Climate impact of fuel cell induced liquid water droplet emissions

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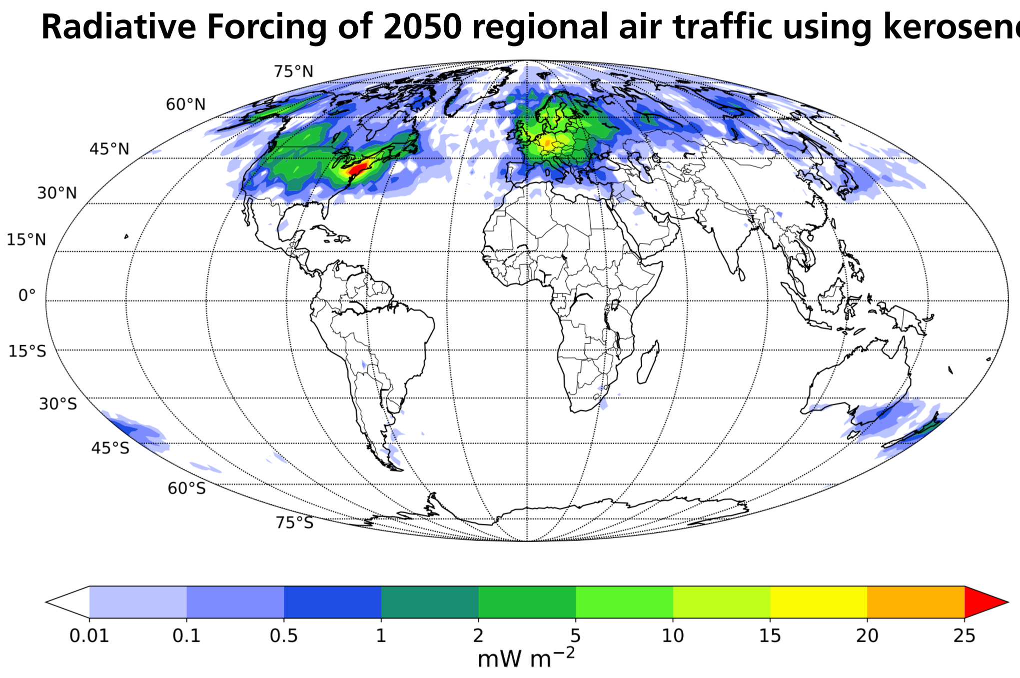
Future fuel cell powered aviation

Radiative Forcing of 2050 regional air traffic using kerosene



To improve the sustainability of air transport, efforts are being made to transition to alternative fuels. In order to facilitate the changeover, regional flights may be targeted first. One possible concept is based on the use of fuel cells. Similar to conventional jet engines, fuel cells emit liquid water droplets and water vapor into the atmosphere, but no soot particles or sulfate. Beside the emitted droplets, additional droplets may form e.g. by activation of ambient aerosols or spontaneous nucleation. Activation of ambient aerosols is unlikely to be significant as long as many small water droplets are emitted. Atmospheric conditions and the size of the water droplets control how many of the emitted droplets will freeze. We study the number of droplets freezing within the plume in order to estimate the associated climate impact.

Motivation

We estimate the maximum possible climate impact assuming that all emitted droplets freeze.

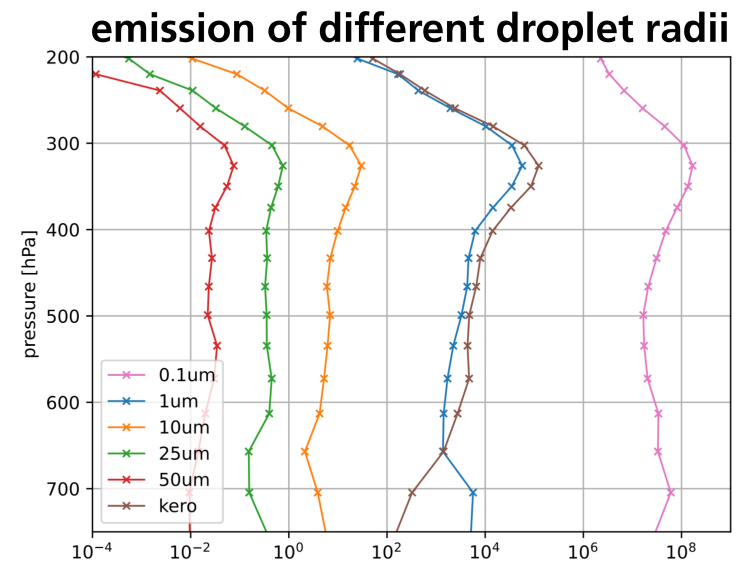
Assumptions:

- constant liquid and water vapor flow rates
- variation of emitted mean droplet radii: 0.1µm, 1µm, 10µm, 25µm, 50µm

→ determination of emitted ICNC for a constant aircraft speed and cross sectional area

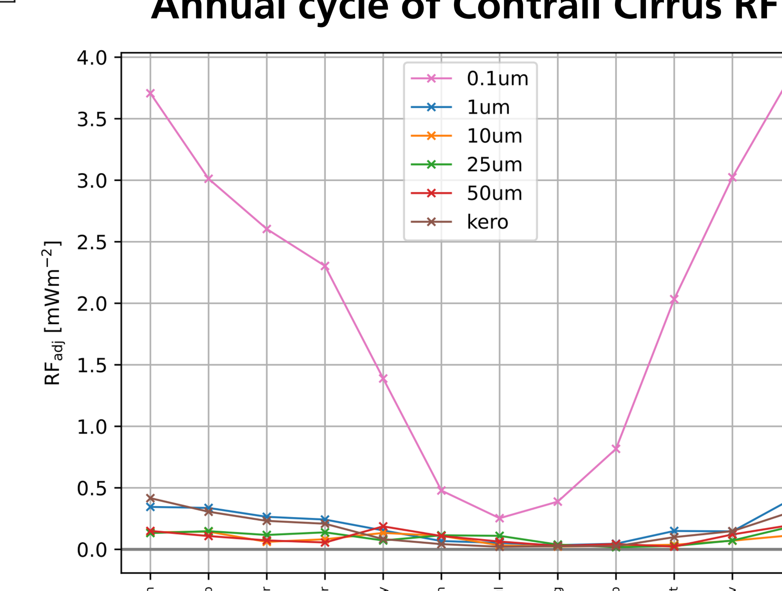
droplet radius [µm]	0.1	1	10	25	50
ICNC [m^{-3}] at emission	3.2×10^{11}	3.2×10^{8}	3.2×10^{5}	2.0×10^{4}	2.5×10^{3}

Profile of contrail cirrus ICNC for emission of different droplet radii



- large differences of ICNC at emission maintained throughout live-cycle
- when emitting droplets with a radius of 1µm ICNC are comparable to the conventional kerosene case
- for emission of larger droplets ICNC would be smaller if new droplet formation could be neglected but high plume ice supersaturation points at additional droplet formation

Annual cycle of Contrail Cirrus RF



- RF as large as in kerosene case when emitting 1µm droplets
- RF potentially very large when emitting 0.1µm droplets
- large sensitivity of RF to droplet size

Key questions:

- How many droplets can freeze within the plume?
- Can additional droplets form?

We mainly study emissions of droplets with sizes of 0.1µm and 1µm which are able to reduce supersaturation effectively, making additional droplet formation unlikely.

Droplet freezing

Box model simulations of droplet freezing dependent on ambient conditions and droplet sizes.

Number of ice crystals forming are calculated by simulating the plume evolution after emission by the fuel cell.

- plume dilution leads to cooling and to an increase in relative humidity and droplet growth
- droplet freezing dependent on plume conditions and droplet size
- growth of ice crystals decreases relative humidity and leads to evaporation of droplets

Determination of young contrail ice crystal number concentration (**ICNC**) and ice water content (**IWC**) as input for the climate model

ECHAM5-CCMod climate model

ECHAM 5 - German community climate model (T63L41)

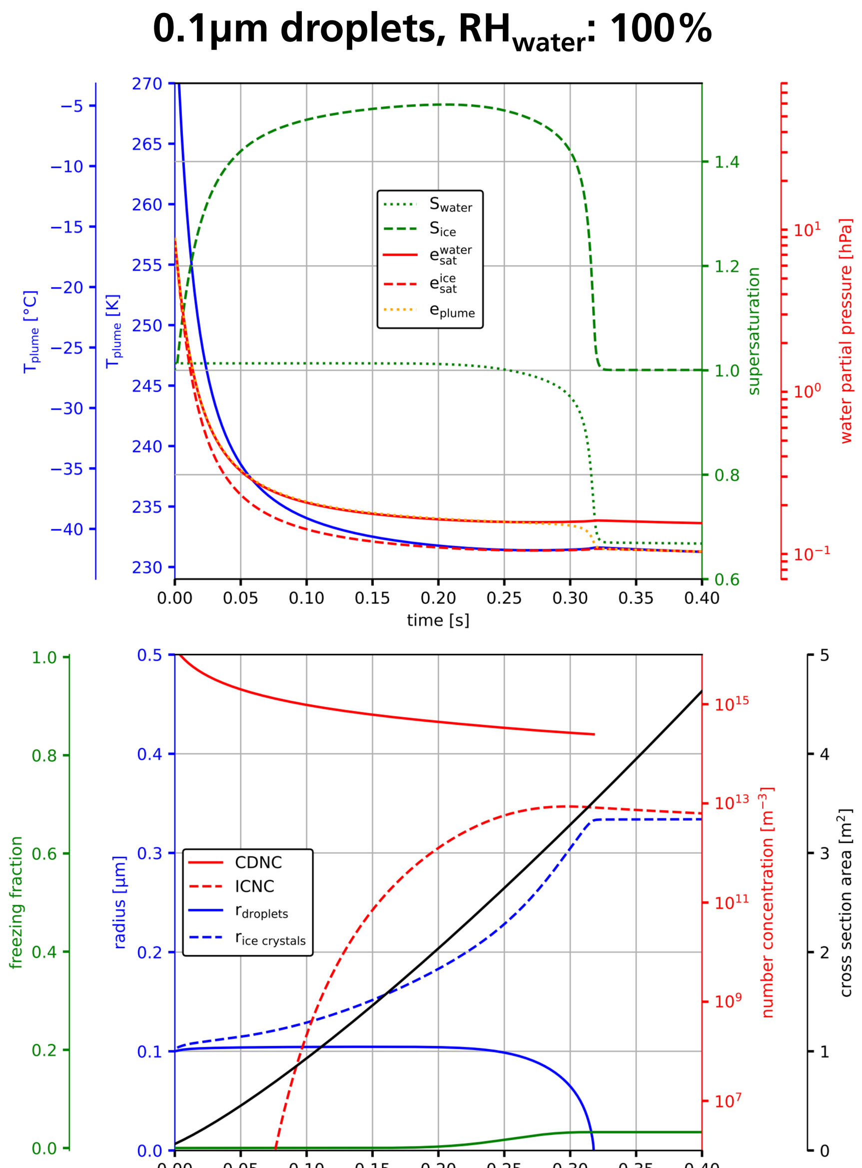
CCMod - Simulation of a new cloud class: persistent contrail cirrus

- Microphysical 2-moment-scheme
- parameterization for ice nucleation and ice crystal loss in the vortex phase
- deposition, sublimation and sedimentation of ice crystals
- advection and spreading of contrails
- evolution of contrails in cloud-free ice supersaturated areas (fractional grid boxes)

See: Burkhardt and Kärcher, JGR, 2009; Bock and Burkhardt, JGR, 2016; Bier and Burkhardt, 2022

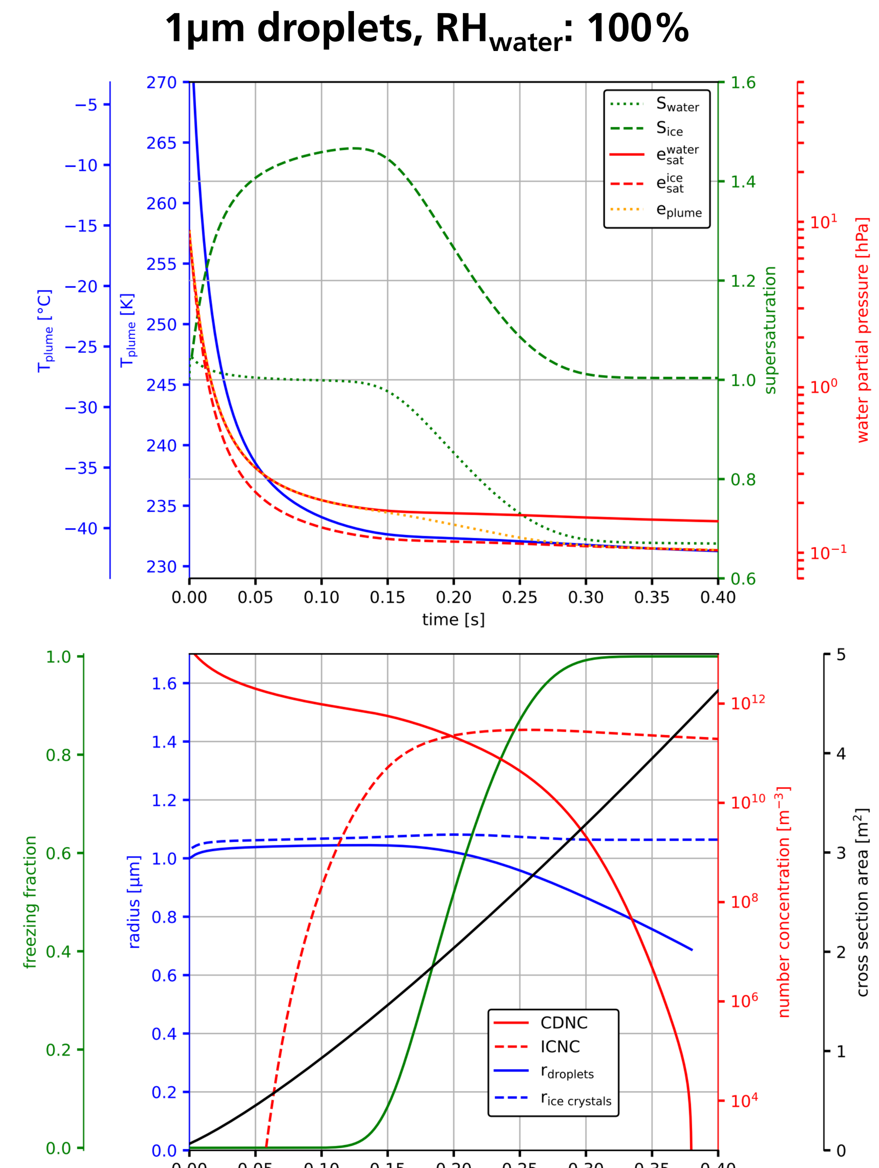
Freezing of emitted droplets

0.1µm droplets, RH_{water}: 100%



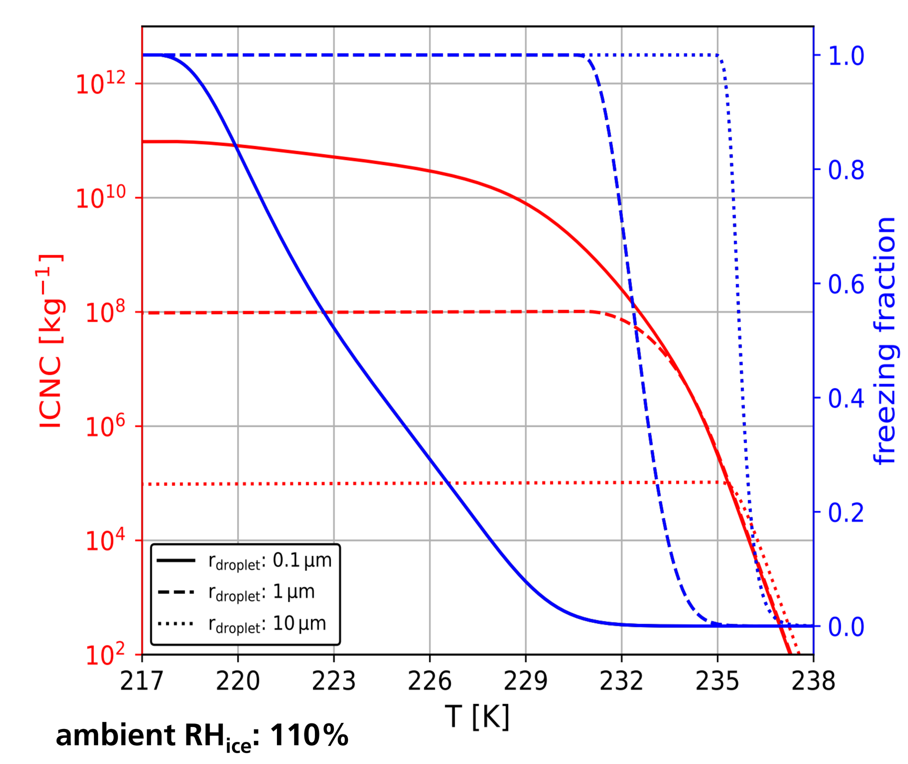
- rapid cooling (blue line, upper panel) results in an increase in ice saturation ratio (green dashed line)
- low freezing rate (green solid line) due to small droplet size and high temperature
- early end of freezing pulse due to growth of ice crystals and evaporation of droplets

1µm droplets, RH_{water}: 100%



- as for 0.1µm droplets: rapid cooling (blue line, upper panel) results in an increase in ice saturation ratio (green dashed line)
- significantly larger freezing rate for 1µm droplets than for 0.1µm droplets
- the faster freezing of droplets results in a significantly larger freezing fraction, relaxing ice supersaturation fast

Dependency on ambient temperature



- The final ICNC (red lines) and freezing fraction (blue lines) are strongly dependent on the emitted droplet size and on ambient temperatures.
- The smaller the droplets the lower ambient temperatures are needed to freeze all emitted droplets.
- ICNC at warm ambient temperatures are independent of droplet size as emitted water mass is constant

Conclusions

- depending on droplet size contrail cirrus induced by fuel cell emissions could potentially have a larger climate impact than kerosene
- when emitting small droplets only a fraction of droplets will freeze depending on ambient temperatures
- when emitting large droplets plume saturation may reach high supersaturation leading to additional droplet formation (not shown)
- large potential for mitigation efforts due to large sensitivity of droplet freezing on emission characteristics and ambient temperatures → work ongoing

References

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