

Czy możemy zrozumieć chmury nie rozumiejąc turbulencji?

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KMMF, 12.04.2012i



Turbulence: what is it ?

turbulence —

1. **Irregular fluctuations occurring in fluid motions.** It is characteristic of turbulence that the fluctuations occur in all three velocity components and are unpredictable in detail; however, statistically distinct properties of the turbulence can be identified and profitably analyzed. Turbulence exhibits a broad range of spatial and temporal scales resulting in efficient mixing of fluid properties.

2. **Random and continuously changing air motions that are superposed on the mean motion of the air.**

Glossary of Meteorology, American Meteorological Society

turbulence — In fluid mechanics, **a flow condition** (see turbulent flow) **in which local speed and pressure change unpredictably as an average flow is maintained.**

atmospheric turbulence — **small-scale, irregular air motions characterized by winds that vary in speed and direction.** Turbulence is important because it mixes and churns the atmosphere and causes water vapour, smoke, and other substances, as well as energy, to become distributed both vertically and horizontally.

Cloud: what is it?

Cloud – A visible aggregate of minute water droplets and/or ice particles in the atmosphere above the earth's surface

Glossary of Meteorology, American Meteorological Society

Cloud – any visible mass of water droplets, or ice crystals, or a mixture of both that is suspended in the air, usually at a considerable height

Britannica Online

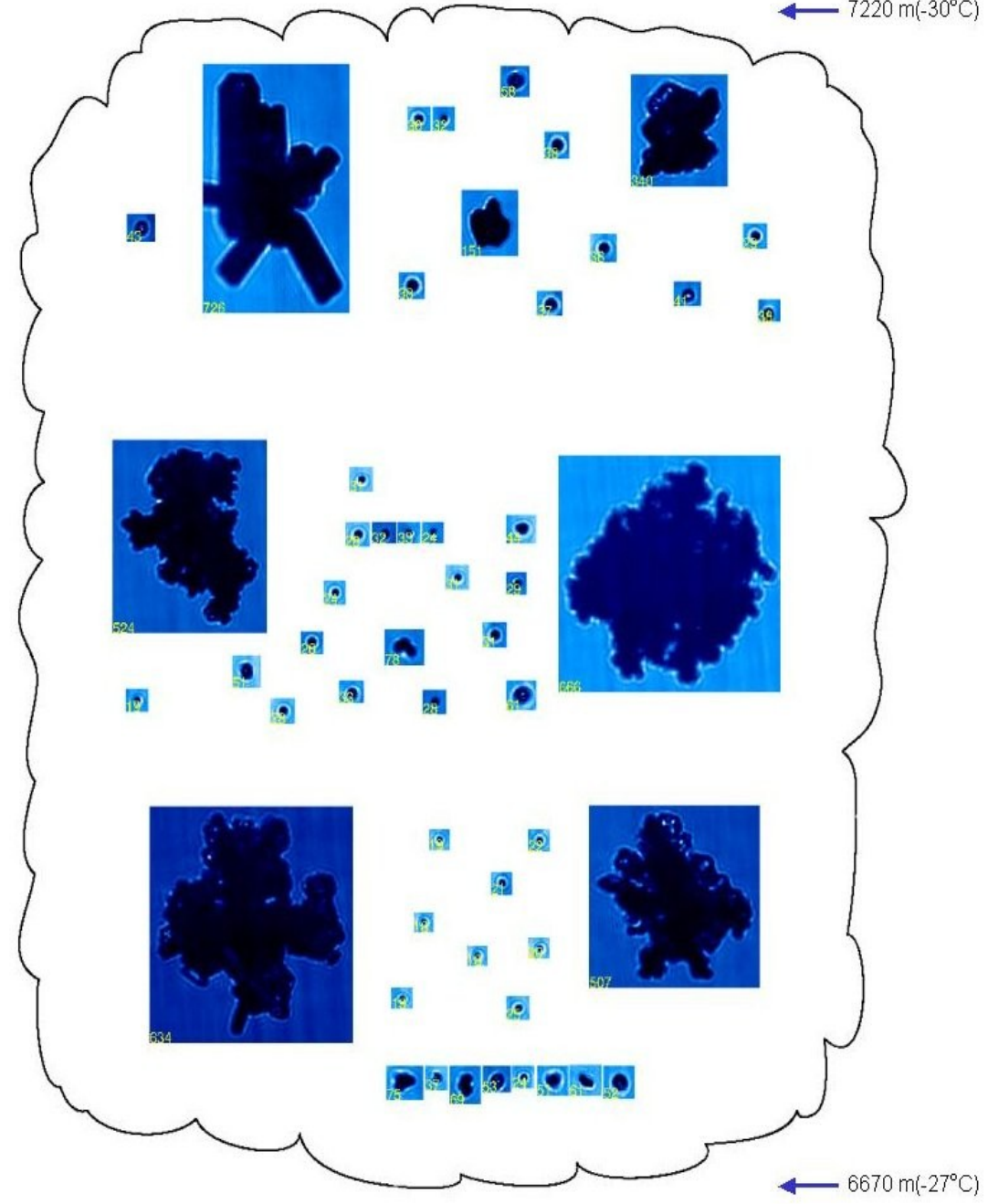
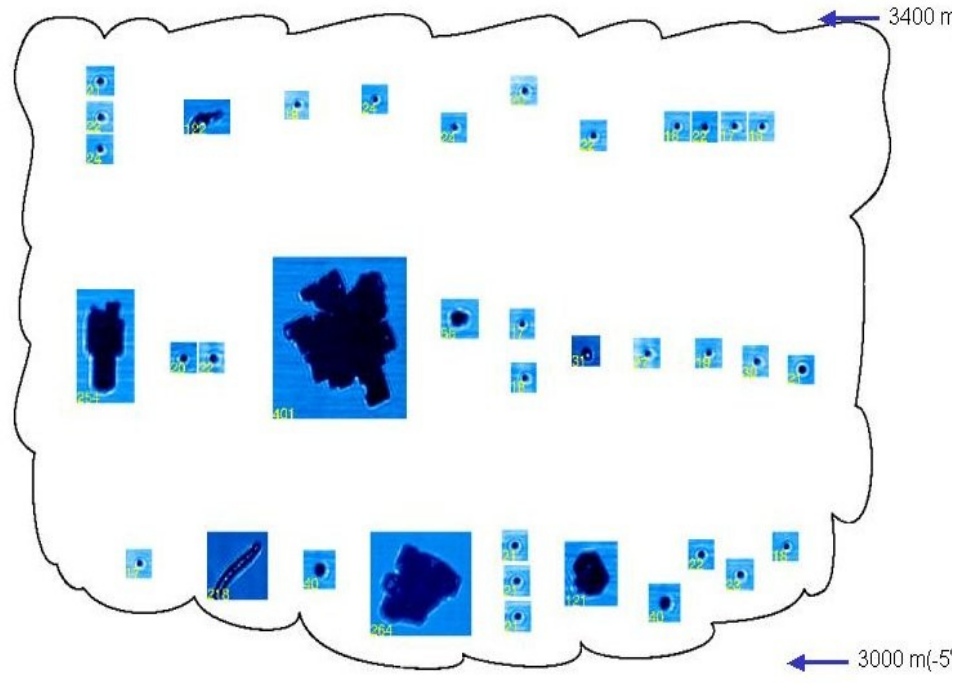
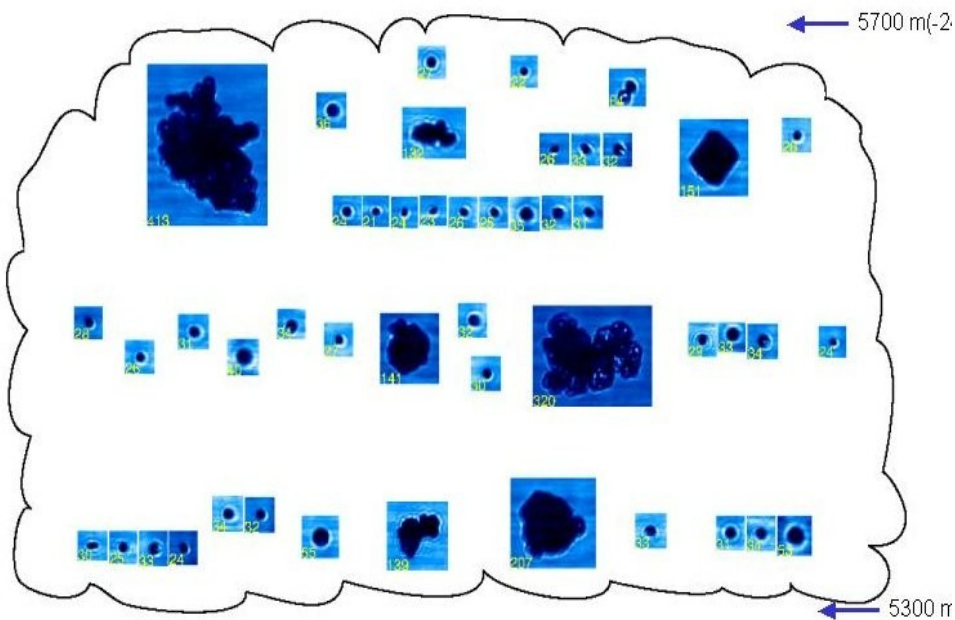
What is the typical size of aerosol and cloud particles ?

From a few nanometers: a few molecules condensed

To a few centimeters: hailstones

Measurable parameters from in-situ observations

Particle size.....	$\mu\text{m}, \text{mm}, \text{cm}$	$1\mu\text{m} < D < 10\text{cm}$
Number Concentration.....	$\text{cm}^{-3}; \text{l}^{-1}; \text{m}^{-3}$	$1000\text{cm}^{-3} < N < 1\text{m}^{-3}$
Extinction Coefficient.....	km^{-1}	$100\text{km}^{-1} < \beta < 0.01 \text{ km}^{-1}$
Water Content.....	g/m^3	$10\text{g}/\text{m}^3 < W < 0.0001\text{g}/\text{m}^3$



Cloud particles at various heights (temperatures) imaged by CPI (SPEC Inc.)

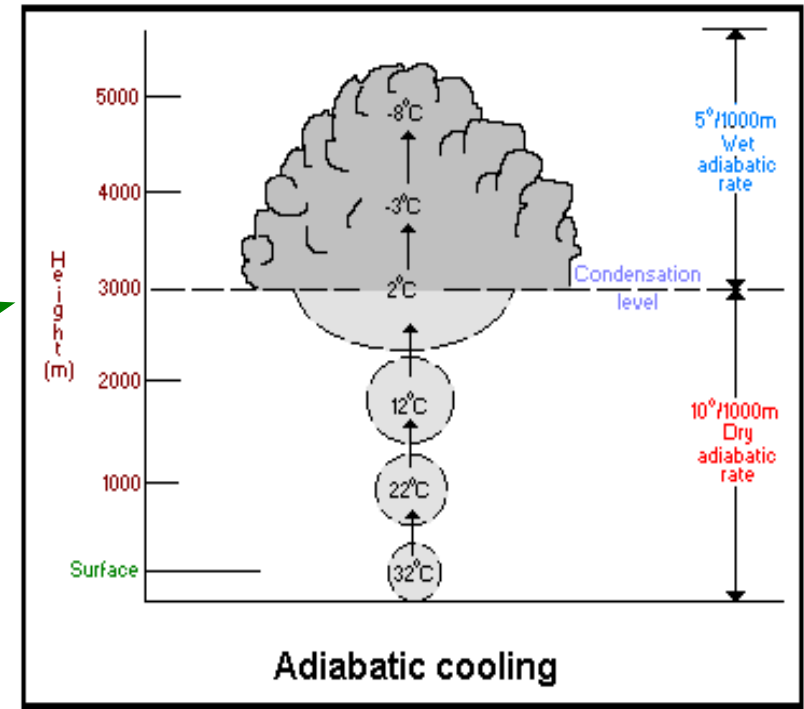
Cloud formation processes:

Condensation of water vapour into small droplets

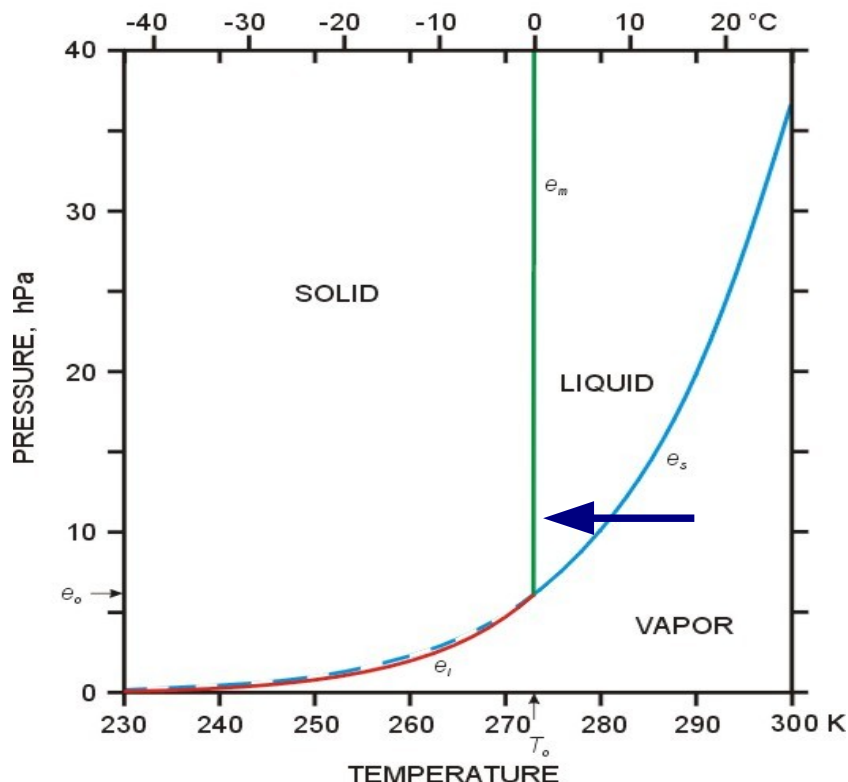
adiabatic expansion (e.g. ascending motions);

isobaric cooling (radiative, conductive);

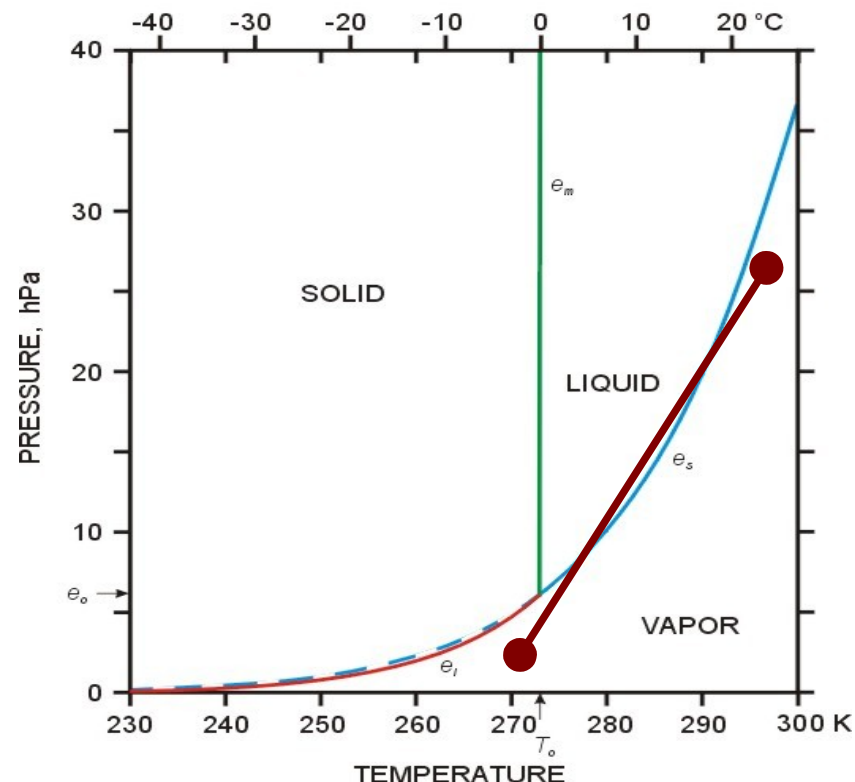
isobaric mixing.



PHASE DIAGRAM OF WATER

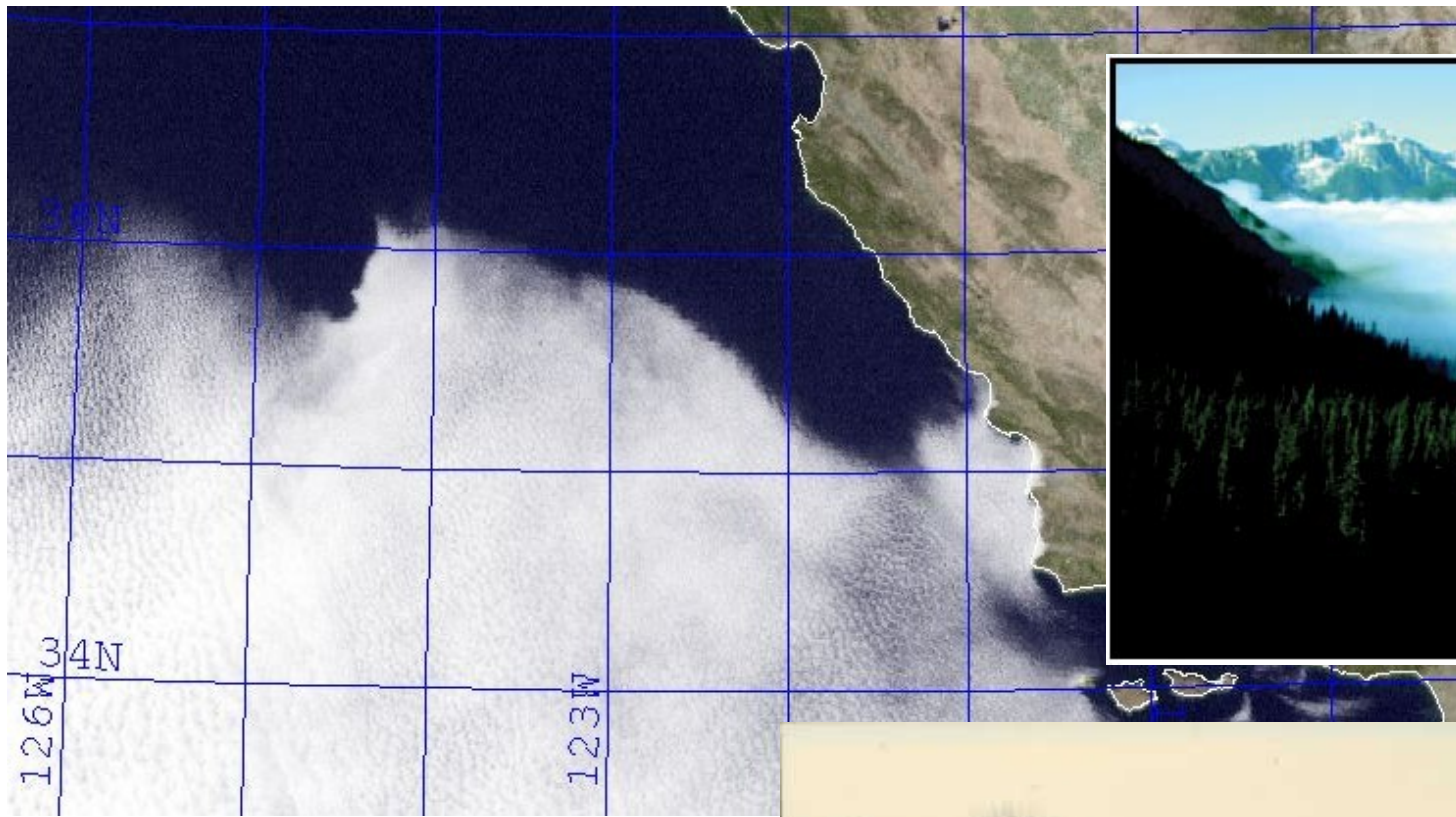


PHASE DIAGRAM OF WATER





Examples of condensation (formation of clouds) due to adiabatic expansion.



Examples of condensation
(formation of clouds)
due to isobaric cooling.



Examples of condensation (formation of clouds) due to isobaric mixing of two humid unsaturated airmasses.



Clouds and Turbulence – overview.

Cloud topped boundary layer:

- turbulence in Stratocumulus clouds;
- turbulence in cumulus convection.

Condensation in convective motions.

- a sketch of Koehler's theory;
- collisions and coalescence and a „bottleneck” problem.

Experimental evidence of warm rain formation

- drizzle in Stratocumulus;
- warm rain in cumulus clouds.

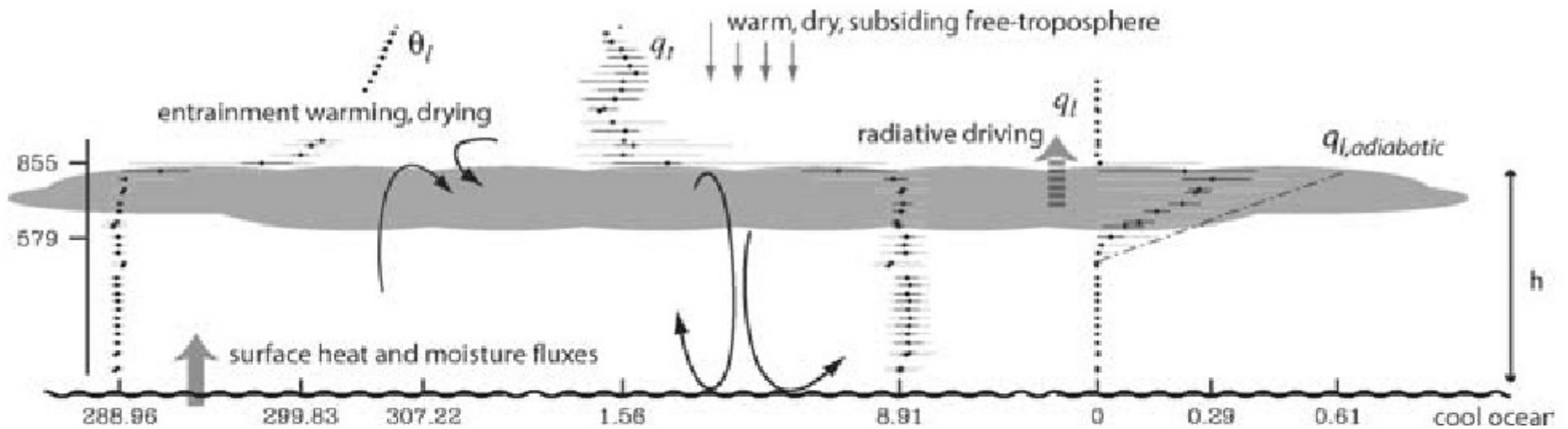
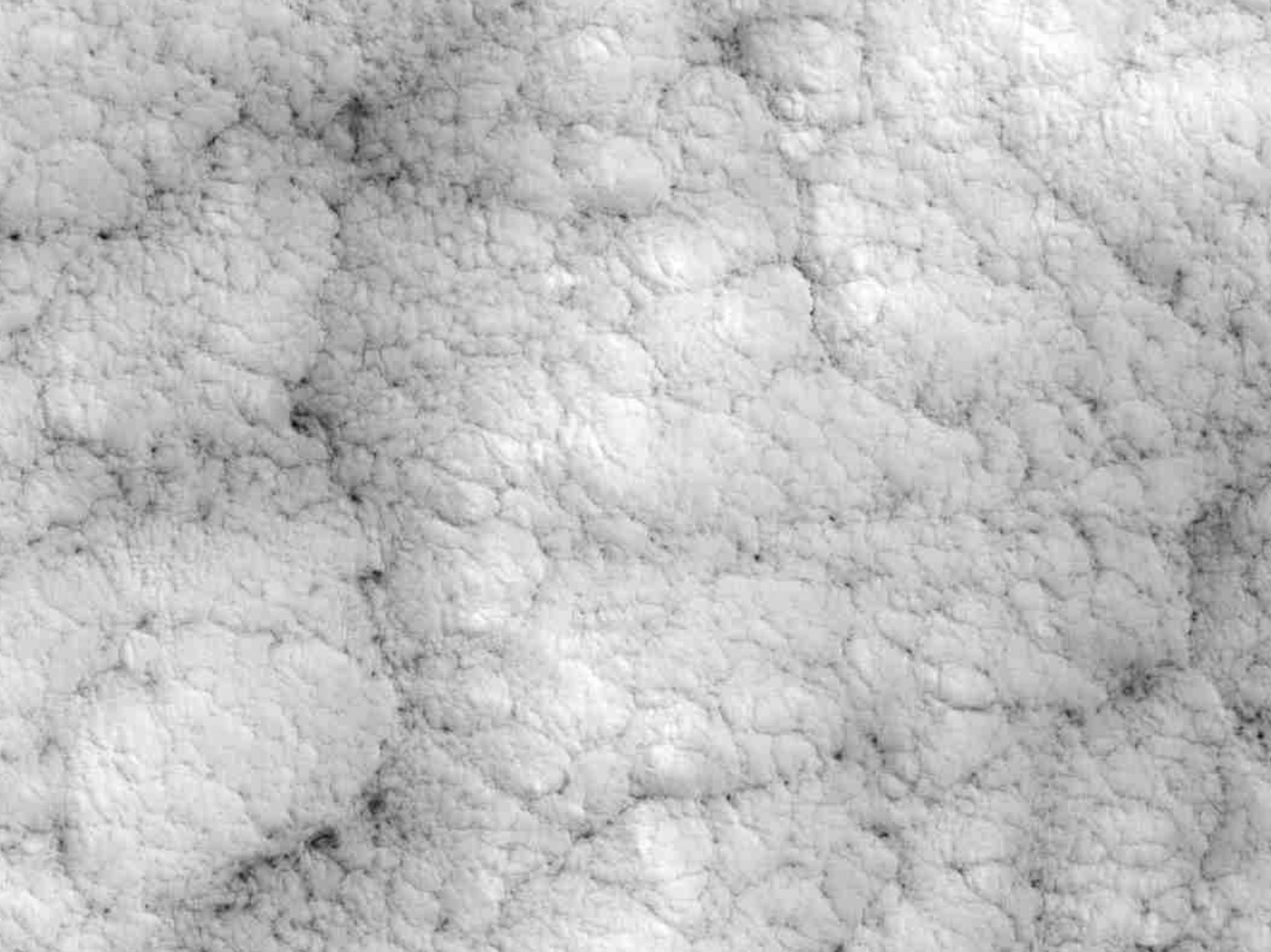
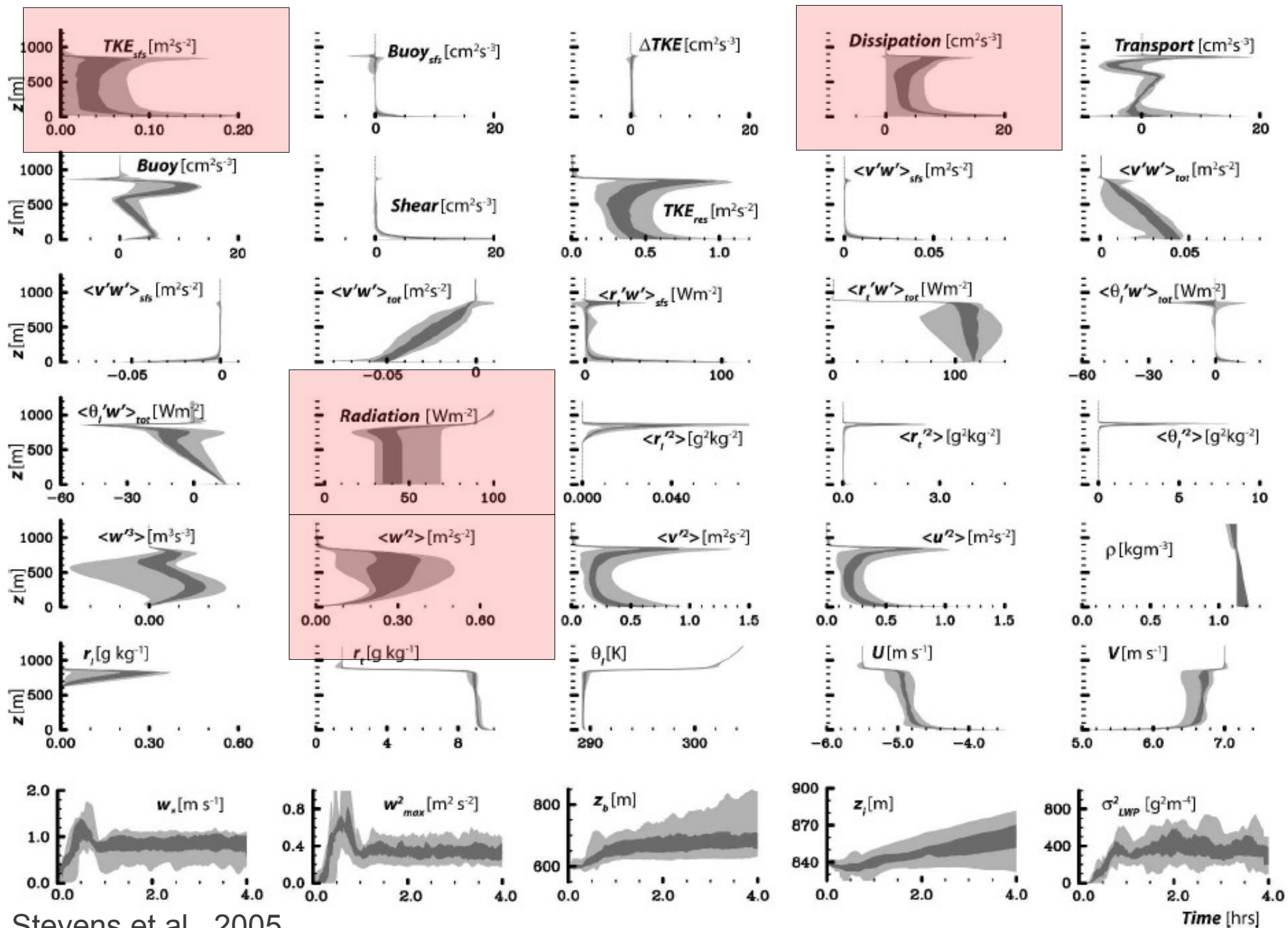


Figure 4 Cartoon of well-mixed, nonprecipitating, stratocumulus layer, overlaid with data from research flight 1 of DYCOMS-II. Plotted are the full range, middle quartile, and mean of θ_l , q_t , and q_l from all the data over the target region binned in 30-m intervals. Heights of cloud base and top are indicated, as are mixed layer values and values just above the top of the boundary layer of various thermodynamic quantities. The adiabatic liquid water content is indicated by the dash-dot line.





Stevens et al., 2005

FIG. C1. (upper six rows) Thumbnails of profile and (last row) time series statistics for the master ensemble.

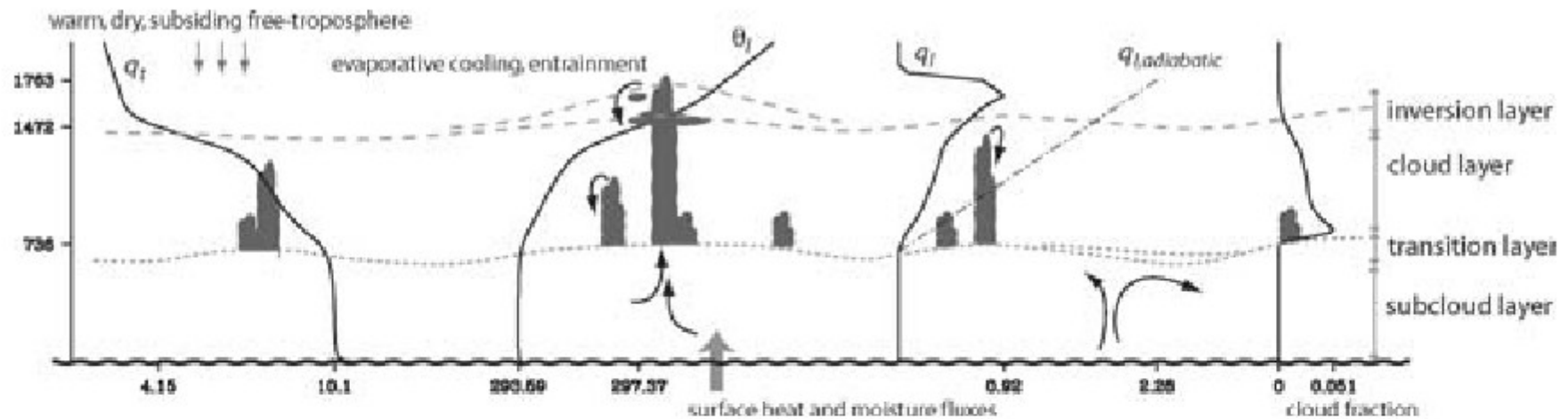
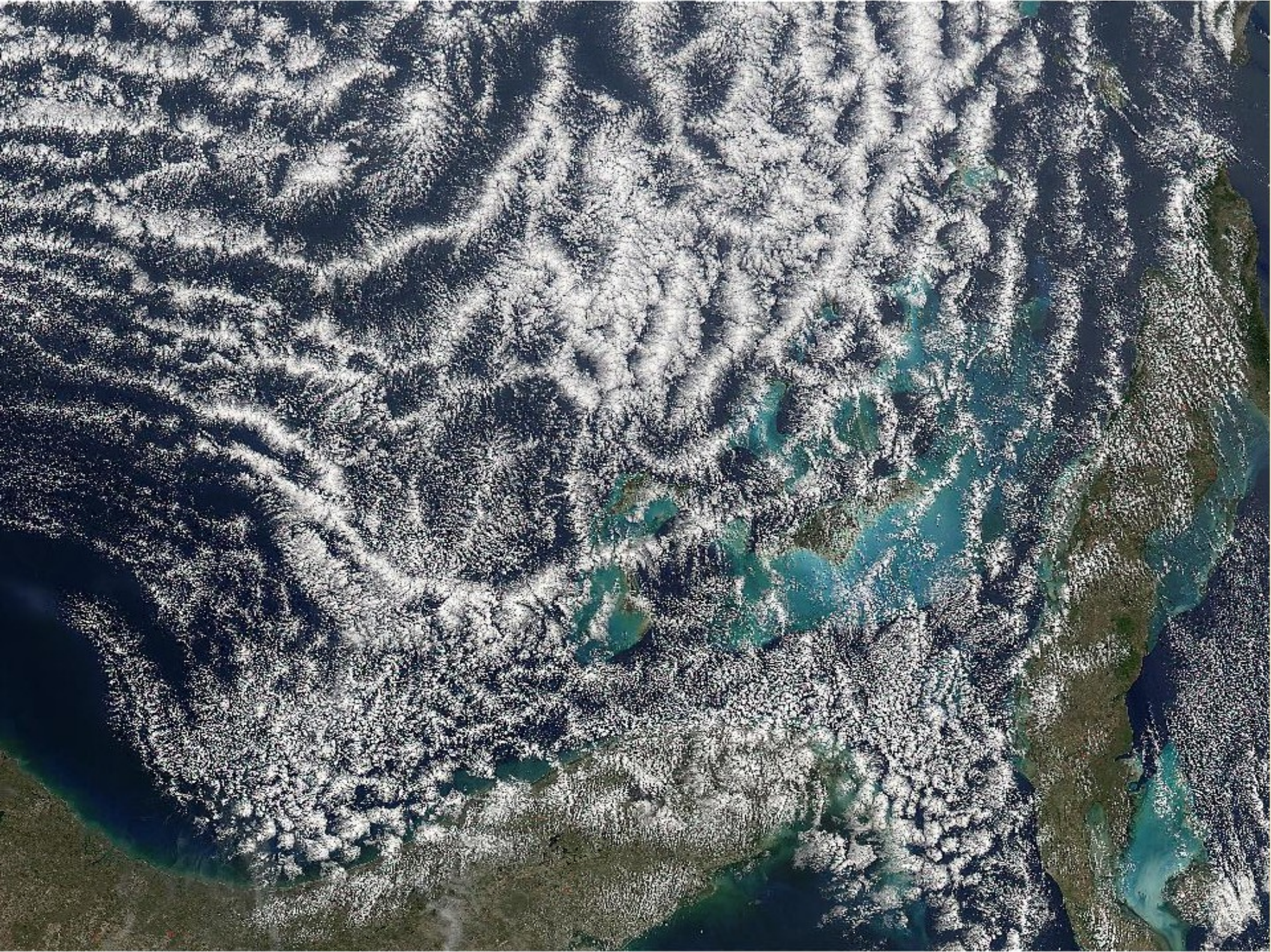


Figure 6 Cartoon of trade-wind boundary layer from large-eddy simulation. Heights of cloud base, level of maximum θ_l gradient (inversion height), and maximum cloud penetration depth are indicated, as are subcloud layer and inversion-level values of thermodynamic quantities. Cloud water contents are averaged over cloudy points only, with adiabatic liquid water contents indicated by the dash-dot line. The far right panel shows cloud fraction, which maximizes near cloud base at just over 5%.



Courtesy B. Stevens



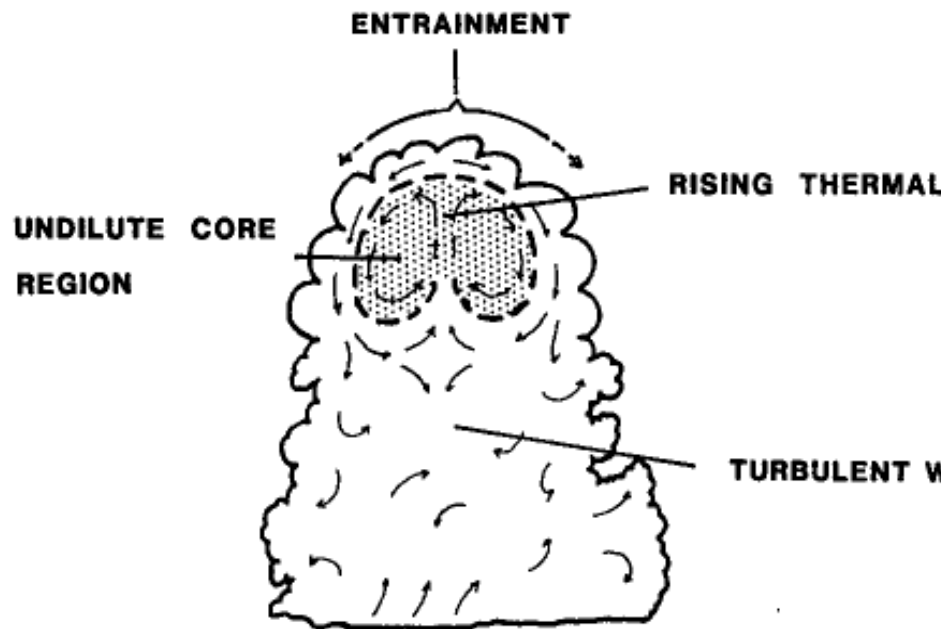


FIG. 14. Schematic model of a cumulus cloud showing a she thermal that has ascended from cloud base. Continuous entrainment into the surface of the thermal erodes the core, and the rema undiluted core region continues its ascent, leaving a turbulent of mixed air behind it. See text for further discussion.

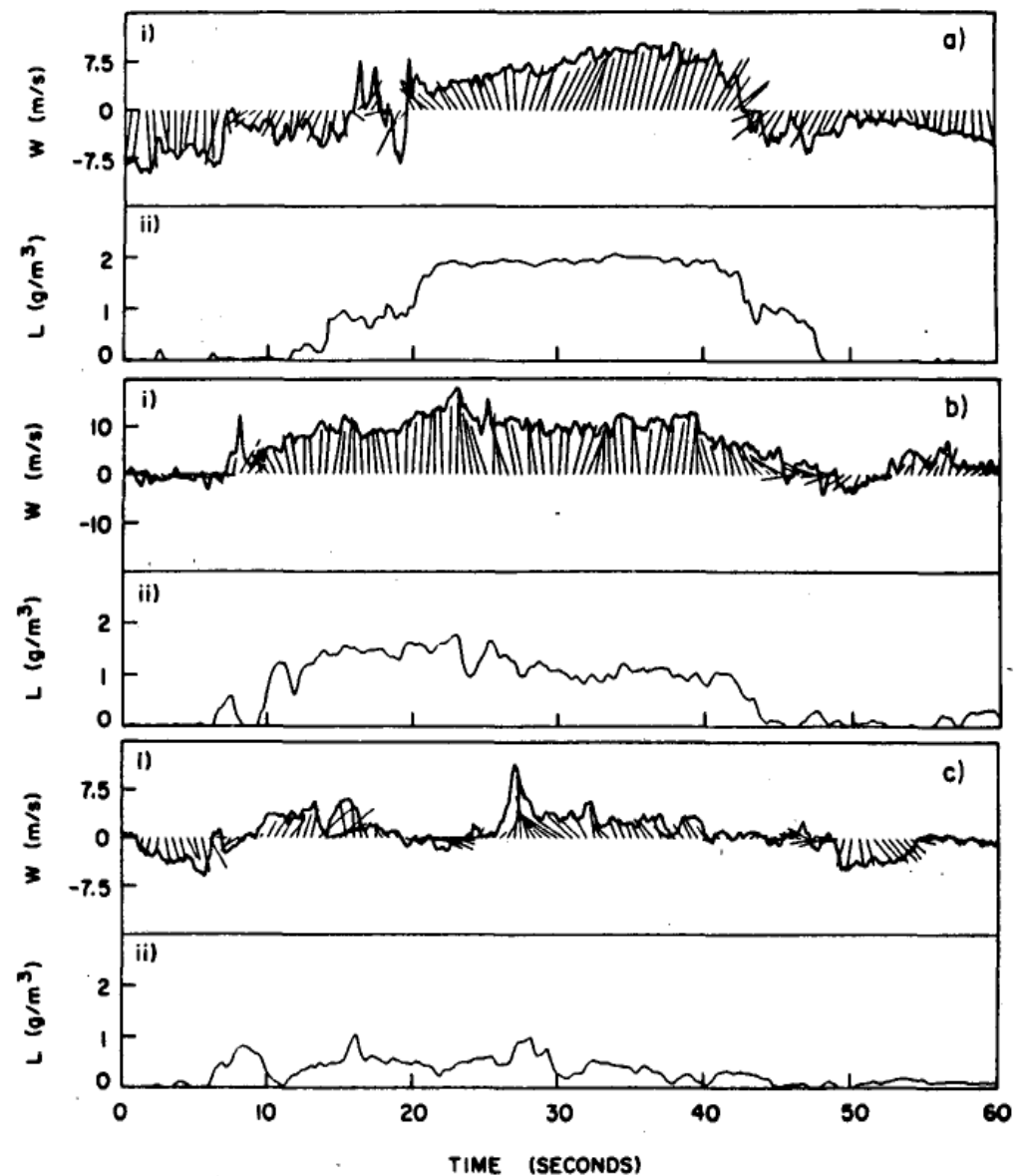


FIG. 17. Wind velocity (i) and liquid water content (ii) for three KA penetrations from 1625 to 1633 MDT in the 19 July 1981 cloud: (a) 472 mb, (b) 514 mb and (c) 527 mb. The wind vectors are formed from the vertical wind and the wind along the flight path and are drawn to scale.

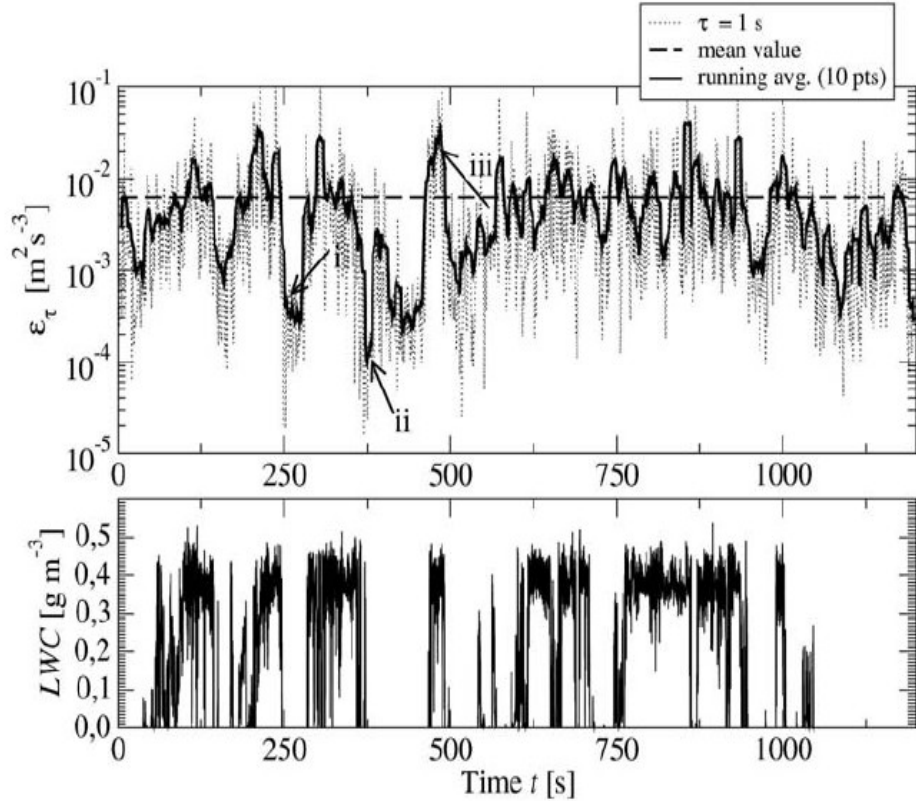


FIG. 8. (top) Time series of local energy dissipation rate ε_τ and (bottom) LWC of BBC2 data. The integration time τ for ε_τ is 1 s; a running average over 10 points is included.

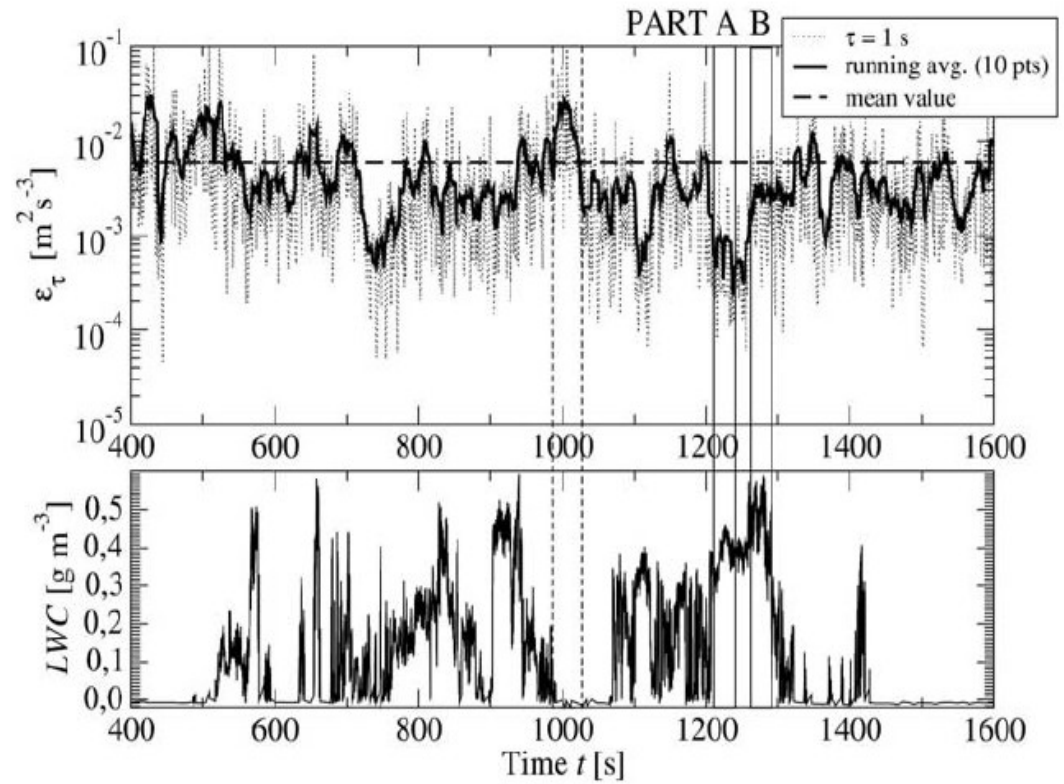


FIG. 9. (top) Time series of local energy dissipation rate ε_τ and (bottom) LWC of INSPECTRO2 data. The integration time τ for ε_τ is 1 s; a running average over 10 points is included.

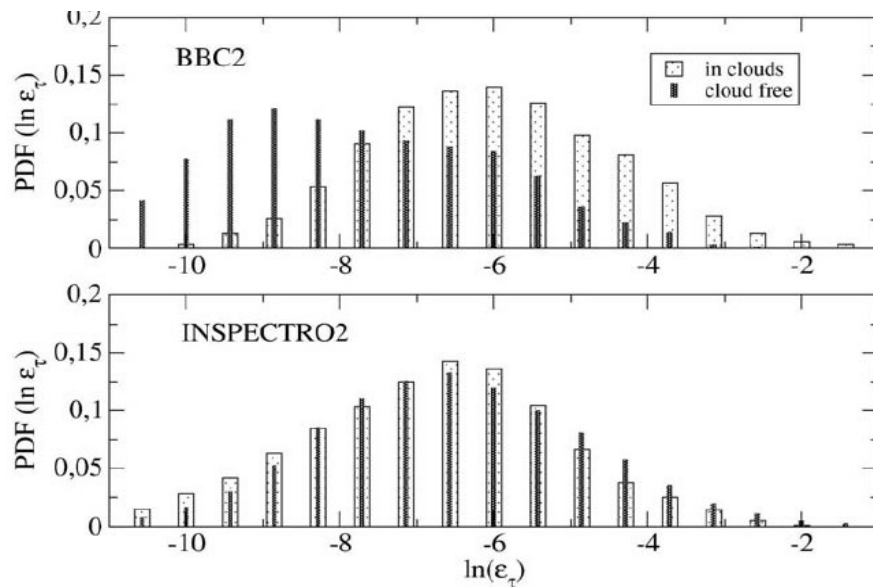


FIG. 12. PDF of natural logarithm of energy dissipation rates of the (top) BBC2 data and (bottom) INSPECTRO2 data inside of clouds and outside of clouds. The energy dissipation rates are conditionally sampled on the LWC.

TKE dissipation in small cumulus clouds

Siebert, Lehmann and Wendisch, 2006.

The following parameters characterize warm turbulent clouds and give some indication of their variability.

Mean ε , can vary from **$\sim 10 \text{ cm}^2\text{s}^{-3}$** in stratiform clouds to **$\sim 2000 \text{ cm}^2\text{s}^{-3}$** in cumulonimbus clouds (e.g. Caughey et al., 1982; MacPherson and Isaac, 1977).

R_λ , varies from **~ 5000** in stratiform clouds to **$\sim 20,000$** in strong deep convective clouds (e.g. Shaw, 2003; Khain et al., 2007);

$\varepsilon \sim 3 \text{ cm}^2\text{s}^{-3}$ and $R_\lambda \sim 5000$ for stratocumulus (Siebert et al., 2010)

$\varepsilon \approx \sim 30 \text{ cm}^2\text{s}^{-3}$ and $R_\lambda \sim 4 \times 10^4$ for small cumulus (Siebert et al., 2006).

The **maximum LWC** are in convective clouds with very strong updrafts and not exceed **$4\text{--}5 \text{ g m}^{-3}$** ; **typically** in cumulus **$0.1\text{--}2 \text{ g m}^{-3}$** depending on the stage of development (Pruppacher and Klett, 1997, §2.1.3).

Most estimates of cloud parameters come from a limited number of measurements at low resolution; only recently (Siebert et al., 2006; Siebert et al., 2010) have higher-resolution ($\sim 20\text{cm}$) measurements.

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CCN activation:
Kohler theory

$$S = \frac{e}{e_s} \approx 1 + \frac{A}{r} - \frac{B}{r^3} \quad (2)$$

where $A = \frac{2M_w \sigma_w / \nu}{RT \rho_w}$ and $B = \frac{\nu m_s M_w}{M_s (4/3 \pi \rho_w)}$, where ν is the number of dissociated ions per solute molecule, m_s is the solute mass and subscripts s and w relate to solute and water properties, respectively. The term in A is denoted the Kelvin or curvature term, and that in B , the Raoult or solute term.

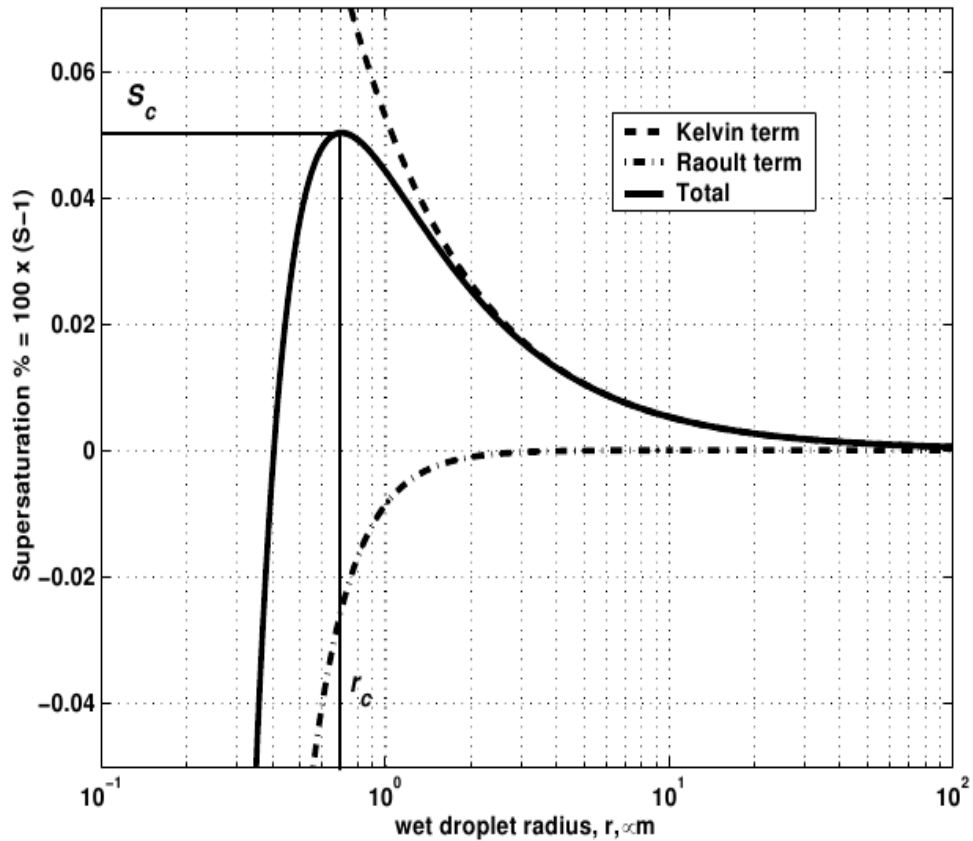


Fig. 1. The Kohler equation can be envisaged as the **competition between the curvature (Kelvin) and solute (Raoult) terms.**

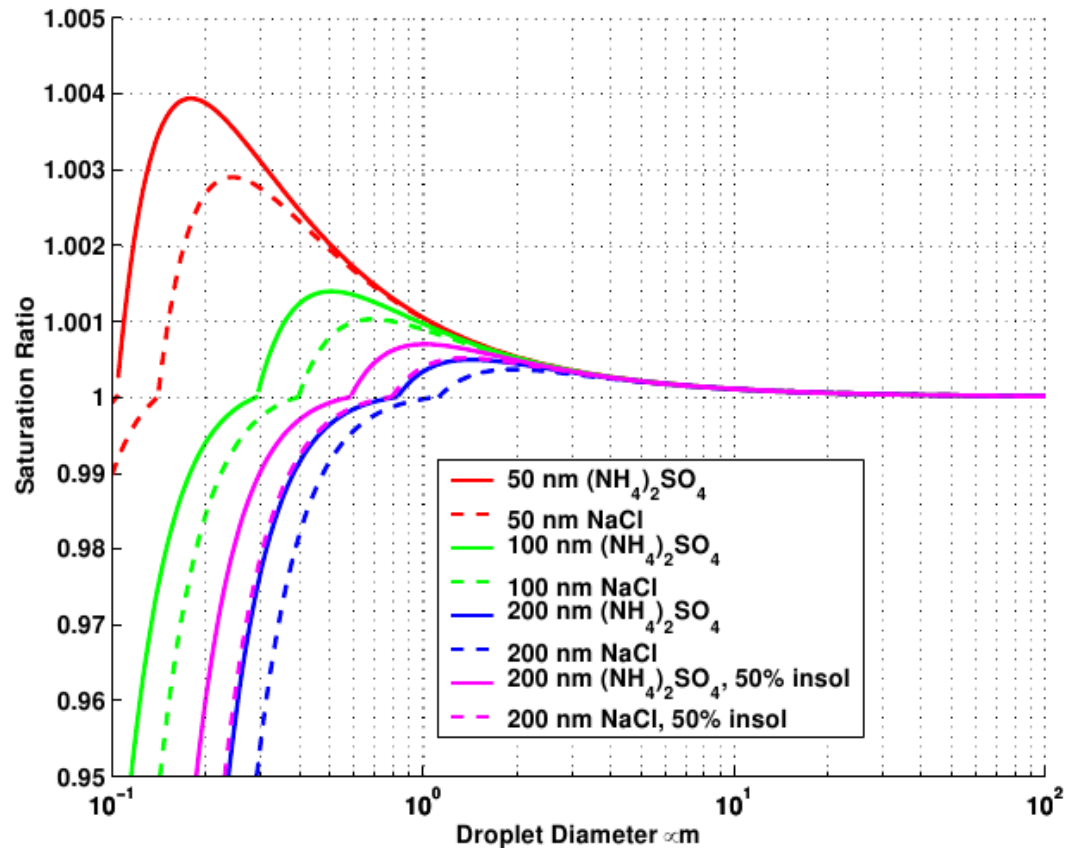


Fig. 3. Activation curves for a range of dry diameter of salt ((NH₄)₂SO₄ – solid, NaCl – dashed) particles (red, green and blue curves) and for 200 nm particles containing 50% by mass insoluble core (magenta).

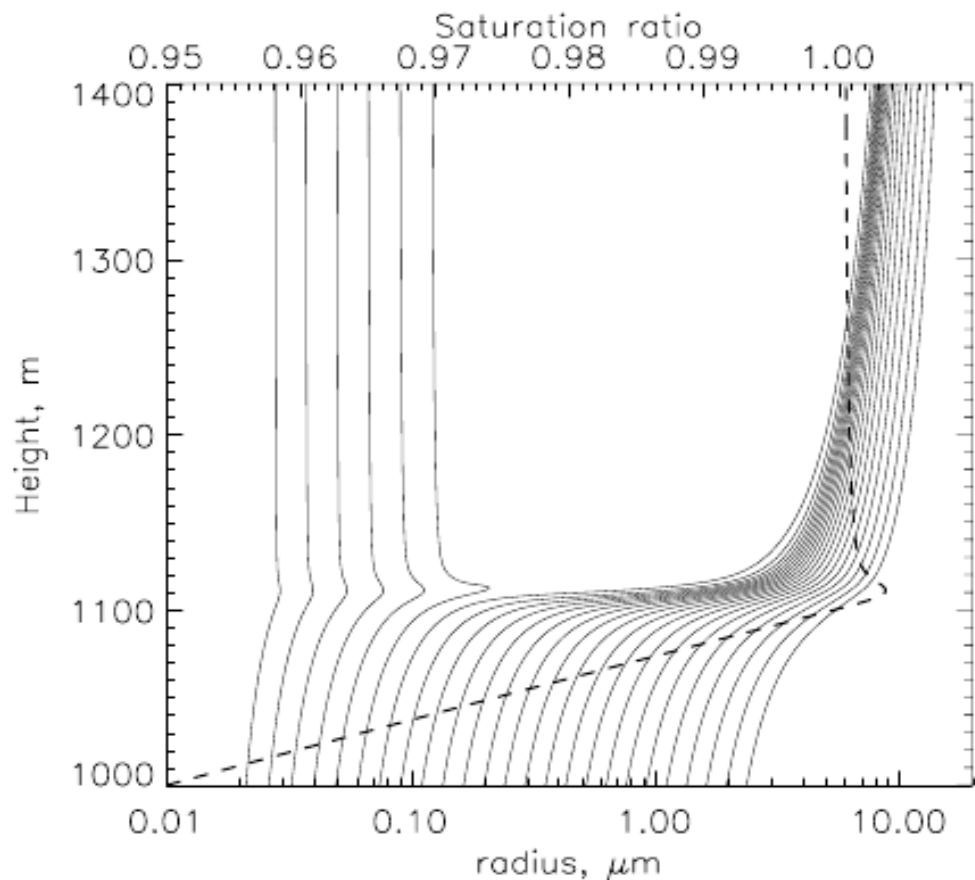


Fig. 4. Simulation showing the change in droplet radius with height in a simulation initialized with an ammonium sulphate aerosol with a geometric mean diameter of 140nm, a geometric standard deviation, σ of 1.7 and aerosol number concentration of 300 cm^{-3} (corresponding to a total mass loading of $0.76 \mu\text{g m}^{-3}$). The simulation was started at an RH of 95% at 1000 m. Solid lines represent selected aerosol size classes. The dashed line is the saturation ratio.

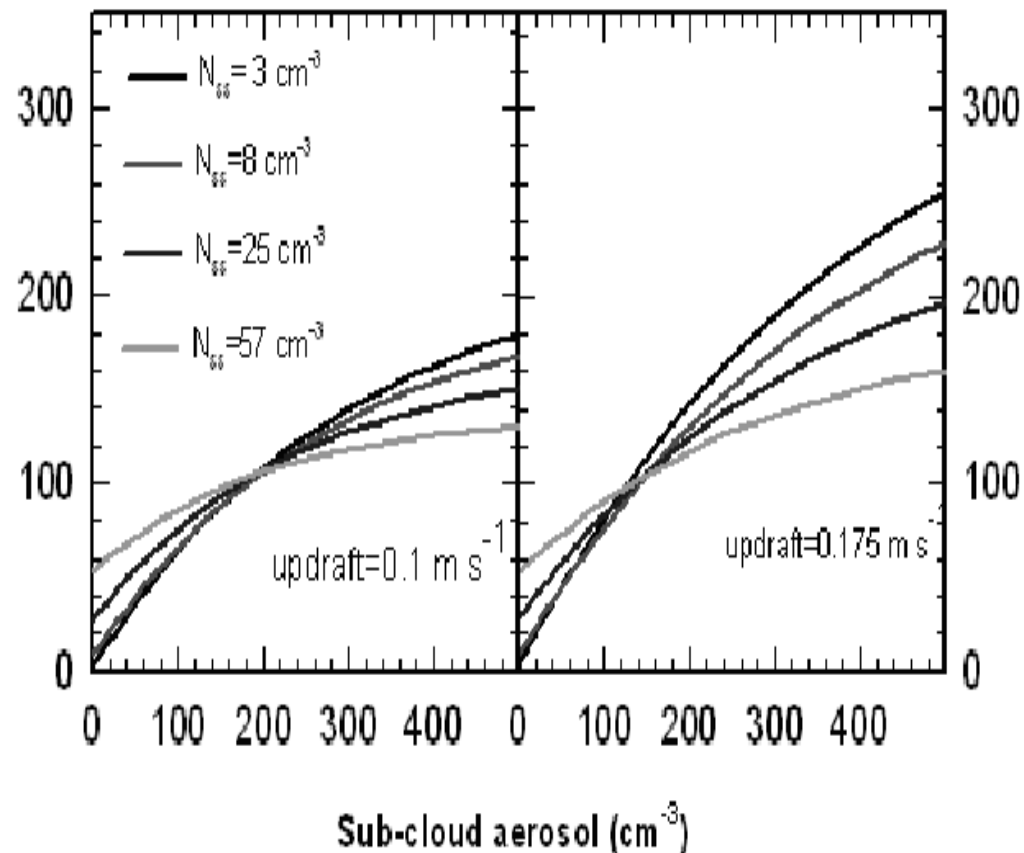
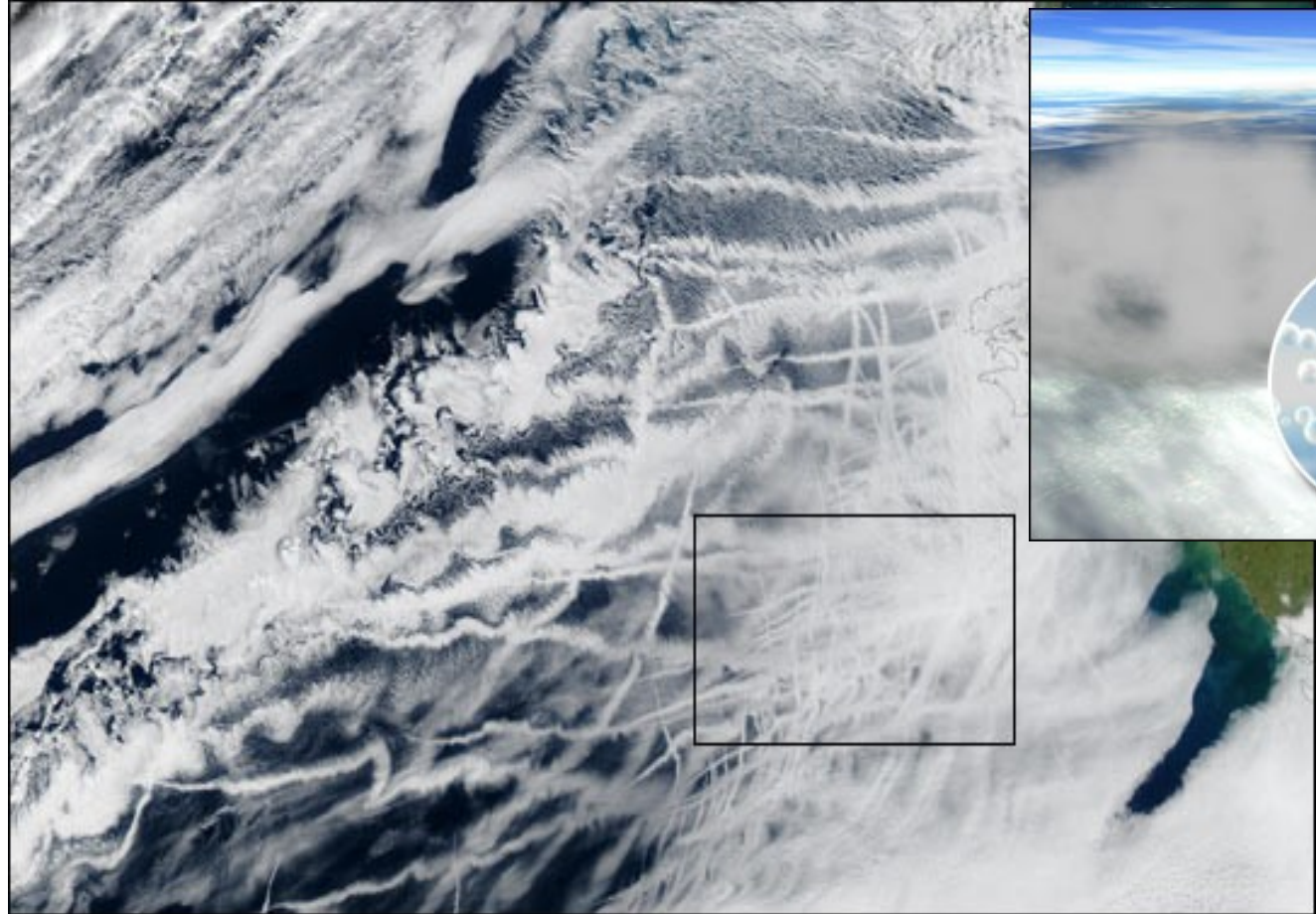
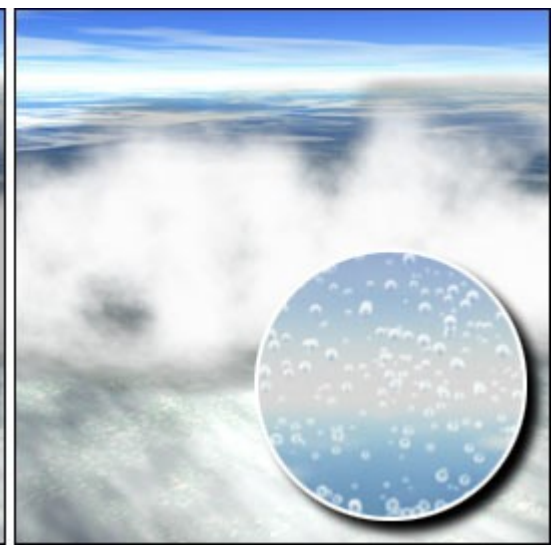
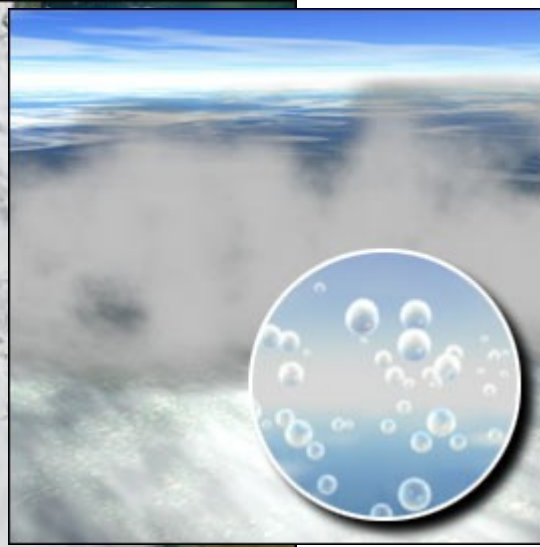


Fig. 5. Cloud droplet concentration as a function of sub-cloud aerosol where the sub-cloud aerosol comprises an external mix of sulphate and sea-salt CCN.

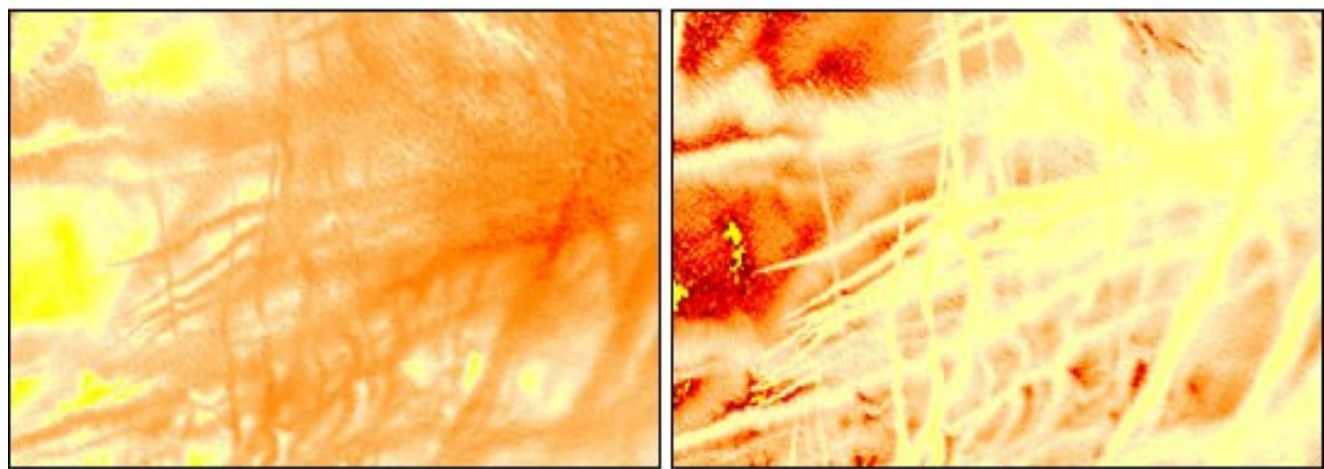
Activation of CCN at cloud base



True Color

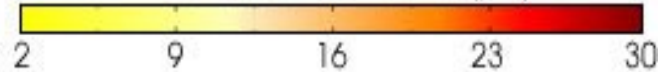
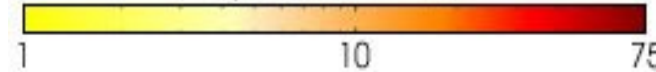


Wpływ aerozolu na budowę chmur (rozmiar kropelek) i w konsekwencji na ich własności radiacyjne: tzw. pośrednie efekty aerozolowe - pierwszy (albedo) drugi (czas trwania).



Optical Thickness

Effective Particle Radius (μm)



What is rain?

rain — Precipitation in the form of liquid water drops that have diameters greater than 0.5 mm, or, if widely scattered, the drops may be smaller.

The only other form of liquid precipitation, drizzle, is to be distinguished from rain in that drizzle drops are generally less than 0.5 mm in diameter, are very much more numerous, and reduce visibility much more than does light rain.

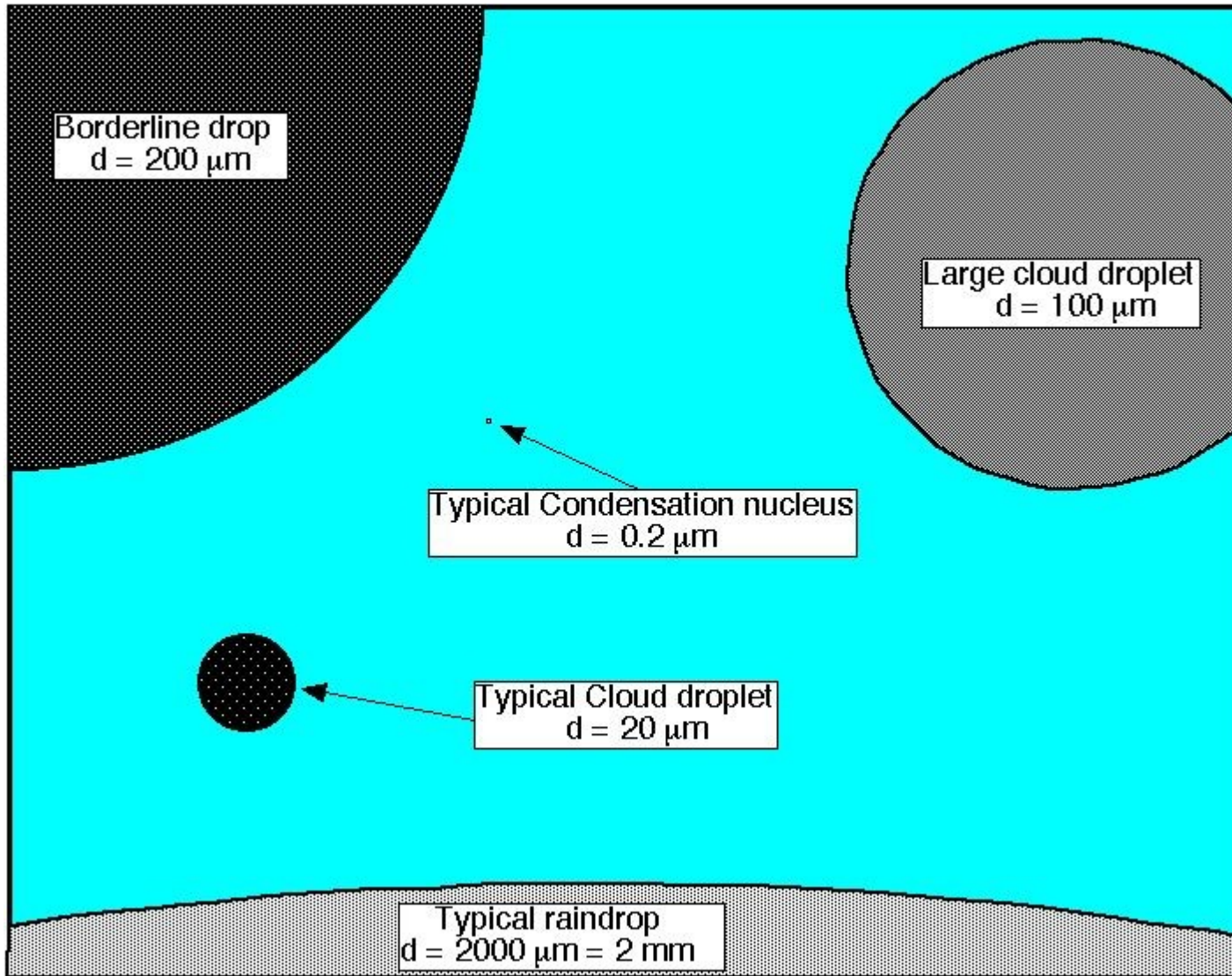
warm rain — Rain formed from a cloud having temperatures at all levels above 0°C (32°F), and resulting from the droplet coalescence process.

Glossary of Meteorology, American Meteorological Society

rain — Precipitation of liquid water drops with diameters greater than 0.5 mm (0.02 inch). When the drops are smaller, the precipitation is usually called drizzle. See also precipitation.

Britannica Online

Aerosol, cloud and rain droplets:



From: What about weather modification? By Chuck Doswell, <http://www.flame.org/~cdoswell/wxmod/wxmod.html>
After: McDonald, J.E., 1958: The physics of cloud modification. Adv. Geophys., 5, 223-303.

CLOUD-PARTICLE FALLSPEEDS

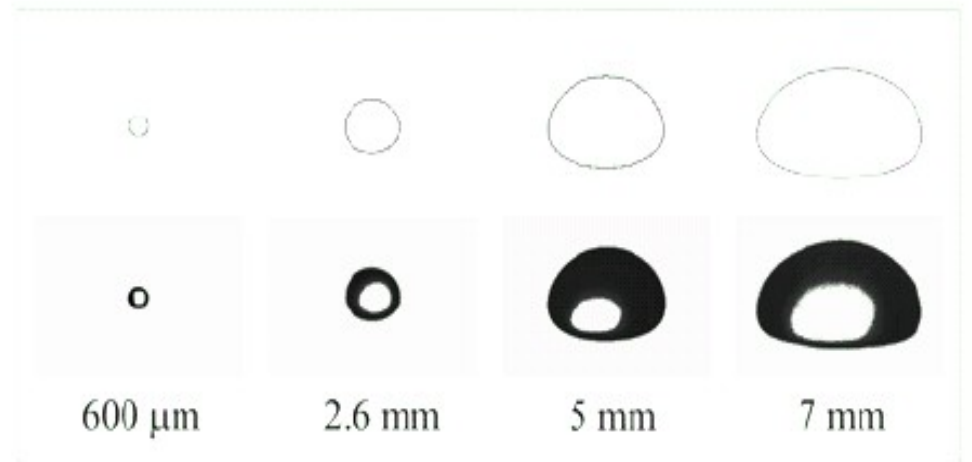
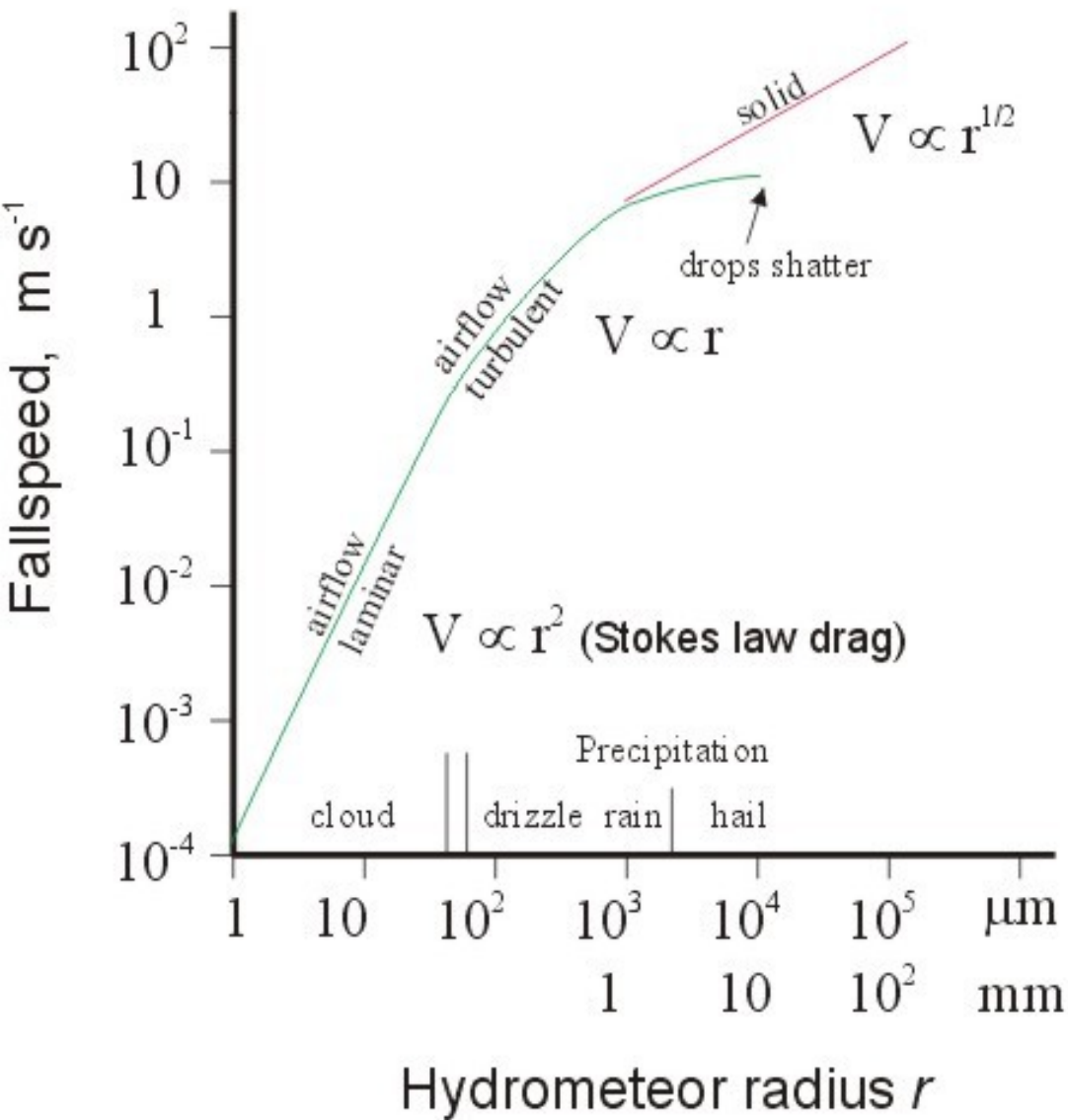


Fig. 1. Calculated drop shapes and real images of drops with different sizes floated in the Mainz vertical wind tunnel

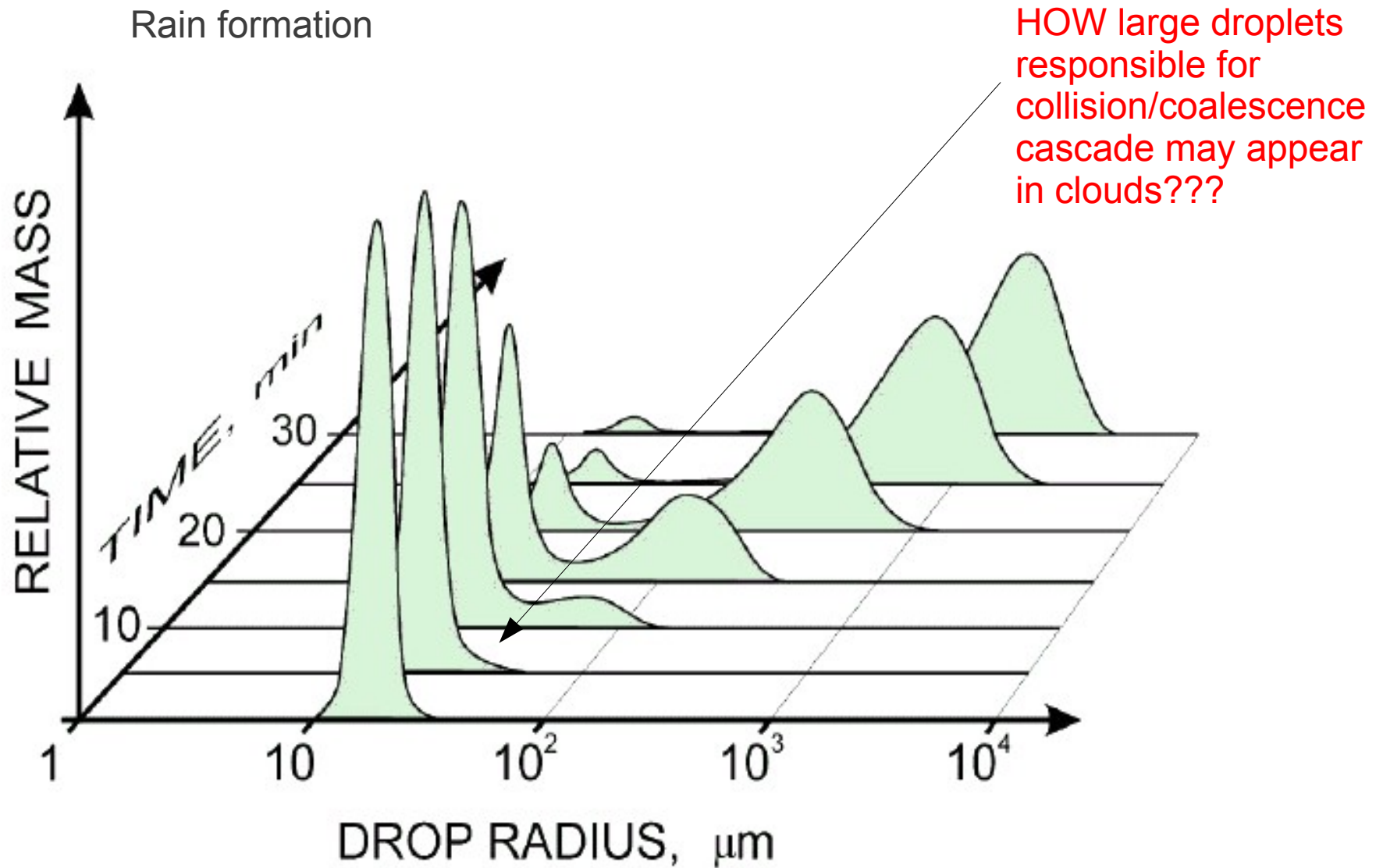


Figure 3 Illustration of the evolution of a droplet size distribution during the onset of the collision-coalescence process. Figure adapted from Berry & Reinhardt (1974) and Lamb (2001), courtesy of D. Lamb, Penn State University.

After Shaw, 2003.

Concepts of rain formation:

1. Giant Condensation nuclei
2. Entrainment and secondary activation
3. “Something to do with turbulence”

Clouds and Turbulence – overview.

Cloud topped boundary layer:

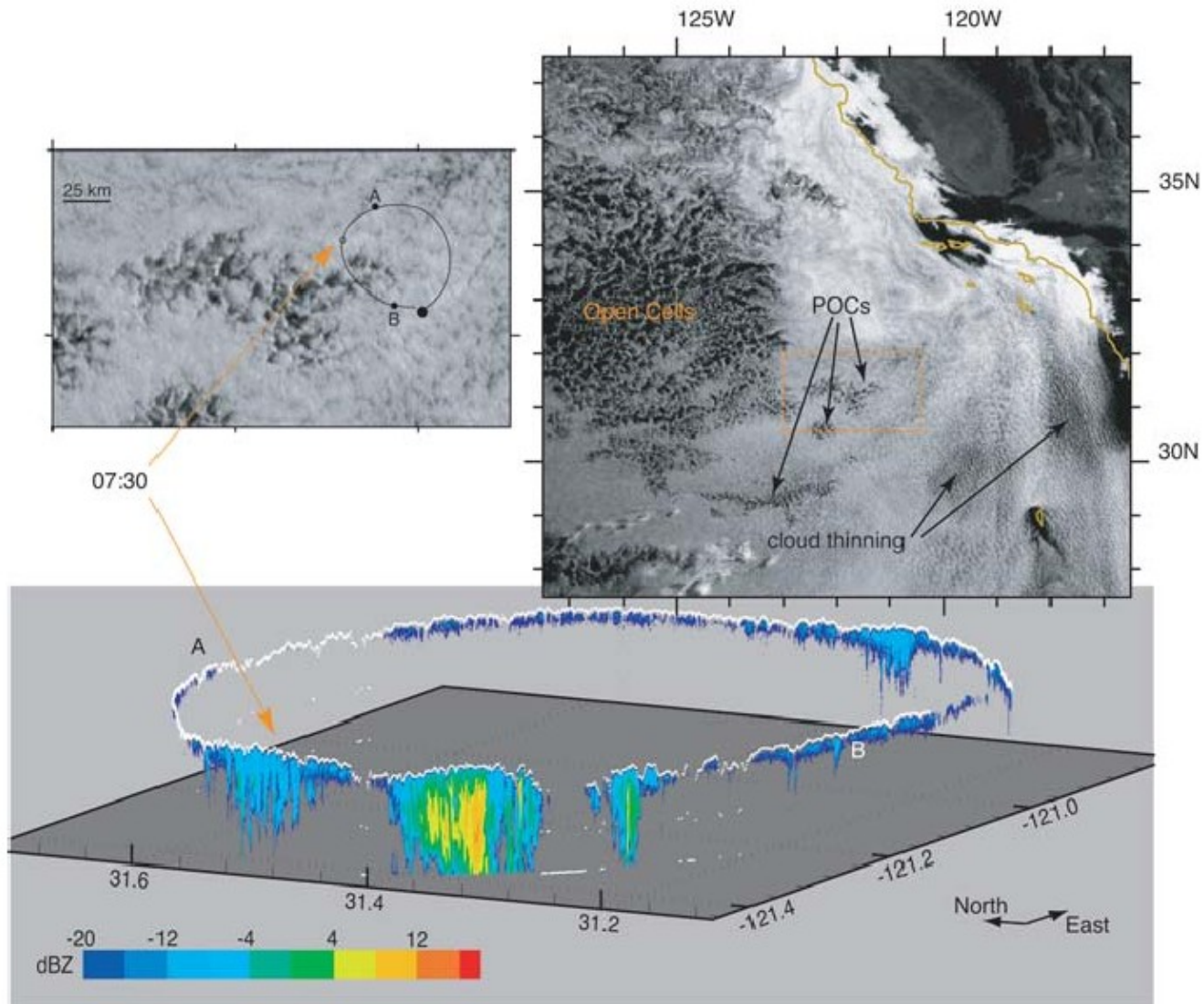
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Stevens et al.,
2005

FIG 3. (top right) Channel I ($0.6 \mu\text{m}$) reflectance over the northeast Pacific from GOES-10 at 0730 LT (1430 UTC) for 11 Jul 2002. (top left) Zoomed image of reflectance field from boxed region in regional image; overlaid on this image is a flight segment from RF02 that spans the time of the overpass and from which radar and lidar data is presented in top left panel. The zoomed image highlights a tilde-shaped POC boxed in the image. (bottom) Time–height radar reflectivities filled, with cloud top height as estimated by downward-looking lidar shown by white line. Regions where lidar detects no cloud are shown by a lidar trace at the surface. The time for which the satellite image is valid is indicated on the flight tracks.

Observations on many scales of a precipitating small cumulus (17 January, 13:59 UTC).

A: Satellite image from DMSP recorded 10 minutes before penetration by the Wyoming King Air.

B: SPol radar image at 3.5° elevation; the cloud is about 46 km from the radar.

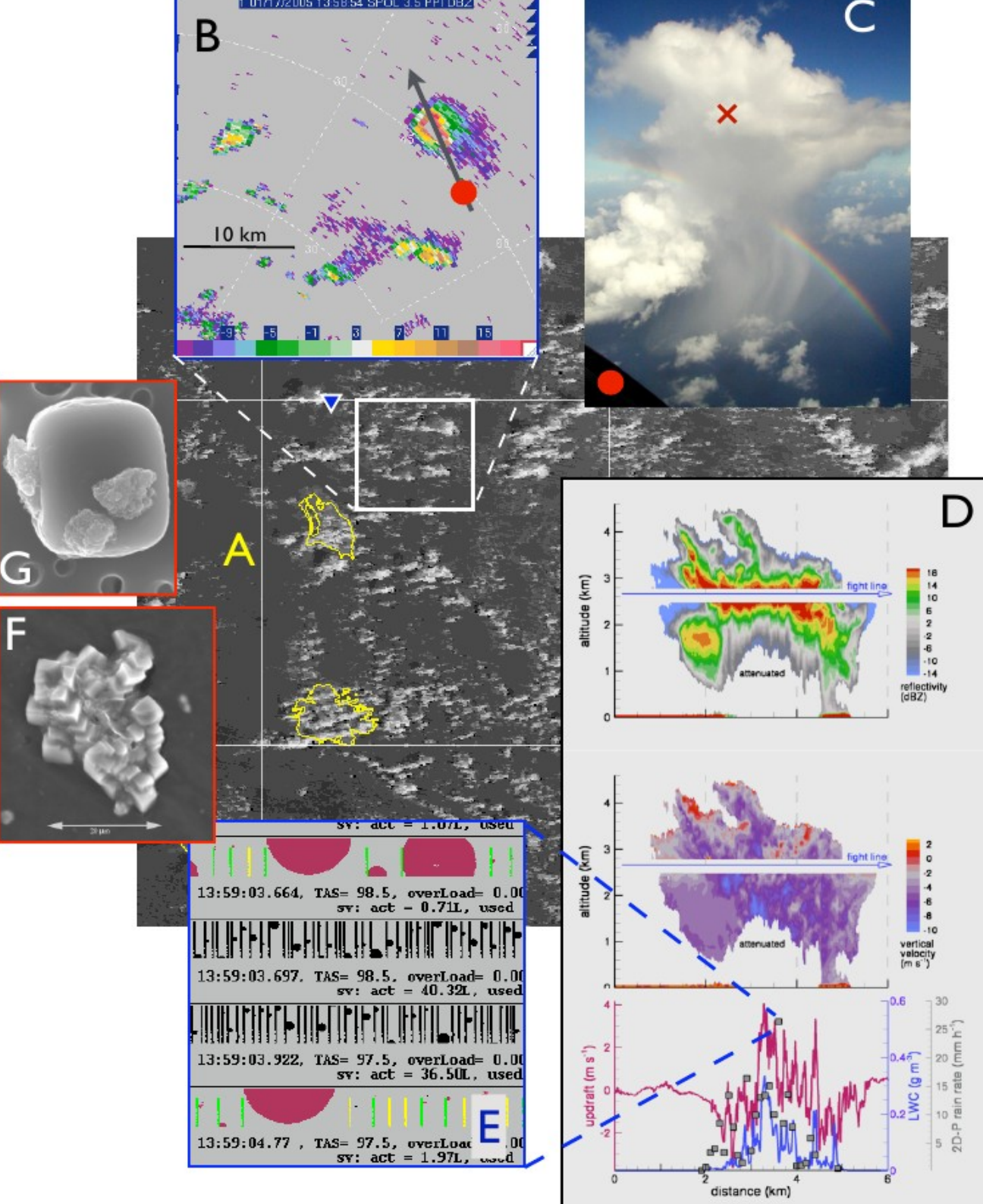
C: Photograph taken from a position marked with the red dot in B. The cross marks the approximate location of the aircraft penetration at 2630 m altitude.

D: Vertical sections of radar reflectivity and of Doppler velocity from the Wyoming Cloud Radar and plots of the in situ updraft, liquid water content and rain rate measurements. Note that the high rain rates and large drops are within the updraft.

E: Millimeter sized drops seen at two different magnifications from imaging probes on the King

Air. Also shown in F/G are scanning electron microscope images such as were made from data collected on NSF/NCAR C130 sub-cloud circles: 2 μm sea-salt particle collected by the total aerosol sampler (F); giant sea-salt particle (20 μm scale) collected with the giant nuclei sampler (G). The location of the Research Vessel Seward Johnson is marked with a blue triangle in A.

Rauber et al., 2007



Cloud-scale and small-scale turbulence

Entrainment and mixing:

Cumulus

Stratocumulus

Mechanisms for entrainment in clouds

Already partially discussed

Turbulence and cloud microphysics:
motion of cloud droplets

Droplet size distribution

Condensational growth and turbulence

Collisions, coalescence and turbulence

Droplet relative velocity

Droplet clustering (preferential concentration)

Preferential sweeping

The effect of entrainment on the droplet size distribution

Homogeneous and inhomogeneous mixing

Entrainment into cumulus:

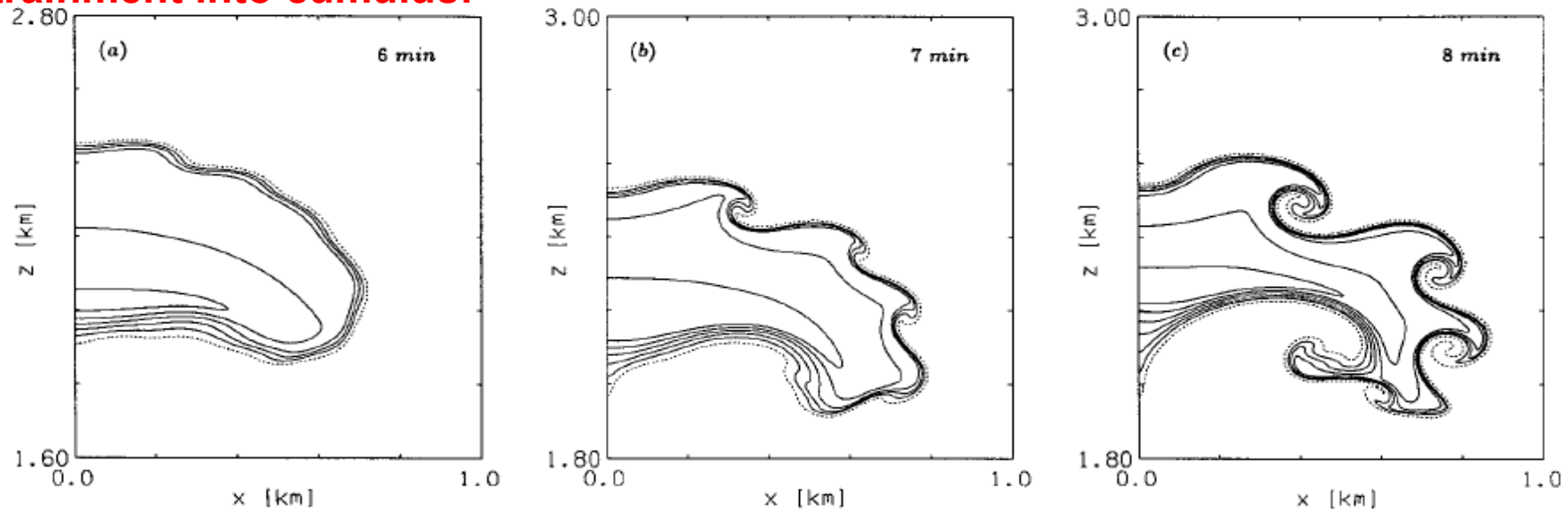


FIG. 19. Isolines of the q_c field at $t = 6$ (a), 7 (b), and 8 min (c) for the simulation of the large thermal with $K = 1 \text{ m}^2 \text{ s}^{-1}$ and excitation as described in section 5. Contour interval is 0.3 g kg^{-1} .

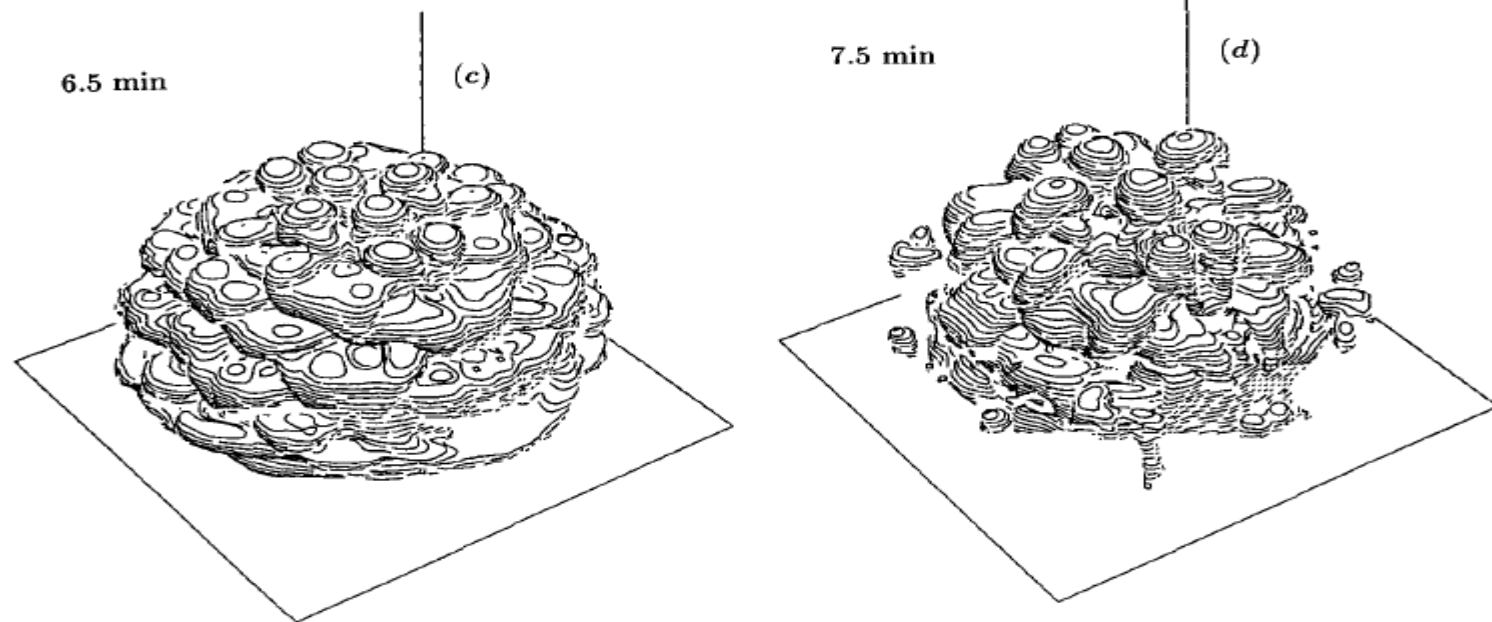
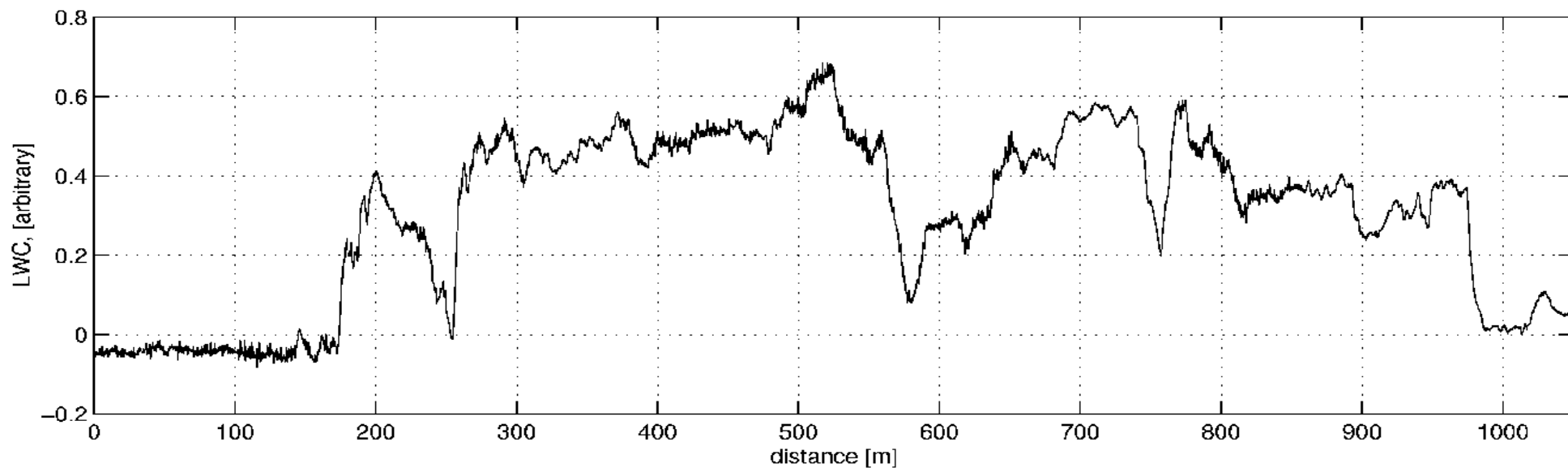
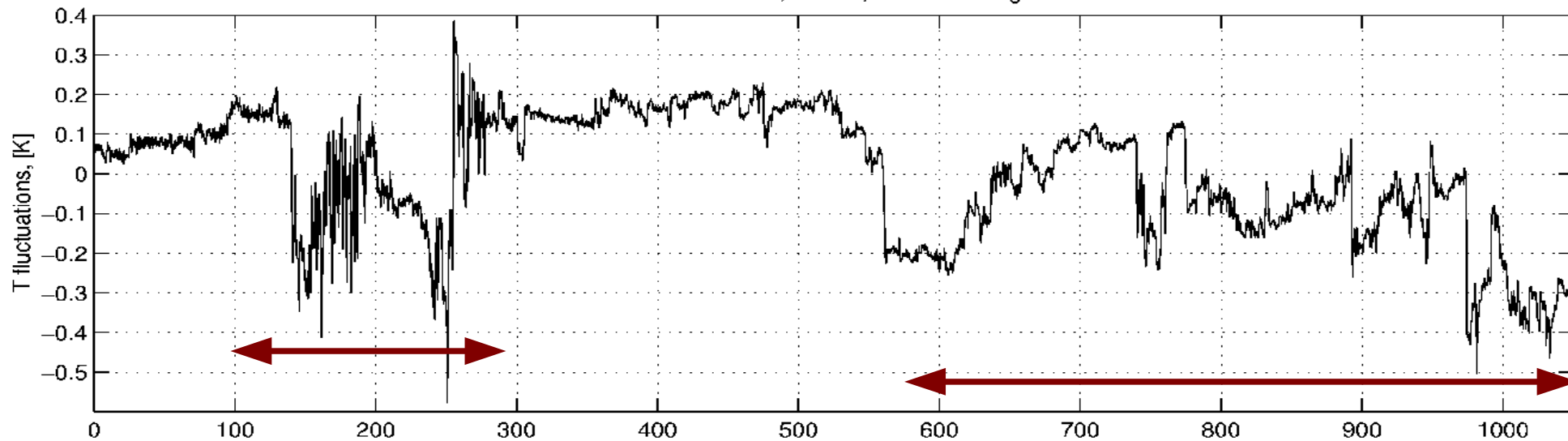


FIG. 4. As in Fig. 3 but for the perturbed 3D3M experiment. Note that data for the quarter of the thermal were used to plot the whole thermal with symmetries as assumed in the experimental setup.

Entrainment as a result of interfacial instabilities: Klaasen, Clark, Grabowski.....
Illustrations from Grabowski and Clark 1991, 1993

WAWA950922, lfast03, 100Hz averages



Arrows indicate filamentation due to entrainment-mixing

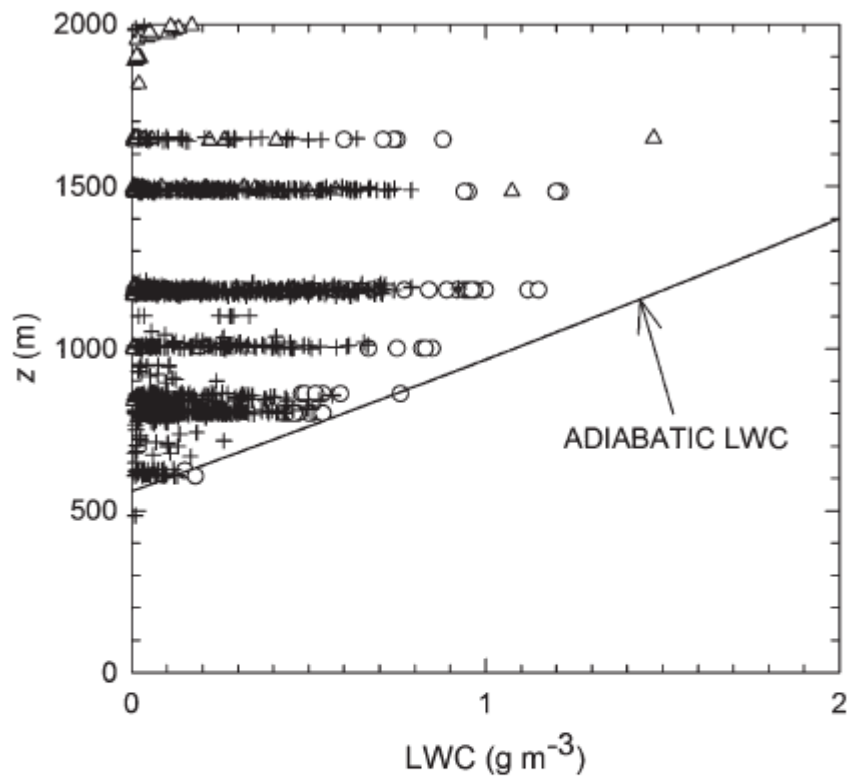


Fig. 1. Liquid water content LWC as a function of height z in RICO trade-wind Cu on C-130 flight RF12. Crosses are 1-hz PVM data, circles are 1000-hz PVM data, and triangles are 1-hz 2D-C data. The curve indicates the expected adiabatic LWC profile given cloud-base temperature and pressure.

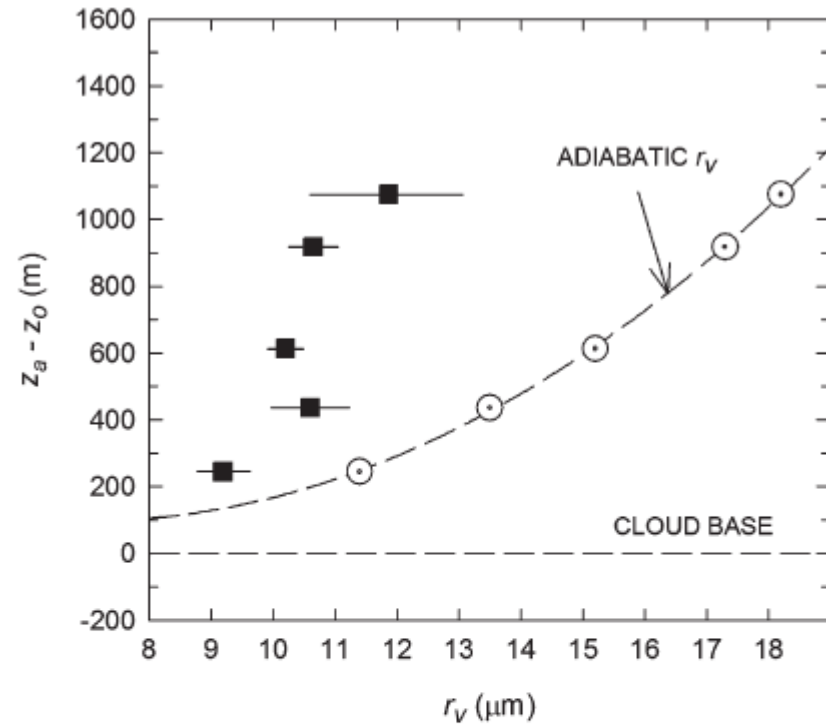
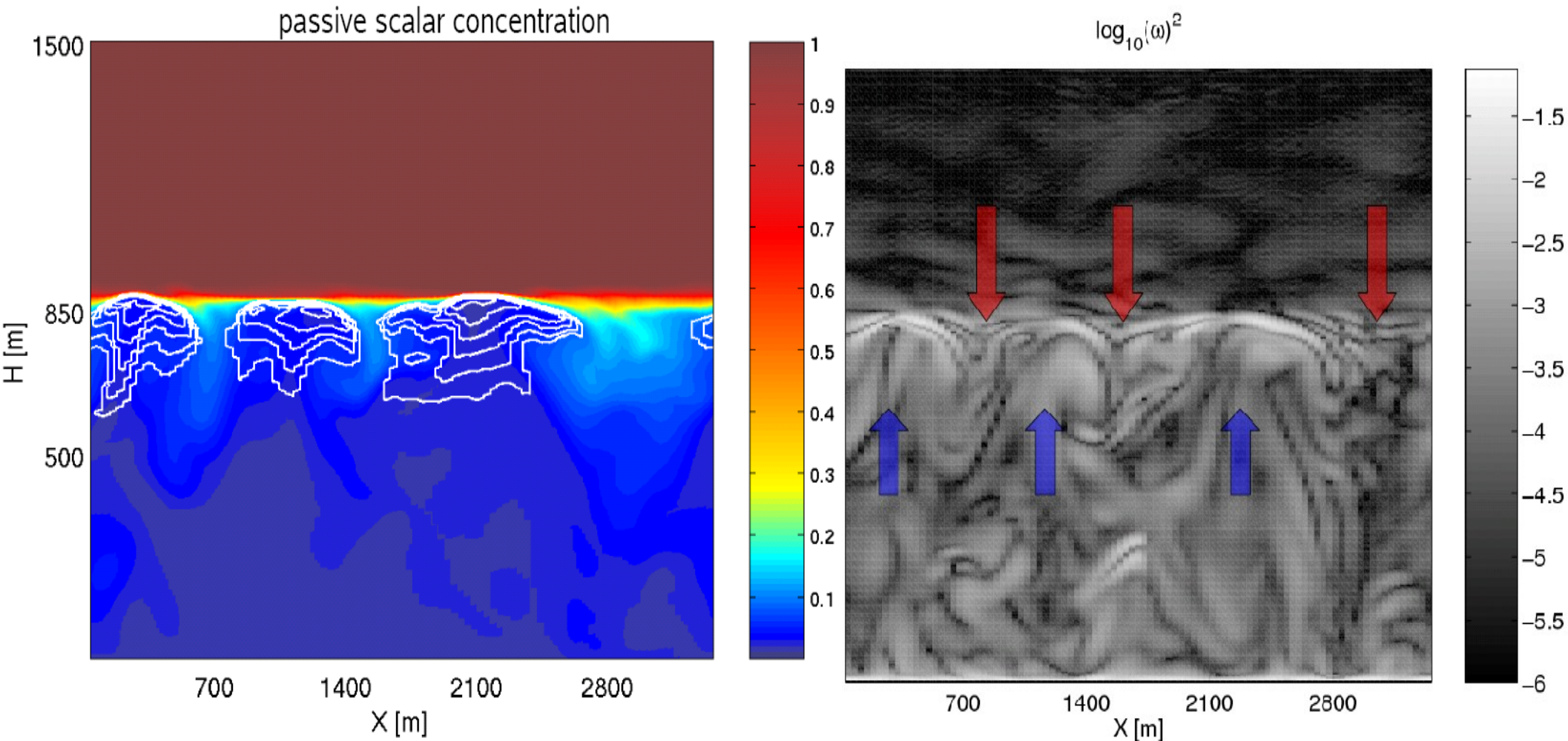


Fig. 3. Average measured values of mean volume radius r_v for the 7 conditionally-sampled Cu at each of 5 levels flown by the aircraft (solid squares); horizontal lines through the data indicate 2 standard deviations of data variability (similar horizontal lines in subsequent plots have the same meaning). Dashed line is the expected value of r_v given adiabatic ascent in the Cu.

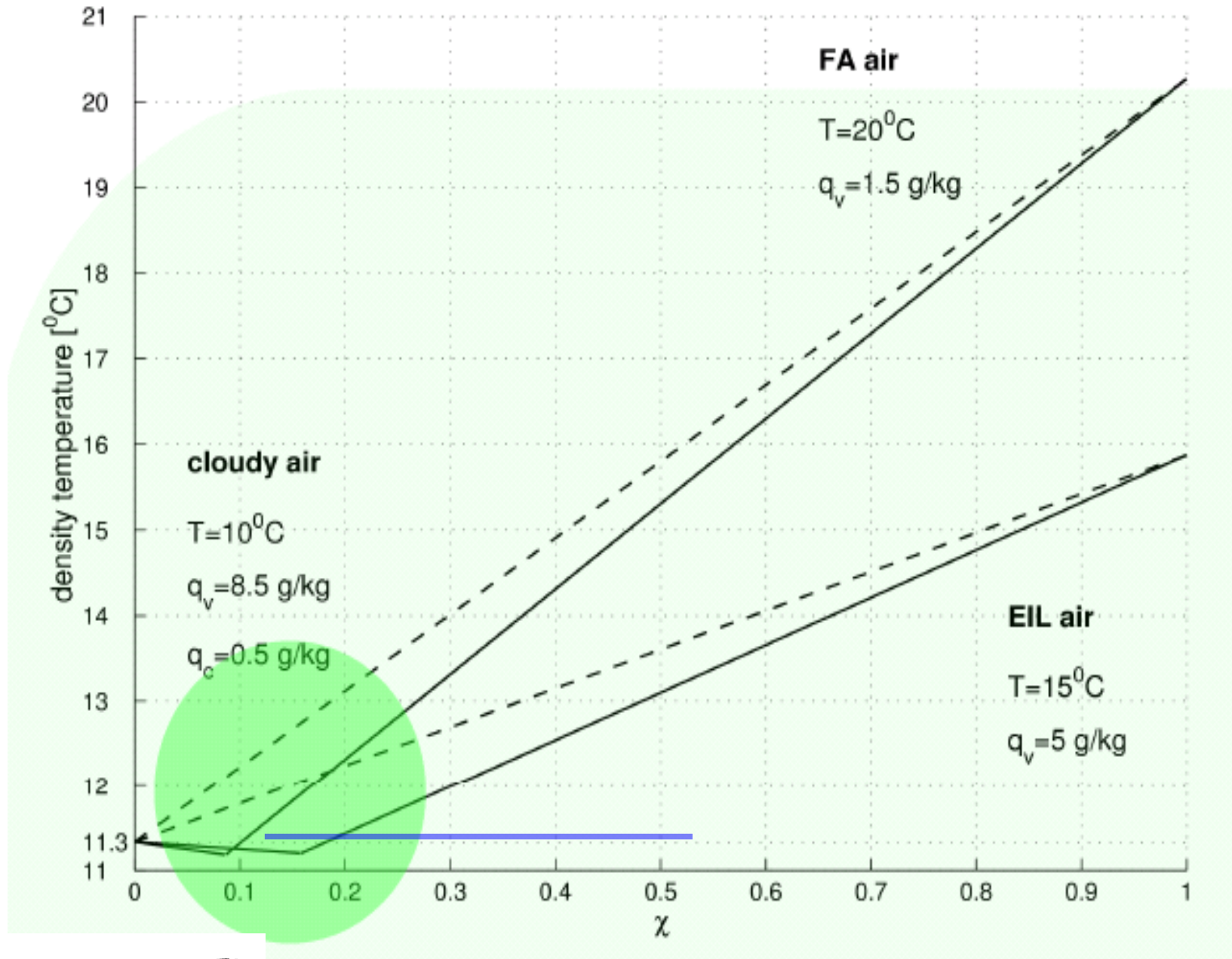
Entrainment into stratocumulus:



Passive scalar concentration χ (left, cloud water contours shown by white lines) and enstrophy (right), at 6 hours of simulations.

Mixing diagram showing buoyancy (density temperature) of mixture of cloud and free-tropospheric air (upper lines) and cloud and EIL air (lower lines).

Negative buoyancy – below the blue line.



$$T_{\rho} = T (1 + \varepsilon q - l)$$

T is the temperature, q is the water vapor mixing ratio, l is the liquid water (cloud droplet) mixing ratio, and $\varepsilon = (R_v / R_d - 1) \sim 0.61$; R_d and R_v are gas constants of dry air and water vapor

Cloud-scale and small-scale turbulence

Entrainment and mixing:

- Cumulus

- Stratocumulus

- Mechanisms for entrainment in clouds

Turbulence and cloud microphysics: motion of cloud droplets

Droplet size distribution

- Condensational growth and turbulence

- Collisions, coalescence and turbulence

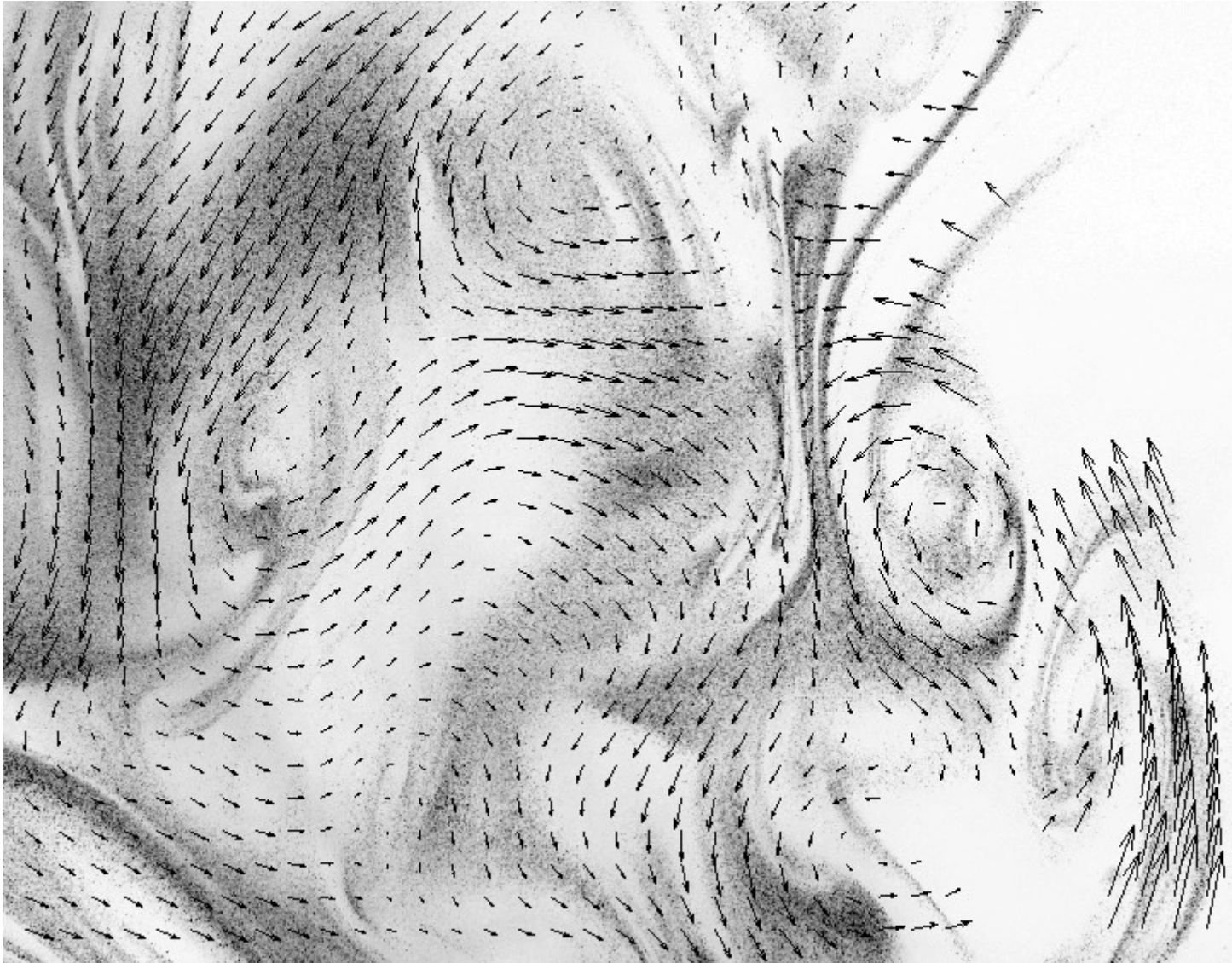
 - Droplet relative velocity

 - Droplet clustering (preferential concentration)

 - Preferential sweeping

- Entrainment and the droplet size distribution

- Homogeneous and inhomogeneous mixing



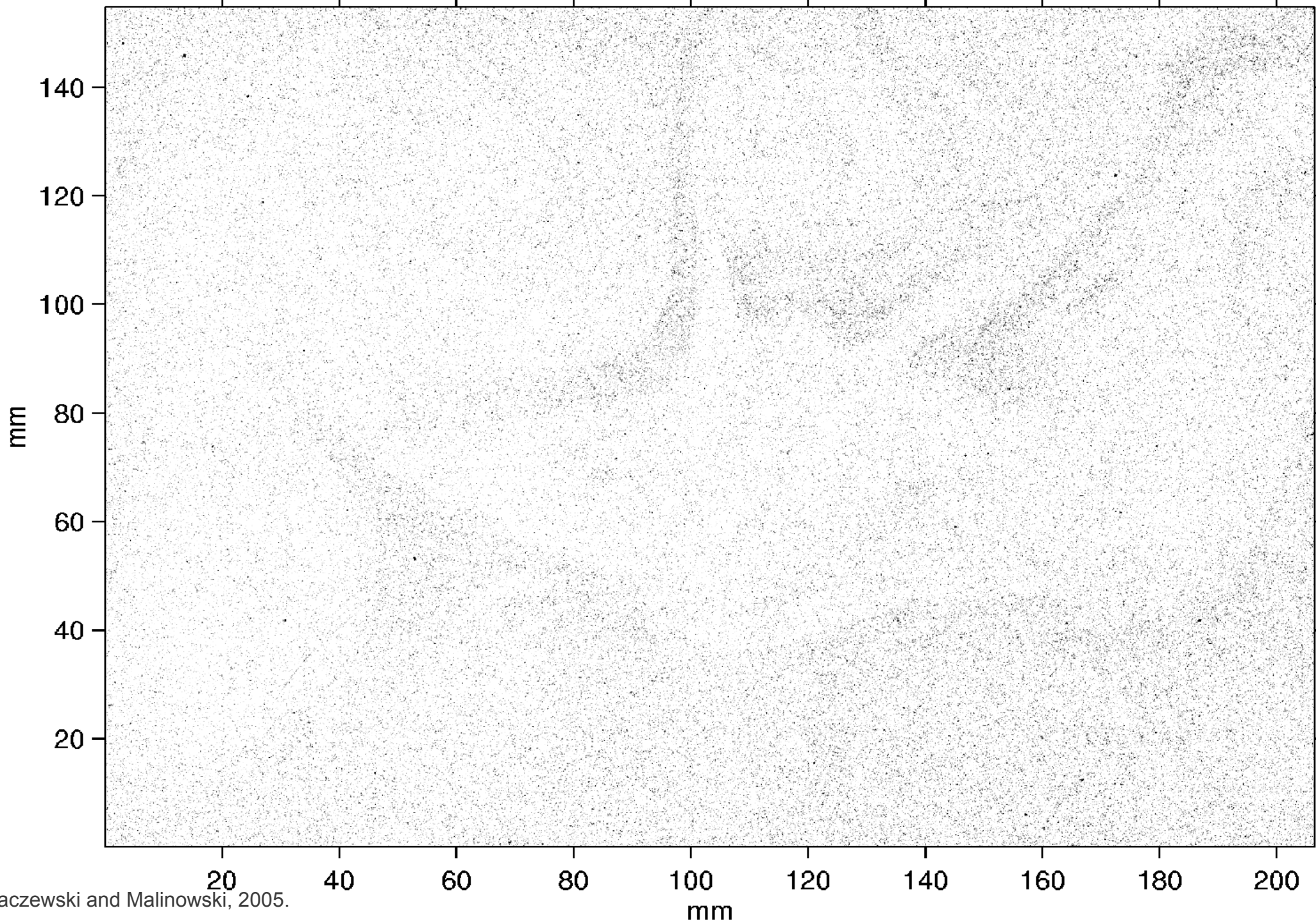
Effects due to turbulence:

preferential concentration,

various mechanism of enhanced collisions,

homogeneous vs. inhomogeneous mixing.

Preferential concentration weak turbulence in cloud chamber.



EXAMPLE: droplets in prescribed stretched vortex flow – 2D projection

Bajer et al., 2000

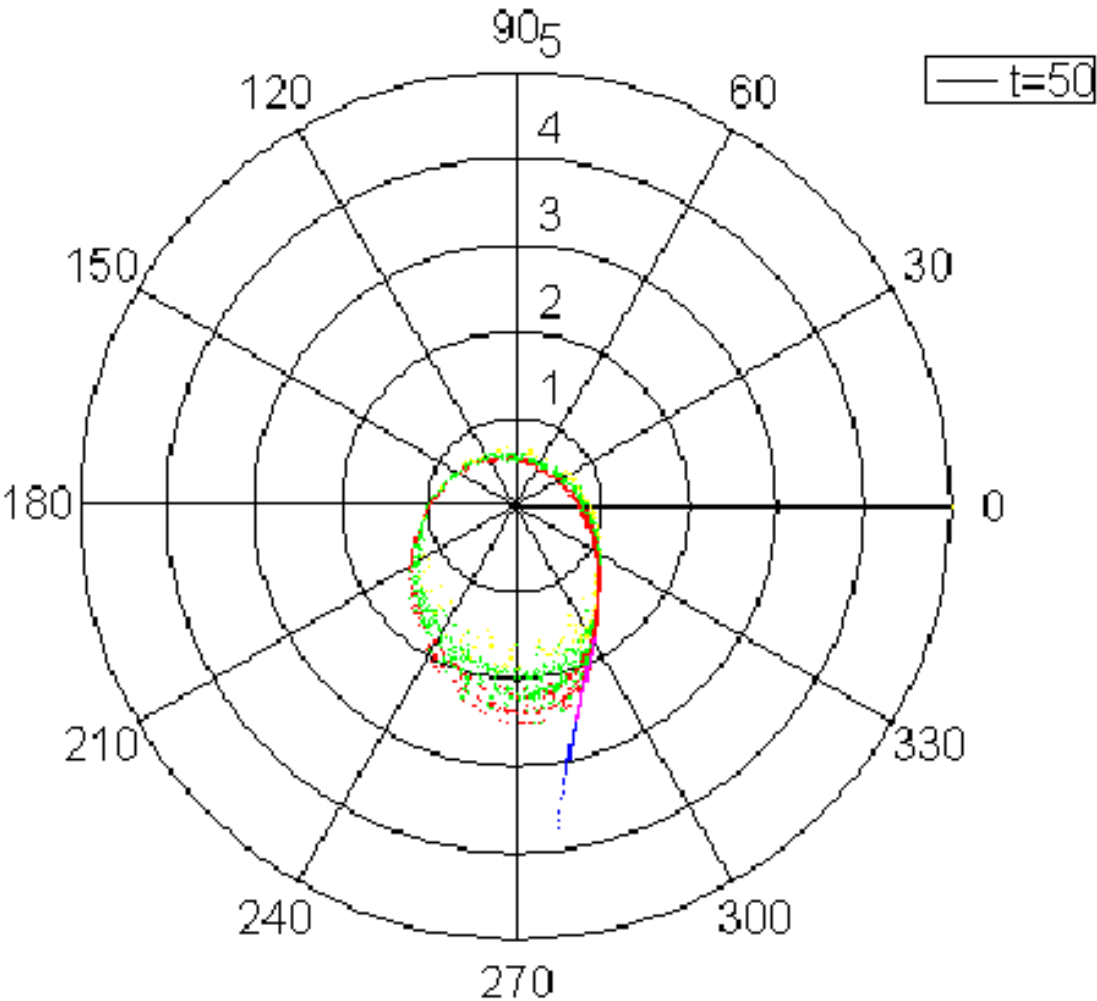


Figure 5: Distribution of droplets with gaussian spectrum after 2.5 turnover times of the vortex. Initial distribution was spatially uniform.

Example: motion of droplets in small-scale vortical structure in fluid.

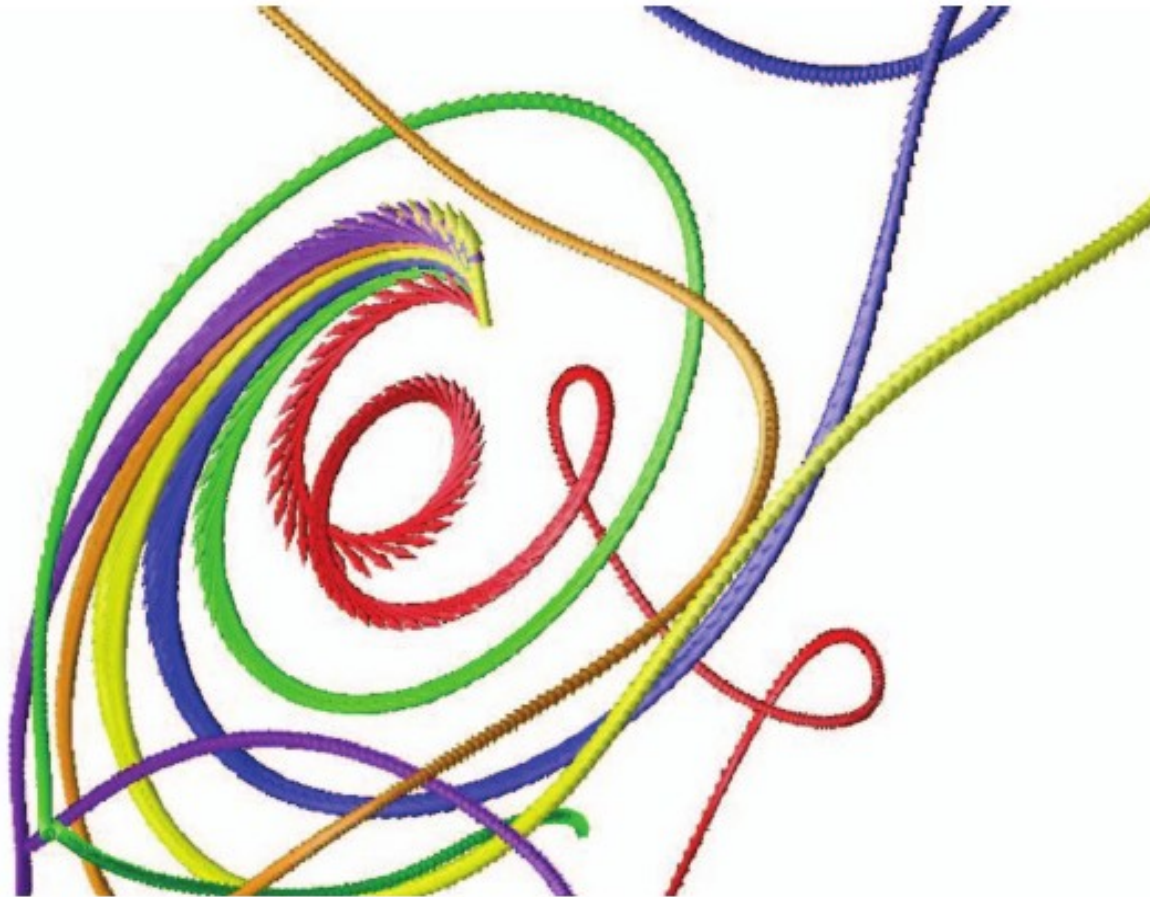
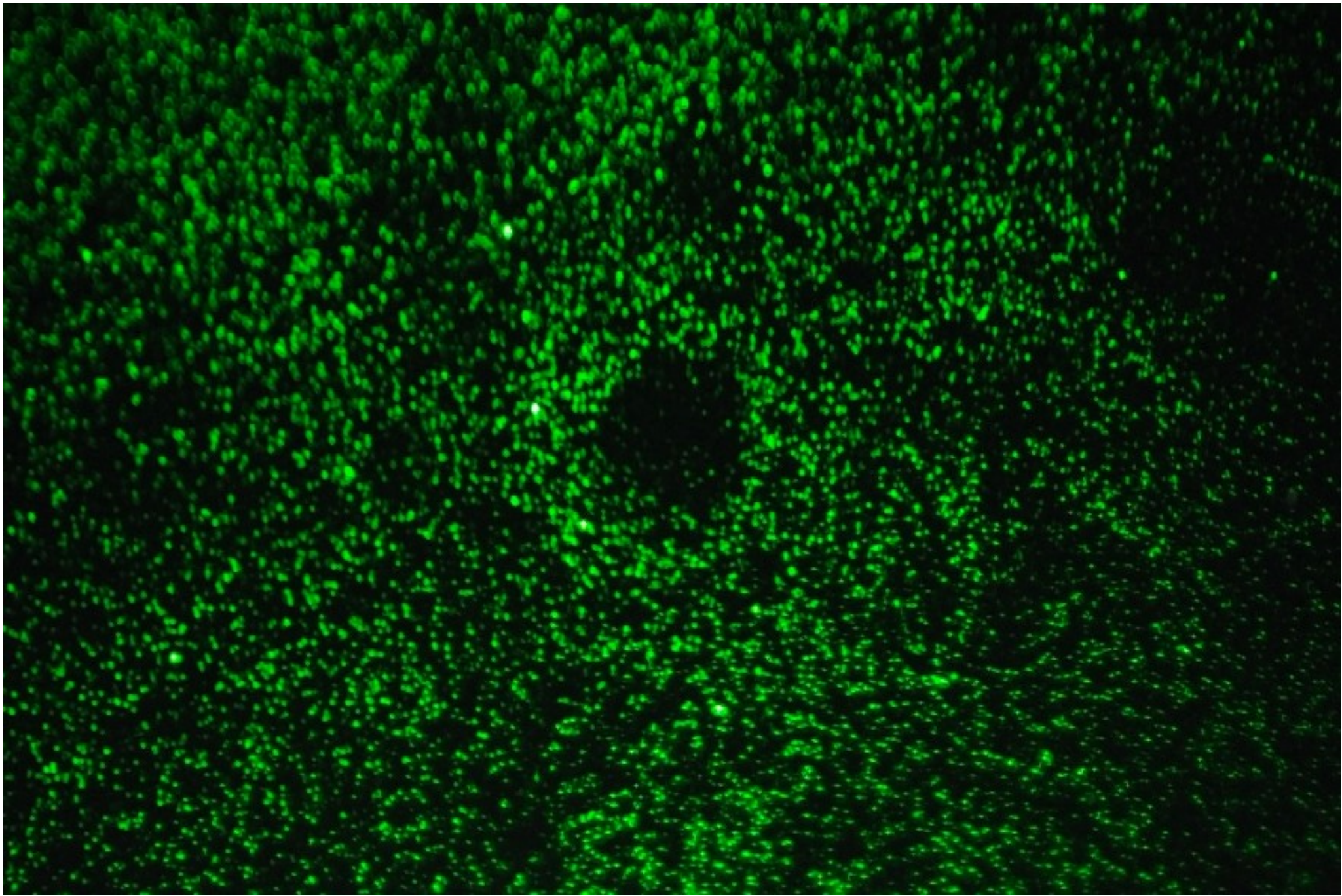


FIGURE 1. – *Particles with different inertia released at the same position and inside a small scale vortical structure of the fluid. The neutrally buoyant particles (red) remain strongly trapped, while particles with higher and higher inertia, respectively green, blue, yellow etc, are less and less sensitive to small scale vorticity.*



First experimental evidence of droplets expelled from vortex tubes in real clouds –
Bodenschatz, Xu, Malinowski et al., 2011, Zugspitze cloud campaign – not published yet....

Length scales associated with condensational growth of droplets.

The condensational growth of droplets is characterized by vapor pressure gradients and temperature gradients.

When the growth of an ensemble of droplets in turbulent air is considered, the temperature and the moisture fields away from the droplet may vary considerably and the concept of ambient conditions becomes vague. The 'boundary conditions' imposed between droplets may depend on both the spatial distribution of droplets as well as on the supersaturation and temperature fields

Vaillancourt et al. (2001) defined the ambient conditions to be the moisture and temperature fields in the vicinity of a given droplet averaged over the volume defined by the mean distance between droplets (so-called point-particle approach to describe the evolution of the droplet phase (adopted by Celani et al., 2007; Lanotte et al. 2009).

Most studies of the growth of an ensemble of droplets neglect the direct thermodynamic interaction between droplets, arguing that the mean distance between cloud droplets (**$\sim 2\text{mm}$ for a typical concentration of 100 cm^{-3}**) is at least an order of magnitude larger than the distance affected by the variation of moisture and temperature due to cloud droplet growth.

Time scales associated with condensational growth of droplets

Scale of diffusional growth of an isolated droplet and in typical conditions is less than 1×10^{-3} s.

Another **time scale** occurs when the boundary conditions for water-vapor concentration and temperature at the surface of the droplet are not assumed constant. During condensation **water vapor diffuses onto the surface of the droplet, latent heat is released, and consequently the surface temperature (the psychrometric temperature) of the droplet changes**. The **relaxation time** associated with this process lies typically between 5×10^{-4} s and 1×10^{-2} s for droplet radii between $5 \mu\text{m}$ and $25 \mu\text{m}$) SLOWEST!!!

Vaillancourt et al. (2001) showed that, for $a=20\mu\text{m}$ and $\varepsilon=100 \text{ cm}^2 \text{ s}^{-3}$, the ratio of this time scale to fastest time scale associated with changes to the ambient conditions due to turbulence (either τ_η or τ_v) is much less than one and the assumption of a steady-state distribution of water-vapor concentration and temperature is valid.

Numerical simulations by Celani et al. (2005, 2007), Lanotte et al. (2009), Sidin et al., (2009) suggest that cloud droplet spectra can be broadened during condensation, which is different from simulations of Vaillancourt et al. (2002) and from the measurements in real clouds (as we can interpret them).

Collisions, coalescence and turbulence

The collision and coalescence of droplets in a turbulent flow are governed by

- (i) **geometric collisions due to droplet-turbulence interactions;**
- (ii) **collision efficiency due to droplet-droplet interactions**
- (iii) **coalescence efficiency due to droplet surface properties.**

In practice, it is difficult to distinguish between collision and coalescence and the experimentally measurable quantity is collection efficiency defined as the ratio of the actual cross-section for droplet coalescence to the geometric cross-section.

Geometric collisions

DNS results (e.g. Franklin et al. 2007; Ayala et al. 2008a) show that **turbulence can increase the collision kernel relative to the case of stagnant air by two effects:**

droplet relative velocity

droplet clustering.

Turbulence may also affect the droplet relative velocity through preferential sweeping whereby droplets bias their downward trajectories towards regions of higher turbulence thus increasing their terminal velocities relative to still air.

Caustics (sling effect) are also considered (e.g. Falkovich and Pumir, 2007)

In multidisperse suspensions, w_{12} is always larger than its monodisperse counterpart.

This can be understood by considering a limiting case of monodisperse suspension, in the absence of gravity. For low St , velocities of equally sized droplets are strongly correlated, both with the fluid and each other.

As St increases, the correlation of the droplets with the flow and each other decreases and $|w_{12}|$ increases. However, for $St \gg 1$, droplets respond slowly to changes in the fluid velocity and $|w_{12}|$ decreases.

For multidisperse droplets, the velocities of the droplets decorrelate more rapidly than the equivalent monodisperse cases since the droplets with different inertia respond differently to changes in the flow.

Computational results

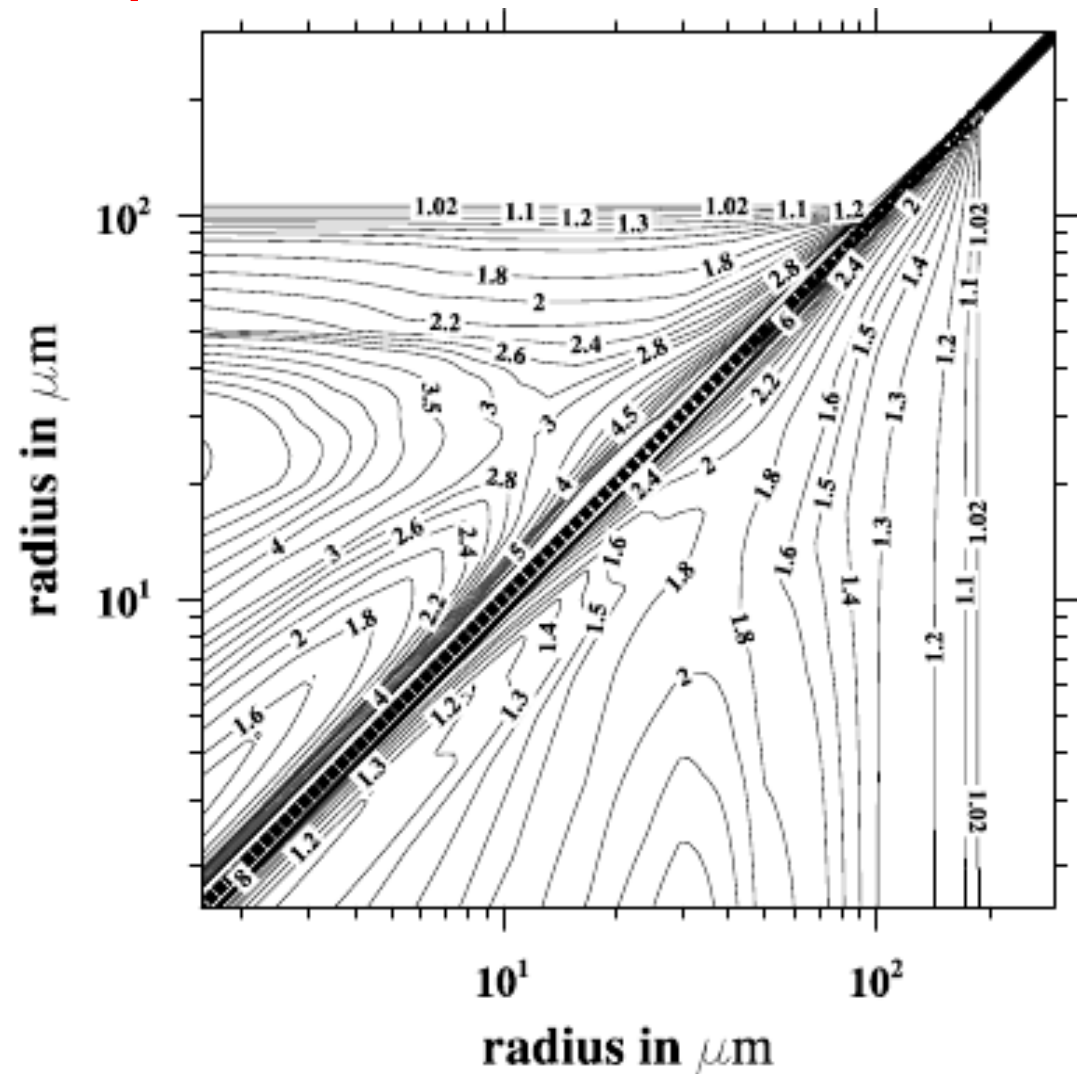


Figure 2. The ratio of a typical turbulent collision kernel to a purely gravitational collision kernel (Grabowski and Wang, 2009). The ratio on the 45° degree line is undefined due to the zero value of the gravitational kernel. The ratio is essentially one when droplets are greater than $100 \mu\text{m}$. The flow dissipation rates are $400 \text{ cm}^2 \text{ s}^{-3}$ and $100 \text{ cm}^2 \text{ s}^{-3}$ in the upper-left and lower-right part of the figure respectively.

However....in situ measurements...

With the **improved** size and spatial resolutions of the Fast-FSSP measurements it has been possible to identify **very narrow spectra** in most of the cloud traverses ...

These spectra are **much narrower than previously measured with the standard probe.**

The regions of narrow spectra show characteristics close to the adiabatic reference, such as LWC values slightly lower than the adiabatic value at that level and values of droplet concentration close to the maximum value within the cloud traverse. **The spectra observed in these regions are narrow but still broader than the adiabatic reference.**

The high concentration densities of droplets with diameter smaller than the mode can be attributed to partial evaporation of some droplets resulting from the mixing with dry air. The occurrence of this process is attested by the slightly subadiabatic values of LWC.

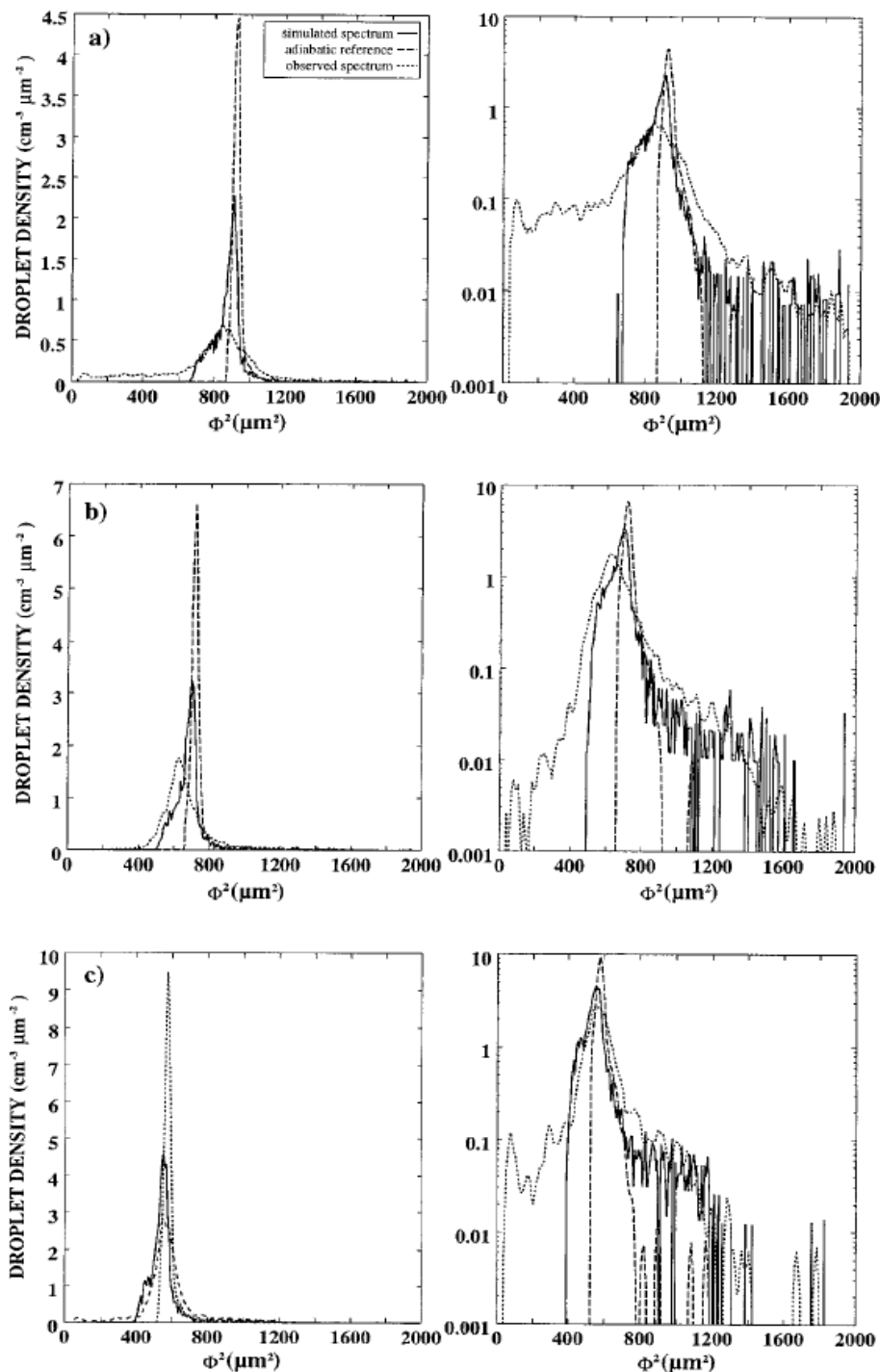


FIG. 4. Three examples of the comparison between an observed spectrum (dotted line) and the adiabatic reference (dashed line), after instrumental broadening by the Fast-FSSP simulator (solid line). The total droplet number concentrations are, respectively, 225 (a), 329 (b), and 455 cm⁻³ (c).

Short summary of clustering and collisions:

Observations of droplet clustering in real clouds remain ambiguous which has led some authors to question its importance in real clouds.

Moreover, DNS of sedimenting droplets has shown that turbulent enhancement of collision rates occurs primarily through changes to the droplet relative velocity and the collision efficiency.

Nevertheless, some argue that the vortex tubes that are associated with small-scale turbulence at high Reynolds numbers persist for long and droplets with a considerable range of St are able to spin out of the vortex.

The importance of intermittency in potentially increasing droplet clustering has also been raised by Falkovich et al. (2002) who based on theoretical arguments claim that clustering can increase collisions by a factor of 10.

Without a clear theoretical basis for the R_λ -dependence of clustering, which will remain valid in the large- R_λ limit, it is likely that these arguments will continue.

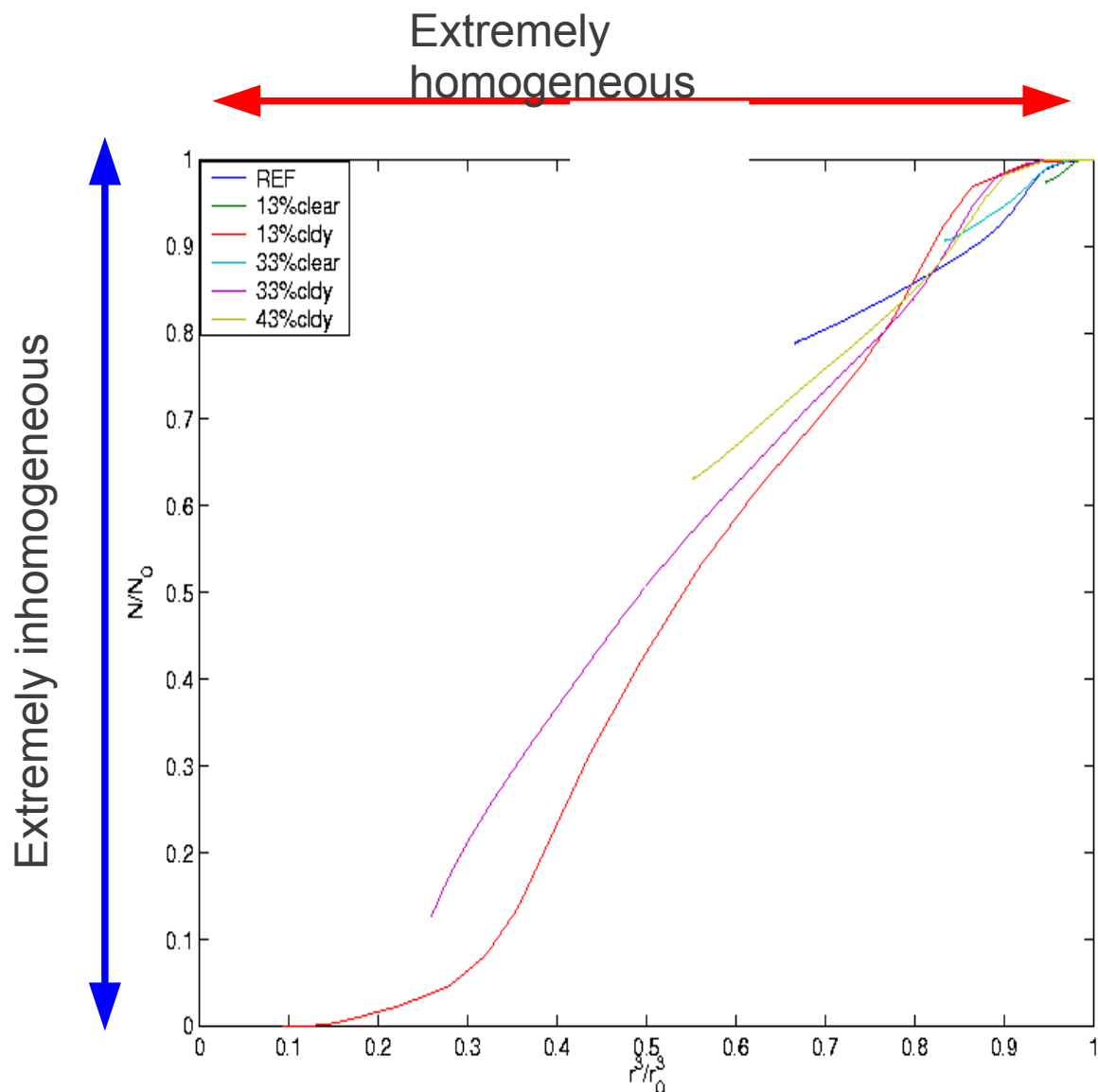
Homogeneous vs. Inhomogeneous mixing (Baker and Latham 1979)
 n numerical simulations of small-scale mixing

$$\tau_{mix} \equiv \frac{L}{U(L)} \sim \left(\frac{L^2}{\epsilon}\right)^{1/3}$$

$$\tau_{evap} \equiv \tau \left(\frac{dr}{dt}\right)^{-1} = \frac{r^2}{A(1 - RH)}$$

In the homogeneous mixing scenario, the number of droplets does not change and the mean droplet size decreases. In the extreme inhomogeneous mixing scenario, droplets from a fraction of the cloudy volume evaporate completely to bring the mixture to saturation, and the droplets from the rest of the cloudy volume are dispersed over the combined volumes without changing their size.

If the droplet evaporation time scale is much larger than the time scale of turbulent homogenization, the mixing is expected to be close to homogeneous. In the opposite limit (i.e., the droplet evaporation time scale much smaller than the time scale of turbulent homogenization), the mixing is supposed to be close to the extremely inhomogeneous.



Small-scale turbulence/rain formation in clouds – a subgrid scale process

- a) inadequate measurement capabilities
(resolution problem, different sampling volumes of various sensors)
- b) subgrid-scale processes in cloud resolving and LES simulations.

Closing the gap in resolved scales

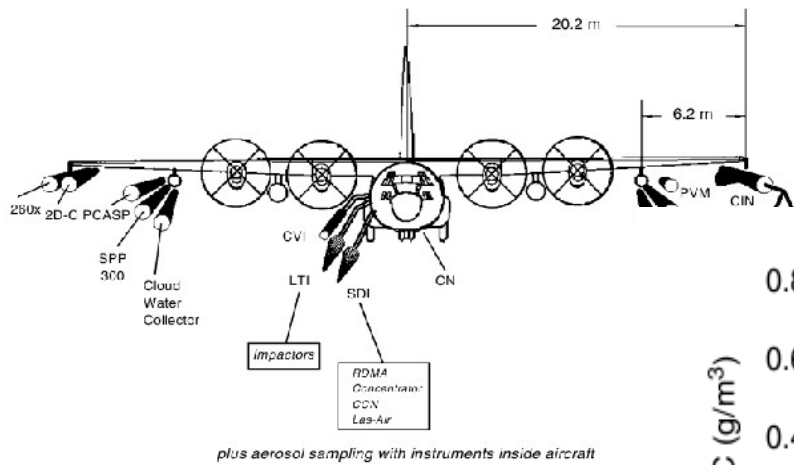
- a) DNS and particles in turbulence;
- b) laboratory experiments with particle tracking and collisions.
- c) in situ efforts.

Issues

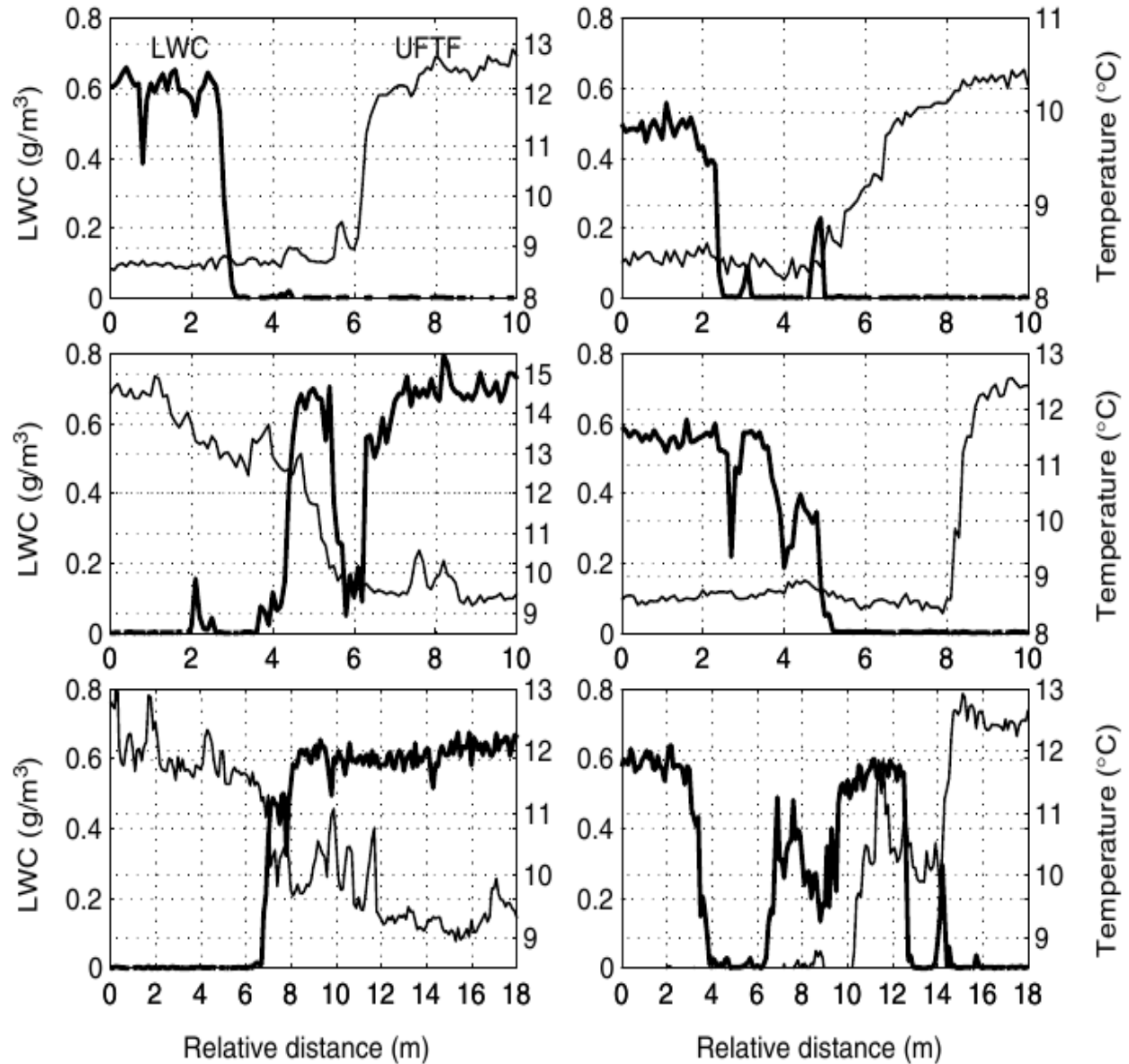
- a) (almost) no combined measurements of microphysics, turbulence and dynamics in small-scales;
- b) problems with the statistical interpretation of data from measurements;
- c) unclear subgrid-scale parameterizations in cloud simulations.

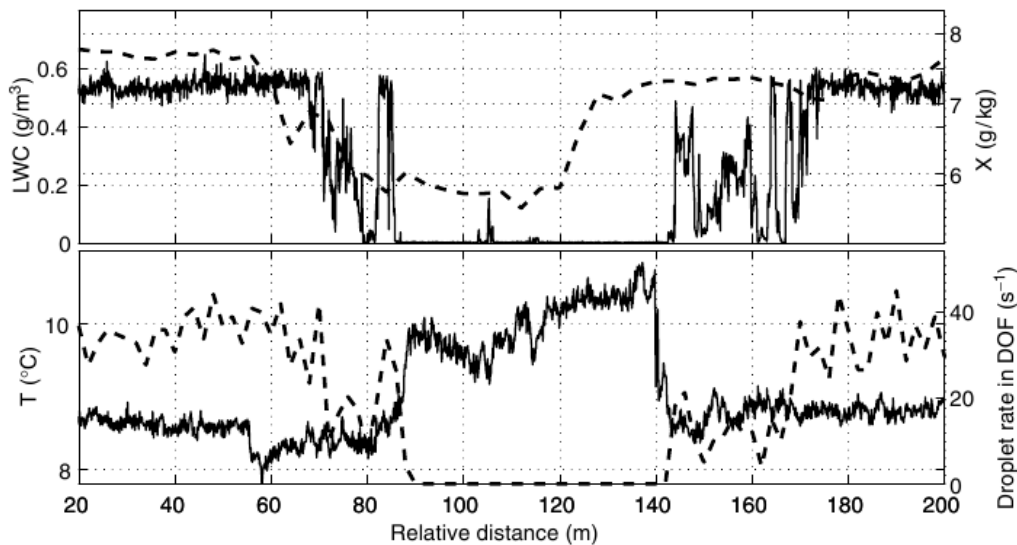
In the following: my efforts to address issues....

DYCOMS-II Probe Locations

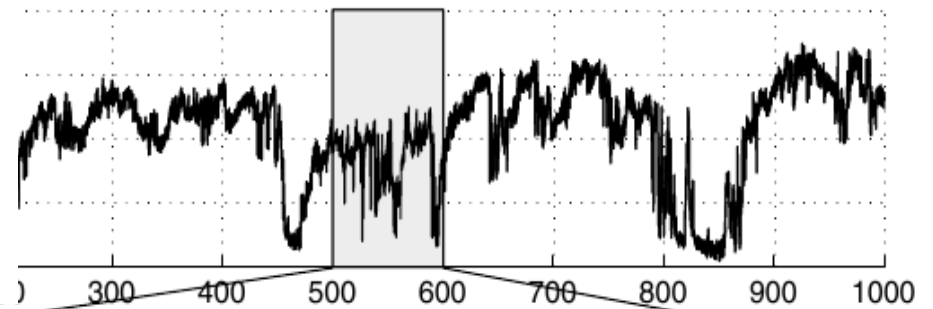
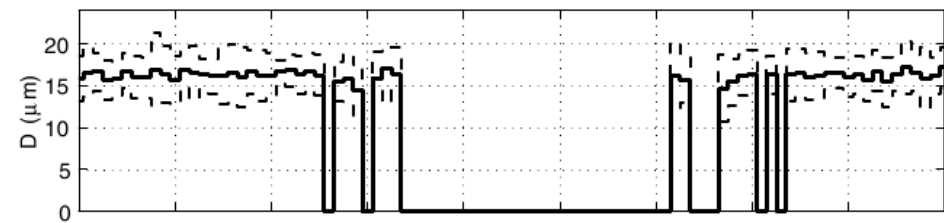


Examples of the cloud edge in 1000 Hz temperature (thin line) and LWC (thick line) records. Sharp jumps in LWC and temperature at distances of the order of 10 cm (data resolution) are currently observed. Notice a shift between the temperature and LWC records resulting from the 6 m separation between the instruments and the low pitch angle of the aircraft with respect to the cloud clear air interface.

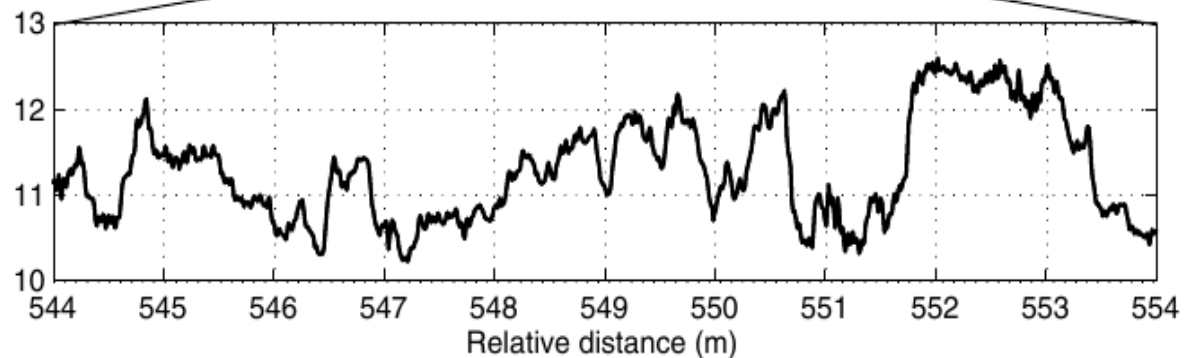
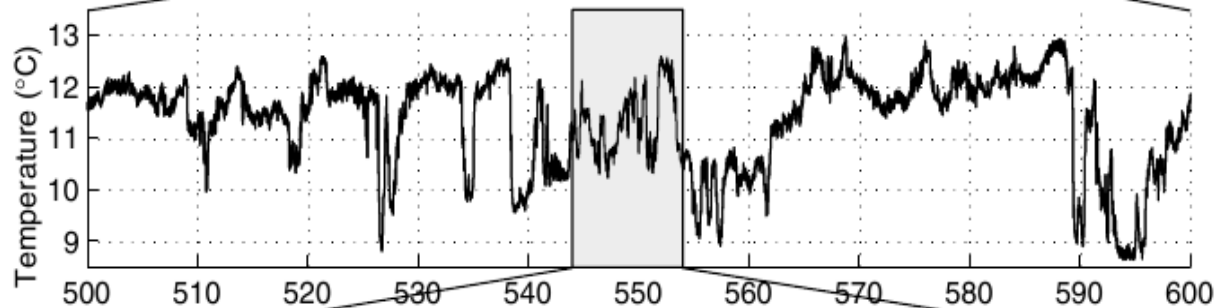




Penetration through a mixing event at Sc top



From the top to the bottom: successive ‘blow ups’ of 10 kHz temperature records showing self-similar structures – filaments of significantly different temperatures separated by narrow interfaces. The bottom panel presents the evidence for filaments of thickness of the order of 10 cm as well as for the steep gradients of temperature. Notice that UFT-F in its present configuration and signal conditioning (low-pass filtering) is still too slow to resolve adequately all interesting small-scale features of the temperature field.



Airborne measurements of small-scale turbulent mixing in clouds

POST – Physics of Stratocumulus Top, California, 2008

aerosol (CCN)



microphysics

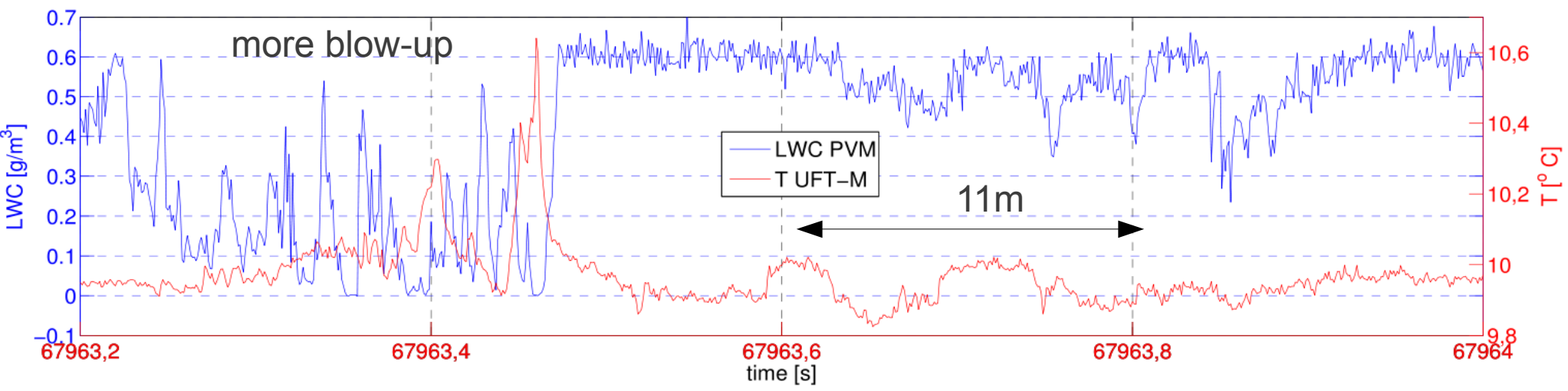
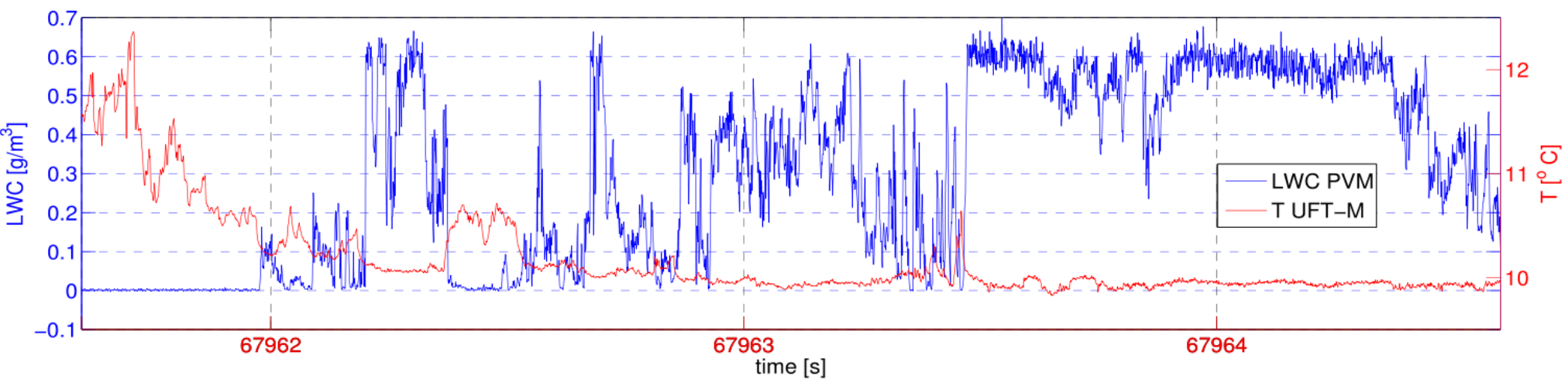
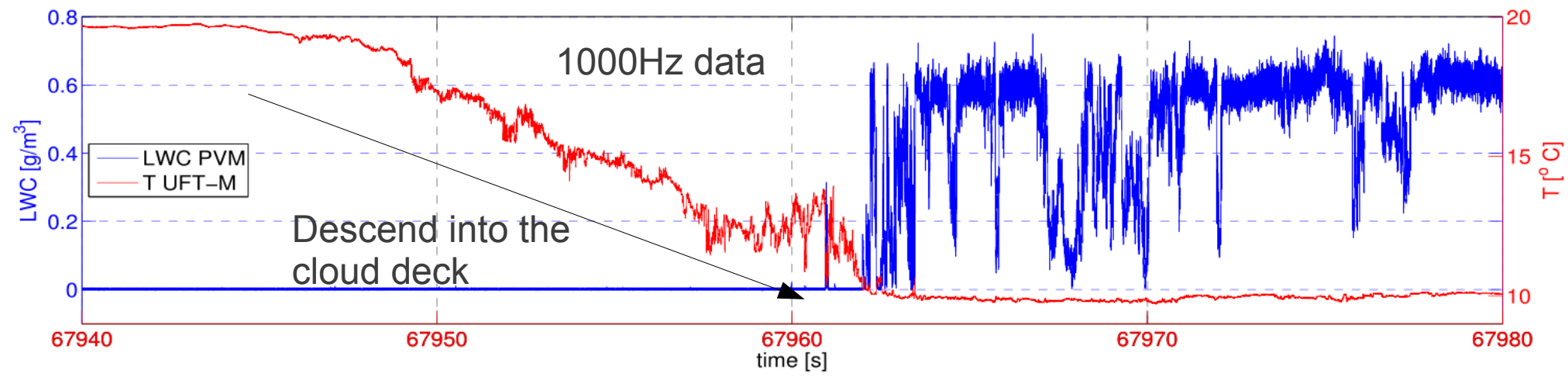


temperature,
humidity,
liquid water,
turbulence,



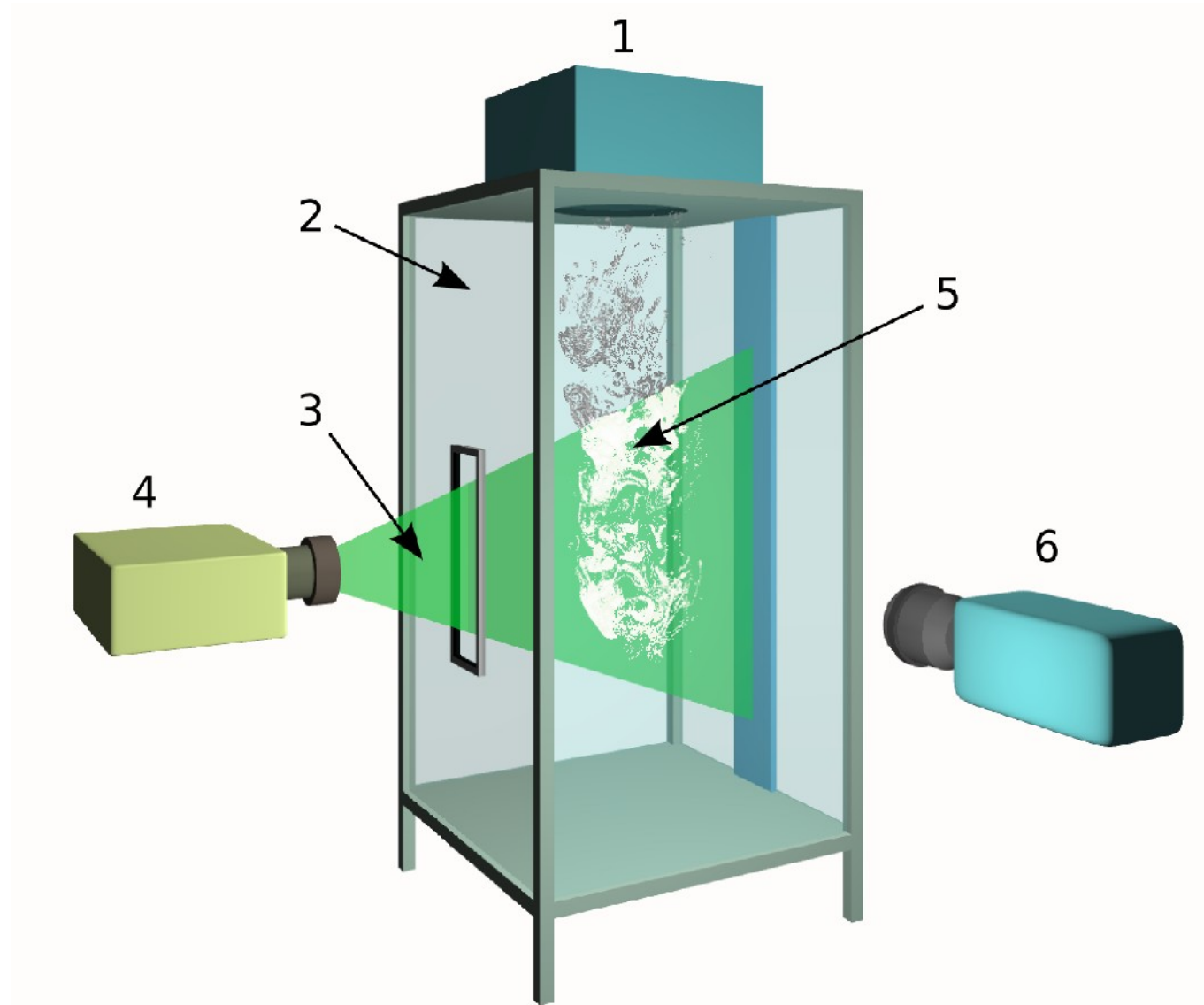
droplet counting





Turbulent cloud chamber.

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.



PIV – Particle Imaging Velocimetry

Principle:

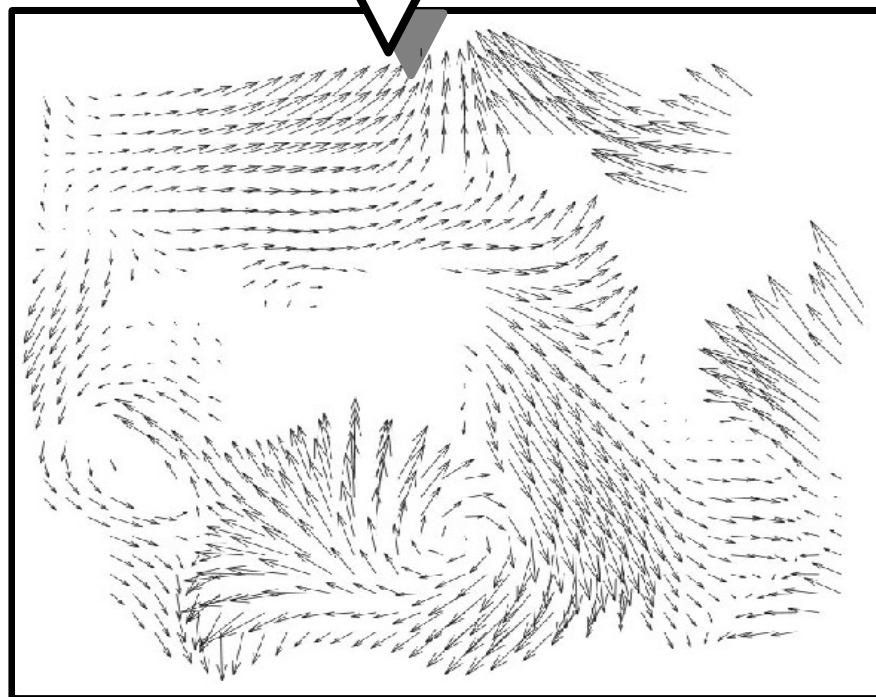
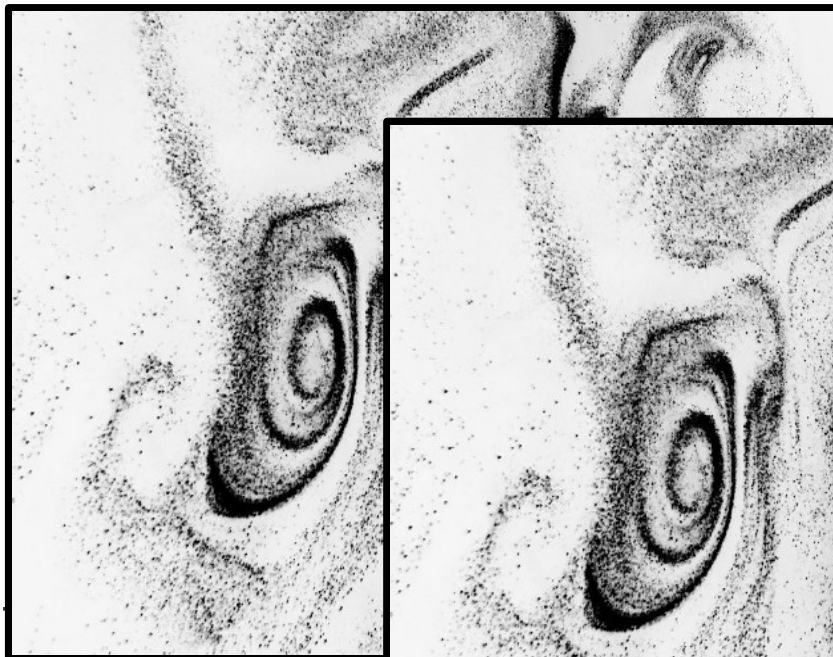
two consecutive frames compared; displacement of patterns allows to determine two components of the velocity

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.



Numerical simulations of small scales of cloud mixing with the environment.



$$B \equiv g \left[\frac{T - T_0}{T_0} + \varepsilon(q_v - q_{v0}) - q_c \right],$$

Equations for dynamics,
thermodynamics and
microphysics (droplets)

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

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

Non-standard symbols:

π – normalized pressure fluctuation

C_d – condensation rate

q_v, q_c – specific humidity, liquid water content

B – normalized buoyancy

$$\nabla \cdot \mathbf{v} = 0,$$

$$\frac{DT}{Dt} = \frac{L}{c_p} C_d + \mu_T \nabla^2 T,$$

$$\frac{Dq_v}{Dt} = -C_d + \mu_v \nabla^2 q_v,$$

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

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

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

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

Andrejczuk et al., 2004,
Andrejczuk et al., 2006
Malinowski et al., 2008
Andrejczuk et al., 2009

Simplified set of equations of cloud dynamics, thermodynamics and microphysics :

$$D/Dt \equiv \partial/\partial t + \mathbf{v} \cdot \nabla \quad B \equiv g \left[\frac{T - T_0}{T_0} + \varepsilon(q_v - q_{v0}) - q_c \right], \quad (2)$$

π – normalized pressure fluctuation

C_d – condensation rate

q_v, q_c – specific humidity, liquid water content

B – normalized buoyancy

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

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

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

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

$$\frac{Dq_c}{Dt} = C_d. \quad (3)$$

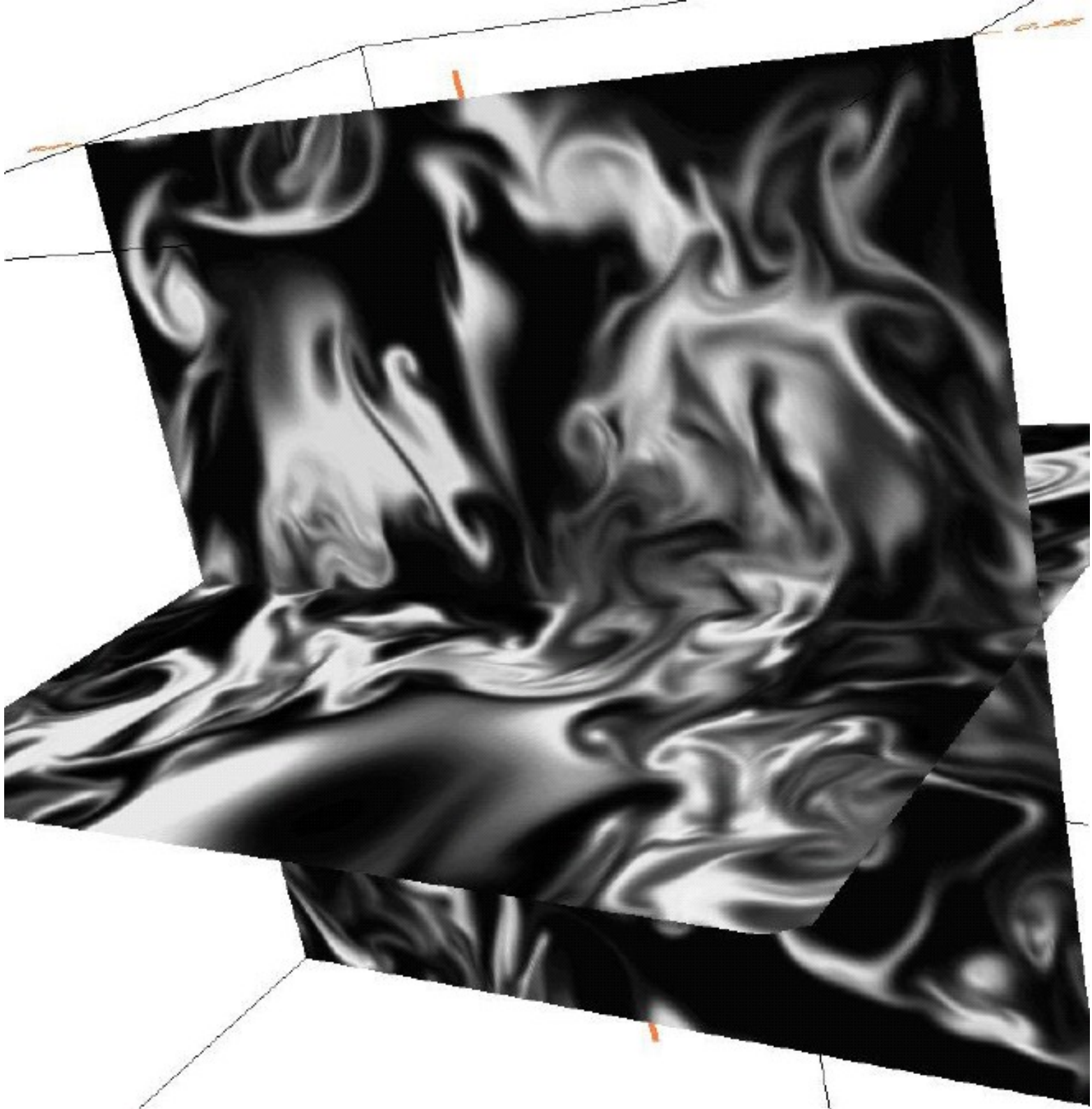
$$C_d = \int f \frac{dm}{dt} dr,$$

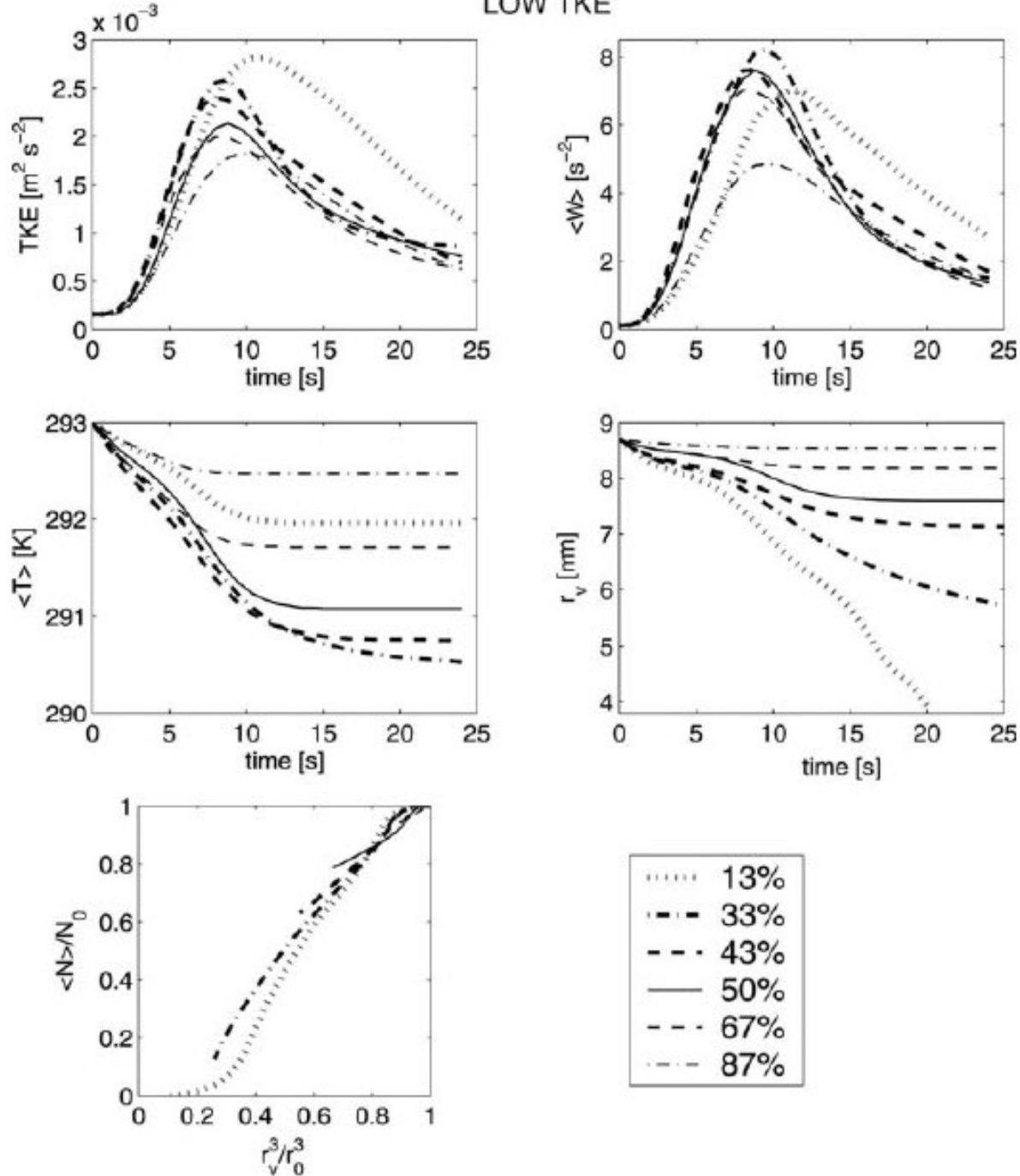
$$\frac{D^* f}{D^* t} = -\frac{\partial}{\partial r} \left(f \frac{dr}{dt} \right) + \eta,$$

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

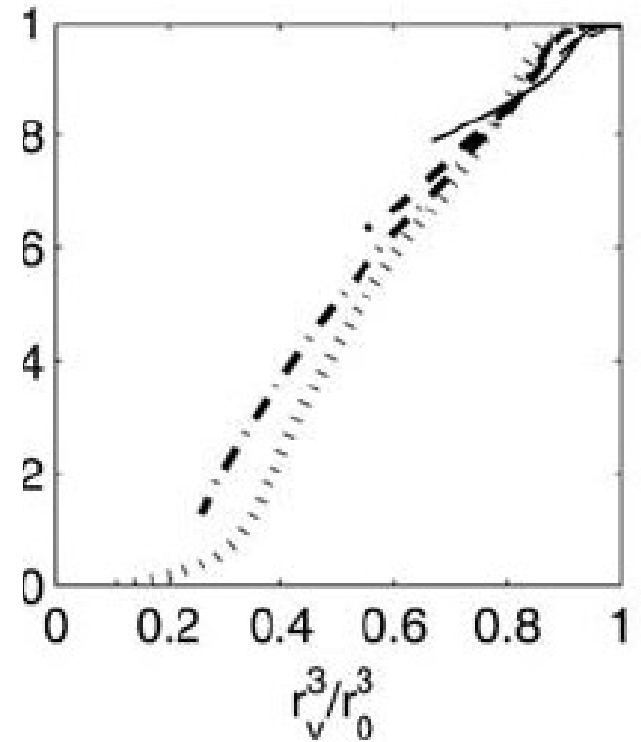
$f(\mathbf{x}, r, t)dr$ is the number of cloud droplets in a unit mass of air (viz. the mixing ratio) of the radius between r and $r + dr$, at a given point (\mathbf{x}, t) in space and time.

LWC
after
11s





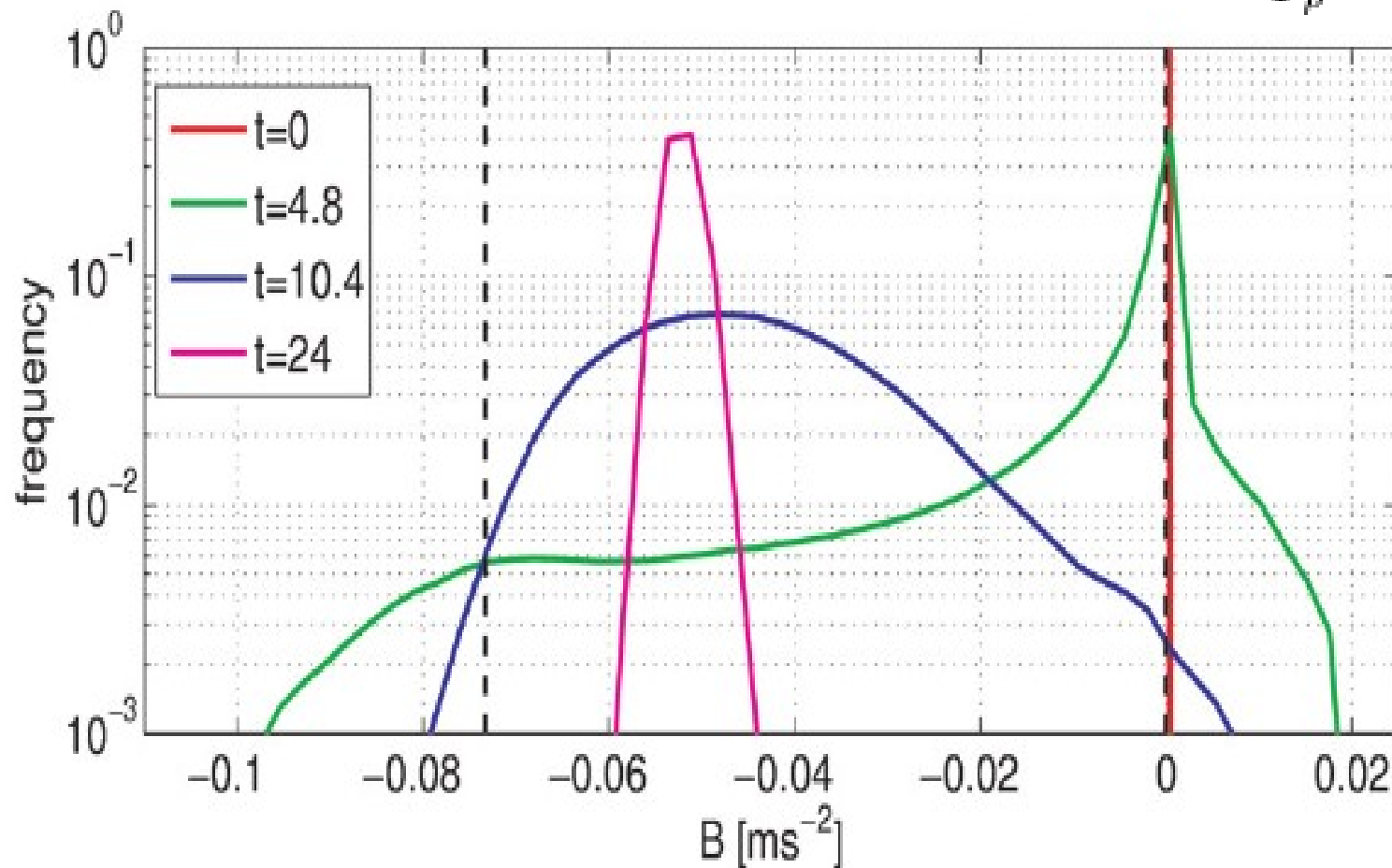
Evolution of flow parameters in several runs



Andrejczuk et al., 2006

FIG. 6. Results from the set of numerical simulations with low-TKE input and detailed microphysics applying the reference setup: set S2a. The evolution of the (top left) TKE and (top right) mean enstrophy. The evolution of the (middle left) mean temperature and (middle right) mean volume radius. (bottom left) The evolution of the microphysical properties using the $r - N$ diagram.

$$T_\rho = T (1 + \varepsilon q - l) ,$$



Evolution of buoyancy in model domain: irreversible evaporative cooling

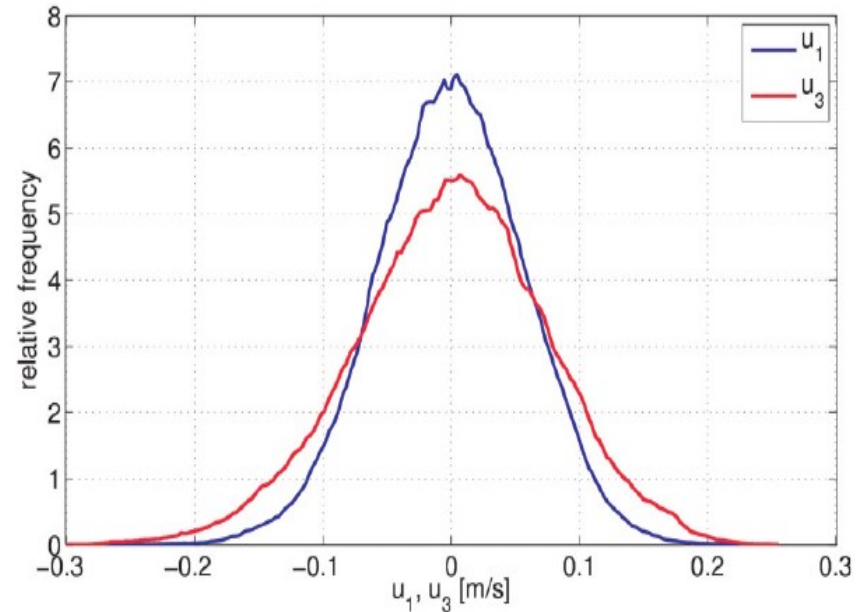
Figure 3. Histograms of buoyancy within the model domain at the beginning of calculations and at times of 4.8, 10.4 s and at the end of calculations (24 s). Dashed black lines show the range of buoyancy fluctuations due to isobaric and adiabatic mixing.

Anisotropy of turbulent velocities due to buoyancy production by evaporative cooling (Malinowski et al., 2008, Korczyk et al., 2012).

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

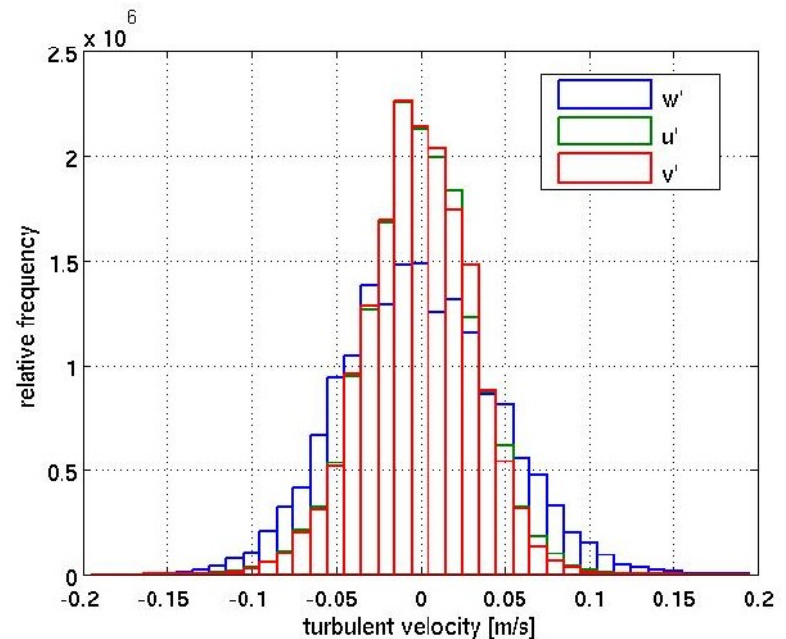
$$(u_1)^2 / (u_3)^2 = \mathbf{0.46 \pm 0.07}$$

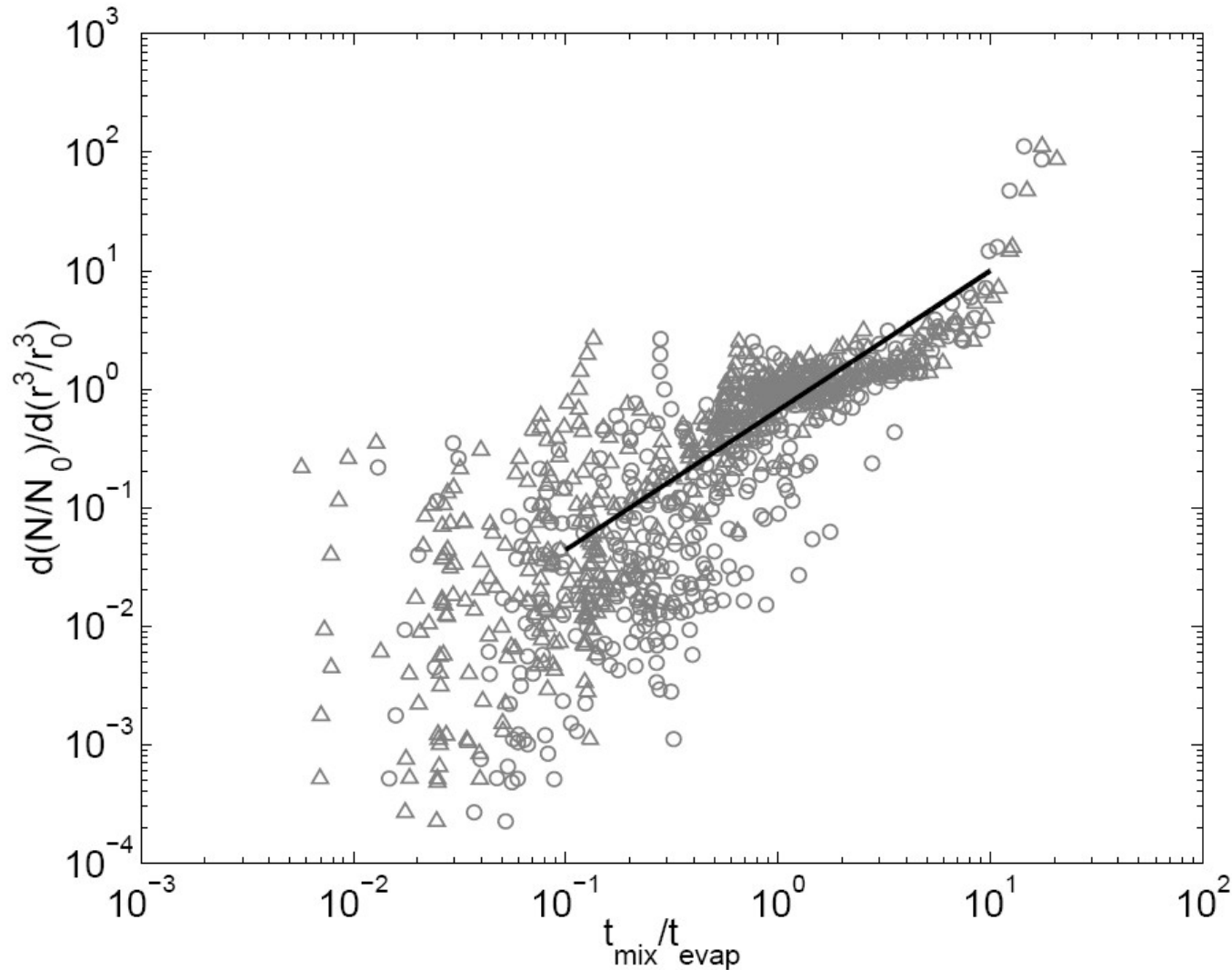


Numerical (LWC 3.2 g/kg):

	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

$$(u_{hor})^2 / (u_3)^2 = \mathbf{0.52 \pm 0.07}$$





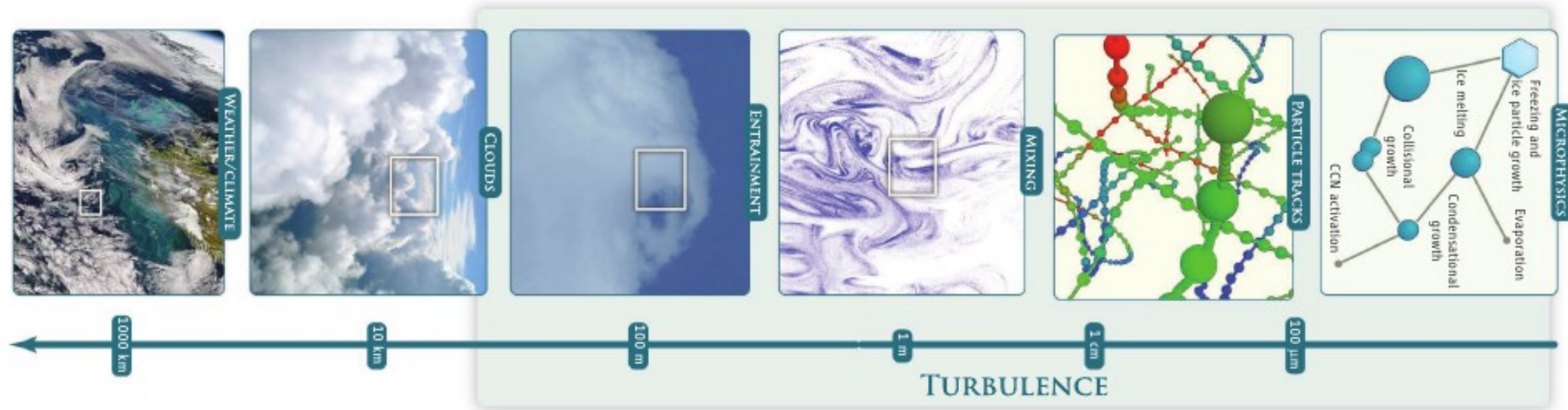
$$\tau_{mix} \equiv \frac{L}{U(L)} \sim \left(\frac{L^2}{\epsilon} \right)^{1/3}$$

$$\tau_{evap} \equiv r \left(\frac{dr}{dt} \right)^{-1} = \frac{r^2}{A(1 - RH)}$$

Scatter plot of the slope of the mixing line on the $r - N$ diagram versus the ratio between the turbulent mixing and the droplet evaporation time scales. Each data point represents analysis of instantaneous DNS data as explained in text, with triangles (circles) depicting data points with the mixing time scale calculated using TKE (enstrophy). The solid line is the proposed relationship to be used in subgrid-scale modeling.

SUMMARY AND COCLUSIONS:

CREDIT: (MICROPHYSICS) F. STRATMANN; (TRAJECTORIES) E. BODENSCHATZ, SCIENCE MAGAZINE TABLE OF CONTENTS, 10 FEBRUARY 2006; (MIXING) S. MALINOWSKI, (ENTRAINMENT AND CLOUD) R. A. SHAW; (GLOBAL) NASA EARTH OBSERVATORY



Clouds are dispersions of drops and ice particles embedded in and interacting with a complex turbulent flow. They are highly nonstationary, inhomogeneous, and intermittent, and embody **an enormous range of spatial and temporal scales**. Strong **couplings across those scales between turbulent fluid dynamics and microphysical processes** are integral to cloud evolution.

Turbulence drives entrainment, stirring, and mixing in clouds, resulting in strong fluctuations in temperature, humidity, aerosol concentration, and cloud particle growth and decay. It **couple to phase transition processes** (such as nucleation, condensation, and freezing) **as well as particle collisions and breakup**. All these processes feed back on the turbulent flow by buoyancy and drag forces and affect cloud dynamical processes up to the largest scales.

The last decades have seen the emergence of new views into the “inner workings” of both clouds and turbulent flows.

For example, **high-resolution measurements** of temperature, liquid water content, aerosol physical and chemical properties, and airflow **reveal fascinating small-scale cloud structures**, invisible with earlier technology.

Laboratory experiments and **numerical simulations** are allowing us to study details of cloud microphysics, the **fine structure of turbulence**, turbulent **Lagrangian dynamics, interactions and collisions between droplets**.

Scale-resolving simulations merging computational methods from both cloud and turbulence communities are yielding new insights into the wide **variety of circulation regimes**.

These new tools, experimental and computational, have begun to make it possible to explore the full complexity of microphysical and fluid-dynamical interactions within clouds.

We can now begin to address:

- How does **turbulence influence phase transition processes** like condensation, evaporation, activation, and freezing taking place inside clouds?
- How does **turbulence influence particle-particle interactions** like collisions, coalescence efficiencies, ice aggregation, and drop- or ice-breakup?
- How do **microphysical processes feed back on the turbulence** through latent-heat release, energy injection at small scales, and buoyancy reversal?
- How do **small scale processes propagate to and couple to the larger scales**, such as, cloud dynamics, precipitation formation, and radiative properties?

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