THE SMALL-SCALE STRUCTURE OF TURBULENCE IN MARINE STRATOCUMULUS

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1 INTRODUCTION

The statistics of small-scale turbulence in clouds is an important issue when dealing with mixing and coalescence processes. Many of these turbulent processes take place on small scales down to the distances between the cloud droplets themselves, which also corresponds to the energy dissipation scale ($\sim$ mm for atmospheric conditions). However, whereas measurements of small-scale turbulence under cloud-free conditions have been successfully performed for many decades, measurements under cloudy conditions with sub-meter resolution are still an experimental challenge and are quite rarely presented. The main reason for the lack of high-resolution turbulence data in clouds might be based on the typically high true air speed (TAS) of research aircraft and, therefore, the high sampling frequency needed to resolve sub-meter structures of the flow field. On the other hand, sensors typically used in laboratory or atmospheric (but ground/tower-based) experiments such as hot-wire anemometers are fragile and only a few airborne turbulence measurements (e.g., Lenschow et al., 1978) and especially in two-phase flows are presented (Merceret, 1970, 1976; Sheih et al., 1971; Andreas et al., 1981).

In this work we present high-resolution turbulence data based on hot-wire anemometry measured in marine stratocumulus. Based on the experience from laboratory experiments (Siebert et al., 2007) we are convinced that hot-wire anemeometers can be useful for experiments in a two-phase flow under certain conditions, e.g., comparable low TAS and low droplet concentration. The low TAS could be realized by using the helicopter-borne measurement payload ACTOS (Airborne Cloud Turbulence Observation System) where the hot-wire anemeometer is attached among other turbulence and cloud probes (Siebert et al., 2006a). Comparable low droplet concentrations ($\sim 100\,\mathrm{cm}^{-3}$) can be found in clean environments such as marine clouds.

The aim of this work is to investigate the intermittent character of small-scale turbulence even under calm conditions as typically found in stratocumulus clouds. The motivating question is if turbulence has the potential to significantly influences the collision process even under such conditions where the average energy dissipation rate is low and corresponding turbulence induced acceleration of air parcels is low compared with gravitational acceleration.

The article is organized in the following way: first an introduction of the experimental setup is given followed by an overview of the data analysis with special emphasis on the use of the how-wire anemometer and spike removal due to drop impaction. The small-scale features are investigated by means of velocity increments, their probability density functions (PDF), and structure functions. Local estimates of the energy dissipation rate together with its probability density function (PDF) are presented with a spatial resolution of 10 m. Finally, the results are summarized and discussed.

2 EXPERIMENTAL

The helicopter-borne payload ACTOS was used to perform high-resolution measurements of turbulence and cloud microphyiscal parameters in stratocumulus clouds at the coast of the Baltic Sea around Kiel, Germany. ACTOS is an autonomous measurement system which is attached to a helicopter with a 140 m long tether and carried with a true airspeed (TAS) of 15 - 20 $\mathrm{m\,s^{-1}}$ which is much lower compared with typical research air-

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craft yielding higher spatial resolution. A picture of ACTOS during a measurement flight shortly before diving into a cloud field is shown in Fig. 1 and a general introduction of the experimental setup is presented in Siebert et al. (2006a).

In addition to the standard equipment, a one-dimensional hot-wire anemometer was installed on ACTOS. The general use of a hot-wire in (primarily artificial) clouds for turbulence measurements was discussed in Siebert et al. (2007). In contrast to that work, where a more complex de-spike algorithm is presented, here the spikes are removed by a more simple running median filter. A typical spike due to droplet impaction lasts about 2 ms, that is, about four samples (sampling frequency 2 kHz). A running median filter with a rank of 10 and final block averages over 10 samples remove the spikes and reduces the resolution from 2 kHz to 200 Hz which yields (with a TAS = 16 $\mathrm{m\,s^{-1}}$) a spatial resolution of 8 cm. The hot-wire data were corrected for temperature drift and calibrated with an ultrasonic anemometer.

Figure 1: A picture of ACTOS during a measurement flight shortly before diving into a cloud field. The picture is taken from the helicopter 140 m above ACTOS. All turbulence sensors are attached to an outrigger (right part of ACTOS in the picture) to minimze flow distortions due to the solid body of ACTOS. The flags which are attached to the tether (see left part in the picture) are used to increase visibility for other aircraft.

3 DATA ANALYSIS

3.1 Overview and Cloud Structure

Before investigating the small scale structure of cloud turbulence a brief overview of the large scale cloud structure is presented. Data were sampled in a field of dissipating stratocumulus clouds about 15 km off the coast. The analyzed flight leg was performed along the mean wind direction. From vertical profiling (data not shown here) cloud top was observed in 1120 m above sea level and the vertical thickness of the cloud layer was about 200 m. The 6 km long (6 minutes) leg which is analyzed in detail was flown against the mean wind at a height of 1090 m, about 30 m below cloud top. The mean temperature was slightly below the freezing level.

Figure 2a presents a time series of the liquid water content (LWC, measured with a Particle Volume Monitor, PVM-100A, see Gerber et al. (1994) for more details). The LWC was slightly increasing from 0.4 to 0.5 $\mathrm{g\,m^{-3}}$ with increasing distance from the coast. The vertical velocity w (Fig. 2b) shows limiting values of ± 1.3 $\mathrm{m\,s^{-1}}$ with a mean value close to zero. The horizontal wind velocity U (Fig. 2c) was quite calm inside the cloud layer and ranges from 0 to 2.5 $\mathrm{m\,s^{-1}}$. The vertical and horizontal wind velocities which are shown here were derived from the ultrasonic anemeometer and were corrected for attitude and platform motion. The stratocumulus layer was capped by a strong temperature inversion with significantly increasing wind speeds.

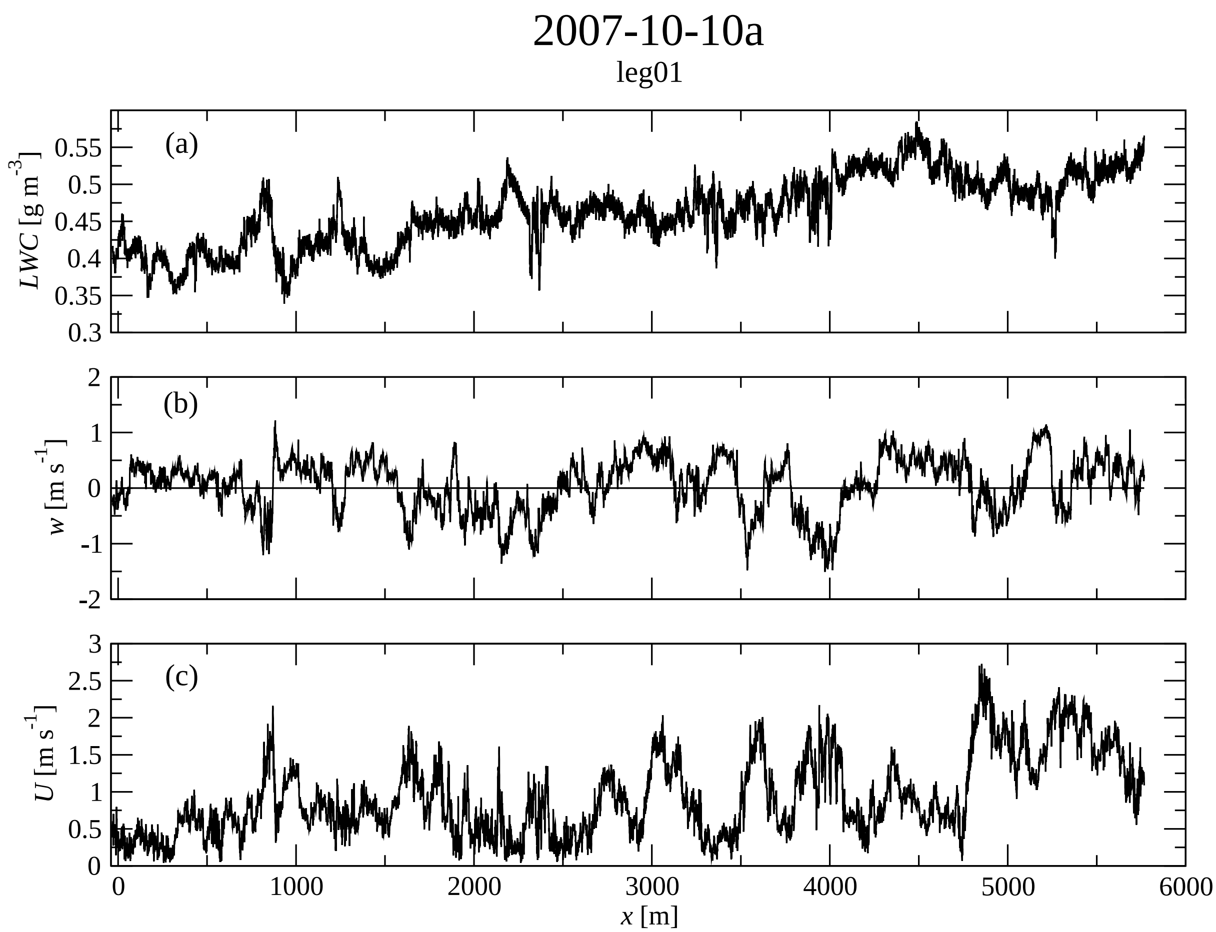

Figure 2: Time series of (a) Liquid Water Content (LWC), (b) vertical velocity component w, and (c) horizontal wind velocity U of a 6 km long ($\sim$ 6 min) leg in a stratocumulus layer. The data was sampled in a nearly constant height of 1090 m (a slow variation of the measurement height of $\pm$10 m was due to technical reasons).

3.2 Hot-Wire Data

For the same leg as shown in Fig. 2, the velocity fluctuations $u'(x)$ (high-pass filtered at 0.1 Hz corresponding to a length scale of 160 m) and the velocity increments $\Delta u'(x) = u'(x+r) - u'(x)$ are shown with $r = 7.5$ cm (distance between two subsequent measurement points). The data are derived from the hot-wire anemometer and processed as described in Sec. 2. The intermittent character of these data (see Fig. 3) is obvious, regions with high fluctuations and regions with comparable low fluctuation can be found close to each other. The standard deviation is $\sigma_{u'} \approx 0.13\,\mathrm{m\,s^{-1}}$ and $\sigma_{\Delta u'} \approx 0.03\,\mathrm{m\,s^{-1}}$, respectively.
Using classical Kolmogorov scaling one can esti-

mate the mean energy dissipation rate $\varepsilon \sim \sigma_{u'}^3/l$, with l is a typical length scale. Since the measurements are performed close to cloud top and the cloud thickness is about 200, l is assumed to be in the order of a few tens of meters which yields $\varepsilon \sim 10^{-4}\,\mathrm{m\,s^{-3}}$, a typical mean value for stratocumulus clouds.

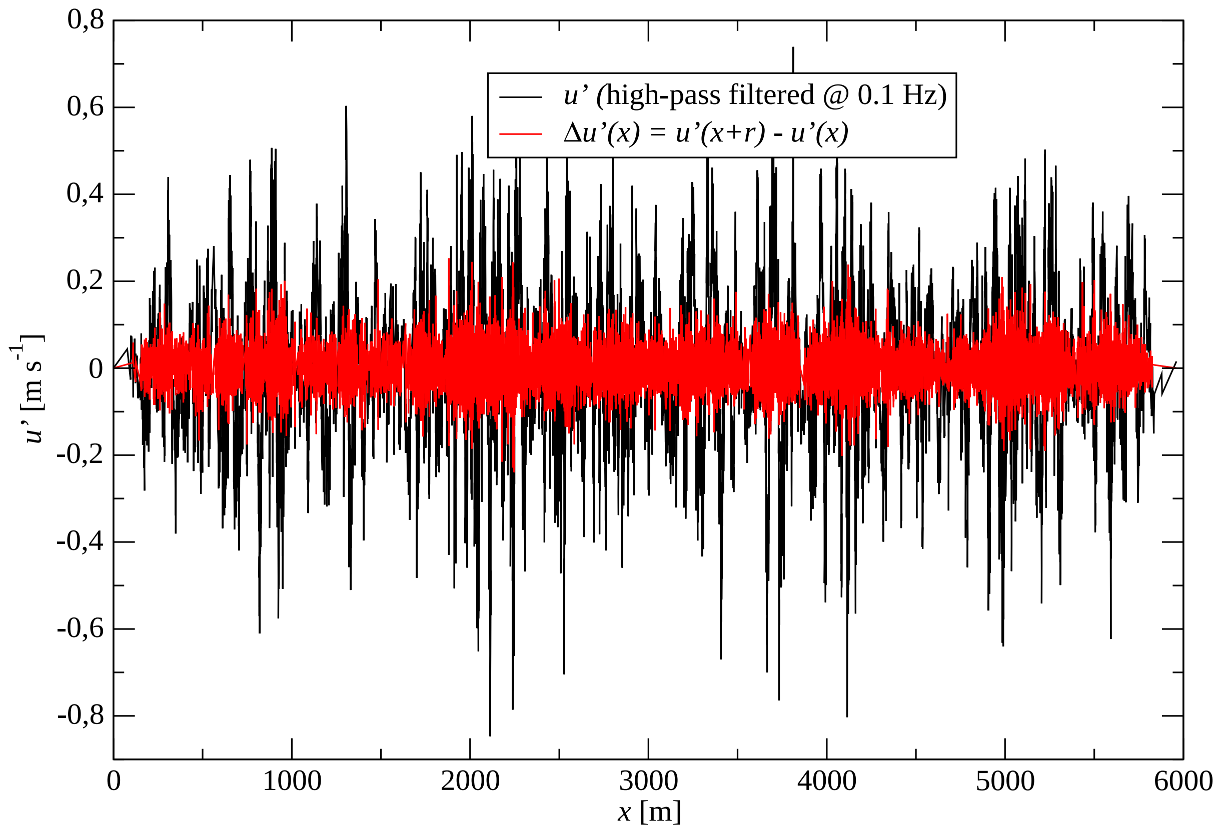

Figure 3: Time series of velocity fluctuations u' and increments $\Delta u(x) = u'(x+r) - u'(x)$ (with fixed $r = 7.5$ cm) derived from hot-wire data. The data is from the same record as for Fig. 2.

Next, we investigate the statistics of u' and $\Delta u'$ by means of probability density functions (PDFs). From basic considerations one would expect the fluctuations to be nearly Gaussian distributed since u' is the result of many randomly distributed vorticies along the flight path. On the other hand, the velocity increments depend on the direct neighborhood and the velocity at two points close together should be highly correlated and, therefore, the PDF($\Delta u'$) is highly non-Gaussian (see discussions about velocity and increment PDFs in Frisch (1995) and Davidson (2004) for example). In Fig. 4 the normalized PDFs of u' (Fig. 4a) and $\Delta u'$ (Fig. 4b) are plotted. The PDF(u') could be sufficiently approximated with a Gaussian fit, whereas the tails of PDF($\Delta u'$) are more exponential ($\sim e^{-x/\sigma_{\Delta u}}$).

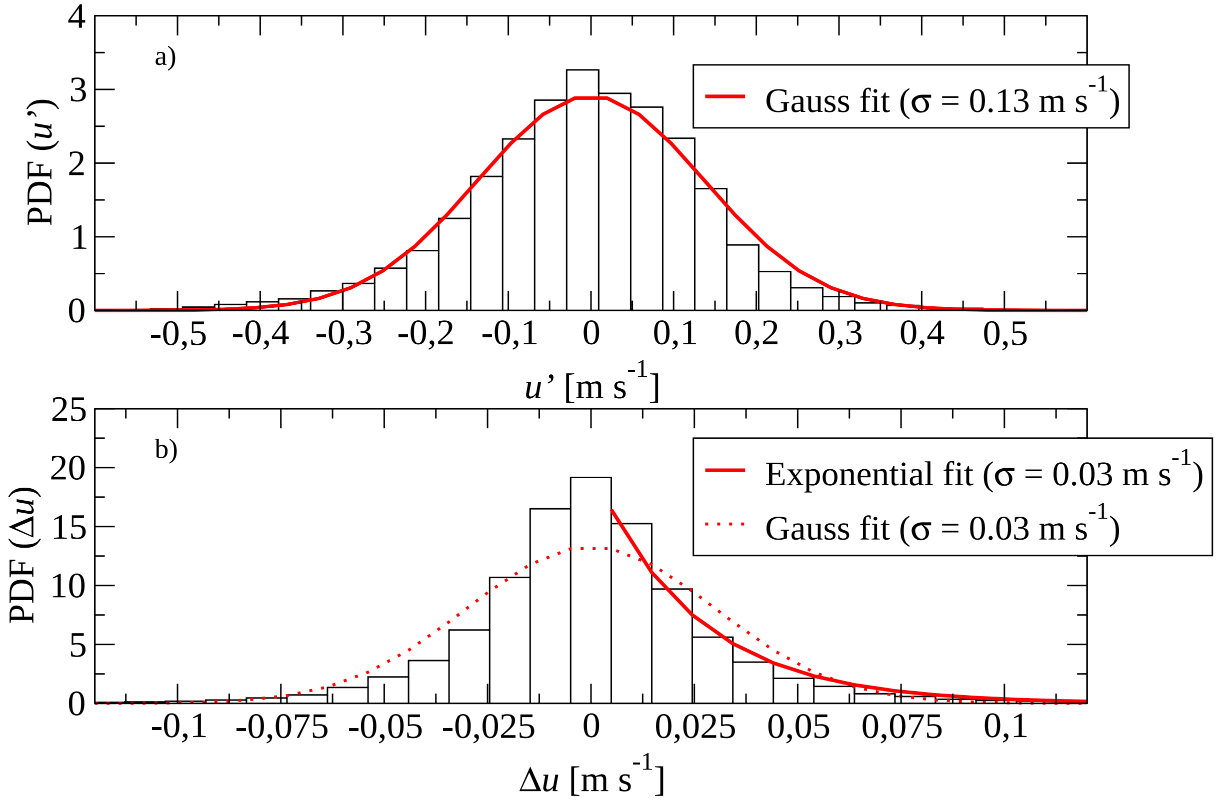

Figure 4: Probability density functions (PDFs) of the velocity fluctuations u' and increments $\Delta u'$ as shown in Fig. 3.

Another way to investigate the small-scale statistics of velocity increments is the scaling behavior of so-called "nth-order structure function $D^{(n)}$":

$$D^{(n)}(r) = \langle \Delta u(r)^n \rangle = C_n(\varepsilon r)^{\zeta}, \qquad (1)$$

with a constant C_n and the scaling exponent $\zeta = n/3$ for classical Kolmogorov scaling in the inertial subrange. For intermittent turbulence, this scaling exponent was modified in Kolmogorov's refined similarity theory (Kolmogorov, 1962) which leads to $D^{(n)} \sim (\varepsilon r)^{(n/3-\mu n(n-3)/18)}$ with the intermittency constant $\mu \approx 0.25$ (Davidson, 2004)

Before estimating $D^{(n)}$, the velocity data were transferred from time to space domain by a applying local Taylor hypothesis ($u'(t_i) \rightarrow u'(x_i = t_i \cdot u_i)$. Due to the pendulum motion of ACTOS using a constant TAS would lead to misinterpretation. In the space domain, the data were interpolated and re-sampled with a constant spatial resolution of 7.5 cm. From this equidistant data $D^{(n)}$ were calculated for $n = 2$ and 4 and plotted in Fig. 5a together with a classical $r^{n/3}$-fit function and the modified model which takes intermittency into account.

The second-order structure function shows nicely a 2/3 slope indicating inertial subrange scaling; only for scales smaller ~ 1 m $D^{(2)}$ drops significantly off - probably due to a low-pass filter which was set at 200 Hz (corresponding to 7.5 cm). The difference between classical 2/3 scaling and the intermittency correction is negligible for low-order structure functions. The fourth-order structure function shows a steeper slope compared with classical $r^{4/3}$ scaling for $r < 4$ m but agrees much better with the intermittency model. For $r > 8$ m, $D^{(4)}$ starts to flatten which is obviously due to the short distance of the measurement height to cloud top which might violate the assumption of isotropy.

In the lower panel (Fig. 5b) the compensated 2nd-order structure function $\left[1/2\, D^{(2)}(r)\right]^{1/\zeta}/r$ is plotted with $\zeta = 2/3$ (K41 scaling) and $\zeta = 2/3 - \mu\, 2(2-3)/18$. Following Eq. 1 (with the Kolmogorov constant $C_2 = 2$) the compensated structure function equals the energy dissipation rate $\varepsilon \approx 1.6 \cdot 10^{-4}\,\mathrm{m}^2\,\mathrm{s}^{-3}$ which agrees well with the estimate at the beginning of this subsection. It is obvious that the scaling exponent which accounts for the intermittent character of the turbulence results in a more flattened curve compared with K41-scaling.

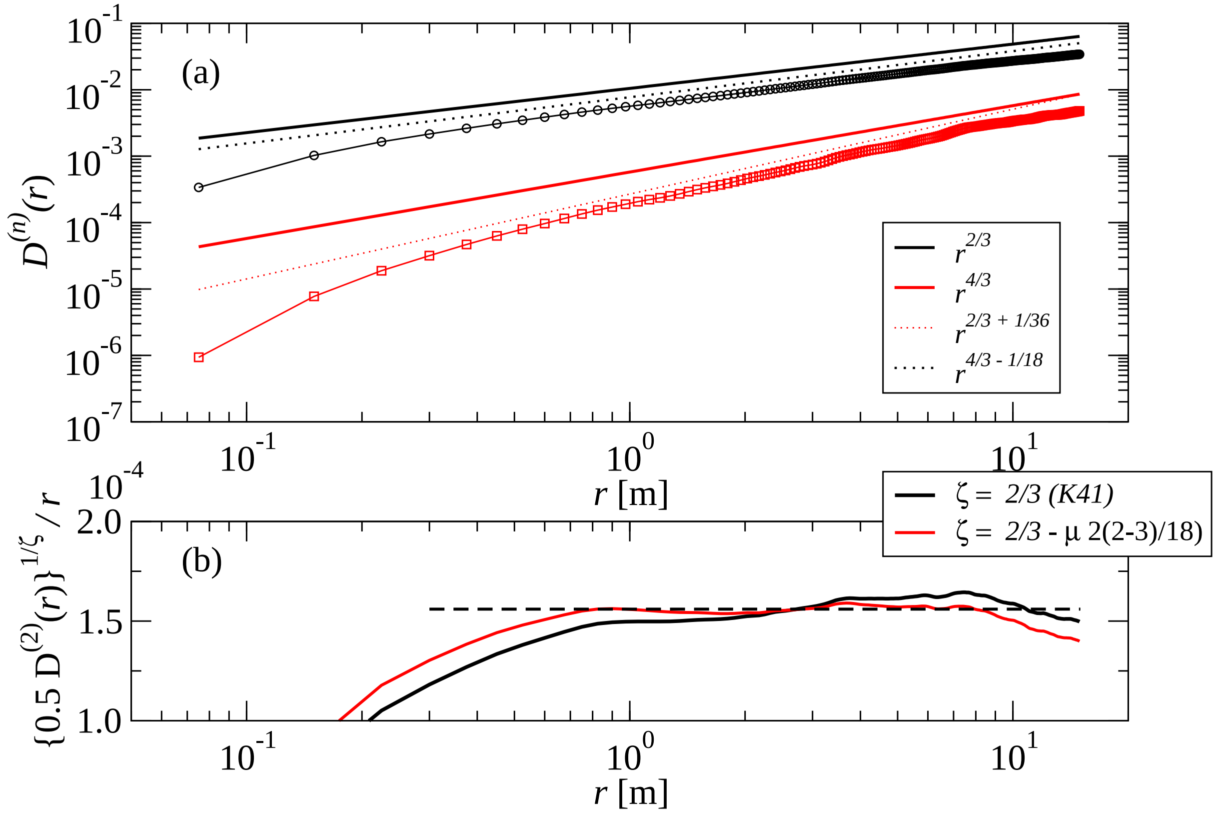

Figure 5: a) nth-order structure functions $D^{(n)}$ of the data presented in Fig. 3. b) Compensated structure function $\left[1/2D^{(2)}(r)\right]^{1/\zeta} = \varepsilon$

3.3 Local Energy Dissipation Rates

Instead of using an average value of the energy dissipation rate ε, intermittent turbulence is better described by a local value ε_τ integrated over the time τ. This concept (Kolmogorov, 1962) is based on the assumption that ε_τ is an independent variable. The high temporal resolution of the hot-wire allows us to estimate ε_τ from 2nd-order structure functions calculated from 0.5 s long subrecords (see Siebert et al., 2006b, for a more detailed discussion). In Fig. 6 the time series of $\log_{10}\varepsilon_\tau$ is shown together with its PDF. From peak-to-peak, ε_τ covers a range of three orders of magnitude and regions with ε_τ values more than one order of magnitude higher than the average value occur quite frequently. The PDF of $\log_{10}\varepsilon_\tau$ is shown in Fig. 6b and can be well approximated with a Gaussian fit which means a log-normal distribution of ε_τ. All these findings agree well with the classical picture of intermittent turbulence.

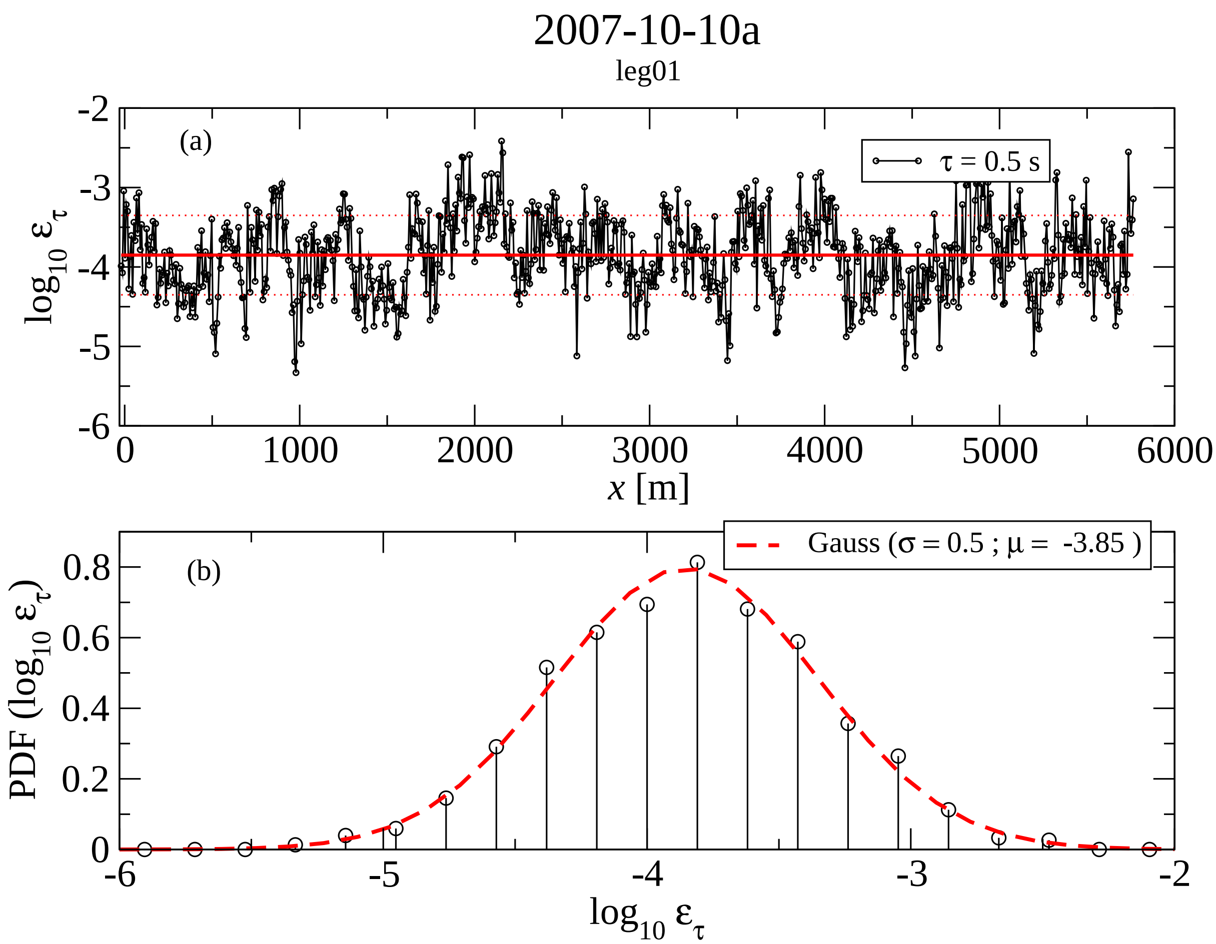

Figure 6: Time series of the logarithm of the local energy dissipation rate ($\log_{10} \varepsilon_\tau$) derived from one-dimensional hot-wire data. ε_τ values are derived from 2nd-order structure functions averaged over $\tau = 0.5$ s (e.g., 100 samples). The horizontal red lines mark the average values and the standard deviation $\pm\sigma_{\varepsilon_\tau}$. A PDF of $\log_{10} \varepsilon_\tau$ is shown together with a Gaussian fit in the lower panel (log-normal distribution of ε_τ)

4 SUMMARY AND DISCUSSION

A case study of turbulence in a field of stratocumulus clouds is presented. The measurements were performed close to cloud top of a 200 m thick cloud layer; the flight path is 6 km long. The average degree of turbulence in terms of energy dissipation is comparable low ($< \varepsilon > \sim 10^{-4}\,\mathrm{m^2\,s^{-3}}$). The statistics of velocity fluctuations and increments are analyzed. The results indicate a classical picture of intermittent turbulence with a highly variable local energy dissipation field. We wish to point out that in the two proceeding ICCP conferences, both the 2000 conference in Reno and the 2004 conference in Bologna, comments were made by prominent members of the cloud physics community questioning whether “Kolmogorov turbulence” is a realistic picture of turbulence in clouds. Admittedly such statements are vague and can be addressed in many ways, but one conclusion we draw from the analysis presented here is that the turbulence in these stratocumulus clouds is strikingly representative of any classical, single-fluid, statistically-homogeneous, isotropic turbulent flow. Intermittency corrections that have been developed in well characterized water and air flows, mostly in carefully controlled laboratory experiments, match the cloud data very well. This is perhaps even somewhat surprising given that we know the stratocumulus cloud is not isotropic on the largest scales — nevertheless, the revised Kolmogorov concept of the energy cascade hold remarkably well.

A second conclusion that can be drawn from this work is that in order to evaluate the influence of turbulence on cloud processes it will be necessary to go beyond the simple use of average turbulence quantities such as energy dissipation rate and instead to find methods for representing the statistical distribution of highly intermittent events. Even in these weakly-turbulent stratocumulus clouds we observe that the broad regions of mild turbulence are punctuated by rare bursts of intense energy dissipation. The intermittent nature of cloud turbulence is likely to influence many cloud processes, ranging from mixing to droplet coalescence. These data support, for example, the development of collision kernels which take the intermittent character of the turbulent velocity field on small scales into account.

Finally, we note that because the scale of our ε_τ measurements (~ 10 m) is still four orders of magnitude greater than the dissipation scale (~ 1 mm), one would expect on smaller scales locally much higher values of ε_τ than we estimated. As is discussed in an accompanying abstract this is likely to result in local acceleration of air parcels comparable to gravitational acceleration.

5 ACKNOWLEDGMENTS

We acknowledge Rolf Maser and Dieter Schell from the enviscope GmbH (Frankfurt/M, Germany) for technical support and the two pilots Alwin Vollmer and Oliver Schubert from the rotorflug GmbH (Friedrichsdorf, Germany) for great helicopter flights. RAS acknowledges support from the Alexander von Humboldt Society during the period in which this research was carried out.

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