HIGH RESOLUTION SIMULATIONS OF CONTRAILS BEHIND FUEL CELL PROPELLED AIRCRAFT

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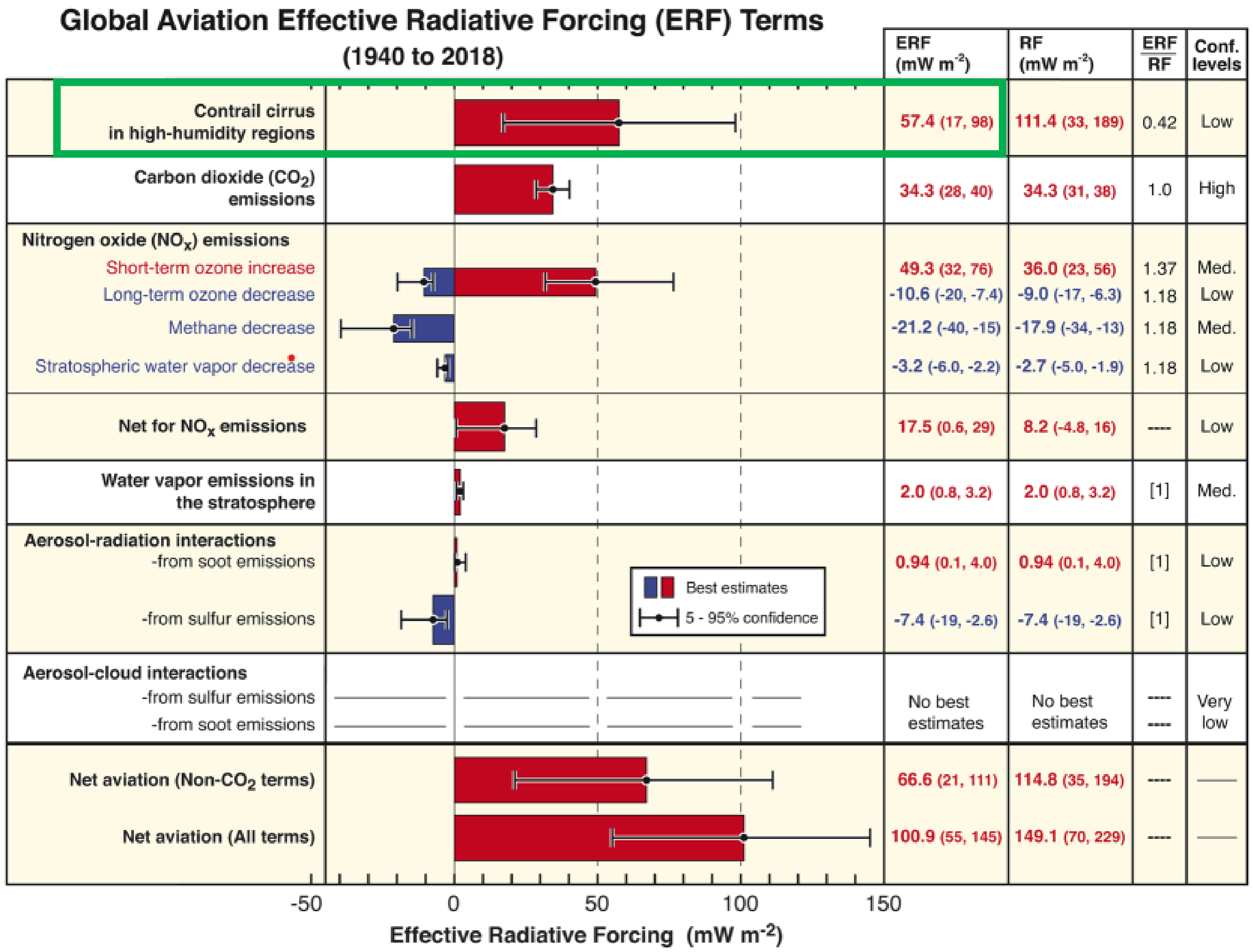
Why do we look at contrails?



Lee et al (2021); Fig. 1

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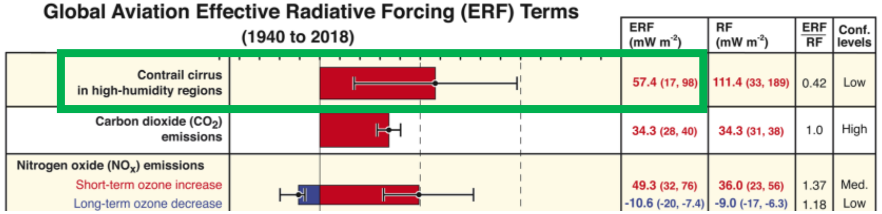

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6^{th} Januar 2025, Munich Pasing

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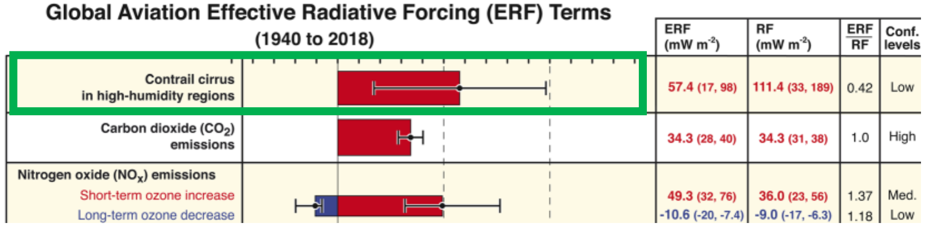

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https://skybrary.aero/articles/contrail

JET PHASE

0 - 10 s

- Expanding and cooling of exhaust plume
- Water droplet formation and freezing into ice crystals

6th Januar 2025, Munich Pasing

Fuel cell propelled aircraft

- No soot, CO_2 and NO_x emissions (when using H_2)
- Climate effect dominated by contrail effect
- **More flexible treatment of exhaust products**

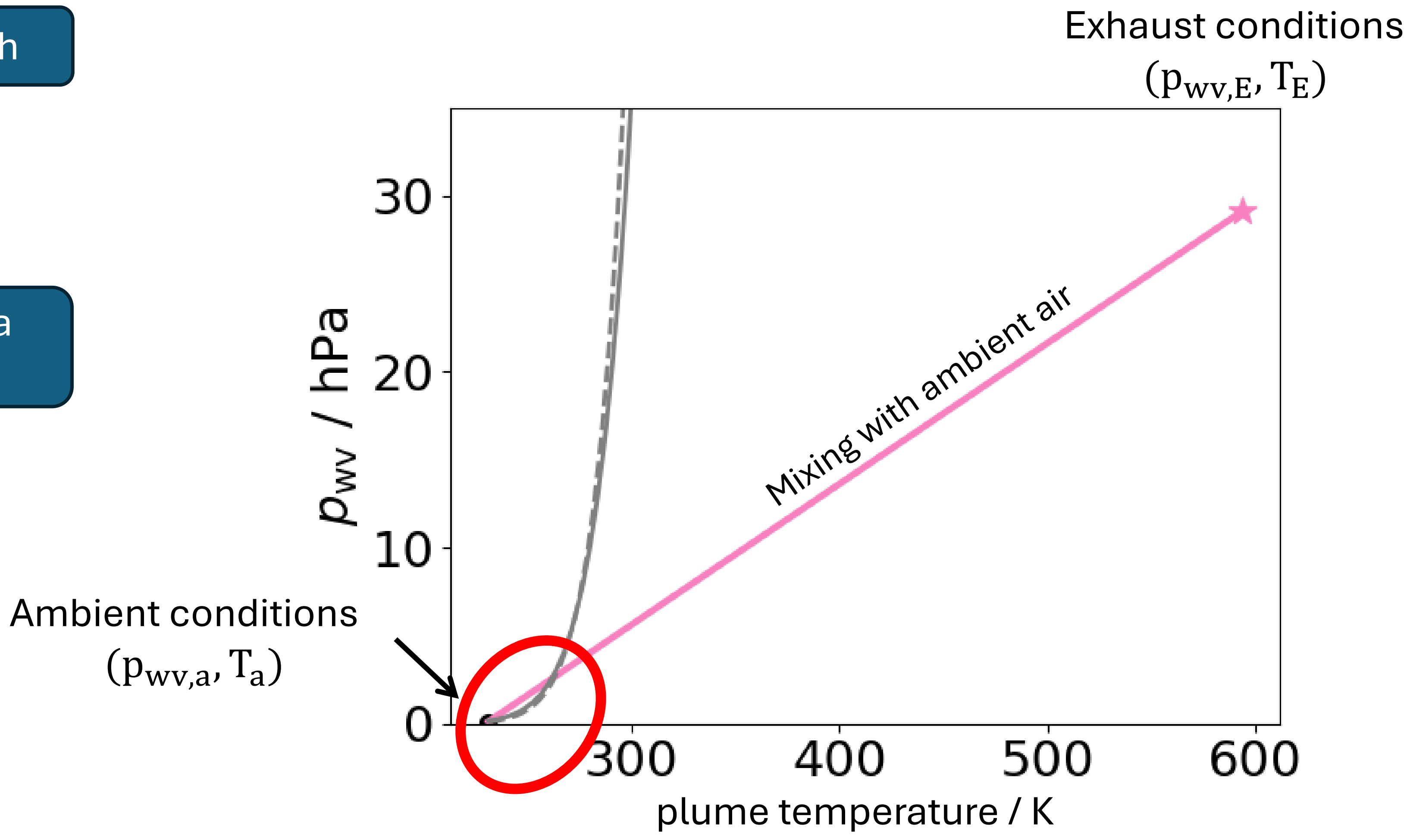
- No solution for the near future (first commercial aircraft planned for next decade)
- Probably only applicable for regional aircraft

https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe-our-hydrogen-powered-aircraft

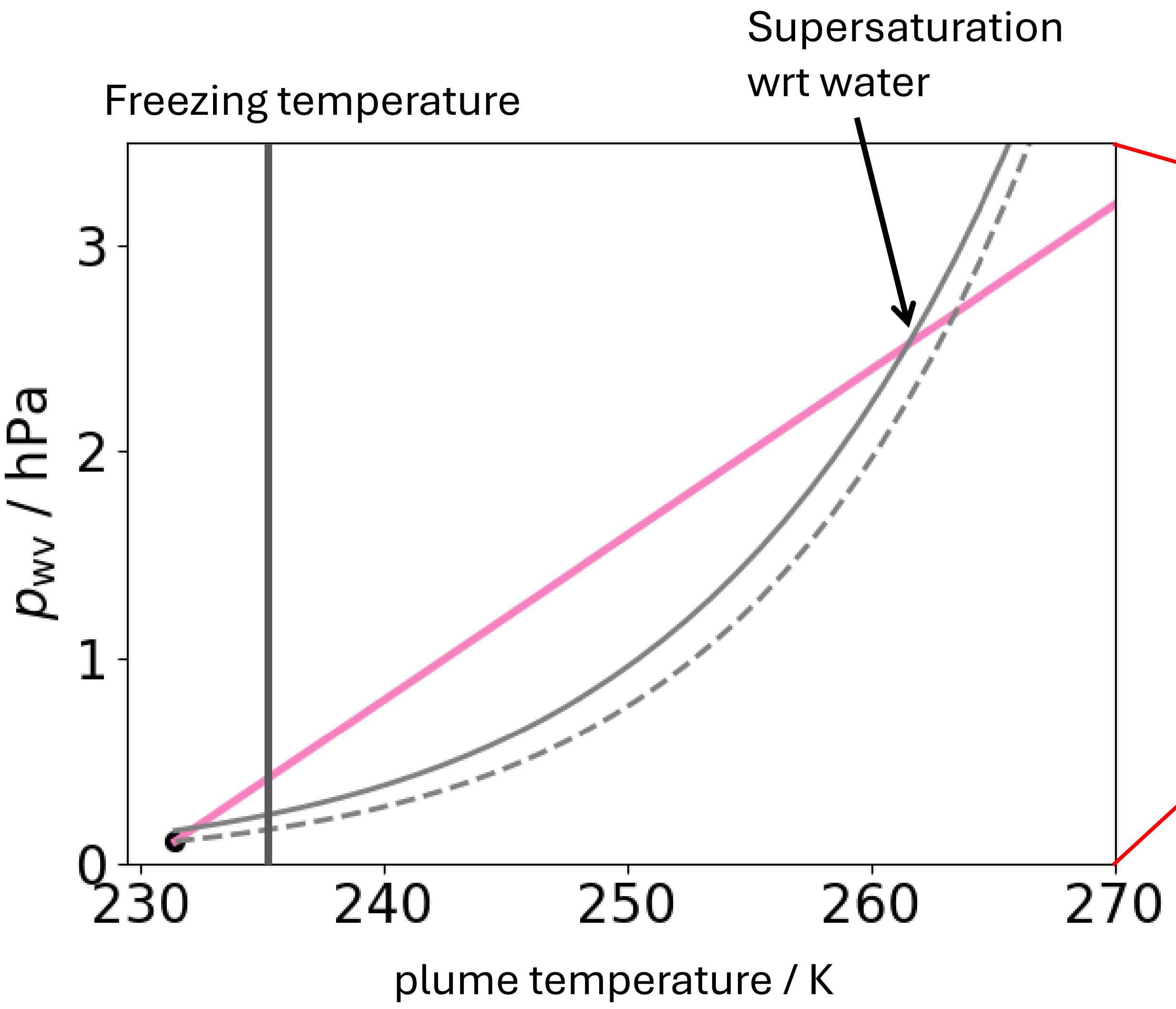
Contrail Formation – Mixing line

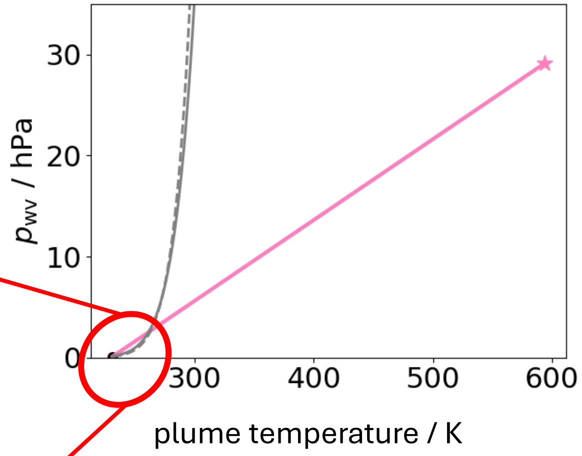
Thermodynamic approach

Binary decision whether a contrail forms or not



Contrail Formation – Mixing line





Mixing line slope: $$G = \frac{\mathrm{EI}_{\mathrm{H_2O}}\, c_p\, p_\mathrm{a}}{Q\,(1-\eta)\,\epsilon}$$

EI_{H2O} : Emission index of water
Q: combustion heat
c_p : heat capacity ≈ 1005 J (kg K)$^{-1}$
p_a : ambient pressure
η : efficiency
ε : ratio molar masses ≈ 0.622

Emission manipulation - Reduction

Remaining water vapor (WV) factor : $\gamma = \frac{\text{actual wv emission}}{\text{theoretical wv emission}}$

Remaining heat factor: $\delta = \frac{\text{actual heat emission}}{\text{theoretical heat emission}}$

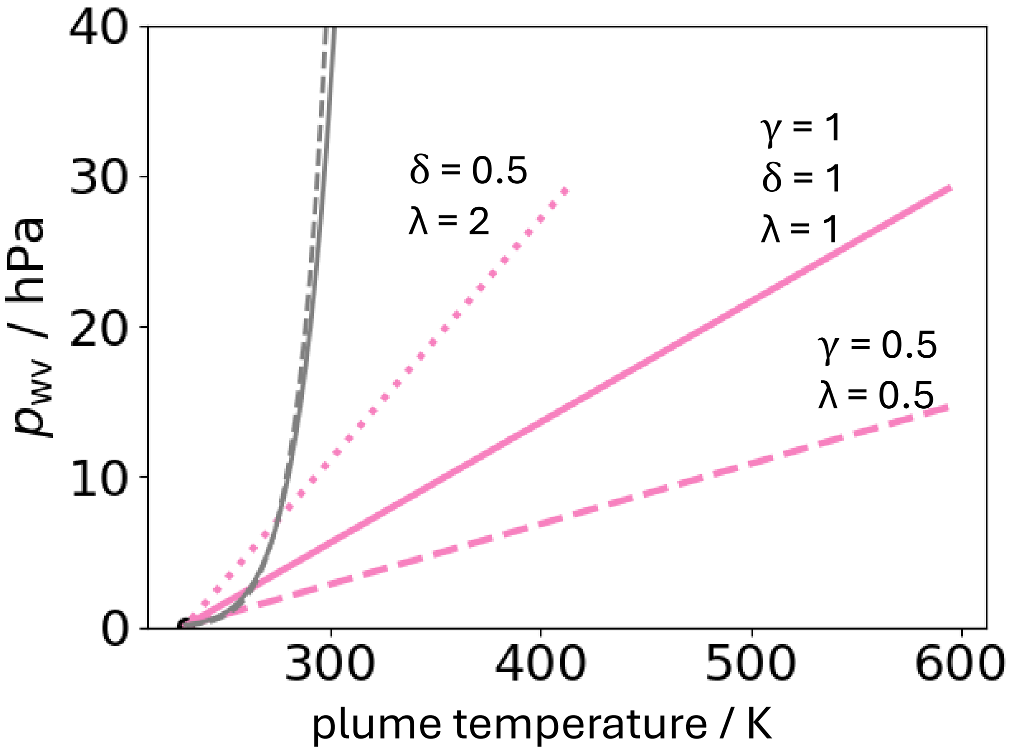
relative heat – water vapor emission $\lambda = \frac{\gamma}{\delta}$ matters

Adapted mixing line slope:

$$G_{FC} = \frac{\gamma\, EI_{H_2O}\, c_p\, p_a}{\delta\, Q\,(1-\eta)\,\epsilon}$$

WV reduction → $\lambda < 1$ → **Less** contrail formation

heat reduction → $\lambda > 1$ → **More** contrail formation

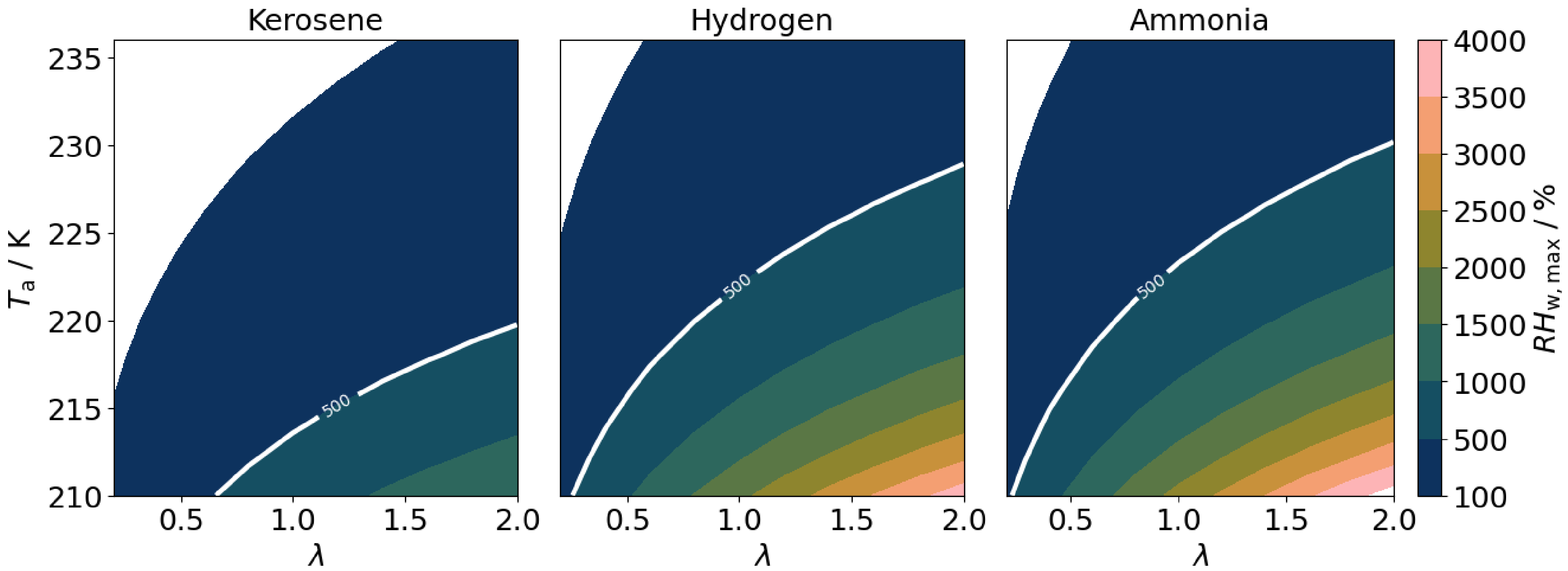


Supersaturation increase for heat reduction

Effect of emission reduction on the maximum relative humidity of plume during cooling

Values are upper limits when no microphysics take place

FL 240
p_a = 400 hPa
$RH_{i,a}$ = 100 %



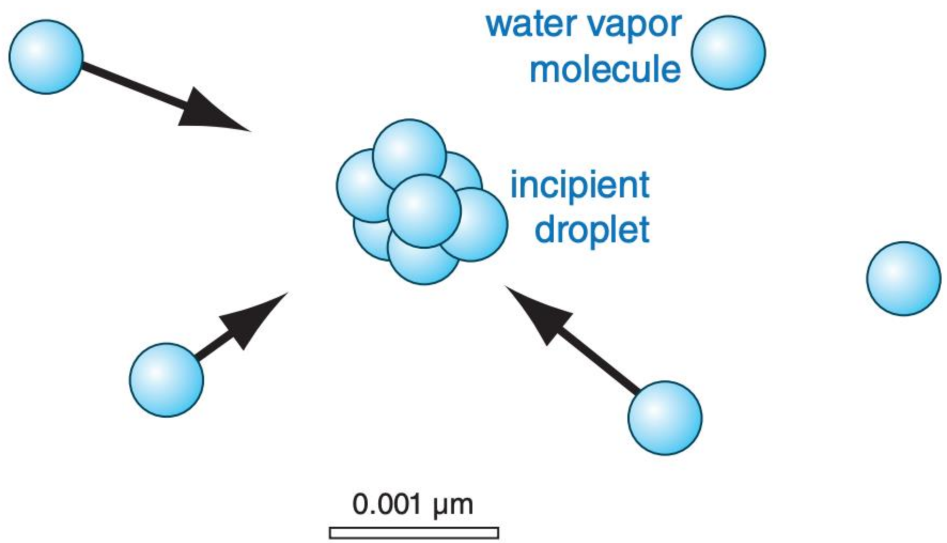
Effect of high supersaturation

For **RHw > 500%** an additional microphysical process can be triggered:
Homogeneous Droplet Nucleation (HDN)

- Spontaneous formation of water droplets without any nucleation particles
- Creation of many very small droplets
- Highly non-linear nucleation rate

→ Numerical treatment challenging
→ Potentially increases the number of ice crystals by orders of magnitude

→ Has to be avoided!

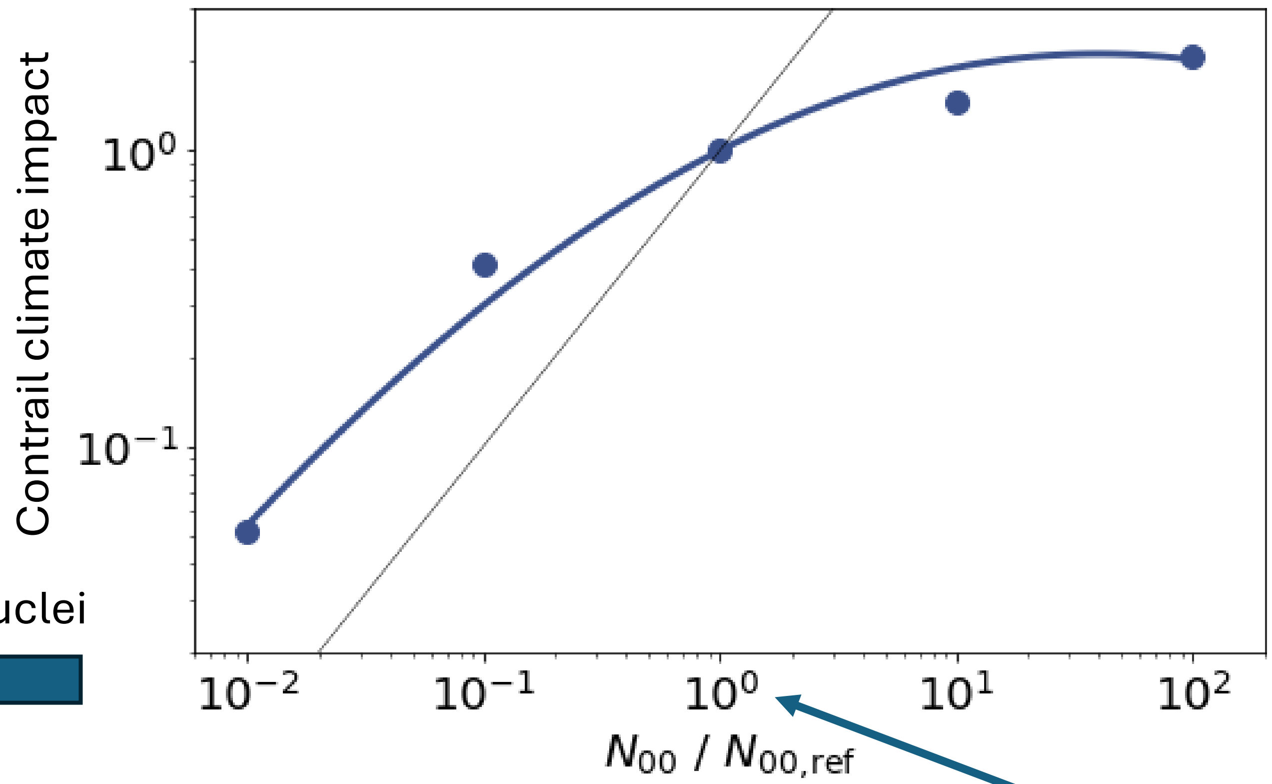


Remark: The 500% limit is no hard limit, but we can ensure that HDN is not significant if RHw < 500%

Climate impact of contrails

Formed number of ice crystals

Metric for contrail radiative effect: Time-integrated total extinction $\hat{E}$



Adapted from Fig. 10 in Lottermoser, Unterstrasser (2025)

Hydrogen
Fewer available ice nuclei

Hydrogen
with HDN

kerosene

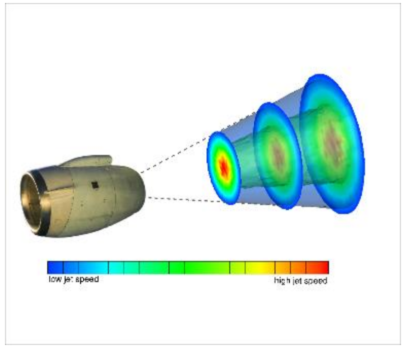
Simulation model - Microphysics

Temperature evolution for an ensemble of plume-sampling trajectories

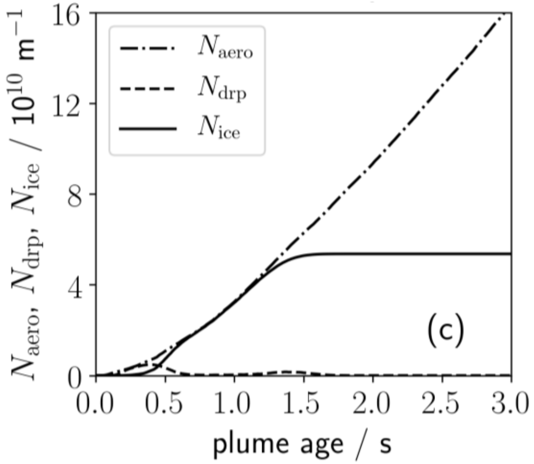
LCM box model

Ice crystal number
Ice mass
- Temporal evolution
- Separately for each particle type

CFD simulation



- Lagrangian particle tracking
- Microphysical processes:
  - Nucleation
  - Condensation
  - Freezing
- Various ice forming particle types can be simulated



Simulation setup

- 3D turbulent CFD simulation of plume behind aircraft (provided by Airbus)
- Temperature evolution derived for mean trajectory
- Pure hydrogen used as fuel
- No particles initially present in the exhaust
- Timestep $\Delta t = 10^{-4}$ s; simulation time $t_{sim} = 6$ s
- HDN process included

Ambient conditions

p_{amb}	400 hPa
T_{amb}	{210, 230} K
$RH_{i, amb}$	100 %
Aerosols	n =1000 cm^{-3}, r = 10 nm

Exhaust conditions

Propulsion efficiency	η	{0.3, 0.5}
WV reduction	γ	{1, 0.25}
Heat reduction	δ	{1, 0.25}

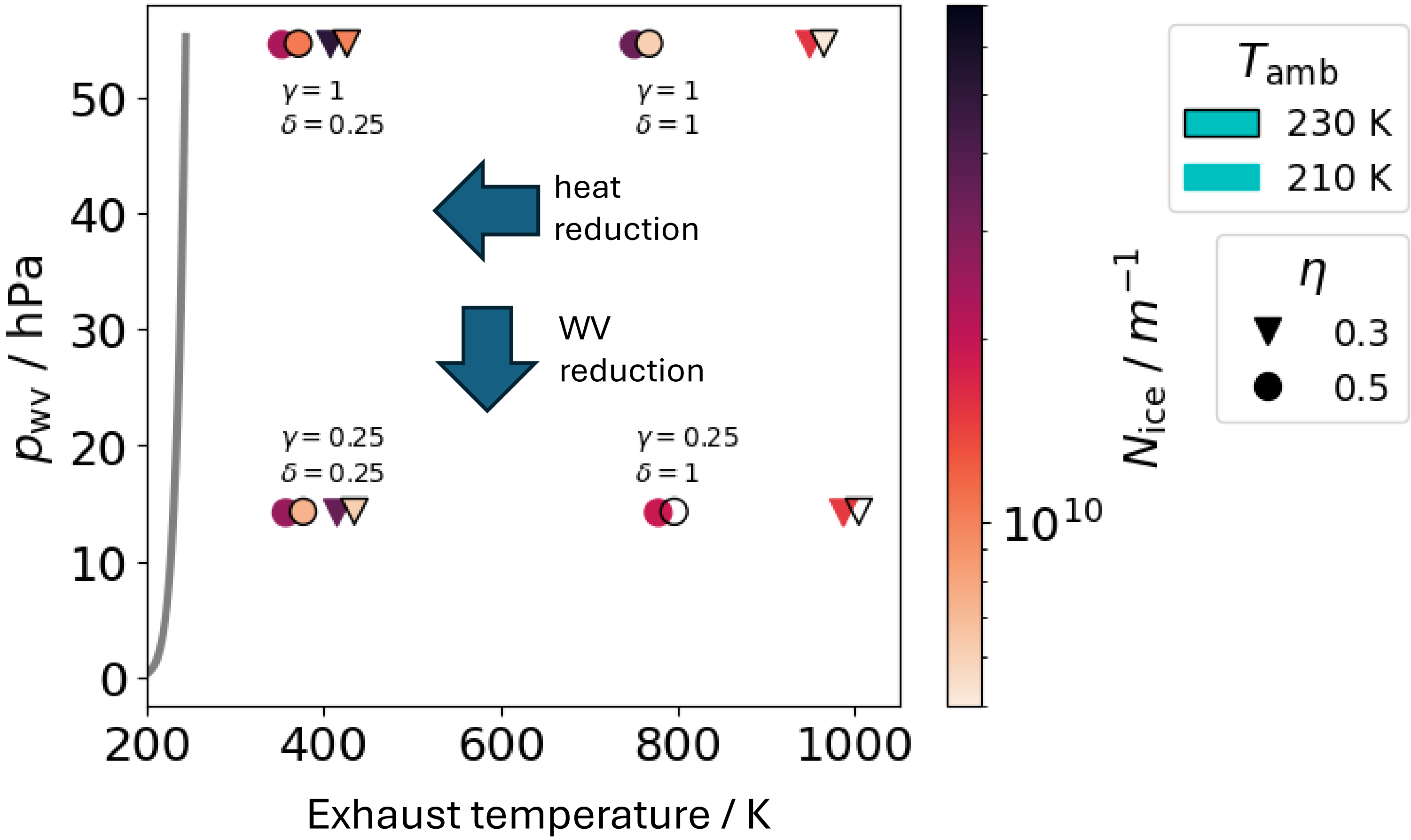
Simulation results

Higher efficiency leads to more ice crystals

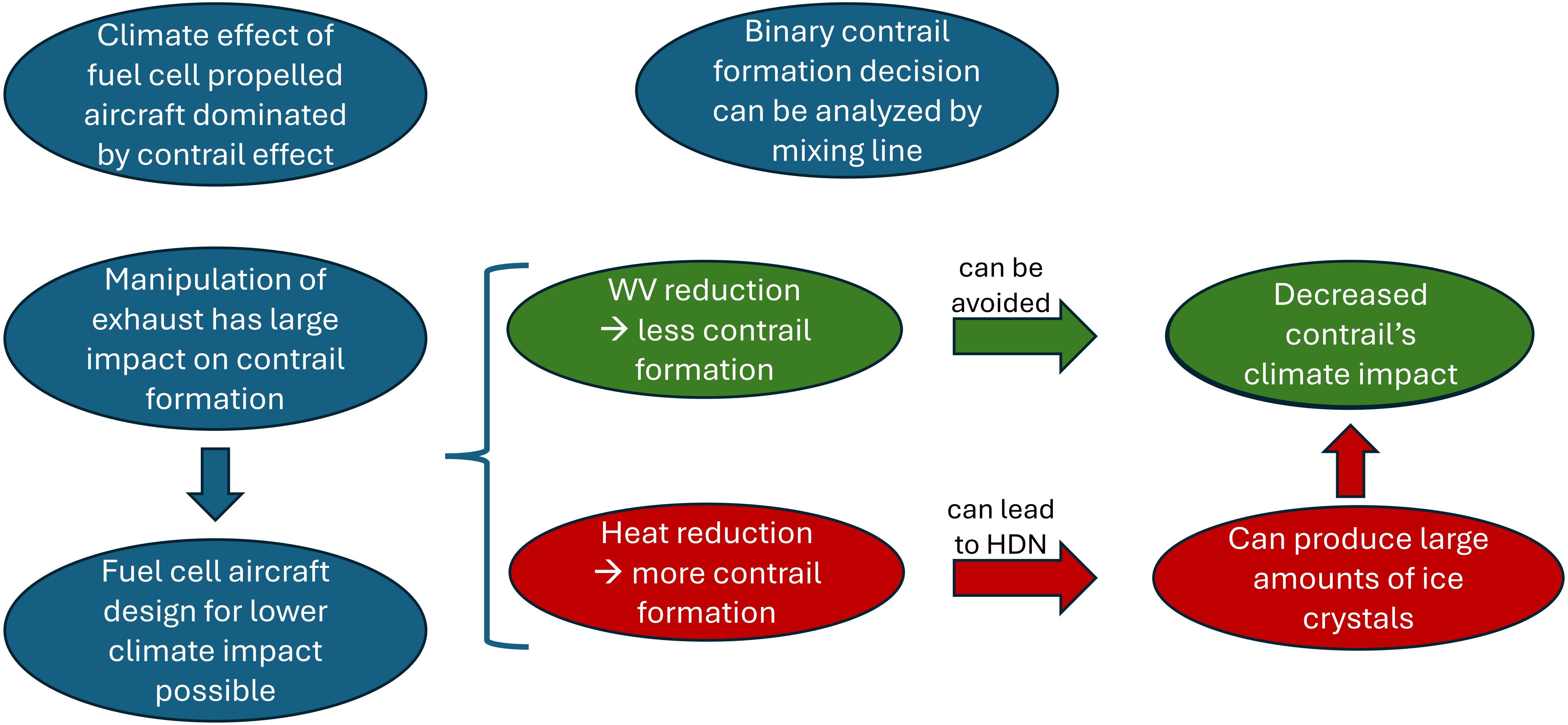
Highest N_{ice} when HDN occurs

HDN more relevant for cold conditions

WV reduction can avoid contrail formation



Take home messages



THANK YOU

https://cosmosmagazine.com/wp-content/uploads/2020/03/200213-Contrails.jpg