

Evaluation of Non-CO₂ SAF Benefits

Presentation on the local air
quality, non-CO₂ climate,
ecological services, and other
benefits of SAF

Prepared for: CAAFI Biennial General Meeting

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Chief Scientific and Technical Advisor for
Environment and Energy
Federal Aviation Administration

Date: June 3, 2022

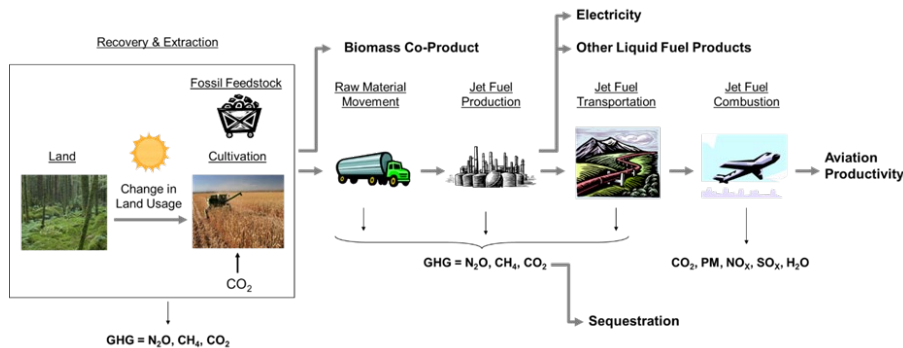


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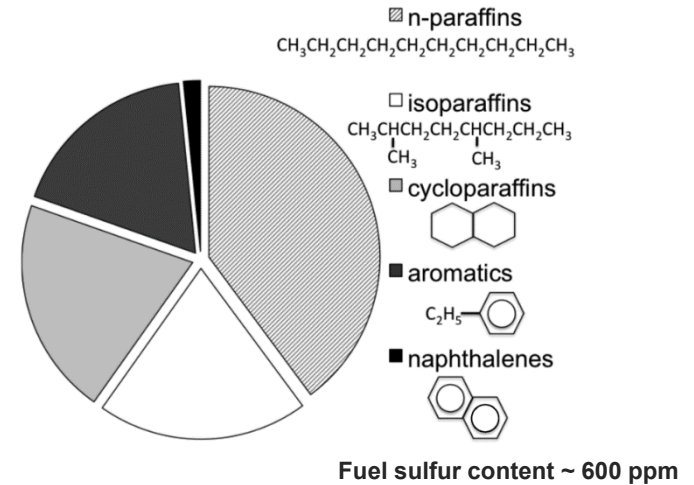


Key Differences - Conventional Jet Fuel and SAF

Feedstock Source



Fuel Composition



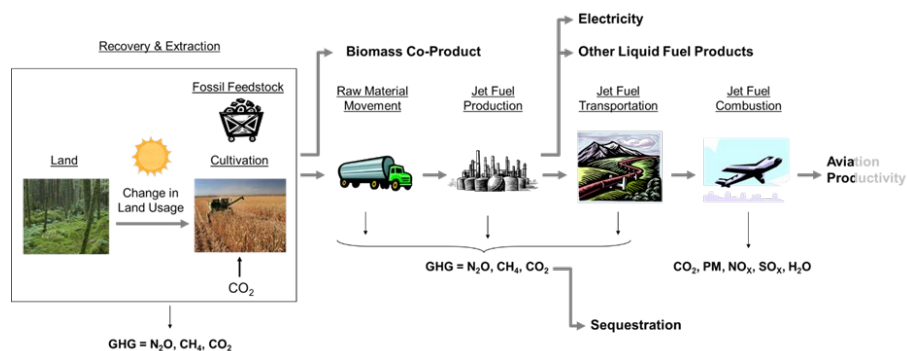
- Shifting from petroleum to renewable and waste feedstocks presents opportunities, but need to carefully consider environmental sustainability
- Land changes, water, soil, air, conservation, wastes and chemicals

- Conventional jet fuel composed of variety of hydrocarbons
- Changing fuel composition could reduce air quality and non-CO₂ climate impacts

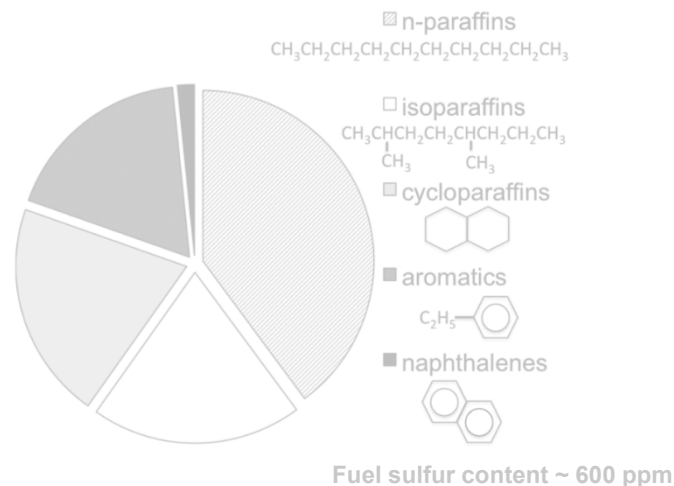


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Sustainable Aviation Fuels and CORSIA

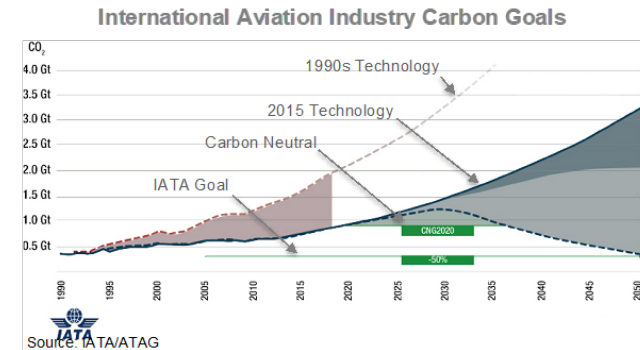
International Civil Aviation Organization (ICAO) established CORSIA to help international aviation meet Carbon Neutral Growth goal (relative to a 2019/2020 baseline)

Two means for an aeroplane operator to comply with CORSIA

1. Offsetting with Emissions Units
2. Emissions Reductions from CORSIA Eligible Fuels

Two means of determining life cycle emissions credit

- Default life cycle values provided by ICAO
- Actual life cycle values, certified by a third party, that are computed using a process provided by ICAO



To be eligible for CORSIA, a fuel needs to meet the CORSIA Sustainability Criteria as certified by ICAO Council Approved Sustainability Certification Scheme (SCS)

CORSIA Eligible Fuels – Key Documents

There are a number of ICAO documents that contain information related to CORSIA Implementation

Annex 16 Volume IV

See: <https://www.icao.int/environmental-protection/CORSIA/Pages/SARPs-Annex-16-Volume-IV.aspx>

CORSIA Implementation Elements

See: <https://www.icao.int/environmental-protection/CORSIA/Pages/implementation-elements.aspx>

Five ICAO documents relate to CORSIA Eligible Fuels

See: <https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx>

The screenshot shows the ICAO ENVIRONMENT website page for CORSIA Eligible Fuels. The page layout includes a top navigation bar with links for About ICAO, Global Priorities, Events, Information Resources, Careers, Uniting Aviation, ICAO TV, and Subscribe. A search bar is located in the top right corner. The main content area is titled "CORSIA Eligible Fuels" and contains the following text: "This ICAO CORSIA Implementation Element is reflected in five ICAO documents referenced in Annex 16, Volume IV. They are available for download below." Below this text is a grid of five document thumbnails, each with a title and a date. The titles are: "CORSIA Eligibility Framework and Requirements for Sustainability Certification Schemes", "CORSIA Approved Sustainability Certification Schemes*", "CORSIA Sustainability Criteria for CORSIA Eligible Fuels", "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels**", and "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values". A sidebar on the left contains navigation links for ENV Homepage, CORSIA Homepage, CORSIA IMPLEMENTATION, and ACT CORSIA. At the bottom of the page, there is a note: "**The CORSIA Supporting Document 'CORSIA Eligible Fuels - Life Cycle Assessment Methodology' provides technical information and describes ICAO processes to manage and maintain the ICAO document 'CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels', including the process to add new default values to this ICAO document." and a thumbnail of the supporting document cover.

Sustainability Certification Schemes

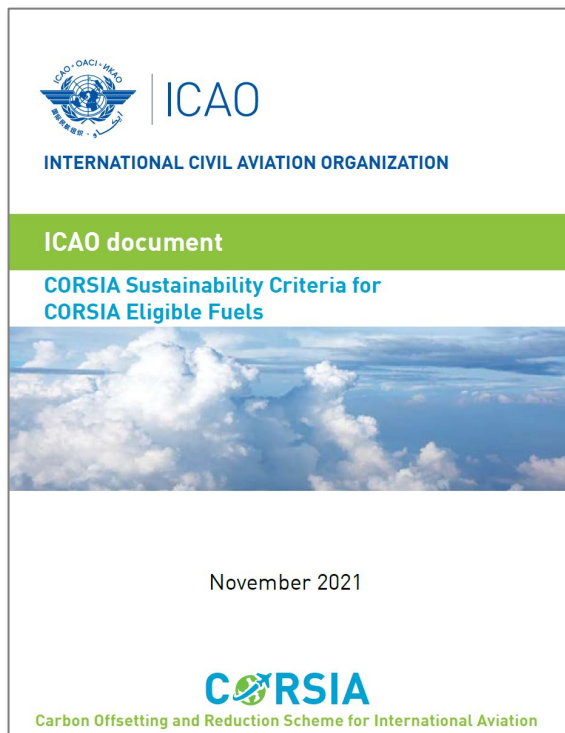
- CORSIA Eligible Fuel need to come from a fuel producer that is certified by an ICAO Council approved Sustainability Certification Scheme (SCS)
- SCSs need to meet requirements of ICAO document entitled "CORSIA Eligibility Framework and Requirements for Sustainability Certification Schemes"
- Two SCSs approved for CORSIA:
 - International Sustainability and Carbon Certification (ISCC)
 - Roundtable on Sustainable Biomaterials (RSB)
- Applications by SCSs being reviewed on an ongoing basis by the SCS Evaluation Group (SCSEG).
- SCSs interested in being considered should complete an application (link below).



•To download document: <https://www.icao.int/environmental-protection/CORSIA/Documents/ICAO%20document%20004%20-%20Approved%20SCSs.pdf>

Sustainability Criteria

Compiled within the ICAO Document “CORSA Sustainability Criteria for CORSIA Eligible Fuels”

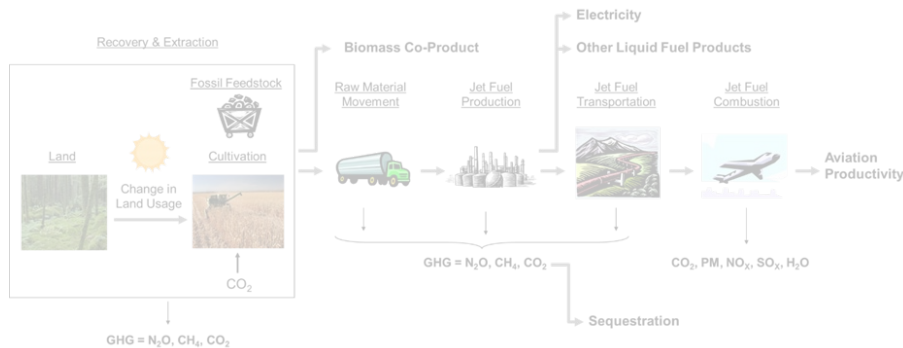


Chapter 2: CORSIA SUSTAINABILITY CRITERIA APPLICABLE FOR BATCHES OF CORSIA SUSTAINABLE AVIATION FUEL PRODUCED BY A CERTIFIED FUEL PRODUCER ON OR AFTER 1 JANUARY 2024

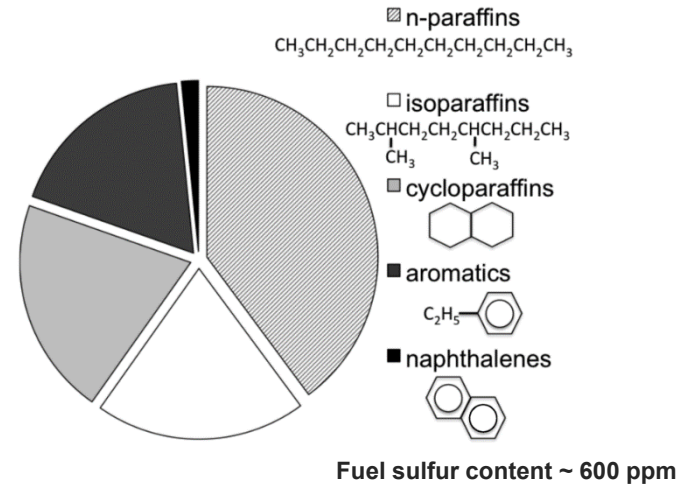
3. Water	Principle: Production of CORSIA SAF should maintain or enhance water quality and availability.	<p>Criterion 3.1: Operational practices will be implemented to maintain or enhance water quality.</p> <p>Criterion 3.2: Operational practices will be implemented to use water efficiently and to avoid the depletion of surface or groundwater resources beyond replenishment capacities.</p>
4. Soil	Principle: Production of CORSIA SAFs should maintain or enhance soil health.	Criterion 4.1: Agricultural and forestry best management practices for feedstock production or residue collection will be implemented to maintain or enhance soil health, such as physical, chemical and biological conditions.
5. Air	Principle: Production of CORSIA SAF should minimize negative effects on air quality.	Criterion 5.1: Air pollution emissions will be limited.
6. Conservation	Principle: Production of CORSIA SAF should maintain biodiversity, conservation value and ecosystem services.	<p>Criterion 6.1: CORSIA SAF will not be made from biomass obtained from areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area, unless evidence is provided that shows the activity does not interfere with the protection purposes.</p> <p>Criterion 6.2: Low invasive-risk feedstock will be selected for cultivation and appropriate controls will be adopted with the intention of preventing the uncontrolled spread of cultivated alien species and modified microorganisms.</p> <p>Criterion 6.3: Operational practices will be implemented to avoid adverse effects on areas that, due to their biodiversity, conservation value, or ecosystem services, are protected by the State having jurisdiction over that area.</p>
7. Waste and Chemicals	Principle: Production of CORSIA SAF should promote responsible management of waste and use of chemicals.	<p>Criterion 7.1: Operational practices will be implemented to ensure that waste arising from production processes as well as chemicals used are stored, handled and disposed of responsibly.</p> <p>Criterion 7.2: Responsible and science-based operational practices will be implemented to limit or reduce pesticide use.</p>

Key Differences - Conventional Jet Fuel and SAF

Feedstock Source



Fuel Composition



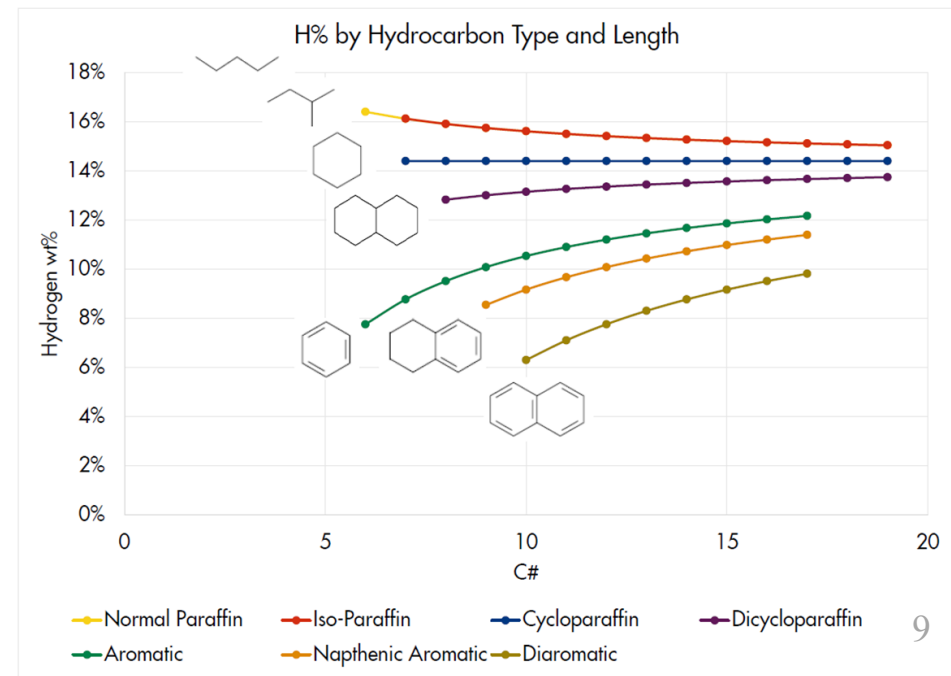
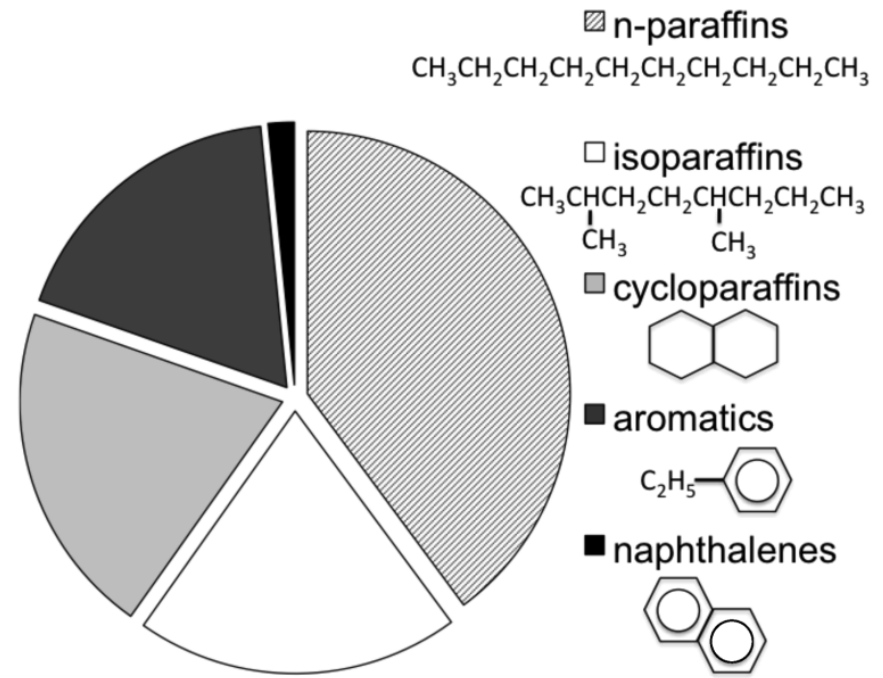
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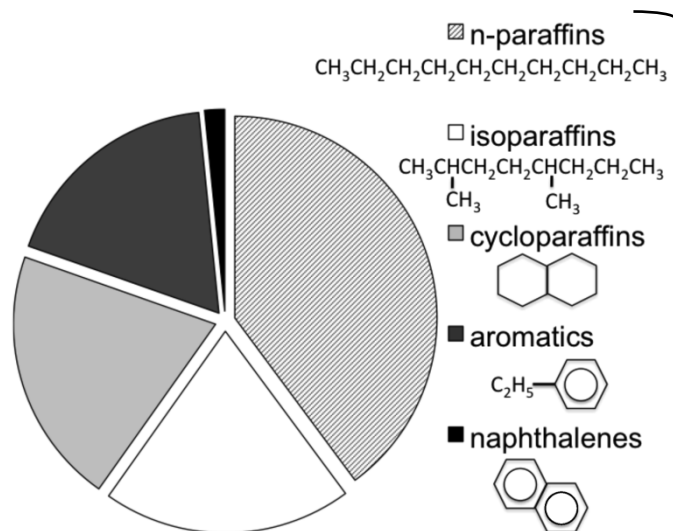
Jet Fuel Composition

- Conventional jet fuel composed of variety of hydrocarbons
- ASTM D1655 limits aromatics to be less than 25% and naphthalenes to be less than 3%
- Approved alternative fuels composed mostly of normal and isoparaffins
- Next set of fuel approvals contains larger variety of “jet fuel” hydrocarbons



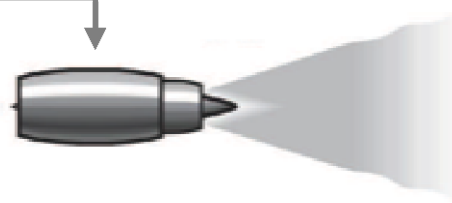
Using Fuel Composition to Reduce Emissions

Fuel composition and engine design determine emissions



Fuel: $\text{C}_n\text{H}_m + \text{S}$

Air:
 $\text{N}_2 + \text{O}_2$



Tank-to-Wake Actual Combustion Emissions

$\text{CO}_2 + \text{H}_2\text{O} + \text{NO}_x + \text{SO}_x + \text{soot} + \text{CO} + \text{HC} + \text{N}_2 + \text{O}_2$

Weighted Mean Fuel Sulfur Content (PPM)		
	2006	2007
US East	446	321
US Gulf	858	800
US West	240	395
Nationwide	709	677

Well established that fuel composition can be modified to reduce soot and SO_x emissions

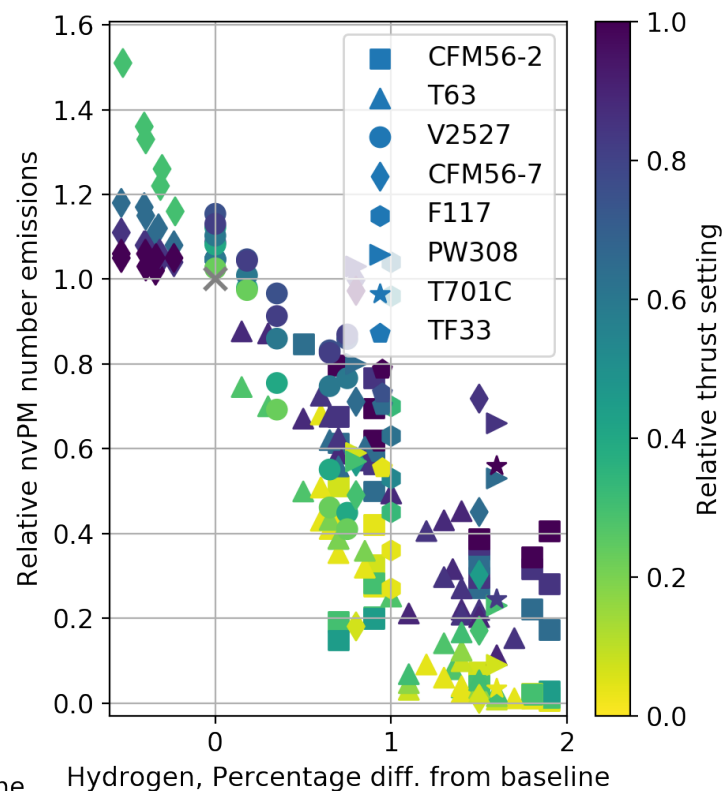
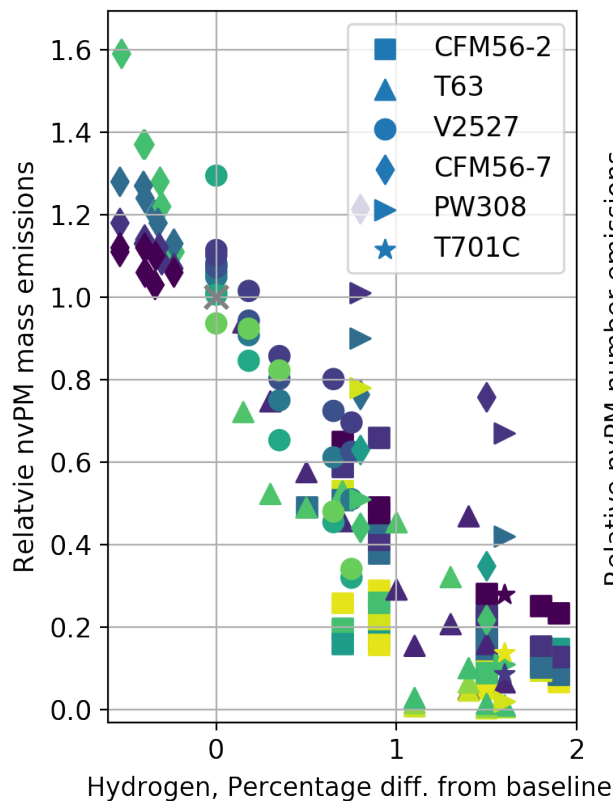
Terms “soot”, “nvPM”, “primary PM2.5”, and “BC” are used interchangeably in this briefing



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Fuel Composition and non-volatile Particular Matter (nvPM)

- Relative nvPM emissions decrease with increasing hydrogen content (i.e., decreasing fuel aromatics content)
- Effect of fuel composition decreases with engine thrust setting
- Combustor design can also give significant reductions in nvPM emissions



Similar trends for mass and number emissions

Environmental Impacts of Aviation

COMBUSTION EMISSIONS

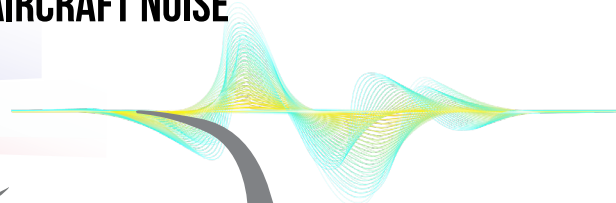
AIRCRAFT NOISE



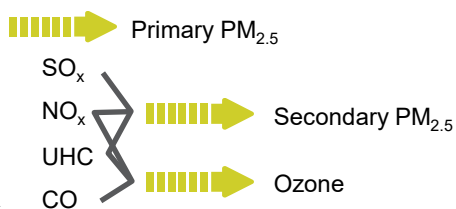
CO₂: 71%

Water: 28%

CO, HC, NO_x, SO_x, Primary PM_{2.5}: <1%



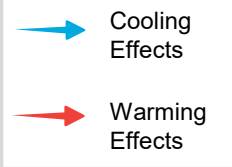
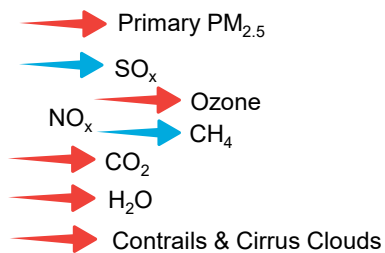
ATMOSPHERIC CHEMISTRY & PHYSICS



POPULATION EXPOSURE AND HEALTH IMPACTS

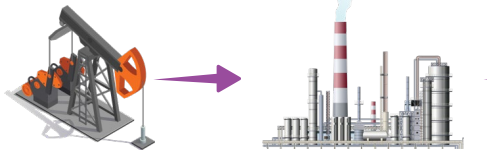


GLOBAL CLIMATE CHANGE



OZONE LAYER

EMISSIONS FROM FUEL PRODUCTION



SUSTAINABILITY IMPACTS

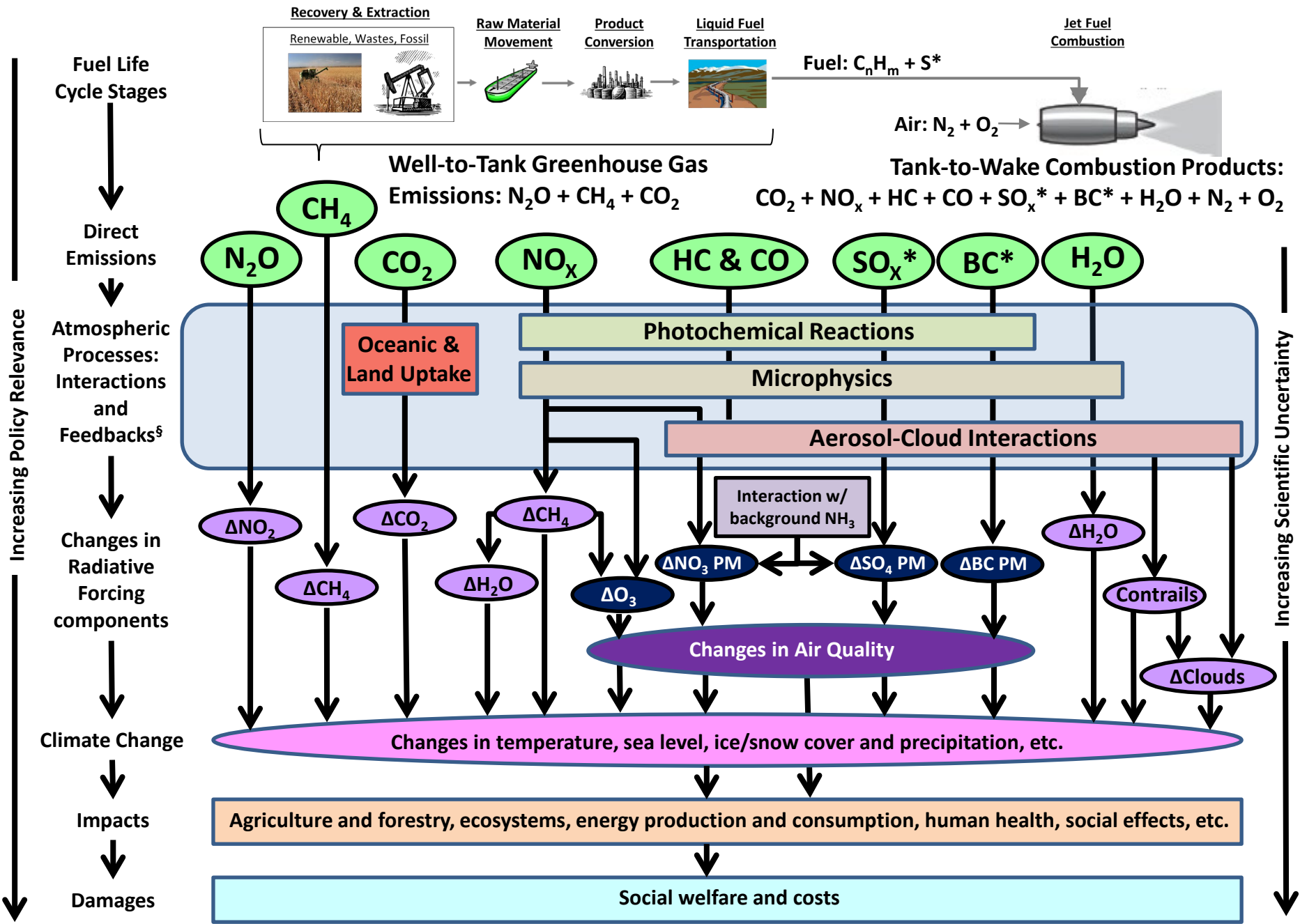


CH₄, N₂O, CO₂

Slide created in collaboration with NASA ARMD



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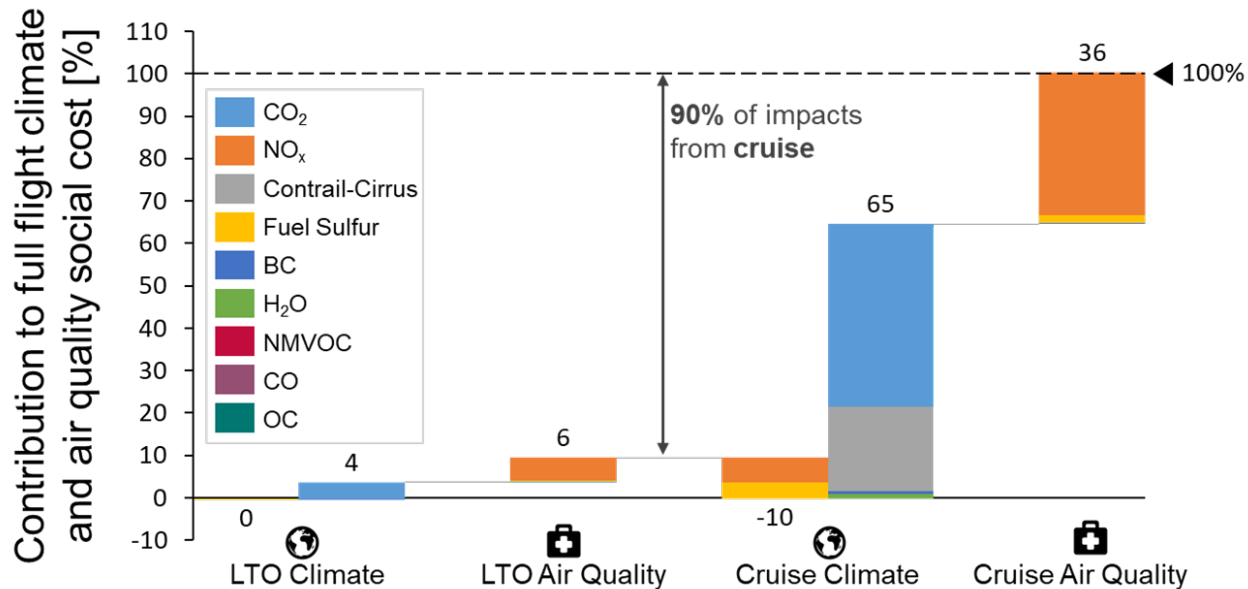


[§]Account for radiative, chemical, microphysical and dynamical couplings along with dependence on changing climatic conditions and background atmosphere
^{*}Sustainable aviation fuels can be produced with zero sulfur related emissions and reduced black carbon emissions
 Modified from Brassuer et al 2016

Impacts of Aviation Emissions

Impacts of Full Flight Emissions on Air Quality, Climate, and Ozone

- Project continues long-standing FAA-funded effort at MIT to use analytical tools to model global movement and transformation of aircraft emissions as well as their impacts on surface air quality, global climate change, and the ozone layer
- Team have found that globally, impacts of cruise emissions on surface air quality are larger than those attributed to landing and takeoff (~16,000 premature mortalities¹ or 0.2% of the 9 million premature mortalities from combustion emissions globally²)
- However, the results have considerable uncertainty and we continue to do work to better understand the impacts of cruise emissions on surface air quality

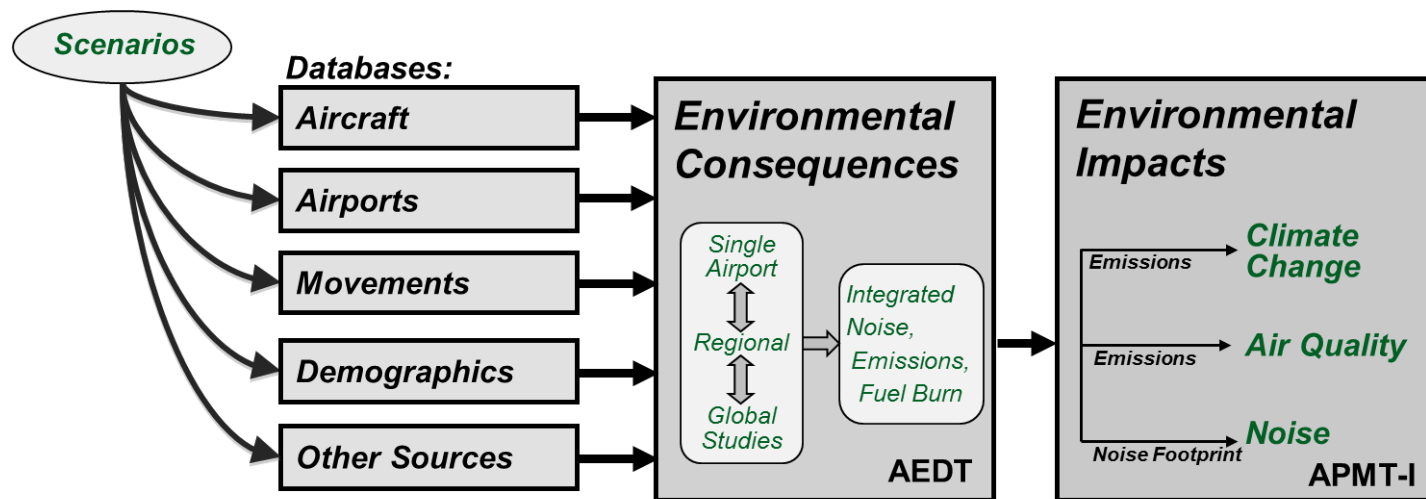


1. Grobler et al, Environmental Research Letters 2019. Data updated with more recent social cost of carbon, 3% discount rate; Country specific VSL.
 2. Landrigan et al., The Lancet 2017

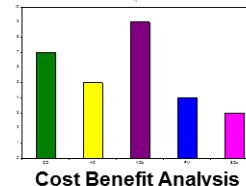
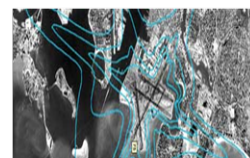
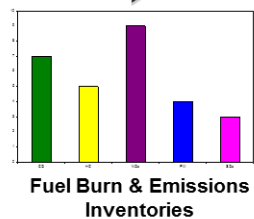


Environmental Cost Benefit Analysis Tools

Changes in aviation technology could impact noise, global climate and air quality. Developed an aviation environmental tool suite to assess the impacts of noise and emissions to inform decision-makers.



Analytical tool suite being used to quantify costs and benefits of changing fuel composition of today's conventional jet fuel to reduce emissions impacts



Changing Fuel Composition from Conventional Jet Fuel

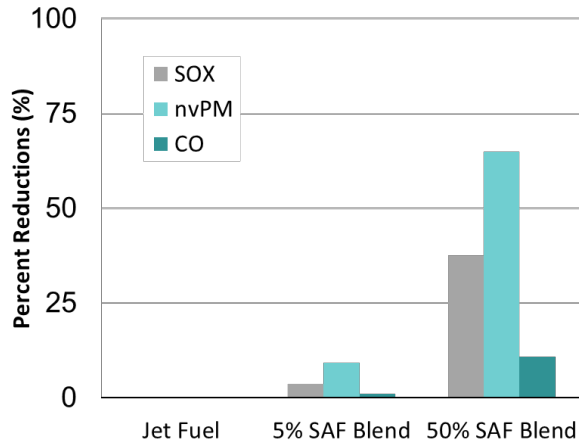
(Slide provided to CAAFI BGM in December 2018)

- **Changes in fuel composition could reduce emissions**
 - Get reduced nvPM with reduced fuel aromatics – expect larger impact with reductions in naphthalenes and other more complicated aromatic compounds
 - Get reduced sulfates with reduced fuel sulfur content
- **Environmental impacts from reduced nvPM and sulfates**
 - Air quality benefit - less nvPM and no SO_x pollution from aircraft operations (noting that the majority of impacts are due to NO_x emissions which are not impacted by SAF)
 - Climate impact is mixed – less radiative forcing from black carbon but increased radiative forcing from removal of sulfates; contrail impact is uncertain
- **Sulfur and Naphthalene Removal Cost-Benefit Analyses (CBA)**
 - Expect a net cost from reducing sulfur concentration in jet fuel to ULS levels
 - Might be a net cost with naphthalene removal using Hydro De-Sulfurization and extractive distillation, but need to account for contrail impacts before being certain
- **CBA Implications**
 - CBA studies are exploratory in nature - interested in knowing the relative merits of various means of reducing emissions from aircraft engines
 - Sustainable Aviation Fuels would provide air quality benefits relative to conventional fuel
 - Need to know more about contrail formation to get full story on climate impacts associated with changes in jet fuel composition



Airport Air Quality Evaluation

Environment International 158 (2022) 106958



Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint



Air quality and health-related impacts of traditional and alternate jet fuels from airport aircraft operations in the U.S.

Calvin A. Arter^a, Jonathan J. Buonocore^b, Chowdhury Moniruzzaman^a, Dongmei Yang^a, Jiaoyan Huang^a, Saravanan Arunachalam^{a,*}

^a Institute for the Environment, The University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA

^b Center for Climate, Health and the Global Environment, Harvard T.H. Chan School of Public Health, Boston, MA 02115, USA

Health Endpoint		2016	2016 AJF 5%	2016 AJF 50%
Premature Mortalities	PM _{2.5}	88 (75 - 100)	87 (73 - 100)	72 (61 - 84)
	O ₃	-54 (-27 - -110)	-54 (-27 - -110)	-54 (-27 - -110)
	NO ₂	1,100 (570 - 1,700)	1,100 (570 - 1,700)	1,100 (570 - 1,700)
	Total	1,200 (610 - 1,700)	1,200 (610 - 1,700)	1,100 (600 - 1,700)
Asthma Exacerbations Ages 5 to 17	PM _{2.5}	2,300 (0 - 4,600)	2,200 (0 - 4,500)	1,900 (0 - 3,800)
	NO ₂	170,000 (4,400 - 340,000)	170,000 (4,400 - 340,000)	170,000 (4,400 - 340,000)
	Total	170,000 (4,400 - 340,000)	170,000 (4,400 - 340,000)	170,000 (4,400 - 340,000)

Emissions factors in top table taken from Alternative Jet Fuels Emissions Quantification Methods Creation and Validation Report, Hamilton et al. 2019 ACRP 02-80

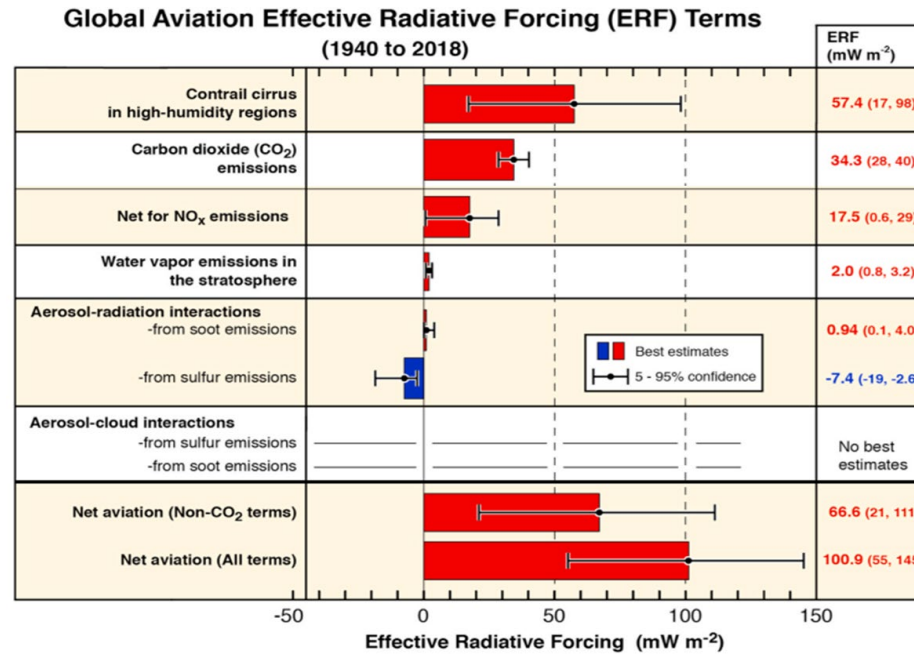
Health endpoint evaluation from the publication by Arter et al. (2022)



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Climate Impacts of Aviation Induced Cloudiness

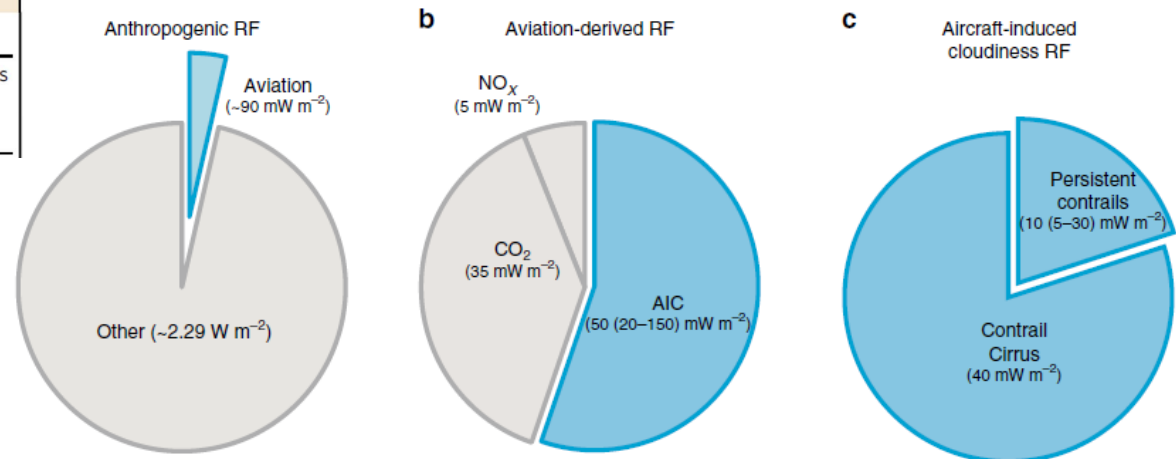
Lee et al., Atm Env, 2021



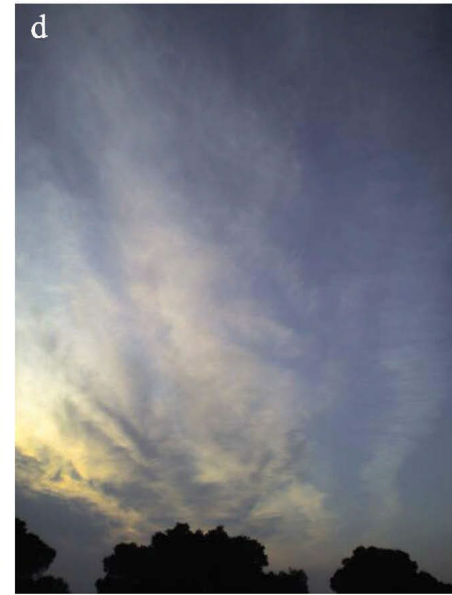
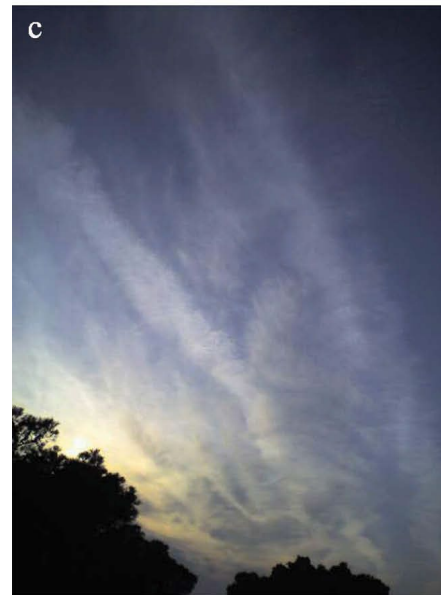
B. Kärcher, Formation and radiative forcing of contrail-cirrus, Nature Communications, 2018

Table 1 Characteristics of contrails and contrail cirrus

AIC	Short-lived	Long-lived	
Ice cloud type	Contrail	Persistent contrail	Contrail cirrus
RF potential	Negligible	Small	Large



Aviation Induced Cloudiness



Photographs of contrail spreading into cirrus taken from Athens, Greece, on 14 Apr 2007 at 1900, 1909, 1913, and 1920 local time (from top left to bottom right). Courtesy of Kostas Eleftheratos, University of Athens, Greece. →

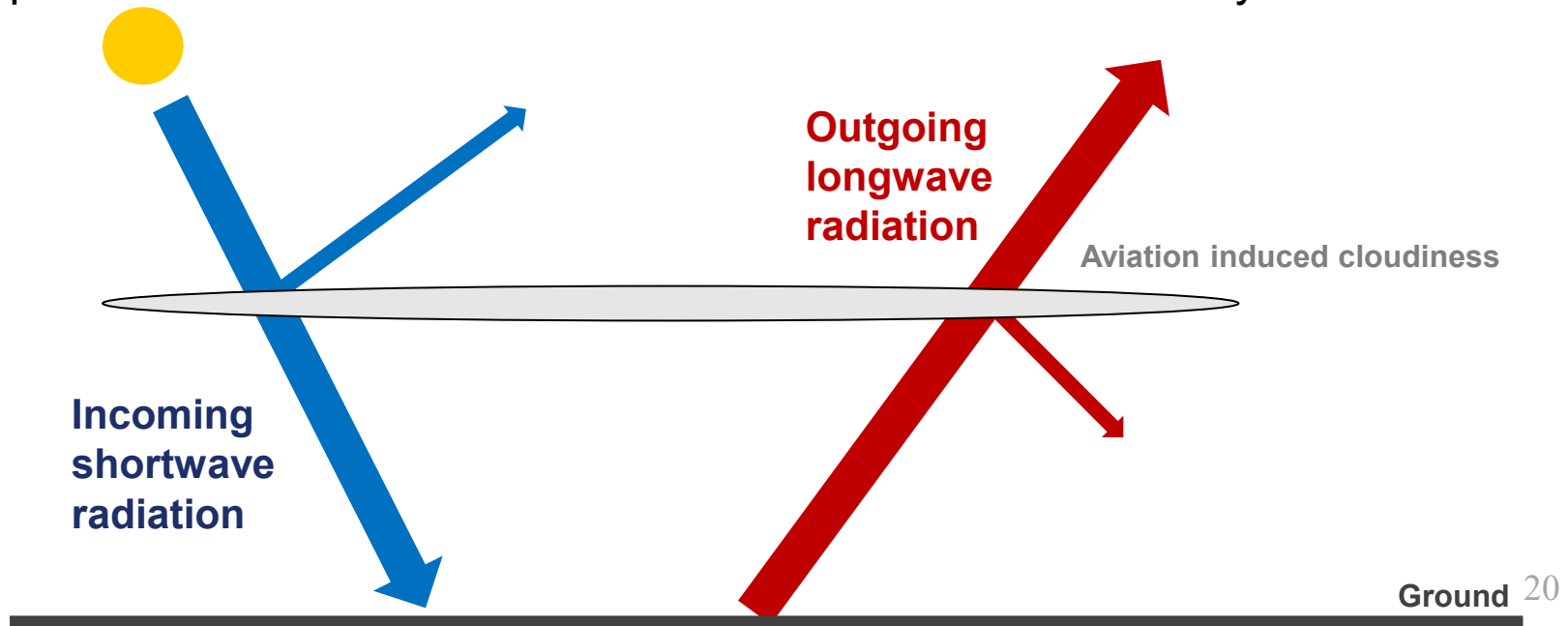
From: Heymsfield et al. BAMS 2010



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Aviation Induced Cloudiness – Some Basics

- Contrail formation and aviation induced cloudiness determined by atmospheric conditions – contrails can form and disappear, or can form and persist, depending on temperature and humidity where the aircraft is flying
- Climate impact of aviation induced cloudiness is due to small differences in the amount of incident solar radiation and outgoing heat from the planet
- Magnitude and sign of climate impact is determined by season, time of day, and presence of other clouds underneath the aviation induced cloudiness
- Impact is measured in minutes to hours - if aviation activity were to stop, the impact of aviation induced cloudiness would cease within a day



Aviation Induced Cloudiness (AIC) and SAF

- **Contrails form from condensation of water**
- **Aviation induced cloudiness is composed of ice crystals that form from persistent contrails**
- **Changing fuel composition effects:**
 - Hydrogen-to-carbon ratio (hence amount of H₂O vapor in the engine exhaust) – *SAF combustion results in more water vapor*
 - Number of soot particles (nvPM) in the exhaust – these particles are condensation nuclei for contrails and aviation induced cloudiness – *SAF combustion produces fewer particles*
 - Sulfur oxides in the exhaust have an impact on how ice forms on the soot particles – *SAF combustion has no sulfur oxides*
- **Effect of SAF on warming from AIC depends on the balance of these competing effects (while accounting for uncertainties of each effect)**



Initial Analysis of SAF and AIC Climate Impacts

- Caiazzo et al (2017) evaluated the effects of changes in aircraft fuels and emissions on contrail warming using scenarios which consider reductions in ice nuclei emissions either from the use of paraffinic (i.e., zero aromatic fuels) or through improvements in combustor technology which decrease nvPM emissions.
- Considered changes in nvPM emissions, water vapor, and exhaust temp.
- In the case of using different fuels, contrails are found to form more frequently due to the higher water emissions index of paraffinic fuels, and this leads to a change in net RF of -4 to $+18\%$ compared to conventional fuels.
- This effect is composed of an increase in daytime RF ($+10$ to $+22\text{mW/m}^2$) and a decrease in nighttime RF (-6 to -21mW/m^2), so by selectively using these fuels at night, a reduction in contrail RF could be achieved.



Summary of the Issue

- SAF use will result in contrails that are different than contrails produced from using conventional jet fuel
- SAF: more water vapor → greater contrail frequency (Radiative Forcing, RF, increased)
- SAF: no sulfur → potentially less particulate activation (effect unclear)
- SAF: lower nvPM, i.e., fewer particulates for ice nucleation → shorter contrail lifetimes (RF decreased) and thinner clouds (effect varies)



In-Flight Measurements

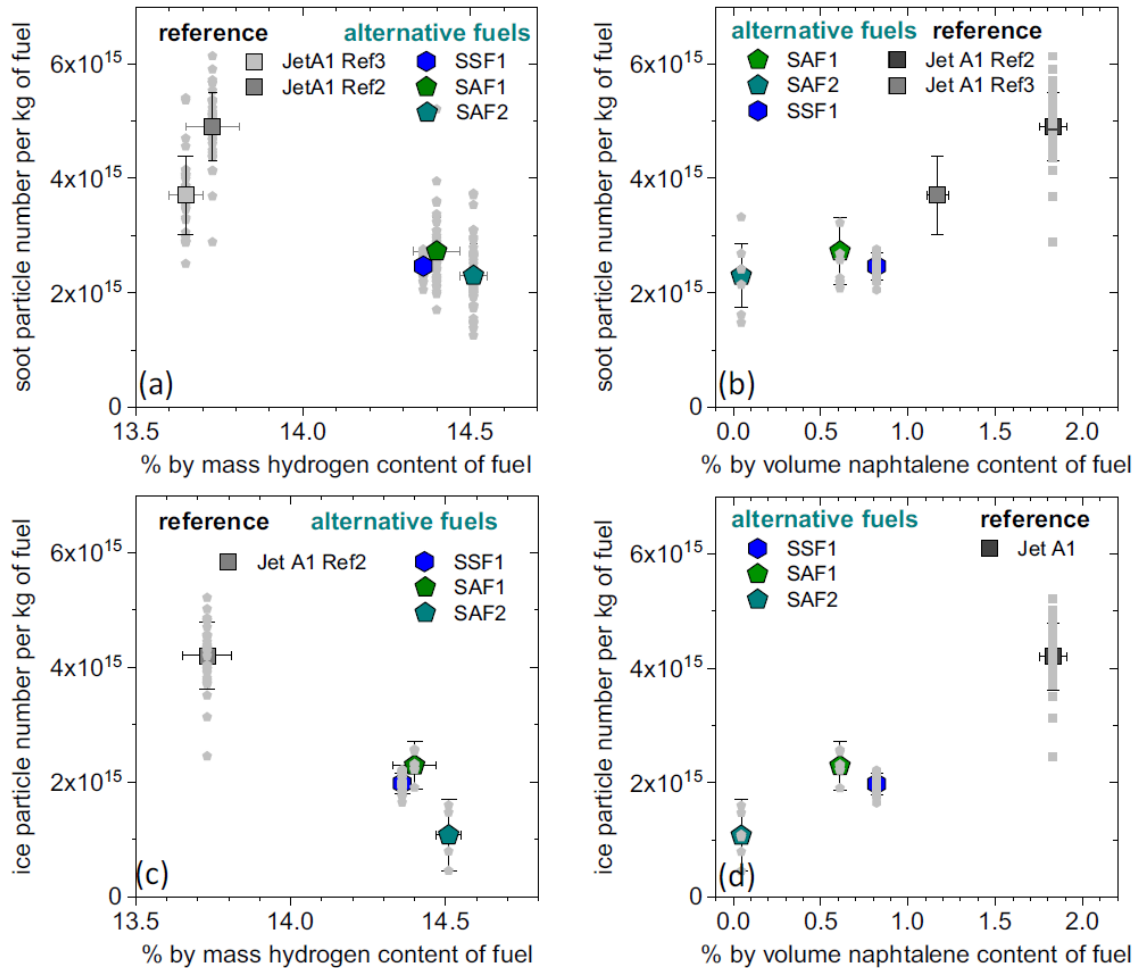
- FAA, NASA, NRC-Canada, and DLR have been collaborating with industry to measure measurements from SAF use – ground and in flight



- Focus of measurements has been to understand how fuel aromatic content and fuel sulfur content can be modified to change contrail properties



ECLIF2/NDMAX Campaign Results (2018 Campaign) – 1 of 2

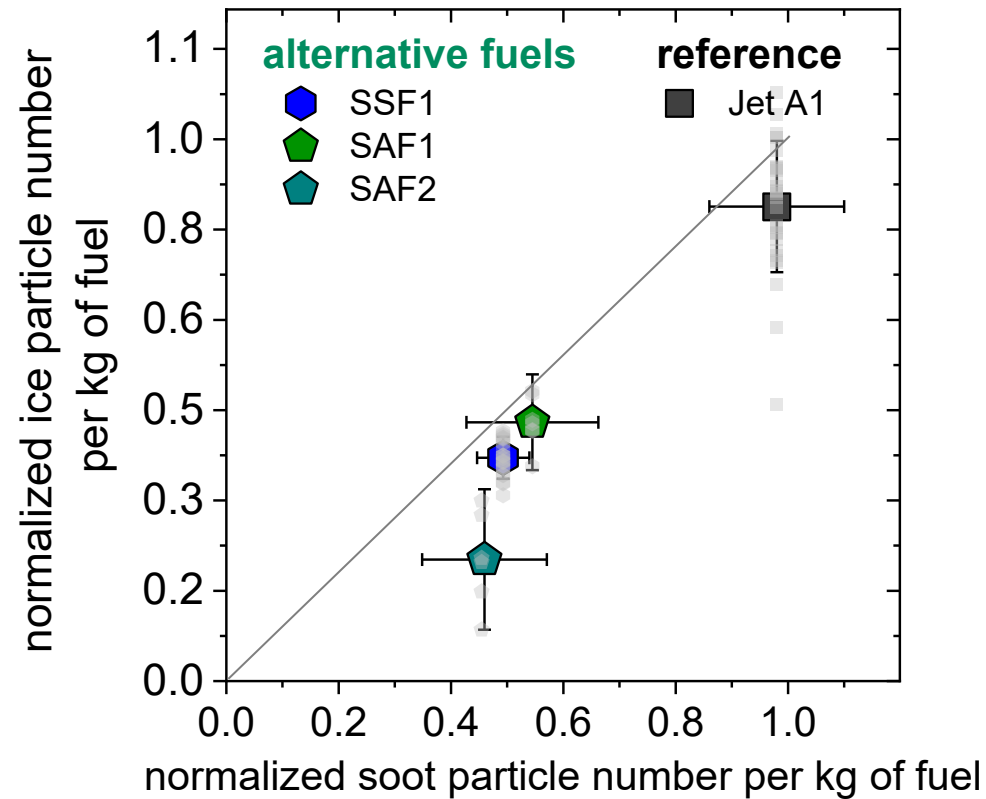


Non-volatile and apparent ice particle emissions per kg of fuel at cruise conditions for the reference Jet A1 fuels and for the low aromatic alternative jet fuel blends

ECLIF2/NDMAX Campaign Results (2018 Campaign) – 2 of 2

Fuel aromatic and sulfur content have a significant impact on number of ice particles that are formed within the contrail

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%



Next Steps

- More recent test campaign measurements currently being analyzed (e.g., ECLIF3)
- Setting up additional ground and in-flight measurements to better understand effects of different compositions and combustor technologies on nvPM and contrail formation
- Once measurements are sufficiently robust, conduct new analytical efforts to understand full benefits of changing fuel composition



Potential Mitigation Measures for Aviation Induced Cloudiness

- Changing flight altitude / horizontal flight track (need to avoid / minimize increased fuel burn)
- Developing engines with changes in engine exhaust temperature / non-volatile particulate matter within exhaust
- Changing fuel composition with modifications to fuel sulfur content and fuel aromatic content

Caution with contrail mitigation measures

- Need to weigh any changes in fuel burn carefully – time scales of impacts are very different
- Not all aviation induced cloudiness is climate warming and some is actually climate cooling



Closing Observations

- SAF can provide substantial life cycle CO₂ emissions benefits – potentially decoupling aviation CO₂ emission from aviation growth
- SAF combustion results in substantial reductions in nvPM emissions
- Neat SAF does not contain sulfur compounds
- SAF use **will** provide a modest air quality benefit
- SAF use **could** further reduce climate impacts from aviation induced cloudiness
- **Need to do additional in-flight measurements and analysis to determine the actual benefits**



First flight from continuous commercial production of SAF
UAL 0708, 10 March 2016, LAX-SFO

Fuel from World Energy - Paramount (HEFA-SPK 30/70 Blend).





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