Alternative-Fuel Effects on Contrails & Cruise EmiSSions (ACCESS-2) Flight Experiment

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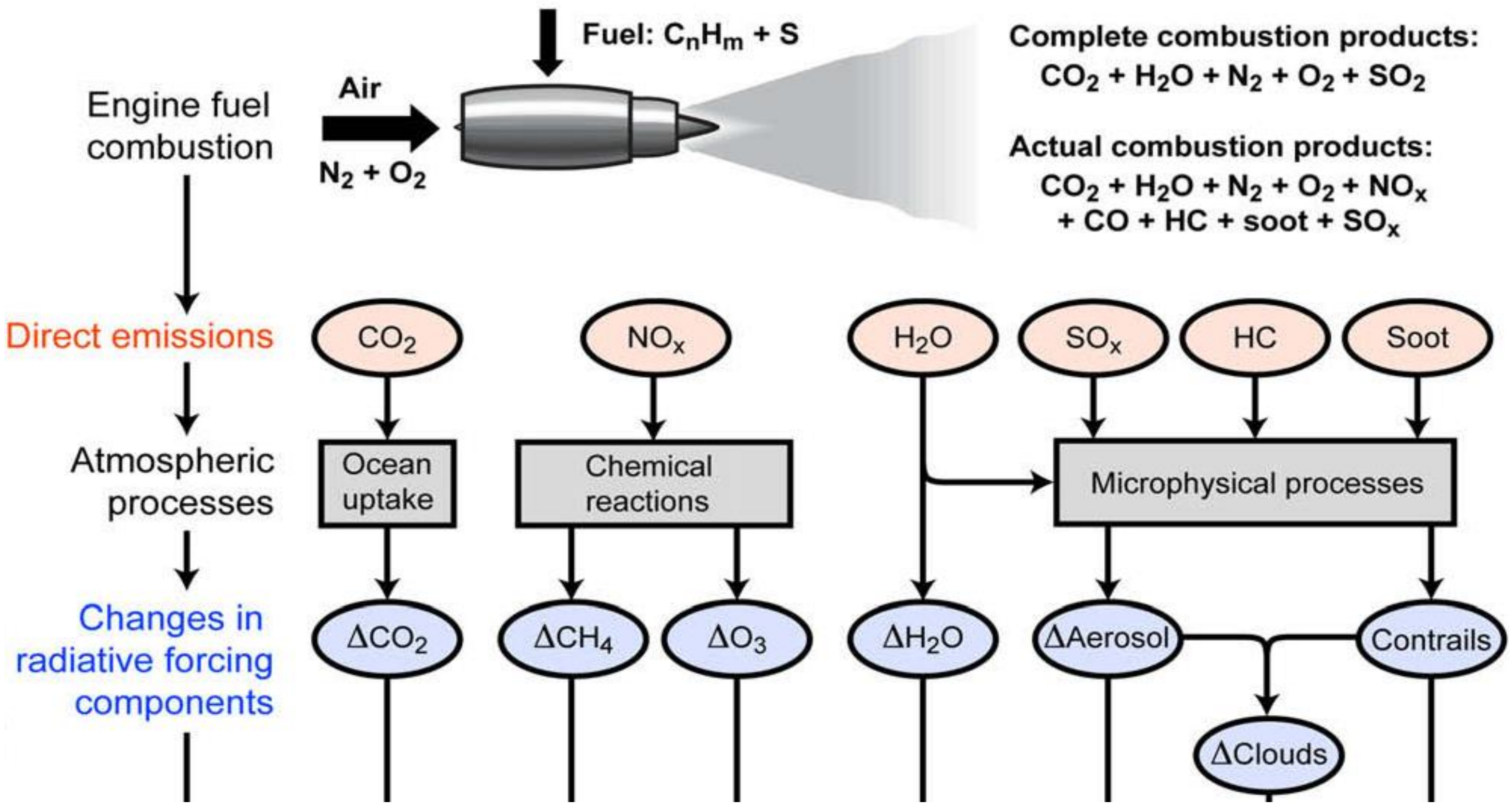
and the ACCESS-II Science and Implementation Teams

Fundamental Aeronautics
Fixed Wing Project

DLR Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

National Research
Council Canada

How Does Aviation Effect the Environment?

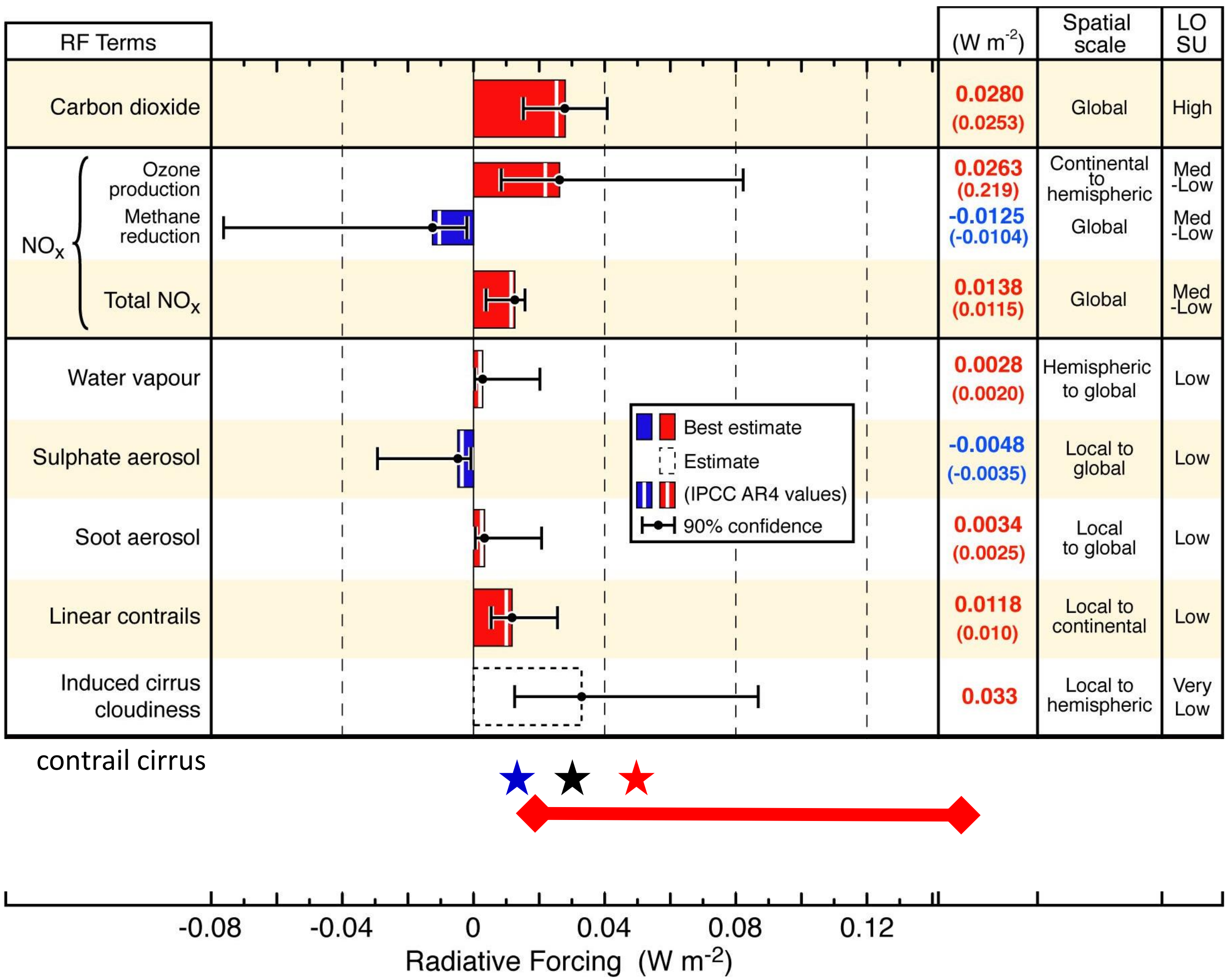


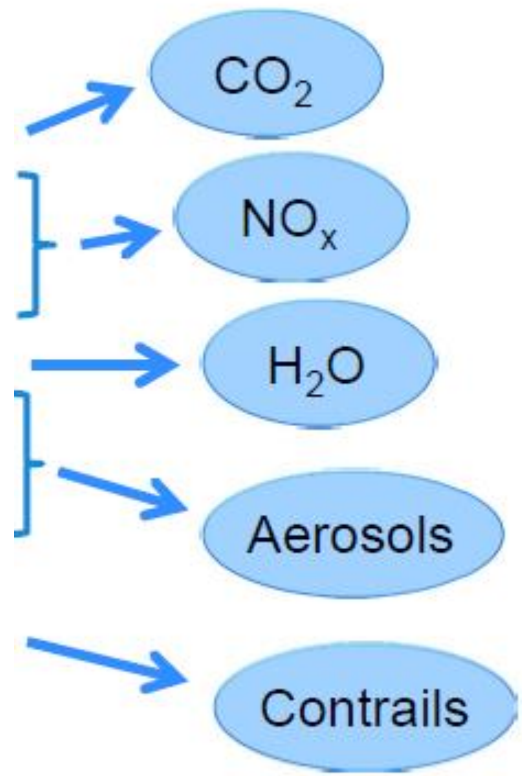
Lee et al., Atmos. Env., 2009

- Aerosol and gas-phase emissions effect air quality near airports
- NOx emissions effect background Ozone concentrations
- Aerosols can influence cloud formation and radiative properties
- Contrails, Black Carbon, and CO_2 can enhance anthropogenic radiative forcing

ICAO considering new regulations to reduce particle emissions

Aviation Radiative Forcing Impacts a Major Concern



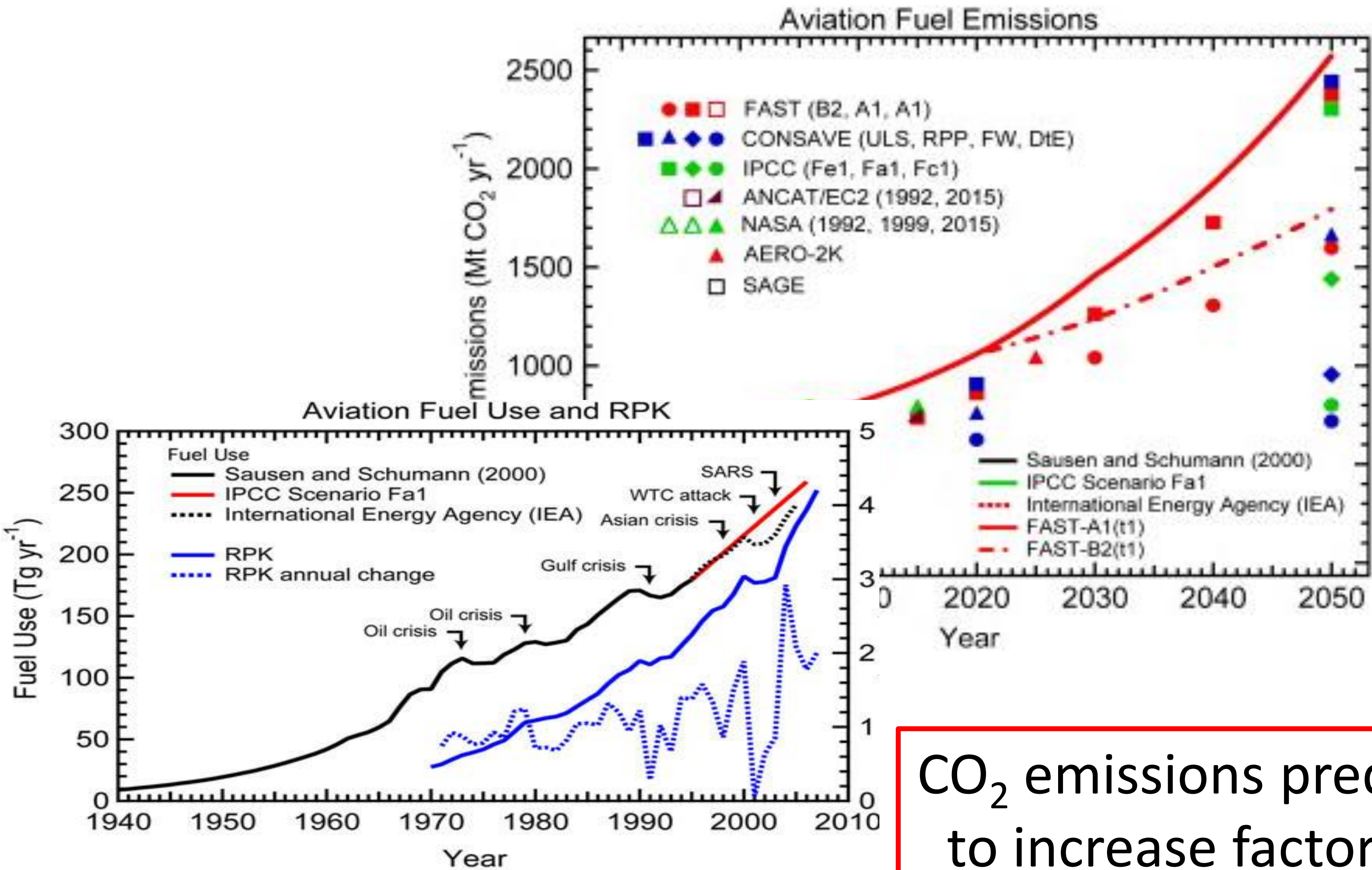


contrail cirrus

★ Chen & Gettelman, 2013
Burkhardt & Kärcher, 2011
★ Schumann & Graf, 2013
★ Red bar : IPCC, 2013

Present Fleet Accounts for ~5% of All Anthropogenic Forcing!
Uncertainties in Aerosols and Contrail Forcing are very high

Aviation Fuel Usage Growing Rapidly

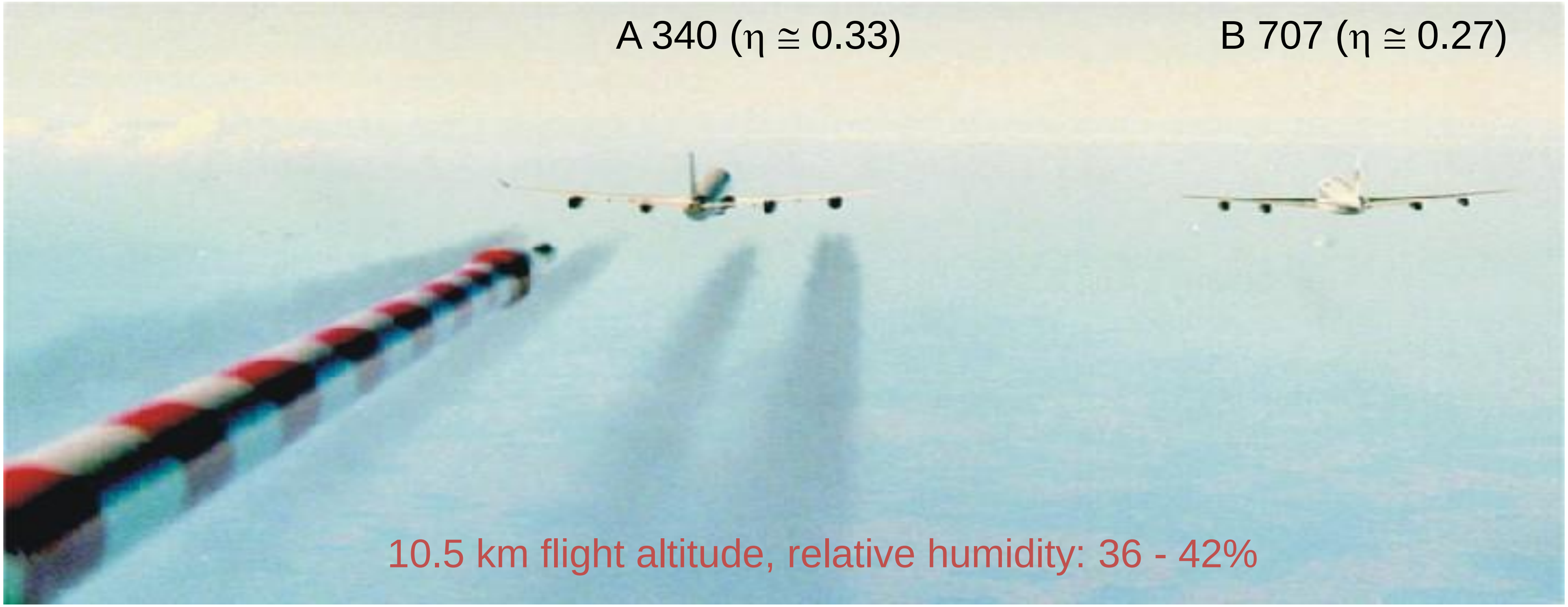


Lee et al., 2009, 2010

CO_2 emissions predicted to increase factor of 3 to 5 by 2050

More Efficient Aircraft Create more Contrails

Newer engines extract more heat to perform work, have cooler exhaust, higher %RH



U. Schumann, 2000

Contrail-induced cloudiness may increase on par with or more rapidly than CO_2 emissions

Alternative Fuels Offer Avenues for Mitigating Environmental Impacts of Current Fleet

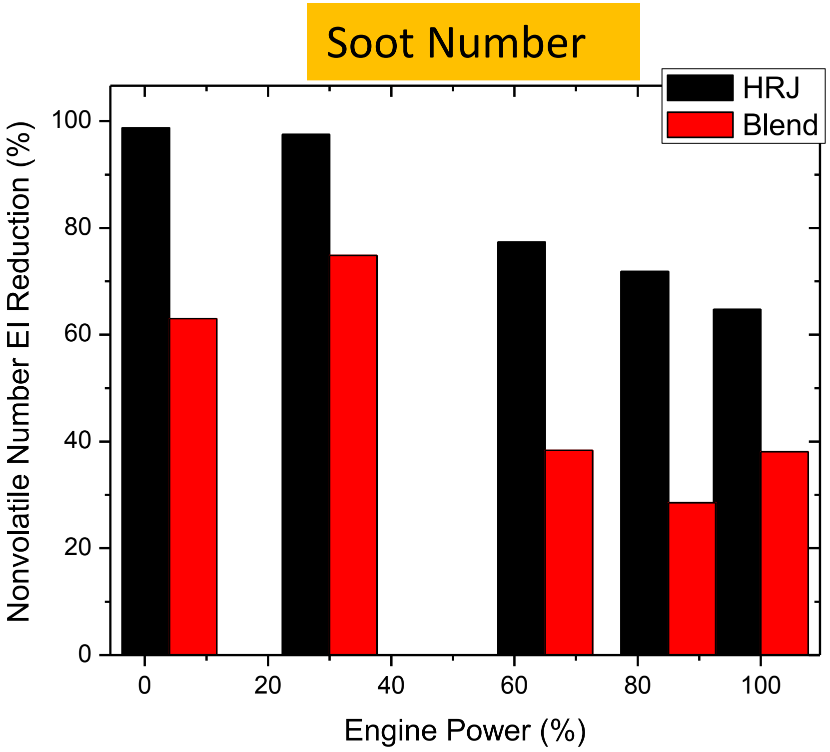
- Can be made from renewable, sustainable feed-stocks to reduce CO2 emissions
- Contain no aromatics hydrocarbons, thus greatly reduce soot emissions
- Contain no sulfur, greatly reduce volatile aerosol and cloud condensation nuclei emissions
- Lower aerosol and soot emissions predicted to reduce contrail coverage and radiative forcing effects

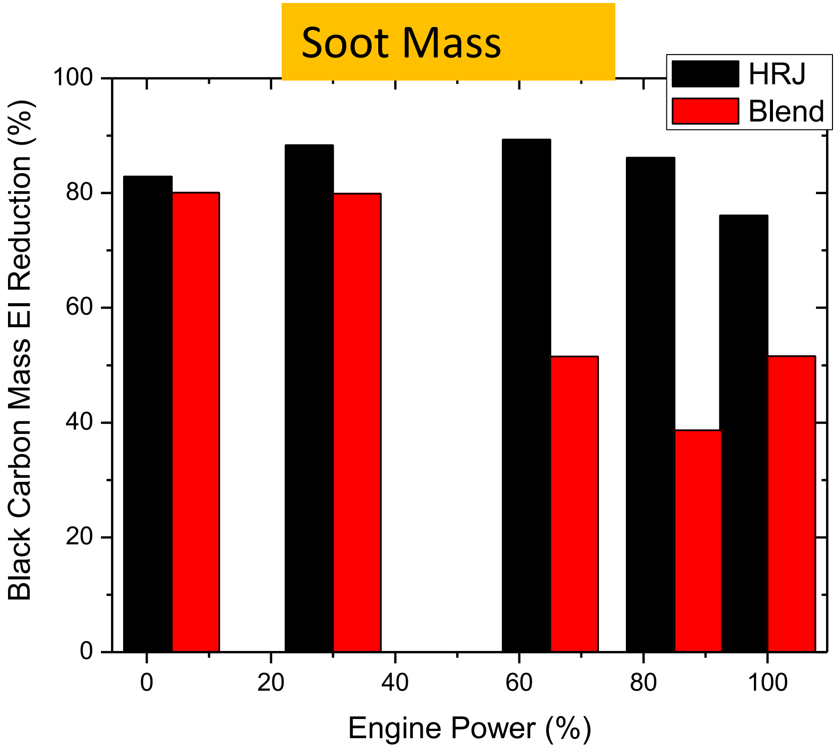
ACARE Alt Fuel Tragets: 2% in 2020, 25% in 2035, 40% in 2050)
United States FAA Goal: 1 Billion gallons of renewable jet fuel by 2018

NASA ARMD Alt Fuel Research

- **Laboratory tests** to determine alternative fuel combustion and emissions characteristics
  - High-pressure flame-tube experiments on LDI fuel injectors—ongoing
  - High-pressure tests on GE & PW sector rig combustors—2013
- **Ground-based engine tests** to evaluate alternative fuel effects on emissions under real-world conditions
  - PW308—March 2008
  - AAFEX-I—January 2009
  - AAFEX-II—March 2011
- **Cloud chamber tests** to examine PM effects on contrail formation
  - ACCRI/FW Tests—2010 thru 2015
- **Airborne experiments** to evaluate fuel effects on emissions and contrail formation at cruise
  - **ACCESS-I: Feb-April, 2013**
  - **ACCESS-II: May, 2014**

AAFEX-II Clearly Demonstrated Alt Fuel Benefits





- Ground tests cannot simulate engine operations and ambient conditions at cruise
- Flight tests also required to advance understanding of fuel effects on contrails

ACCESS Objectives

1. Examine the effects of Alt fuels on aircraft cruise-altitude gas and particle emission indices
2. Characterize the evolution (growth, changes in composition) of exhaust PM how this is impacted by fuel composition
3. Investigate the role of soot concentrations/properties and fuel sulfur in regulating contrail formation and the microphysical properties of the ice particles.
4. Survey soot and gas-phase emissions in commercial aircraft exhaust plumes in air-traffic corridors to provide context for DC-8 measurements

Source Aircraft: NASA Dryden DC-8

- Uses CFM56-2-C engines; NASA asset, no restrictions on data use or for burning alt fuels
- Ground-based emissions studied in over 75 hours of tests during APEX, AAFEX-I, and AAFEX-II
- In-flight emissions previously characterized during SUCCESS and POLINAT

Previous Tests Indicate DC-8 PM Emissions Significantly Reduced by Burning Alt Fuels

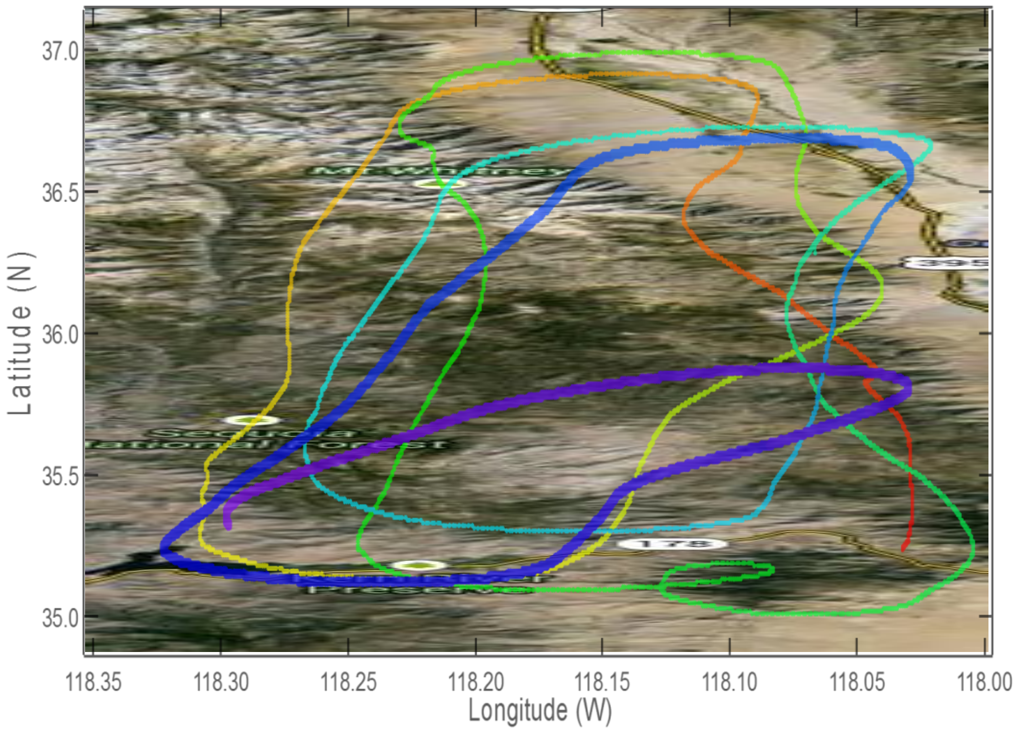
ACCESS-1 Experiment Activities

- Selected and modified chase aircraft (HU-25) with sample inlets and cloud probes
- Mounted extensive instrumentation package in HU-25 cabin
- Established project hazards/mitigations and flight rules
- Procured JP-8 and Camelina-based HEFA fuels
- Deployed aircraft and Mobile Lab to Palmdale 2/19/2013
  - Mixed 50:50 JP-8/HEFA and obtained fuel certification
  - Performed "practice" flight with DC-8 to hone techniques
  - Performed 4 exhaust and contrail sampling missions with DC-8 in 32 kft to 37 kft altitude range
  - Conducted extensive ground sampling of DC-8 exhaust to obtain more detailed emissions data
- Transited Home to Langley 4/14/2013

Project went on Hiatus from March 7 to April 2, 2013 for Dryden Safety Stand-Down

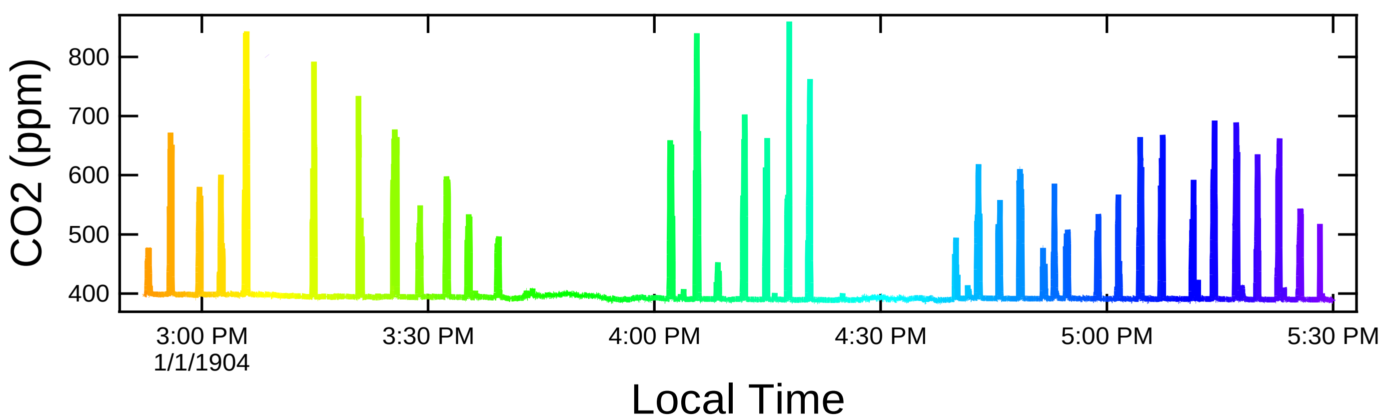
Flights Entailed flying Racetracks over Edwards

Thick Line = HEFA Blend; Thin Line = JP-8



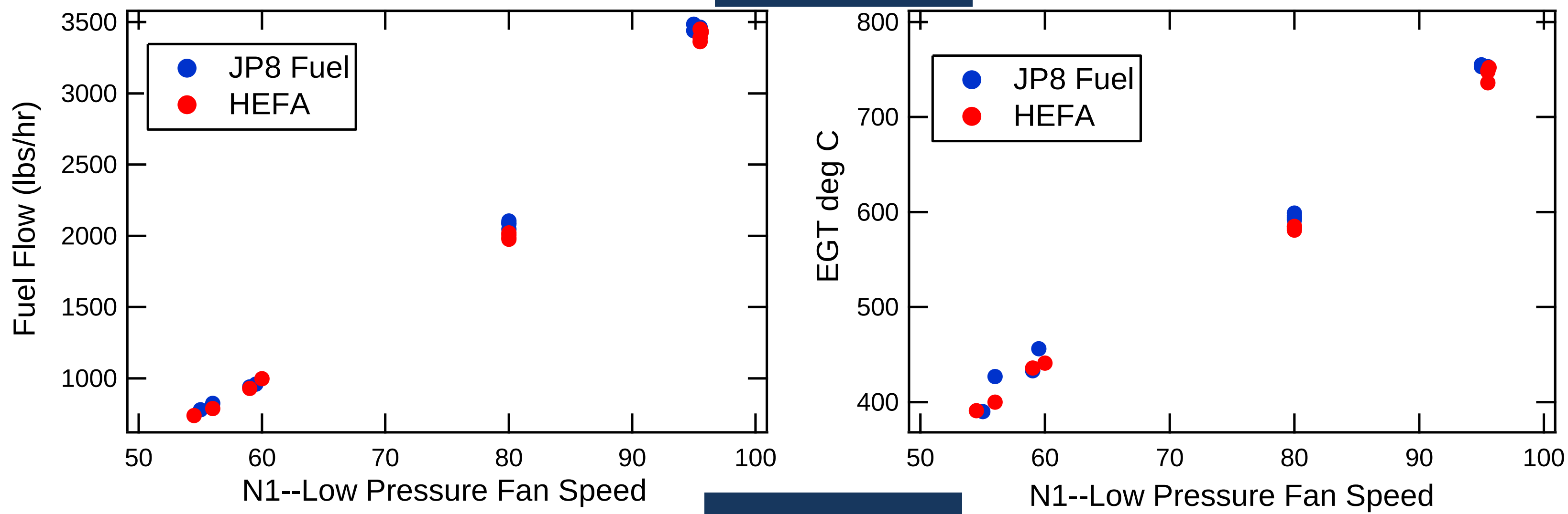
<u>Flight Rules</u>

- Contrails must be visible to outline wingtip vortices
- Falcon to exit plume when wake-vortex roll-up evident
- Far-field measurements restricted to sampling exhaust/ice detraining from top of wake vortices
- Falcon to remain clear of contrail until wake vortices decay
- Must remain < 50 NM from landing strip

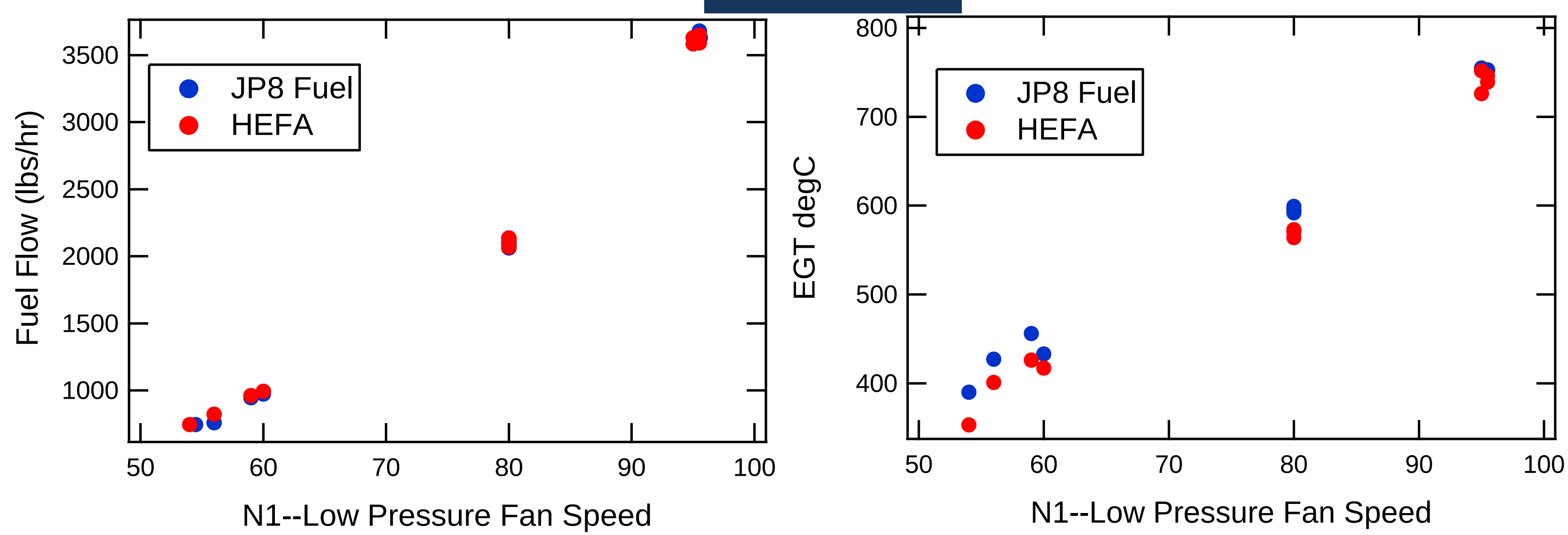


Fuels Exhibited Similar Performance at Cruise

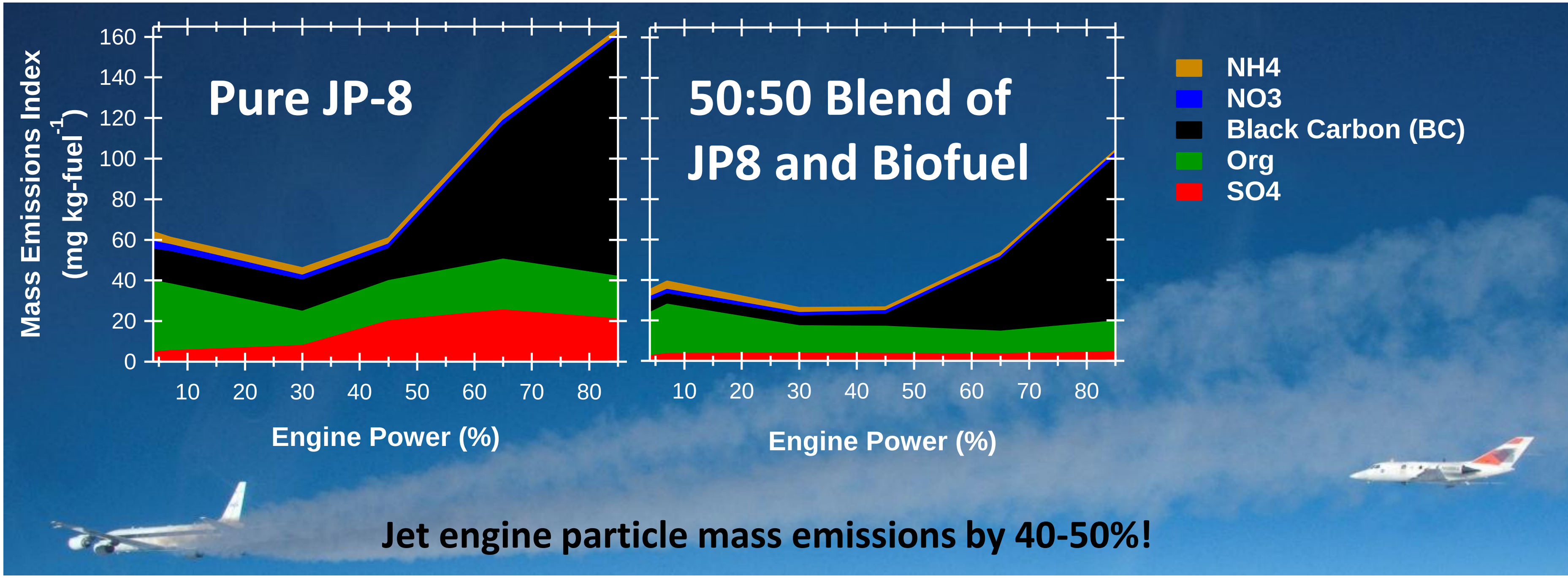
#2 Engine

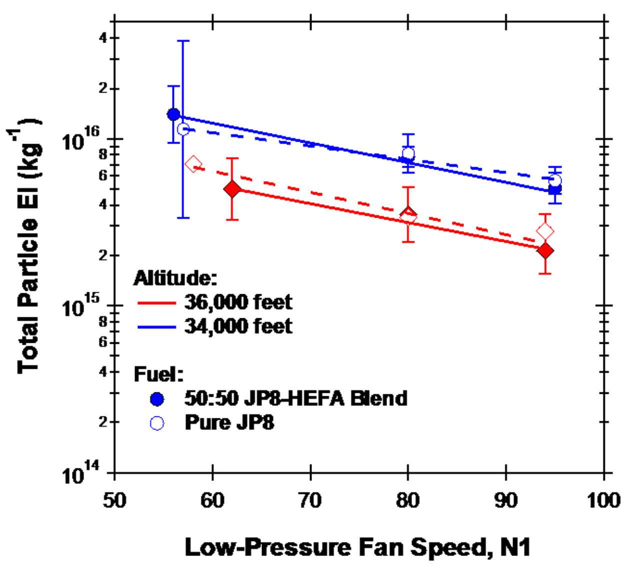


#3 Engine

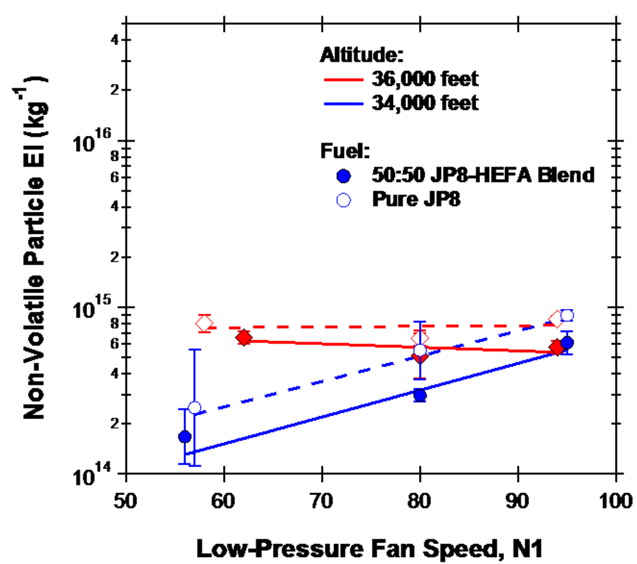


Blended Bio-Fuel Clearly Reduced PM Emissions





Soot number density also reduced by half, but total PM number unchanged because of nonlinear dependence on fuel sulfur concentration



ACCESS-1 was Mostly Successful, But……

- DC-8 fuel system led to slow contamination of the JP-8
- Did not have persistent contrails, which limited far-field sampling
- Flight rules did not allow entering contrails as long as vortical motion was present, further restricting sampling in aged plumes
- Found that ice particles scavenged aerosols, observations highly variable
- Found that cloud particles were mostly smaller than our instruments could detect
- Instrument suite wasn't adequate to address aerosol composition questions

ACCESS-2 Objectives

•Establish fuel and thrust effects on emissions at cruise and the relationship between ground and cruise black carbon emission indices

•Examine the impact of contrail processing on aerosol emission indices

•Investigate the relationship between BC #/size and ice particle characteristics as a function of ambient conditions

•Investigate the role of fuel sulfur in volatile aerosol and contrail formation at cruise

•Obtain detailed wake turbulence measurements to validate wake-vortex model predictions

ACCESS-2 Plan was presented at the International Forum for Aviation Research Meeting in July 2013 international partners were invited to participate—NRC-Canada, DLR-Germany and JAXA-Japan signed on.

Benefits of Collaborations

- International participants bring a broad range of scientific expertise to ACCESS—many have been doing this type of work for 20 years!
- Conducting work in cooperation reduces duplication of effort, helps build scientific consensus in interpreting observations
- Resources are limited, fuels and flight hours are expensive-- partnerships help spread the costs
- Sampling aircraft capabilities limited, multiple platforms with complementary instruments greatly broaden measurements suite
- Piloting sampling aircraft highly demanding, multiple platforms reduces work load, increases time on station
- Multiple sampling platforms provide opportunity to simultaneously observe exhaust plume/contrails at different ages


DLR Team


NRC Team


NASA GRC, LaRC

ACCESS-2 Experiment Summary

Sponsor:	NASA ARMD Fixed Wing Project
Participants:	NASA GRC, LaRC, AFRC, DLR, NRC-Canada
Dates:	May 5-30, 2014
Location:	Armstrong Flight Facility, Palmdale, CA
Fuels:	40,000 gals Low S Jet A 6,250 gals HEFA (blended 50:50 w/Jet A)
Source:	DC-8 w/CFM56-2C engines
Sampling: Aircraft	NASA HU-25 Falcon DLR Falcon 20 NRC Canada T-33
Flights:	28 Hours of DC-8 flight time enough for 7, 4-hour flights
Ground:	4 hrs engine run time

ACCESS-2 Source and Sampling Platforms

Variable	DC-8	HU-25C	Falcon 20	T-33
Overall Length	187 ft	56 ft	56 ft	38 ft
Wingspan	148 ft	53 ft	53 ft	42 ft
Max Landing Wt	275,000 lb	28,880 lbs	28,880 lbs	
Max Gross Wt	355,000 lb	30,325 lbs	30,325 lbs	16,800 lbs
Powerplants	(4) CFM56-2B	(2) Garrett ATF-3-2C	(2) Garrett TFE 731-5BR-2C	RR Nene 10 turbojet
Cruise	0.8 mach	0.65 mach	0.72 Mach	0.8 mach
Range	7,000 mi	2,080 mi	2,080 mi	1,275 mi

Platform Instruments

Parameter	NASA HU-25	DLR Falcon 20	NRC CT-133
CO_2	LGR, Licor 820 (Wing)	Picarro	Licor 840A
CO	LGR		
CH_4		Picarro	Offline Flask Canisters
H_2O	DLH		Licor 840A
Hydrocarbons		Chemical Ionization MS	Offline Flask Canisters
H_2SO_4		Chemical Ionization MS	
NO and NO_2	LGR Cavity Ringdown	Chemiluminescence	Thermo 42I (Chemlum.)
O_3	2B Tech	2B Tech	
Ultrafine Aerosol (>3-5 nm)	TSI 3025 CPC	CPC	
Fine Aerosol (>10 nm)	TSI 3010 CPC	2 CPCs (>10nm , >14 nm)	TSI 7610 CPC
Nonvolatile Aerosol >10 nm	TSI 3010 CPC w/ thermal denuder	CPC w/ thermal denuder	
Fine Aerosol Size	TSI SMPS 3776	Multiple CPCs	
Accumulation Mode Aerosol Size	DMT UHSAS	Optical Particle Counter, DMT UHSAS, PCASP	
Soot Mass	PSAP	PSAP, SP2	Artium LII-200 BC
Aerosol Composition	HR-ToF-AMS		
Cloud Particle Size	CDP, FSSP-300	FSSP-100	FSSP-100
Cloud Particle Size/Images	CAPS	CAPS-DPOL	
T, P, Altitude, TAS, IAS, etc.	Air Data / Ballard	Air Data	Air Data
Platform Position, Attitude and Accelerations	Applanix INS/GPS	INS/GPS, Gust Probe	INS/GPS, Gust Probe

Flight Plan for 3 chase planes

- DC-8 and T-33 take off together and T-33 samples in the climb
- After 40-50 minutes, first Falcon takes off and joins the formation at 32-36 kft
- T-33 RTB after 1 hr, leaves Falcon to sample solo for ~40 mins
- Second Falcon takes off 40 minutes after first and joins formation for tag-team sampling
- First Falcon RTB after 3 hrs, leaves second Falcon to sample solo for 40 mins
- Typical flights lasted 4.5 hours

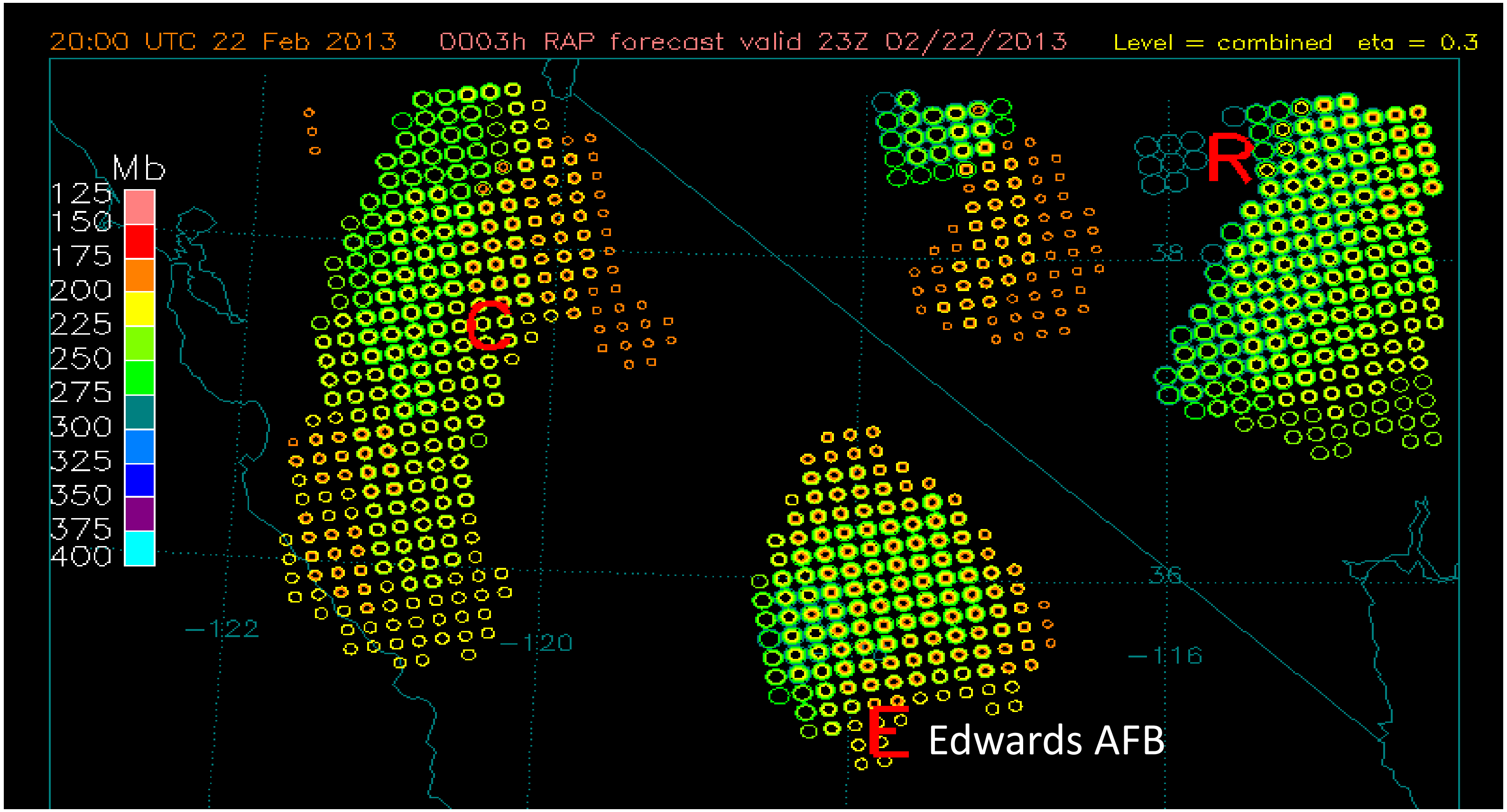
Engine Thrust Varied to Study Power-Dependent Emissions

Inboard Engines Idled Back

Outboard Engines Idled Back

Varied Engine FF from ~1000 to 3000 lbs/hr, balancing Inboard/Outboard thrust to maintain constant 200 knots IAS

Contrails Scarce, Used LaRC and DLR Models to Plan Flights



Langley Contrail Forecast Model (Pat Minnis, PI)
http://enso.larc.nasa.gov/sass/contrail_forecast/contrail_prediction.html

Special Thanks to Ulrich Schumann for providing high quality contrail predictions and meteorological products on a daily basis during all of ACCESS-II

ACCESS Also Included Ground Test Measurements

Enabled additional measurements, power settings, and traceability to past results

- Probe stands mounted at 30 m behind both inboard engines
- Falcon instrument payload + the mobile laboratory with additional instruments (shown at right)
- Cycle through fuels, power settings over an approximately 4-hr. experiment

Summary of Field Activities

- Flight 1: Standard Jet A, 4-aircraft test plan verification, May 7
- Flight 2: Low S Jet A/HEFA Blend, all aircraft, May 8
- Flight 3: Low S Jet A/HEFA Blend, all aircraft, May 9
- Flight 4: Low S Jet A/HEFA Blend, all aircraft, May 10
- **Flight 5: DC-8 Fuel System Problem, May 12---Stand-down for 10 days**
- **Bolden Visit, mini-science team meeting, May 13**
- Flight 6: Chase Aircraft sample each other, May 15
- Flight 7: Falcon 20/HU-25 chase each other, May 16
- **Falcon 20 and CT-133 depart for home, May 17**
- DC-8 Ground Test, May 21
- Flight 9: Med S Jet A/HEFA Blend, DC8+HU-25, May 22
- Flight 10: Med S Jet A/HEFA Blend, DC8+HU-25, May 27
- Flight 11: Med S Jet A/HEFA Blend, DC8+HU-25, May 29
- Flight 12: Med S Jet A/HEFA Blend, DC8+HU-25, May 30
- HU-25 Transit home, May 31

ACCESS-2 Major Accomplishments and Results

Accomplishments

- Developed/applied successful multiplatform sampling techniques
- Acquired detailed cruise emissions data at 3 power settings and 5 altitudes for 3 fuels
- Obtained comprehensive wake vortex observations for model development and validation
- First observations of aerosol composition in aircraft exhaust plume
- First direct measurements of contrail EI_ice with corresponding EI_soot data

Significant Results

- No difference in DC-8 performance or fuel system operations between fuels
- No difference in NOx, CO, and HC emissions between fuels
- Blend reduced soot particle number and mass emissions by 50% on ground and at cruise
- Sulfate aerosol number and mass depends fuel sulfur—no difference between Blend and low-S JetA
- Volatile aerosol showed strong engine oil signature at altitude
- EI_ice increases with EI_soot
- Ice particle sizes decrease with increasing soot emissions
- Between 10 and 100% of soot particles activated to form ice

Needed Research and Opportunities

ACCESS was a good start, but….

- Only a single fuel examined, need emissions data for fuels with different hydrocarbon compositions
- Detailed data only available for 30-year-old technology (DC-8), need to observe other platforms
- Fuel sulfur story far from complete, need data for broad range of Sulfur concentrations
- Contrail statistics poor, need observations across a broad range of conditions, fuel and contrail ages

There were no observations within Persistent Contrails in ACCESS

Upcoming Opportunities

NASA APU fuel characterization at GRC—Feb, 2015

- Will measure gas and aerosol emissions for 5 different alt fuels
- Will include fuel sulfur and aromatic content experiments

DLR ECLIF—2014 thru 2018

- Includes laboratory, ground and airborne studies of multiple fuels
- Airborne component will use A320 and sampling aircraft to study fuel effects on emissions and contrails, similar to ACCESS-2

QUESTIONS?