EVIDENCE OF ANIZOTROPY OF SMALL SCALE TURBULENCE IN THE LABORATORY MODEL OF AN ATMOSPHERIC CLOUD

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Summary Cloudy air, containing small water droplets, undergoes mixing with the unsaturated environment inside the cloud chamber in the process resembling smallest scales of entrainment and mixing in real clouds. Particle Image Velocimetry (PIV) applied to images from the chamber interior is used to investigate dynamics of the process in scales from 0.07 mm to few centimeters, i.e. an order of magnitude better than the Kolmogorov length scale. Results of laboratory experiments clearly indicate that evaporative cooling of cloud water at the cloud-clear air interface affects in small-scale turbulence statistics. This can affect droplets collision rate being responsible for drizzle formation.

INTRODUCTION

The so called "warm rain initiation problem" attracts attention of cloud physicists, turbulence researchers, engineers and meteorologists [1,2]. It is still uncertain which mechanism is responsible for the formation of drizzle and rain (precipitation) drops. Understanding effects of turbulence on droplets agglomeration may appear necessary to improve modelling of formation and evolution of man made aerosol plums. Papers concerning the impact of high Reynolds number turbulence on spatial distribution of cloud droplets, their diffusional growth, collisions, and coalescence are published at high rate. Our understanding of particle motion in turbulent flows is based on both theoretical and experimental studies. In particular, these works show that small-scale turbulence, i.e. with spatial scales comparable with the Kolmogorov length scale, may influence the spatial distribution of droplets and yield non-Poisson statistics. Due to the inertia, the relative velocity between falling droplets depends not only on their terminal velocity and collision efficiency increases. On the other hand, droplets can mechanically and thermodynamically (latent heat release) influence the small-scale flow in a complex manner. The flow in regions of mixing may not be isotropic because of the negative buoyancy produced by droplet evaporation. Hence, it is expected that the -5/3 power law observed in cumulus clouds at scales between 15 and 200 m also extends down to the smaller scales in the cloud core.

Unfortunately, due to the experimental constrains, properties of the cloud turbulence at scales relevant for the interactions between droplets and the air flow have never been documented. We present laboratory cloud chamber experiments with turbulent mixing between cloudy air and unsaturated clear air at scales down to a fraction of a centimeter. It appears that at these scales turbulence is substantially anisotropic due to the action of buoyancy forces resulting from evaporation of cloud droplets. DNS simulations performed to mimic laboratory experiment reported by Malinowski et al. [3] evidently confirm that buoyancy forces resulting from evaporation may substantially modify smallest scales of turbulence.

EXPERIMENT

Experiments described here are aimed to simulate small-scale details of process of turbulent mixing of cloud with unsaturated environmental air. The process occurs inside the experimental chamber (1.0m x 1.0m x 1.8m). The negatively buoyant cloudy filament is mimicked by a saturated and wet (containing droplets of ~10μm diameter) plume entering the chamber through the round opening at the upper wall. Initial velocity of the plume is about 20cm/s and increases due to acceleration by buoyancy forces to about 30cm/s in the middle of the chamber. Liquid water content of the plume is usually more than 10g/kg (more than in typical clouds), its temperature is around 25°C, similar to the temperature of unsaturated air in the chamber. Relative humidity of the clear air inside the chamber varies from 30% to 75% for different series of measurements.

The plume descends while mixing with the environment, creating complicated, constantly evolving structures (eddies, filaments, etc.). This process is visualized in the planar cross-section of the chamber using the laser light sheet technique. Particle Image Velocimetry method is applied to evaluate velocity field in the cloud model [4,5]. Standard PIV system is used to obtain two component velocity field from pairs of images recorded by one camera, arranged perpendicularly to the laser light sheet. Stereo PIV method with two cameras recording images from different angles relative to the axis perpendicular to the laser light sheet is used to obtain all three components of the velocity field. Both methods are used to retrieve spatial fluctuations of the velocity field. In the separate experiment high speed CCD camera is driven by a stepping motor along the chamber to record long time sequences of images following descending plum of droplets. It allows us to observe changes of the velocity field in time and to retrieve its temporal and spatial fluctuations in the plane. The data were collected in over 30 series of experiments, each in a slightly different thermodynamical conditions inside the chamber. In each series, at least 100 pairs of frames (tens of thousands of velocity vectors in each frame) have been analysed in order to retrieve properties of turbulent velocity fluctuations.

RESULTS

PIV measurements are used to evaluate values characterizing turbulence properties. Collected stereo PIV data indicate that in the horizontal plane flow velocity fluctuations are isotropic with the standard deviation 5.4 cm/s. The distribution of turbulent velocity fluctuations in the vertical direction is almost 50% wider (standard deviation 8.0 cm/s) and has longer tails. Calculated skewness and kurtosis indicate that both distributions are close to the Gaussian (normal). Experimental probability distribution functions (PDF) of velocity fluctuations in horizontal (u_1') and vertical (u_3') directions show remarkable similarity with the numerical simulations performed by Malinowski et al. [3] for a small box containing evaporating cloud droplets.
The two dimensional velocity fields obtained from the PIV measurements in the cloud chamber give us possibility to estimate the Kolmogorov length scale. It is found that it varies in the narrow range from about 7.2 10^{-4} m to 7.8 10^{-4} m. These values are typical for cumulus clouds in presence of weak convection [6]. It is worth noting that the Kolmogorov length scale measured in the cloud chamber appears to depend on the relative humidity of air, i.e. initial humidity measured in the chamber before the plum with droplets is introduced.
The Reynolds number evaluated from mean velocity of falling down cloud structures (~30cm/s) and width of flow (~50cm) is of the order of 10^4. Mean Taylor microscales estimated independently for horizontal (λ_u) and vertical (λ_w) velocity components are 7.5mm and 9.2mm, respectively. These values, obtained on a basis of measurements resolving smallest scales of the flow, indicate anisotropy of the turbulent fluctuations.

CONCLUSIONS

Small scale mixing of cloud with unsaturated environment is investigated in laboratory cloud chamber allowed us to evaluate statistics of the turbulent flow field down to the Kolmogorov length. The results indicate that small-scale turbulence in such conditions is highly anisotropic with the preferred vertical direction. The present investigation indicates also that properties of turbulence in small scales is sensitive to the initial air humidity. Hence, obviously buoyancy forces resulting from evaporation of cloud droplets substantially influence smallest scales of turbulence. Typically, $<(u')^2>$ is about two times smaller than $<(w')^2>$. These observations overlap results of numerical studies performed for the laboratory scale cloud model. However, it is still uncertain to what extent information gained in the laboratory cloud can be applied to atmospheric systems. Hence, in situ measurements of turbulent velocity fluctuations from various types of clouds are necessary to validate common assumptions on small-scale cloud isotropy.

Acknowledgments

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