6.10 INVESTIGATION OF ATMOSPHERIC TURBULENCE AND CLOUD MICROPHYSICS IN THE TWISTER PROJECT

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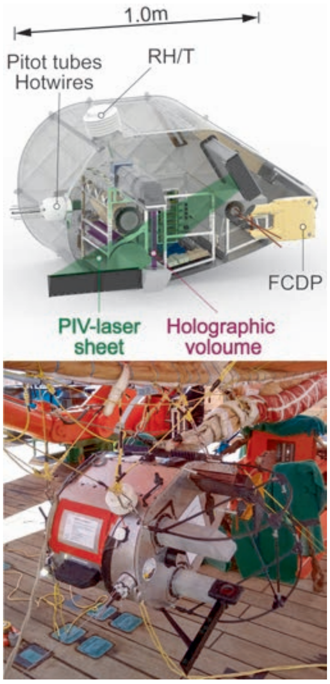

Figure 6.34: The MPCK+ instrument box (top) CAD visualisation with main components annotated, i.e., the holographic and Particle Image Velocimetry (PIV) probing volumes, Fast Cloud Droplet Probe (FCDP), Relative Humidity and Temperature probes (RH/T) and the Eulerian module composed of 1D and 3D Pitot tubes and hot-wires; (bottom) installed on the 250m^3 Helikite.

A major challenge in understanding, modeling and consequently predicting atmospheric flows on our planet arises from the enormous range of scales involved. While weather patterns can extend over hundreds of kilometers, local processes that govern the generation and sustainment of clouds range from sub-km down to μm scales. Even the most advanced simulations of our Earth's climate cannot resolve the complex physics of local atmospheric flows. On these scales, turbulence plays a crucial role, having a significant impact on cloud mixing, the growth of water droplets, and ultimately the initiation of rain. Our current understanding of these processes remains very limited. The Max-Planck-Fraunhofer Collaboration Project TWISTER investigates turbulence in the atmospheric boundary layer in a combined experimental, computational and theoretical approach. In particular, we focus on the interaction of turbulence in the atmospheric boundary layer with cloud microphysics.

The Max Planck CloudKites (MPCKs), each composed of an instrument box and a tethered hybrid of kite and helium-filled balloon commercially known as Helikite, are the main experimental platform in our work for in-situ measurement of fine-scale atmospheric turbulence and cloud microphysics (see also Sec. 6.9). The MPCKs have proven to be very reliable for field measurements during the EUREC^{4}A field campaign [3]. The MPCK+ instrument box shown in Fig. 6.34, equipped with state-of-the-art holography and particle image velocimetry modules, in combination with a variety of meteorological sensors, can provide a detailed picture of the atmospheric boundary layer and the clouds within it. In addition, within TWISTER and in collaboration with Fraunhofer IPM, a compact Light Detection and Ranging (LiDAR) system is being developed specifically for the MPCK to measure the much needed undisturbed three-dimensional wind speeds in the vicinity of the MPCK. These detailed in-situ measurements, together with computational investigations, form the core of the TWISTER project aimed at characterizing the dynamics and evolution of the atmospheric boundary layer and clouds.

A major focus of our current work is the characterization of small-scale turbulence properties. This comprises the accurate determination of the dissipation of kinetic energy as well as a characterization of the local instationarity, inhomogeneity and anisotropy (Fig. 6.35). In addition to field data, numerical simulations provide ground-truth data to develop calibration techniques and software for data analysis.

Collisional droplet growth, a key process in rain formation, is another major focus of our work. To study droplet growth in controlled conditions, we explore in a combined computational and theoretical study how individual droplets grow in a turbulent flow with a statistically stationary background droplet distribution (Fig. 6.36). This enables a precise assessment of the collision kernel and the statistical details of the collision process. For example, we have found significant correlations between subsequent droplet collisions which are commonly neglected in simple models for collisional growth. This theoretical work will guide future analysis of droplet measurements with the MPCK.

We also aim at connecting the microphysical processes in clouds with larger-scale phenomena in the atmosphere. To this end, we perform computational investigations of convective boundary layers (CBLs) in which turbulence is driven by shear and convection. We specifically aim for a statistical description of the relevant atmospheric variables like wind velocity and temperature [1]. To this end, we have derived the evolution equations for the corresponding probability density functions. The equations feature unclosed terms which we investigate using simulations [2] (see Fig. 6.37). The results will help to statistically characterize various atmospheric conditions and to derive accurate statistical models. We plan to compare our results to field measurements obtained within the TWISTER project as described below.

High-resolution wind velocity measurements have been identified as the most important quantity for characterizing atmospheric turbulence. To address this need, a compact Frequency-Modulation Continuous Wave (FMCW) LiDAR is currently being developed by the Fraunhofer IPM to be installed on the MPCK. The unique feature of the design is that the LiDAR will be equipped with three independent telescopes. This creates a flexible system that can measure three line-of-sight wind speeds while keeping weight and power consumption low. The LiDAR can provide three-dimensional wind velocity at a distance of $\sim$15 m from the MPCK, which is far enough from the MPCK so that none of the velocity components are affected by the MPCK itself. With 1 m^3 and 10 Hz spatial and temporal resolutions, respectively, and flexible telescope-head arrangements, which allows it to be used for forward or lateral probing with minor modifications, the LiDAR will significantly enhance the capabilities of the MPCK. While the Continuous Wave (CW) feature allows for high spatial resolutions, the Frequency-Modulation (FM) feature enables it to significantly suppress background from clouds or hard targets (e.g. the ground if facing downwards) as well as a verification of the distance where the wind is measured, yielding a higher measurement accuracy. First tests with the new system are planned for early 2022 in preparation of forthcoming measurement campaigns.

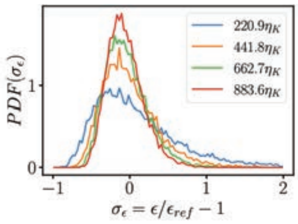

Figure 6.35: Probability density functions of the relative deviation σ_ϵ of the energy dissipation rate derived from the second-order structure function to its reference value from the dissipation field for different averaging windows and a turbulence intensity of 10%.

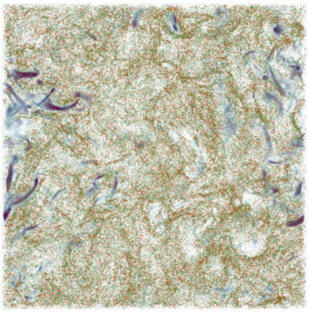

Figure 6.36: Simulations of a population of growing droplets (red) in a statistically stationary background distribution (green). The vorticity amplitude of the turbulent field is shown as a volume rendering.

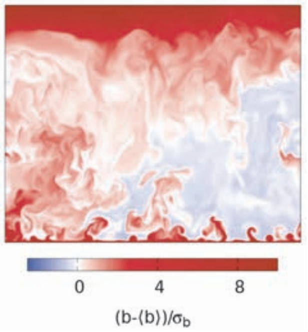

Figure 6.37: Visualization of the standardized buoyancy field in a convective boundary layer. The snapshot shows a small part of the simulation domain.

[1] A.P. Siebesma, et al., Journal of the Atmospheric Sciences **64**, 1230 (2007).
[2] A. Haghshenas and J.P. Mellado, J. Fluid Mech. **858**, 145 (2019).
[3] B. Stevens et al., Earth Syst. Sci. Data **13**, 4067 (2021).