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Contrail aging simulation of a supersonic aircraft

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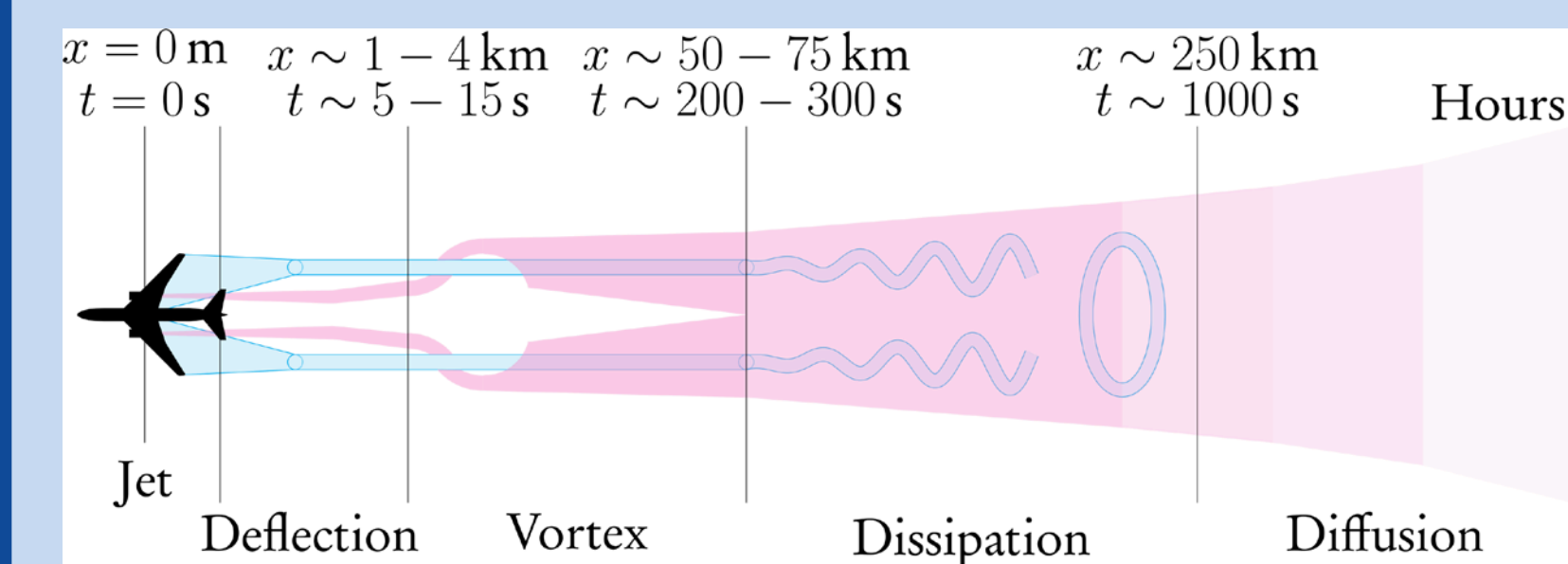
Context

SENECA project ("noiSe and EmissioNs of supErsoniC Aircraft") aims at:

- developing supersonic aircrafts;
- investigating the impact of specific supersonic engine technologies on the aircraft performance and noise;
- quantifying a range of climate impacts of supersonic aviation.

Objectives

- Model and characterize the contrails due to supersonic aircraft during cruise
- Provide data to climatologists to calculate their global impact



Classification of aircraft wake evolution into four regimes [1] following a tracer exhaust emitted at $t = 0$ from the nozzle exit.

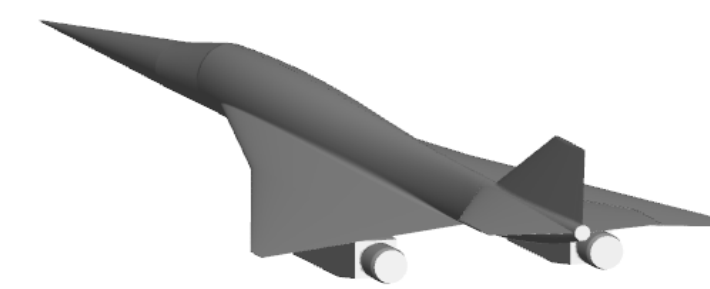
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- [1] Saulgeot, P., Contributions à la compréhension de la formation et de l'atténuation possible des traînées de condensation de l'aviation. Mécanique des fluides [physics.class-ph]. Ecole Polytechnique, 2023. Français. NNT: 2023IPPAX143. tel-04432088
- [2] Kärcher, B., Hirscheberg, M., Fabian P. Small-scale chemical evolution of aircraft exhaust species at cruising. *J. Geophys. Res.*, vol. 101, 1996
- [3] Khou, J.-C., Ghedaffi, W., Vancassel, X., Garnier, F. Spatial Simulation of Contrail Formation in Near-Field of Commercial Aircraft. *J. Aircraft*, vol. 52, pp. 1927-1938, 2015
- [4] Muller, M., Terrenoire, E. Near-field mesh adaptation for contrail modeling of a supersonic aircraft, in 57th 3AF International Conference on Applied Aerodynamics, Bordeaux - France, 29 - 31 March 2023
- [5] Fahey, D., Keim, E.R., Boeing, K.A., Brock, C., Wilson, J., Jonsson, H., Anthony, S., Hanisco, T.F., Wennberg, P. Emission Measurements of the Concorde Supersonic Aircraft in the Lower Stratosphere. *Science*, vol. 270, pp. 70-74, 1995
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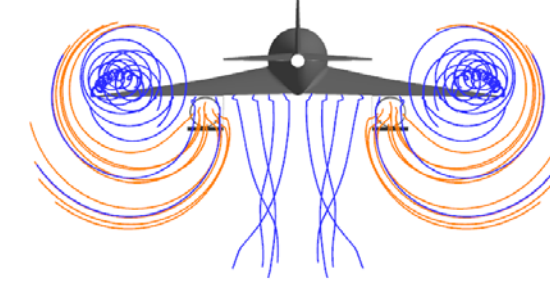
Jet regime modeling

CFD RANS Modeling

- CEDRE/CHARME aerodynamic modeling
- K- ω turbulent model (SST Menter)
- Gas-phase chemistry^[2]
- Microphysics model^[3]



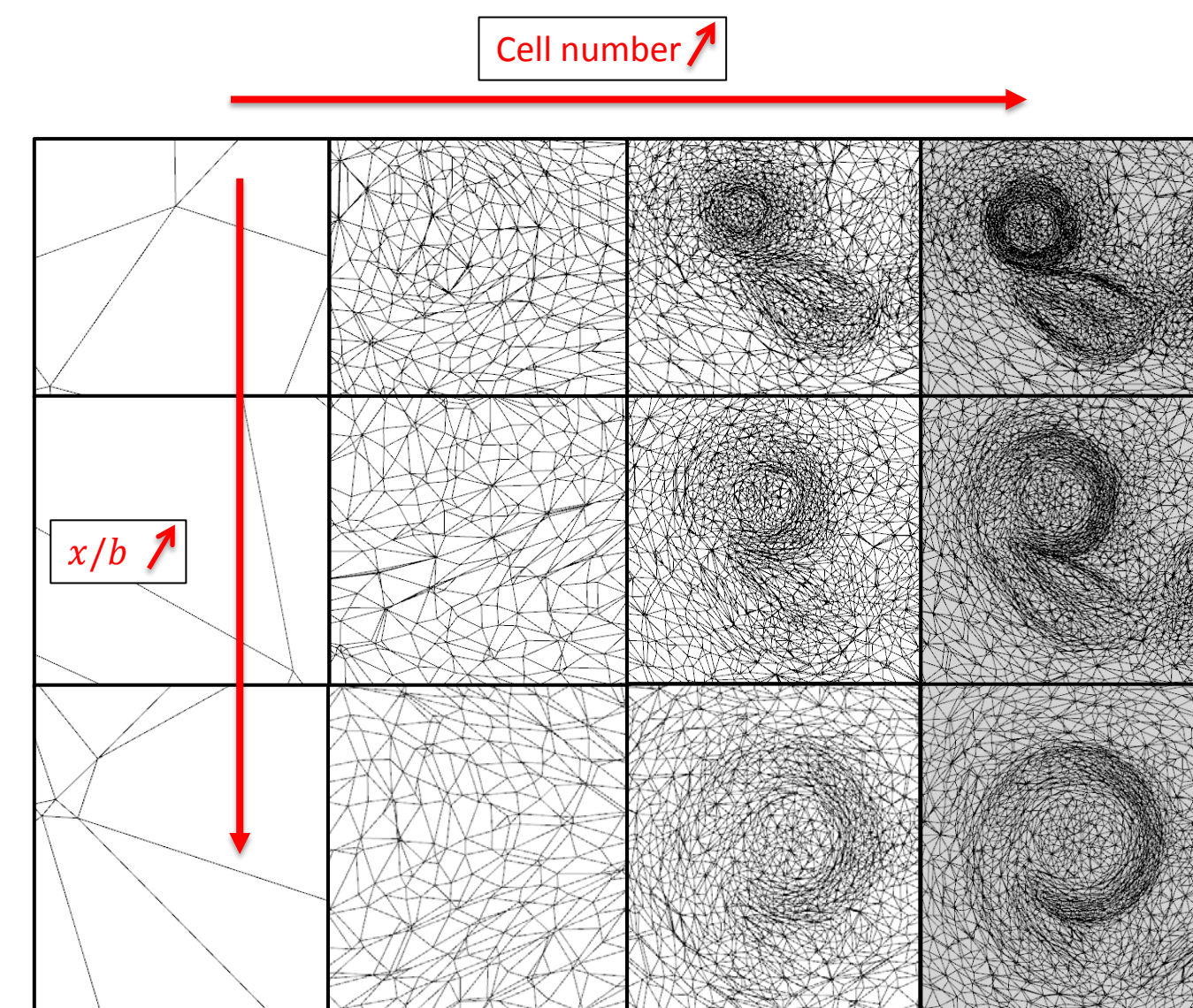
CAD of E19 Aeolus bizjet (Cranfield University)



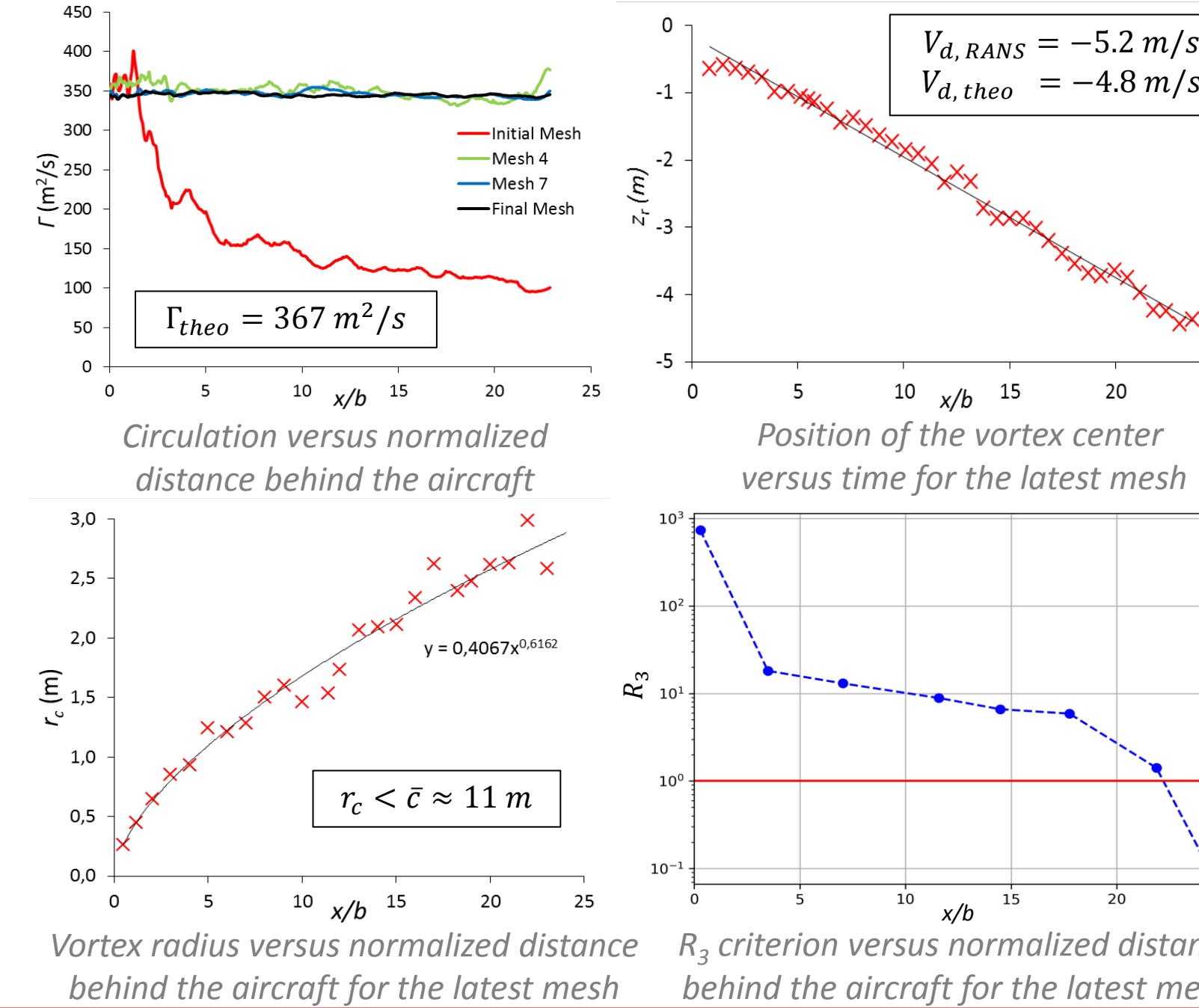
Streamlines behind the E19 bizjet colored by origin: orange for the engine exit and blue for wing

Mesh adaptation procedure (INRIA Tool)

- Variable used to refine the mesh: $V_t = \sqrt{\sum_j (V_j - V_{j,a})^2} + \max(|K - K_a|, K_a)$
- Mesh adaptation illustration^[4]
- 4 criteria to check the mesh quality:



Evolution of mesh through adaptation process (slices behind the aircraft)

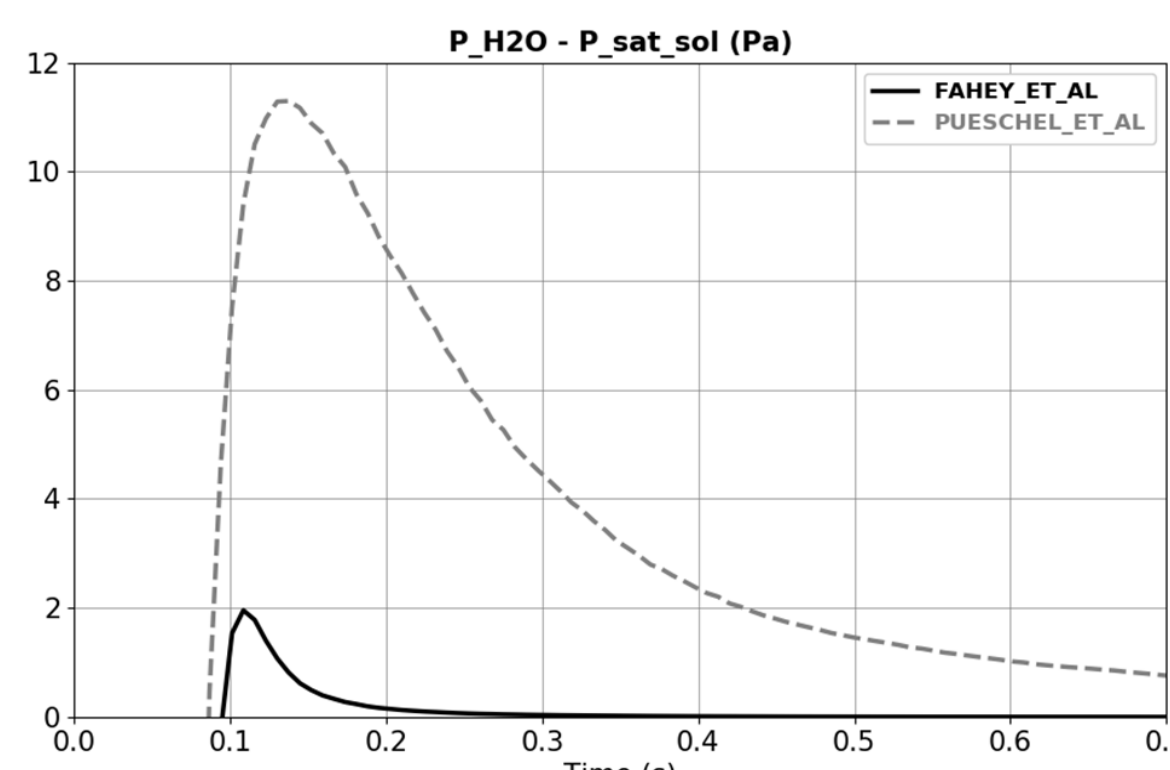


Vortex radius versus normalized distance behind the aircraft for the latest mesh

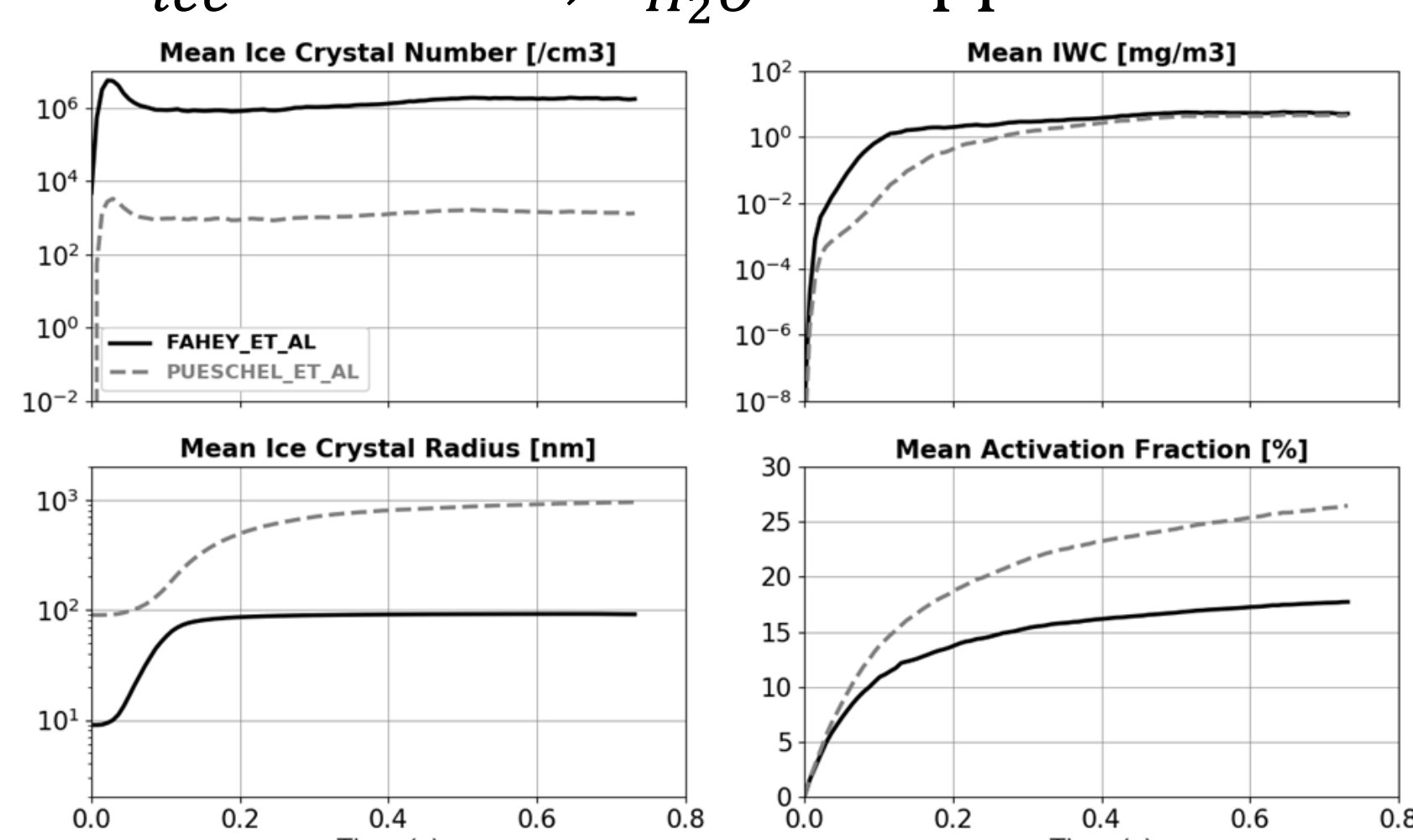
Parametric study

- Tropical conditions in lower stratosphere: $P_a = 9750$ Pa, $T_a = 196$ K
- Ice SuperSaturated Region (ISSR): $RH_{ice} = 100\%$, $X_{H_2O} = 8$ ppmv

Case	r_c [nm]	ρ [kg/m ³]	N_c [1/m ³]
Fahey et al. [5]	9	900	$4.76 \cdot 10^{14}$
Pueschel et al. [6]	90	1600	$2.68 \cdot 10^{11}$



Mean values of difference between the partial pressure of water and the saturation pressure over ice versus physical time behind the aircraft



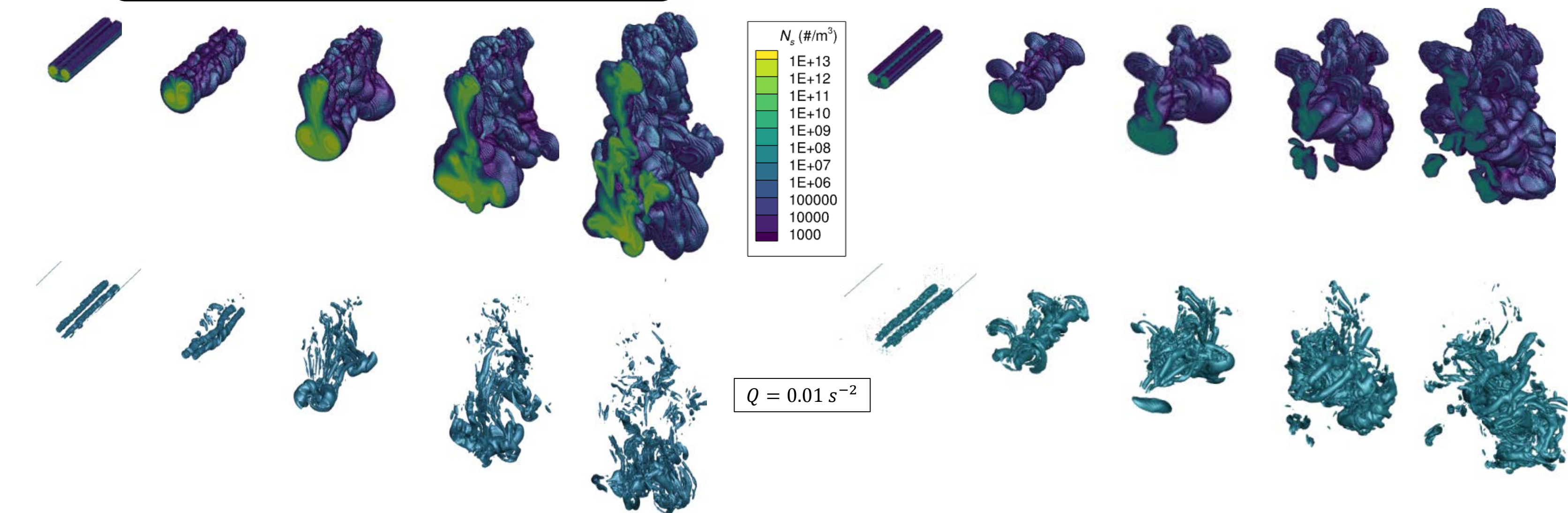
Mean values of difference between the partial pressure of water and the saturation pressure over ice versus physical time behind the aircraft

Vortex and Dissipation regime modeling

CFD LES Methodology^[7]

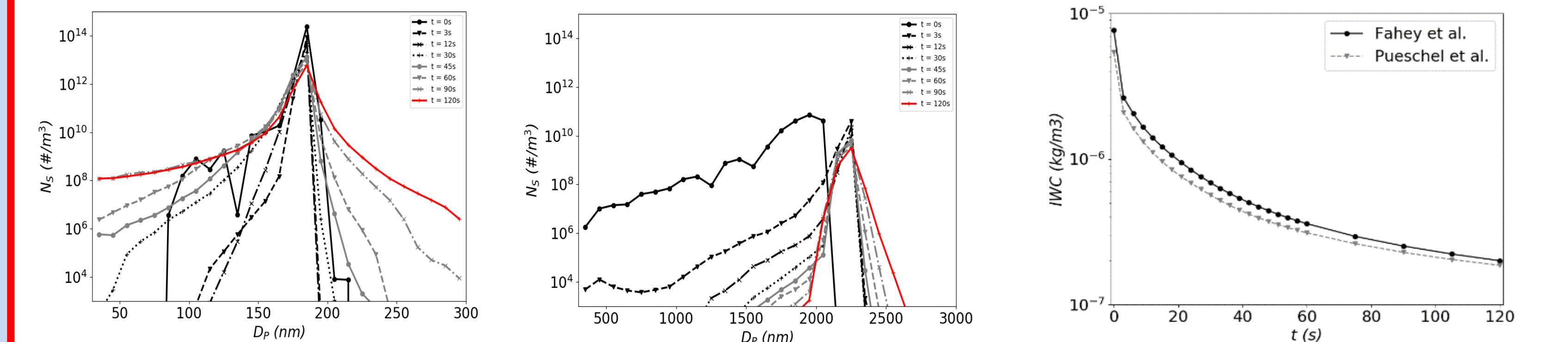
- CEDRE/CHARME aerodynamic modeling
- Smagorinsky model
- Microphysics model^[3]
- 120 s contrail aging simulated
- Characteristic vortex descent time: $t_{descent} = \frac{B_0}{V_{descent}} = 2.1$ s
- LES initialization in 5 steps:
 1. Slice extraction from RANS simulation
 2. LES mesh creation
 3. Interpolation RANS => LES
 4. Adding fluctuations
 5. Adding atmospheric stratification

CFD LES Simulation



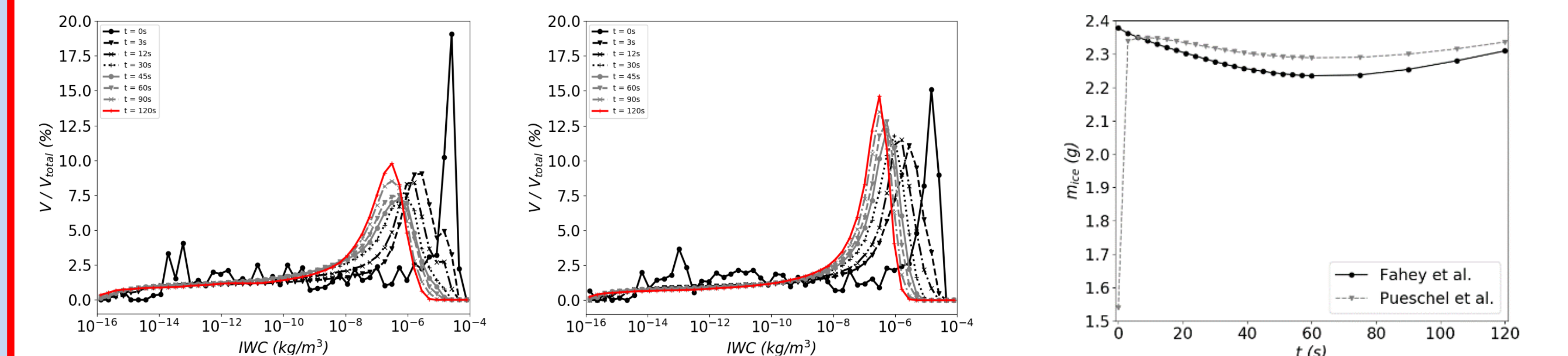
Evolution of the contrail shape and the Q isoline with data from Fahey et al. versus time: 0 s, 3 s, 15 s, 30 s and 60 s

Evolution of the contrail shape and the Q isoline with data from Pueschel et al. versus time: 0 s, 3 s, 15 s, 30 s and 60 s



Ice particle number distribution versus ice diameter bins for the cases with data from Fahey et al. (left) and from Pueschel et al. (right)

Evolution of the mean ice water content inside the contrail for both cases



Contrail relative volume distribution versus ice water content bins for the cases with data from Fahey et al. (left) and from Pueschel et al. (right)

Evolution of the ice mass inside the contrail for both cases