Which parameters govern the strength of entrainment?

Wiebke Frey[1], Silvio Schmalfuß[1], Frank Stratmann[1], and Dennis Niedermeier[1]

[1]Leibniz Institute for Tropospheric Research

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Abstract

One of the key small-scale processes that necessarily require parameterisation is the turbulent mixing of cloudy and cloud-free air, i.e. entrainment and detrainment (in the following simplified as entrainment), which describe the in-mixing of ambient air into the cloud and the mixing of cloudy air into the environment surrounding the cloud, respectively. Entrainment changes cloud particle properties such as number concentrations and sizes, which also modifies the radiative properties of the cloud, and has important implications for cloud lifetime. No reliable formulation exists to date that allows understanding and describing entrainment in terms of cloud- and environmental physical quantities. This is despite the fact that a wide variety of entrainment parameterisations exists. However, their dependencies on meteorological parameters remain controversial. Indeed, the mixing processes (including entrainment) and their treatment in the numerical models have been found to be responsible for much of the large spread found in climate sensitivity estimates. A combination of measurements in the turbulent wind tunnel LACIS-T at TROPOS and computational fluid dynamics (CFD) simulations is used to identify the main parameters that govern the strength of entrainment. Here, we will present first results from the observations in LACIS-T, where the two air streams of the wind tunnel are used to mimic in-cloud and out-of-cloud conditions. Conditions in one of the air streams are varied to test the impact of the corresponding parameters (i.e. temperature, relative humidity, air speed) on the entrainment. Cloud droplets are induced by a droplet generator. The measurements are accompanied by CFD simulations which are verified by the point measurements in the wind tunnel and allow to retrieve full 3D fields.

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Motivation

- entrainment (and detrainment) key small scale process, yet physically not well understood
- parameterisations in models partly disagree on physical basis
- treatment of mixing processes in numerical models found responsible for much of large spread in climate sensitivity estimates

➢ understand which underlying physical parameters govern entrainment

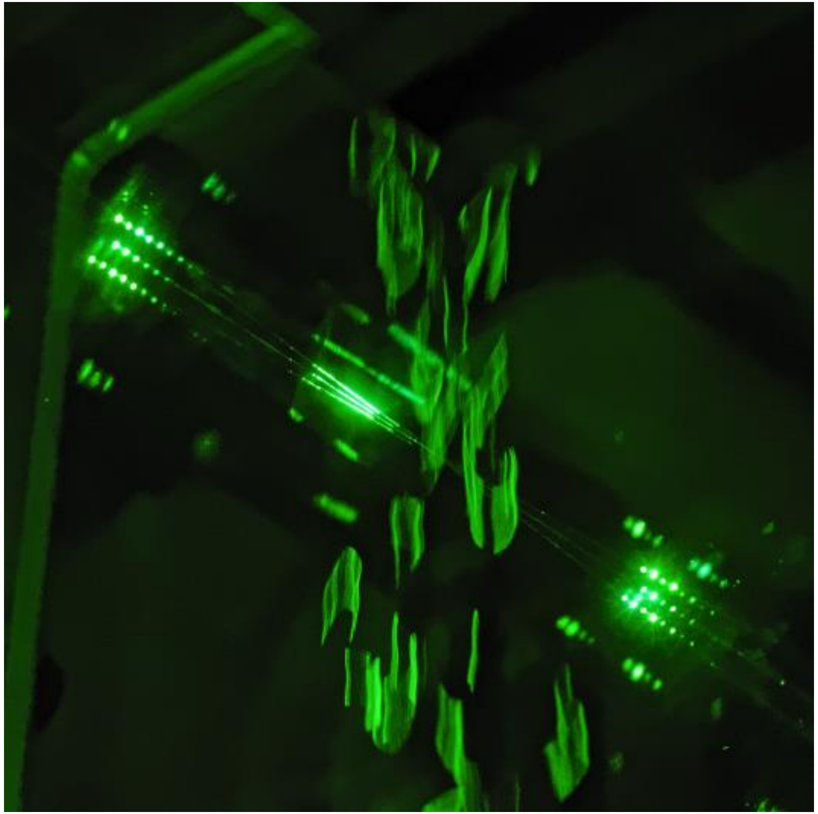

Photo: Tilo Arnhold (TROPOS)

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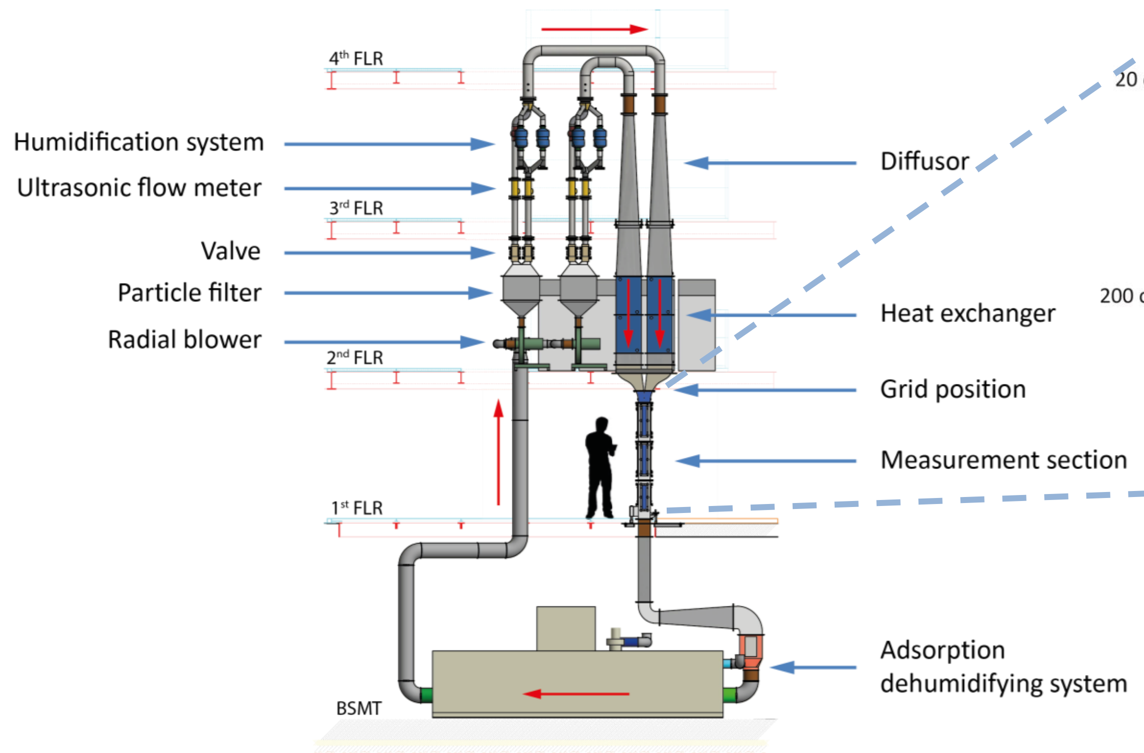
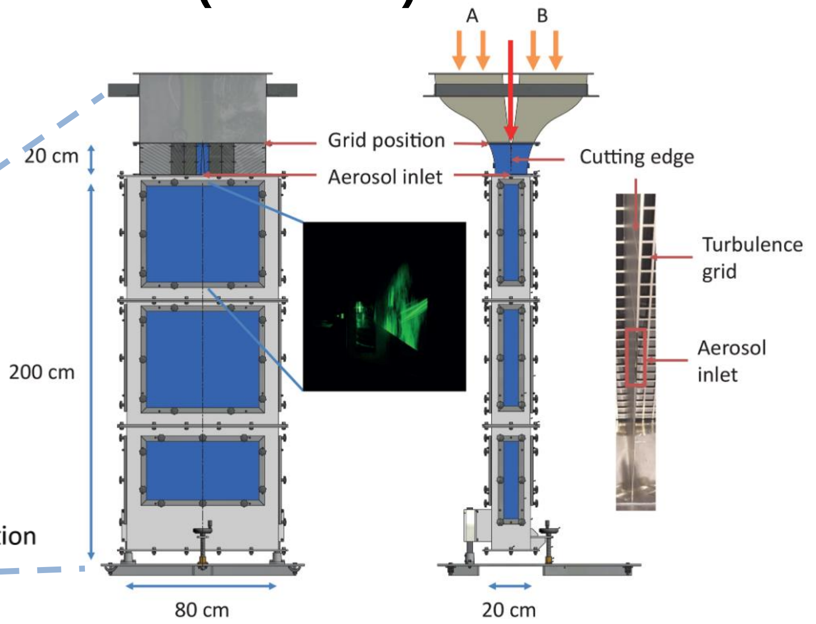
turbulent Leipzig Aerosol Cloud Interaction Simulator (LACIS-T)





turbulent moist-air wind tunnel LACIS-T

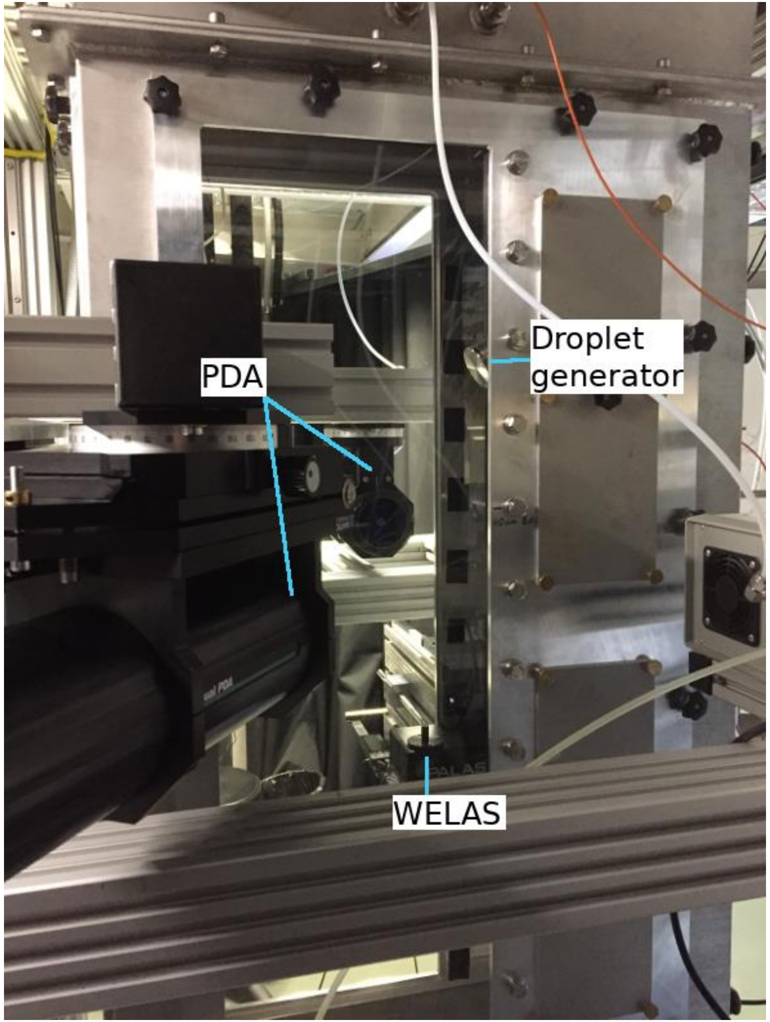
- two air streams, controlled and conditioned separately (T, RH, v)
- combined at inlet of measurement section (ms)
- turbulence induced upstream ms

Niedermeier et al., 2020, *Atmos. Meas. Tech.*, 13, 2015–2033, https://doi.org/10.5194/amt-13-2015-2020

Experimental design

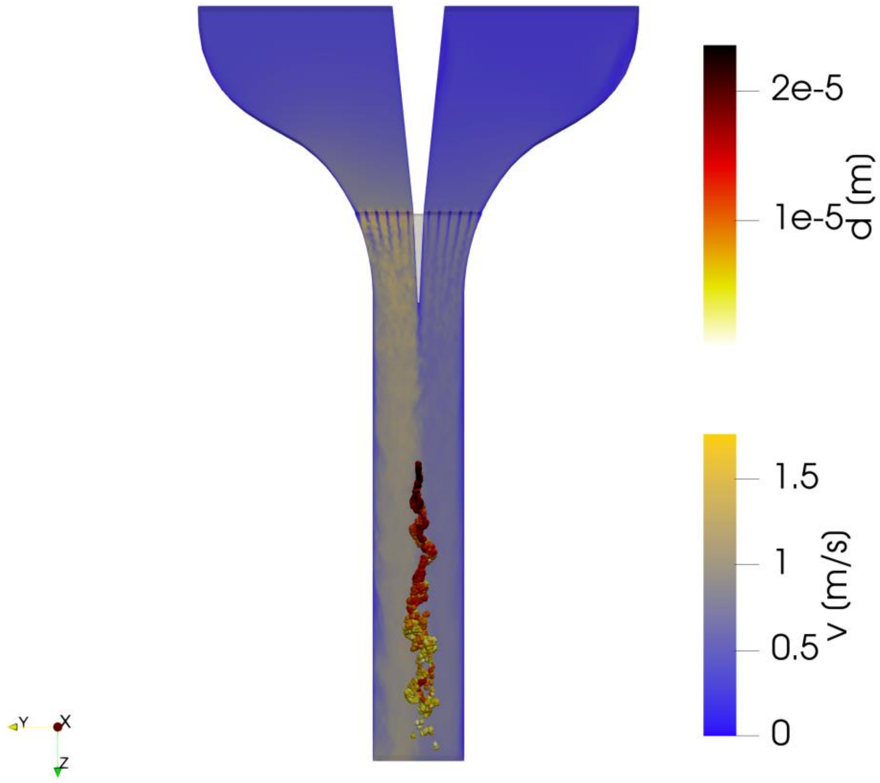
- one stream kept at constant conditions
- second stream varies one parameter (i.e. T, RH, flow speed)
- droplets generated with droplet generator fed into mixing zone – bimodal size distribution to mimic real cloud
- observations of doplets with PDA system at two positions

Droplet generator (MSP Corporation)	17-93µm
Phase Doppler Anemometer (Dantec)	2-73µm
White Light Aerosol Spectrometer (Palas)	0.2-100µm



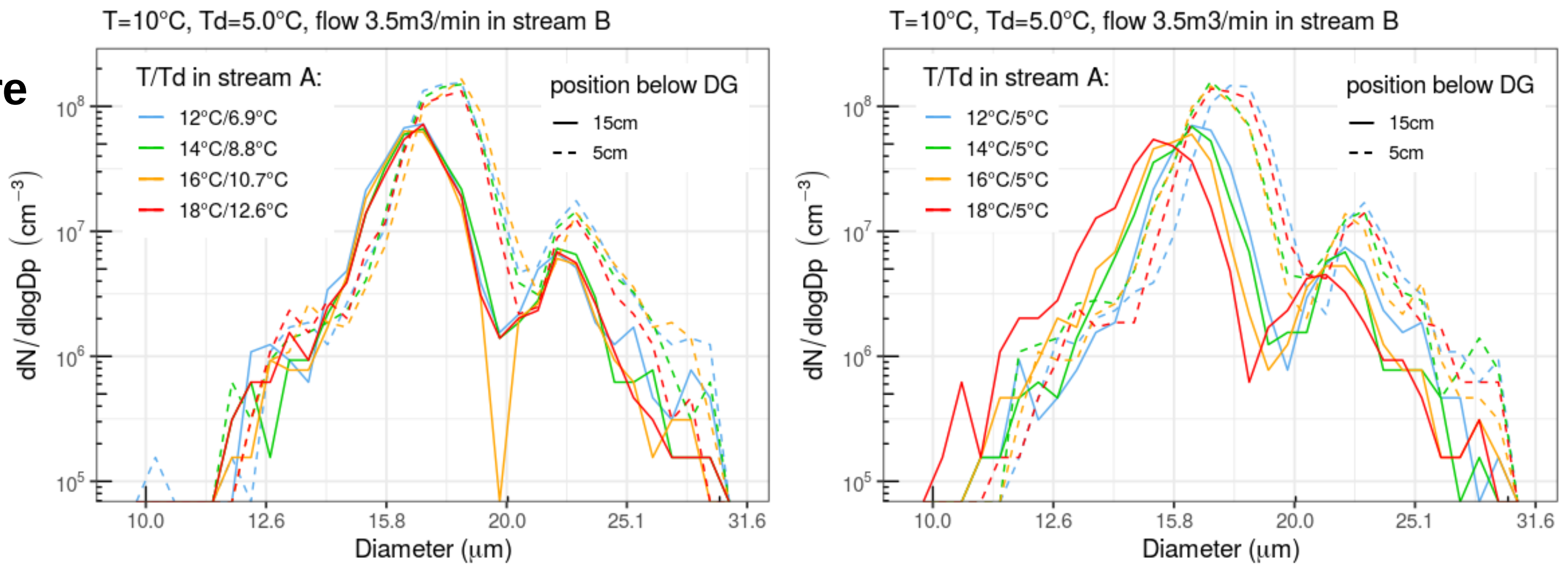
Computational Fluid Dynamics (CFD) simulations

- OpenFOAM
- solving transient, incompressible Navier-Stokes-Equations
- hexahedral dominated mesh grid with approx. 1mm resolution (~7 million cells)
- lagrangian particles/droplet trajectories are calculated during model run time
  - two-way coupling for particles
- delivers full 3D fields (cf. point measurements)



Results

Variable temperature



- left: temperature increase @ RH ~ 70% → consistency in particle sizes
- difference in upper/lower measurement position due to residence time of particles in subsaturated environment

➢ change in temperature by itself has no impact, as expected

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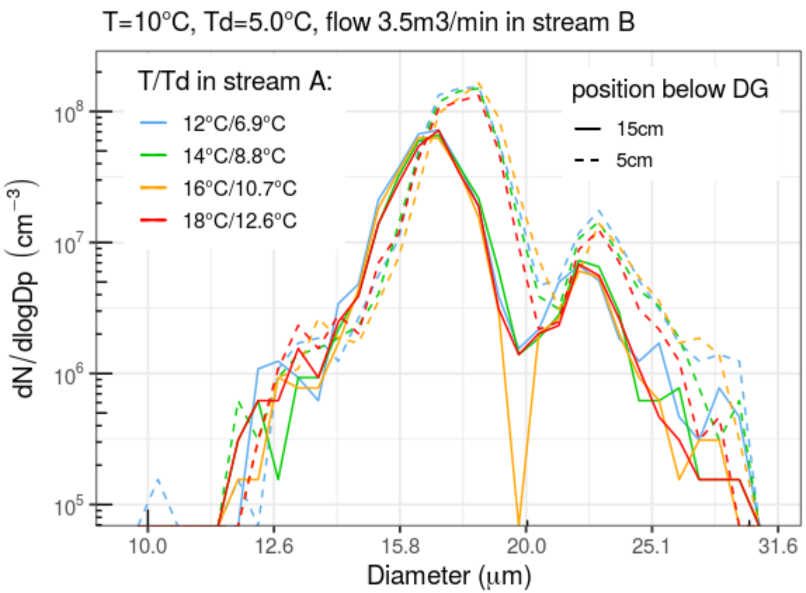
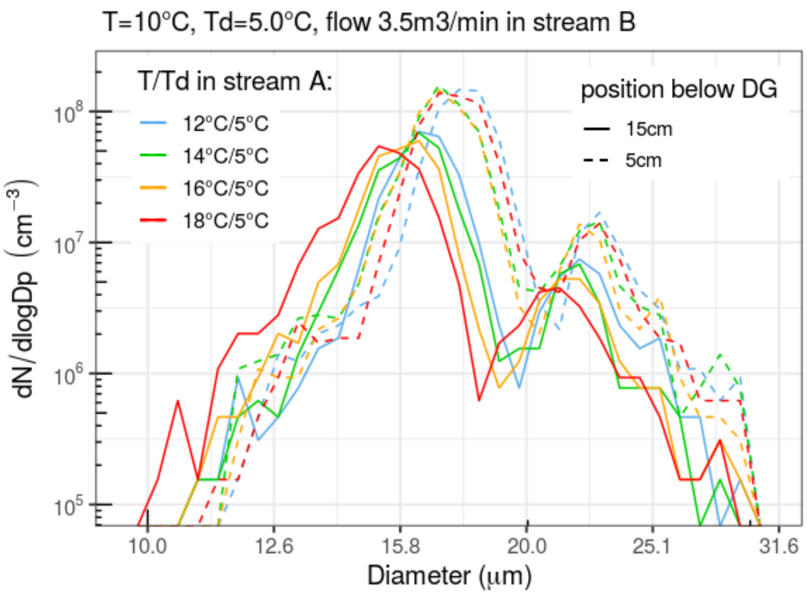
Variable RH





- right: RH drops from 71.1% to 42.3% (@18°C) when temperature increases

➢ slight shrinking of particles, as expected

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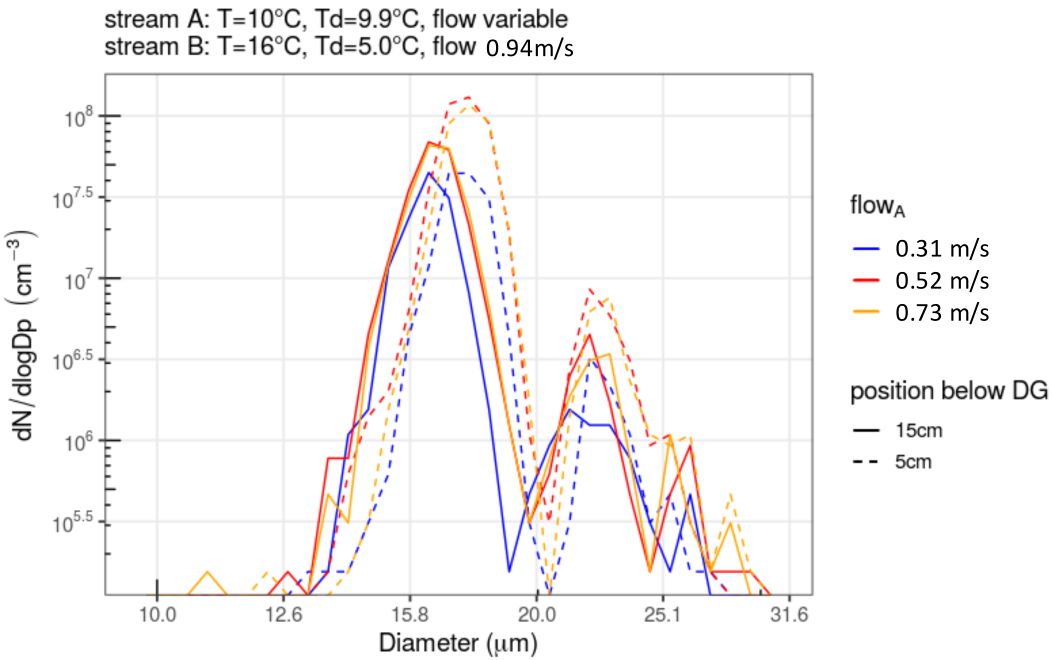
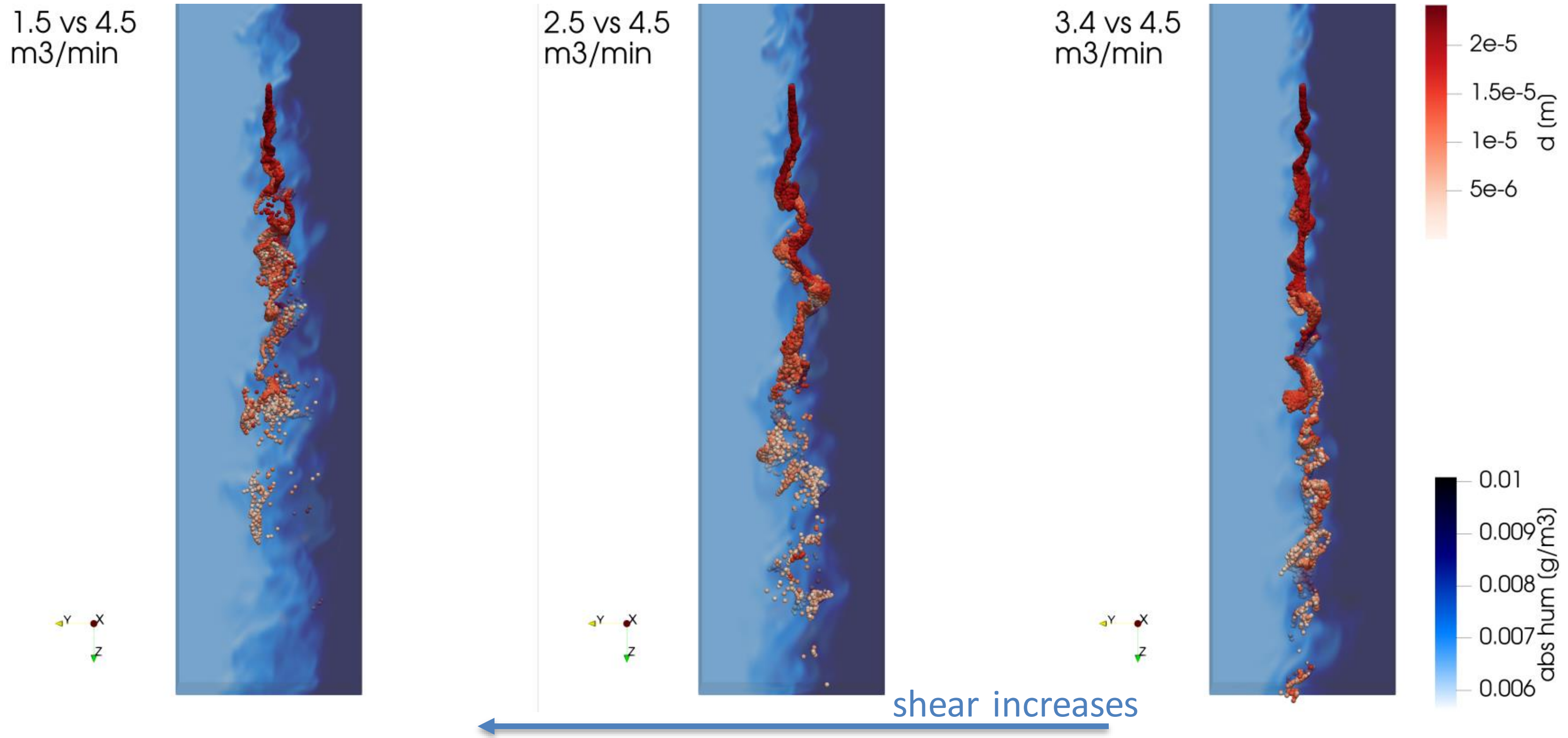
Variable shear flow



- size distributions comparable
- ➢ no change visible though expected in different shear environments

Simulation with variable shear flow



broadening and even breaking up of droplet stream with increased shear => 'patchyness'

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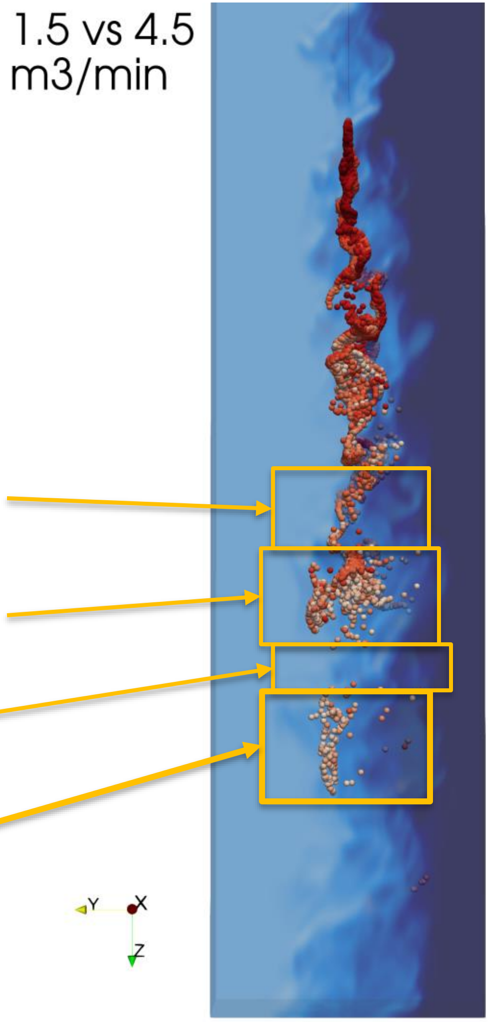
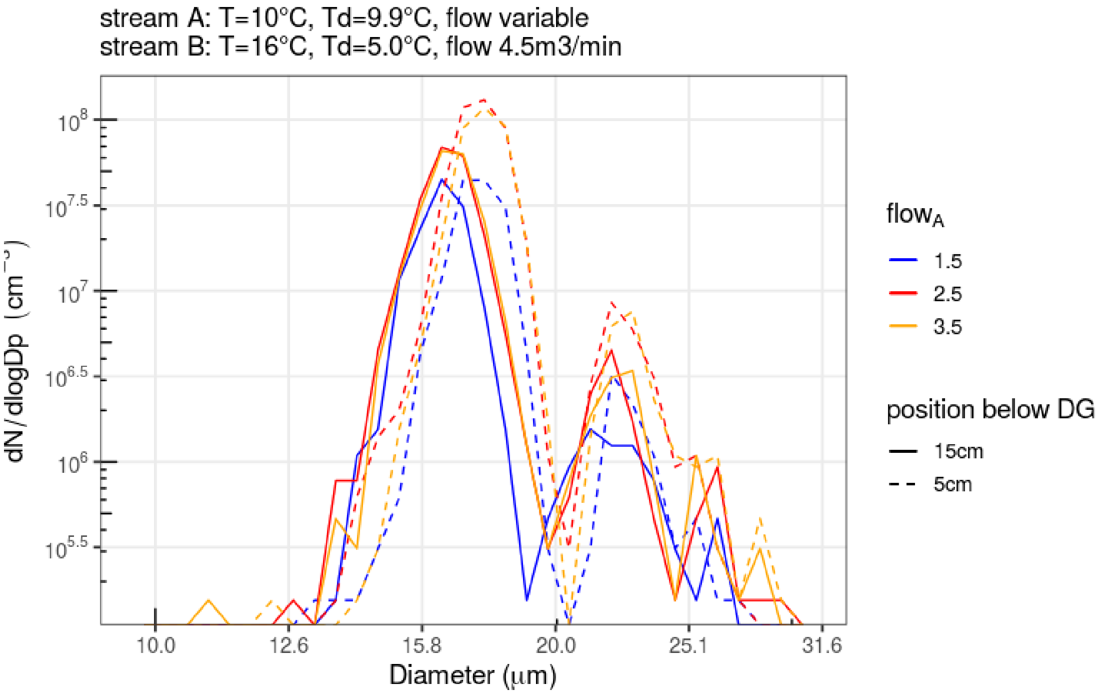
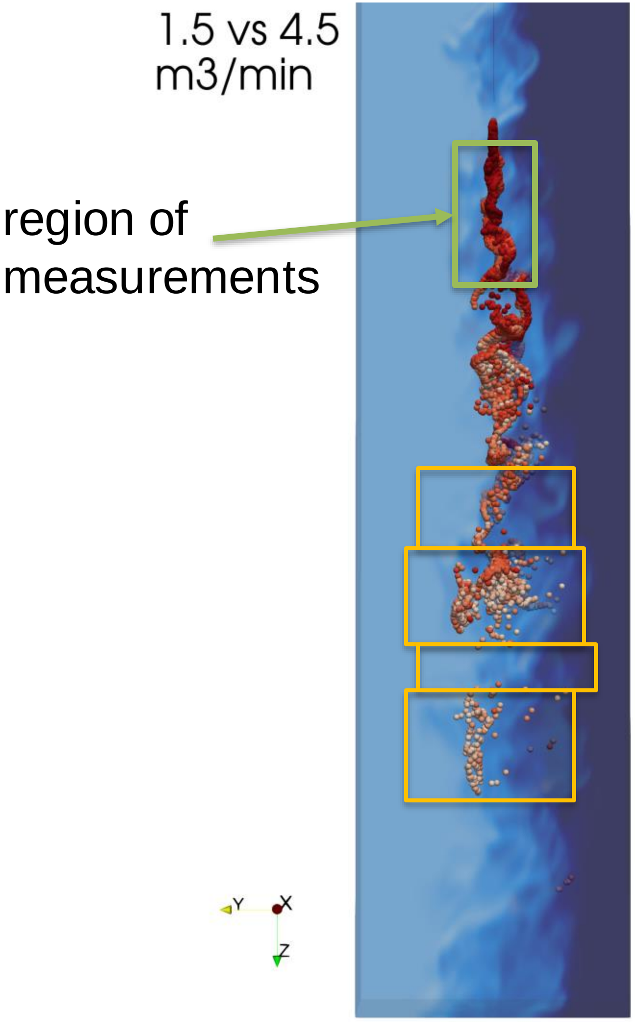
Variable shear flow - simulation

- some particles
- more particles
- no particles
- few particles



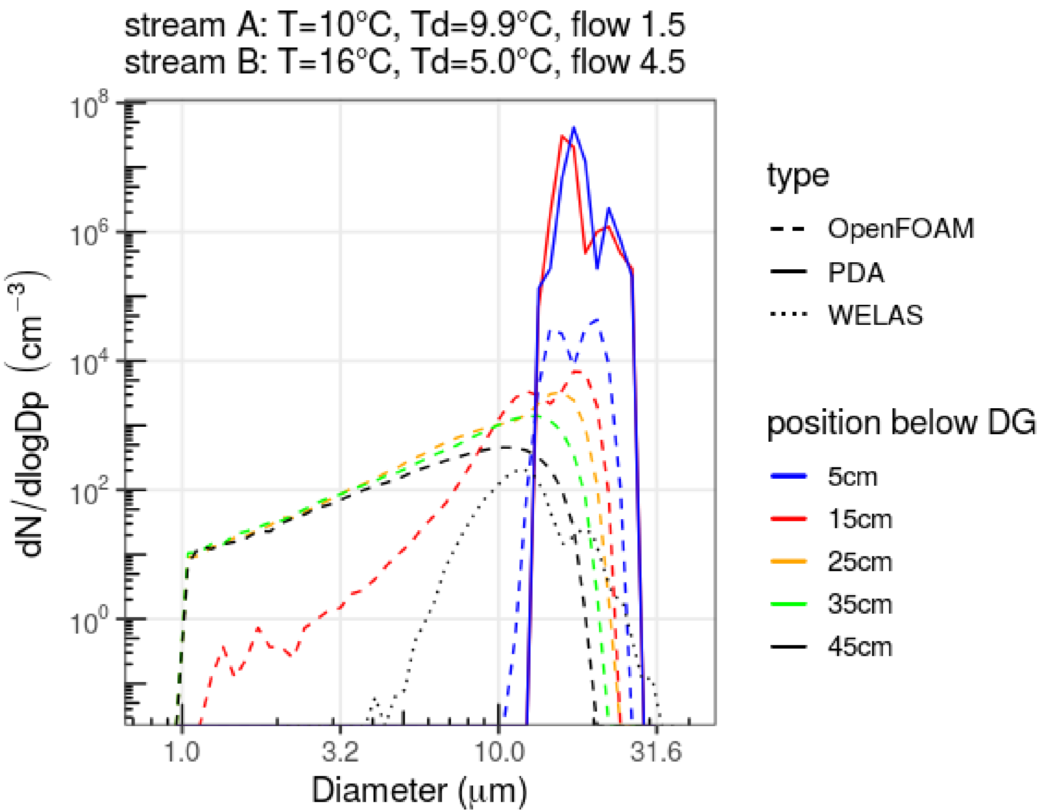
Variable shear flow





- measurements only in upper part of stream
- ➢ observations further down droplet stream needed

Comparison measurements/model – variable shear flow



- simulated peak sizes decrease more than measured

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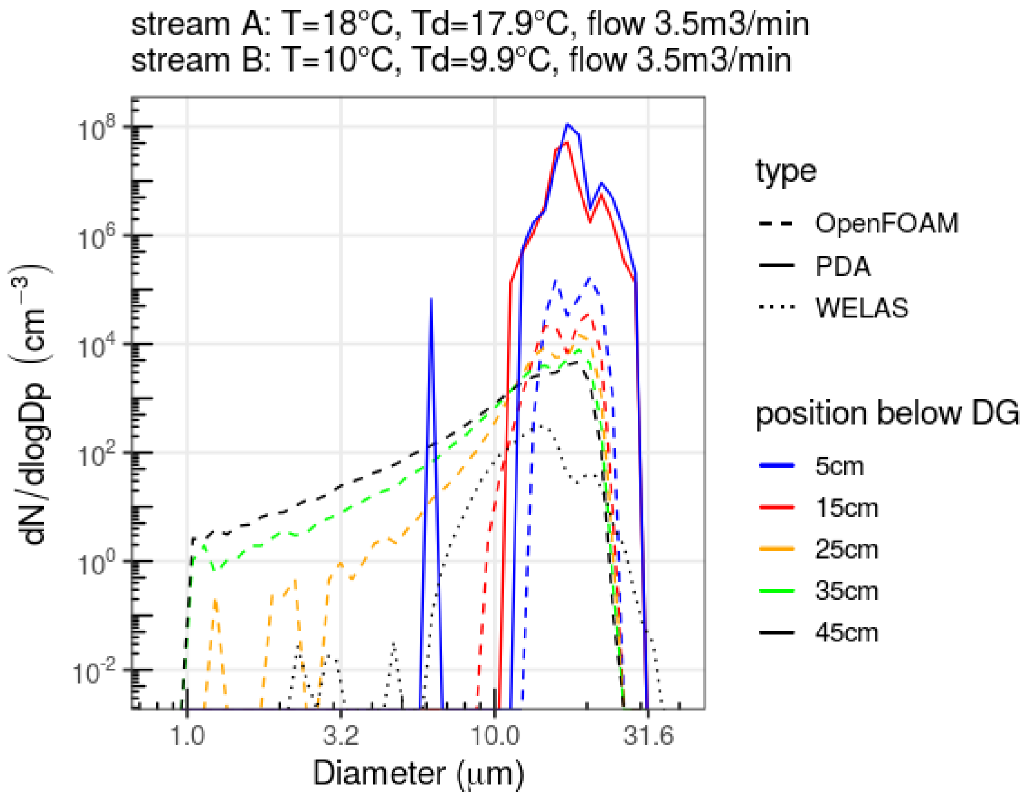
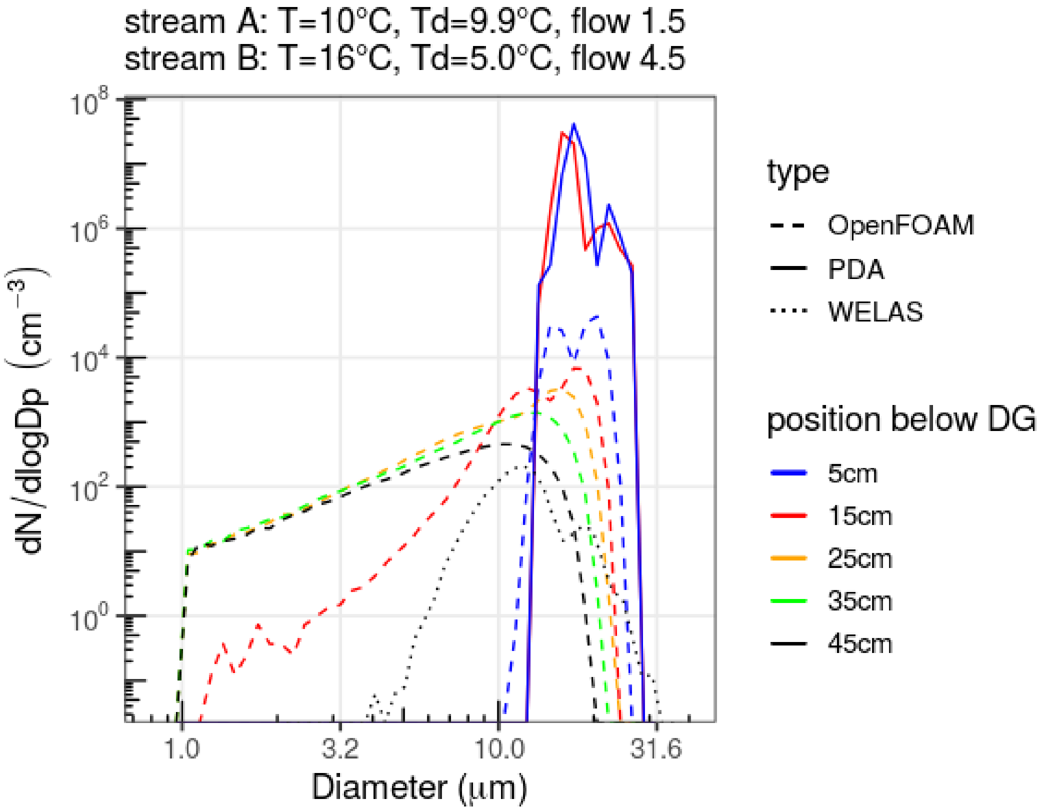
Comparison measurements/model – variable temperature



- simulated peak sizes decrease more than measured
  - not apparent in variable T cases

Comparison measurements/model – shear flow



- simulated peak sizes decrease more than measured
  - not apparent in variable T cases

- stronger broadening of size distributions in model

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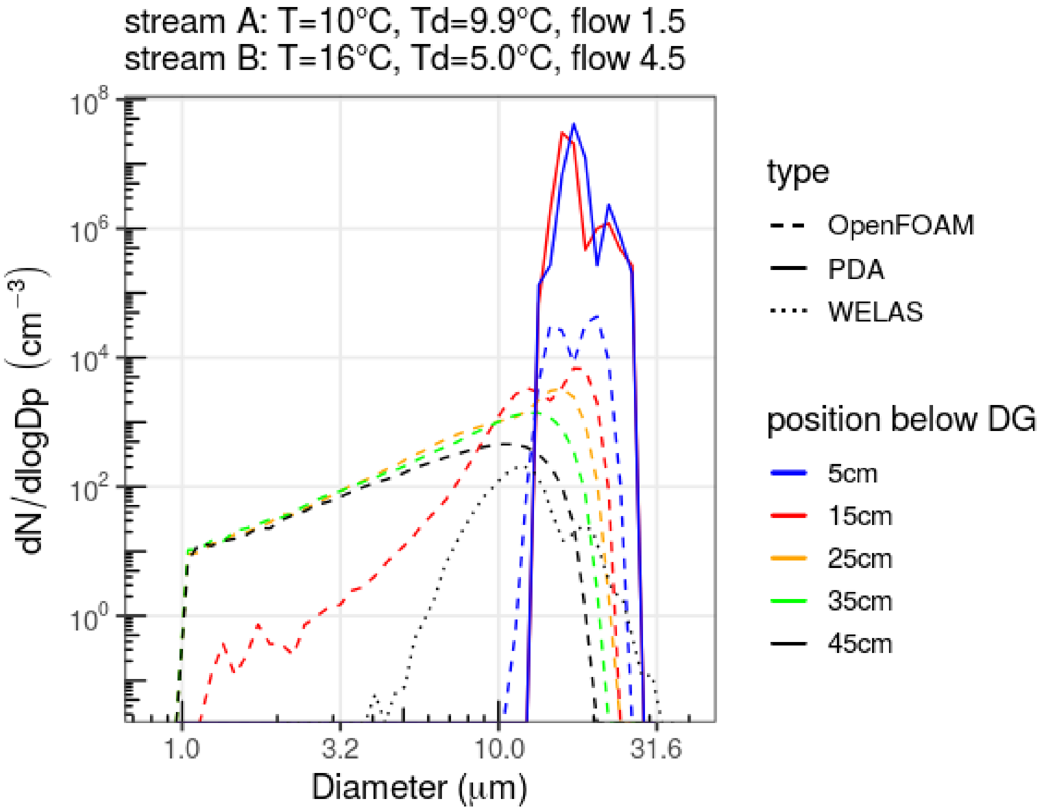
Comparison measurements/model - conclusions



- simulated peak sizes decrease more than measured in variable flow case
- stronger broadening of size distributions in model
- simulated particle mass decreases faster:
  - too small particles in model input
  - velocities in model too small – too long residence time?
  - too low particle numbers in model?

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Summary and Outlook

- first measurements in LACIS-T to study entrainment
    - changing T and RH expected behaviour
    - shear: leads to 'patchyness', more measurements needed
- droplet stream with too high number concentrations
- model helpful tool for identifying ideal measurement setup
- differences model/measurements – under investigation

Future:

- droplet spray system and active turbulence grid
    - possible to fill one stream with droplets
    - variable turbulence
- PDA and WELAS movable through full lengths of measurement section

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Thank you!

contact:
Wiebke Frey (PhD, she/her)
wiebke.frey@tropos.de

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OpenFOAM simulations have been performed using computing time at the ZIH Dresden.

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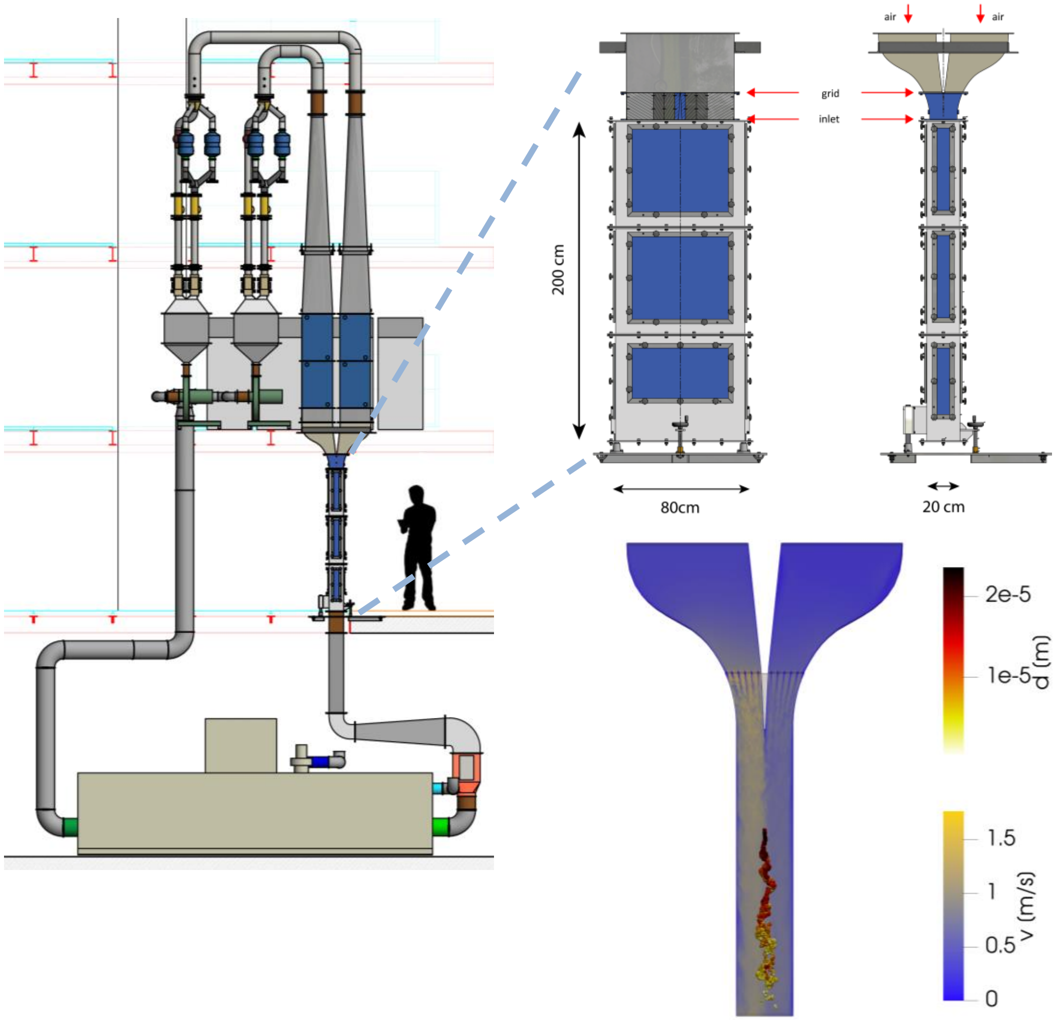
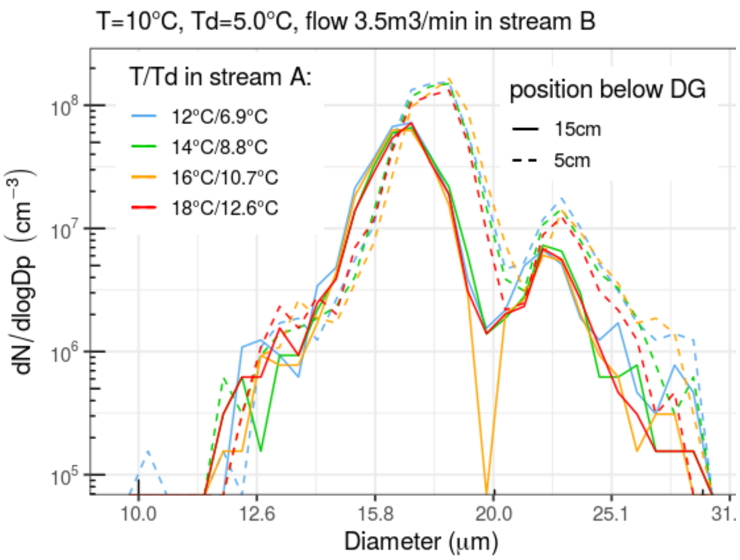
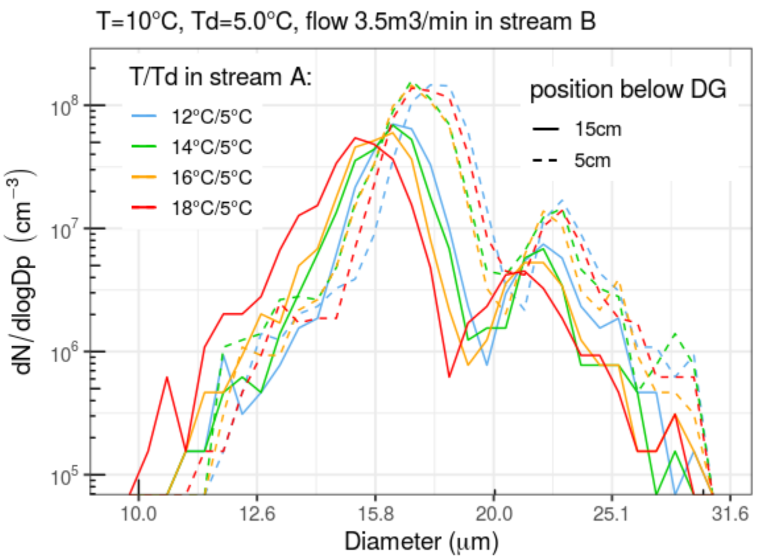
- entrainment (and detrainment) key small scale process, yet physically not well understood

➢ understand which underlying physical parameters govern entrainment, using:
  - measurements in turbulent wind tunnel LACIS-T
  - CFD simulations with OpenFOAM



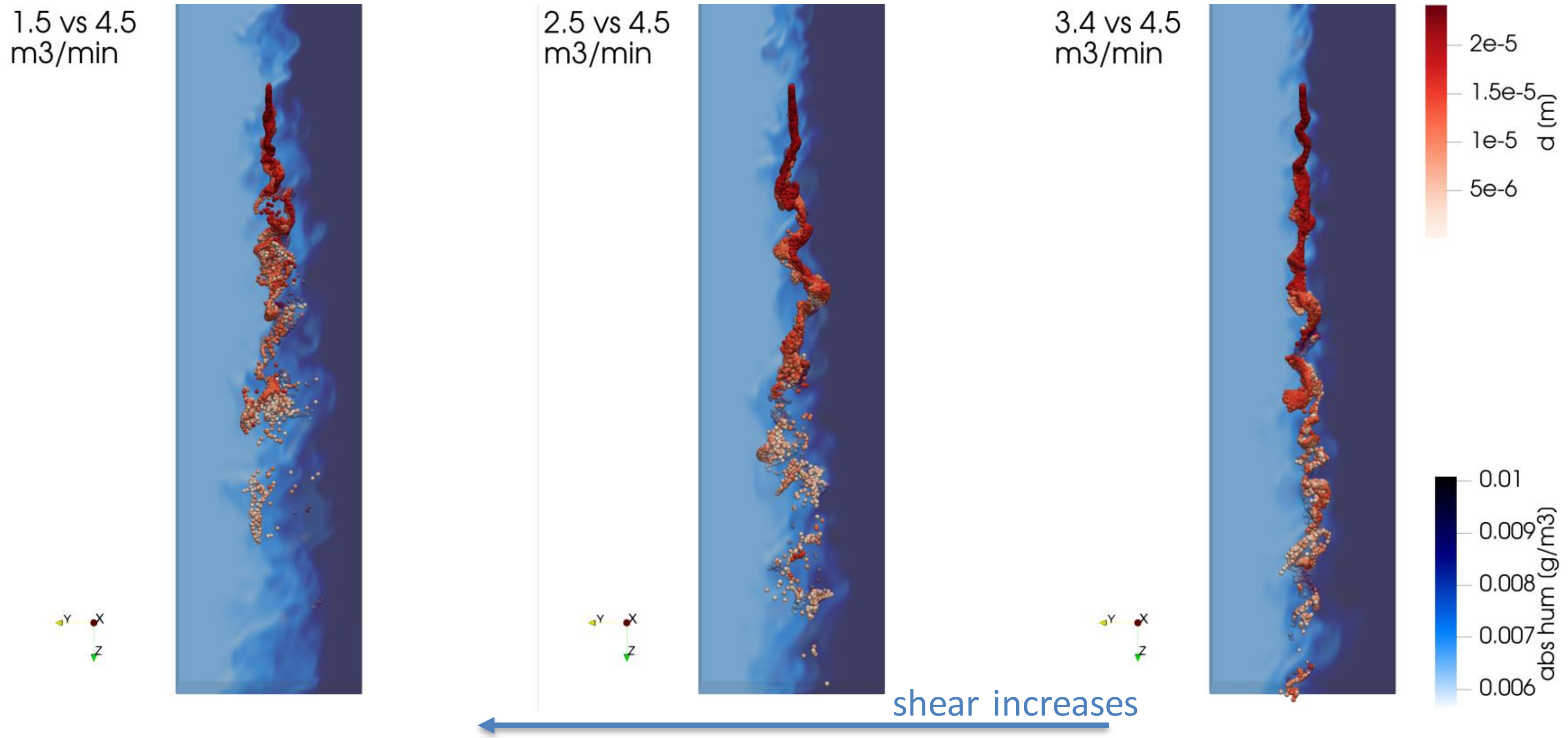
Measurements with variable T and RH





- bimodal size distributions injected by droplet generator
- system behaves as expected for changes in T and RH
    - consistency of sizes in increasing temperature @ same RH
    - decrease of sizes with decreased RH

Simulation with variable shear flow



broadening and even breaking up of droplet stream with increased shear => 'patchyness'

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Significance/Impact

- combination of measurements and model helpful tool for gaining better physical understanding of entrainment process

→ improvement of model parameterisations

→ improved forecasts/predictions of clouds

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frey@tropos.de

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