Small-scale turbulent mixing in clouds

Miroslaw Andrejczuk[1]
Wojciech W. Grabowski
Szymon Malinowski
Piotr K. Smolariewicz

[1]**Los Alamos National Laboratory, NM, USA**
[2] **NCAR, MMM, PO Box 3000, Boulder, CO 80307, U.S.A**
[3]**University of Warsaw, Institute of Geophysics, Warszawa, Poland**

Collaborators:
P. Korczyk, T.A. Kowalewski

MOTIVATION:

Clouds are turbulent. Atmosphere is turbulent. Cloud mix with the environment.

Cloud droplets are particles which may grow or evaporate, depending on humidity (sub- or supersaturation) in their closest vicinity.

Cloud droplets move with respect to air. This means that transport of liquid water differs from transport of temperature, humidity and passive scalars.

Growth/evaporation is is a phase change of water substance. Latent heat of phase change of water is substantial. It affects thermodynamics of the flow surrounding the particles.

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 .

Consider a bubble of saturated air containing droplets of dia ~10 μm, suspended in a still unsaturated environment. The typical distance between droplets in a cloud is ~ 1mm, terminal fall velocity (Stokes regime) ~ 1mm/s, and typical evaporation time of a small droplet is of the order of 1s.

Assume, that the bubble of zero buoyancy (mean density is the same as environmental) and of temperature equal to that of the environmental air. This is possible, since the density deficit due to humidity (virtual temperature effect) can be compensated by the Liquid Water Content (LWC). In terms of atmospheric thermodynamics, we state that the density temperature of the bubble is the same as the density temperature of the environment (see e.g.textbook by Emmanuel, 1994):

$$T_e\left(1 - \left(1 + \frac{R_v}{R_a}\right)x_e\right) = T_b\left(1 + \left(1 - \frac{R_v}{R_a}\right)X_b - w_b\right)$$

T denotes temperature, x is the water vapor mixing ratio (X denotes saturation), w is the liquid water mixing ratio, Rv and Rv stay for gas constants of dry air and water vapor, respectively. Index e denotes the environment, index b denotes the cloud bubble.
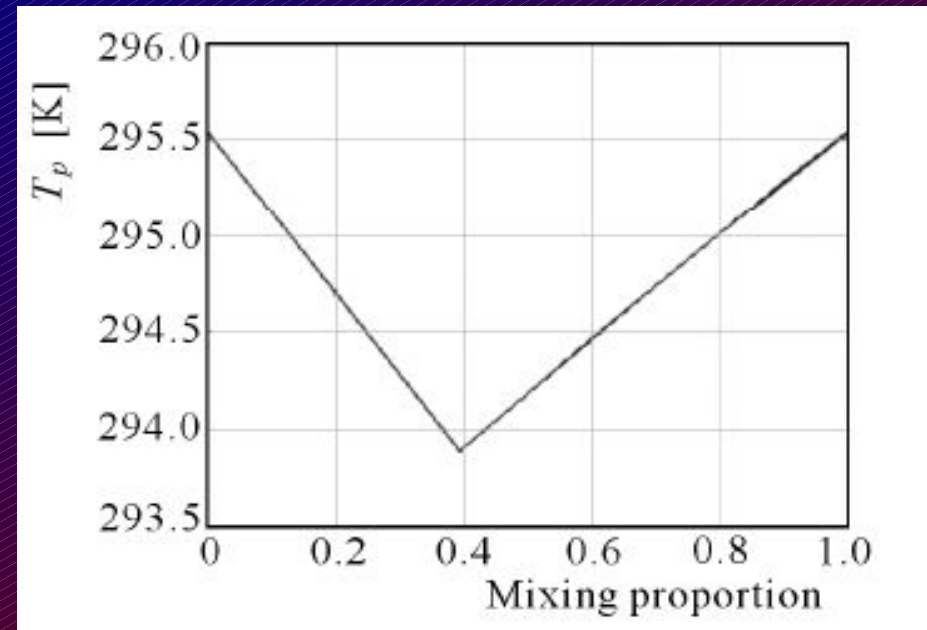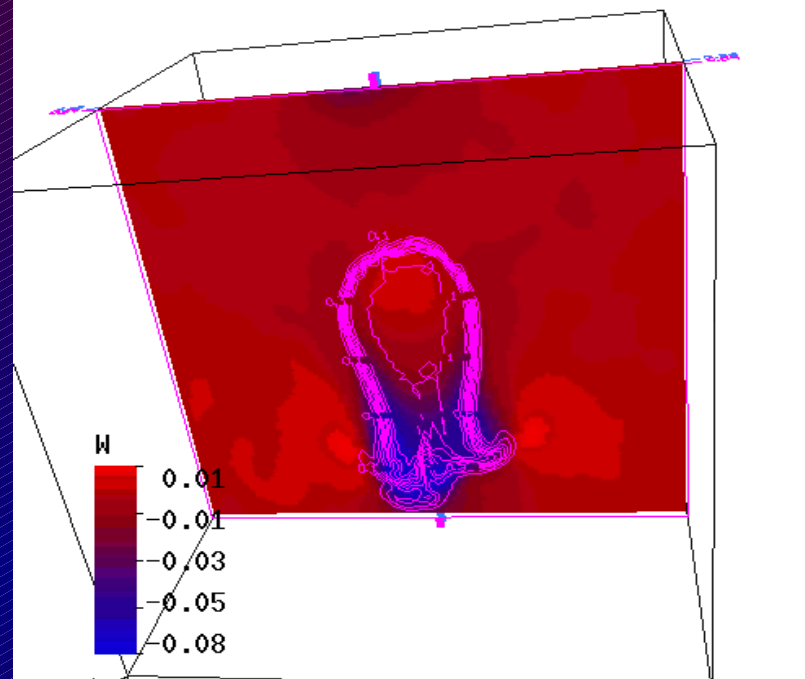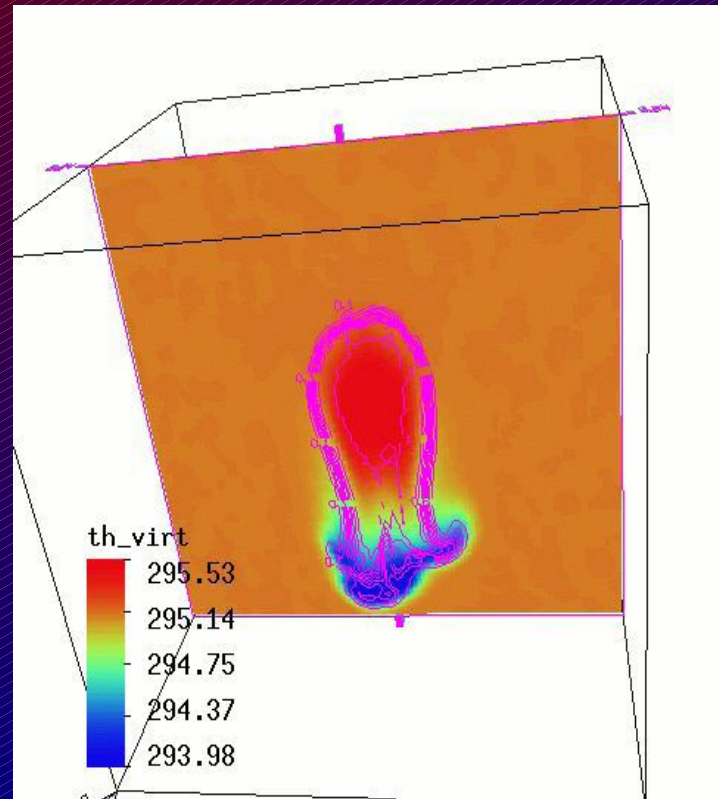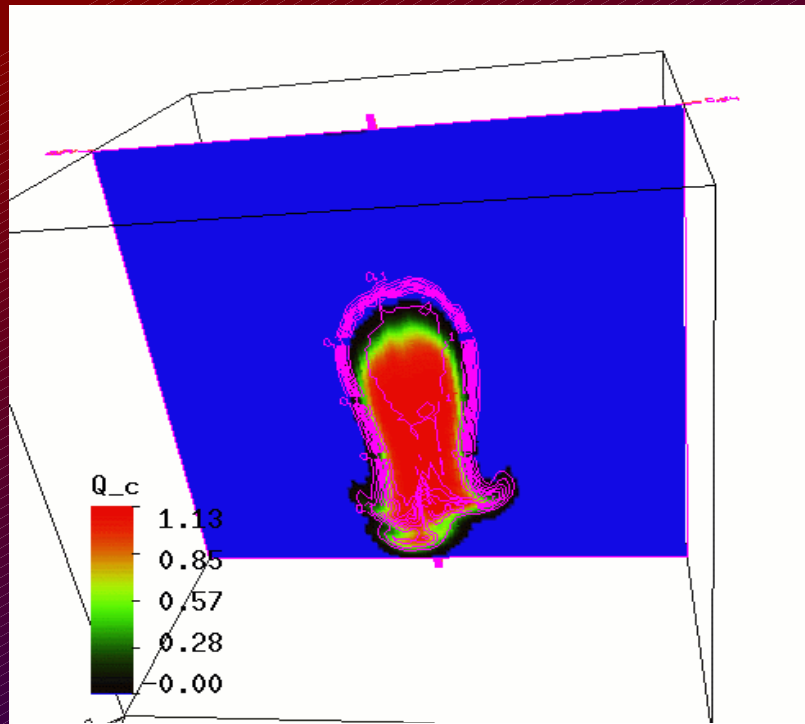
Such a bubble in 1x1x1m volume after 13 s of simulations. Pink isolines – bubble air.

Clockwise from the upper left corner: cloud water content, density temperature, vertical velocity.

Andrejczuk et al., 2000

With EULAG we solve the following equations:

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

$$D/Dt \equiv \partial/\partial t + \mathbf{v} \cdot \boldsymbol{\nabla}$$

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

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

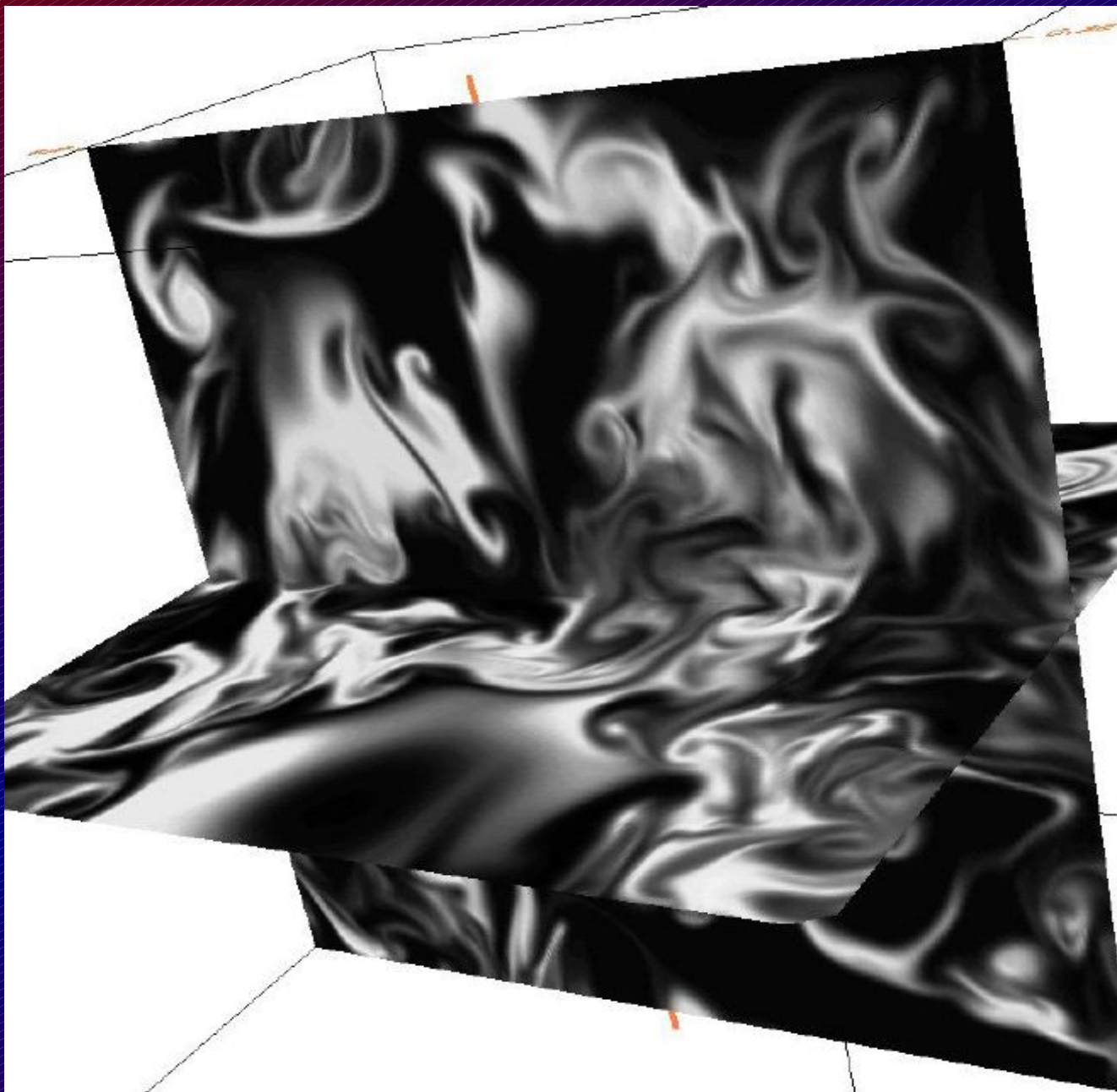$$\frac{DT}{Dt} = \frac{L}{c_p}C_d + \mu_T\nabla^2 T, \qquad (1c)$$

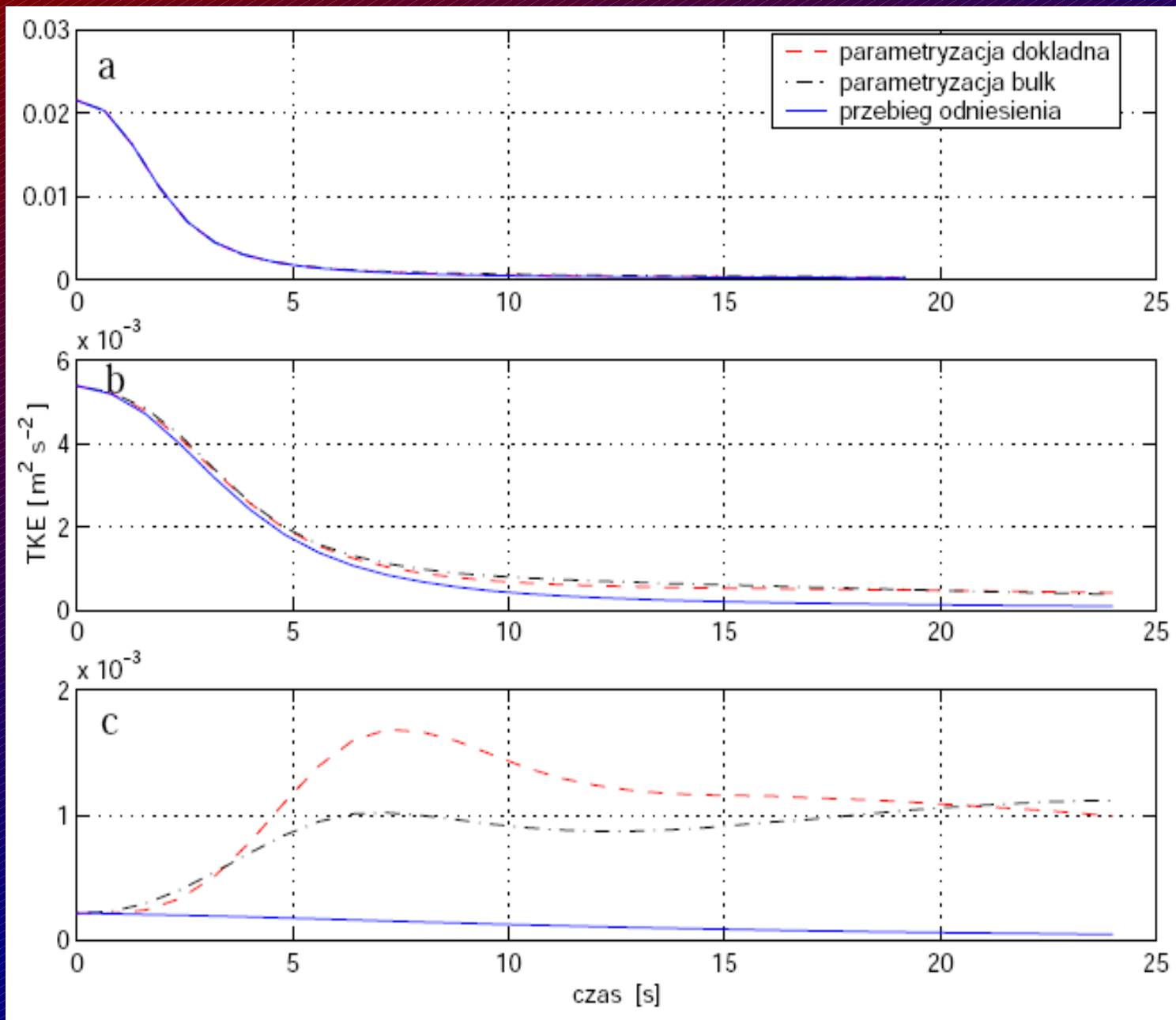$$\frac{Dq_v}{Dt} = -C_d + \mu_v\nabla^2 q_v, \qquad (1d)$$

$$\frac{Dq_c}{Dt} = C_d. \qquad C_d = \int f\frac{dm}{dt}\,dr, \qquad \frac{D^*f}{D^*t} = -\frac{\partial}{\partial r}\left(f\frac{dr}{dt}\right) + \eta,$$

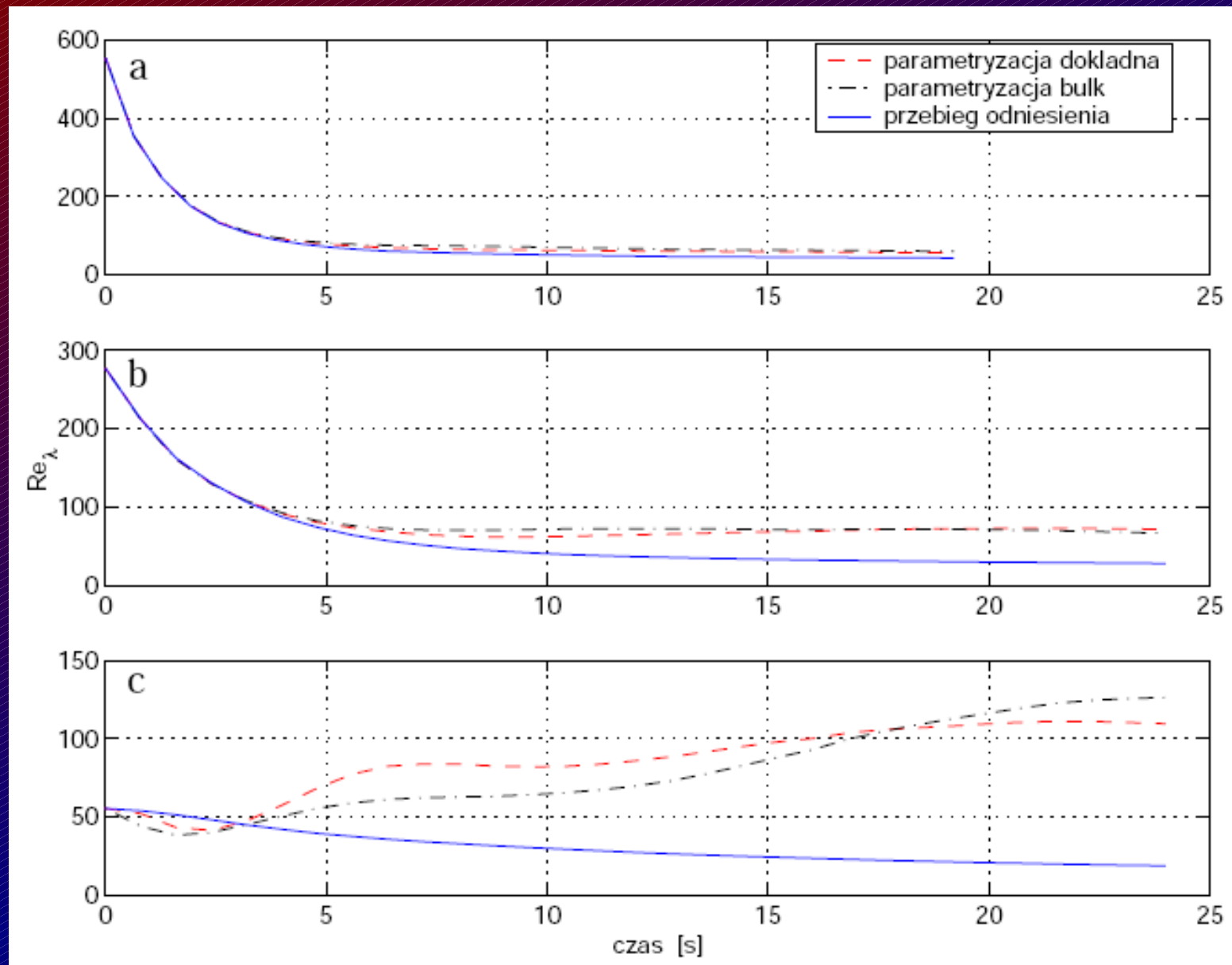$$D^*/D^*t \equiv \partial/\partial t + (\mathbf{v} - \mathbf{k}v_t) \cdot \boldsymbol{\nabla}$$

Andrejczuk et al., 2004

Cloud water
after 11s

Evolution of TKE in all simulations. (top) high-, (middle) moderate-, and (bottom) low-TKE input. Solid lines are for dry reference runs, while dashed and dashed–dotted lines are for detailed and bulk microphysics, respectively.

Evolution of Re_λ in all simulations. (top) high-, (middle) moderate-, and (bottom) low-TKE input. Solid lines are for dry reference runs, while dashed and dashed–dotted lines are for detailed and bulk microphysics, respectively.
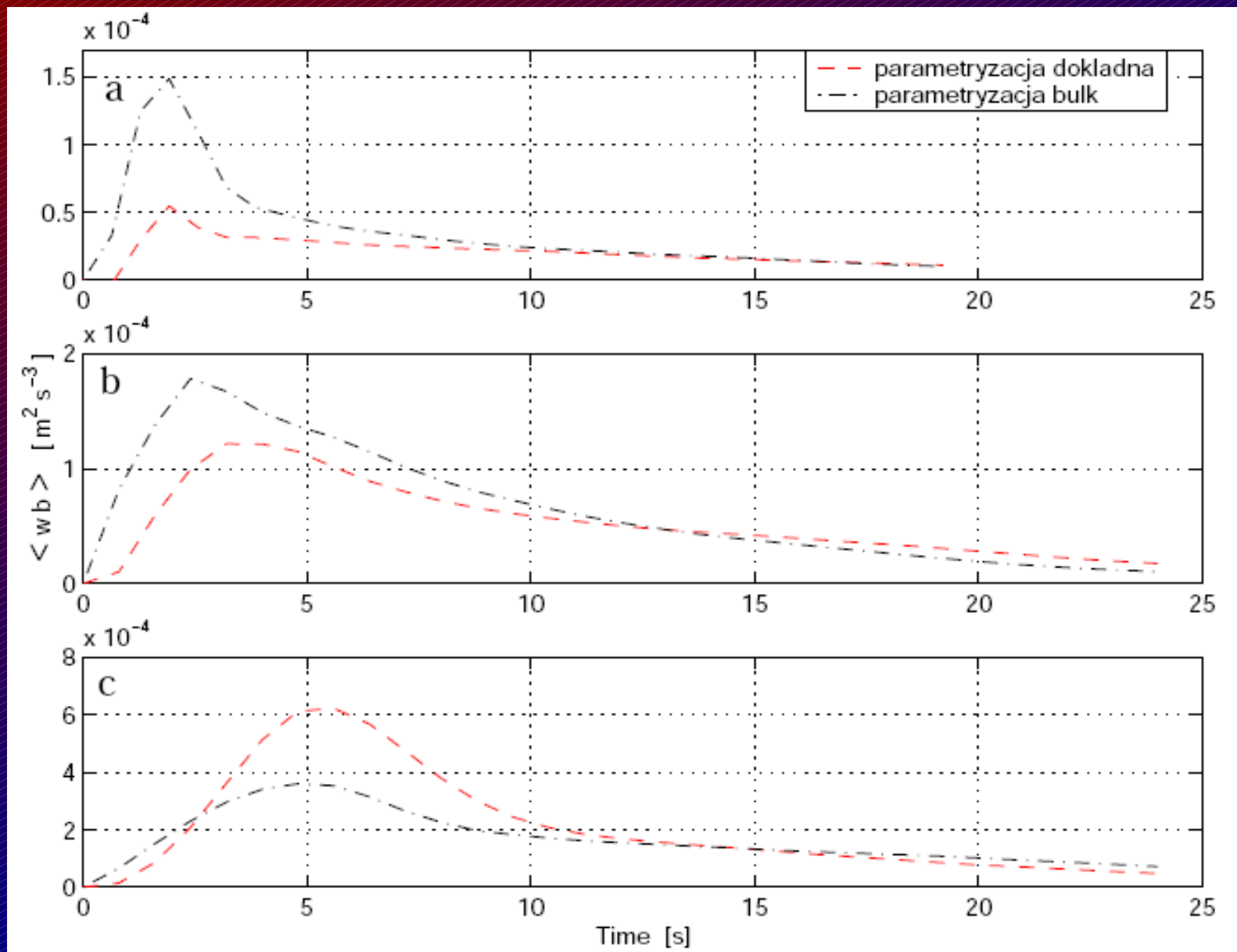
Evolution of TKE production by buoyancy forces in all simulations; (top) high-, (middle) moderate-, and (bottom) low-TKE input. Dashed and dashed–dotted lines are for detailed and bulk microphysics, respectively.
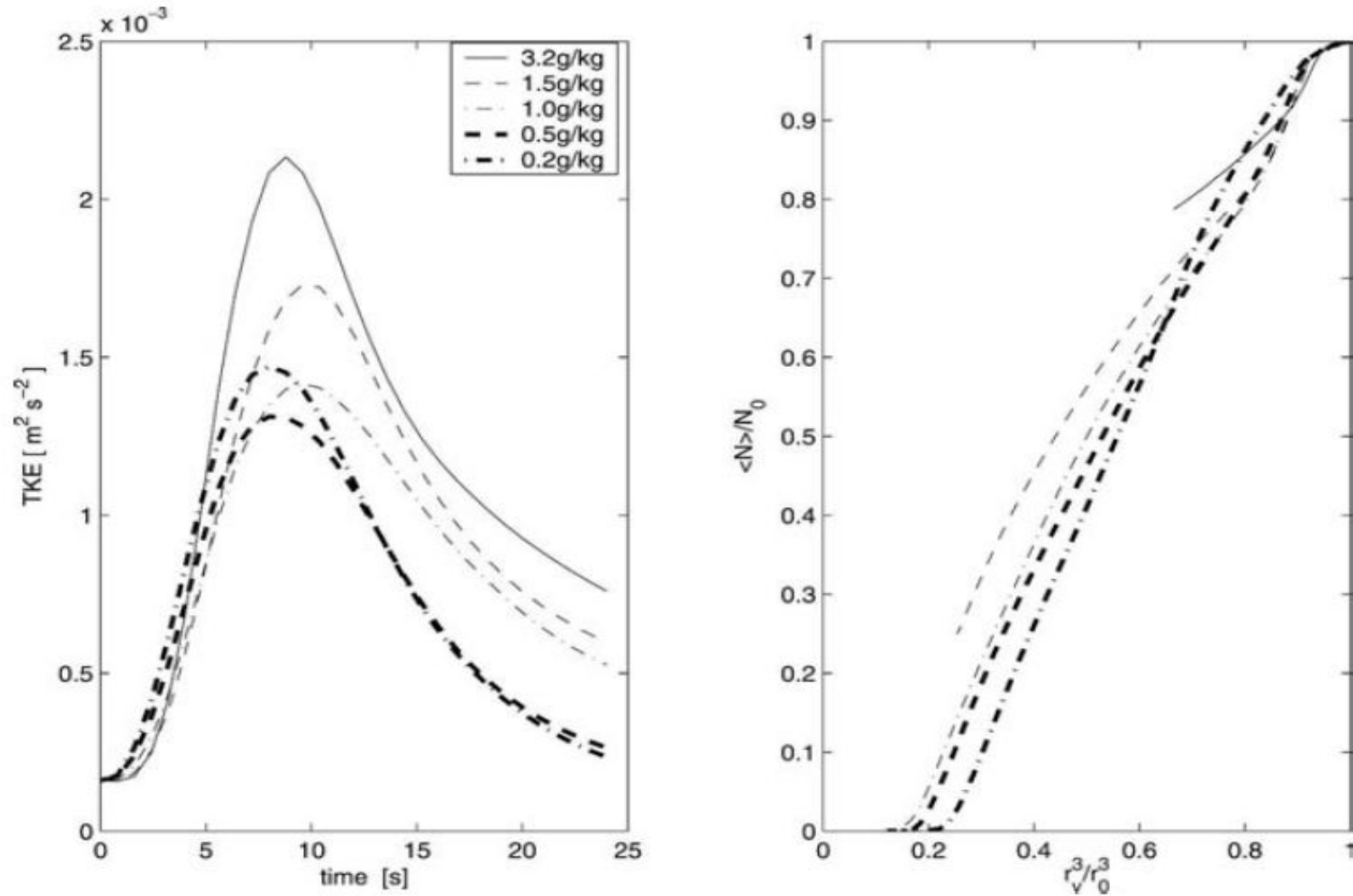
FIG. 9. Results from the set of numerical simulations with low TKE, detailed microphysics, $\chi = 0.5$, and systematically varied cloud water mixing ratio within cloudy filaments: set S3a. The evolutions of the (left) TKE and (right) $r - N$ diagram.
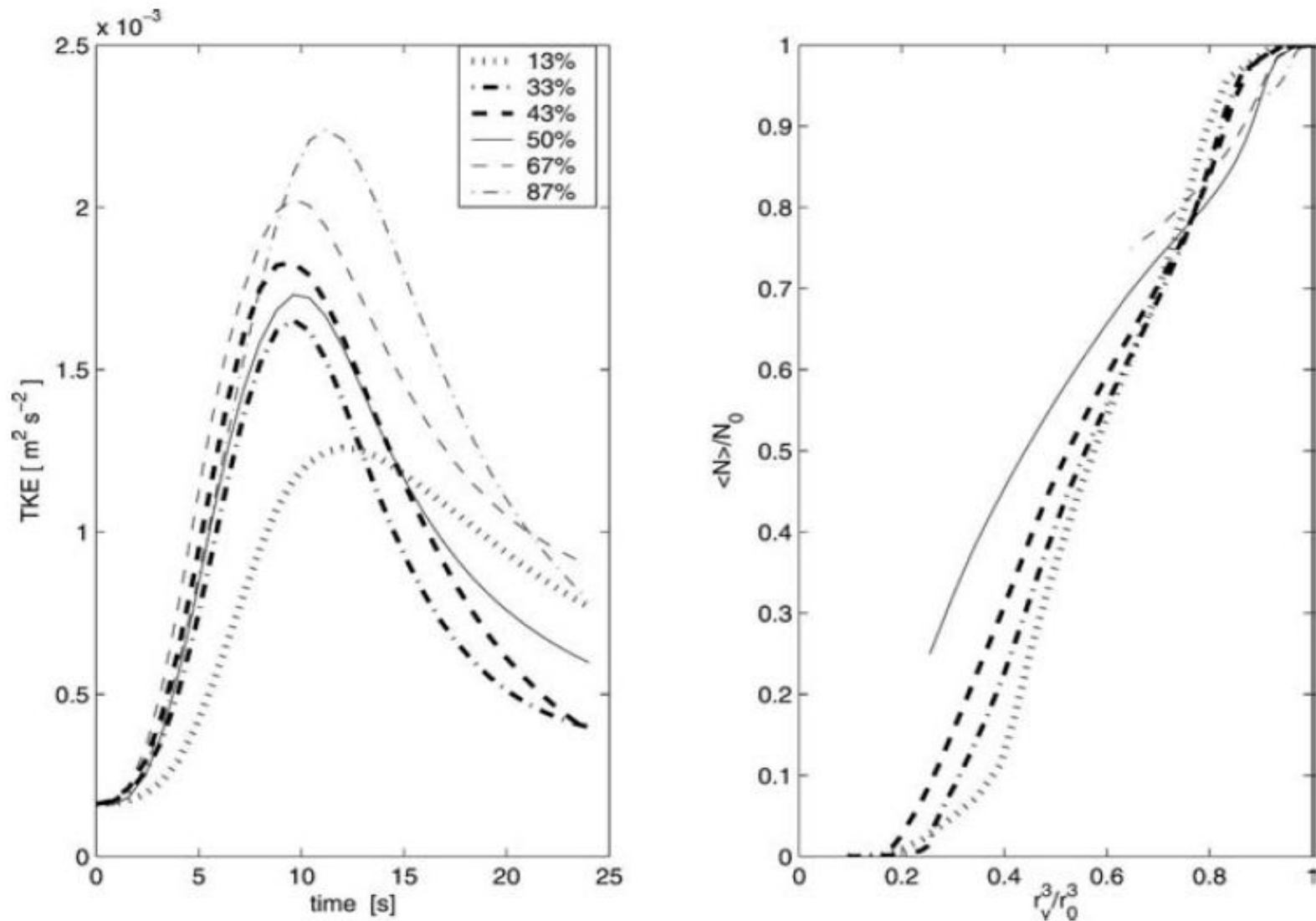
FIG. 10. Results from the set of numerical simulations with low TKE, detailed microphysics, cloud water mixing ratio within cloudy filaments of 1.5 g kg^{-1}, and systematically varied global mixing proportion $\mathcal{X}$: set S4a. The evolutions of the (left) TKE and (right) $r - N$ diagram.
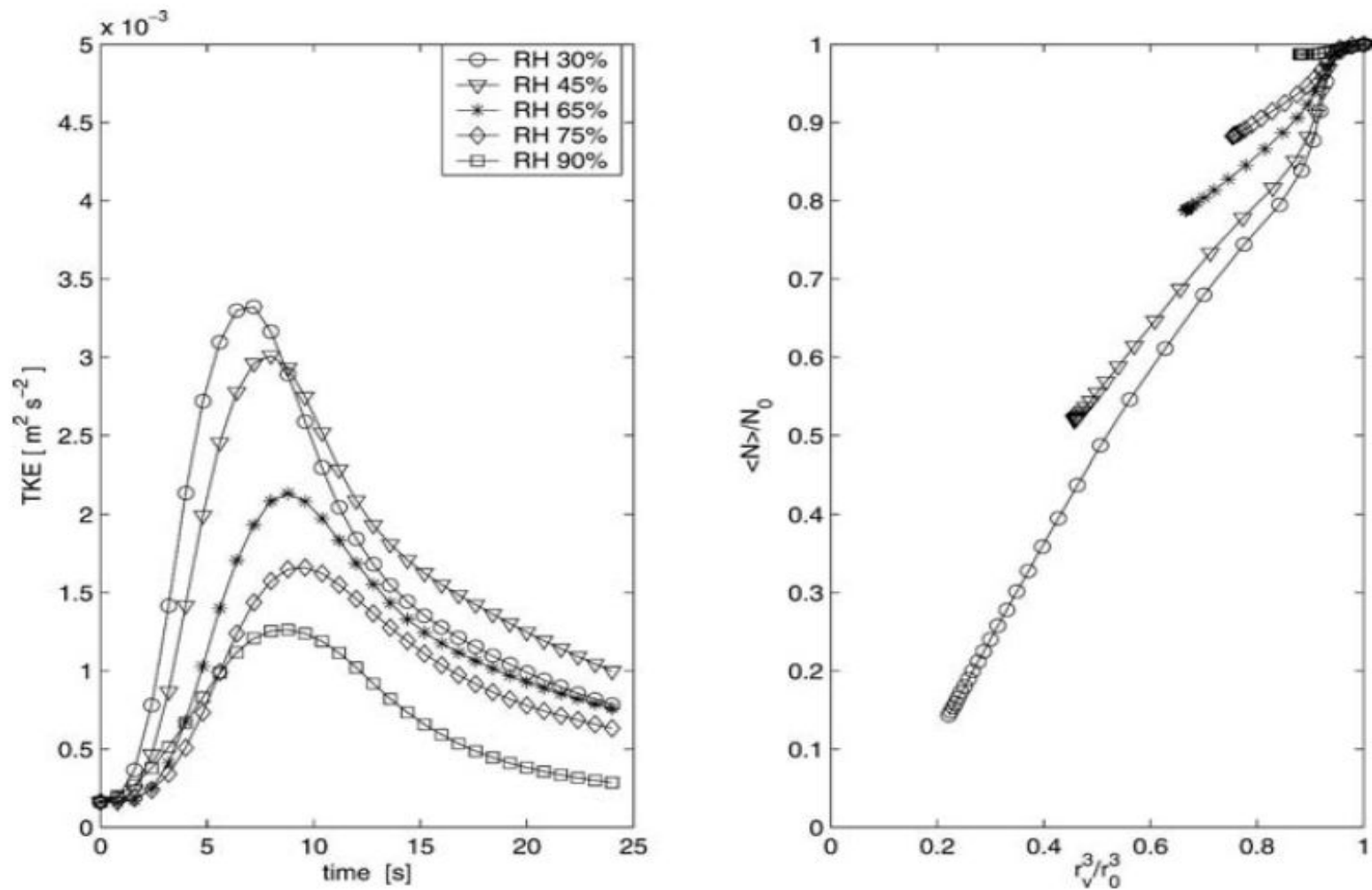
FIG. 13. Results from the set of numerical simulations with low TKE, detailed microphysics, cloud water mixing ratio within cloudy filaments of 3.2 g kg^{-1}, $x = 0.5$, and systematically varied relative humidity within clear air filaments: set S5a. The evolutions of the (left) TKE and (right) $r - N$ diagram. The symbols along the lines are plotted every 1.6 s to demonstrate the elapsed time.
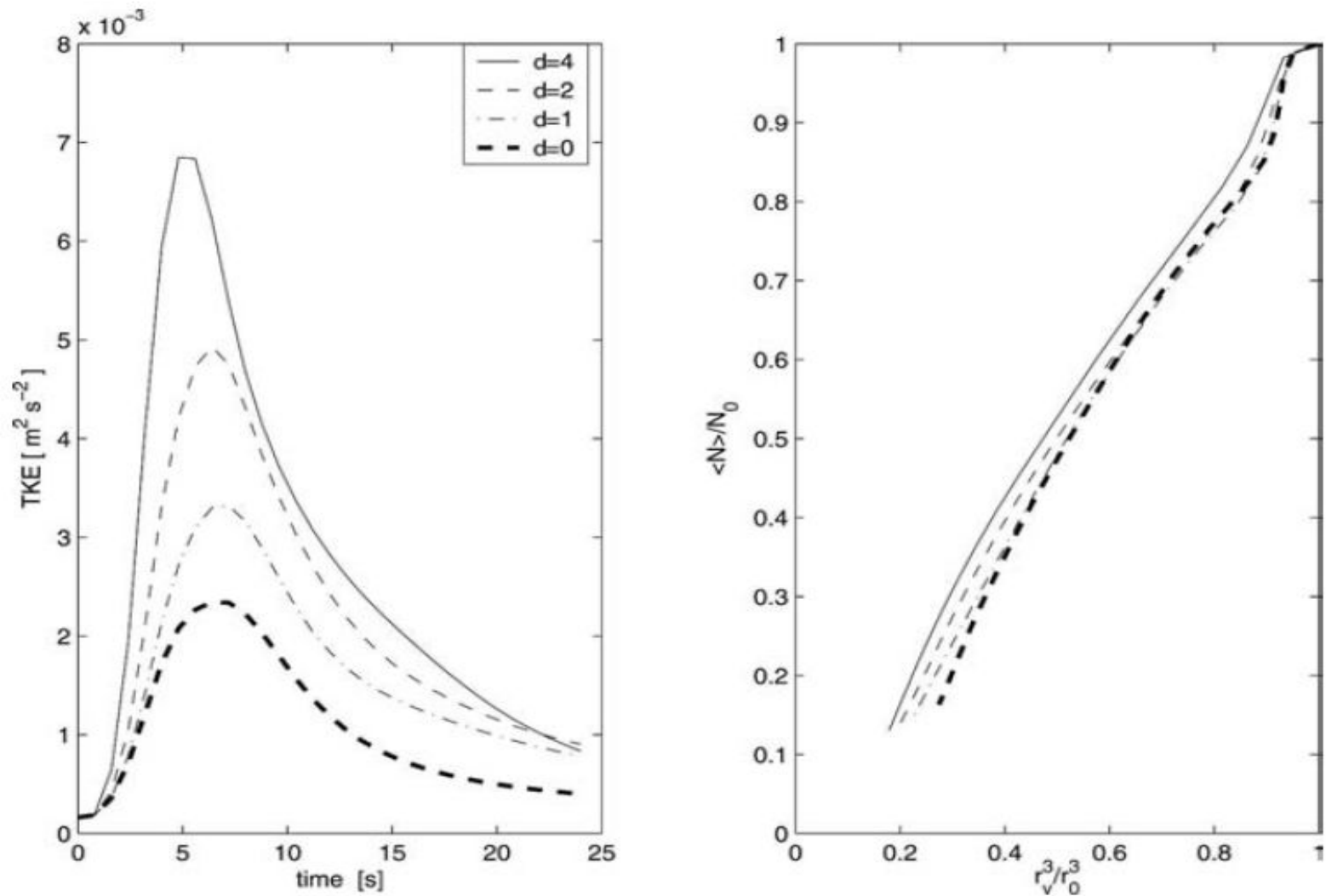
FIG. 14. Results from the set of numerical simulations with low TKE, detailed microphysics, cloud water mixing ratio within cloudy filaments of 3.2 g kg^{-1}, RH within clear air filaments of 30%, $\chi = 0.5$, and systematically varied sedimentation rate of cloud droplets: set S6a. The evolutions of the (left) TKE and (right) $r - N$ diagram.
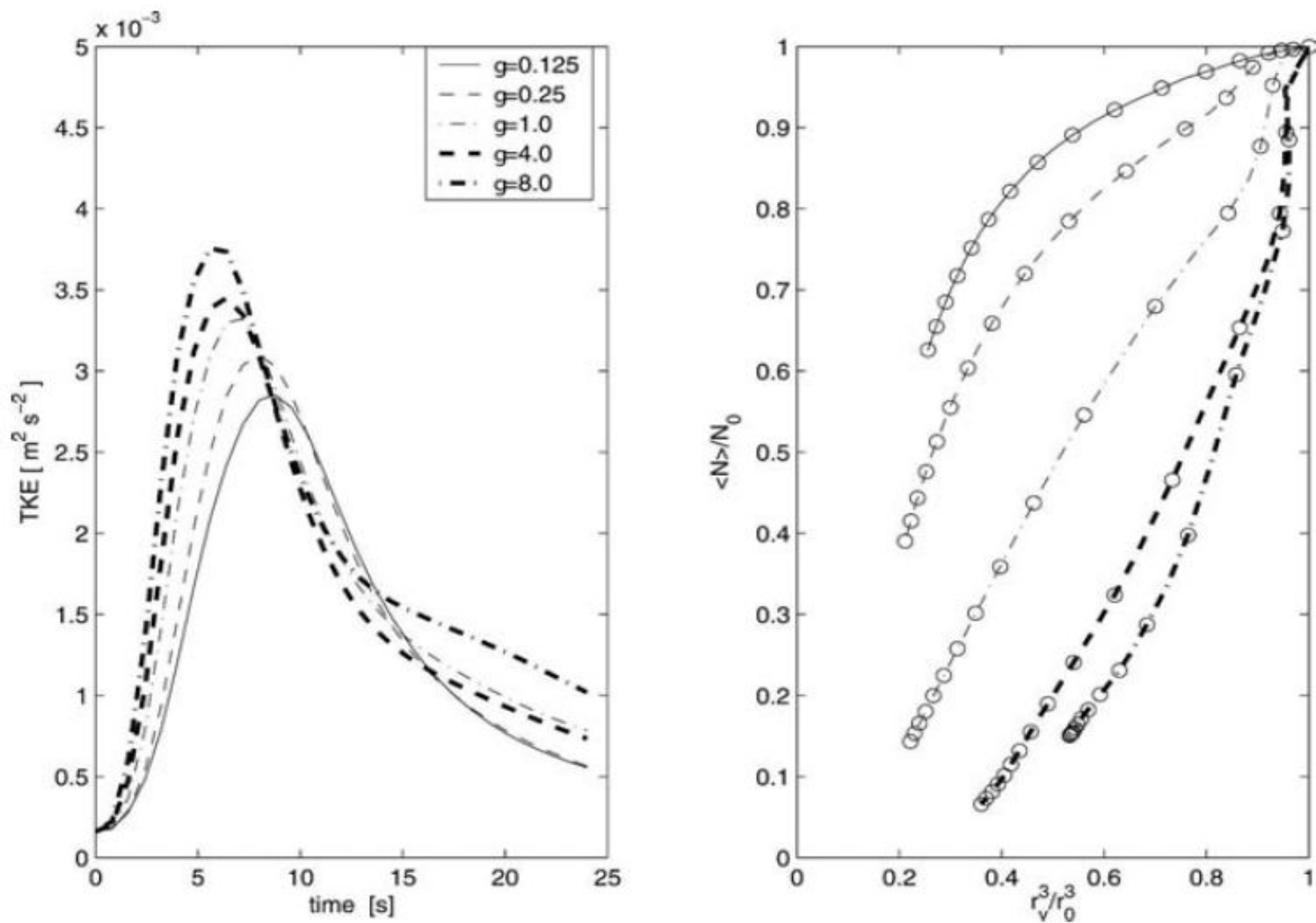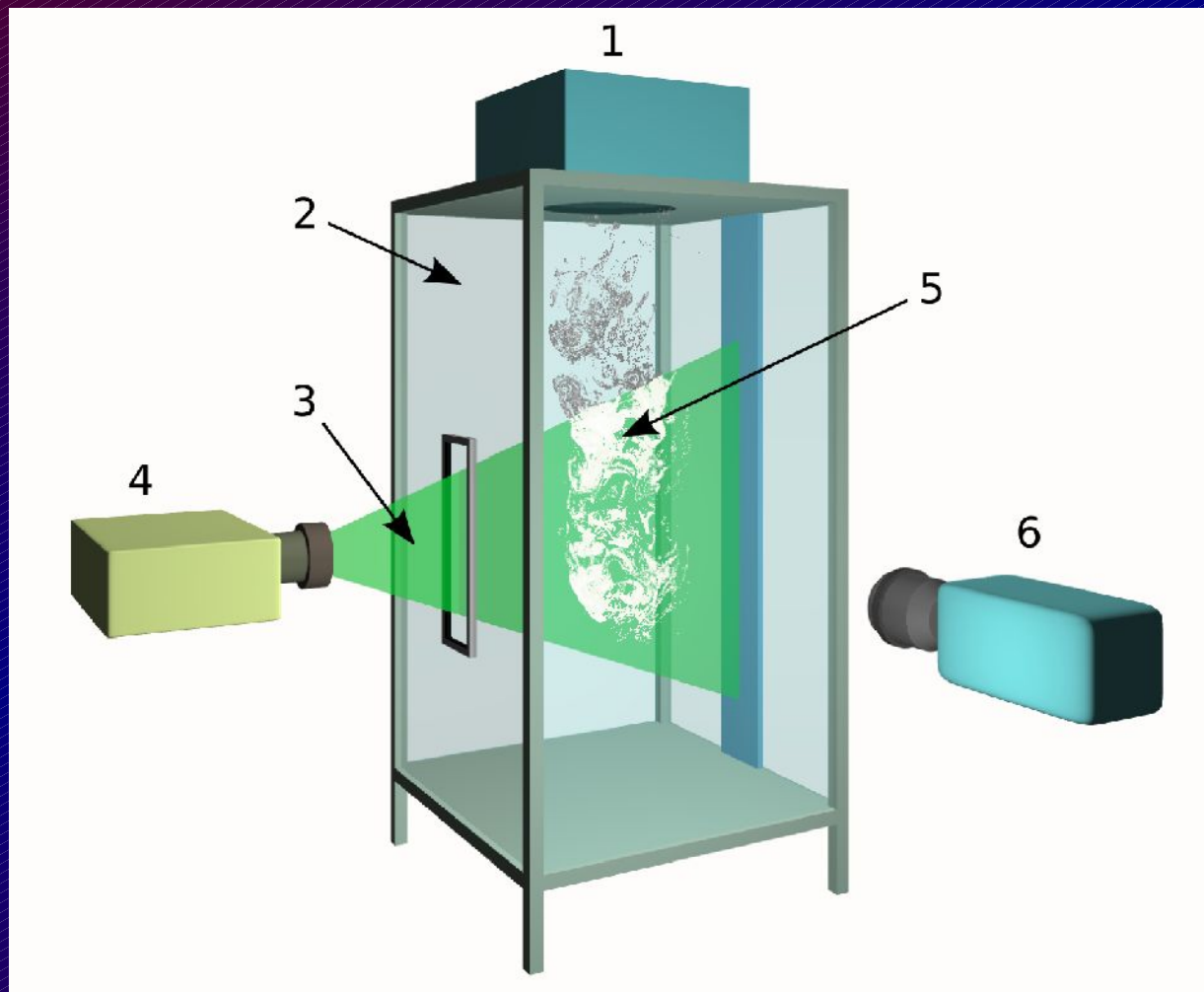
FIG. 15. As in Fig. 14 but with systematically varied evaporation rate of cloud droplets: set S6b. The circles along the lines in the $r - N$ diagram represent the elapsed time, with each circle plotted every 1.6 s.

The set-up of the experiments is designed to mimic basic aspects of small-scale turbulent mixing of a cloudy air with unsaturated environment.

Schematic view of the experimental setup.
1 – box with the droplet generator; 2-cloud chamber; 3 – light sheet; 4 – pulsed laser, 5 – cloudy plume, 6 - camera.

Korczyk et al., 2006

PIV – Particle Imaging Velocimetry

Principle:
two consecutive frames compared; displacement of patterns allows to determine two components of the velocity.

Special algorithm:
➤iterative (with the increasing resolution) correlation of patterns;
➤mean motion removal;
➤iterative deformation of patterns;
➤median filtering.
Result:
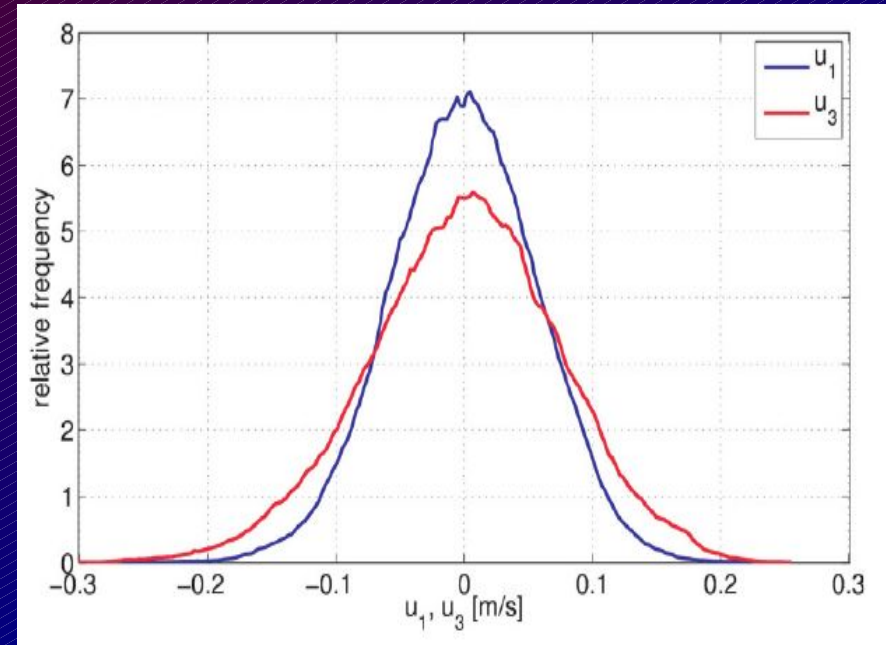benchmark scenes show the average accuracy of the displacement detection =0.3 pixel size.
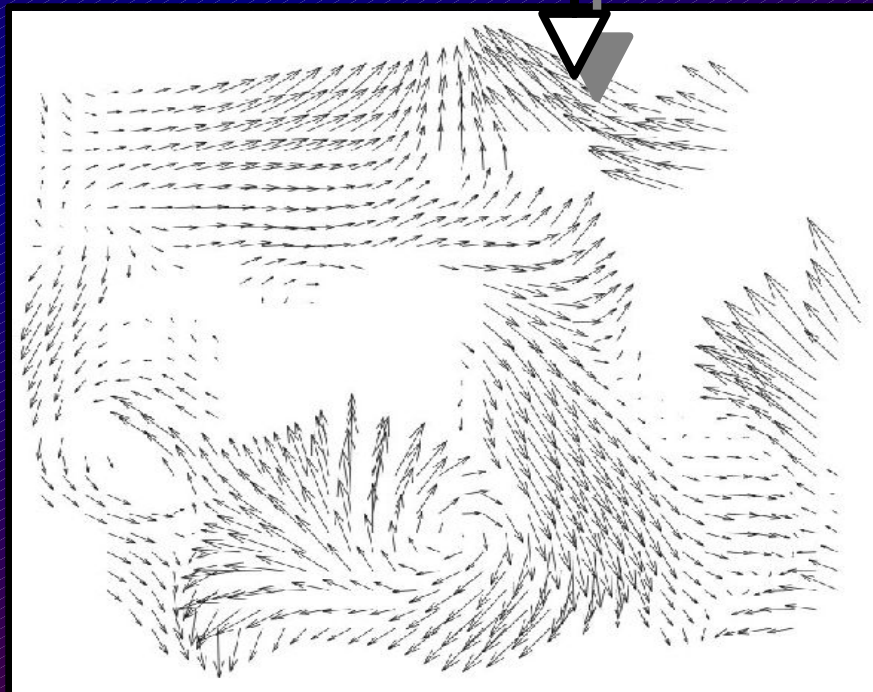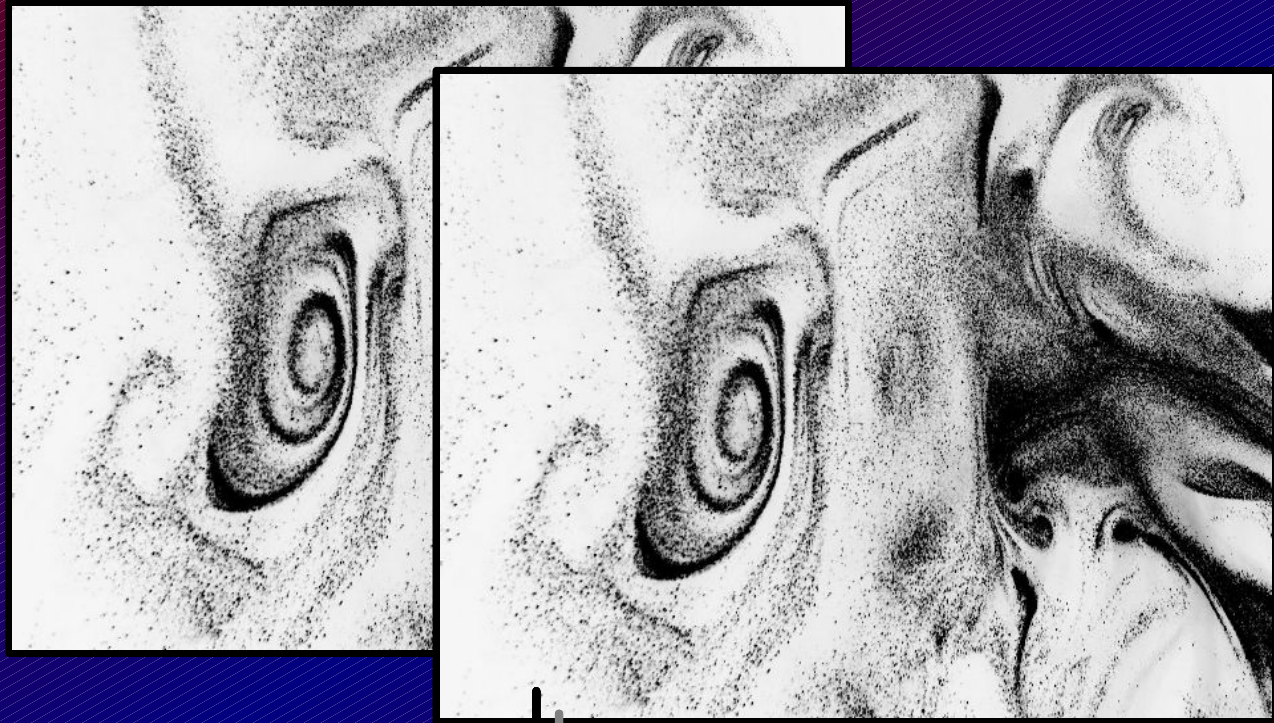
Korczyk 2008, PhD thesis

Experimental - average for 20 different runs:

	Std dev. (cm s^{-1})	Skewness	Kurtosis
u_1	**5.4**	−0.01	3.2
u_3	**8.0**	−0.2	3.1

$$(u_1)^2 / (u_3)^2 = 0.46 \pm 0.07$$

Malinowski et al., 2008

Numerical (LWC 3.2 g/kg):

	Std dev. (cm s^{-1})	Skewness	Kurtosis
u_1	**3,19**	0.01	3.3
u_2	**3,23**	−0.03	3.2
u_3	**4,69**	0.13	2.9

$$(u_{hor})^2 / (u_3)^2 = 0.52 \pm 0.07$$
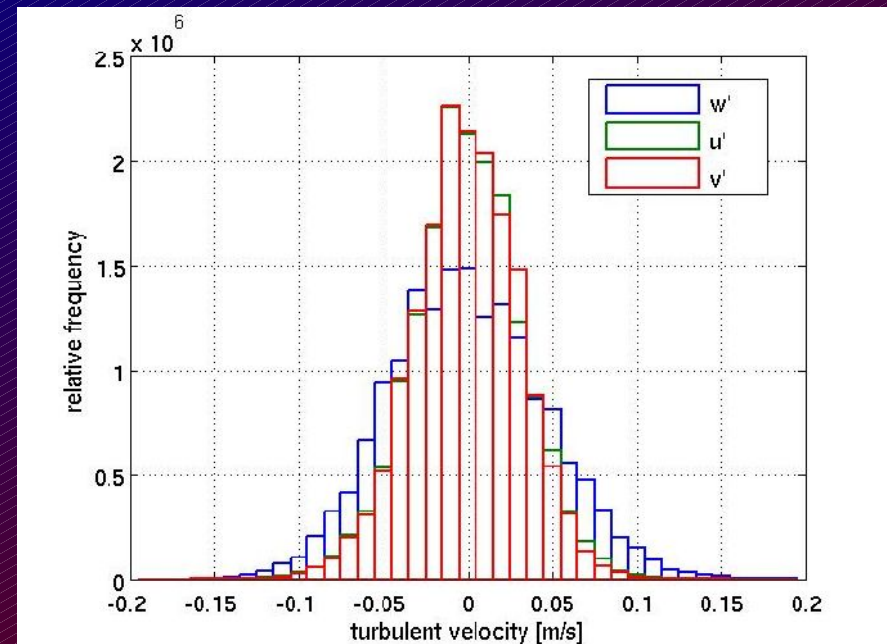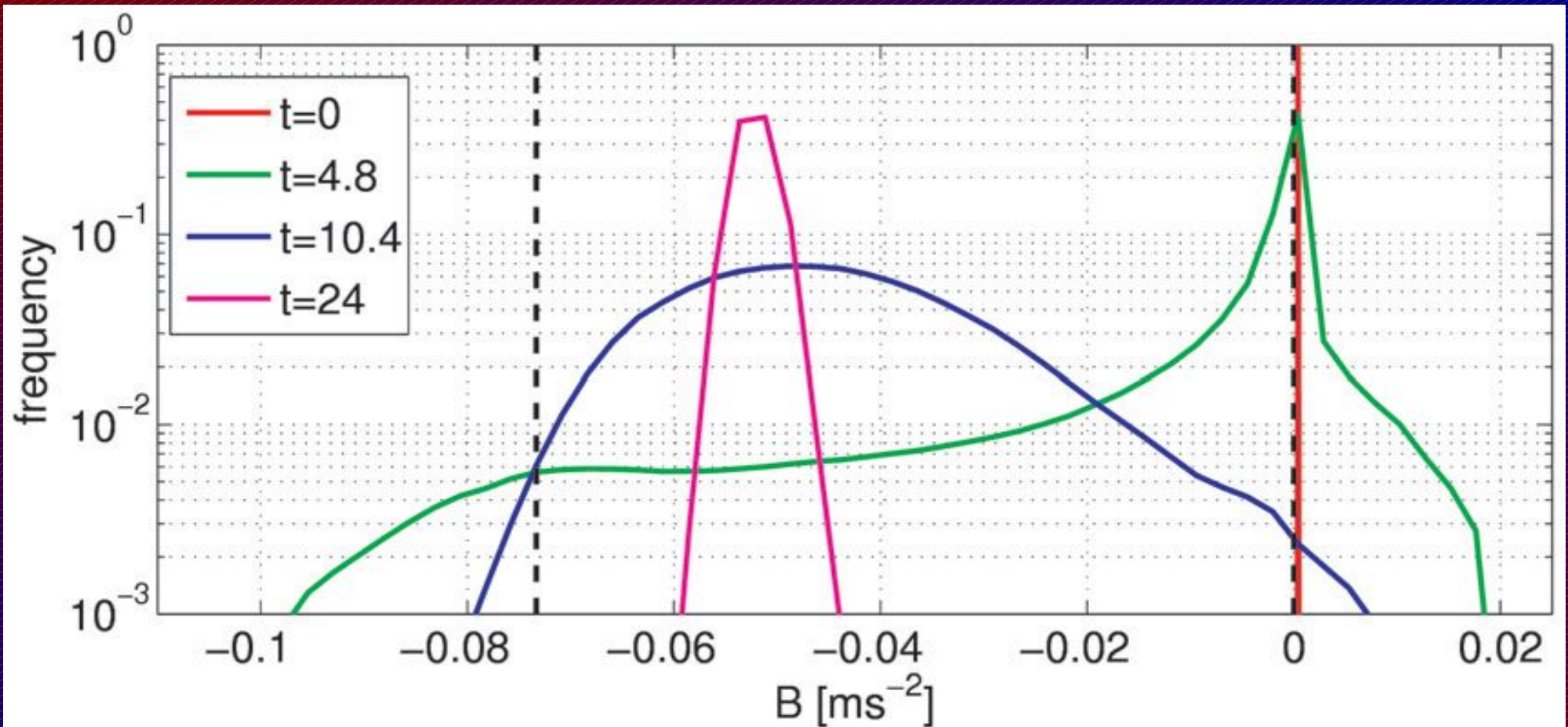
Histograms of buoyancy within the model domain at the beginning of calculations and at times of 4.8, 10.4 s and at the end of calculations (24 s). Dashed black lines show the range of buoyancy fluctuations due to isobaric and adiabatic mixing.
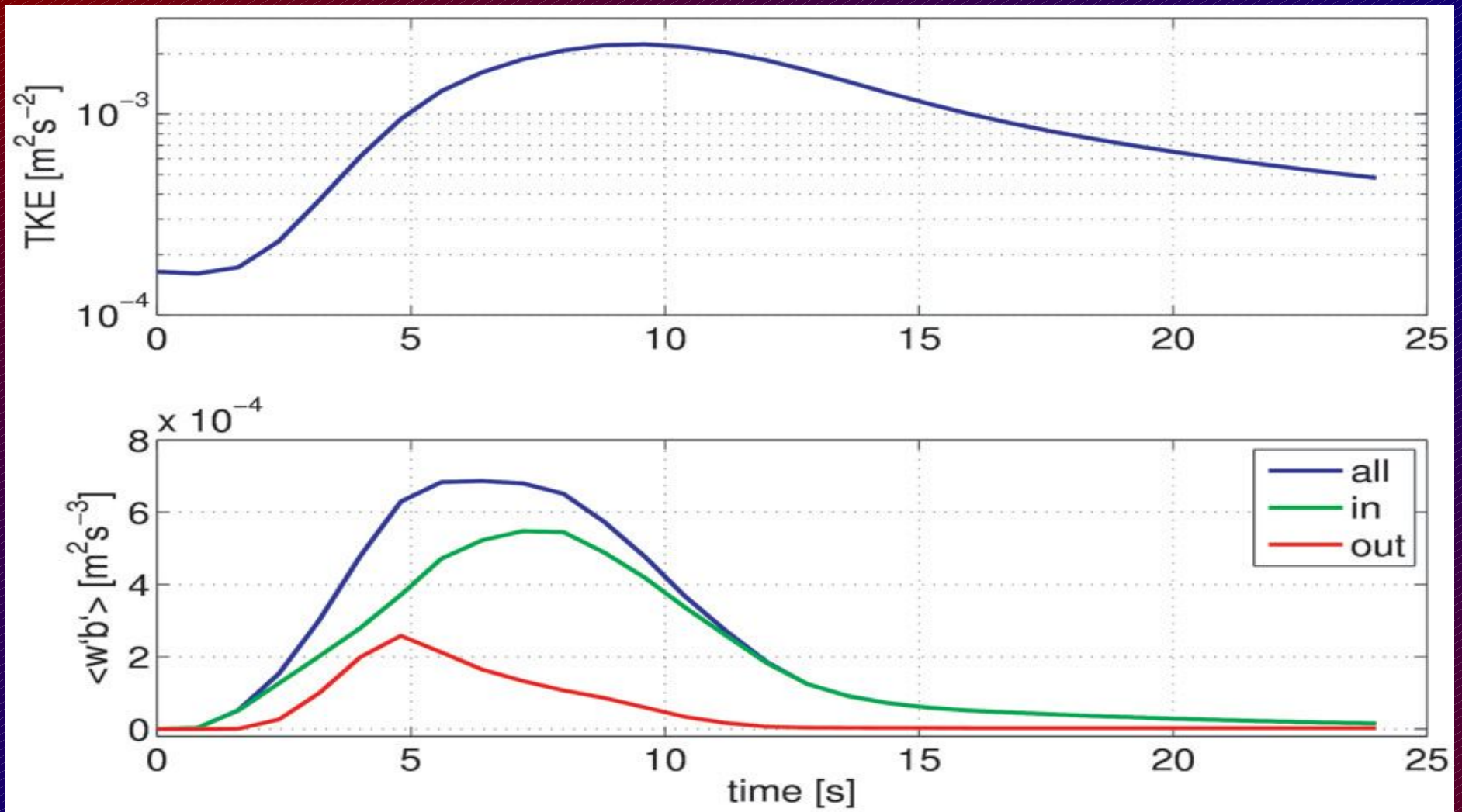
Evolution of the volume-averaged TKE (upper panel) and its buoyant production (lower panel, blue line); contributions to the buoyant production by buoyancy fluctuations within and outside the limits resulting from isobaric and adiabatic mixing are shown in green and red lines, respectively.

SUMMARY

Mixing of cloud with clear air is a two-phase reacting flow. Influence of submerged heavy particles (cloud droplets) on this flow is important.

In the analyzed scales kinetic energy of microscale motions comes not only from the classical downscale energy cascade, but it is also generated internally due to the evaporation of cloud droplets.

For low TKE mixing and homogenization are dominated by the TKE generated as a result of evaporation of cloud water.

Sedimentation of droplets is important as a transport mechanism of liquid water from cloudy to clear air filaments for low levels of initial TKE.

Enstrophy production by microscale buoyancy fluctuations is substantial, and results in anisotropy of small-scale turbulence.

Temperature measurements in clouds indicate filaments due to cloud-clear air turbulent mixing. Turbulence in clouds is very intermittent.

References:

Andrejczuk, M., W.W. Grabowski, S.P. Malinowski and P.K. Smolarkiewicz, **2000**: *Numerical Investigation of turbulent mixing of clouds with clear air in small scales: interactions of turbulence and microphysics.* Proceedings of 13th Conference on Clouds and Precipitation, IAMAP, Reno, Nevada, USA, 14-18 August 2000, 152-154.

Andrejczuk, M., W.W. Grabowski, S.P. Malinowski and P.K. Smolarkiewicz, **2004**: Numerical Simulation of Cloud-Clear Air Interfacial Mixing, *J. Atmos. Sci.,***61**, 1726–1739; DOI: 10.1175/1520-0469(2004)061<1726:NSOCAI>2.0.CO;2

Andrejczuk, M., W.W. Grabowski, S.P. Malinowski and P.K. Smolarkiewicz, **2006**: Numerical simulation of cloud-clear air interfacial mixing: effects on cloud microphysics. *J. Atmos. Sci.,* **63,** *3204–3225; doi: 10.1175/JAS3813.1*

Korczyk, P. M., S.P. Malinowski and T. A. Kowalewski, **2006**: Mixing of cloud and clear air in centimeter scales observed in laboratory by means of particle image velocimetry, *Atmos. Res.,* **82***,* 173-182; *doi:10.1016/j.atmosres.2005.09.009*

Korczyk P.M.*,* **2008:** *Effect of cloud water on small-scale turbulence—laboratory model.* PhD dissertation, Institute of Fundamental Technological Research, Polish Academy of Sciences (in Polish)

Malinowski, S.P., **2007:** *Turbulent mixing of a cloud with the environment: two-phase evaporating flow. Numerical simulations, laboratory experiments and field measurements.* J. Theor. and Appl. Mech., **45,** 587-601.

Malinowski, S.P., M Andrejczuk, Wojciech Grabowski, P Korczyk, T.A Kowalewski and P K Smolarkiewicz, **2008:** *Laboratory and modeling studies of cloud-clear air interfacial mixing: anisotropy of small-scale turbulence due to evaporative cooling,* New Journal of Physics, **10, 7** doi: 10.1088/1367-2630/10/7/075020.