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# SMALL-SCALE TURBULENT MIXING IN CLOUDS: NUMERICAL AND EXPERIMENTAL RESULTS

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Environmental Turbulence from Clouds through the Ocean  
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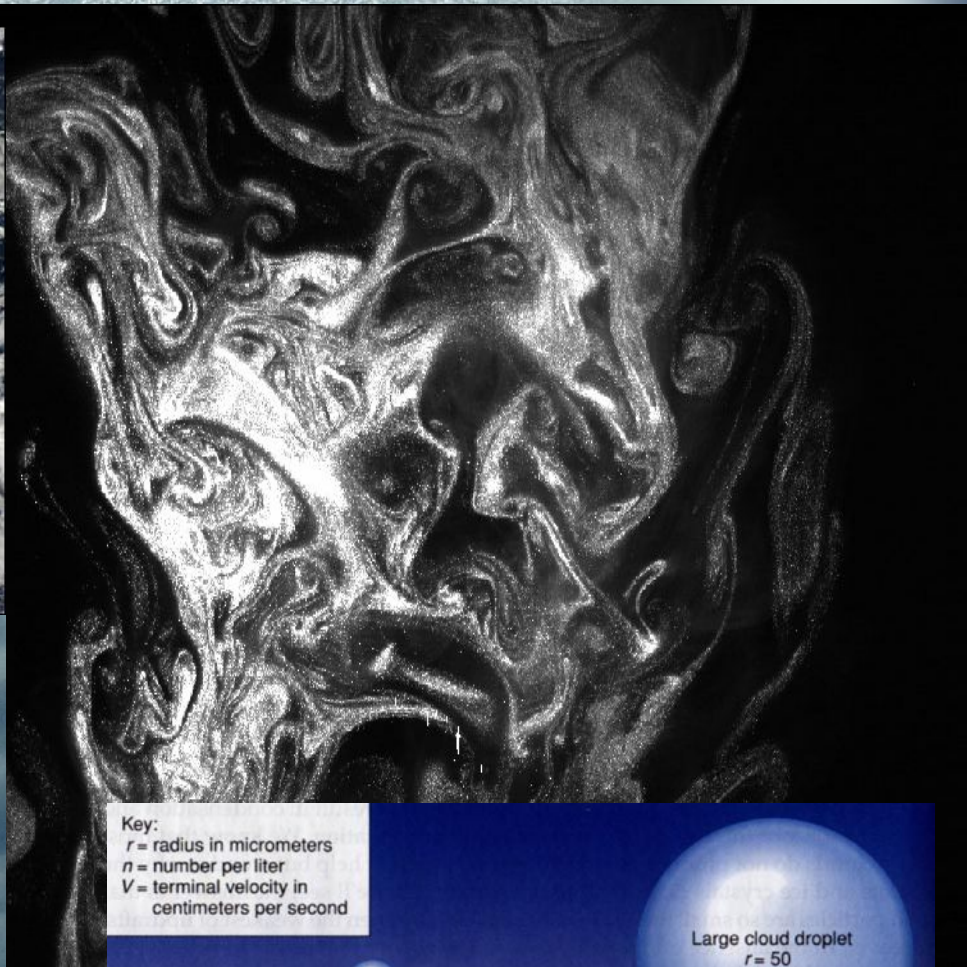
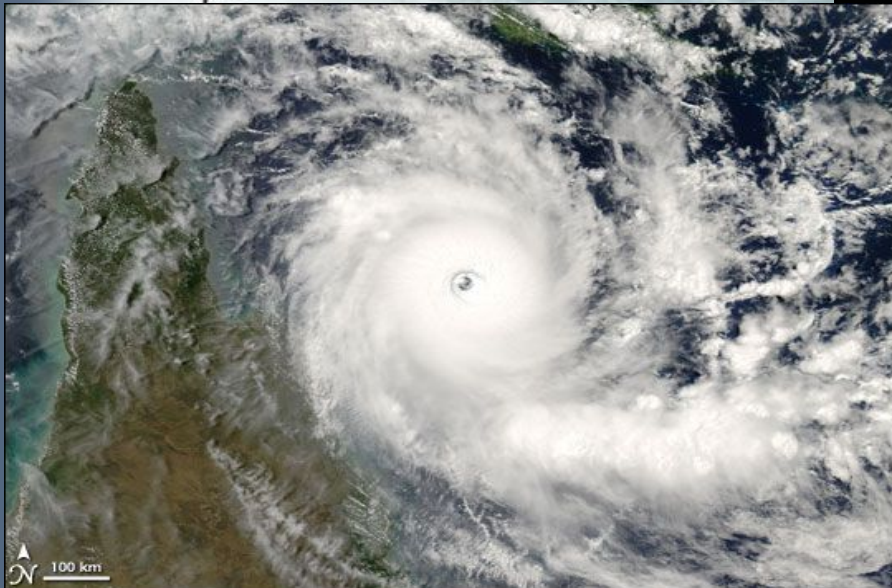
- **MOTIVATION:**

- Cloud droplets are particles which may grow or evaporate, depending on humidity in their closest vicinity. Growth/evaporation influences thermodynamics and microphysics of the flow. Turbulence in clouds is a two-phase reacting flow.
- Cloud droplets move with respect to air. This means that the transport processes of liquid water differs from other variables, like temperature, and humidity.
- Understanding of the above is important for our basic knowledge as well as for applications, like radiative transfer through clouds (climate), warm rain formation (weather and climate), parameterization of small-scale processes in models resolving larger scales .



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Key:  
 $r$  = radius in micrometers  
 $n$  = number per liter  
 $V$  = terminal velocity in centimeters per second

• Typical condensation nucleus  
 $r = 0.1$   
 $n = 10^6$   
 $V = 0.0001$

• Typical cloud droplet  
 $r = 10$   
 $n = 10^6$   
 $V = 1$

• Large cloud droplet  
 $r = 50$   
 $n = 10^3$   
 $V = 27$

• Typical raindrop  $r = 1000$ ,  $n = 1$ ,  $V = 650$



• **FACT 1:**

- Combined measurements aimed at investigations of interaction between turbulence, thermodynamics (phase change) and microphysics (cloud droplets) in small scales have never been documented.
- Even reliable data from the in-situ measurements of small-scale turbulence in clouds are not available.

• **FACT2:**

- Such measurements can hardly be performed in situ due lacking measurement techniques.

• **FACT 3:**

- In theoretical studies turbulent velocities in small scales are assumed to be isotropic and are described by statistical distribution fitting laboratory/wind tunnel/atmospheric boundary layer experimental data or DNS.



- In order to investigate possible differences between the small-scale turbulence in cloud undergoing mixing and the idealized turbulence assumed in theoretical works an attempt to simulate small-scale cloud-clear air mixing is undertaken (Andrejczuk et al., 2004, Andrejczuk et al., 2006).
- A small scale cloud turbulence is investigated by direct simulation of the microscale mixing (i.e., mixing occurring at sub-meter scales).
- The goal is to study the impact of evaporative cooling and cloud droplets' sedimentation on the generation of the turbulent kinetic energy (TKE) and other properties of microscale turbulence.
- Results from a series of idealized numerical simulations of decaying moist turbulence in a sample volume  $64\text{cm} \times 64\text{cm} \times 64\text{cm}$  are presented.
- Evolution of turbulent, filamented cloud-clear air structure is simulated on the mesh of  $64^3$ ,  $128^3$  and  $256^3$  gridpoints.



- Two parameterizations of microphysics: bulk microphysics and detailed microphysics are used. Detailed microphysics parameterization takes into account droplet sedimentation.
- Initial dynamical setup is adopted from typical DNS simulations with decaying turbulence, formulated after Herring and Kerr (1993) in Fourier space.
- Initial TKE value corresponds to low levels of TKE dissipation observed in clouds.
- Initial potential temperature of the cloud and the environmental air is 293K and relative humidity of the environment is 65%, while LWC (Liquid Water Content) in saturated cloudy filaments is 3.2g/kg.



$$B \equiv g \left[ \frac{T - T_0}{T_0} + \varepsilon(q_v - q_{v_0}) - q_c \right], \quad (2)$$

$$\frac{D\mathbf{v}}{Dt} = -\nabla\pi + \mathbf{k}B + \nu\nabla^2\mathbf{v}, \quad (1a)$$

$$\nabla \cdot \mathbf{v} = 0, \quad (1b)$$

$$\frac{DT}{Dt} = \frac{L}{c_p} C_d + \mu_T \nabla^2 T, \quad (1c)$$

$$\frac{Dq_v}{Dt} = -C_d + \mu_v \nabla^2 q_v, \quad (1d)$$

$$\frac{Dq_c}{Dt} = C_d.$$

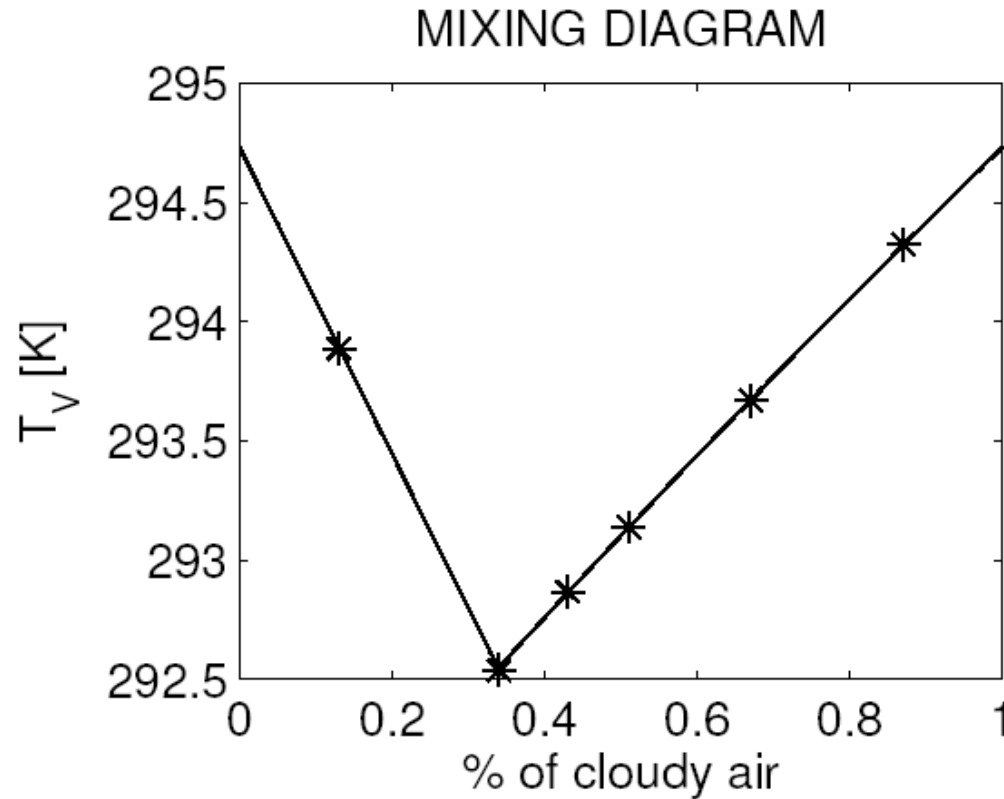
$$C_d = \int f \frac{dm}{dt} dr,$$

$$\frac{D^* f}{D^* t} = -\frac{\partial}{\partial r} \left( f \frac{dr}{dt} \right) + \eta,$$

$$D^*/D^* t \equiv \partial/\partial t + (\mathbf{v} - \mathbf{k}v_t) \cdot \nabla$$



Mixing diagram of  
cloudy and  
environmental air.



$$T_v = T(1 + \epsilon q_v + q_c) - \text{„density temperature”}$$





$$B \equiv g \left[ \frac{T - T_0}{T_0} + \varepsilon(q_v - q_{v_0}) - q_c \right], \quad (2)$$

$$\frac{D\mathbf{v}}{Dt} = -\nabla\pi + \mathbf{k}B + \nu\nabla^2\mathbf{v}, \quad (1a)$$

$$\nabla \cdot \mathbf{v} = 0, \quad (1b)$$

$$\frac{DT}{Dt} = \frac{L}{c_p} C_d + \mu_T \nabla^2 T, \quad (1c)$$

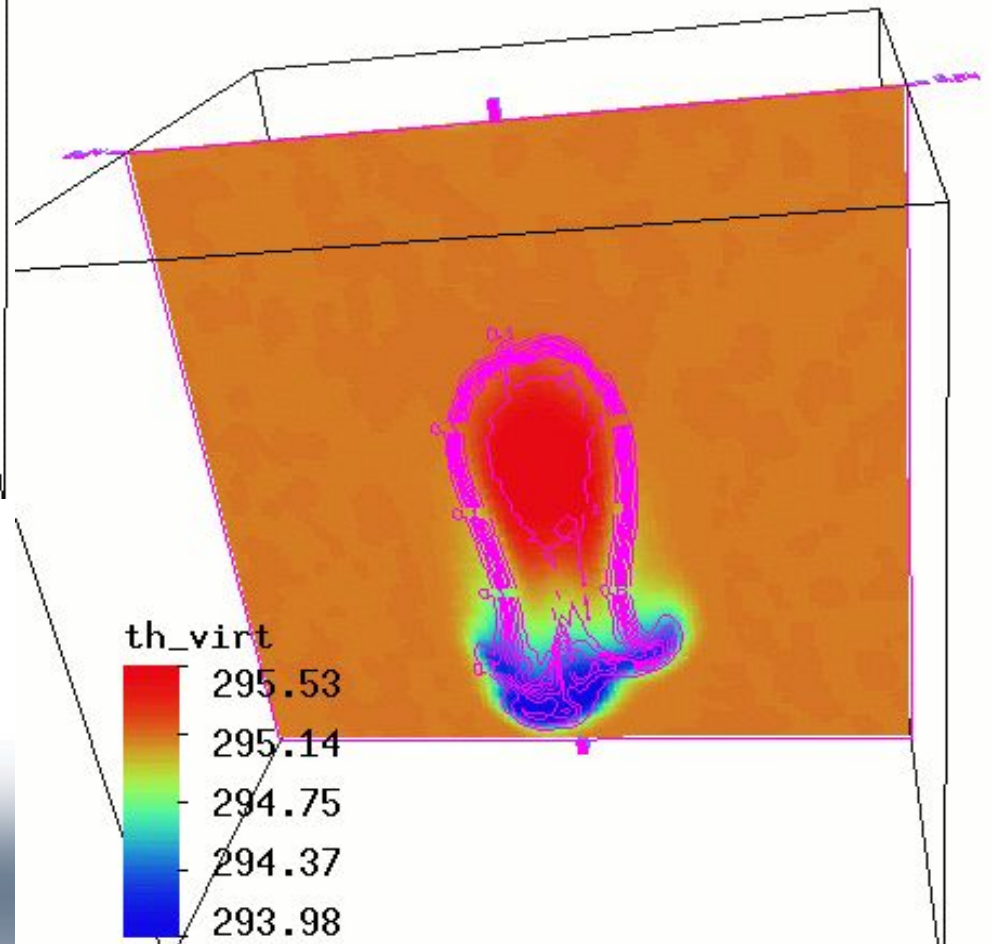
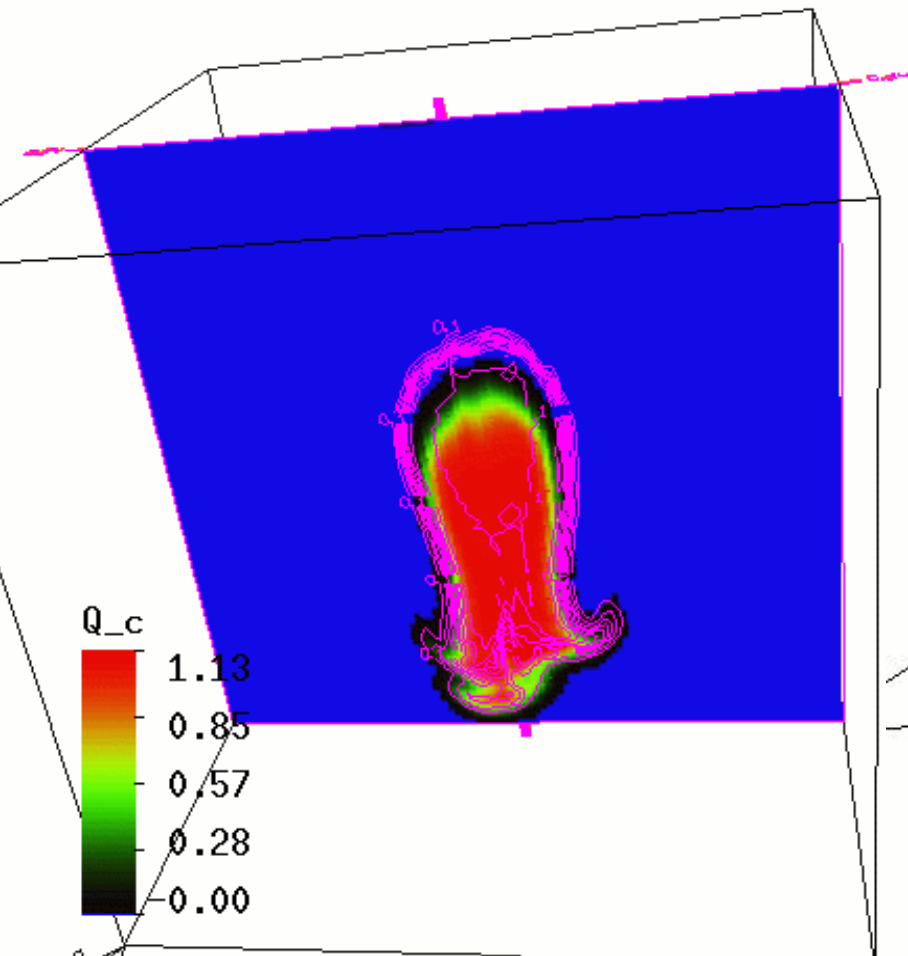
$$\frac{Dq_v}{Dt} = -C_d + \mu_v \nabla^2 q_v, \quad (1d)$$

$$\frac{Dq_c}{Dt} = C_d.$$

bulk

$$C_d = \int f \frac{dm}{dt} dr, \quad \frac{D^* f}{D^* t} = -\frac{\partial}{\partial r} \left( f \frac{dr}{dt} \right) + \eta, \\ D^*/D^* t \equiv \partial/\partial t + (\mathbf{v} - \mathbf{k}v_t) \cdot \nabla$$

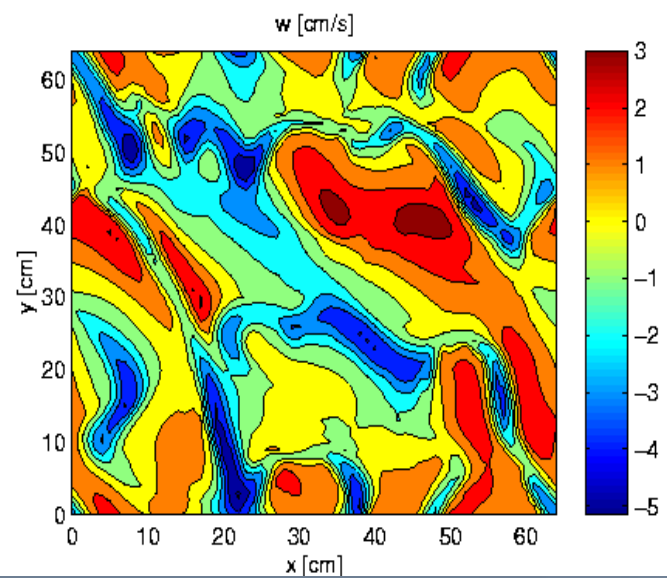
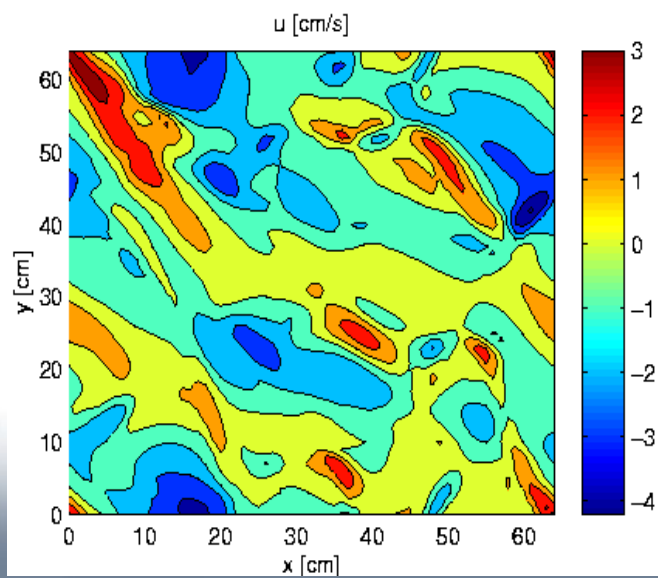
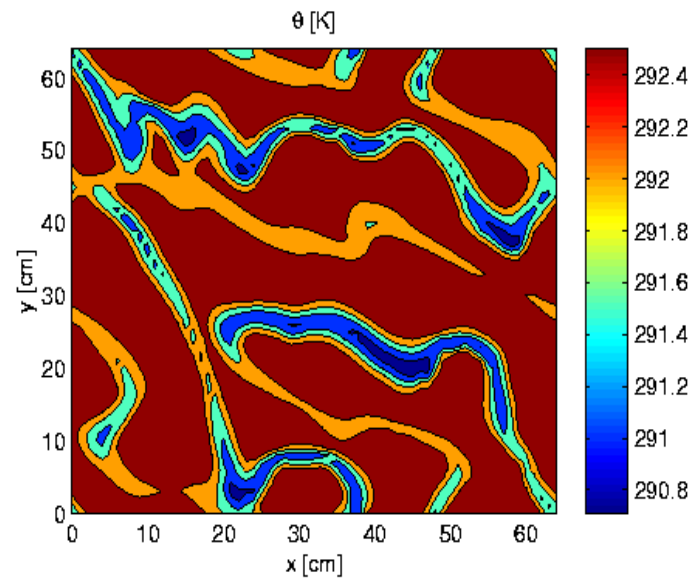
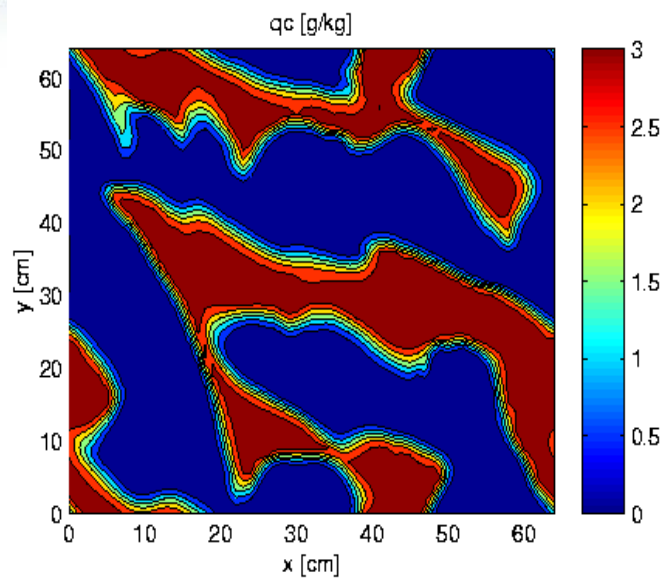
detailed

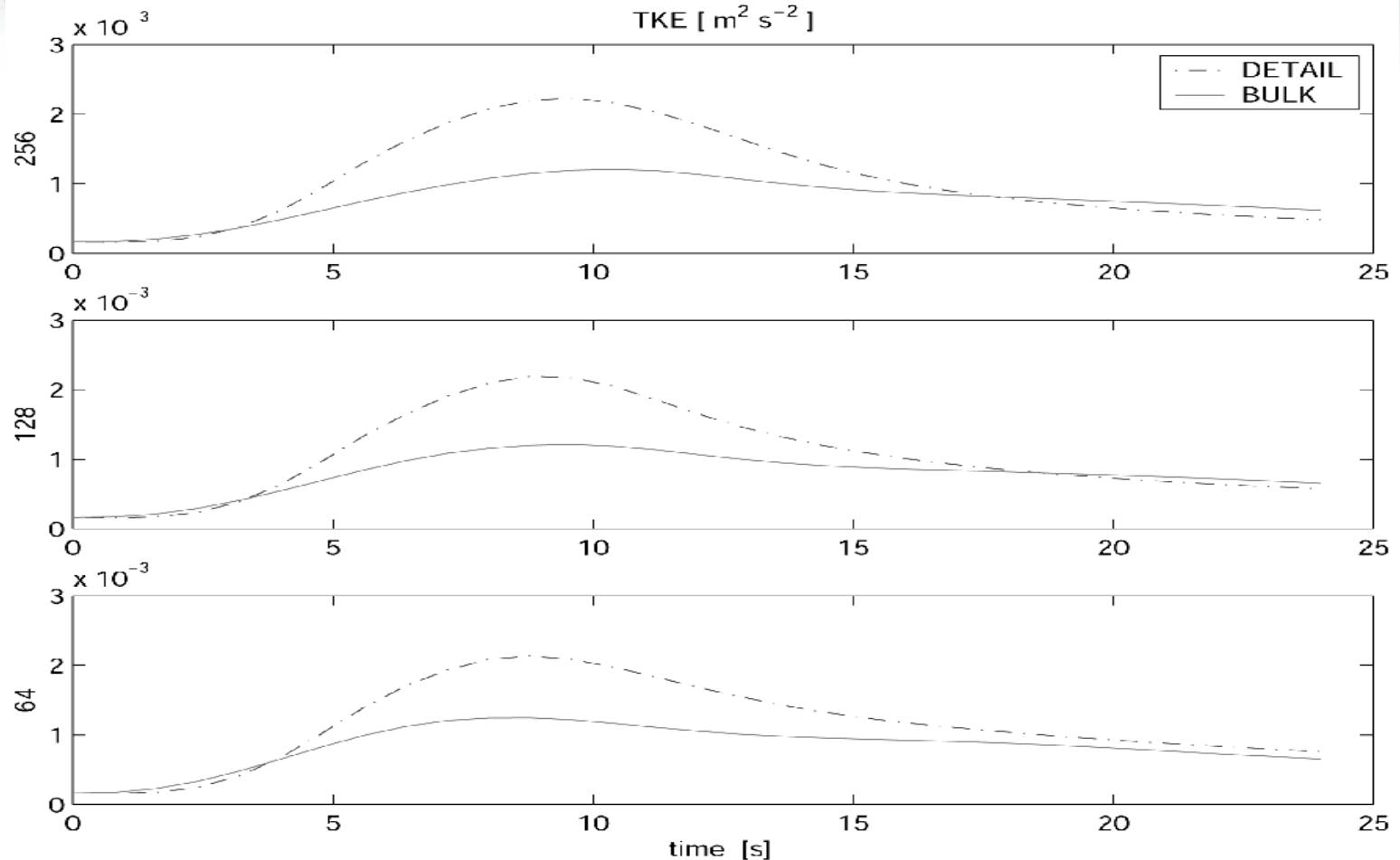




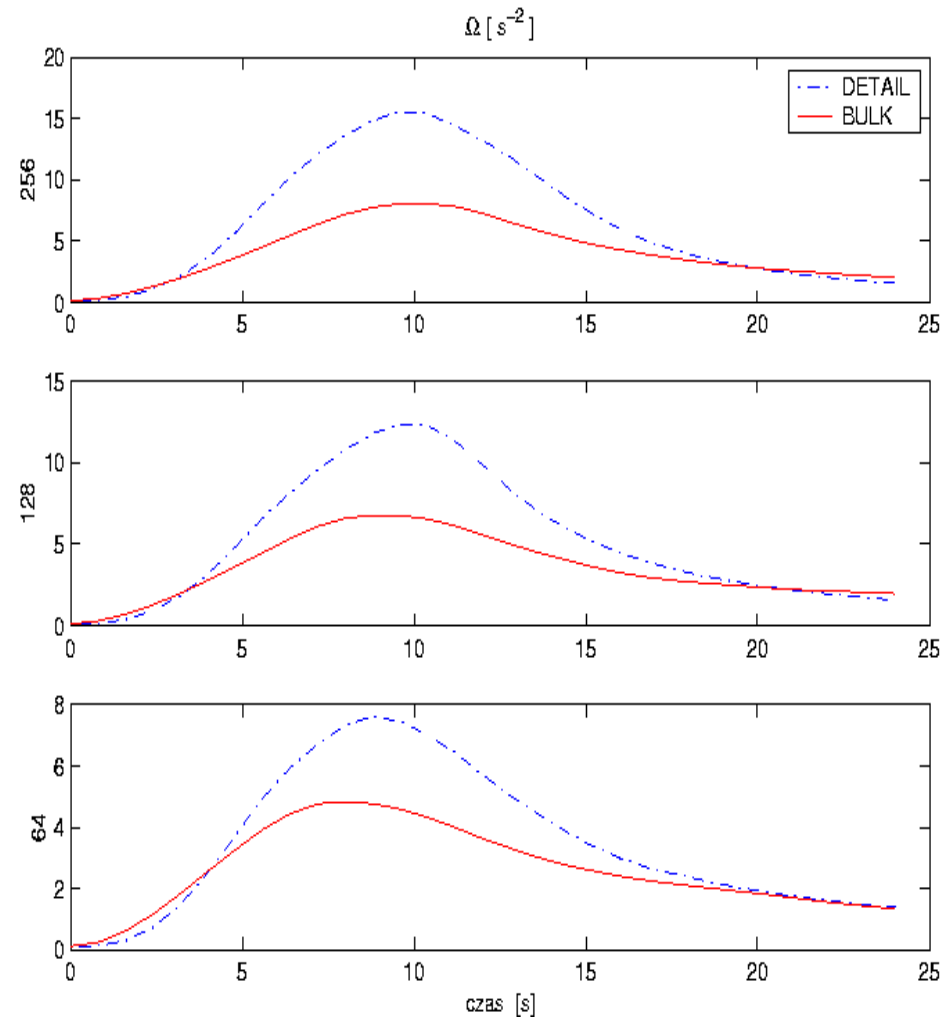
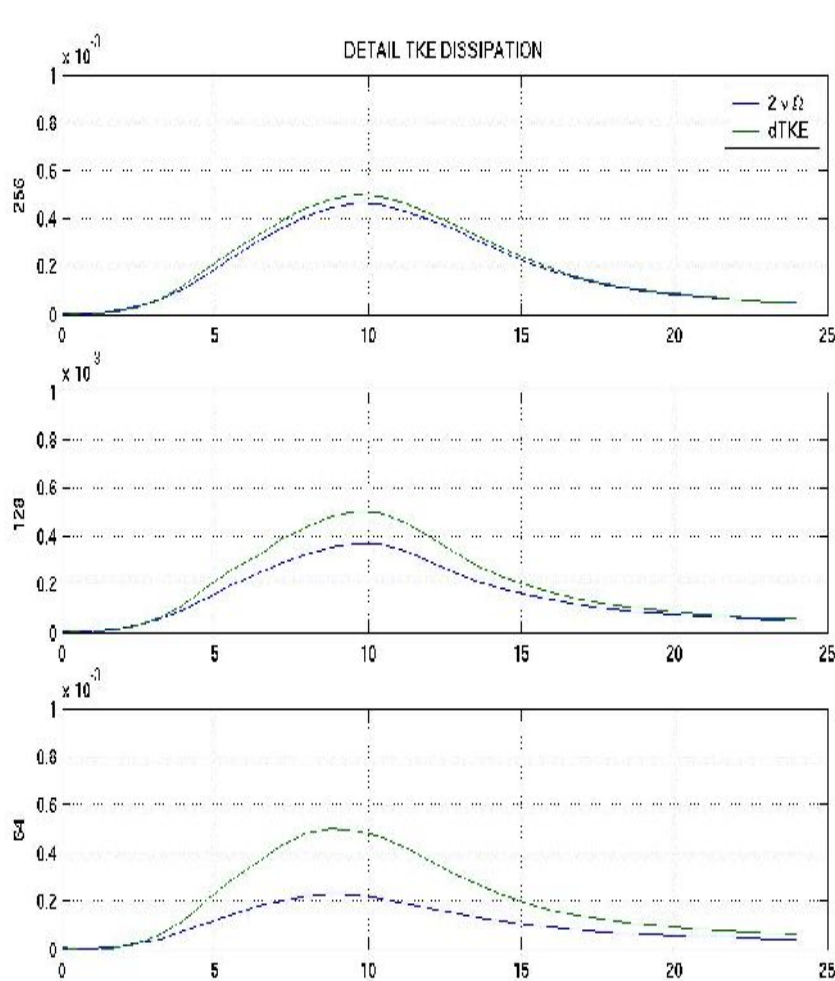
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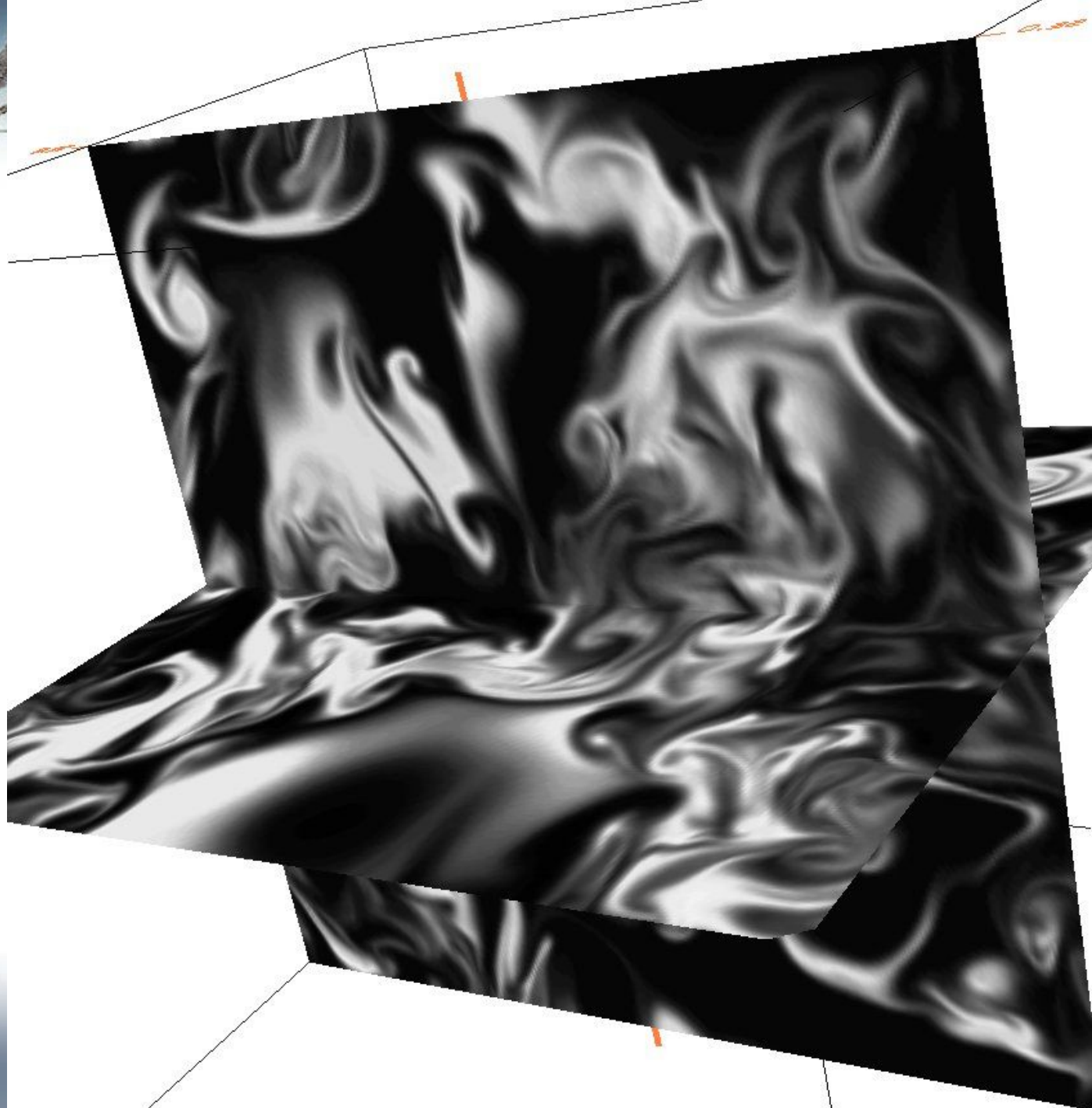


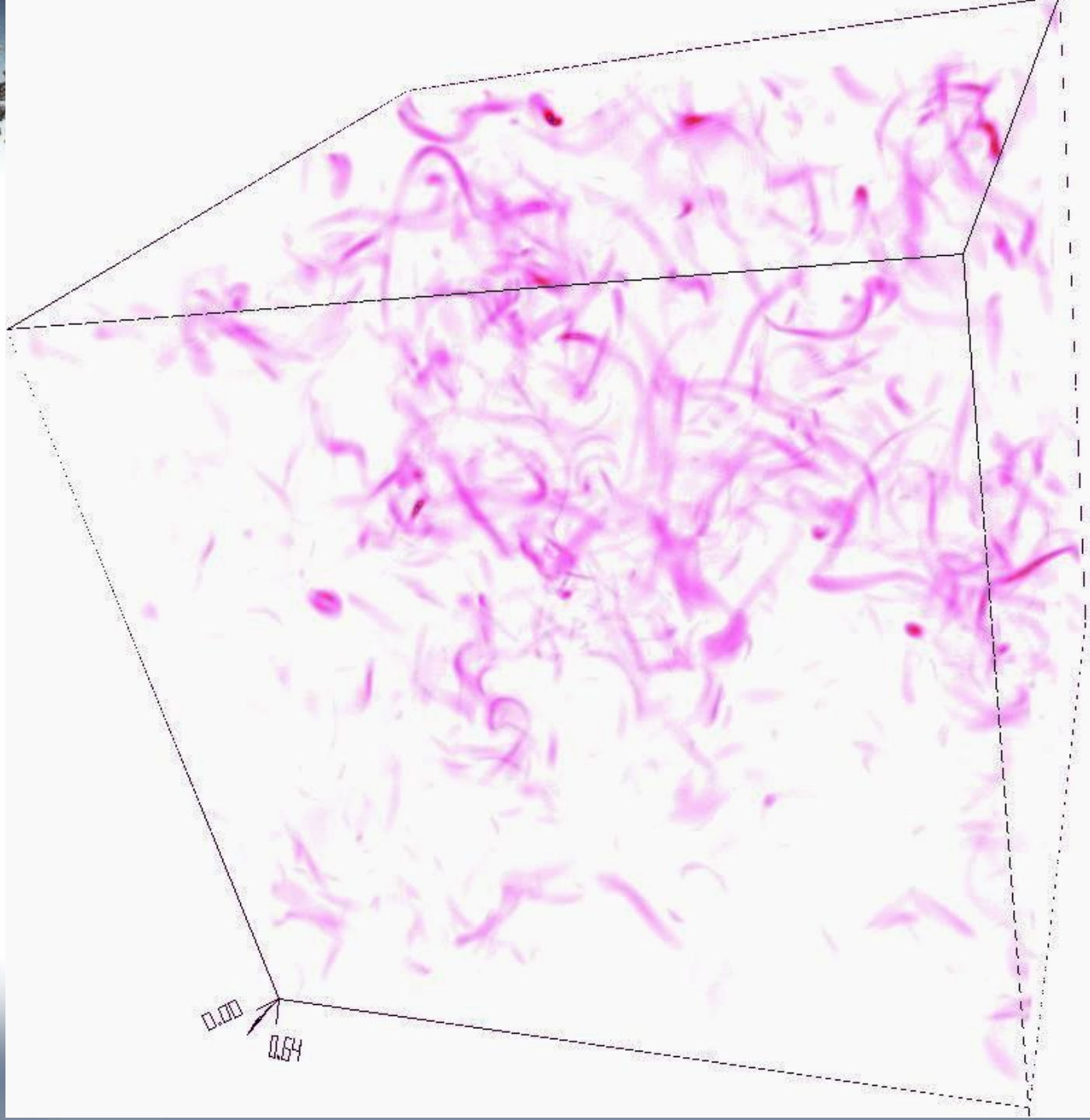


*Temporal evolution of turbulent kinetic energy (TKE) in the experiments with grid 256<sup>3</sup> (upper panel) 128<sup>3</sup> (middle panel) and 64<sup>3</sup> (lower panel). The evolution of TKE is governed by production due to evaporative cooling of droplets (dominating till 9<sup>th</sup> second) and dissipation.*



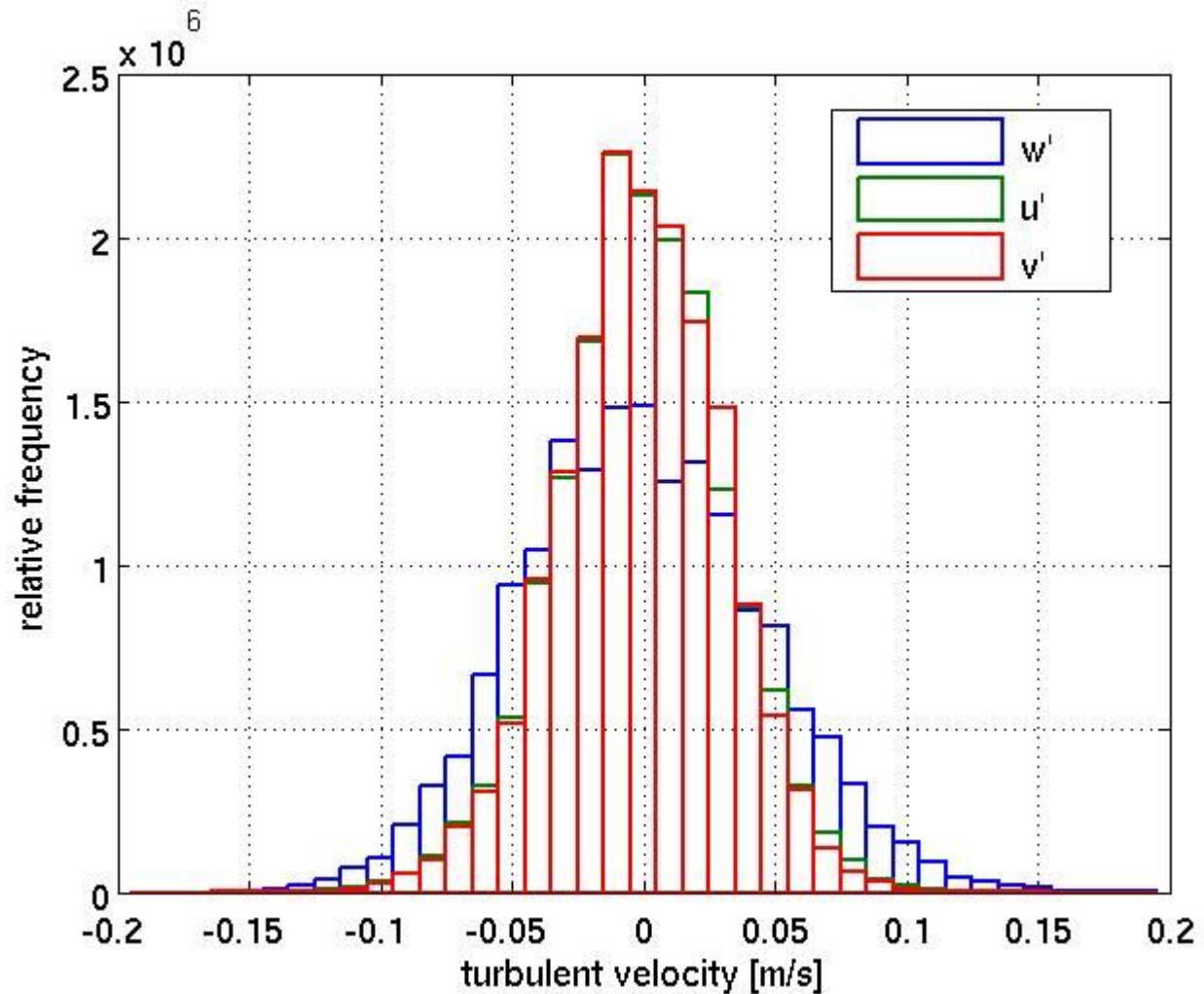
Left: Dissipation of the turbulent kinetic energy (TKE) in the experiment with grid  $256^3$  (upper panel)  $128^3$  (middle panel) and  $64^3$  (lower panel).  
Right: temporal evolution of the mean enstrophy in the experiments with grid  $256^3$  (upper panel)  $128^3$  (middle panel) and  $64^3$  (lower panel).



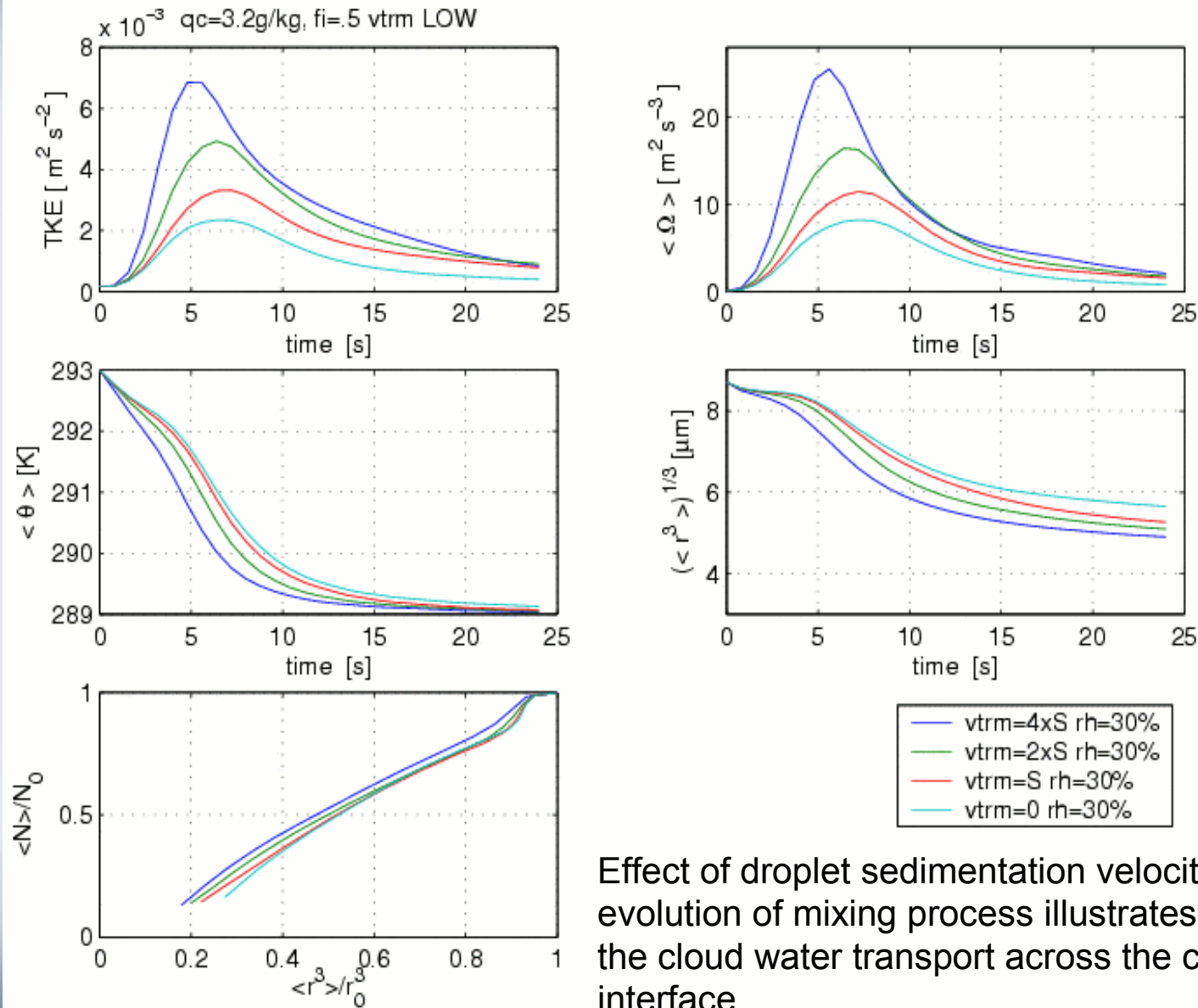




A histogram of horizontal and vertical turbulent velocities after 15 s of calculations.



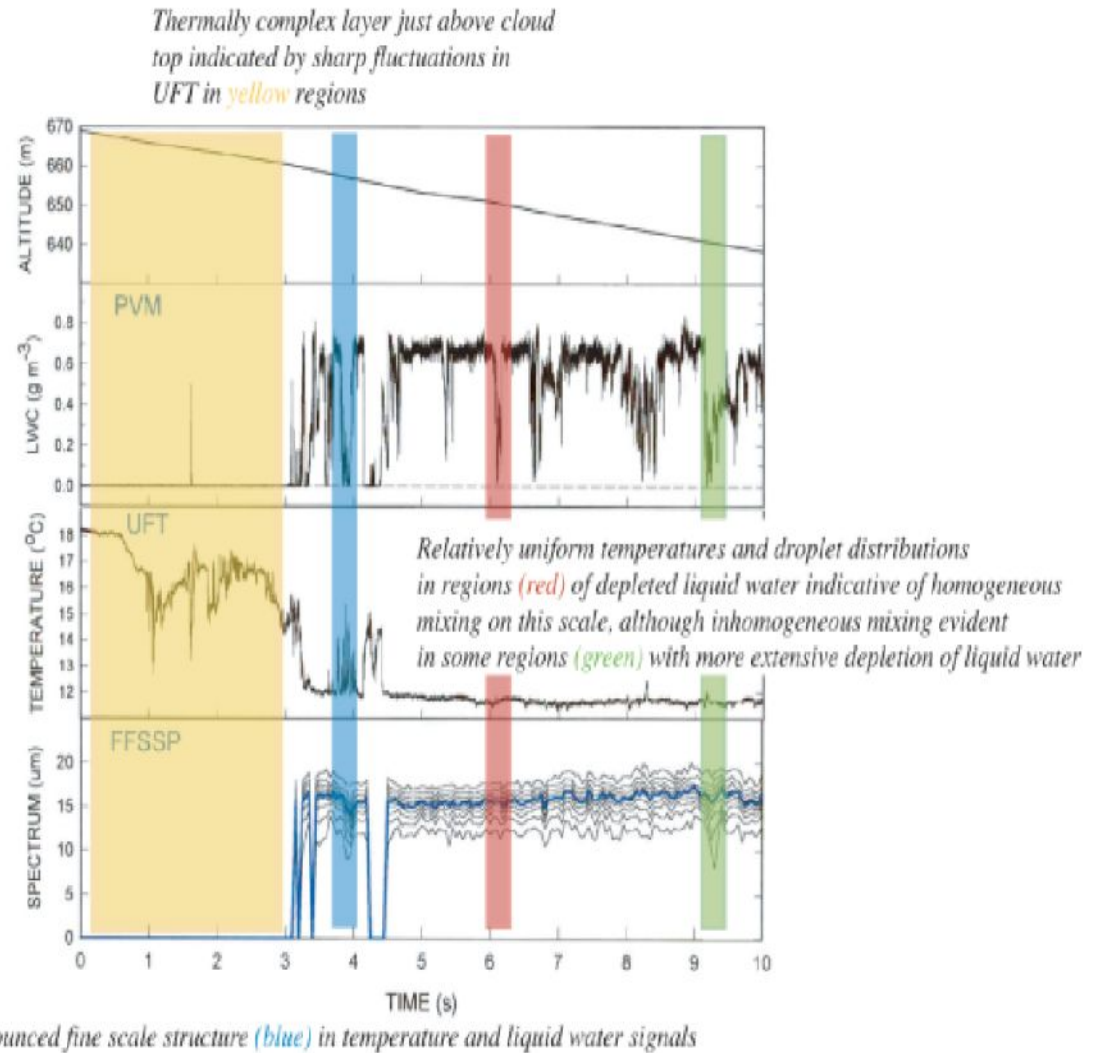


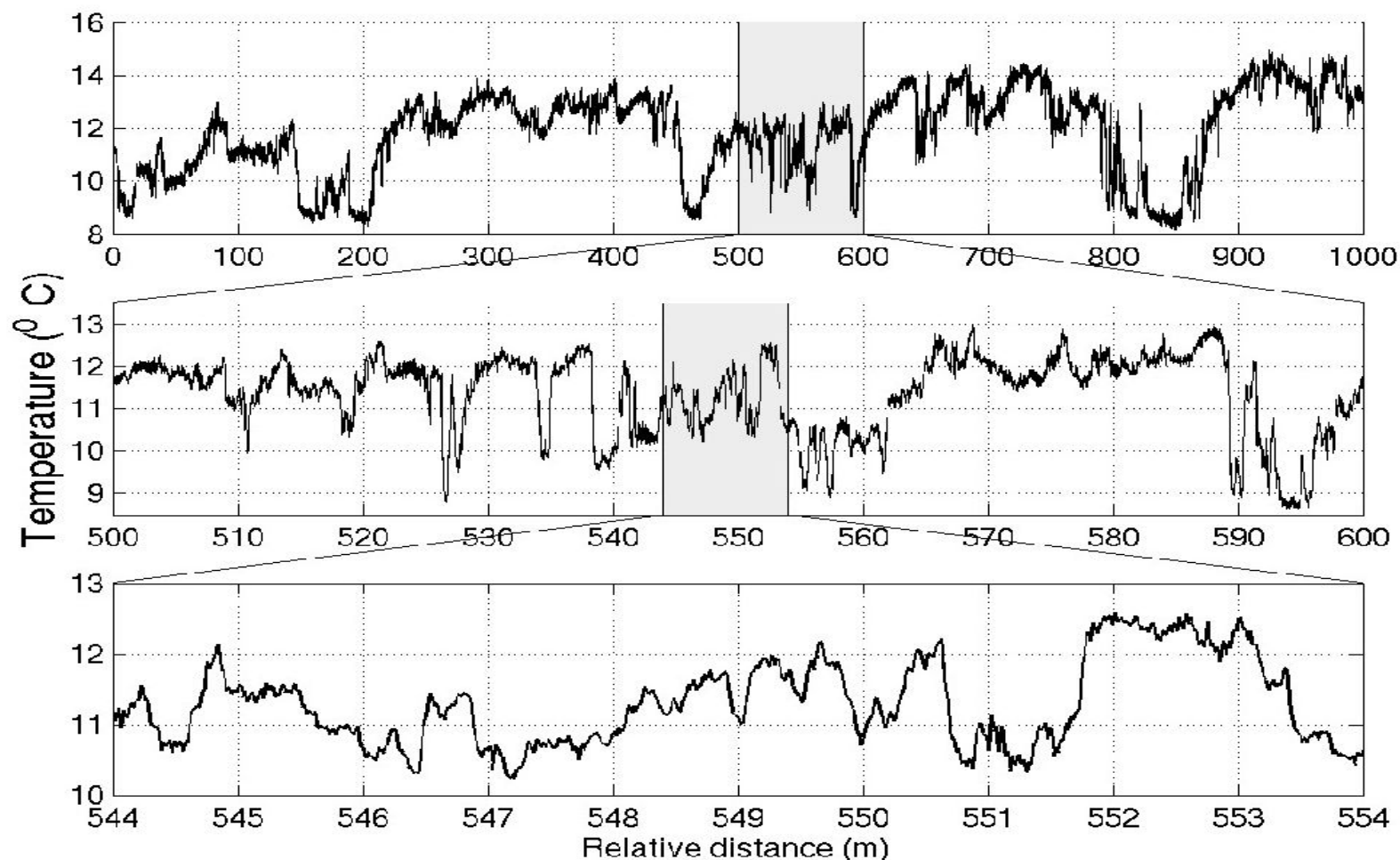


Effect of droplet sedimentation velocity on the evolution of mixing process illustrates importance of the cloud water transport across the cloud-clear air interface.

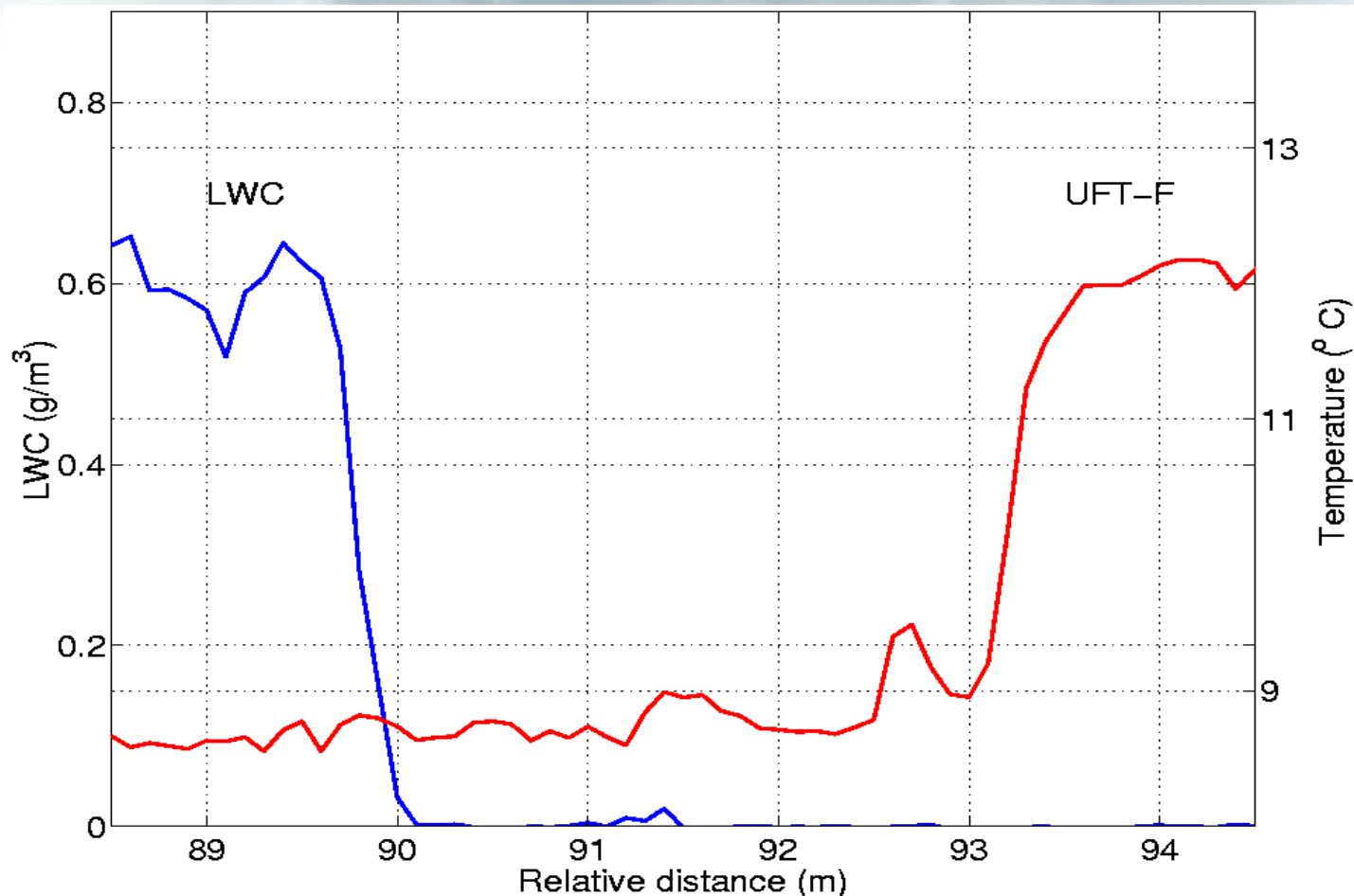


There is an experimental evidence, that small-scale filaments similar to those observed in the presented numerical studies can be observed in real clouds. Temperature records from the ultrafast aircraft thermometer (UFT, Haman et al. 2001) as well as other thermodynamical and microphysical parameters measured at the top levels of Stratocumulus clouds in the experimental campaign DYCOMS 2 (Stevens et al., 2003) are presented in here and the next slides for the illustration.

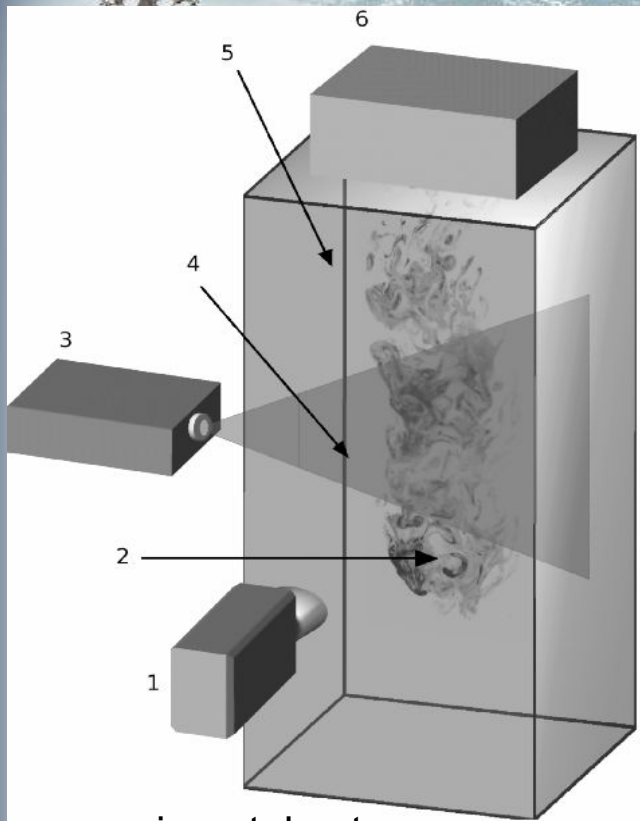




Successive “blow ups” of 10kHz temperature records showing self-similar structures - filaments of air with significantly different temperatures separated by the narrow interfaces with strong gradients (Haman et al., 2006).



The example edge of the cloudy filament recorded with 10cm spatial resolution. Instruments for LWC and temperature measurements were mounted in different locations, separated by 6m distance



Experimental data indicating anisotropy of the small-scale turbulence in clouds which undergoes mixing with the unsaturated environment can be found in the laboratory chamber study by Korczyk et al., 2006.



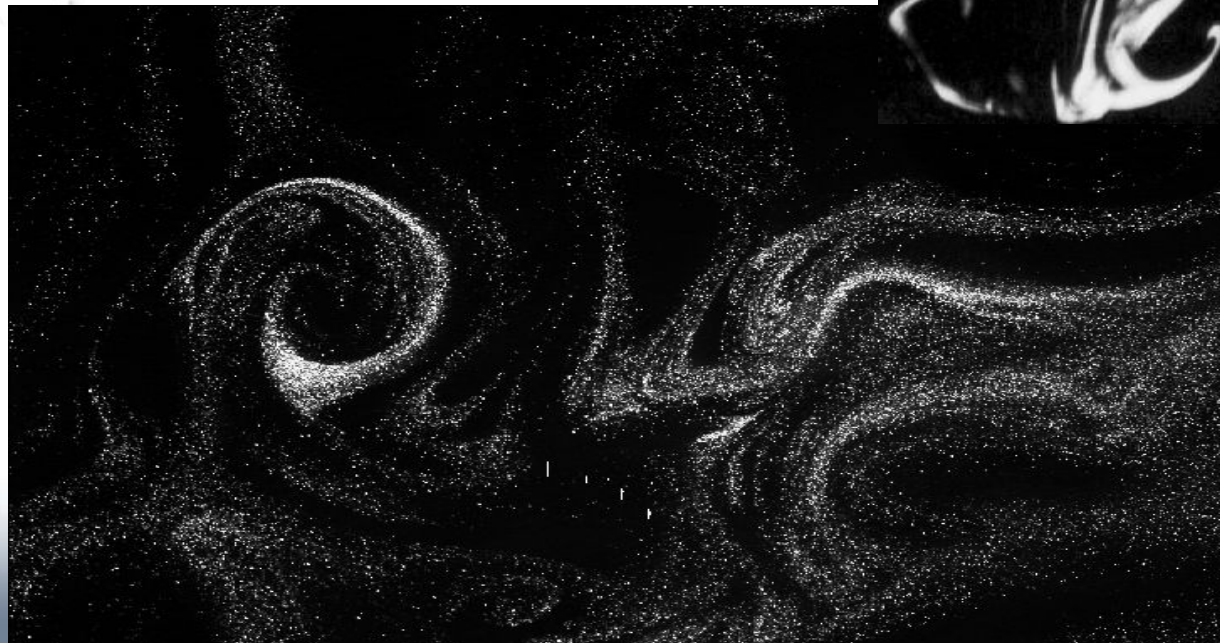
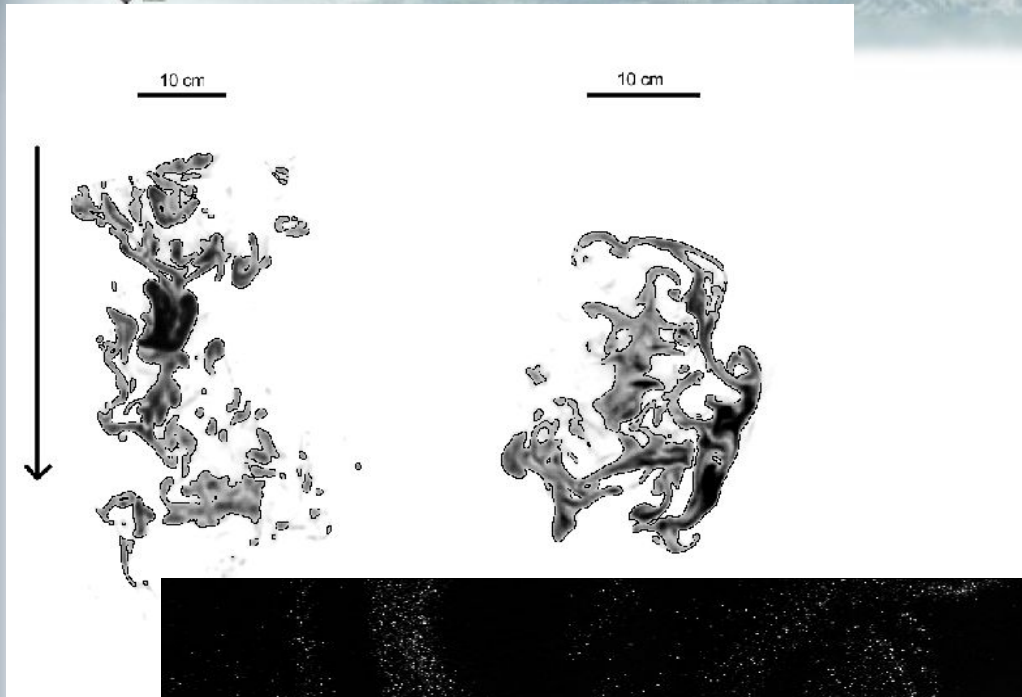
The experimental setup:

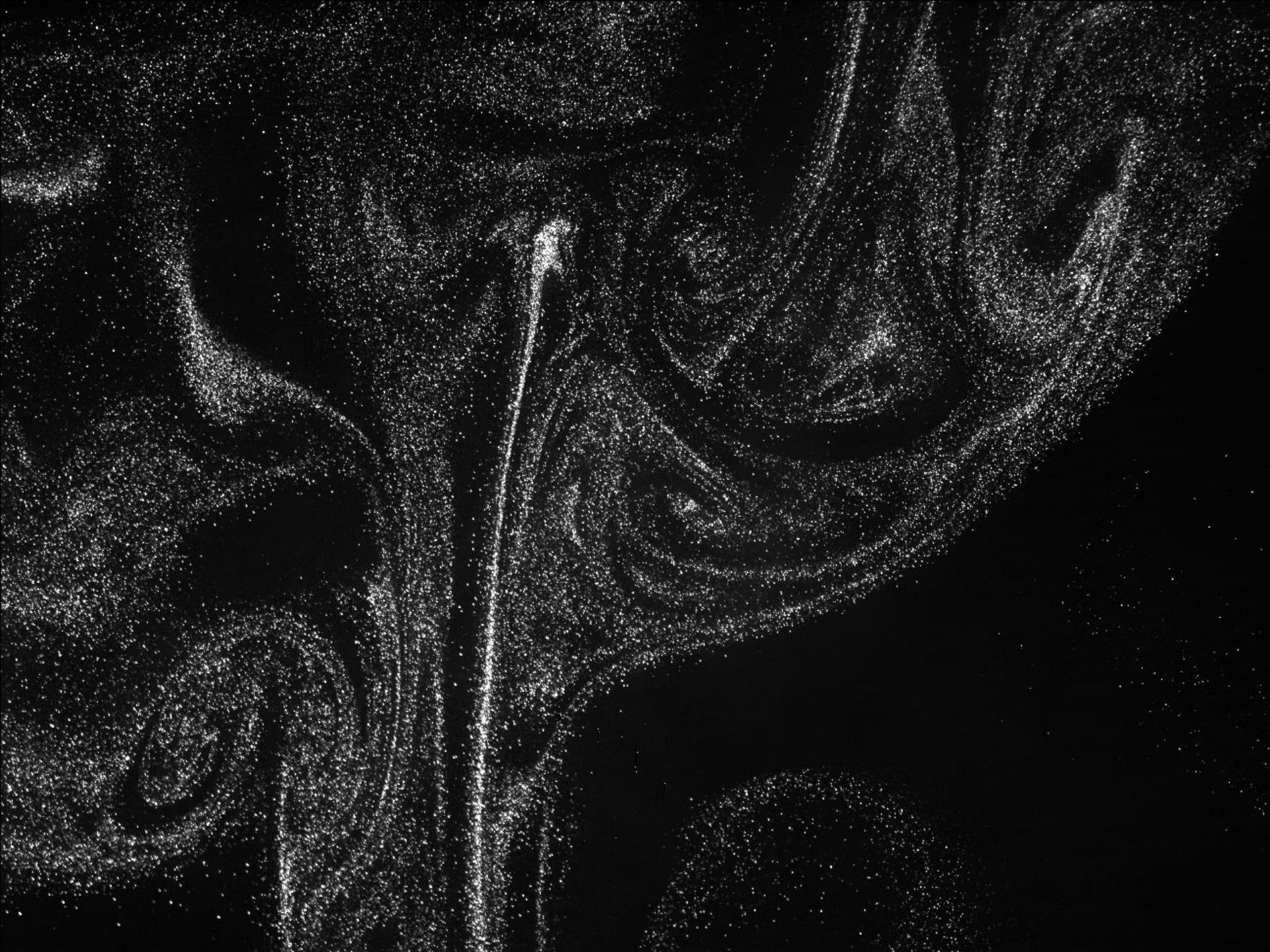
- 1) CCD camera
- 2) cloud during mixing,
- 3) double-pulse laser,
- 4) laser sheet,
- 5) cloud chamber,
- 6) small chamber with the droplet generator inside.

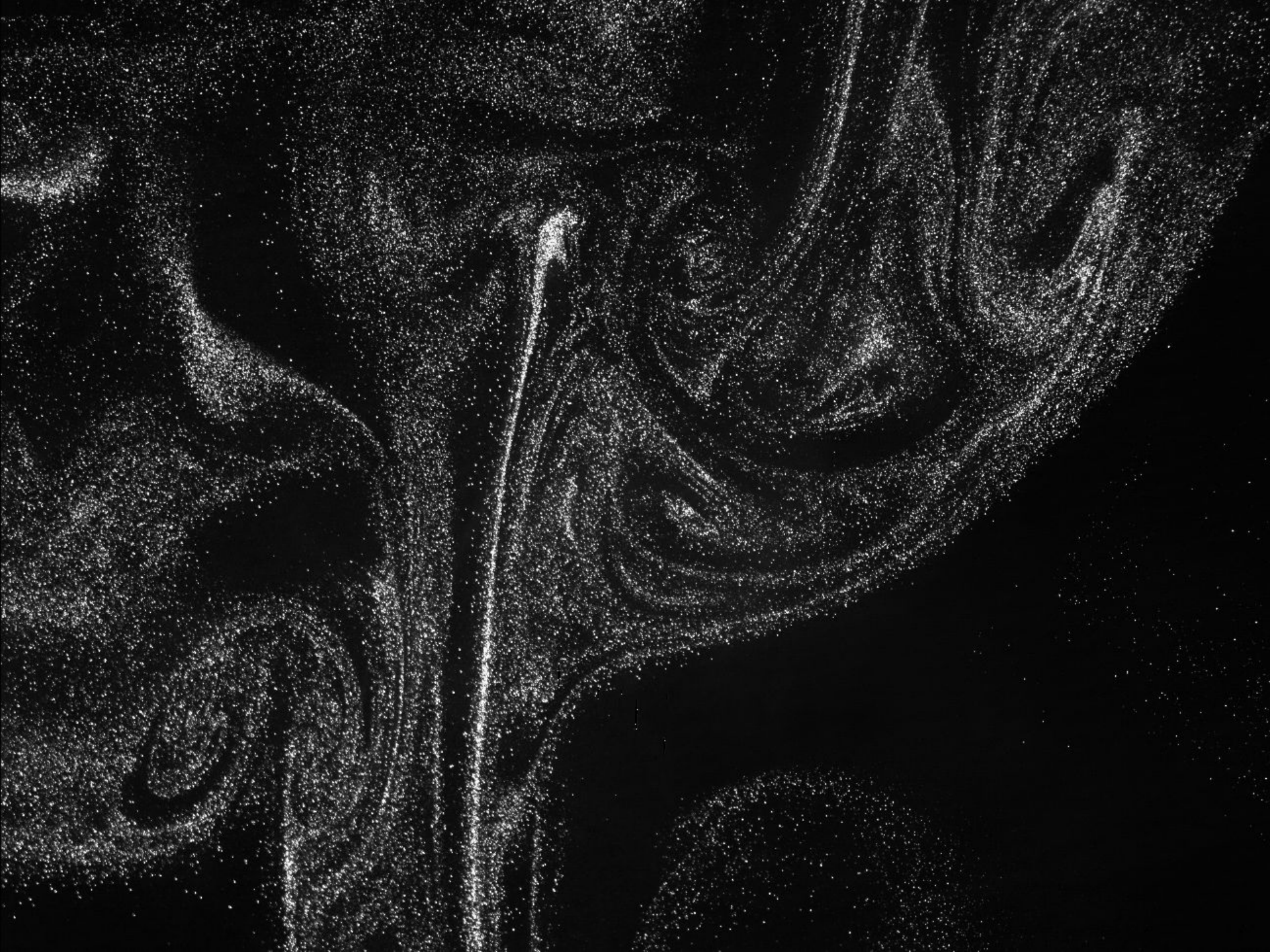


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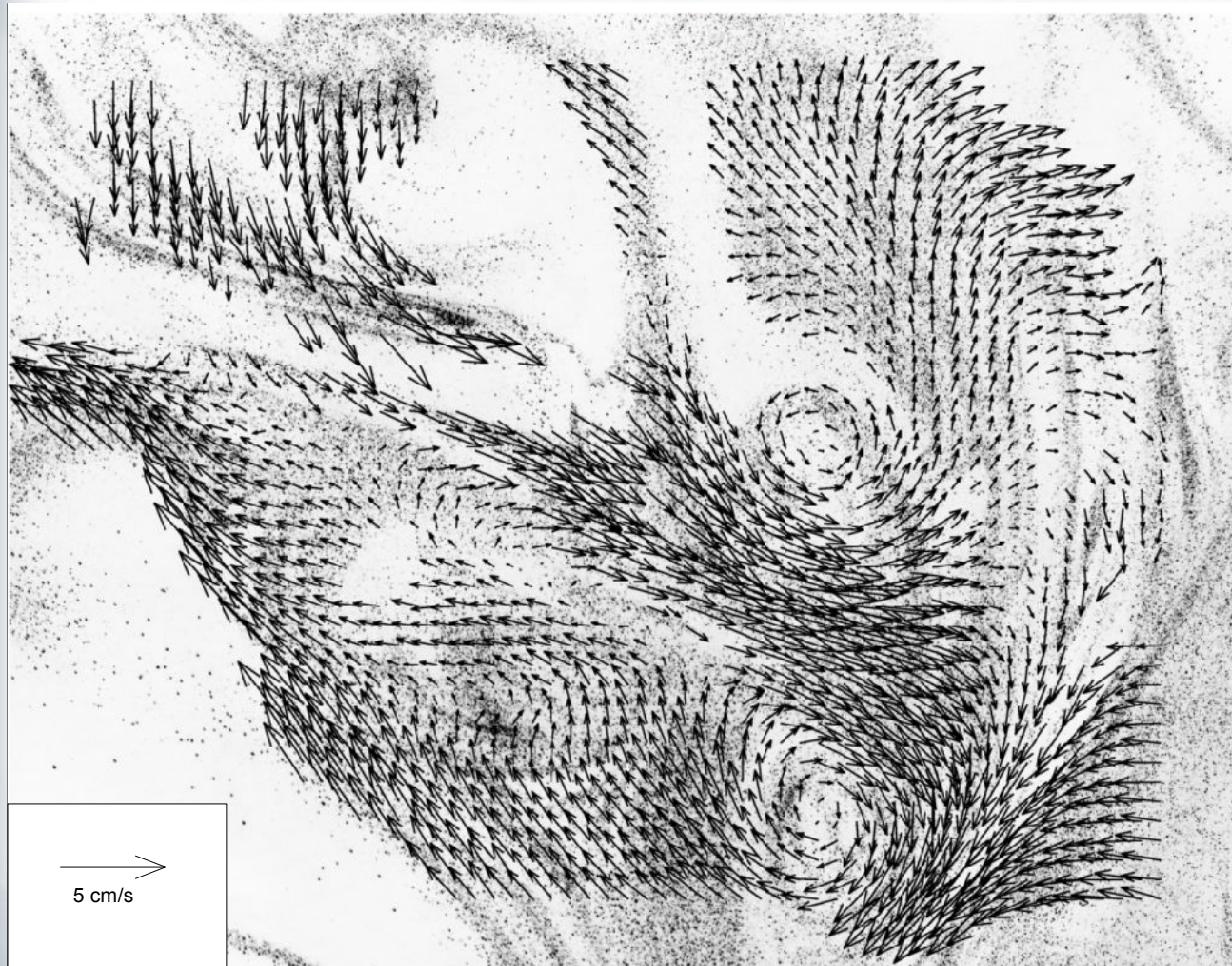




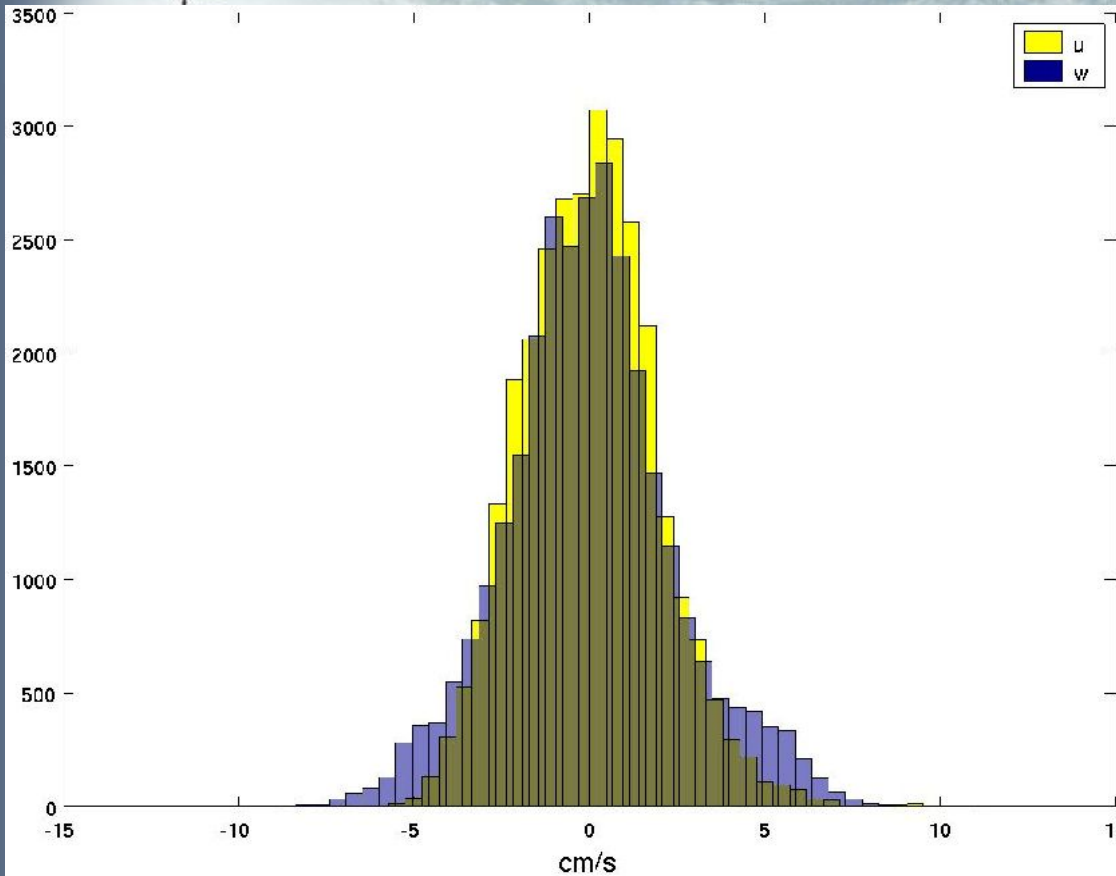


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Velocity field  
evaluated for the  
pair of cloud  
images,  
mapped on one of  
them;  
area of about 7cm  
x 4cm is shown.



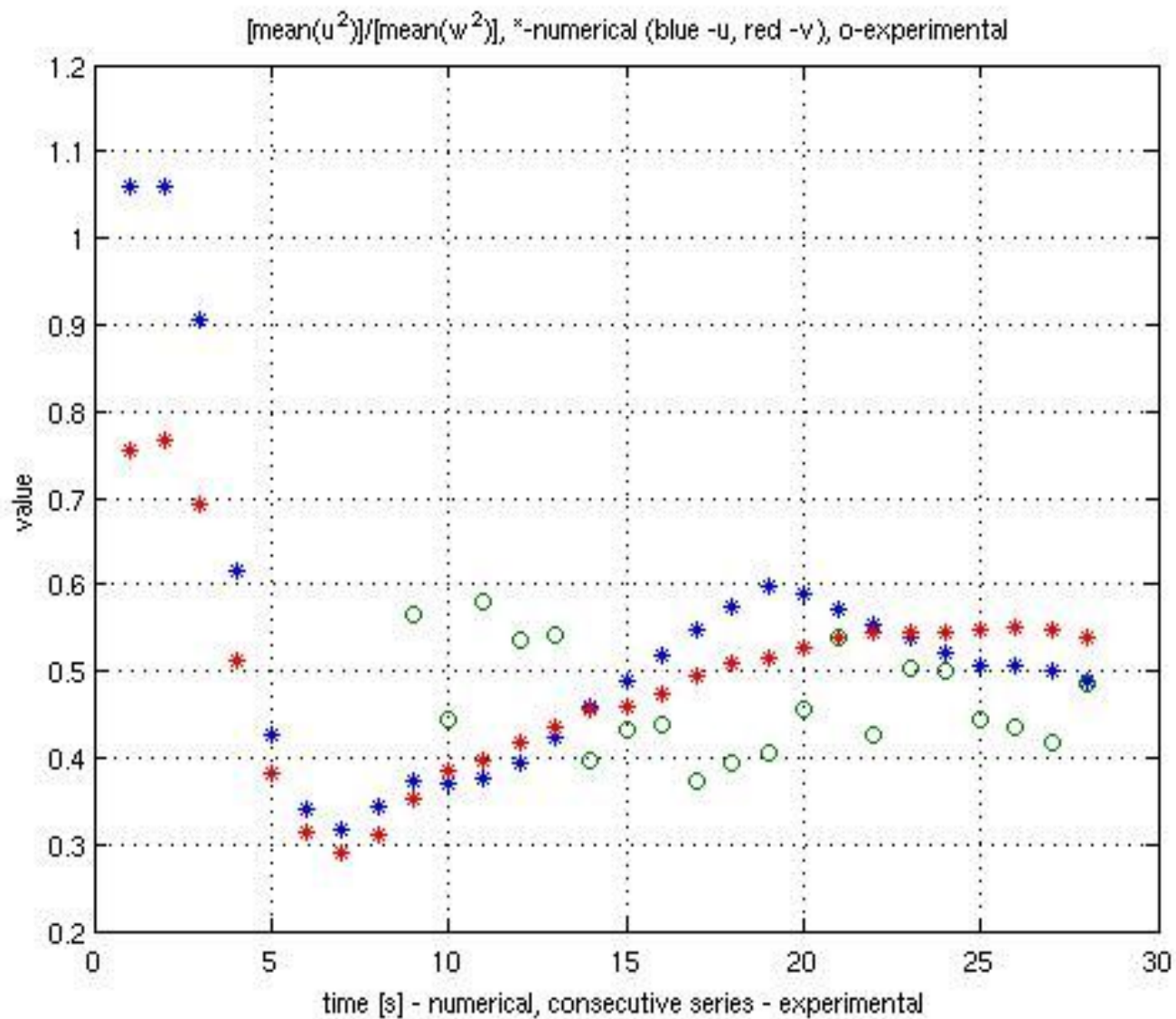
A histogram of horizontal and vertical turbulent velocities evaluated for all experimental runs

	$u'$ [ $\text{cm s}^{-1}$ ]	$w'$ [ $\text{cm s}^{-1}$ ]
Standard deviation	1.9	2,4
Skewness	0.39	0.17
Kurtosis	3.9	3.5



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- **CONCLUSIONS:**

- Mixing of cloud with clear air is a two-phase reacting flow. Influence of submerged heavy particles – cloud droplets on this flow is substantial.
- In the appropriate conditions (mixing with subsaturated air) reaction: droplet evaporation substantially influences smallest scales of turbulence.
- For moderate and small values of initial TKE this influence is substantial or even dominating.
- Sedimentation of droplets is important as a transport mechanism of liquid water from cloudy to clear air filaments for low levels of initial TKE.
- This mechanism depends strongly on the droplet spectral distribution.
- Buoyancy production in cloud-clear air mixing causes that even smallest scales of turbulence are highly anisotropic.
- It is likely, that small-scale anisotropy may also occur in mixing of volumes of slightly different density.

**This is pretty complicated!**



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