

Holographic in-situ measurements of the spatial droplet distribution in stratiform clouds

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ABSTRACT

Ground based in-situ measurements on the small-scale structure of low-level stratiform clouds have been performed utilizing the HOlographic Droplet and Aerosol Recording system (HODAR) of the University of Mainz, Germany. 6 holograms recorded during stratus cloud events on the Kleiner Feldberg Taunus Mountain Observatory (Frankfurt, Germany) were reconstructed in the laboratory and analysed by means of an automated data extraction and image processing system. In post-processing, each originally recorded droplet population was subjected to 2 statistical methods: (1) the sub-cell scanning analyses with statistical “Fishing” tests and (2) measurements of inter-droplet distance frequency distributions. Based on these analyses, significant deviations between the measured spatial droplet distributions and theoretical random distributions were found.

1. Introduction

Most cloud models implicitly assume that the droplets are randomly distributed in space. Since the microphysical processes of collision, coalescence and coagulation are dependent on the absolute distances between droplets, knowledge of the spatial droplet distribution on small scales is required. Another basic assumption inherent in most cloud models is that condensational growth or evaporation of each droplet in the actual water vapour field is independent from the neighbouring droplets, because the droplets are considered as located too far from each other. Pruppacher and Klett (1978) estimated from the ratio of the mean droplet radius r , the mean inter-droplet distance S , and the liquid water content w_L of a cloud droplet population, that $r/S \sim w_L^{1/3} \sim 0.01$. From this, it was concluded that droplets grow and evaporate independently from each other if there are distances between them of at least a few tens

to 100 times their size (Pruppacher and Klett, 1978; and Srivastava, 1989). Srivastava (1989), however, also pointed out that the supersaturation in the immediate vicinity of each droplet (the so-called microscopic supersaturation) can differ significantly between individual droplets due to fluctuations in their spatial distribution. Based on theoretical considerations by Raasch and Umhauer (1989) a homogeneous random dispersion of droplets in space can be described by a Poisson distribution. Evaluations on coalescence theory by Scott (1967) indicate also that a cloud droplet population follows Poisson statistics. Utilizing different experimental approaches deviations of natural cloud droplet populations from random distributions were found by Baker (1992), Baumgardner et al. (1993), and Kozikowska et al. (1984). However, Borrmann et al. (1993) report one case of a randomly distributed stratus cloud droplet population, where the holographic analysis of inter-droplet distances demonstrated that a significant fraction of the droplets can have distances between them, which are smaller than 100 size radii.

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In this paper, examples are given of cloud droplet spatial distributions and inter-droplet distance measurements derived by means of an automated data extraction algorithm from six in-situ recorded holograms.

2. Experimental methodology

The ground based University of Mainz HODAR (HOlographic Droplet and Aerosol Recording system) consists of a recording apparatus for field deployment and a laboratory reconstruction device as characterised in Borrmann and Jaenicke (1993) and Borrmann et al. (1994). The recording optics of the Fraunhofer in-line type is implemented inside a cart, which is retractable into a trailer for storage and relocation. The holographic recording is performed sufficiently far from the trailer and high enough above the surface friction layer. The photographic emulsion on a glass plate is exposed by transilluminating an air sample volume of 1400 cm³ with a single, or double pulsed ruby laser beam (Borrmann, 1991). In order to assess possible flow distortions influencing representative sampling, a 3-dimensional microscale air pollution model (Eichhorn, 1988) has been modified (Kölzer, 1994) to simulate the holographic recording geometry. Based on these model calculations operational conditions under which the recording can be considered as representative are derived. If the wind velocity is smaller than 10 m/s and the Reynolds number is smaller than 30, then a flow undisturbed by the obstructing recording apparatus persists in an angular region of 30° with respect to the plane of the photographic plate. To exclude exposures under unrepresentative sampling conditions wind velocity and direction measurements were recorded at times of hologram exposures.

During the holographic reconstruction in the laboratory a stationary, three dimensional image of the originally recorded air sample volume is obtained. Each droplet image inside this volume can be located and inspected by means of suitable magnification optics and a digital video system. This way the size, shape, and position in space of each hydrometeor contained in the original scene is measured. The absolute inter-droplet distances follow from the position data. A semi-automated method requiring the on-line image recognition of

a human observer takes up to 40 working hours per 1000 analysed droplet images (Borrmann et al., 1993). For this study, the semi-automated method was replaced by a fully automated image processing algorithm (Uhlir, 1996), which performs the tasks of systematically searching through the imaged air volume, and automatically recognizing, locating, and sizing the droplet images. This is still time consuming, but the interaction of an observer for 2 to 4 work hours per hologram is only necessary for post analyses and data quality control. With the automated data extraction method larger sample volumes, higher droplet numbers, and more holograms become amenable to statistical analyses.

The holograms analysed for this study were recorded during campaigns in November 1992 and November 1993 on the Kleiner Feldberg Taunus Observatory (53.13°N, 8.36°E, at an elevation of 825 m above MSL near Frankfurt, Germany) in a forested, mountainous area. The experimental site and the meteorological conditions typically encountered there are described in Wobrock et al. (1994). Table 1 contains a list of the meteorological parameters and sampled cloud types of these meso scale, low level cloud events.

3. Analysis methodology and results

In order to characterize the spatial distribution of the holographically recorded cloud droplet populations, two statistical methods were applied.

(1) Calculation of frequency distributions of the measured inter-droplet distances between neighbouring droplets following Raasch and Umhauer (1989).

(2) Performance of a sub-cell scanning analysis on the sampling volume according to Kozikowska et al. (1984) extended by the application of the so-called "Fishing test" of Baker (1992).

3.1. Inter-droplet distance analyses

For a randomly dispersed droplet population the mean distance S (cm) between the droplets is $S = 0.554/C_T^{1/3}$ (Underwood, 1970), with C_T the number of droplets per cm³ of air. From this Raasch and Umhauer (1989) derived inter-droplet frequency distributions for particles of different rankings of neighbourhood. These theoretical dis-

Table 1. *Meteorological data from the cloud events during the holographic recording: temperature, liquid water content (LWC), horizontal wind velocity and observed cloud type*

Hologram number	Date and time (UTC)	Cloud type	Air temperature (°C)	LWC (mg/m ³)	Wind (m/s)
FB11	7 Nov 1992 22:25	stratocumulus	4.7	436	1.8
FB12	7 Nov 1992 22:43	stratocumulus	4.8	416	2.2
FB19	13 Nov 1992 07:15	stratus/stratus nebulosus	−1.4	313	2.8
FB24	15 Nov 1992 18:45	stratus fractus (stratocumulus)	2.8	312	3.5
FB30	16 Nov 1992 10:46	stratus/stratus nebulosus	2.8	300	3.0
FB40	5 Nov 1993 19:43	stratocumulus	−0.8	485	≈ 0

tributions-based on the values for C_T measured from the holograms are used in this study as references representing perfect random droplet distributions. Once the 3-dimensional coordinates for each droplet's position in space was obtained from the holographic reconstruction analysis, the distances of each droplet to its nearest (first), second-nearest etc. neighbours are calculated. In the vicinity of the boundary of the image volume considered for analysis care has to be taken while searching for the nearest neighbour of any given droplet in order to avoid "wall effects" (see Borrmann et al., 1993, for details). Then for each ranking of neighbourhood a frequency distribution of these distances can be generated and compared to the theoretical result (after Raasch and Umhauer, 1989) for the same C_T and same ranking of neighbourhood. Table 2 gives the results from the six analysed holograms for the mean droplet distances between the nearest neighbours, where a is the average over all measured distances between first neighbours. Additionally,

S is listed, as well as distances $a_{10\%}$, $a_{30\%}$, $a_{50\%}$. Here the table entry of 1250 μm for $a_{50\%}$, for example from Hologram FB11, means that 50% of the distances between first neighbours were smaller or equal to 1250 μm . The values for the errors are based on counting statistics and the error associated with the positioning in the sample volume. Looking at the mean distances a and S for all sample volumes (except FB30) both values agree within the range of counting statistics. The difference between them is not significant.

The mean value a characterizes only one parameter of the distribution of all inter-droplet distances and provides no further information about the variance of these distances inside the cloud volume.

Figs. 1 and 2 display the inter-droplet distance distributions measured from the holograms between the nearest (first) and second-nearest (second) neighbours. To compare the inter-droplet distance distributions of droplet populations with different droplet number concentrations C_T the

Table 2. *Comparison of the measured average inter-droplet distances with a theoretical random distribution*

Hologram number	C_T (cm ^{−3})	Distance a (μm)	$a_{50\%}$ (μm)	$a_{30\%}$ (μm)	$a_{10\%}$ (μm)	Distance S (μm)
FB11	73 ± 7	1349 ± 90	1250	950	400	1325 ± 120
FB12	53 ± 4	1414 ± 100	1350	900	350	1475 ± 104
FB19	135 ± 8	949 ± 55	950	700	300	1048 ± 56
FB24	138 ± 10	1072 ± 45	1050	850	350	1120 ± 71
FB30	240 ± 5	775 ± 30	770	570	450	912 ± 20
FB40	70 ± 6	1212 ± 75	1300	1000	550	1344 ± 105

The inter-droplet distances a are the measured average distances between first neighbours from the chosen sample volumes with the indicated droplet number concentration C_T . The inter-droplet distances S are theoretical estimates assuming of a random droplet distribution with the same droplet concentration C_T . Of all measured inter-droplet distances 10%, 30%, or 50% were smaller or equal to the values $a_{10\%}$, $a_{30\%}$, or $a_{50\%}$, respectively. The errors are given with regard to counting statistics and the position-finding uncertainty.

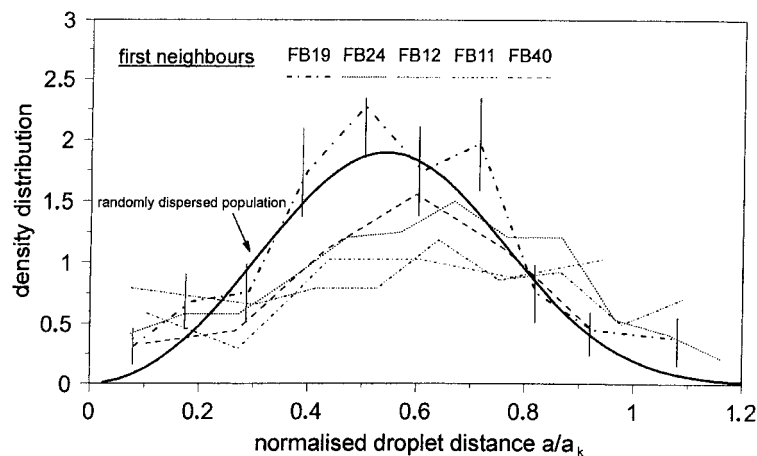


Fig. 1. Inter-droplet distance frequency distributions of the first neighbours in comparison to the theoretical distribution for a randomly dispersed droplet population (as characterized by Poisson statistics).

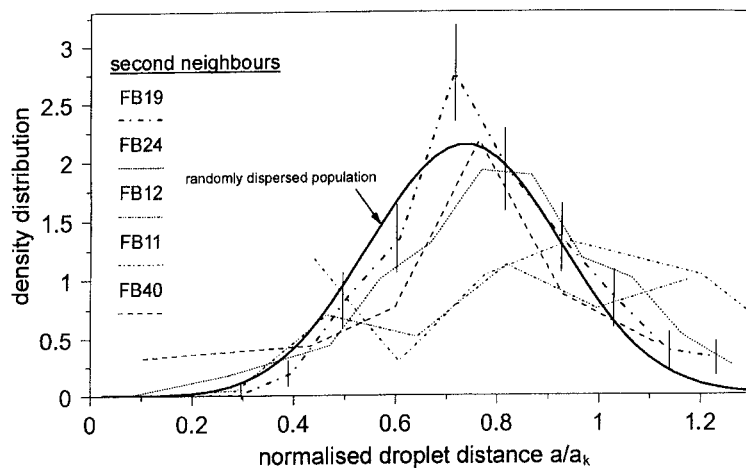


Fig. 2. Inter-droplet distance frequency distributions of the second neighbours compared with the theoretical (Poisson) distribution for a randomly dispersed droplet population.

droplet distances a on the x -axes are normalised through division by $a_k = C_T^{-1/3}$. These distributions are based on analysed sample volumes of slightly less than 2 cm^3 out of each recorded 1.4 liter cloud volume. The theoretical distributions for the randomly dispersed droplet population after Raasch and Umhauer (1989) are represented in these figures by the thick solid lines and the error bars give the uncertainties due to the counting statistics. For clarity the error bars are only indicated for the data from hologram FB19.

The results for the first and second neighbours of all five holograms are similar and differ significantly from the model distribution. If a null-hypothesis is assumed stating that the model distribution from Raasch and Umhauer (1989) represents the measured data, then this hypothesis is rejected for all data sets in Fig. 1 with probabilities larger than 99% based on χ^2 tests.

The distributions of the first neighbours show a significantly increased portion of small distances ($a/a_k < 0.2$) and of large distances ($a/a_k > 0.8$) compared to the model distribution. The occurrence

of a large variance of droplet distances (broad spectrum) explains the similarity of a and S within the range of tolerances listed in Table 2. The increased portions of small droplet distances indicate that more droplets are arranged closer to each other than assumed by homogeneous spatial droplet distribution.

The deviation from Poisson statistics is not as clearly evident from the distance distributions of the second neighbours as for the first neighbours. In order to answer the question whether the deviation from the Poisson distribution for the first neighbours in Fig. 1 is only limited to small volumes a sample volume of 10 cm^3 has been analysed, i.e., a volume considerably larger than the previous 2 cm^3 . The diagram in Fig. 3 displays the inter-droplet distance distribution of first neighbours (hologram FB30) from the whole sample volume. More distinctly than in Figs. 1 and 2, the frequency distribution of hologram FB30 deviates in the entire range of a/a_k from the random distribution. The maximum of the frequency distribution is in the range of the smallest droplet distances ($a/a_k = 0.3$). Regarding the cumulative distribution for the inter-droplet distances in the range $a/a_k < 0.54$ it can be estimated that up to 20% of droplets are closer to each other than 100 size radii. For direct comparison with the results of the holograms from Figs. 1 and 2, the sample volume of hologram FB30 (10 cm^3)

has been subdivided into nine smaller adjacent cubes of 1.11 cm^3 each. The inter-droplet distance distributions for the first neighbours are shown in the two diagrams of Figs. 4a and b. They show with similar deviations from the theoretical distribution for a randomly dispersed droplet population (thick solid line) the enhanced occurrence of small inter-droplet distances. The deviations between the random distribution and those distributions obtained from the observations indicate that the droplets are not randomly dispersed in the small volumes inspected from these cloud events. Furthermore, it can be concluded that the mean inter-droplet distance does not adequately describe the spatial arrangement of cloud droplets for the analysed cloud samples. Table 3 shows the mean droplet radii of the droplet population obtained from the size distribution measured by HODAR and the maximum inter-droplet distance for 10% of the droplets in the chosen sample volume. The comparison of both values demonstrates that a small amount of droplets of every population has distances smaller than 100 radii between them.

The frequency distributions in the previous figures show the inter droplet distances between the droplets disregarding the droplet sizes. In order to characterise the spatial distributions and distances between droplets as function of droplet size Fig. 5 illustrates the inter-droplet distance

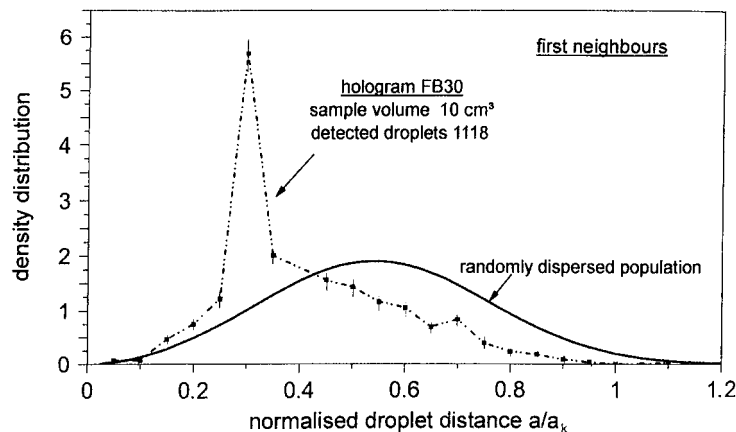


Fig. 3. Hologram FB30: Inter-droplet distance frequency distributions of the first neighbours in comparison to the theoretical distribution for a randomly dispersed droplet population (Poisson statistics) for the whole sample volume of 10 cm^3 .

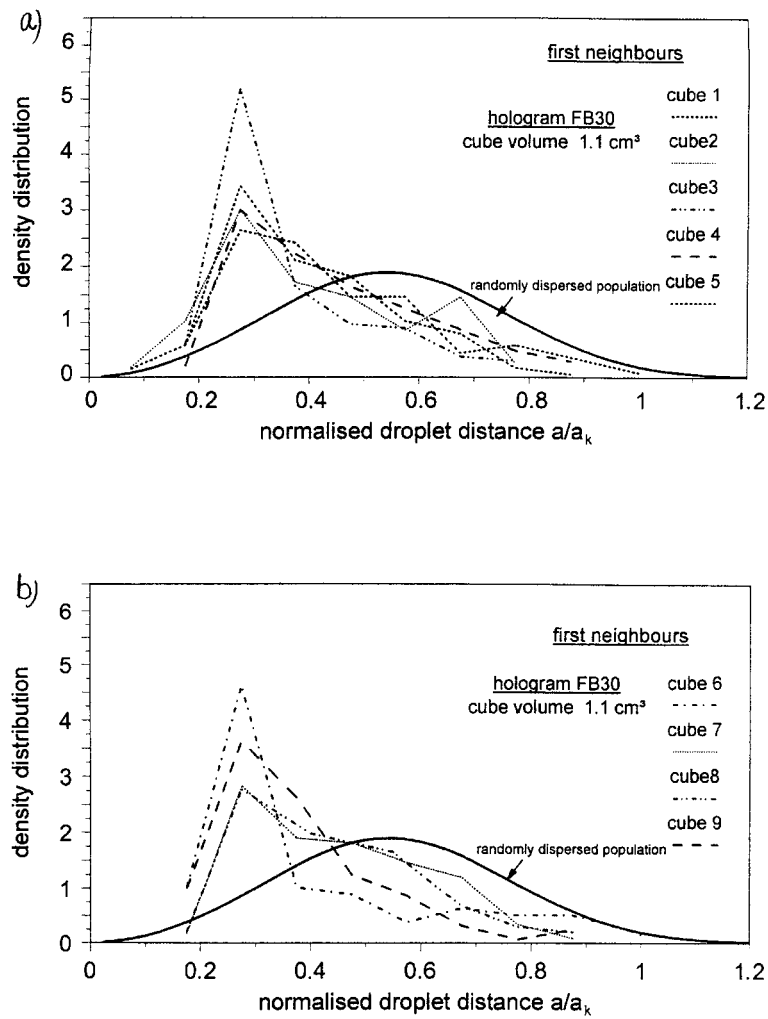


Fig. 4. Hologram FB30: Inter-droplet distance frequency distributions of the first neighbours in comparison to the theoretical (Poisson) distribution for a randomly dispersed droplet population of the nine smaller equal-sized subvolumes of 1.11 cm^3 . Panel (a) subvolumes number one to five, and panel (b) subvolumes six to nine.

Table 3. Comparison between the mean radii (as obtained from the droplet size distributions measured by HODAR) and the inter-droplet distances; the values for $a_{10\%}$ from Table 2 are given for comparison

Hologram number	FB11	FB12	FB19	FB24	FB30	FB40
$a_{10\%}$ (μm)	400	350	300	350	450	550
mean radius (μm)	5.5	6.0	5.0	5.5	5.5	8.0
100 mean radii (μm)	550	600	500	550	550	800

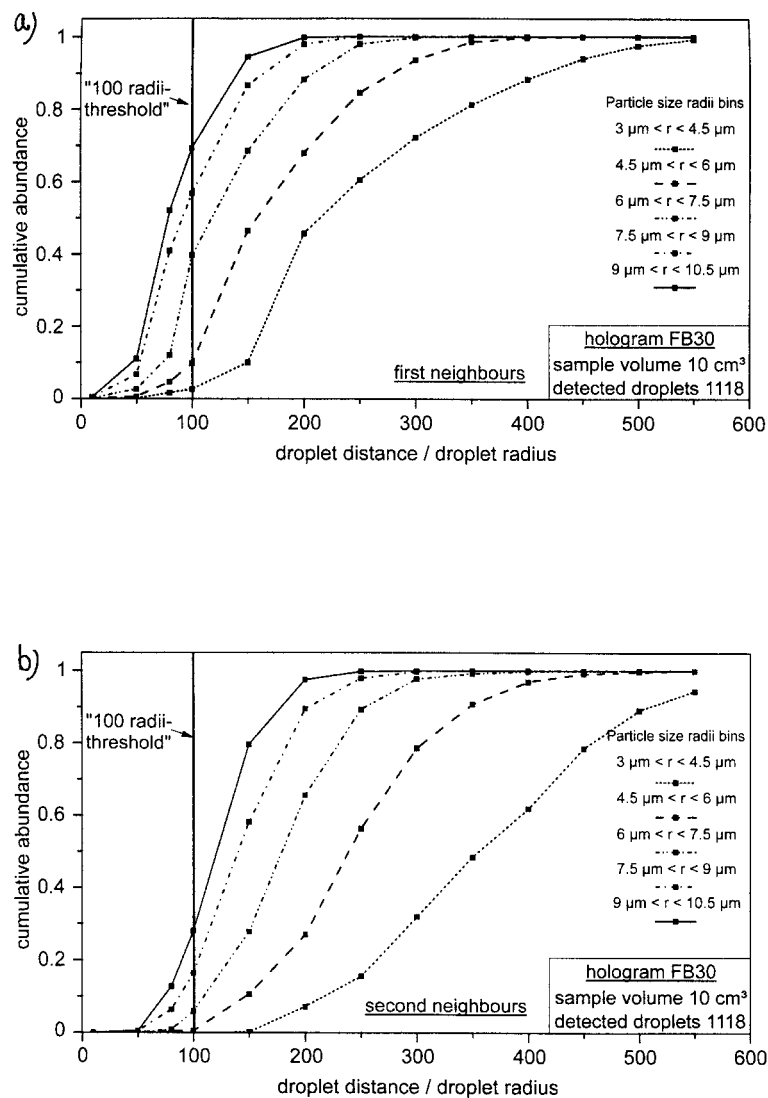


Fig. 5. Hologram number FB30: Cumulative inter-droplet distance distributions of (a) the first and (b) the second neighbours for the different droplet sizes. The deviation from the "100 radii-condition" in cloud physics is plotted versus the measured droplet distance given as the percentage of the considered droplet radius.

frequency distributions for five droplet size bins. Here inter-droplet distance refers to the distance between a given droplet of the size in the indicated bin and its nearest neighbour, the size of which may be different. For reasons of counting statistics the entire sample volume of 10 cm^3 of hologram FB30 (see also Fig. 3) has been analysed. These frequency distributions are plotted versus the

measured inter-droplet distances normalised with respect to the droplet size. Considering the first neighbours (Fig. 5a) a significant fraction of distances is below 100 droplet size radii for all droplet sizes. It becomes evident that a higher number of droplets with radii around $9 \mu\text{m}$ has neighbouring droplets within a surrounding 100-radii boundary than the smaller $3 \mu\text{m}$ droplets. The examples for

the second neighbours in Fig. 5b also show a considerable fraction of distances smaller than 100 radii for most sizes.

3.2. Sub-cell scanning analysis

For the sub-cell scanning analysis, the original sample volume is subdivided into a large number of partial volumes with identical sizes and cubic geometries. The number of droplets contained in each sub-cell can be counted because the droplet positions and the positions of each sub-cell inside the sample volume are known from the coordinate data. The frequency distributions are obtained by displaying for each droplet number n the corresponding number of sub-cells with n droplets inside. This can be repeated for different sub-cell sizes, where the sub-cells sizes need to be much smaller than the size of the sample volume. With the given droplet number concentration of the whole sample and the selected size of the sub-cell volume the sub-cells will on average contain a number of $\bar{n}$ droplets. Assuming that the droplets are randomly dispersed in space Poisson statistics can be used to describe the density distribution function of the sub-cells (Kozikowska et al., 1984; Borrmann et al., 1993; Neumann and Umhauer, 1991). One property of the Poisson distribution is the equality of the expectation value $\bar{n}$ and the variance s^2 . In Fig. 6 the ratios of variance and mean values $(s^2/\bar{n})_{\text{experiment}}$ (as derived from the density distribution of the experimental data) and the theoretical values $(s^2/\bar{n})_{\text{Poisson}} = 1$ are displayed for the holograms FB24, FB30 and FB40 as function of increasing sub-cells size. These three hologram examples represent different total sample volume sizes and different cloud droplet concentrations. The filled dots denote the experimental data and the straight lines the theoretical, randomly distributed population. The error bars give indications of the error due to counting statistics of the number of sub-cells. The number of sub-cells increases with decreasing cell size and the error bars become smaller correspondingly. In order to obtain a quantitative measure of whether or not the experimental data significantly deviate from the random distribution a Fishing test according to Baker (1992) needs to be performed. For this a test variable F is calculated as defined by Baker (1992) for each cell size from the experimental data in Fig. 6. If F is larger than 3, then the

hypothesis that the measured data come from a region of random droplet distribution can be rejected with 99% probability. For example for the hologram FB30 the test variable F attains values between 5.4 and 14.9 for cell sizes between 1000 μm and 4000 μm . Here this Fishing test analysis is restricted to sub cell sizes between 1 mm and 4 mm. If the boxes are too large, then statistics is performed over an insufficient number of boxes. If the boxes are too small then the number of empty boxes becomes too large, which is outside of the range of the test's applicability after Baker (1992). Similar results are obtained for the other holograms, where other limits for the size of the boxes included in the test were applied based on the overall droplet concentration in the fog. In comprehension, the results from the sub cell scanning analyses with application of the Fishing test by Baker (1992) support the hypothesis that the spatial distribution of the droplet populations imaged by the holograms can not be described by Poisson (random) distributions.

4. Discussion and conclusions

To investigate the small scale cloud microstructure ground based holographic measurements were conducted in stratiform clouds at the mountain Kleiner Feldberg near Frankfurt (Germany). For 6 of the holograms, the spatial distributions of cloud droplets have been characterised by means of two methods: inter-droplet distances frequency distribution analyses and sub-cell scanning analyses.

Between the measured inter-droplet distance frequency distributions and those predicted from a theoretically assumed random distribution is no general agreement. Comparing to the randomly distributed droplet population following Poisson statistics the increased portion of small droplet distances is considerable. Furthermore the results demonstrate that about 10 % of the droplets with size radii above 4.5 μm are closer to each other than 100 droplet radii. Placing droplets close to each other, their collision-coalescence-probability increases and their condensation growth rate decreases at the same time. In cloud modelling stochastic collection equations for coalescence and collection of droplets are used (Berry and Rheinhardt, 1974). The calculations are deter-

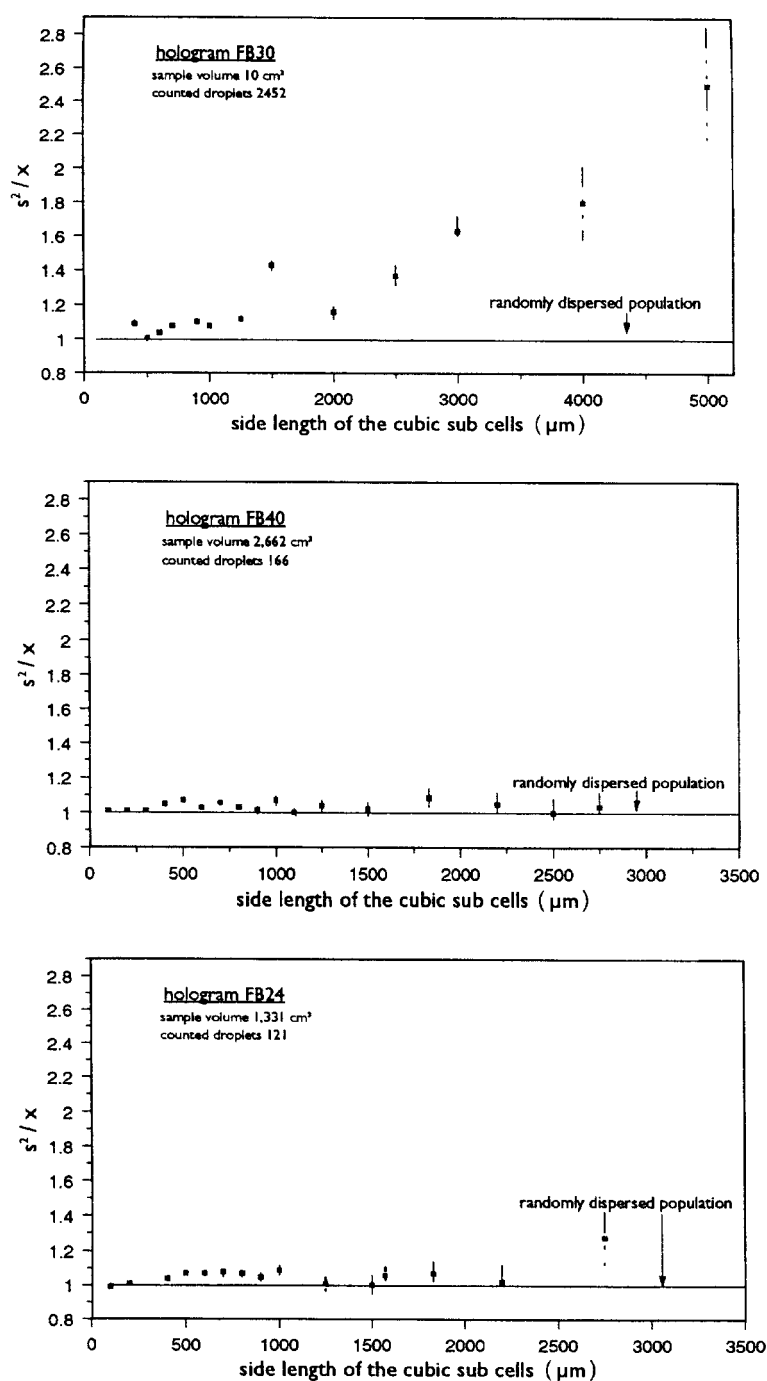


Fig. 6. Concentration frequency distribution: Comparison between the ratio of variance and mean value $s^2/\bar{n}$. The solid line represents $s^2/\bar{n}_{\text{Poisson}} = 1$ and the dots with error bars denote the measured values $s^2/\bar{n}_{\text{experiment}}$. The error bars indicate the uncertainty due to the counting statistics (see text for details).

mined by the average density distribution of droplets and are independent from the inter-droplet distances. Scott (1967) has discussed a Poisson distributed droplet population as an adequate solution of the coalescence equation. This is not supported by the results of this study. The portion of small inter-droplet distances of the measured droplet population was higher than in a randomly dispersed one for the analysed, limited number of samples. Model studies are required to assess the significance of reduced droplet distances and their effects on the temporal evolution of the size distribution and the droplet growth rates. It may be necessary to evaluate an additional correction term to the stochastic equation of Berry and Rheinhardt (1974).

For the quantitative interpretation of the results from the sub-cell scanning analyses for different sub-cell sizes Fishing tests after Baker (1992) have been applied, the results of which also indicate a deviation from random droplet distribution. Considerations like these show the usefulness of performing several analyses on the same cloud droplet population utilising different statistical methods.

The experiments of this study have established that in the small scale region of the sampled cloud events Poisson statistics may not be applicable for the description of the spatial distributions of the droplet populations. However, the 6 holograms evaluated in this study constitute only a very small number of samples. Thus the conclusions drawn

are also very limited. Also the likelihood of finding a significant number of large droplets in such small sample volumes is low and the analyses performed exclude droplets larger than a few tens of microns. Recent modifications of the recording optics by Vössing et al. (1998) allow to record and image cloud volumes as large as 500 liters. Additional limitations concerning the validity to free atmospheric conditions arise from the fact that HODAR operates so close to the ground and that only holograms in stratiform cloud types were recorded. Since the ground based experiments are always influenced by the proximity to the surface the operation of airborne HODAR instruments is needed.

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