Nanoparticle and contrail ice formation in next generation aviation fuels and engines

<u>Fangqun Yu</u>[1], Bernd Kärcher[2], Bruce Anderson[3]

[1]State University of New York at Albany

[2]DLR Oberpfaffenhofen, Germany

[3]NASA Langley Research Center

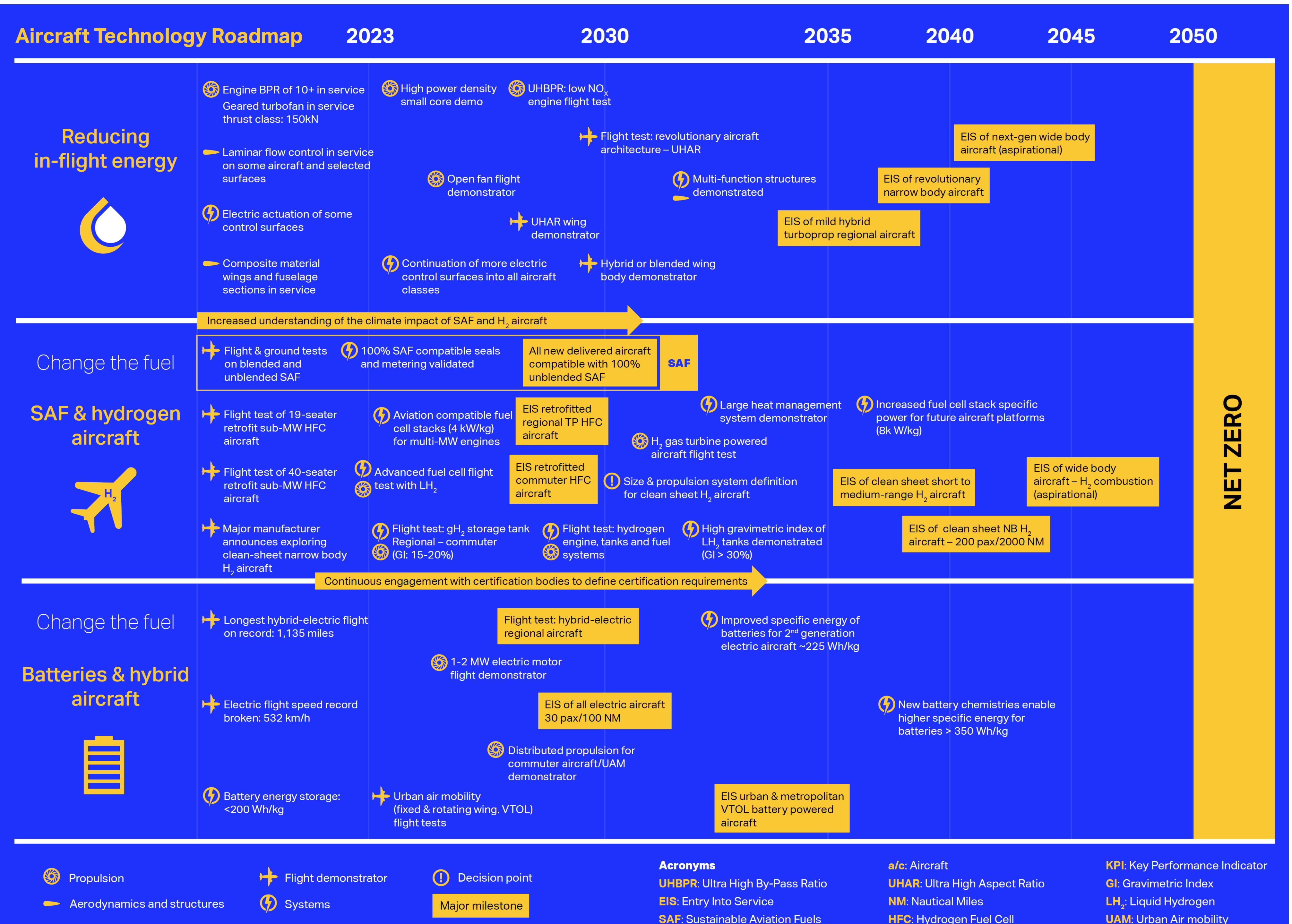
Background contrail photo taken by F. Yu on January 11, 2023

International Air Transport Association (IATA)

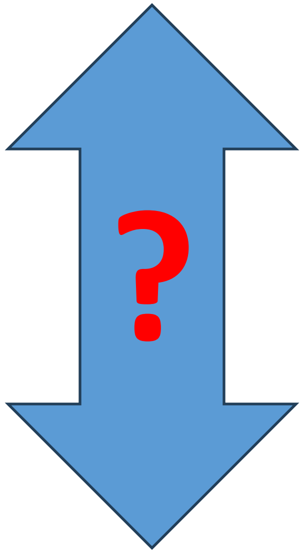
IATA is the trade association for the world's airlines, representing some 330 airlines over 80% of total air traffic.

List of contributing organizations to the technology and infrastructure roadmaps

- Aerospace Technology Institute
- Cranfield University
- Airbus
- DLR
- Air Liquide
- GE Aerospace
- ACI Airports Council International
- GKN Aerospace
- ATAG Air Transport Action Group
- Jacobs
- Air Transportation Systems Lab @ UCL www.ATSLab.org
- NASA
- BlueSky Data 2 Decisions
- to70
- Boeing
- Universal Hydrogen
- Carbon Engineering
- ZeroAvia
- climeworks



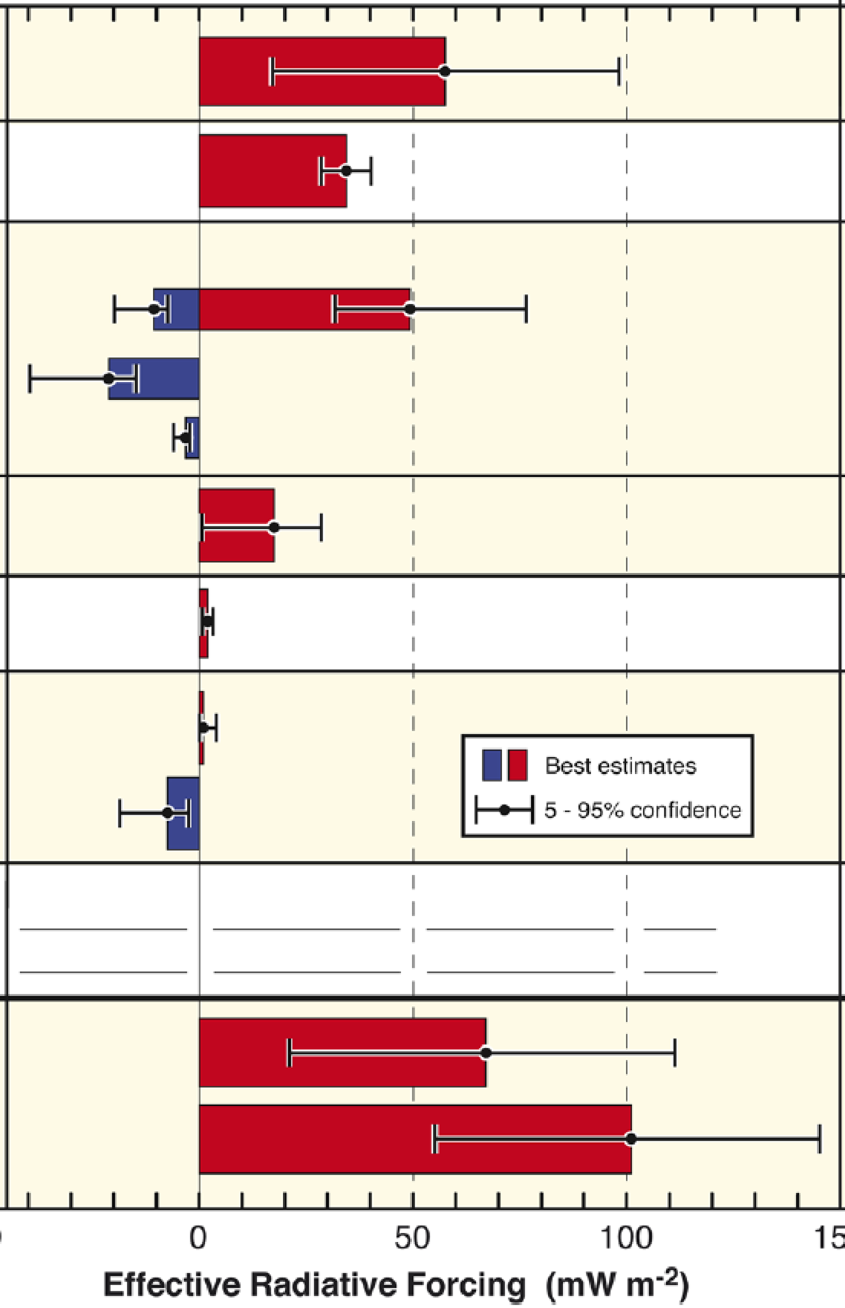
Next generation aviation fuels and engines



Nanoparticles

Lee et al., 2021

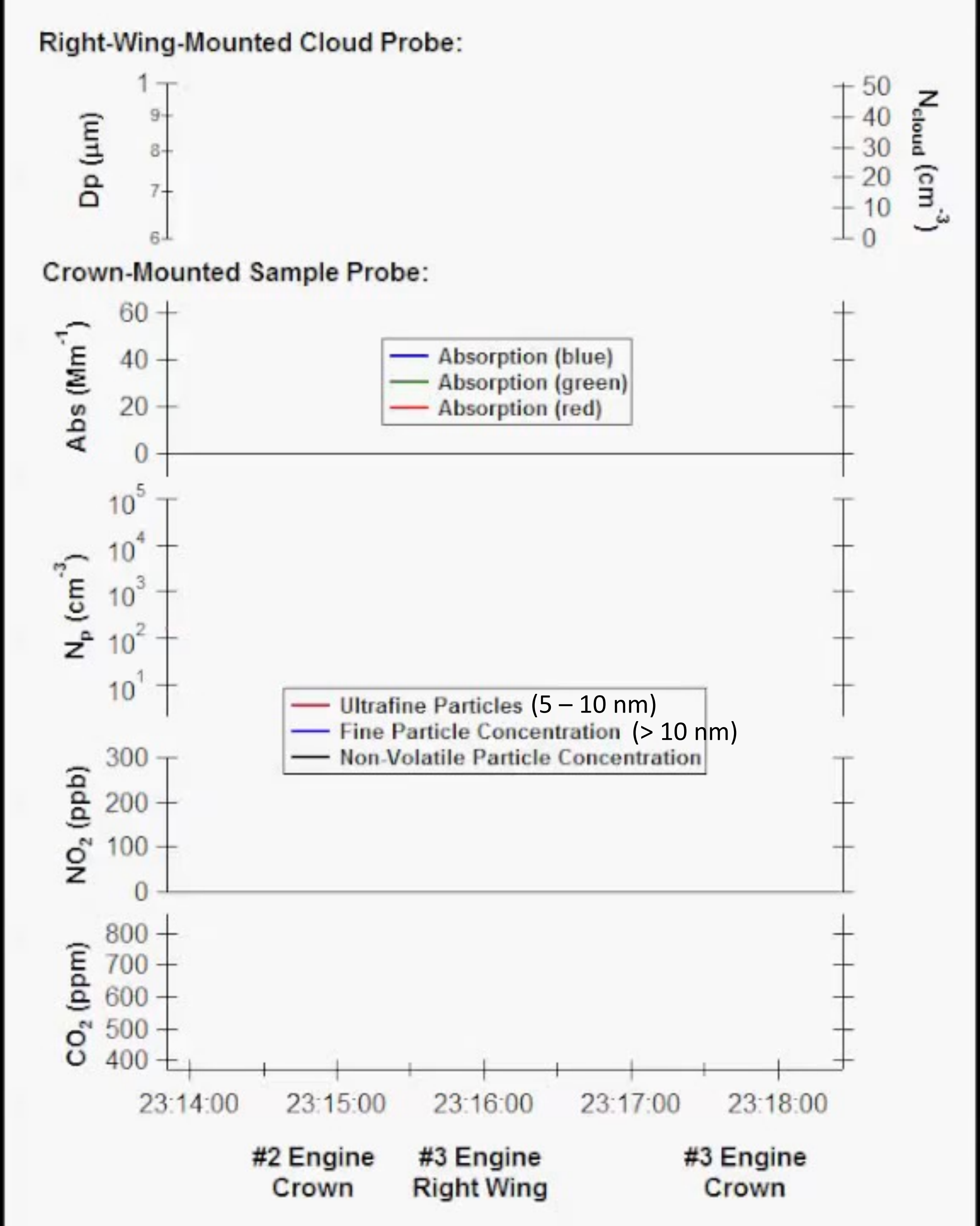
Global Aviation Effective Radiative Forcing (ERF) Terms
(1940 to 2018)

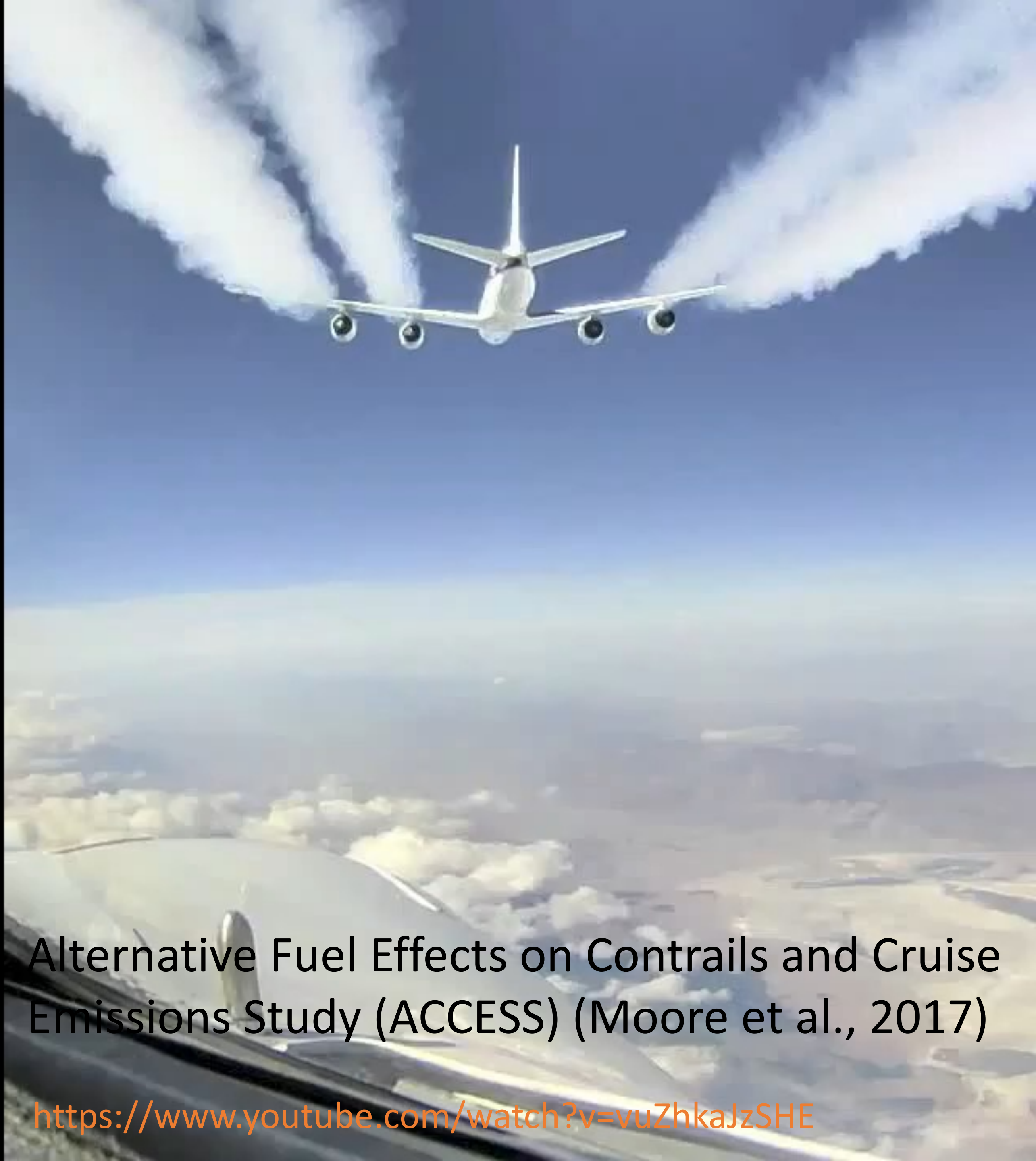


	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions				
-from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
-from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	—
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	—

Nanoparticles

Health





Alternative Fuel Effects on Contrails and Cruise Emissions Study (ACCESS) (Moore et al., 2017)

https://www.youtube.com/watch?v=vuZhkaJzSHE

How <u>measurements</u> combined with <u>theoretical study and numerical modeling</u> can advance process-level understanding and prediction capability

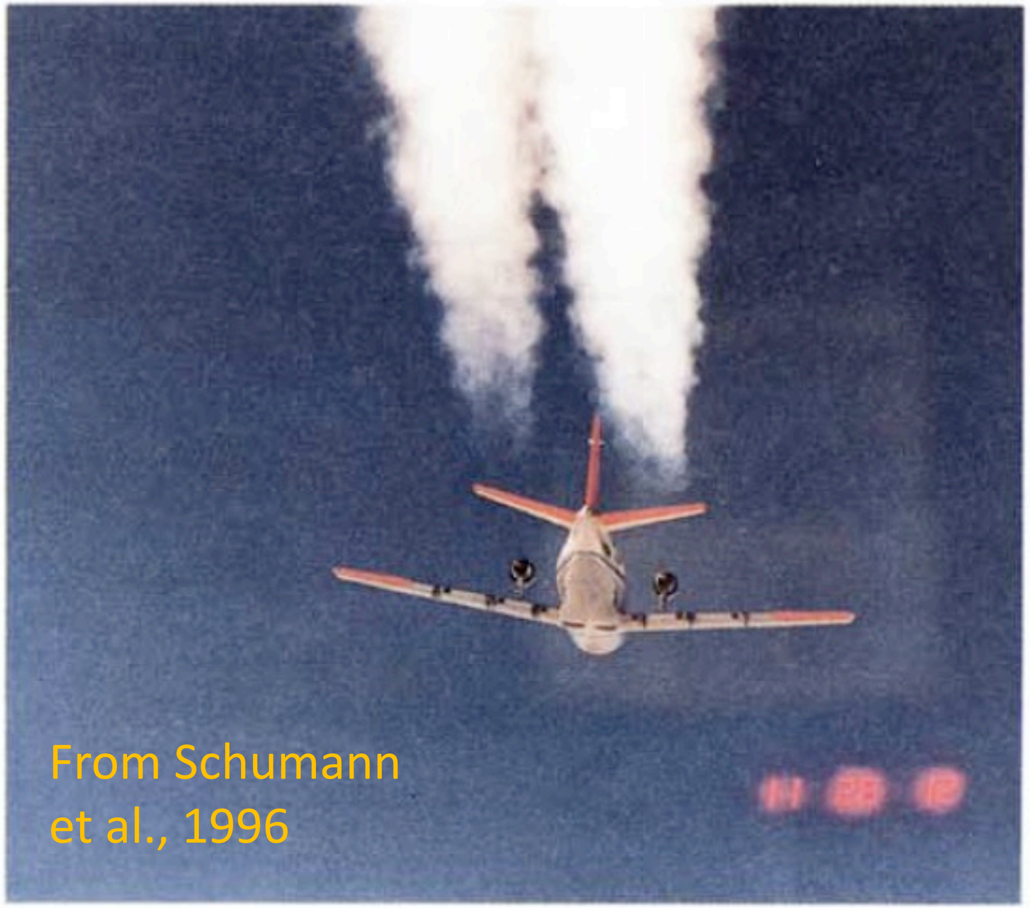
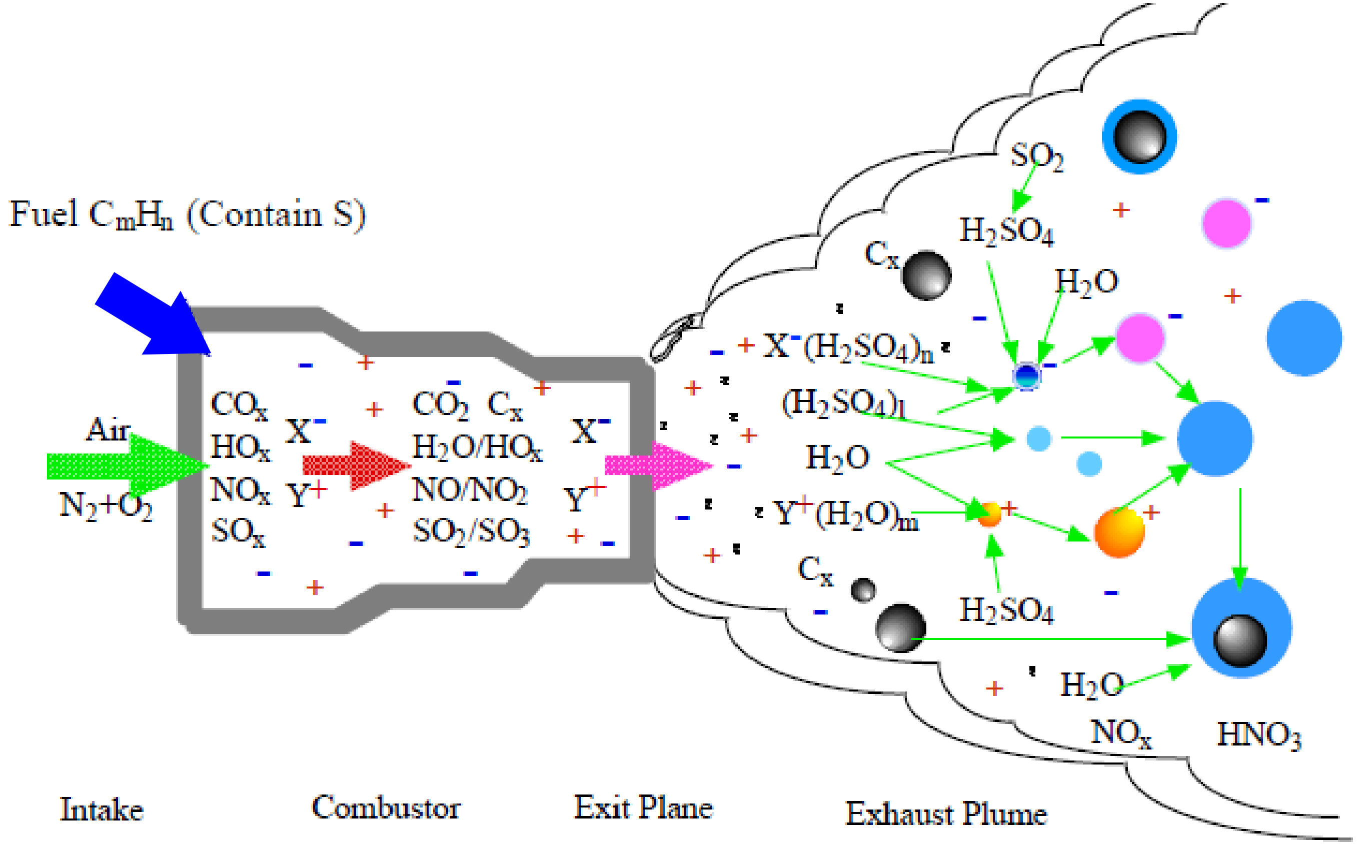
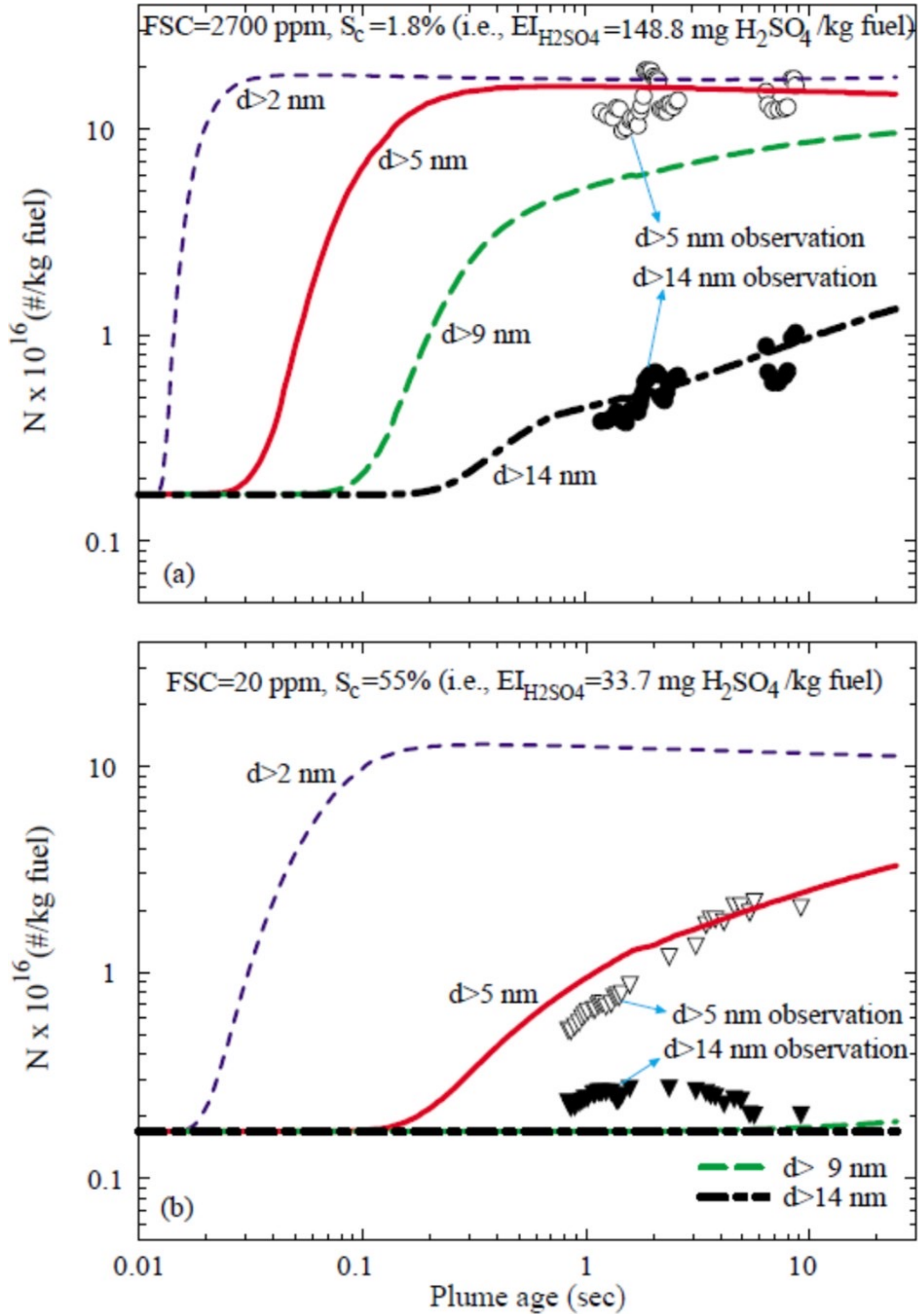


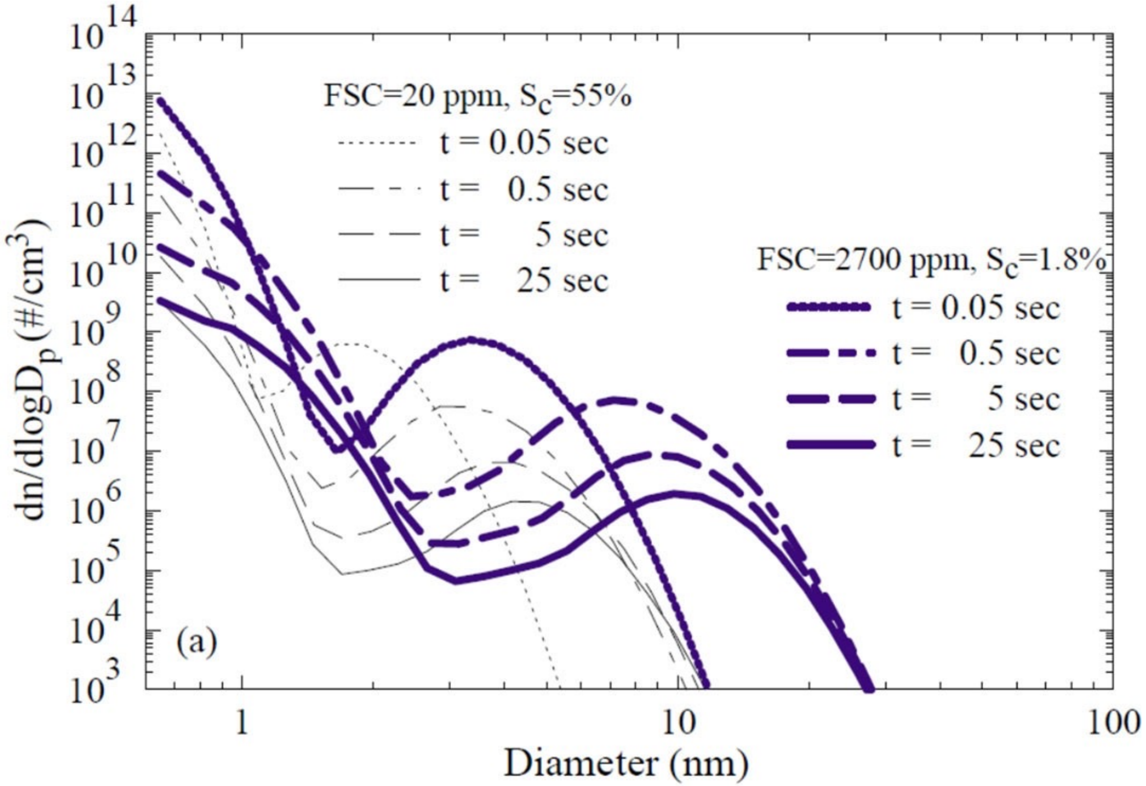
Plate 3. Photo of the ATTAS flying with different fuels as seen from the Falcon cockpit at a distance of less than 100 m, at 1128:12 UTC, at FL 300 (9140 m) on a course toward SWS.



Yu, 1998, Ph.D Dissertation: "A Study of the Formation and Evolution of Aerosols and Contrails in Aircraft Wakes: Development, Validation and Application of an Advanced Particle Microphysics (APM) Model"

Chemi-ions are important for volatile particle formation (Yu and Turco, 1997; Yu et al., 1998, 1999)





Data from SULFUR-5 (Schröder et al., 1998)

Figure from Yu, Turco, Kärcher, and Schröder, 1998

FSC = 20 ppm

Organic species can be essential in volatile particle formation and growth, especially when fuel sulfur content is low.

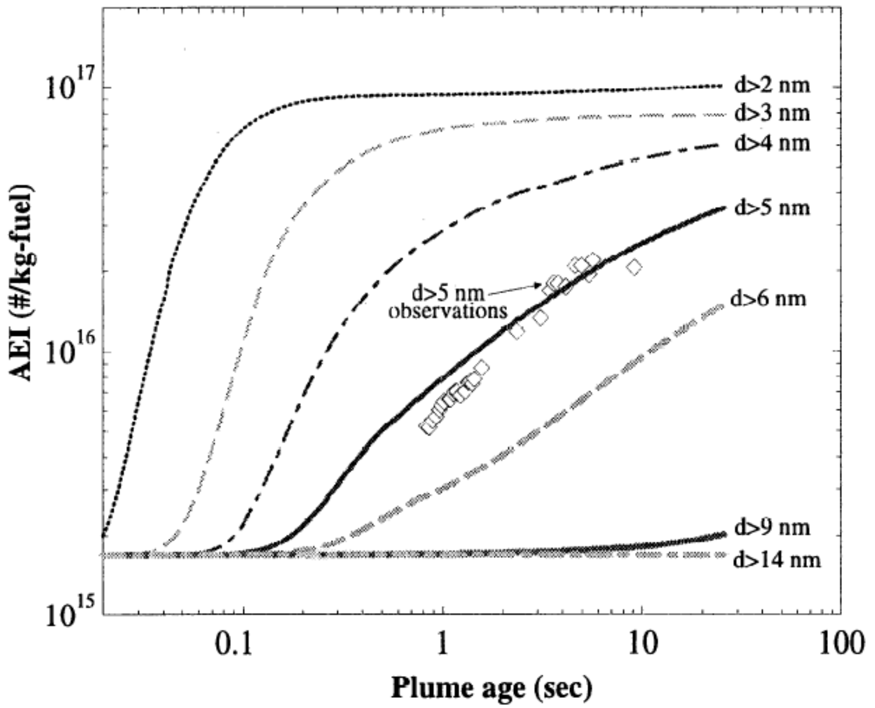


Figure 2. Computed evolution of the AEI for the total number of particles larger than certain assumed cutoff sizes for conditions that apply to the LS SULFUR-5 case (each line represents the variation over time of the AEI corresponding to a specific cutoff diameter). Key model parameters are the sulfuric acid emission index, $EI_{H_2SO_4}$=6 mg/kg fuel (i.e., S_c=10% and FSC=20 ppmm), the emission index of condensable organic compounds, EI_{POM}=23 mg/kg fuel, and the initial chemiion concentration, $n_{io}=2\times10^9$ / cm^3 (with half of the ions being positive and half negative). Shown for comparison are measured AEI values (diamonds) corresponding to particles with d>5 nm taken from *Schröder et al.* [1998].

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 104, NO. D4, PAGES 4079–4087, FEBRUARY 27, 1999

The possible role of organics in the formation and evolution of ultrafine aircraft particles

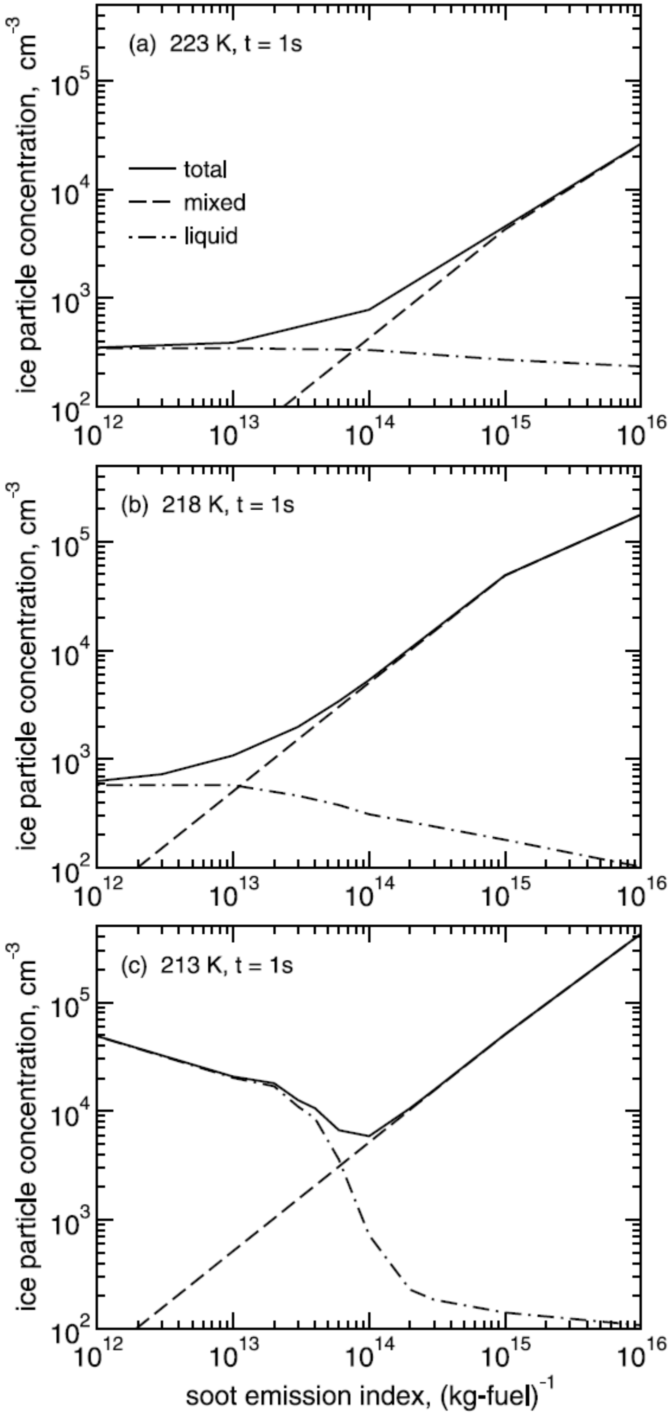
Fangqun Yu and Richard P. Turco
Department of Atmospheric Sciences, University of California at Los Angeles

Bernd Kärcher
DLR Oberpfaffenhofen, Institut für Physik der Atmosphäre, Wessling, Germany

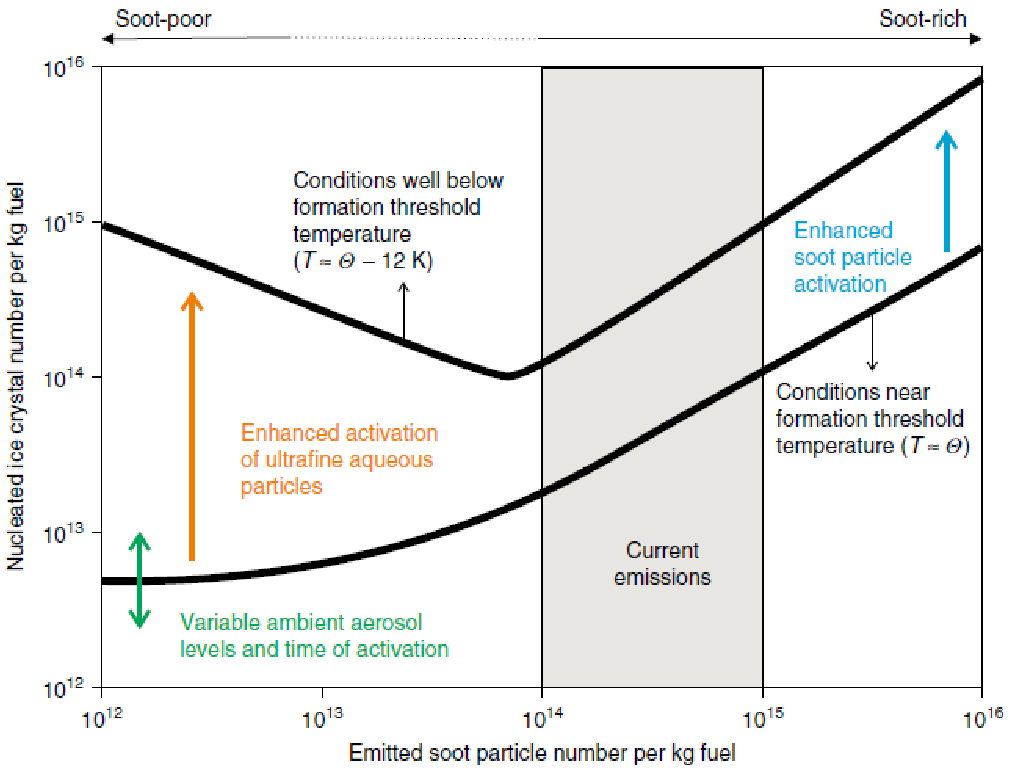
GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L01804, doi:10.1029/2008GL036649, 2009

Role of aircraft soot emissions in contrail formation

B. Kärcher[1] and F. Yu[2]



- Volatile plume and ambient particles **compete** with soot particles for the formation of contrail ice particles.
- Contrail ice formation is **dominated by soot particles in soot-rich regime** but **by volatile particles in soot-poor regime** at T well below the contrail formation threshold T.

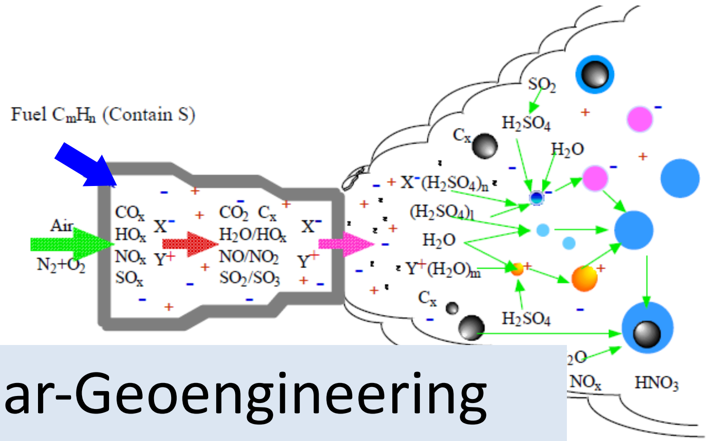


Kärcher, *Nature Communications*, 2018

How good is the model prediction? What are uncertainties?

An updated plume aerosol and contrail microphysics (ACM) model

Particle formation and evolution in aircraft exhaust plume



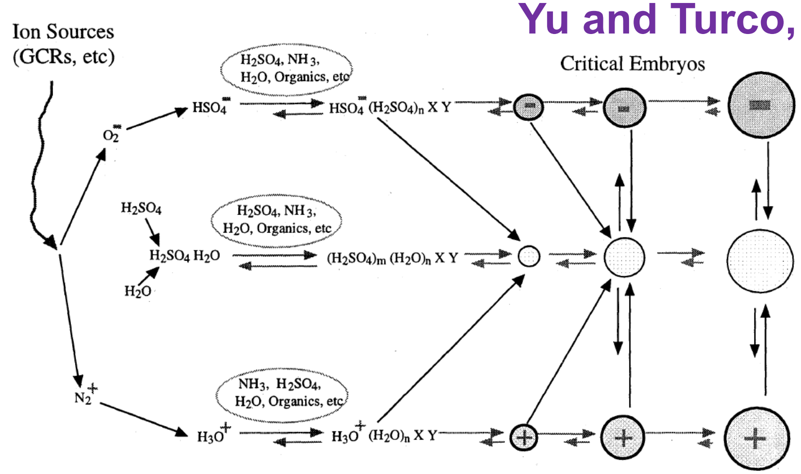
Yu and Turco, 1997, 1998a, 1998b, 1999; Yu et al., 1998, 1999; Turco and Yu, 1997, 1998, 1999. Kärcher et al., 1998, 2000; Kärcher and Yu, 2009

Solar-Geoengineering
SAFs/hydrogen/Contrail

https://www.albany.edu/~yfq/publication.html

Ions and particle formation in ambient air

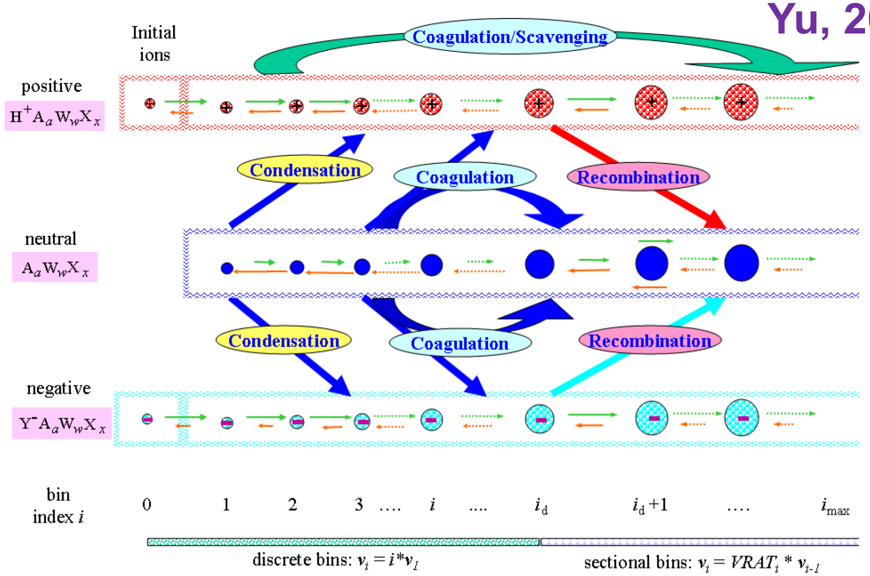
Yu and Turco, 2000, 2001



Nadykto and Yu, **2003**, 2004a,b; Yu, **2005a,b**

Second-generation IMN model

Yu, 2006

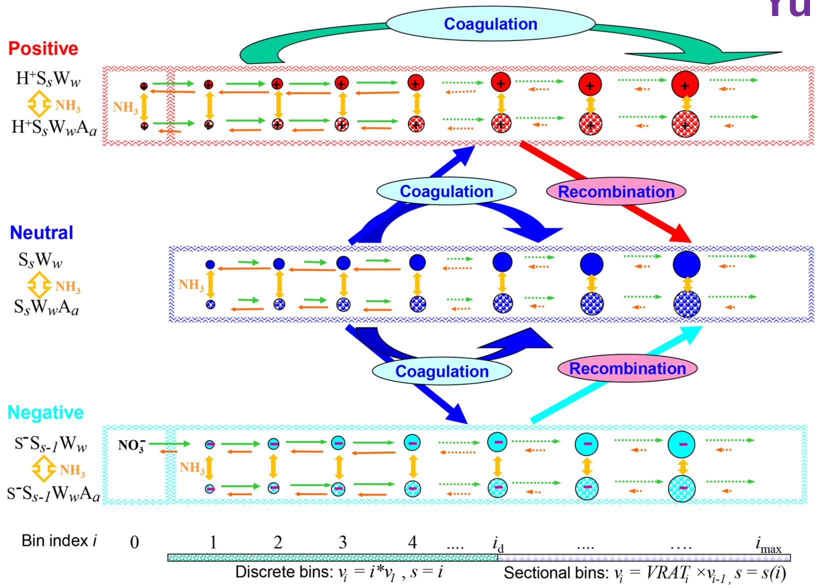


Yu, 2007

Nadykto et al., 2008a,b,c; 2009a,b; Herb et al., 2011, 2013

Third-generation IMN model: Ternary IMN

Yu et al., 2018



Applications of updated plume aerosol and contrail microphysics (ACM) model

Environmental Science & Technology

pubs.acs.org/est
Article

On Nucleation Pathways and Particle Size Distribution Evolutions in Stratospheric Aircraft Exhaust Plumes with H_2SO_4 Enhancement

Fangqun Yu,* Bruce E. Anderson, Jeffrey R. Pierce, Alex Wong, Arshad Nair, Gan Luo, and Jason Herb

Cite This: *Environ. Sci. Technol.* 2024, 58, 6934–6944

Read Online

Yu, F., B. Kärcher, and B. E. Anderson, Revisiting contrail ice formation: Impact of primary soot particle sizes and contribution of volatile particles, Environmental Science & Technology, under review, 2024.

ECLIF (Emission and CLimate Impact of alternative Fuels)

ECLIF campaigns 1-2

Voigt, C., Kleine, J., Sauer, D., ..., and Anderson, B. E.: Cleaner burning aviation fuels can reduce contrail cloudiness. *Commun Earth Environ* **2**, 114 (2021).

Fig. 1 The NASA DC8 research aircraft probing contrails from the DLR A320 burning sustainable aviation fuel blends. Photo showing the DC8 chasing a contrail from the A320 burning a sustainable aviation fuel blend above Germany on 24 January 2018.

ECLIF campaign 3

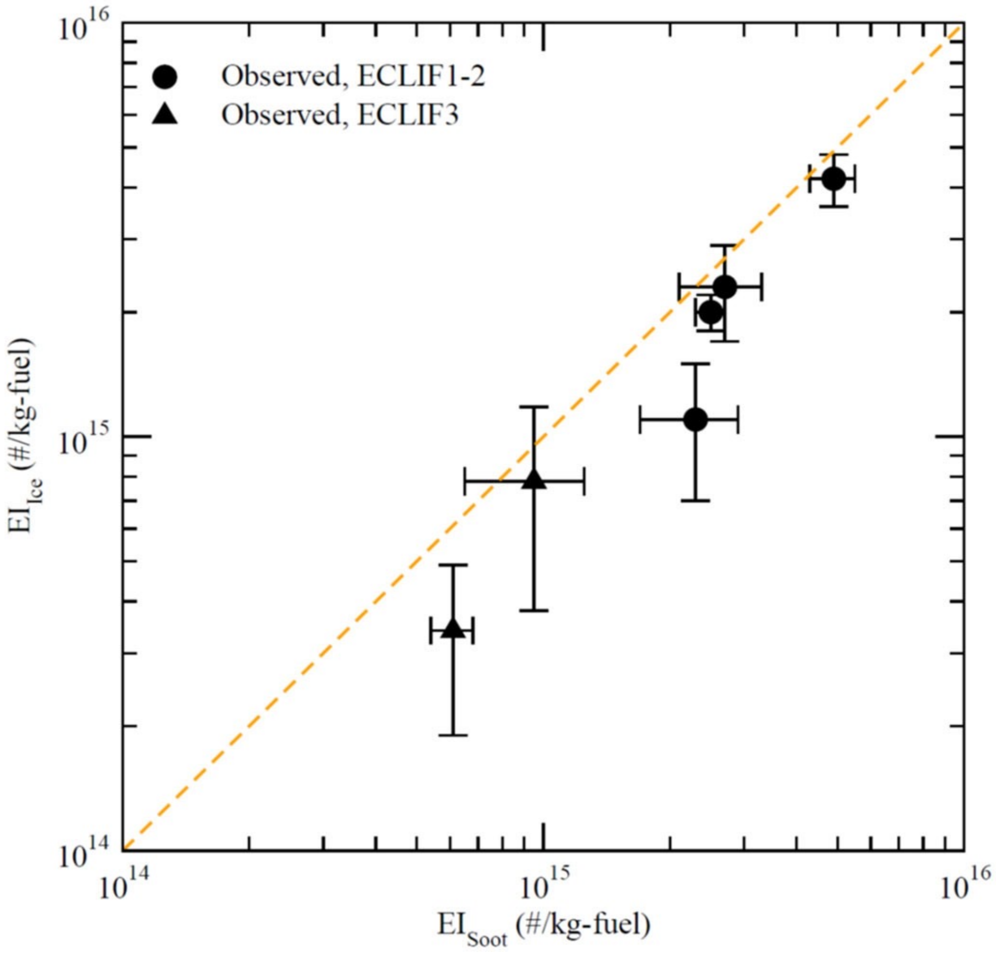
https://doi.org/10.5194/egusphere-2023-2638
Preprint. Discussion started: 21 November 2023

Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails

Raphael Satoru Märkl[1,2], Christiane Voigt[1,2], Daniel Sauer[1], Rebecca Katharina Dischl[1,2], Stefan Kaufmann[1], Theresa Harlaß[1], Valerian Hahn[1,2], Anke Roiger[1], Cornelius Weiß-Rehm[1], Ulrike Burkhardt[1], Ulrich Schumann[1], Andreas Marsing[1], Monika Scheibe[1], Andreas Dörnbrack[1], Charles Renard[3], Maxime Gauthier[3], Peter Swann[4], Paul Madden[4], Darren Luff[4], Reetu Sallinen[5], Tobias Schripp[6], and Patrick Le Clercq[6]

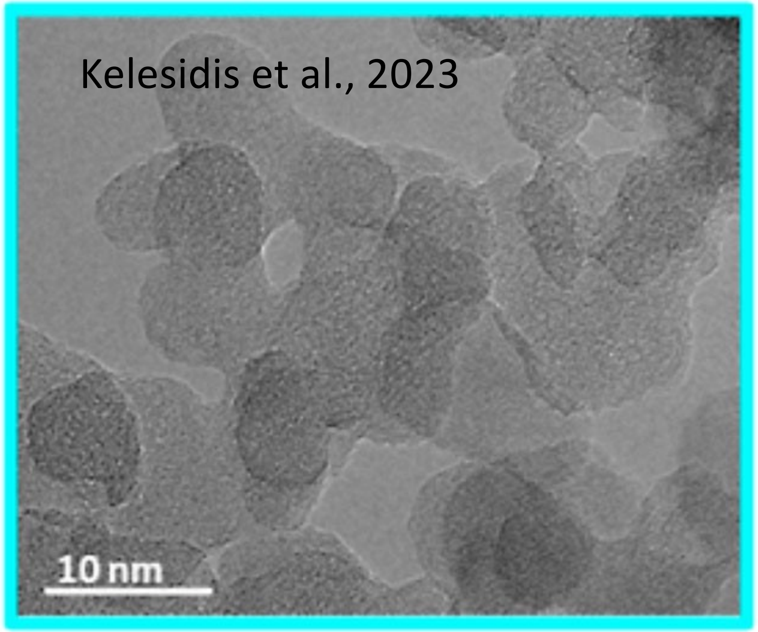
Table 1. Ambient and aircraft conditions and measurements for the six case study of ECLIF campaigns reported in this work. (Data mostly from Voigt et al., 2021 and Markl et al., 2023).

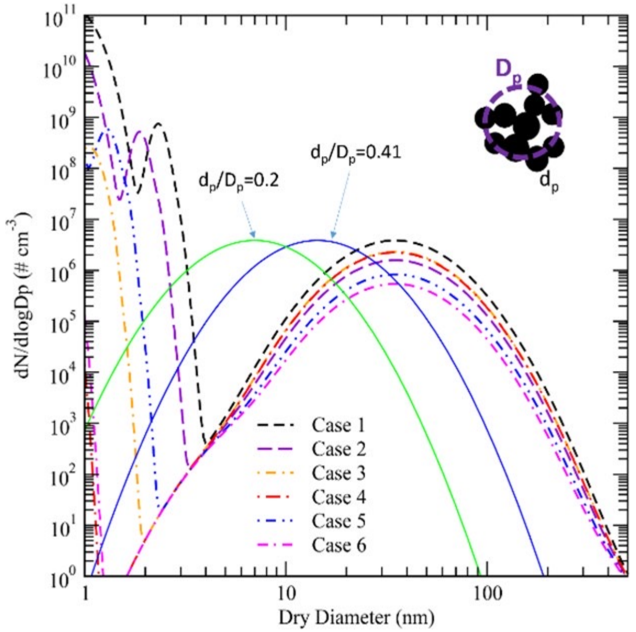
Cases	1	2	3	4	5	6
	ECLIF1	ECLIF1	ECLIF2	ECLIF2	ECLIF3	ECLIF3
Source aircraft	Airbus A320	Airbus A320	Airbus A320	Airbus A320	Airbus A350	Airbus A350
Fuel	100% Jet A-1	59% JetA-1 + 41% FT-SPK	51% JetA-1 + 49% HEFA-SPK	70% JetA-1 + 30% HEFA-SPK	100% Jet A-1	100% HEFA-SPK
H (km)	10.67	10.364	9.726	9.656	10.626	10.621
T_{amb} (K)	215	220	218	216	213.3	213.8
RH_i (%)	120	111.5	120	110	108	107.5
V_{plane} (km/h)	802.75	716.3	938.6	938.6	1044.81	1052.22
FFR (kg/h)	1180	820	1132	1091	2700	2751.3
FSC (ppm)	1350	570	70	4.1	211	7
EI_{H2O} (kg /kg-fuel)	1.227	1.283	1.287	1.297	1.258	1.35
EI_{soot} (10^{15} #/kg-fuel)	4.9±0.6	2.5±0.2	2.7±0.6	2.3±0.6	0.95±0.3	0.61±0.07
EI_{ice} (10^{15} #/kg-fuel)	4.2±0.6	2±0.2	2.3±0.2	1.1±0.4	0.78±0.4	0.34±0.15
F_{ice}	0.86±0.23	0.80±0.14	0.85±0.26	0.48±0.30	0.82±0.68	0.56±0.31

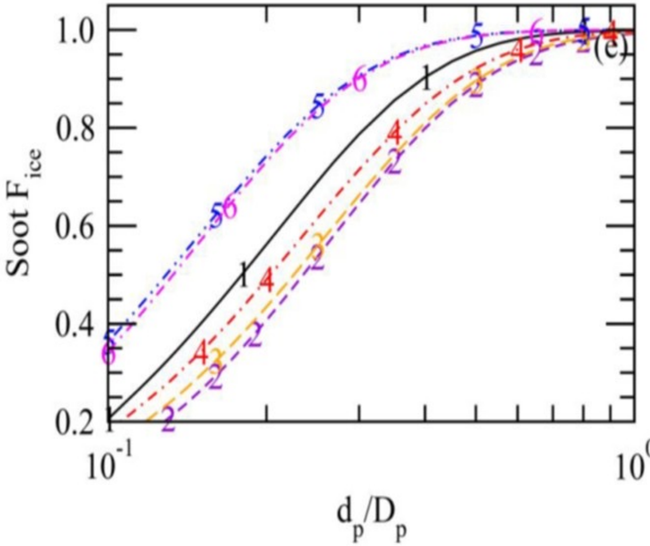


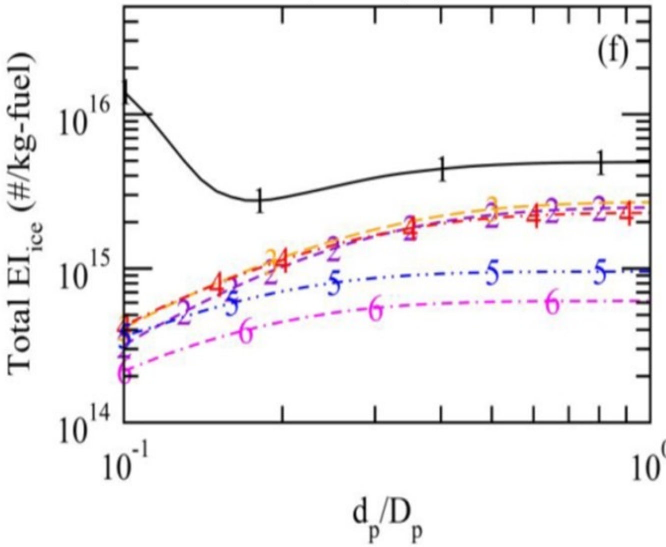
Some soot particles didn't form contrail ice particles: **Why?**

Activation of soot particles is decided by the sizes of primary soot particles







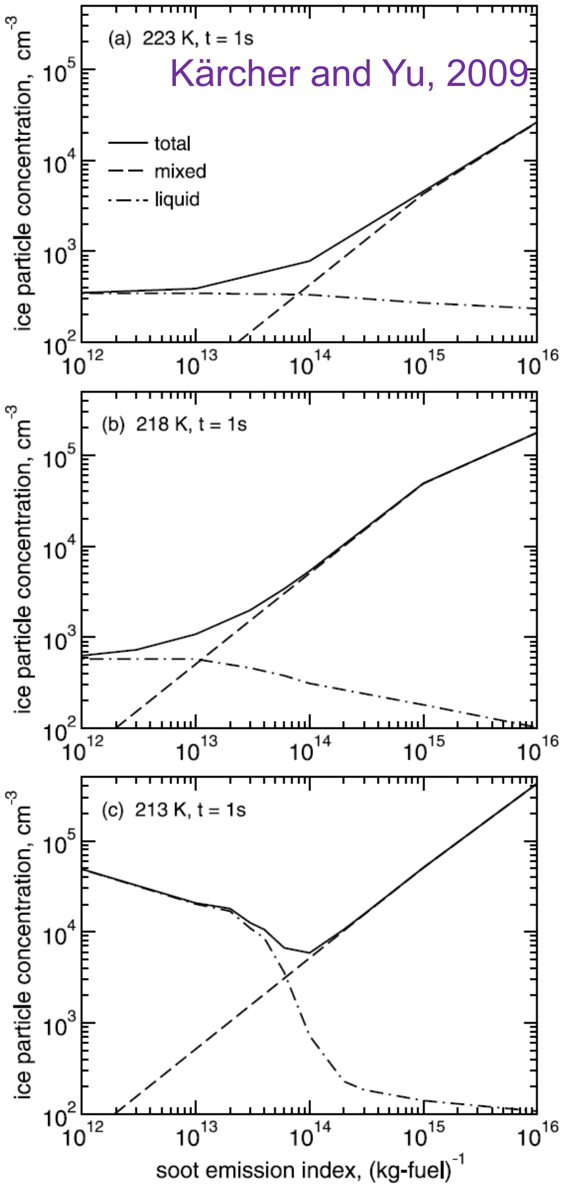


Dependence of apparent contrail ice EI on EI_{soot} under ECLIFs conditions

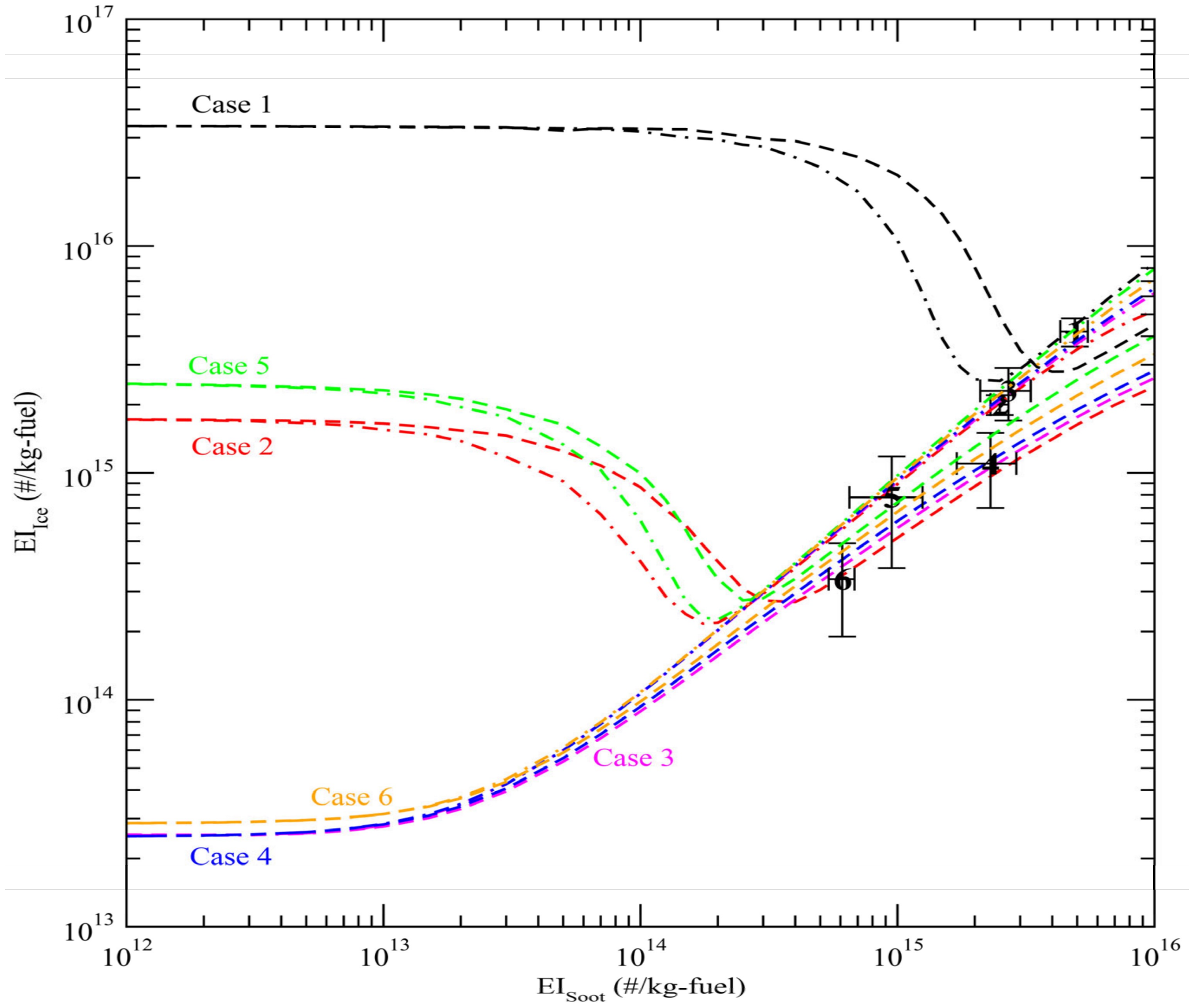
Fig. 1 The NASA DC8 research aircraft probing contrails from the DLR A320 bu
a contrail from the A320 burning a sustainable aviation fuel blend above Germa

Table 1. Ambient and aircraft conditions and me
campaigns reported in this work. (Data mostly fr

Cases	1	2	
	ECLIF1	ECLIF1	E
Source aircraft	Airbus A320	Airbus A320	Airbus
Fuel	100% Jet A-1	59% JetA-1 + 41% FT-SPK	51% Je 49% HEF
H (km)	10.67	10.364	
T_{amb} (K)	215	220	
RH_i (%)	120	111.5	
V_{plane} (km/h)	802.75	716.3	
FFR (kg/h)	1180	820	
FSC (ppm)	1350	570	
EI_{H2O} (kg /kg-fuel)	1.227	1.283	
EI_{soot} (10^{15} #/kg-fuel)	4.9±0.6	2.5±0.2	2.
EI_{ice} (10^{15} #/kg-fuel)	4.2±0.6	2±0.2	2.
F_{ice}	0.86±0.23	0.80±0.14	0.85



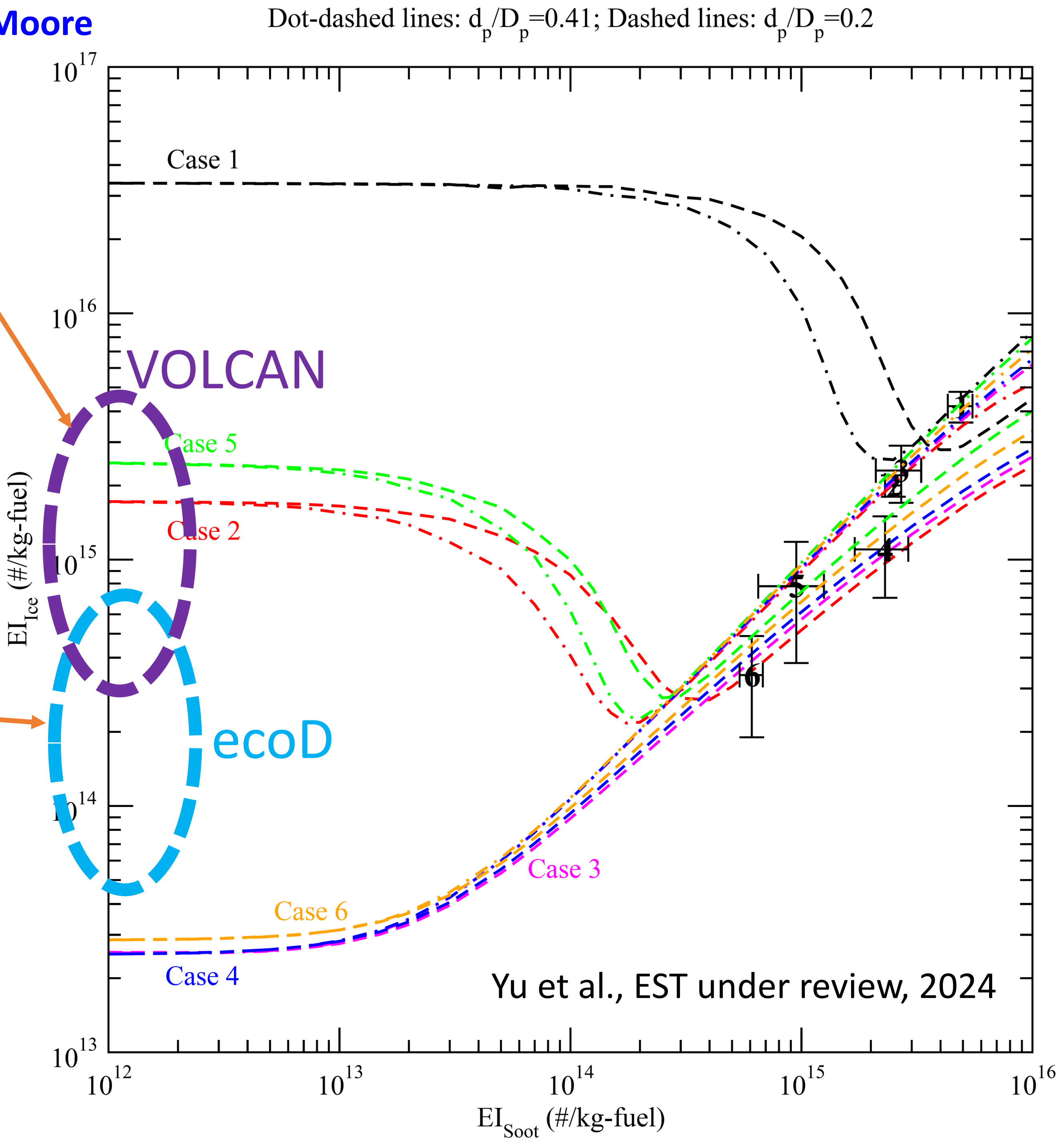
The range of conditions for volatile nanoparticles to contribute significantly to the contrail ice number budget is wider than previously found.



Personal communication with B. Anderson, C. Voigt, and R. Moore

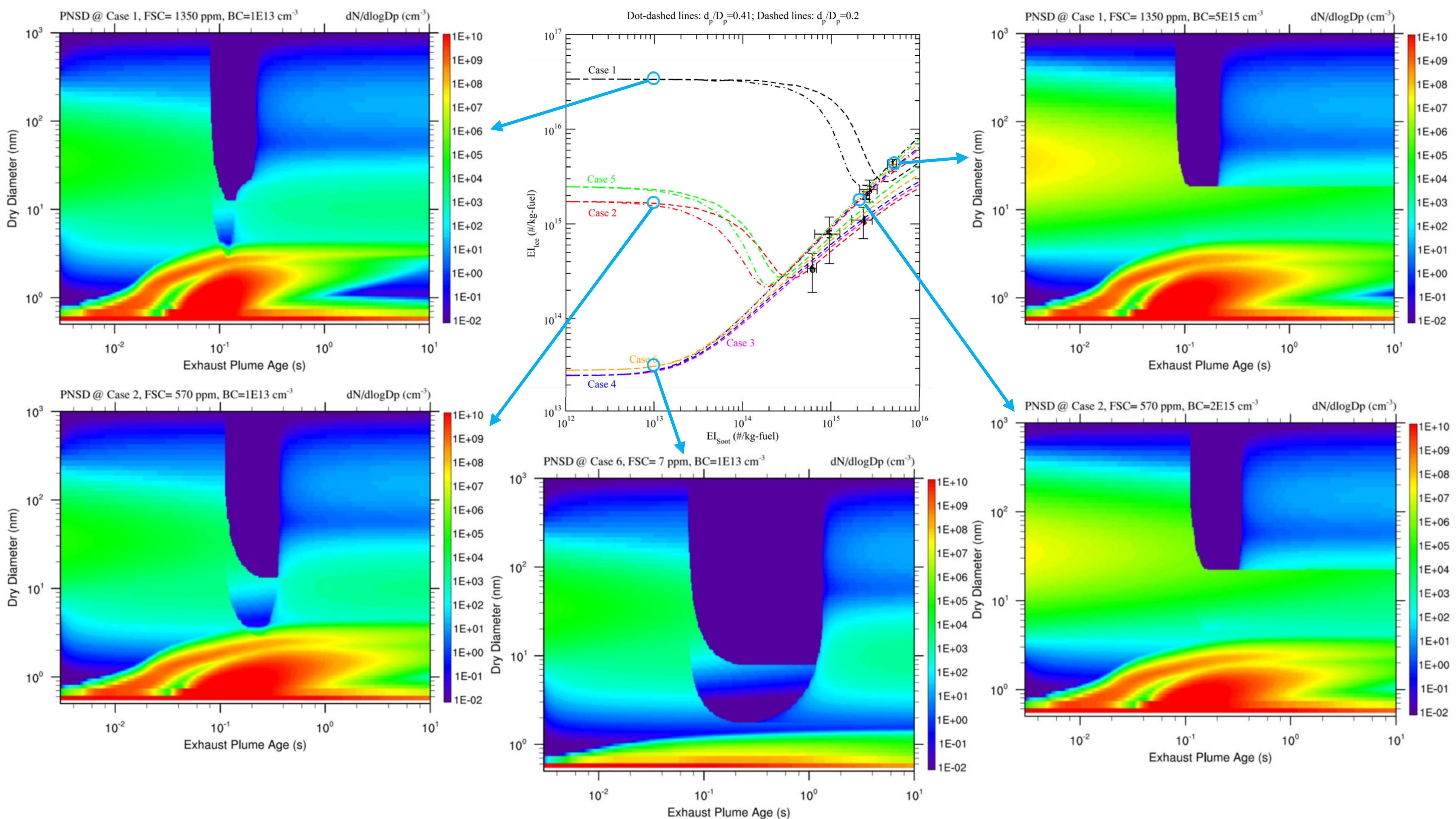
'VOL avec Carburants Alternatifs Nouveaux' (VOLCAN)

Boeing's ecoDemonstrator program



Summary

- The **aviation industry is actively pursuing new engine technologies and aviation fuels** to achieve net-zero carbon emissions by 2050. There is an **urgent need to understand the formation of nanoparticles** under various scenarios and their **implications for non-CO_2 climate impacts**.
- The **activation of non-volatile soot particles** during contrail formation is likely **determined by the sizes of primary soot particles** rather than the effective sizes of soot aggregates.
- The **range of conditions for volatile plume particles to contribute significantly to the contrail ice number budget is wider than previously found**.



Dot-dashed lines: d_p/D_p=0.41; Dashed lines: d_p/D_p=0.2
Case 1
Case 5
Case 2
Case 3
Case 6
Case 4
EI_{Ice} (#/kg-fuel)
EI_{Soot} (#/kg-fuel)
PNSD @ Case 1, FSC= 1350 ppm, BC=1E13 cm^{-3}
PNSD @ Case 1, FSC= 1350 ppm, BC=5E15 cm^{-3}
PNSD @ Case 2, FSC= 570 ppm, BC=1E13 cm^{-3}
PNSD @ Case 2, FSC= 570 ppm, BC=2E15 cm^{-3}
PNSD @ Case 6, FSC= 7 ppm, BC=1E13 cm^{-3}
dN/dlogDp (cm^{-3})
Dry Diameter (nm)
Exhaust Plume Age (s)