ICAO Symposium on Non-CO_2 Aviation Emissions

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Charles Renard

Senior Emissions Advisor

International Coordinating Council of Aerospace Industries Associations - ICCAIA

Speaker

Day 2 - Setting the Scene ***by the Industry***

ICAO Symposium on Non-CO_2 Aviation Emissions

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Setting the Scene – OEM Perspective

International Coordinating Council of Aerospace Industries Associations

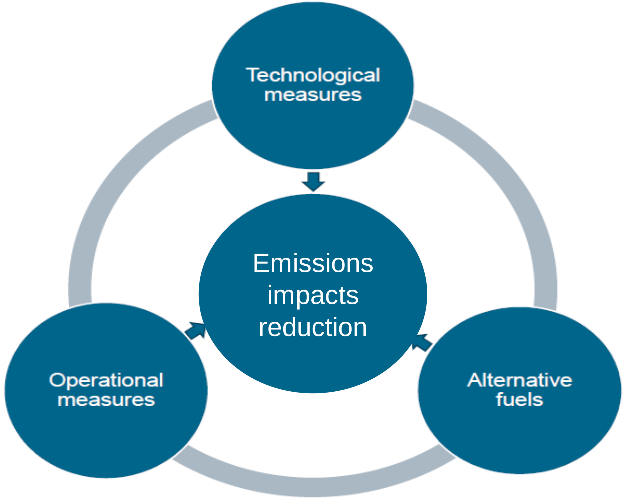
Non-CO_2 Research Activities - Summary

Current scientific and technical status :

Main climate forcers from aviation : CO_2, NO_x, contrails, and the potentially important role of aerosol-cloud interactions.*

Contribution of non-CO_2 forcing is potentially high based on Lee et al. but non-CO_2 uncertainties are still very large (and even larger for the future impacts), while CO_2 impact is well known.*

Mitigation options often involve complex interdependencies and trade-offs between CO_2 and non-CO_2 emissions and effects, and also between emissions and other design requirements.*


Technological measures

Emissions impacts reduction

Operational measures

Alternative fuels

ICCAIA remains strongly engaged on reducing CO_2 emissions whilst accelerating efforts on non-CO_2 emissions

Aviation industry is heavily engaged in several research projects, in collaboration with all the aviation stakeholders :

- to study and assess <u>all</u> potential mitigation options
- to improve as quickly as possible the scientific understanding and the emission/LAQ/climate modelling chains

ICCAIA supports the effort thanks to its knowledge of the products and its tests/modelling/design capabilities.

*See Appendix for more information.

Manufacturers’ contribution to “CO_2 / non-CO_2 emission/impacts” projects

EU_EC_NotListed,
UK_EC_NotListed,
US_EC_EAR99

Mitigation options / Research Axis	**PROJECTS** (Non-exhaustive list)
Aircraft/Engine architecture & design	**Clean Aviation (CA) FAME** (H_2 FC PPS), **FASTER H2** (Advanced low weight integrated fuselage & empennage), **UPWING** (Ultra performance Wing) **CA SWITCH** (Hybrid electric & water-enhanced Turbofan) **CA COMPANION** (In-flight measurement means for future PPS) **CA ACAP Impact Monitor** (Architectures & technology integration for SMR aircraft) **Airbus ZEROe**
Combustor design and technology **Fuels / Energy Change**	**AVIATOR** (On-wing ground measurement incl. vPM, LAQ modelling) **ECLIF3** (Ground & flight measurement of emissions/contrails : 100% SAF, Blends) **CORAC VOLCAN** (100% SAF compatibility, Ground & flight meas. for various fuel compositions & combustion modes), **ecoD** (SAF emissions testing) **CORAC CIRRUS H2** (H_2C contrail modelling, H_2C demo candidates evaluation, lab expe. + link with DGAC/Climaviation), **BLUE CONDOR** (H2C contrail experiment) **CA HYDEA** (H_2C demo prepa., Comb. dev, Low NOx techno, Contrail modelling)
Aircraft operations	**SESAR CICONIA** (Contrail avoidance/climate optimised trajectory modelling & flight demo, eco/env impact evaluation), **LuFo D-KULT** (similar scope) **ARPA-E PRE-TRAILS** (contrails prediction, humidity sensor, sat. obs, weather pred.,...) **CORAC OPTIMIST**(trajectory optimisation modelling incl. emissions & contrails) **ERI IAGOS** (Atmos. meas. incl. humidity)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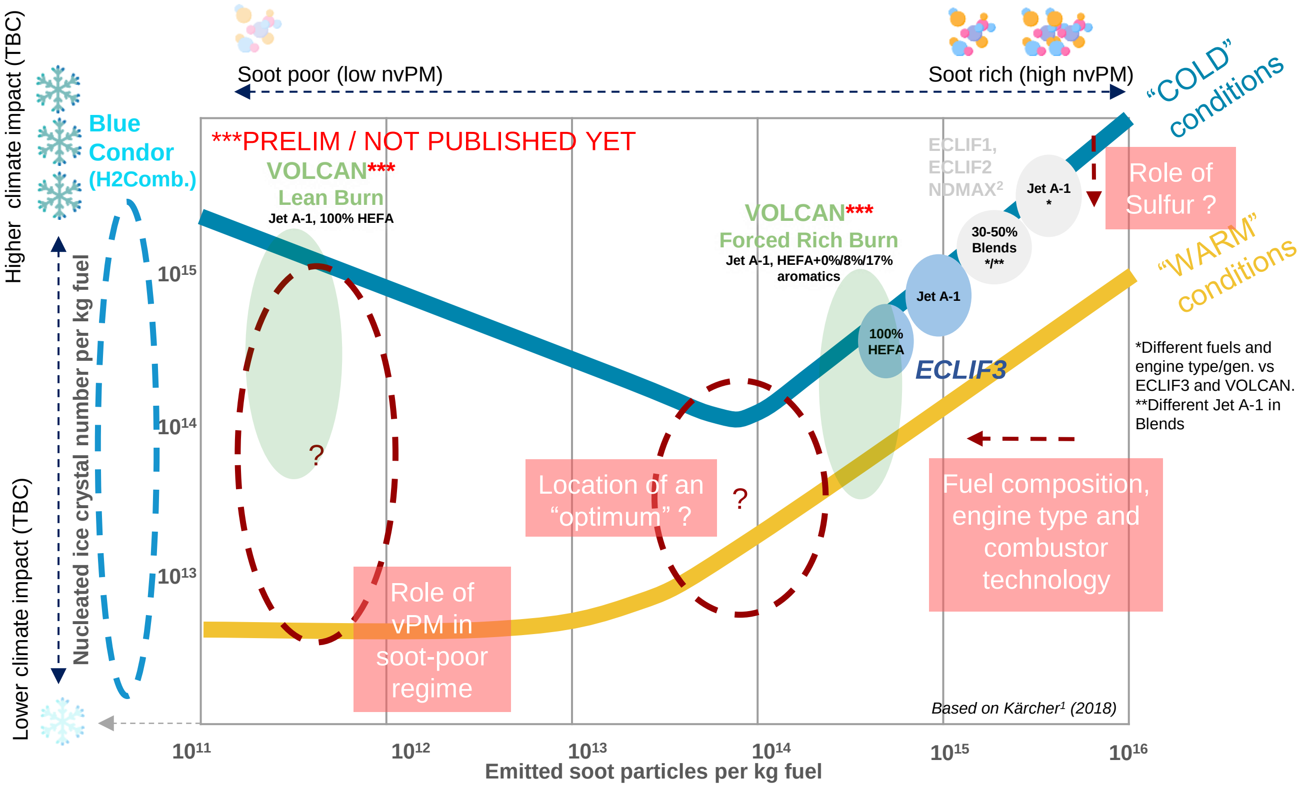
ECLIF3 ground emission measurements


Courtesy of DLR

VOLCAN in-flight measurements

Large involvement covering design studies, experiments, modelling from emissions up to impact evaluations.
Collaboration between OEMs, Research Institutes, Fuel suppliers, ATC/ATM, Airlines to gather all the required skills.

Key learning so far from contrail experiments



- ECLIF3 data analysis completed : **3 papers/preprints are available on-line.**
- VOLCAN and ecoD analyses on-going
- Measurements in **soot-rich regime**
  - nvPM reduction trend with SAF use confirmed, especially paraffinic SAF
  - contrail ice crystals number reduction to be further investigated (vs Sulfur level)
- Measurements in **soot-poor regime**
  - Prelim results in line with theory for "cold" contrails
  - Ice nucleation (temperature dependency) to be better understood (role of vPM ?)
- **Future campaigns needed to:**
  - expand the range of tested fuel compositions, engine type and combustor technologies
  - <u>understand effects of other species</u>: vPM (incl. from engine oil?), ions,...
  - understand engine-engine variability / engine aging effects
  - understand evolution of contrails properties with time.

Note 1: ECLIF 1, ECLIF2/NDMAX partners were DLR and NASA
Note 2: ECLIF3 partners are Airbus, DLR, Rolls-Royce, NRC, University of Manchester, NESTE
Note 3: VOLCAN is a CORAC-DGAC funded project. Partners are Airbus, DLR, ONERA, SAE, DASSAULT AVIATION
Note 4 : Blue Condor partners are Airbus, AVExperts, DLR

[1] *B. Kärcher (2018). Formation and radiative forcing of contrail cirrus. Nature Communications OPEN. DOI: 10.1038/s41467-018-04068-0*
[2] *Moore et al. (2017) ; Voigt et al. (2021)*

Recommendations for future research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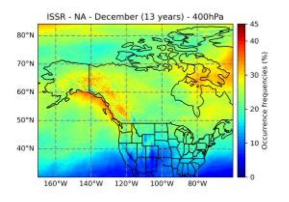
- **Direct/indirect emission properties vs main drivers ⇨ New experiments**
  - Influence of fuel composition, engine & aircraft design/architecture, combustor technologies

  ⇨ Develop complementary atmospheric/emission measurement means

- **Emission impacts and environmental trade-offs – Improve modelling / quantification**
  - **Contrails** : improved GCM parameterization, Instantaneous RF measurements, efficacies,…
  - **NOx** :
    - Climate* : more models for NOx efficacy evaluation, NO_x / CO_2 effect trade-off rate studies
    - LAQ* : Amplitude of cruise NO_x contribution, relative importance of emission types on human health
  - **Aviation aerosol-clouds interactions** : more experimental data required



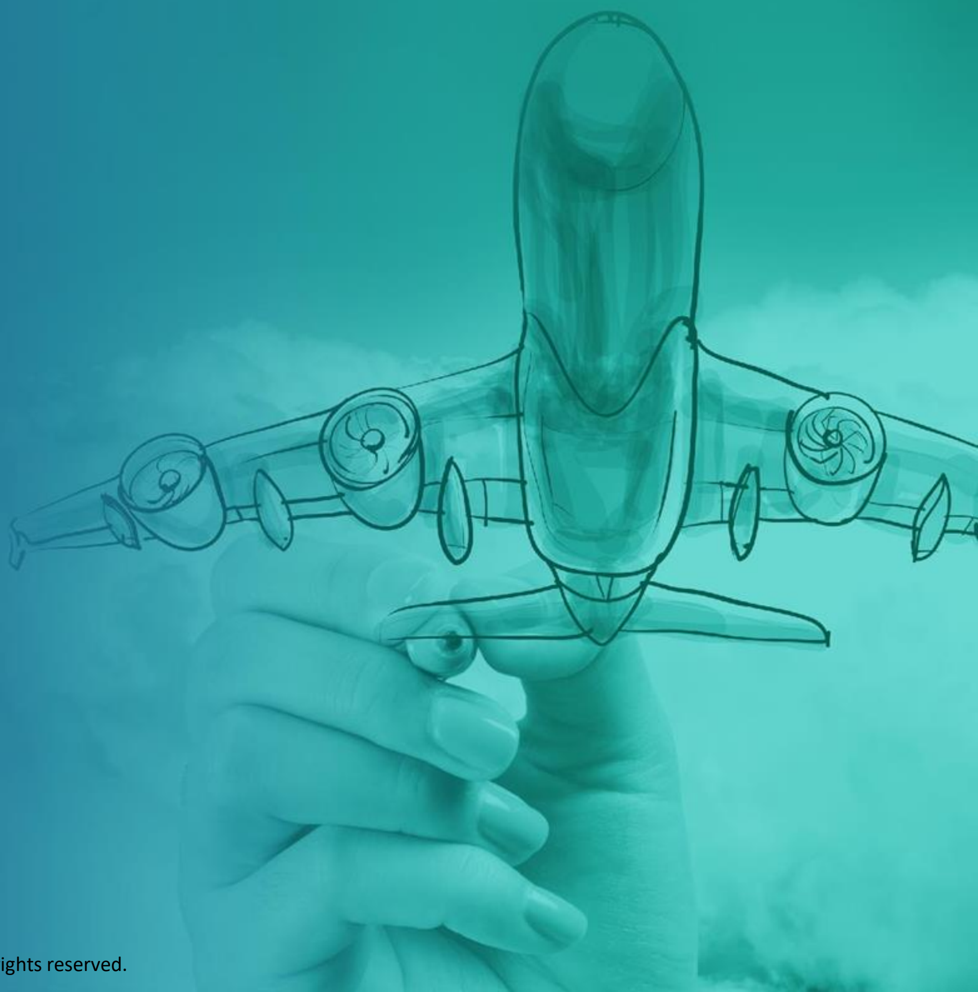
- **Operational approaches – Improve Weather Forecasts, Demonstrate feasibility & benefits**
  - Specific humidity and ISSR forecasts, Accurate enough flight-by-flight impact analysis

Ultimate goal

Take the right decisions (design, operations & regulations) to reduce environmental impacts, based on appropriate scientific knowledge, adapted tools and metrics.

*See Appendix for more information.

Thank you!



Appendix

(Not presented)

Impacts of past and current aviation on Climate -Synthesis

Aviation contributions in 2018 (sources: Lee at al., 2021 and IPCC AR6)

2.4% of anthropogenic CO_2 emissions (direct emissions)

3.7% of anthropogenic ERF, ~2/3 due to non-CO_2 effects (with high uncertainties)

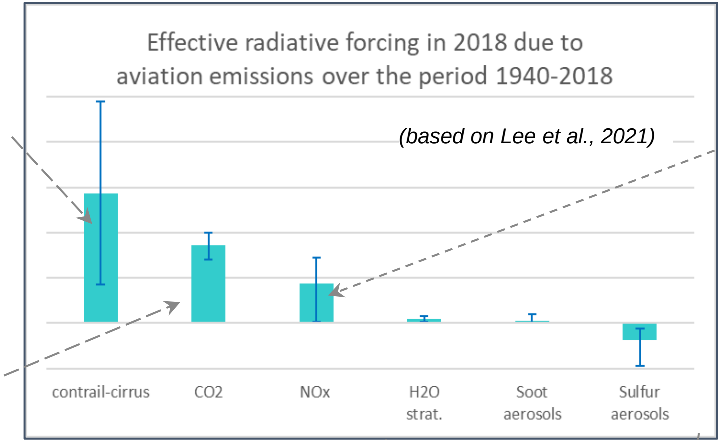
NOTE **:** no consensus on the “best metric” to correctly quantify the climate impact of aviation emissions

Contrail-cirrus: globally warming

- Very short lifetime ⇨ indiv. contrail : very large positive or negative ERF
- Strong dependence on aircraft & fuel types, weather, coverage, lifetime & position (Earth’s surface albedo, Sun position, natural cloudiness)
- Low confidence level

CO_2: globally warming

- Very long lifetime ⇨ small ERF per emis. unit, but cumulative effect
- High confidence level



Effective radiative forcing in 2018 due to aviation emissions over the period 1940-2018

(based on Lee et al., 2021)

NO_X: globally warming

- Short lifetime ⇨ individually, positive or negative ERF (>0 with O_3 formation,<0 with CH_4 destruction)
- Effect depends on emission location & time, and on atm. background
- Low confidence level

Other contributors

- Small positive and negative ERFs
- Medium to low confidence levels

Impact of aerosol-cloud interactions from soot emissions and from NOx/SOx emissions ?

- Very low confidence level, no “best estimate” possible at the moment
- Each interaction could induce very large positive or negative forcings ⇨ significant impact on the total aviation ERF ?

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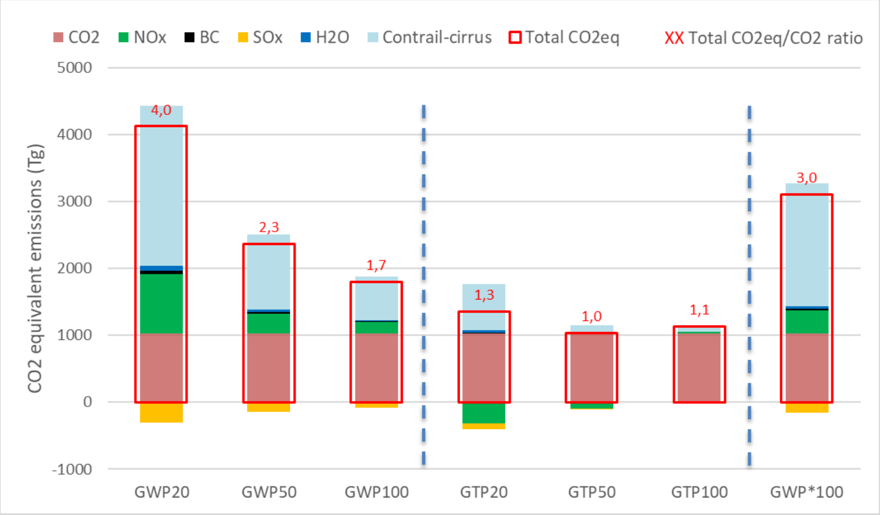
Impacts of future aviation emissions on Climate -Synthesis

Evaluate the climate impact: metric and time horizon to chose

- Lee *et al.*, 2021 does NOT assess the climate impact of future aviation emissions
  ⇨ Need for a realistic projection of future fleet emissions (aircraft/engine techno, routes network, market penetration) & weather conditions / atmospheric background, including the latest scientific knowledge & modelling
- Radiative forcing is only a proxy for climate change : IRF → RF → ERF → ΔTs
- Choice of the metric needs to be based on the definition of a clear objective and rationale
  - NOTE : CO_2eq. value is highly dependent on this choice and can change with the considered year



Climate impact (in CO_2eq) of 2018 aviation emissions using different metrics and time horizons (*based on Lee et al., 2021*)

NOTE : Other climate metrics exist, like ATR over different durations (L.Megill, Msc Thesis, 2022).

IRF : Instantaneous Radiative Forcing
RF : Radiative Forcing
ERF : Effective Radiative Forcing
ΔTs : global-mean surface temperature Change
GWP : Global Warming Potential
GTP : Global Temperature Change Potential
ATR : Average Temperature Response

Impacts of NOx emissions on Climate - Synthesis

Climate impact of NOx emissions

ERF Uncertainty assessment and confidence level for Past/Current Fleet (Lee *et al.* 2021/2023) :

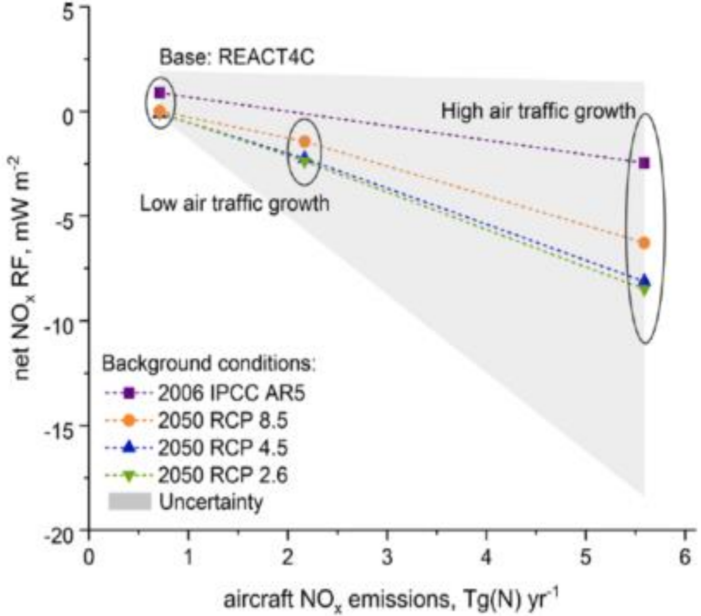
- Impact calculated in models strongly influenced by the atmospheric background evolving over time
- Uncertainty level based on a statistical analysis of past model simulations
- Some processes are not or poorly modelled in global models
- Only one attempt to model NOx efficacy for quantifying ERF
- NOx RF based on combination of 4 individual positive/negative forcings with variable uncertainties

⇨ Low overall confidence level, to be considered in mitigation (standards) studies

For Future Fleet :

- Uncertainty on the estimated value is even larger : evolution of the atmospheric background with time is difficult to predict.
- Recent papers : Net NOx radiative forcing could be lower than that of the current fleet, and even become negative
  ⇨ need to be confirmed with additional studies
  ⇨ need to be confirmed using IPCC preferred metric (ERF)

Net NOx radiative forcing by emission rate, using updated methane parameterisation in modelling
(*Skowron et al., 2021*)



Impacts of Contrails on Climate - Synthesis

Climate impact of contrail-cirrus coverage

Uncertainty assessment and confidence level for Past/Current Fleet (Lee et al. 2021/2023) :

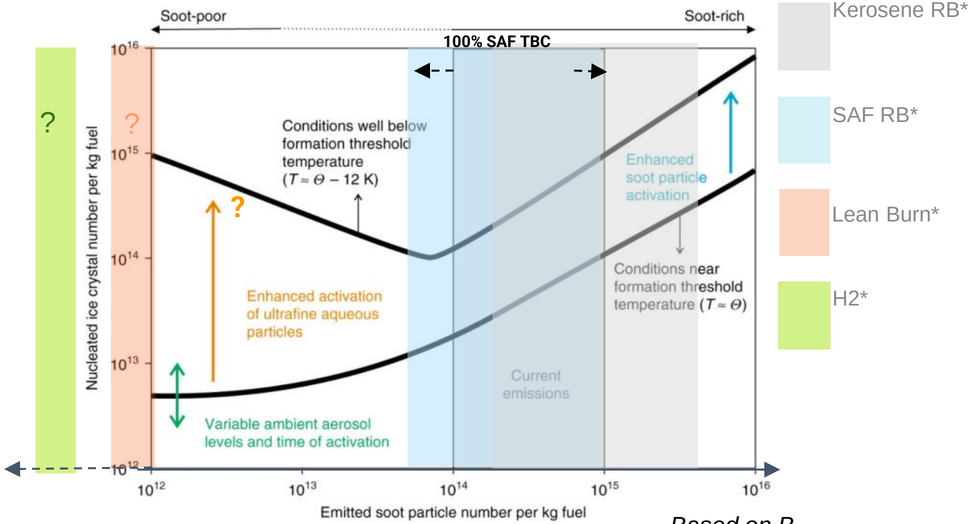
- Large uncertainties : lack of physical understanding and quantification of processes
  ⇨ uncertainty largely based on expert judgment.
- Very small number of GCMs* available, highly parameterized ; ONLY one study for which ERF is quantified ;
- More contrail in-situ data available **but** still Poor IRF observational basis for more direct verification

⇨ Low overall confidence level.

*GCM : General Circulation Model

Still work to be done to understand ice crystal formation process and properties when moving to significantly lower nvPM emission indices :

- Use of blends or pure paraffinic SAFs on Rich Burn engines with low soot emission level
- Lean Burn combustion (i.e very low soot)
- And potentially in the future, H_2 fuel use ⇨ NO soot



Based on B. Kärcher (2018).

Impacts of aviation emissions on LAQ - Synthesis

LTO emissions and local air quality issues

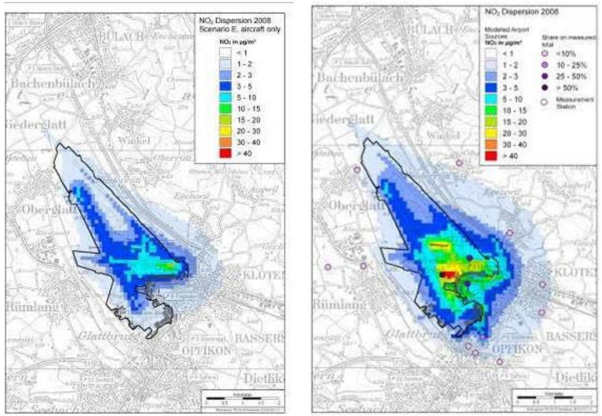
Aircraft (A/C) contribution to ground-level pollutant concentrations (cc) in the airport vicinity

- Variable but generally small : effect depends also on the atmospheric background (local pollution) and weather conditions ⇨ A/C emission contribution to future LAQ ?
- Attribution to aircraft only possible via modelling
  - Lack of standardized method
  - Accurate determination of actual A/C contribution not possible : no unique marker or signature ; can only compare estimated total cc with measured ambient cc
  - Contribution decreases with distance from the airport
  - Formation of vPM** from a/c emissions or by association with emissions from other sources : highly variable and not well quantified

Effects of pollutant concentrations (from all sources) on human health

- WMO, 2021: impact mainly due to PM (92%) and O_3 (8%) ; relative importance of vPM** vs nvPM* not indicated
- More fundamental research is required into toxicology of pollutants
  - Toxicological effects of NO_2 do not seem very clear (difficulty to isolate their direct effects from those of co-emitted UFPs); nevertheless WHO limits were recently significantly reduced.
  - UFPs are clearly an area of concern. Impacts on human health can differ significantly depending on their composition (e.g coated vs. “raw” soot particles).
- Note: aviation contribution to total health impacts estimated from its assumed contribution to LAQ change only (independently from the vPM type/composition)

(Zurich Airport report, 2012)



Aircraft only
(NO_2 concentrations)

All modelled Airport sources

⇨ progress required to guide emission reduction prioritization for future designs, considering also trade-offs between emissions and effects (NOx/nvPM, NOx/CO_2).

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*nvPM = non-volatile Particulate Matter, mainly soot from combustion

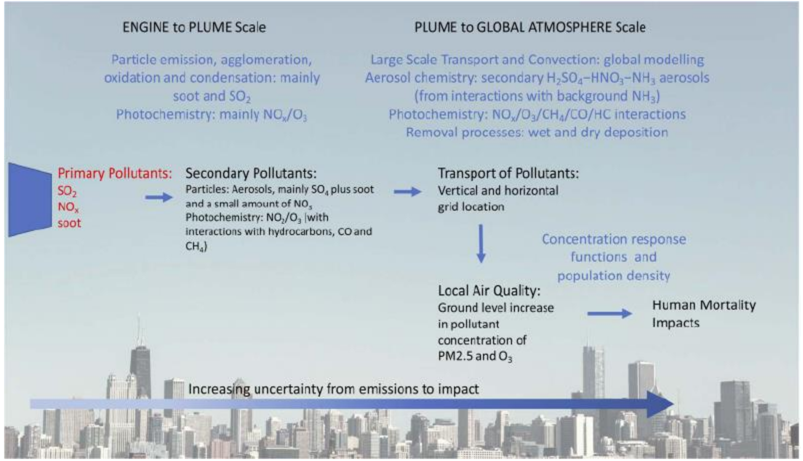
**vPM = volatile Particulate Matter, produced by condensation from gaseous precursors (NOx, SOx, Unburnt Hydrocarbons)

Impacts of aviation emissions on LAQ - Synthesis

Non-LTO emissions: potential contribution to surface air quality change ?

- Increasing number of publications since 2004 highlight a role of cruise NOx emissions on surface O_3 and PM concentrations (mainly secondary vPM such as ammonium nitrate and acidic sulfate aerosols)
- But, current modelling not able to properly simulate the scale of the contribution
  - coarse-resolution models, limited representativity of ground-level pollutant concentrations
  - long-distance lateral/vertical transportation of pollutants that increases modelling difficulties and uncertainties
  - small contributions relative to background levels
- Uncertainty level on the impact even higher than that of LTO emissions

⇨ Actual level of contribution is unknown.



Schema of processes that lead to potential changes in surface air quality and human health from aircraft cruise emissions (Lee et al., 2023)

Potential mitigation options and associated challenges

A complex topic due to trade-offs between non-CO_2 and CO_2, or between non-CO_2 (emissions/effects)

Mitigation options	Technical Axis and Potential Benefits	Trade-offs/Challenges and Unknowns
Engine architecture and cycle (Kero)	• Lower OPR/T4 help to reduce EI_NOx • Lower overall engine efficiency / higher exhaust temperature to reduce contrail formation proba • Some architectures (e.g TP/OR vs TF) may have plume dynamics limiting supersaturation • Innovative cycle (e.g. Hybrid WET) ⇨ Potential FB/CO_2 + NO_x/Contrails benefits	• May or will limit future CO_2 emission reductions ⇨ resulting climate impact of NOx vs CO_2 trading ? (Only a few studies, not comprehensive enough). • FB/CO_2 impact ; an increase of contrail formation proba does not necessarily imply an increase of contrail impact. • Effects of architecture on ice crystal formation TBD • More complex configuration, plume/contrail properties TBD
Combustor design and technology	• Further improve RB combustor NOx perfo • Or design for lower nvPM for LAQ & contrails • Lean Burn systems have a higher potential to reduce NOx AND nvPM • Multi-point injection: better mixing / lower emis. • WET/Water inj.: Potential SFC/NOx benefits	• NOx/nvPM design trade-off (RQL) with potential feedback on FB/CO_2 + LTO nvPM reqts to be met (since CAEP/11) • No known example of atmos. science study on this trade-off + LAQ Priority between NOx and nvPM ? • Ice crystals nb increases below a certain nvPM threshold ? • More complex systems => FB penalty risk + higher operability/thermo-acoustics risks + scalability issues ⇨ More research, high cost/dev time

Potential mitigation options and associated challenges

A complex topic due to trade-offs between non-CO_2 and CO_2, or between non-CO_2 (emissions/effects)

Mitigation options	Technical Axis and Potential Benefits	Trade-offs/Challenges and Unknowns
Fuels / Change of Energy Source	SAF/Blends (ie lower/no aromatics and Sulfur) ● Lower LTO/cruise nvPM and ice crystal number ● Better LHV, and CO_2 Life Cycle benefits ⇨ potential “indirect” lever to design for lower NOx ● Better thermal stab ⇨ lower coking risk ⇨ helps for LB or use as heat sink for lower SFC ● Could work for all A/C types HydroTreated (HT) Jet A-1 pending SAF ramp-up ?	● SAF non-drop in properties + Aromatics compatibility concerns with some A/C and infrastructures. ● Relatively slow ramp-up + would require to be able to take credit of SAF in the aircraft/engine cert. processes + would limit nvPM benefits on RB combustors ● SAF + “lower nvPM” combustor techno : Ice crystal number increases below a certain nvPM threshold ? ● Relationship between detailed fuel compo/engine cycle and nvPM/contrail benefits not fully understood ● HT : benefits on modern engines TBD + LCA study
	Hydrogen ● NO Soot/NOx trade and NO CO_2/NOx trade ● Reduced fuel flow thanks to high LHV and H2 can burn at a more homogeneous mixture thanks to better flame stability. ⇨ helps to lower NOx	● Risk of locally higher NOx if fuel/air mixing not well controlled ; flash-back risks ; integration : bigger lines, ... ⇨ Specific combustion system design required AND new Aircraft/Engine architecture ⇨ High dev time ● H_2Comb. / H_2FuelCell contrail properties / impact TBD ● Not yet applicable to LR Aircraft (low density)
	Fully Electric Propulsion / Aircraft	● Limited to very short range aircraft

Potential mitigation options and associated challenges

A complex topic due to trade-offs between non-CO_2 and CO_2, or between non-CO_2 (emissions/effects)

Mitigation options	**Technical Axis and Potential Benefits**	**Trade-offs/Challenges and Unknowns**
Aircraft Architecture / Design	● Optimized engine position / integration vs Jet / Wake Vortices interaction ⇨ better plume dilution + increase of ice crystal losses in the vortex phase ● Wing aspect ratio increase ⇨ Lower FB/Emissions ● Design for lower cruise alt./speeds to reduce NOx/ contrail impacts while minimizing Fuel/CO_2 impacts ● Optimisation of A/C size/range and flight network to reduce emissions	● Aircraft constraints : A/C handling quality aspects (engine failure) + Structural/weight aspects + … ● Reduced vortex descent ⇨ net effect on ice crystals ? ● Effects of aerosols on lower altitude clouds ? + Impacts of speed on the Direct Operating Costs ⇨ reduction of benef. if compensating with more aircraft? ● Difficult implementation : no more LR A/C => increased airport congestion ? ; increased Noise ?
Aircraft operations (Current A/C)	● Vertical/lateral rerouting to minimize/avoid persistent contrails formation or “big hit” contrails ● Vertical/lateral rerouting to minimize the climate (CO_2 & non-CO_2) impact of the flight	● Such optimizations may be at the expense of FB/CO_2 ● Main challenges today : weather forecast accuracy + operational/safe feasibility + evaluation of the actual flight-by-flight climate impact ● Trade-off between minimizing short term vs long term climate impacts

Various options with various levels of implications and potential implementation dates.
It is paramount to improve science understanding to take the right decisions.