6.9 PHYSICS OF CLOUDS AND ATMOSPHERE

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Water droplets, ice crystals, and aerosols (dust, volcanic ash, pollen, soot, pollutants, etc.), which we collectively refer as particles, are ubiquitous in Earth's atmosphere. Aerosols are the seeds (condensation nuclei), which are essential for the formation of water droplets and ice crystals. These particles affect precipitation and radiative transfer due to their light-scattering and absorbing properties, which has impacts on both local weather and global climate.

Yet, much remains to be understood about the dynamics of cloud particles, in large part due to the large range of scales involved, from the size of the particles themselves (nanometres to millimetres) to thousands of kilometres. One of the problems concerns the transport and settling of non-spherical and irregular particles such as aerosols and ice crystals, which determines how far particles can be transported and how long they stay in the atmosphere before settling to the ground (or in the case of ice crystals, possibly sublimating before they reach the ground).

In clouds, how particles grow is yet another open question. It starts with the activation of cloud aerosols where water vapour condenses onto them to form droplets and ice crystals. The growth dynamics of water droplets across the so called "size gap" between the diffusive growth regime dominated regime ($d < 20\ \mu$m) and differential gravitationally settling induced collision dominated regime ($d > 100\ \mu$m) remains unclear. These problems make accurate aerosol transport, rain, and snow prediction difficult and a detailed understanding is necessary for reliable climate prediction and weather forecasting. To better understand these processes, the LFPB investigates many aspects of these problems by carefully controlled laboratory experiments, numerical simulations and field measurements in atmospheric clouds. These range from experiments with small settling ellipsoidal particles and activation in the cloud aerosols in hydrometeor wakes all the way to direct measurement of water droplets at small scales in atmospheric clouds in the field.

Figure 6.27: The particle tracking experiment at the Zugspitze during measurements.

6.9.1 *Clustering of cloud droplets*

(G. Bagheri, J. Moláček) The life-cycle of clouds strongly depends on the poorly understood collision rate between cloud particles in the "size gap". Quantifying the collision rate in a laboratory setting or numerical simulations is complicated by the potential influence of hydrodynamic interaction or electrostatic forces between the droplets, and by the low dissipation rate and large Reynolds number typical for atmospheric flows. To investigate the cloud droplet collision rate, we have built a particle tracking setup (see Fig. 6.27 and [1]) at the environmental research station Schneefernerhaus, dubbed the "Seesaw" for its ability to tilt. With this device, we can not only obtain the three-dimensional droplet positions to within a few micrometers, but also deduce the individual droplet diameters from the amount of light scattered onto each camera aperture.

From the position information, we can derive the droplet velocities and accelerations, and thus quantify both the droplet spatial distribution and the statistics of their relative velocities, the two main components yielding the collision rate. Knowing the droplet sizes on the other hand allows us to compute the Stokes number, the dimensionless parameter capturing the droplets' inertia, and thus compare our measurements with results of existing numerical simulations and theory. The clustering and velocity statistics that are most interesting from the point of view of droplet collisions are naturally those for droplets at smallest, nearly touching separations. Although such separations are inaccessible to us due to the fundamental limits of the optical method used, we were nevertheless able to resolve sufficiently close separations (see Fig. 6.28) to essentially confirm the validity of certain numerical simulations [2] and rule out observable hydrodynamic interaction effects reported in some laboratory experiments [3]. More work is needed to put our data on droplet relative velocity statistics into the context of existing literature, due to their higher dimensionality.

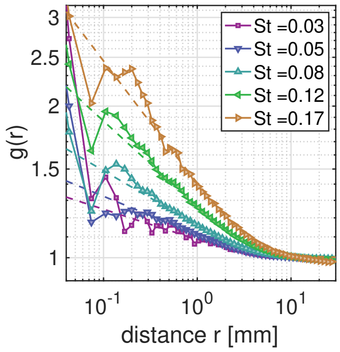

Figure 6.28: Sample radial distribution functions for droplet pairs of equal size for different values of Stokes number, as a function of droplet distance $0.04 \leq r \leq 30$ mm. Experimental data are plotted with markers, dashed lines are fits.

6.9.2 *The Max Planck CloudKites (MPCKs): Airborne characterisation of cloud microphysics and atmospheric turbulence*

(G. Bagheri, F. Nordsiek) In order to investigate the dynamics of cloud droplets relevant to better understanding their growth processes, the MPCKs were flown to measure clouds *in situ* and their surrounding environment. The LFPB's MPCKs are 35–250 m^3 helium-filled aerostats carrying atmospheric instrument packages to size and image cloud droplets and measure turbulent and thermodynamic quantities. Helium-filled aerostats were chosen because their low flight speed compared to airplanes and helicopters, which must fly at medium speed to keep instruments out of the prop wake. Using the MPCKs allows higher spatial resolution measurements, higher cargo capacity than UAVs/drones, longer flight times (limited only by the instrument battery) compared to powered aircraft including UAVs/drones, and greater travel distance from topographic effects than surface stations.

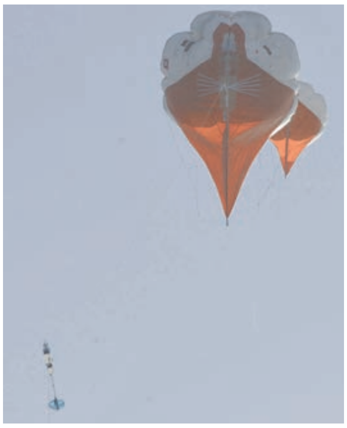

Figure 6.29: The 250 m^3 MPCK flying with a 35 m^3 aerostat flying in tandem for more lift from the RV Maria S. Merian as part of the EUREC^{4}A campaign. The instrument package is hanging on the line in the bottom left of the photo.

The MPCKs have flown on two ocean based field campaigns to investigate marine boundary layer clouds: a campaign in the Atlantic Ocean on the RV Maria S. Merian (MSM82-2, 2019), and the EUREC^{4}A campaign (2020) in the vicinity of Barbados on the RV Maria S. Merian (MSM89) and RV Meteor (M161) together with CIMH (Caribbean Institute for Meteorology and Hydrology) as part of the EUREC^{4}A collaboration [4]. The MPCK is also part of the TWISTER collaboration

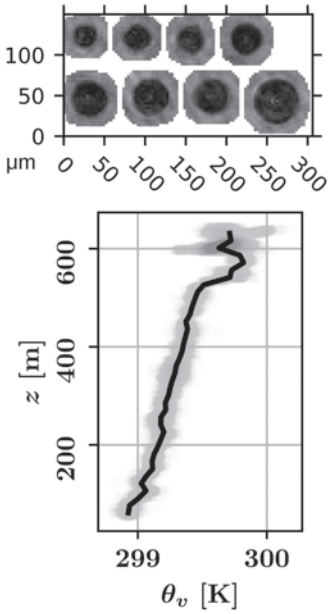

Figure 6.30: (Top) Hologram reconstruction of large cloud droplets. (Bottom) vertical profile of the virtual potential temperature θ_v from a fast ascent (grey points are ind. measurements and black line is the 15 m average).

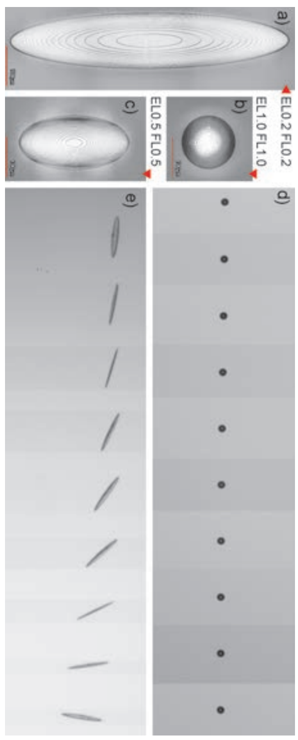

Figure 6.31: (a-c) Particles created using 2-Photon-Polymerisation. (d-e) A sphere and an ellipsoidal particle in free fall.

to investigates the dynamics of atmospheric boundary layer through numerical and experimental approaches, see 6.10.

One MPCK from EUREC^{4}A is shown in Fig. 6.29. During EUREC^{4}A; 28 flights with recoverable data were flown (there were 4 additional flights: 2 test flights with no instruments, 1 test flight with just a radiosonde, and 1 flight lost to the sea) for a total of approximately 250 flight hours with data being successfully acquired for approximately 210 of those hours. This includes 144 hr of CDP (Cloud Droplet Probe) data, 900879 holograms (about 200 min worth), and 447737 images from the 2-frame PTV/PIV system (about 250 min worth).

Fig. 6.30 shows hologram reconstructions of several large droplets from a cloud and a vertical profile of the virtual potential temperature during an ascent in stable conditions ($\partial\theta_v/\partial z > 0$). The long endurance of the MPCKs allowed long flights up to 19.5 data hours (nearly double the endurance of the other long endurance aircraft). The MPCKs , along with the P-3, were also the only aircraft to fly at night which was, coupled with the long flight endurance and many flight hours, very important for capturing the full diurnal cycle.

6.9.3 *Dynamics of non-spherical particles*

(G. Bagheri, Y. Wang) The settling of small non-spherical and irregular particles (includes most aerosols and ice crystals) is poorly understood. In particular, it is not quantitatively understood how particles of different shapes orient themselves in turbulent flows and how fast their orientation responds to flow fluctuations. Experiments on single particles in a quiescent medium are the first step to characterise this.

Our work was initially focused on freely falling ellipsoidal particles in the "intermediate" regime of particle Reynolds number 1–10 using shadowgraphy in an air-filled column setup. The particles are well-defined ellipsoids with the same volume (equal to that of a 140 μm diameter sphere), but different ratios of their axes. This only became possible thanks to 2-Photon-Polymerisation, a recent commercially available 3D-printing technique with unmatched accuracy (down to 200 nm). The density ratio between the particles and the medium (air) is approximately 1000, which is representative of atmospheric particles. The experiments are performed using four high-speed cameras to capture both the transient and the terminal state. Fig. 6.31 shows several printed particles in free fall as recorded with the described setup. In addition, Lattice-Boltzmann simulations are being performed as a base for comparison and to widen the parameter space. This allows us to look into terminal velocities, drag, and the transient dynamics to answer the following questions. Do stable fixed points in the orientation or oscillatory motions exist and is there a stable orientation that the particle will take? For particles with unstable transient orientation, what is the steady-state orientation? Further shapes are currently under research, covering non-homogeneous particles and complex shapes, such as irregular ice crystals and aggregates.

6.9.4 *Cloud aerosol activation by precipitating hydrometeors*

(G. Bagheri, Y. Wang) One of the many mysteries in clouds is that we still do not understand how and why the number of ice particles inside clouds exceed the number of ice nucleating particles that could be activated based on the bulk temperature and super-saturation. What are the major sources behind this excess (secondary) production of particles? We have found and investigated a possible mechanism – how large precipitating raindrops and ice particles can cause surrounding cloud aerosols to activate, thereby resulting in new water droplets and ice crystals [5]. As the large hydrometeors fall under gravity, they can activate in their wake aerosols that would not be activated otherwise. Warm droplets with a diameter of ~ 2 mm were able to induce activation of the ambient sodium chloride and silver iodide aerosols as water droplets and ice crystals in their wake when precipitating through a sub-saturated colder environment (Fig. 6.32). Extending the experiments, the numerical work [6] studied the flow pattern around hydrometeors (e.g., droplets, sleet, or hail) and presented a detailed analysis of various physical factors that lead to an excess of water vapour condition behind the hydrometeors and investigated the effectiveness of this process on activation of aerosols to create new cloud particles [7]. It is found that not all aerosols, but only some 'lucky aerosols' are entrained in the wake behind such precipitating hydrometeors, where they can reside in a highly humid environment for a sufficiently long time (Fig. 6.33). This fulfills the necessary conditions for the aerosols to be activated as new cloud condensation nuclei or ice nucleating particles by deposition of water vapour.

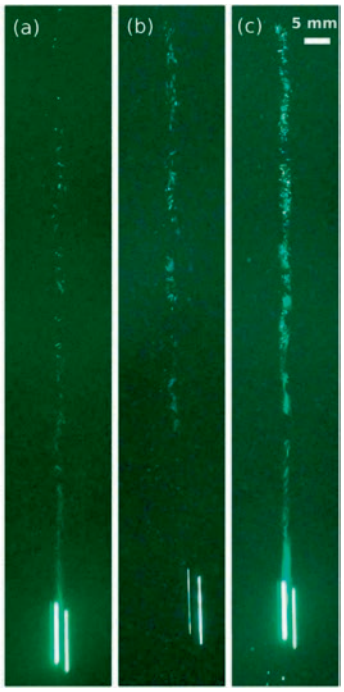

Figure 6.32: Nucleation of water droplets and ice particles in the wake of a falling drop (diameter $\sim$ 2 mm) that is warm relative to the ambient cold conditions. Ambient temperature ~ -18 °C, relative humidity $\sim$ 60 %. The initial drop temperatures are (a) 10 °C, (b) 10 °C, and (c) 20 °C. The number concentration of the Snomax aerosol particles in the chamber was $\sim 10^4$ cm^{-3} in all cases except in (a), where it was $\sim 10^3$ cm^{-3}.

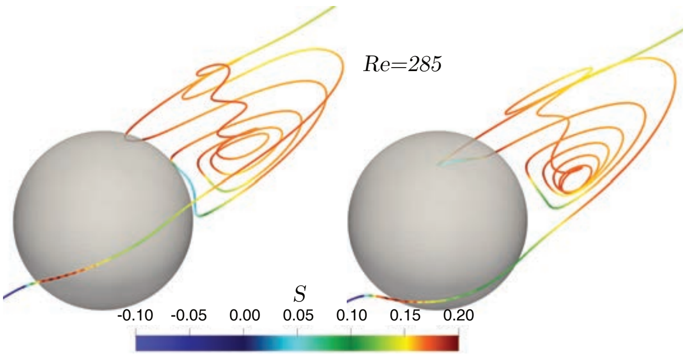

Figure 6.33: Tracks of the excess water vapour (S>0) that two aerosols experience when they entered the water vapour rich environment behind a precipitating frozen hydrometeor at 0 °C temperature falling through an ambient at -15 °C and 95% relative humidity condition.

[1] G. Bertens et al., submitted to Rev. Sci. Instr.
[2] E. W. Saw et al., New J Phys. **14**, 105030 (2012)
[3] M. A. Yavuz et al., Phys. Rev. Lett. **120**, 244504 (2018)
[4] B. Stevens et al., Earth Syst. Sci. Data, **13**, 4067 (2021)
[5] P. Prabhakaran et al., Geophys. Res. Lett. **47**, e2020GL088055 (2020)
[6] T. Bhowmick et al., Symmetry **12**, 1498 (2020)
[7] T. Bhowmick et al., Geophys. Res. Lett. **47**, e2020GL091179 (2020)