Small-scale mixing at cloud top
observed in a laboratory cloud chamber - preliminary results

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1. INTRODUCTION

We simulate mixing at the top of a cloud in a laboratory chamber by means of Particle Image Velocimetry (PIV) technique. Cloud droplets, visualized with a sheet of light serve as markers allowing to determine flow in a planar cut through the cloud. The goal of experiments is to create a laboratory analog of Stratocumulus and Cumulus cloud top in order to observe details of entrainment and small-scale turbulent mixing.
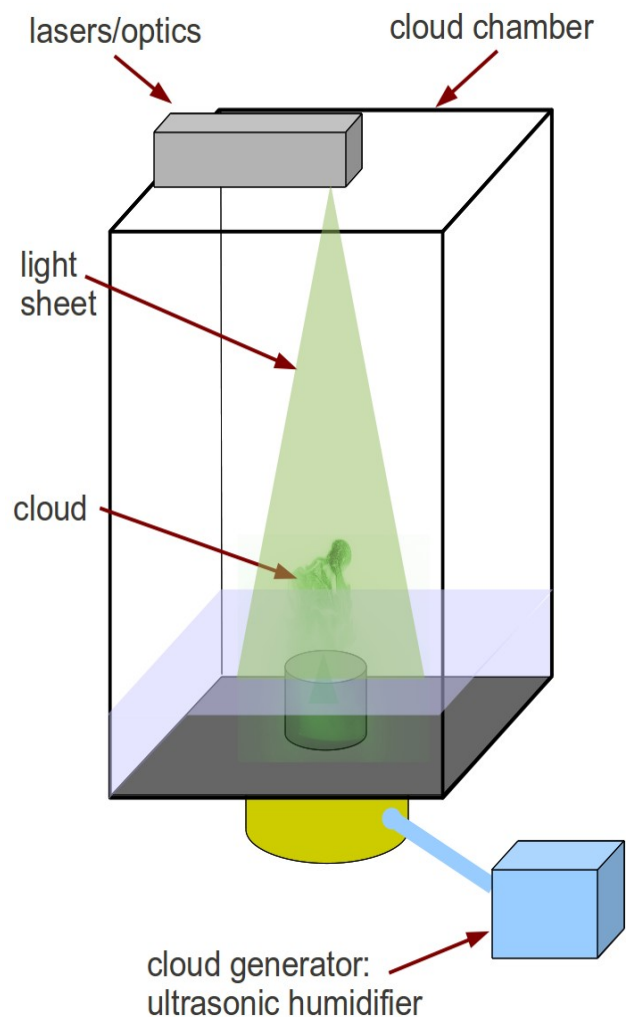
2. EXPERIMENTAL SETUP

Setup of the experiment evolved from previous laboratory studies of small-scale mixing in clouds by Malinowski et al. (1998, 2008) and Korczyk et al., (2006, 2008, 2010). We use the same laboratory cloud chamber, similar cloud surrogate (negatively buoyant saturated air containing droplets of diameters as observed in natural clouds) and the same visualization technique (illumination of the chamber interior with a thin sheet of laser light enabling imaging planar cross section through the cloud with a high-resolution CCD camera). An important difference is organization of the flow inside the chamber and some details of imaging.

In a series of experiments described here cloud chamber is filled from below through a round opening in the bottom. Under the opening there is a container filled with misty air from three ultrasonic humidifiers (sources of cloud droplets). Flow rate is controlled by a ventilation speed by adjustment of knobs on the humidifiers and switching the humidifiers on/off. Liquid water content can be varied by controlling production rate of the mist.

By slow (almost laminar) filling the chamber with the negatively buoyant mist through the opening in the bottom one may reproduce conditions in the chamber somewhat similar to that in a topmost part of Stratocumulus capped by a strong inversion.

A schematic sketch of the present experimental setup is presented in Fig.1, view of the cloud chamber

Fig.1. *A schematic view of the experimental setup. A CCD camera used for imaging and PIV not shown.*

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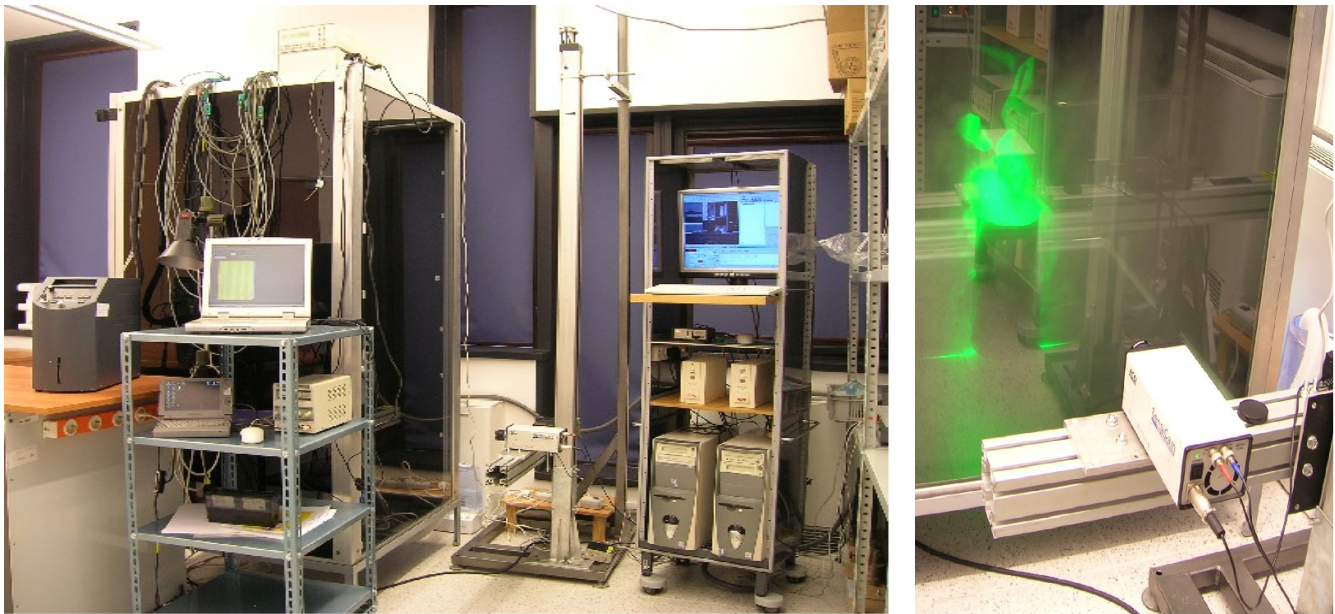
Fig.2. *Left: view of the experimental system. In the front of a cloud chamber (black box with cables) there is a power supply for the laser and computers which collect data on temperature and humidity in the chamber. CCD camera and computers for PIV are in the front of glass window.*

Right: CCD camera imaging the cloud surrogate.

in the lab is shown in Fig.2. Cloud chamber has dimensions of 1.0 m × 1.0 m × 1.8 m. Front side of the chamber is transparent, all other walls are covered by black foil in order to reduce scattering of the laser light. PIV imaging system consists of double-pulsed Nd:YAG laser (SoloPIV from NewWave Research Inc., wavelenght: 532 nm, pulse energy: 30 mJ, pulse width: 5 ns). Optical system forms a flat sheet of light which enters the chamber through opening in the top and enlightens central cross-section of the chamber. Light, scattered by droplets is imaged by double-shutter 12-bit CCD camera with resolution 1280x1024 pixels (SensiCam from PCO IMAGING) with the optical axis perpendicular to the light sheet. Vertical profile of temperature and humidity in the chamber is monitored by a vertical chain of 15 thermometers and 4 capacitance humidity meters.

3. DETAILS OF THE EXPERIMENT

In the beginning of the experiment chamber is cleaned. Opened back doors of the chamber allow to fill its interior with the air from the lab (temperature ~25°C and relative humidity of 35%). After closing the door a saturated and negatively buoyant cloudy plume (containing droplets of ~10 μm diameter) is pushed into the chamber through the round opening in the floor.

A 30 cm high tube ("chimney") placed on top of the opening allows to produce well organized almost laminar updraft. Vertical velocity of the plume at the top of the tube measured by pressure velometer is about 15 cm/s. LWC in the plume is typically more than 10 g/kg - higher than in natural clouds. The plume's temperature is about 21°C. Tubes of various heights and diameters can be used in order to create various dynamical conditions in the updrafts and adjust height of the mixed layer in the chamber.

A negatively buoyant plume ascends 5-10 cm above the tube top, mixes with the environment and descends, spreading in the bottom of the chamber. Vertical profile of temperature in the chamber is measured close to the chamber wall every 10 cm. Its evolution in course of the measurement series with the tube of height of 30 cm on top of the bottom opening is presented in Fig.3.

After a short initial episode with the unmixed plume hitting the bottom part of the chamber (red line in Fig.3) a relatively stationary layer of depth of ~35 cm, containing saturated, cloudy, well mixed air forms in a bottom part of the chamber. This layer is capped by dry, unsaturated air and an inversion of ~15 cm thickness is formed in between these layers. some configurations of the flow, when updraft does not penetrate through the inversion, observer notices buoyant waves excited by the updraft, traveling along the density jump towards chamber walls and eventually reflecting from them.
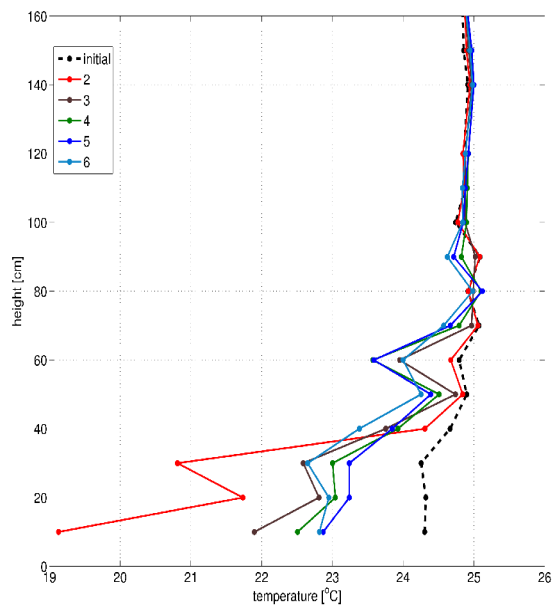
Fig.3 *Evolution of temperature profile in course of experiment. Profiles taken every 90 s show initial weak inversion (humid bottom plate of the chamber), formation of the 30 cm deep mixed boundary layer capped with strong inversion (2-6).*

Signature of such waves is visible also in temperature profiles shown in Fig.3 by a local minimum at the height of 60 cm. The temperature sensor located close to the wall is wetted in the crest of the wave and afterwards cooled due to evaporation in through of the wave. The sensor is relatively slow (response of order of 60 s, in the average) and the drop of the air temperature is present on the display.

Buoyancy and temperature jump at the inversion is not just the effect of colder, negatively buoyant plume. It is also result of mixing of the cloudy plume with the unsaturated environment and of the evaporative cooling at the top of the cloudy layer.

Lightening of the mixing region with the laser light sheet reveals complicated continuously evolving structures (eddies, filaments, etc.). These structures are imaged by a CCD camera in front of the chamber. In the image one pixel corresponds to ~2 mm deep volume with about 0.25 µm^2 area in the plane of the laser-light sheet. Such elementary volumes occupied by droplets are represented by bright pixels; dark pixels correspond to volumes void of droplets in Fig.4.

Pattern recognition in two consecutive images separated by a known time interval allows to retrieve two velocity components in the image plane. This
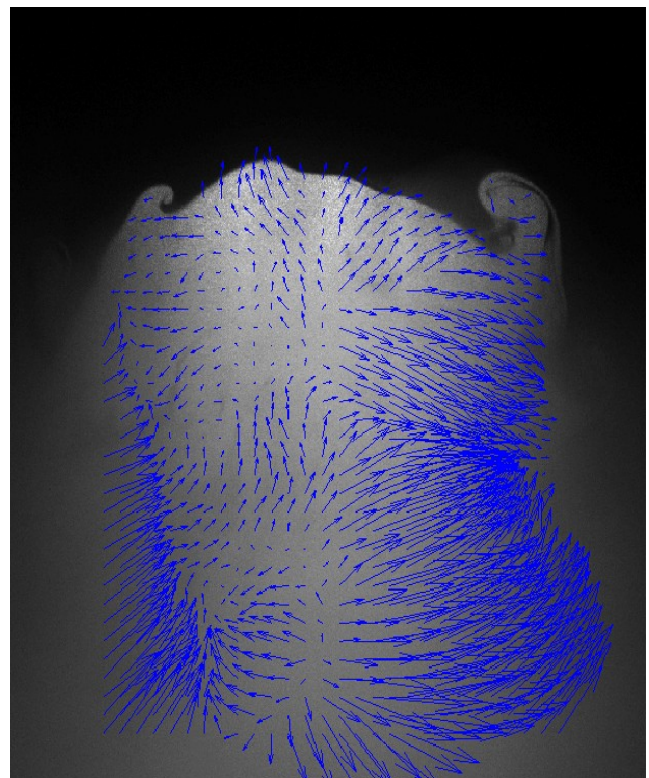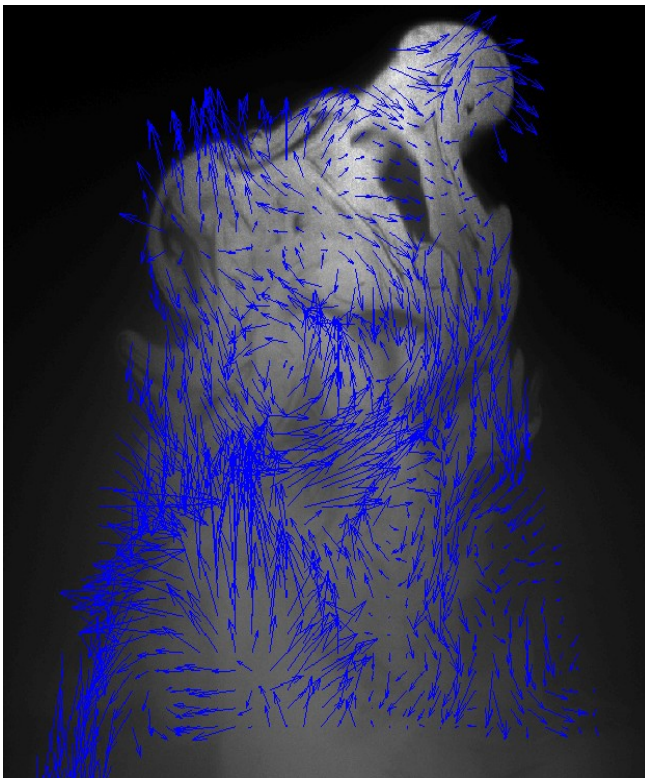
Fig.4. *Example images from the experiment. Left - an analog of overshooting Cumulus; right - an analog of updraft in Sc; arrows: first retrievals of velocity in laboratory analogs of convective clouds with PIVKor algorithm (subject of further refinements).*

technique, referred to as Particle Image Velocimetry (PIV) (Raffel 1998), is widely adopted in experimental fluid mechanics. Correlation of patterns in two consecutive images allows to retrieve 2-D velocities in the plane of the image, as shown in Fig.4.

In order to retrieve velocities we tried a couple of algorithms. A commercial algorithm (VidPIV from ILA GmbH) produced velocity fields which were reliable in the images showing wavy patterns on the capping inversion (Fig.5.). It occurred unreliable when adopted to updrafts impinging upon inversion or penetrating into the unsaturated layer above. In such cases of complicated, quickly evolving filaments, agreement between the vectors and the image layout was questionable.
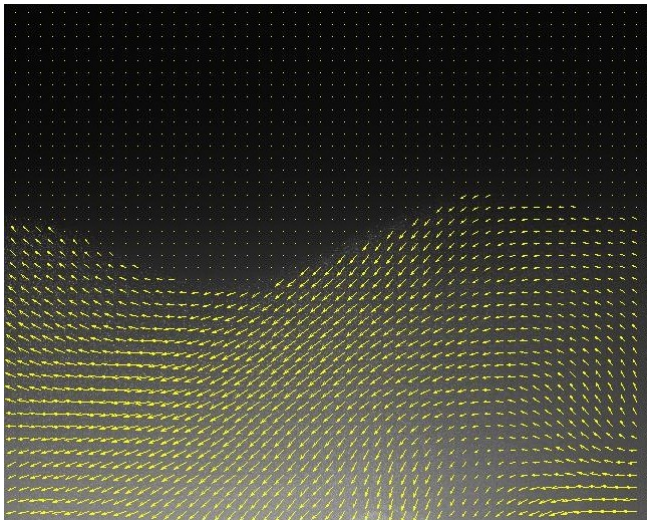
Fig.5 *Buoyant wave on the top of the cloudy layer imaged in course of the experiment. Arrows show velocity vectors retrieved inside cloud with use of VidPIV algorithm.*

As an option, an original, accurate multi-scale PIVKor algorithm, developed in course of former cloud chamber experiments (Korczyk et al., 2006), (Korczyk 2008) was adopted. This is a multi-scale algorithm identifying in a first step displacement of largest structures and then subsequently iterating displacements within smaller and smaller patterns. Use of this algorithm gave satisfactory results only in a few cases. Difficult lightening conditions, different from the former experience caused failures resulting with wrong velocity retrievals.

Cloud layer on the bottom of the chamber, which is essential to reproduce cloud-op conditions in the experiment, results in multiple scattering. Remarkable amount of diffused light deteriorates image quality. This deterioration – light pollution – is unevenly distributed within the image area affecting correlations of light intensity in image pairs and thus affecting velocity retrievals. In future we have to experiment with various correction algorithms.

Improvements in imaging optics, especially narrowing of the depth of the field of camera should also help. Light sheet leaning should reduce amount of scattered light and careful addition of fluorescent dye into droplet generators should enhance visibility of cloud patterns.

Summary

In this preliminary study we demonstrated that reproduction of basic features of cloud topped boundary layer in the laboratory cloud chamber are possible. In order to study details of entrainment/mixing process by PIV technique improvements in visualization are necessary.

Acknowledgments:

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