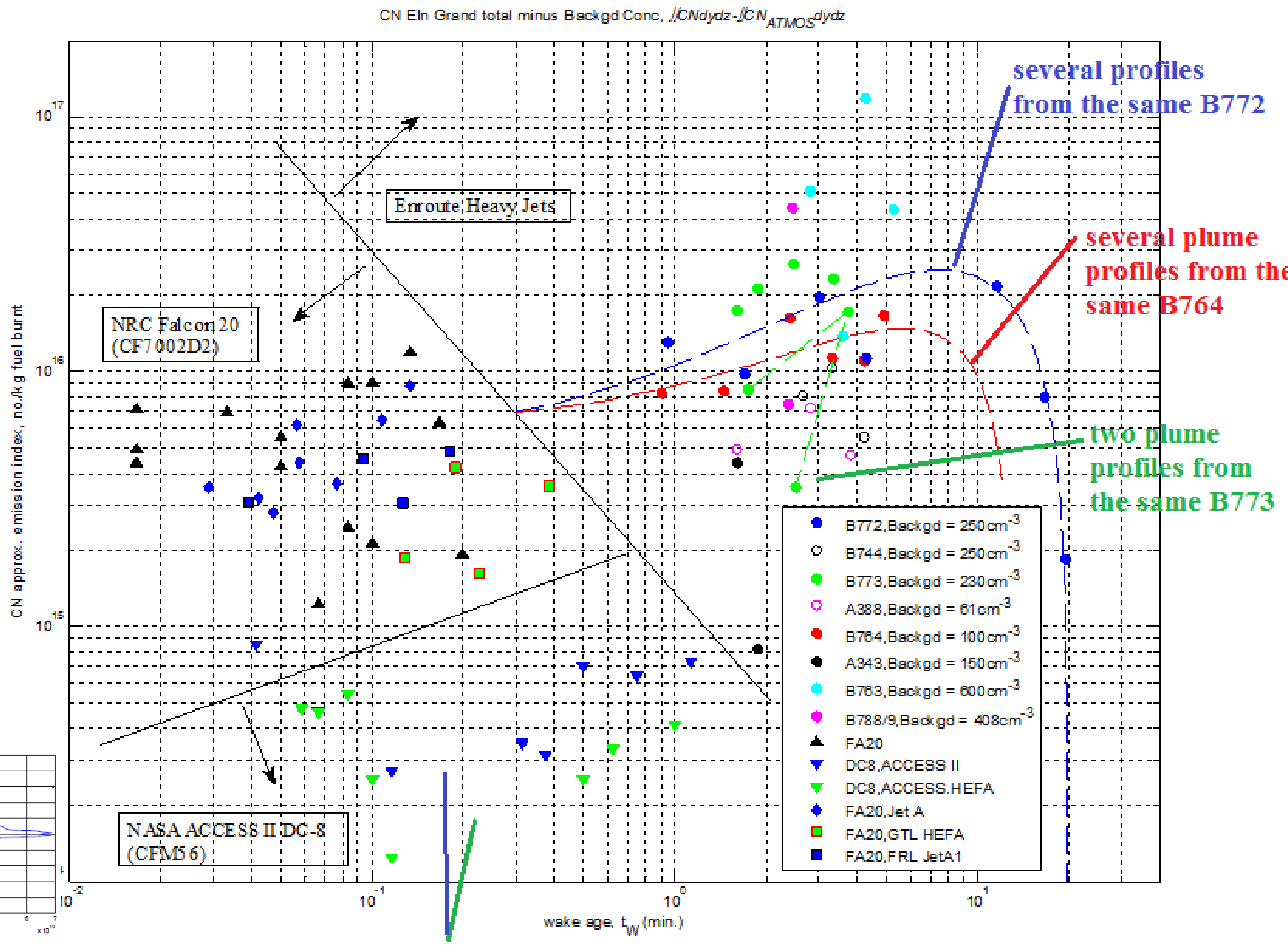


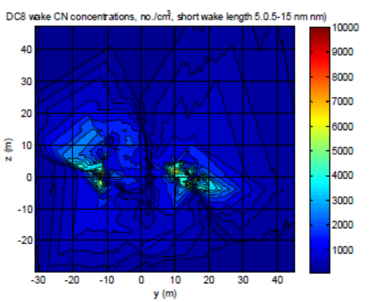
Individual inboard engine, contrails & water vapour plumes (Courtesy: ACCESS II Project)

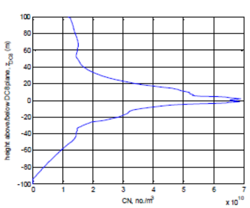
NRC's T-33 CN Data Summary

- **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

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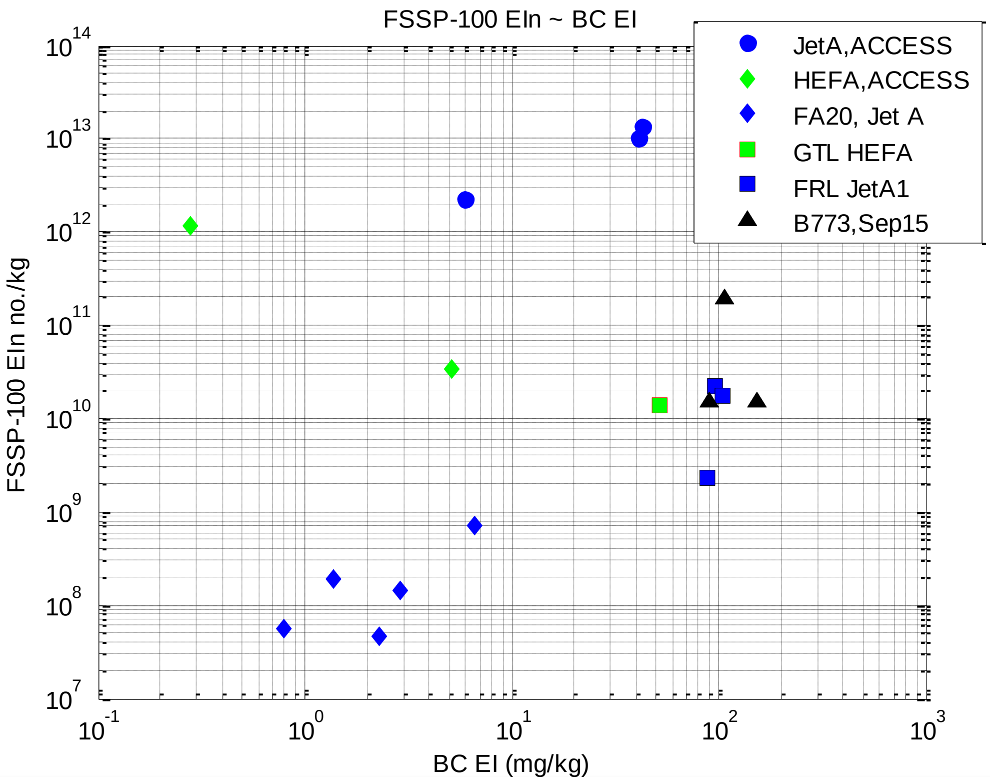
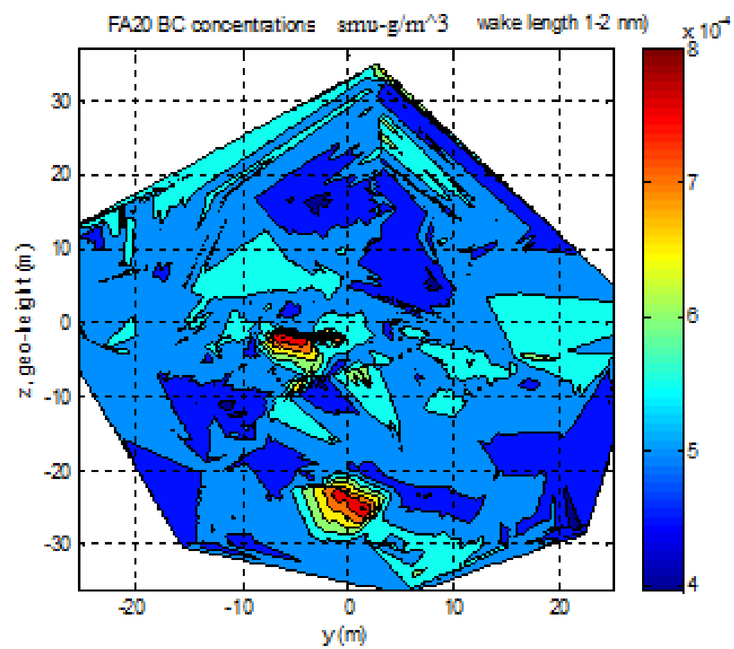
Post ACCESS II sidebar – T33 with LII 300 installed (2015) for Black Carbon Measurement

BC EIm & 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)**





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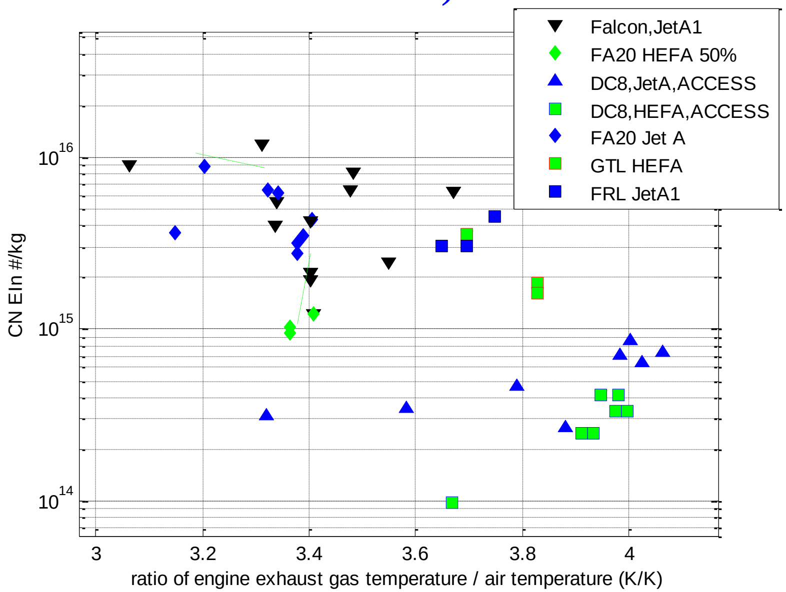
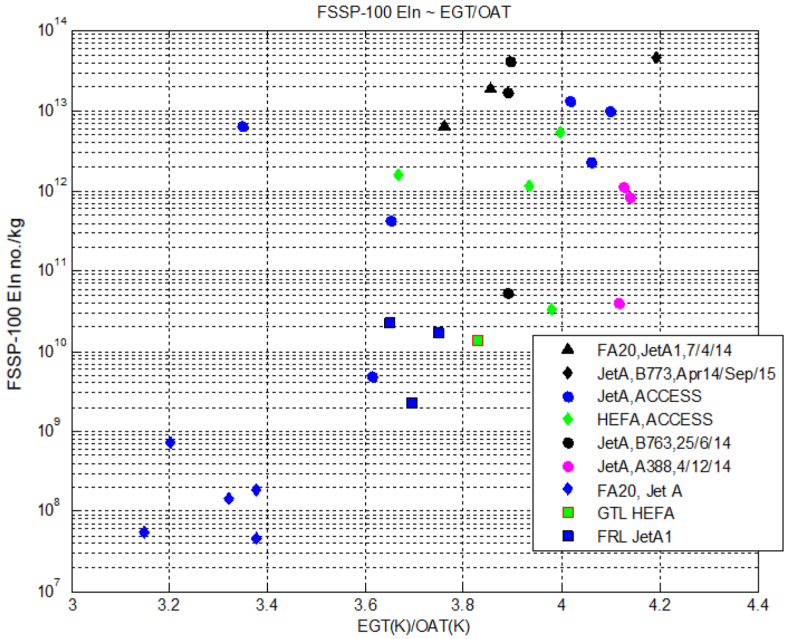
Parametric influences upon contrail ice particle number density (BC is one)

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)





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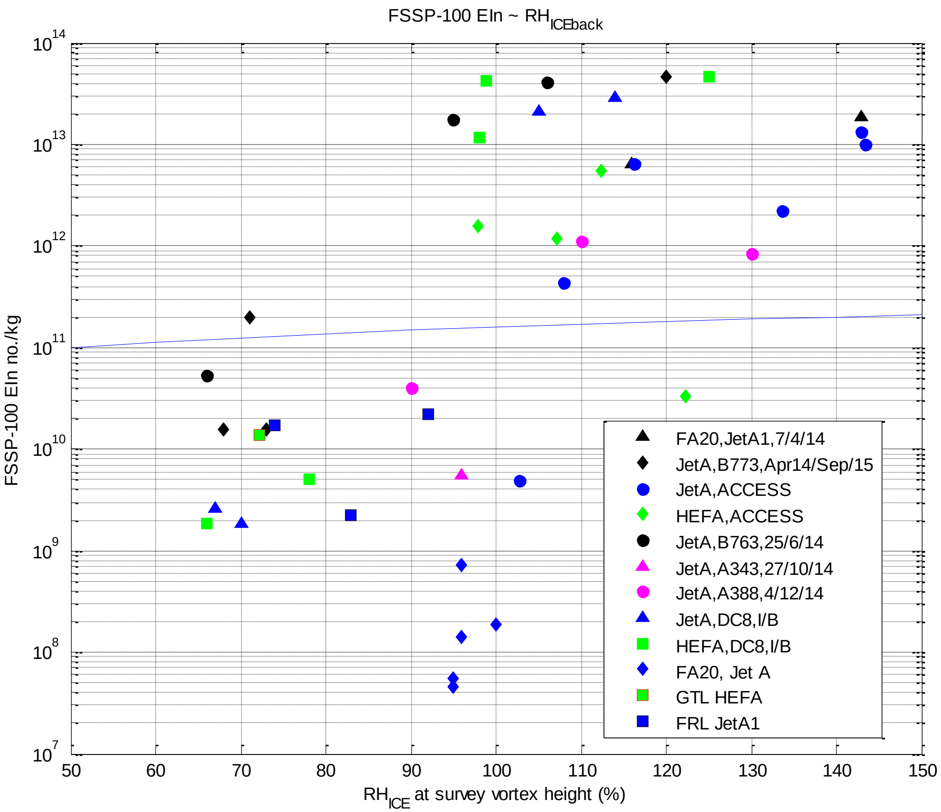
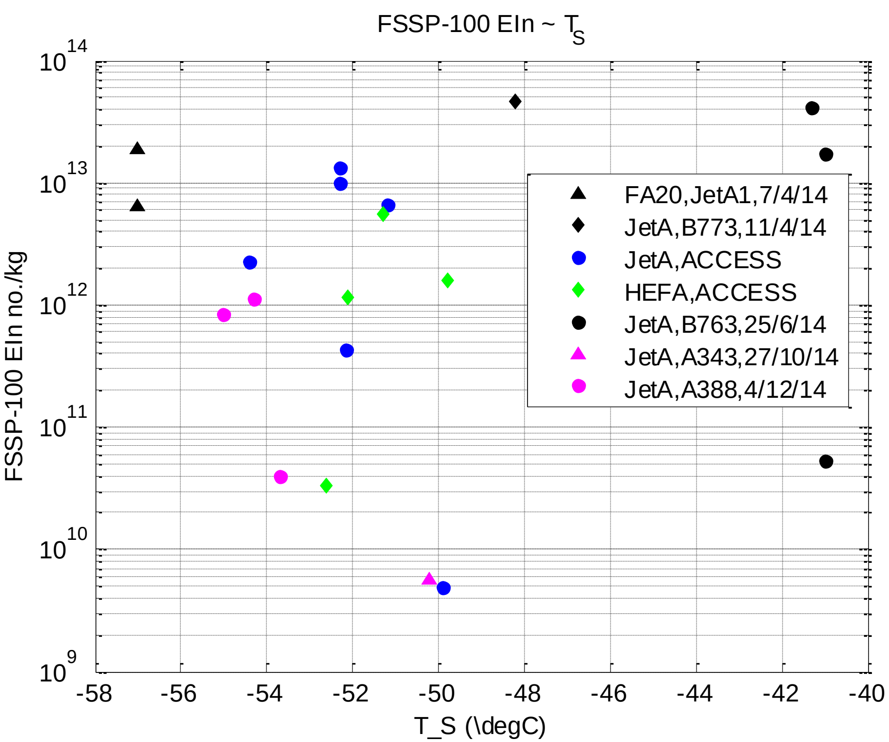
Parametric influences upon contrail ice particle number density, cont.

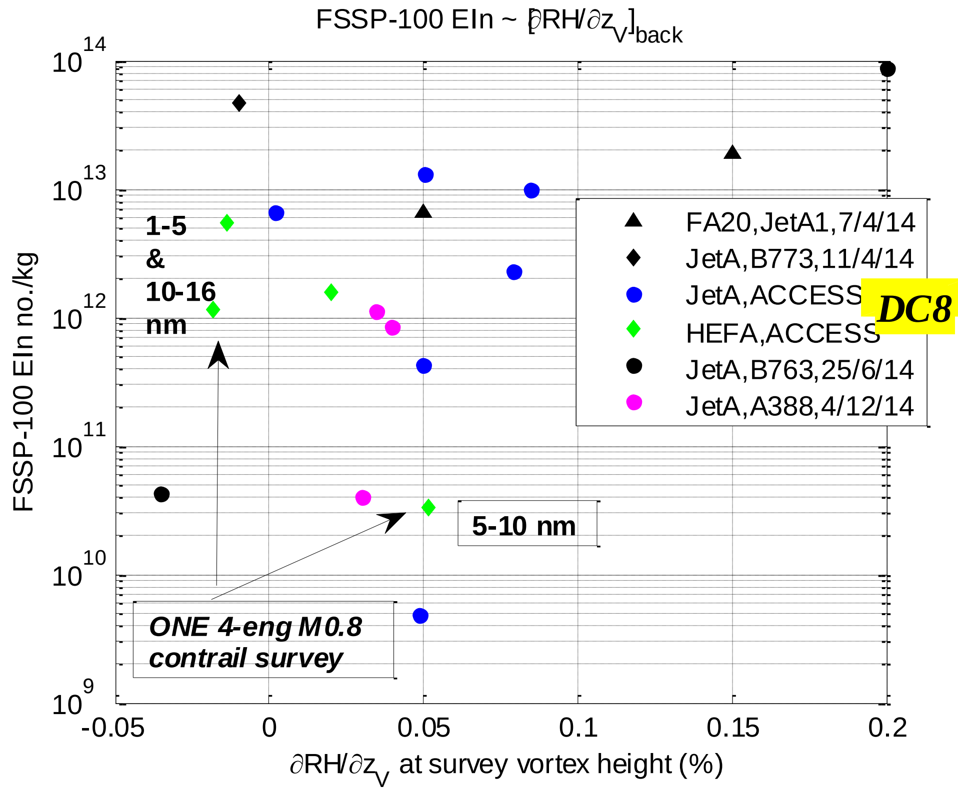
Ice particle EIn ~ background RH_{ice}



Parametric influences upon contrail ice particle number density, cont.

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





$$EIn_{PL} = a_0 \, T_S^{a1} \, RH_i^{2/3} \, a_2^{(-RHg)} \, EI_{CN}^{a3}$$

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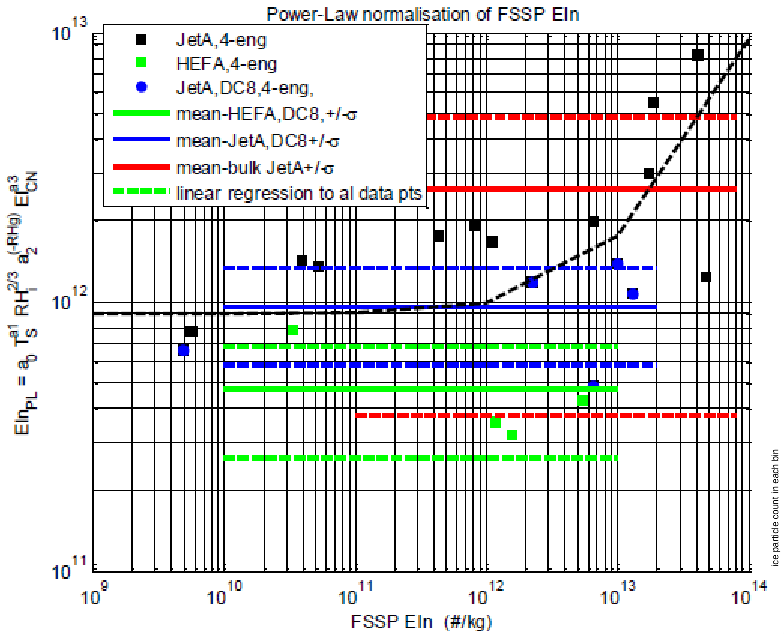
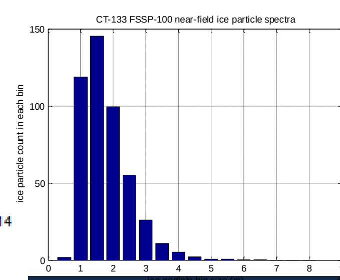
- **Contrail ice particle number density data:-**
  - e.g. cross-section of contrail centred on TWV region (below right, contours to 1200 ice particles per cc)

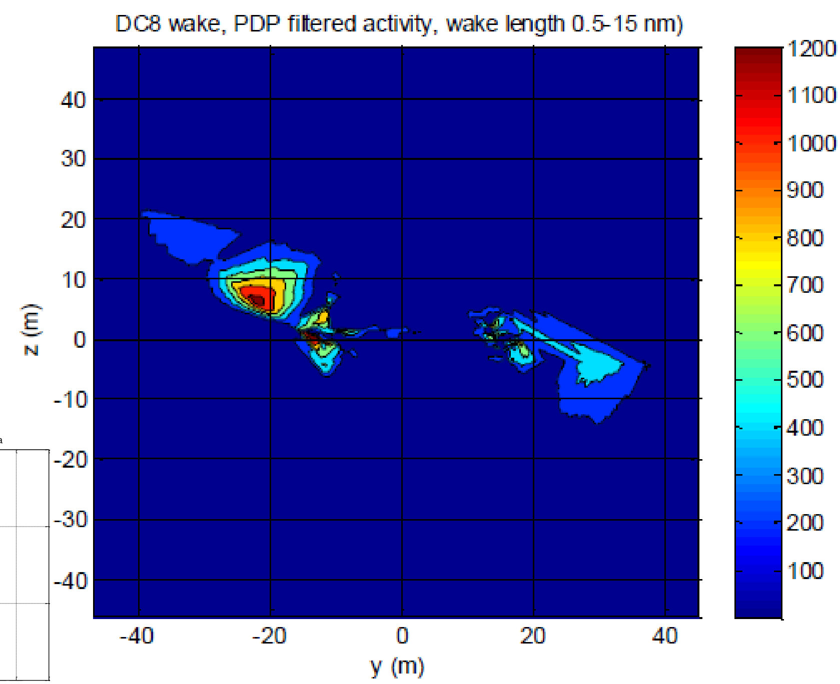
DC8:- 10-15 nm vortex contrail

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



Ice particle size spectrum (below) has MED ≈1-3 μm





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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 ($3\text{-}10^3$)
  - Very sound measurement FSSP (Wasey calibrations)
    - Highly sensitive to background atmospheric conditior
      - improve parametric grouping as Δ is 1-2 σ only

Fuel:	FRL JetA1	JP8 HEFA 50%
Mean EIn_{CN}	3.56e+15	2.35e+15
EIn_{CN} σ	8.63e+14	1.06e+15
Average σ	9.62e+14	

	mg/kg	
Fuel:	FRL JetA1	JP8 HEFA 50%
mean EI_{BC}	95.46	44.57
EI_{BC} σ	7.73	18.08
Average σ	12.5	

	Mean(EIn_{PL})	Standard deviation
	(% of the mean of all Jet A data)	
Bulk JetA (Falcon 20(CF700), B773, A388, B 763, A343, DC-8 'high-sulphur')	125	107
DC-8, low-sulphur Jet A	45	18
DC-8, HEFA blend	22	10

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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.

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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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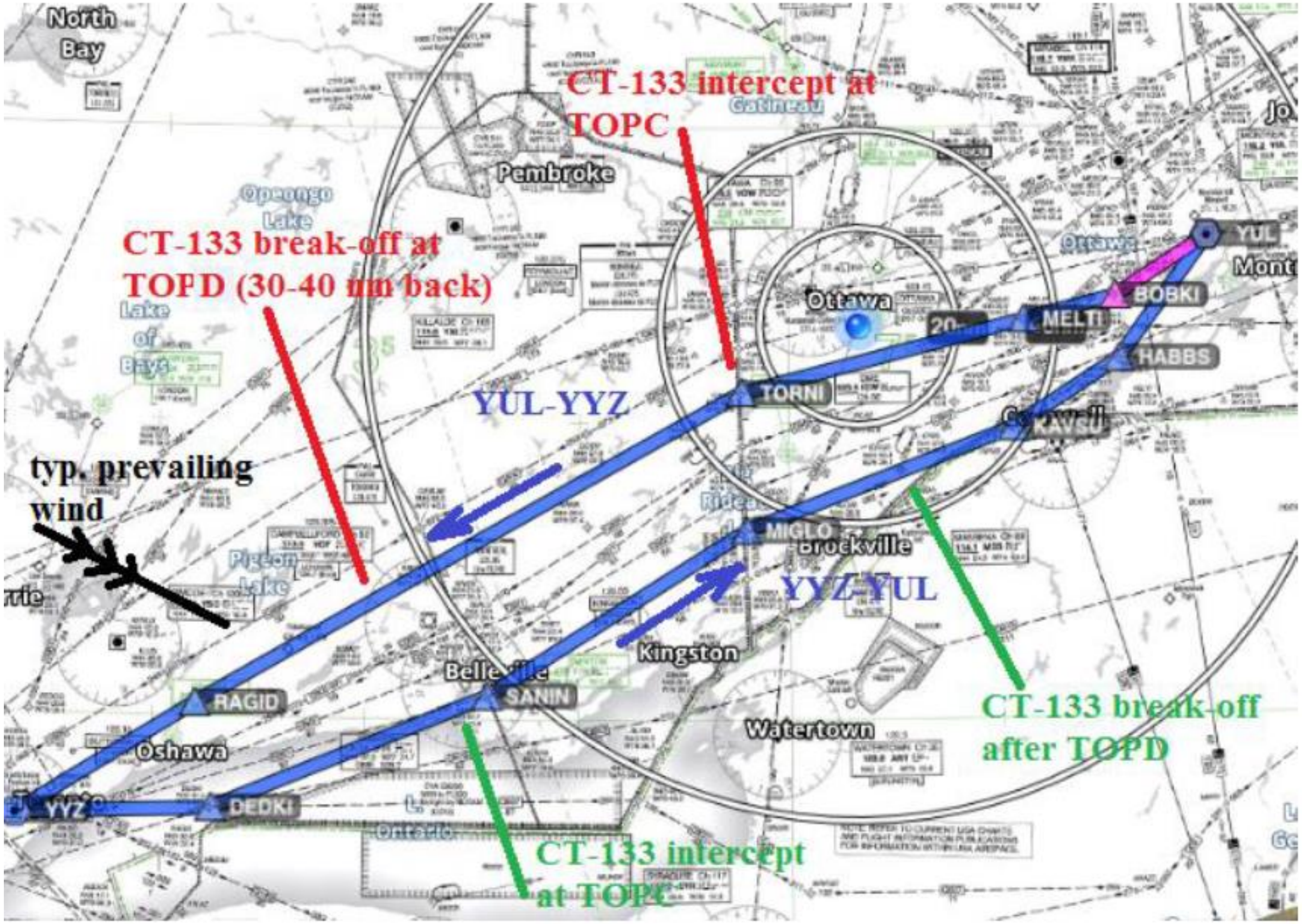
CAAFCER flights:



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CAAFCER flights:

Date, 2017	Flight, YUL-YYZ (43% HEFA/JetA1)				Flight, YYZ-YUL (Jet A1)			
	Flt No.	Aircraft	Engines, Type, S/N, hours		Flt No.	Aircraft	Engines, Type, S/N, hours	
20th April	ACA411	A320	-	-	nil	nil	nil	nil
25th April	ACA401	C-GPWG A320-211			ACA402	C-GITY A321-211		
28th April	ACA401	C-FGKN A321-211 FIN461	CFM56-5B3-P L73 HRS 21501 CYC 15907	L74 HRS 24685 CYC 15373	ACA402	C-GJWD A321-211 FIN457	CFM56-5B3-P L03 HRS 51191 CYC 18324	L42 HRS 50585 CYC 17167
3rd May	ACA411	C-FNVU A320-211 FIN415	CFM56-5A1 M16	M98	ACA412	C-FPCA B767-375 FIN637	CF6-60C2 B1F/B6F E75	E52
4th May	ACA401	C-FDRH A320-211 FIN203	CFM56-5A1 702	M06	ACA402	C-FXCD A320-214 FIN239	CFMK56-5B4/P L41	L60
4th May	ACA413				ACA414			
11th May	nil	nil	nil	nil	ACA402	A320	-	-

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CAAFCER flight, contrail example, A320 (stem/crown dominated):

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CAAFCER biofuel contrail, A320 (stem/crown dominated): (1) c.15 nm

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CAAFCER biofuel contrail, A320: (2) 20 nm

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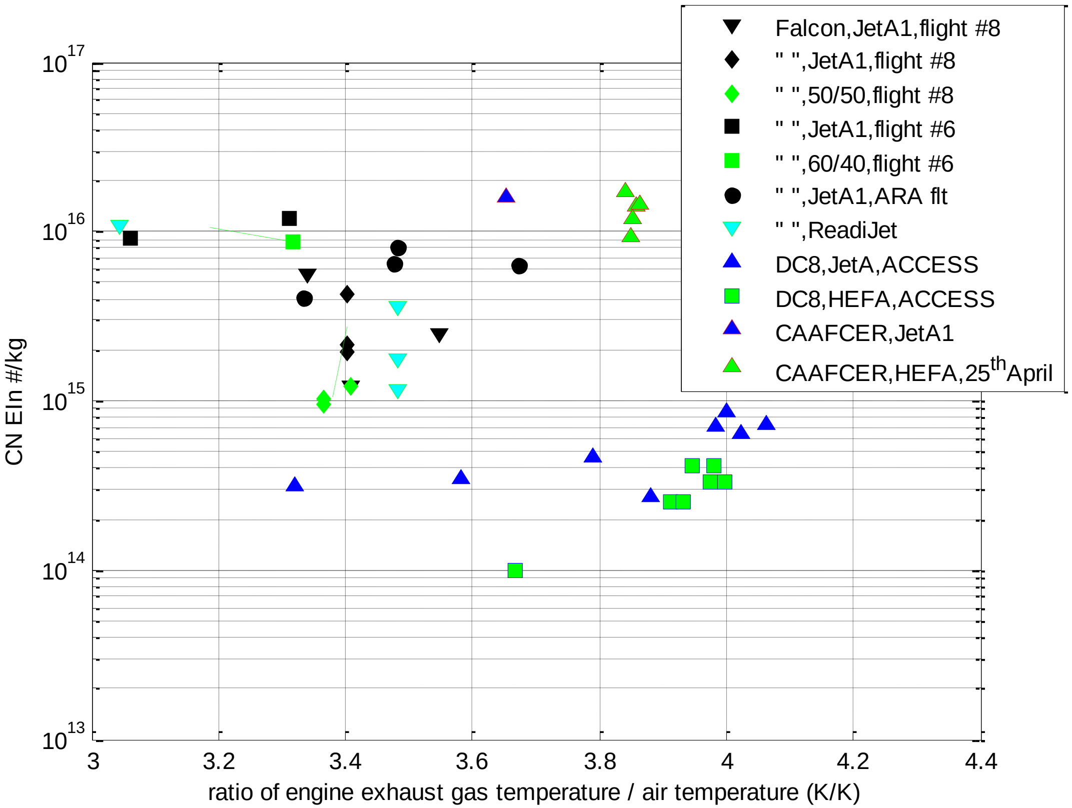
CAAFCER flight, contrail example, A320: (3) 25 nm, transformation of the crown to cirro-cumulus

Petroleum & Biofuel contrail flight data

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

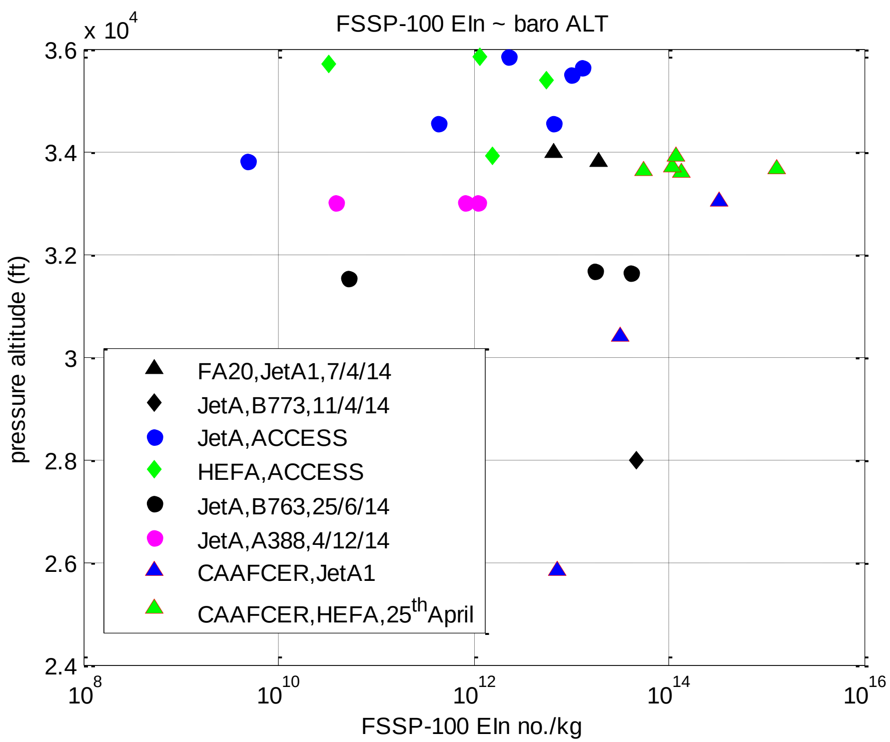


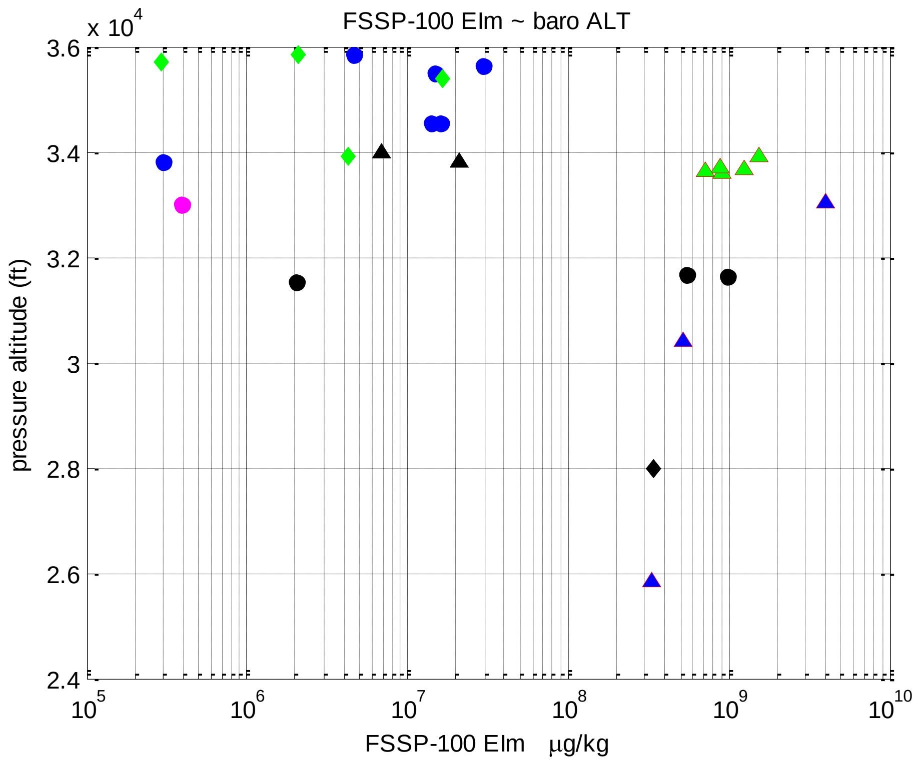
NRC·CNRC

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





NRC·CNRC

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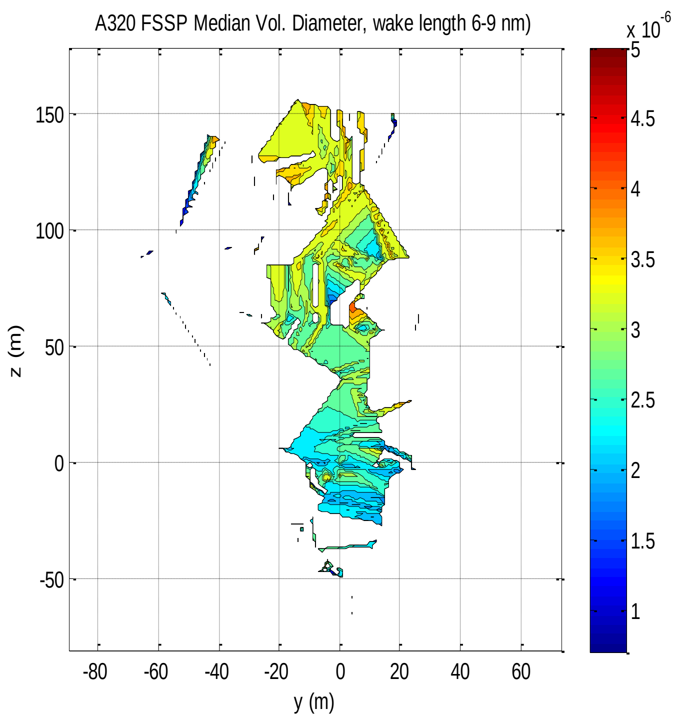
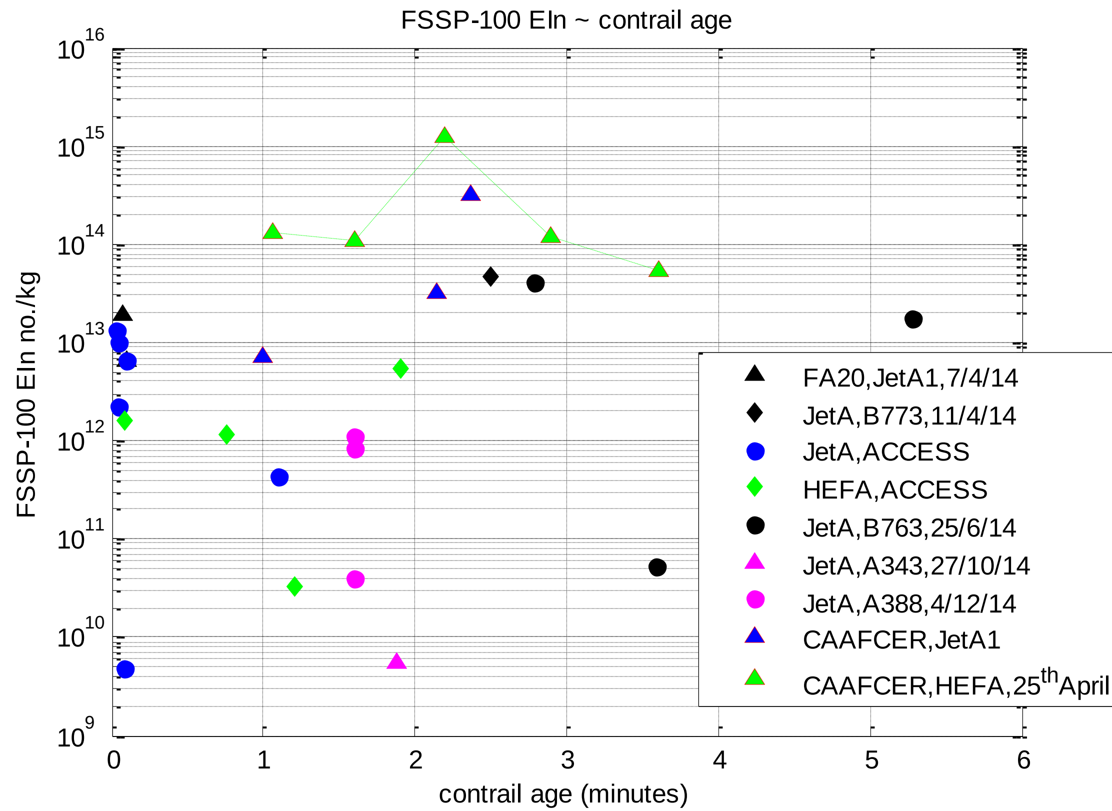
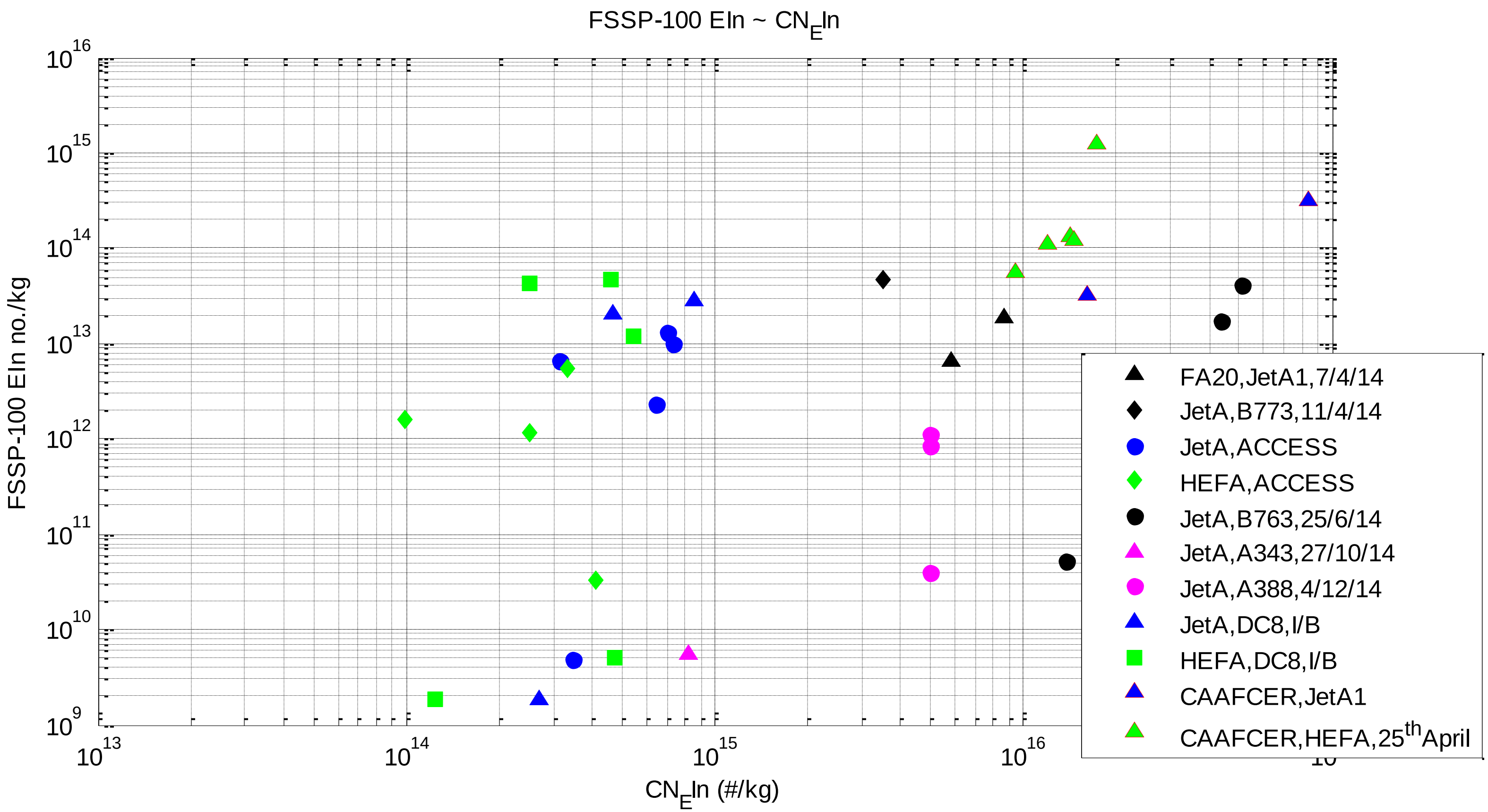
CAAFCER flights, preliminary data, FSSP MVD size distribution, showing larger UJW growth rates (*left*) & EIn behaviour with age (*right*):





Petroleum & Biofuel contrail flight data

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



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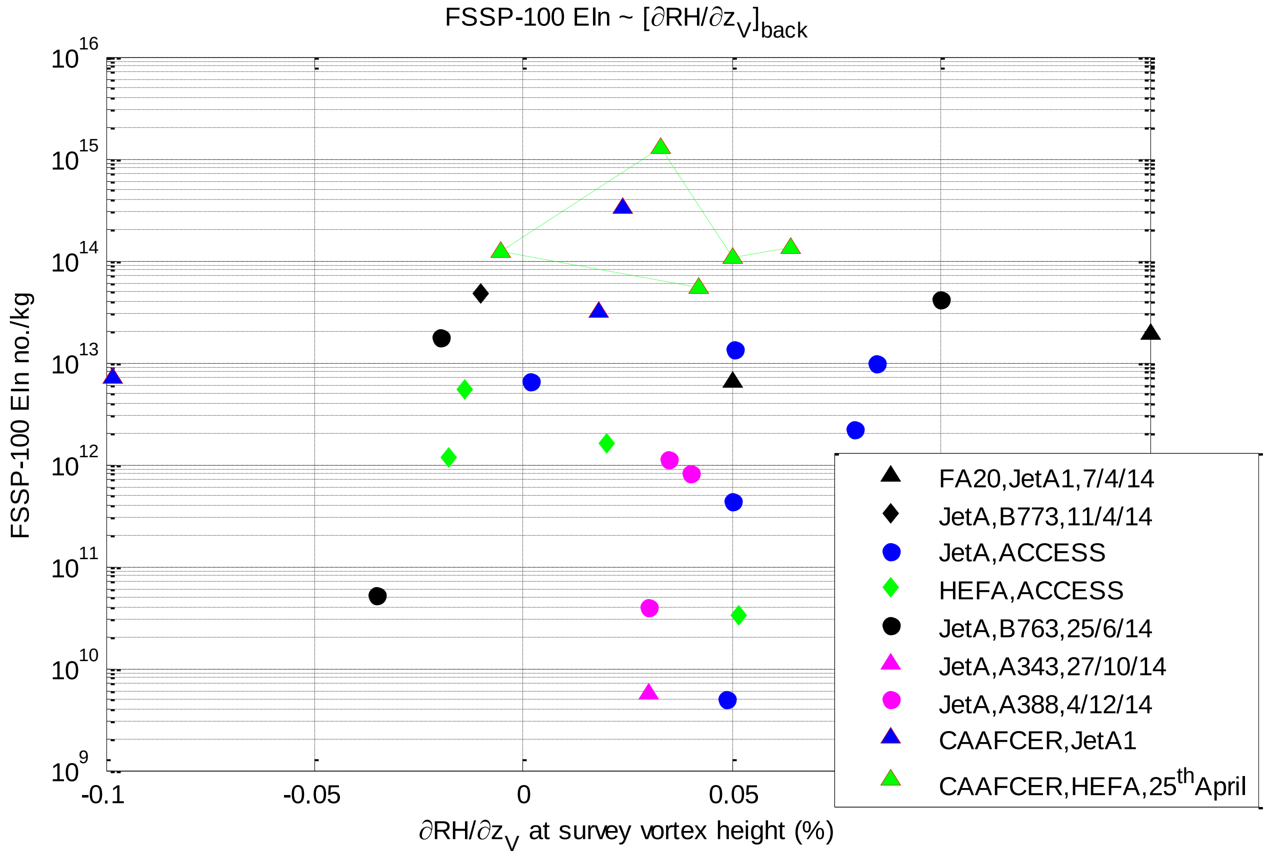
Petroleum & Biofuel contrail flight data

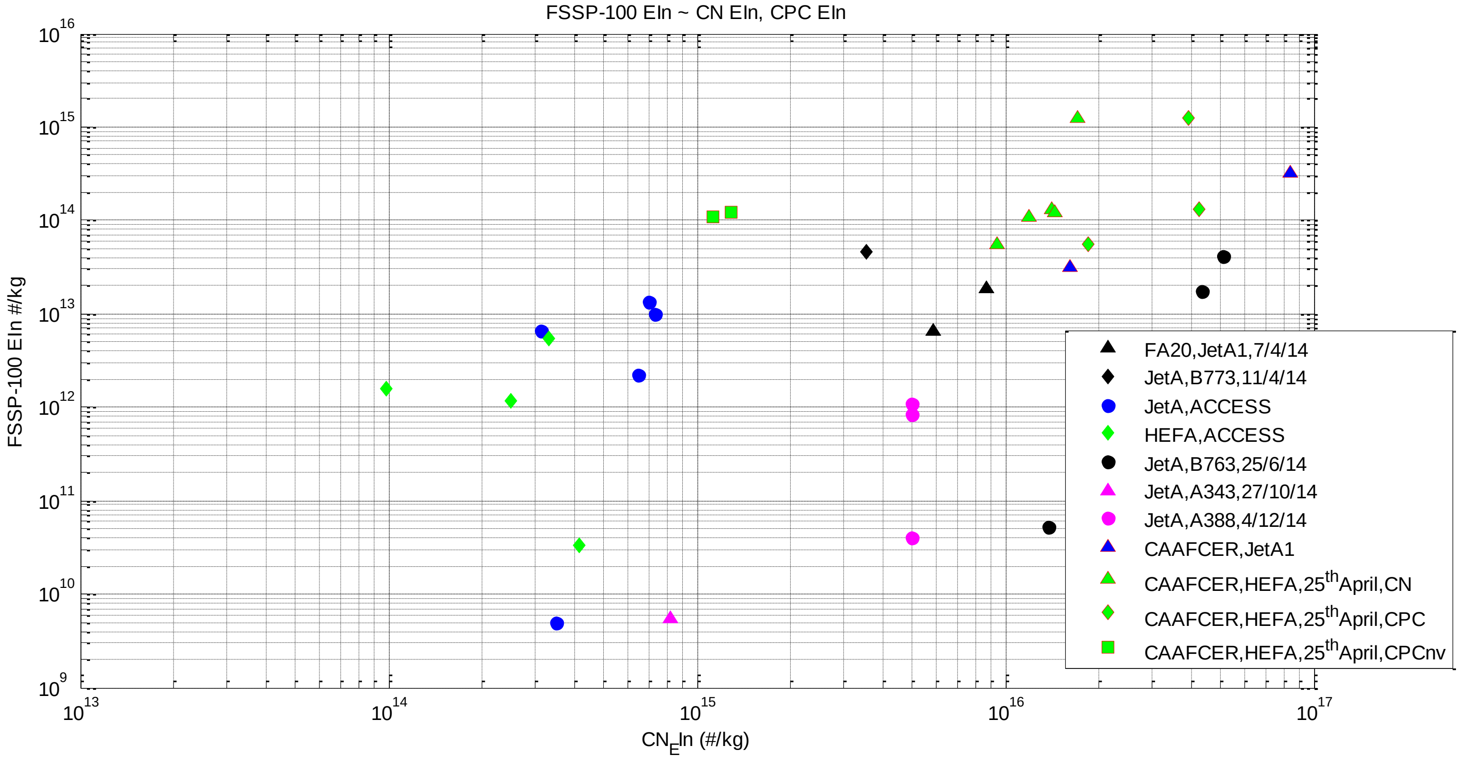
CAAFCER flights, preliminary data, FSSP EIn with relative humidity (RH) lapse rate:



NRC·CNRC

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

NRC·CNRC

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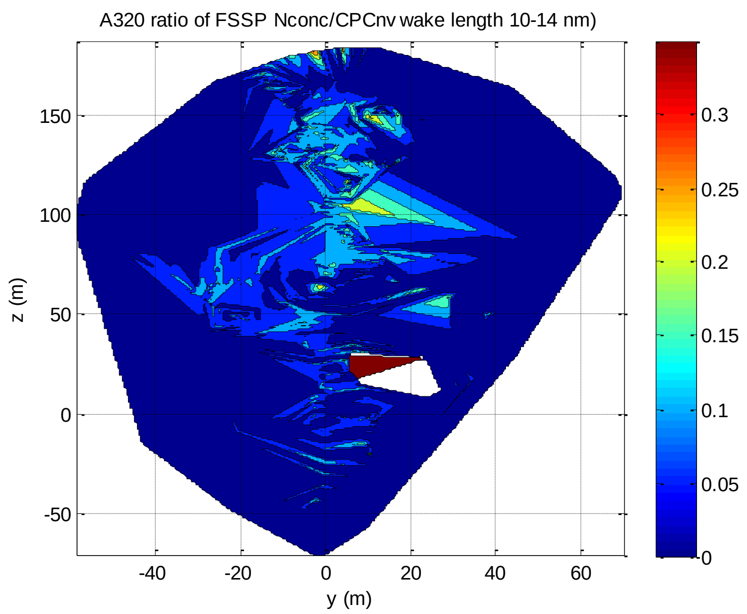
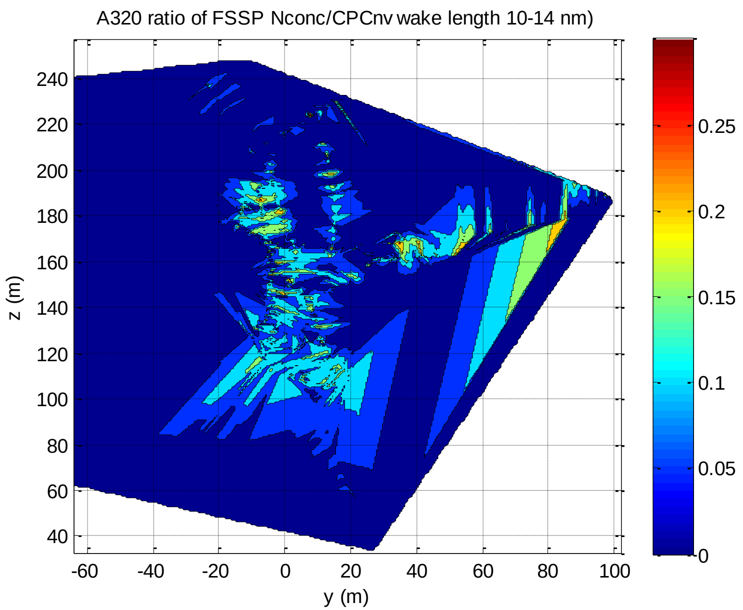
Soot activation (from previous page)

- 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





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Future work

- Optical characteristics of contrails
  - Relating to RF (integrates sum of ice particles/shapes), <<0.5μm
  - 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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