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Measurement of small-scale heterogeneity in rain using a high-resolution research Doppler radar

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1 Introduction

As was stated by Uijlenhoet and Sempere Torres (2006), many physical processes that occur at the land surface and in the atmosphere cannot be viewed without considering the microstructure of rainfall. In the introduction to the special issue of the Journal of Hydrology on "Measurement and Parameterization of Rainfall Microstructure", Uijlenhoet and Sempere Torres (2006) list many examples of the importance of this in both a scientific and a societal context. They also state that our current knowlegde concerning the microstructure of rain is far from complete, and needs to be studied in more detail.

If we consider a finite event consisting of purely homogeneous rain that is allowed to fall freely through an atmosphere that has constant winds without interactions between raindrops, the rain will become inhomogeneous (i.e. the size distributions are a function of time and space) due to differences in velocities of the different drops. However, interactions between drops and breakup of large drops may preserve the homogeneity in rain. If the number occurrences of these interactions and breakups is limited within the finite event considered, this means that if the rain measured at the ground is homogeneous, it was necessarily inhomogeneous aloft, and vice versa.

There has been much discussion in the recent literature about the microstructure of rain in space and time. For example it has been suggested that rain is clustered (e.g. Jameson and Kostinski, 2000) or (multi)fractal (e.g. Lovejoy and Schertzer, 1990, 1995), but there is also evidence of purely homogeneous rain (Uijlenhoet et al., 1999; Larsen et al., 2005). There has been no conclusive evidence that either of these is generally true because it is very difficult to test the suggested structures, as point-scale ground measurements of drop size distributions (DSDs) only resolve time (at a relatively coarse resolution) and not space. An instrument that may be used to investigate the space and time structure of rain simultaneously is a high-resolution vertically pointing Doppler radar. The extremely high resolution (< 3 m in range) of the radar that is used in this study means that this instrument may be used to study this microstructure of precipitation down to very small scales. Palmer et al. (2005) have used a 0.915 GHz turbulent eddy profiler to study the link between small-scale structure of precipitation to that of turbulent eddies. However, the sizes of their measurement volumes are more than 15 times as large as those of the radar used in the present study, which is mainly caused by the fact that the range resolution is more than 10 times as large.

A Doppler spectrum can be converted to a DSD using knowledge about the wind field. The microstructure of rain can be investigated using time series of profiles of these radar-derived DSDs. This paper will provide the theoretical background for studying the microstructure of rain using a high-resolution Doppler radar. This background is discussed in Sec. 2. Some preliminary analyses of radar data, as well as a description of the experimental site and the radar will be presented in Sec. 3. Preliminary conclusions will be drawn in Sec. 4.

2 Theoretical background

2.1 Drop size distribution

In the study of the microstructure of rain, the most important property of rainfall is its drop size distribution (e.g. Marshall and Palmer, 1948). Traditionally, a DSD is defined as the expected number of raindrops per unit drop diameter interval per unit volume of atmosphere. This means that DSDs are formed by the spatial distribution of raindrops in a volume of air (which governs the raindrop concentration) and the prob-

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ability distribution of their sizes. A basic hypothesis with regard to the existence of a DSDs is that it is independent of the size and shape of the reference volume under consideration. This assumes spatial homogeneity and temporal stationarity of the rainfall process. Jameson and Kostinski (2001) give an overview of the hypotheses on which the concept of the DSD is based.

2.2 Doppler spectrum

The Doppler spectrum measured by a vertically pointing radar can be used to estimate the DSD (e.g. Hauser and Amayenc, 1981; Peters et al., 2005). This assumes a deterministic relation between the diameter of a raindrop and its terminal fall velocity (e.g. Beard, 1976). However, this one-to-one transformation from velocity to diameter will not be valid in the case of vertical wind, which is present in all but the most exceptional cases of rainfall. Hauser and Amayenc (1981) allow for a constant vertical wind, which allows for a more precise derivation of the DSD, but the broadening influence of turbulence on the Doppler spectrum remains a source of error. Therefore, care must be taken when interpreting DSDs derived from Doppler radar measurements. Preferably additional measurements of vertical wind should be used to at least verify the correction for the vertical wind.

The Doppler spectrum can be written as a function of the DSD, while taking a constant vertical wind into account. Inverting this relation gives a relation for deriving the DSD $N(D)$ from the Doppler spectrum $S_D(v)$ (assuming Rayleigh scattering)

$$N(D) = D^{-6} S_D\big(v(D) + w_z\big)\frac{\mathrm{d}v}{\mathrm{d}D}. \tag{1}$$

The diameter D in this relation is obtained through inversion of the $v-D$-relation. The vertical wind velocity w_z can be measured or may be obtained by fitting a DSD of known shape to this relation with w_z as a variable, as suggested by Hauser and Amayenc (1981).

2.3 Spatial representation of rain

The time-height structure of rainfall could in principle be converted into a two-dimensional spatial picture of rainfall. This conversion requires measurements or at least good estimates of the horizontal wind profile. However, as noted by Fabry (1996), this conversion is far from problem-free as the wind is usually a function of both space and time and especially the largest drops only partly act as passive tracers of the wind field due to their relatively large moments of inertia. If the wind is assumed to be a sufficiently smooth function of time and space, the position of a drop at time t_0, $\boldsymbol{x}(t_0)$, can be solved from

$$\boldsymbol{x}(t_0) = \boldsymbol{x}(t) - \int_{t_0}^{t} \big(\boldsymbol{w}(\boldsymbol{x}(t'), t') + v\boldsymbol{e}_z\big)\mathrm{d}t', \tag{2}$$

where $\boldsymbol{e}_z$ is the unit vector in the z direction. This relation can be used to create a two-dimensional map of DSDs at a given time t_0.

If the drop size distribution of the rain can be obtained as a function of height and upwind distance, the spatial structure of the DSD can be analyzed. This can be done by assuming a parameterization of the DSD and investigating the spatial structures of the parameters. Alternatively, the raw DSDs can be analyzed by looking at three-dimensional (the third dimension being the drop size) structures of drops. The former type of analysis is the simpler of the two, as there usually is a limited number of parameters and the problem is two-dimensional. however, essential properties of the microstructure of rain may not be uncovered using this approach.

3 Radar measurements

3.1 CESAR

The Cabauw Experimental Site for Atmospheric Research (CESAR, van Ulden and Wieringa, 1996) is a consortium of major research institutes and universities in The Netherlands involved in research on the atmospheric boundary layer and its interaction with the land surface. The experimental site operated by the Royal Netherlands Meteorological Institute (KNMI) and is located in the center of The Netherlands. In addition to a 213 m tower for atmospheric boundary layer obsevations, many ground-based instruments have been installed there since the site was built in the 1970s. Among these instruments are two radars (35 GHz and 3.3 GHz), a wind profiler (1 GHz) and a varying collection of raingauges and disdrometers. The radar that is used in this study is the 3.3 GHz radar, and it will be described in Sec. 3.2.

The presence of all of these instruments at a single location makes this location highly suitable for the study of the microstructure of rain. The radar-derived DSD can be compared to that measured by the ground-based disdrometers and raingauges. In addition to that, the intercomparison of the DSDs measured by the different disdrometers may also yield valuable information on their small-scale spatial variation. Wind measurements made both in the mast and by the wind profiler may provide useful additional information for deriving DSDs from radar measurements.

3.2 TARA

TARA (Transportable Atmospheric RAdar, Heijnen et al., 2002) is a polarimetric FM-CW Doppler radar that is operated by the IRCTR group of the Delft University of Technology. It has a central frequency of 3.3 GHz, a range resolution that can be easily adjusted between 2.885 m and 75 m, and a beam width of 2 degrees. Besides using the main beam, TARA has the option of using two off-axis beams at angles of 15° from the main beam. The sweep time is 1.0 ms, so that the maximum unambiguous velocity of the computed

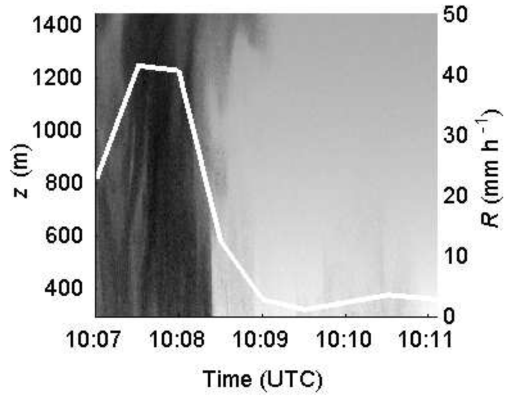

Fig. 1. Distribution of the logarithm of the total signal power in time and space (darker colors indicate higher power), with corresponding disdrometer rainfall intensity measurements (white line).

Doppler spectrum is ±22.7 m s^{-1}. A 512-point (standard in TARA processing) Doppler spectrum thus needs 0.512 s of data, yielding a velocity resolution of 0.089 m s^{-1}. Polarimetry and off-axis beams will not be used here because this will reduce the maximum unambiguous Doppler velocity. The zenith angle of the radar can be set manually, and therefore the radar can only be operated at one angle at a time. We will use data collected while the radar was pointing vertically in order to be independent of the wind direction to maximally take advantage of the Doppler signal.

3.3 TARA measurements

In this paper, we focus on an event that took place on September 22, 2002, between 10:00 and 10:30 UTC, where the period between 10:07 and 10:11 UTC (see Fig. 1) will be the focus of our analyses. This event was a very short convective event with rainfall intensities at the ground exceeding 40 mm h^{-1}. As no correct radar power calibration procedure for this event was conducted, the absolute power of the reflected signal is not available. However, for this study, we are mainly interested in the time signature of the signal, which does not need any calibration.

Figure 1 shows the distribution of power in time and in height, along with rainfall intensity measured by a nearby Joss-Waldvogel disdrometer. The abrupt change in reflected power between 10:08 and 10:09 UTC along the entire profile indicates that there is significant horizontal wind and that the rain has large variations on relatively small time scales.

Figure 2 shows the distribution of power in both height (z) and time (t) for different Doppler velocity intervals. This power was obtained by integrating the Doppler spectrum $P(v)$ over the given velocity range. No color scale is given in this figure as the absolute power is unknown. The figure also shows lines representing the bounds of the different velocity classes, indicating the development of the position of a drop if it were allowed to fall vertically with a constant velocity through the entire column of atmosphere above the radar. The fact that the structures in Fig. 2 do not have the same orientation suggests that the rain is highly variable in time and space, and the raindrops do not fall vertically with a constant velocity, but are influenced by wind, as would be expected in any rain event.

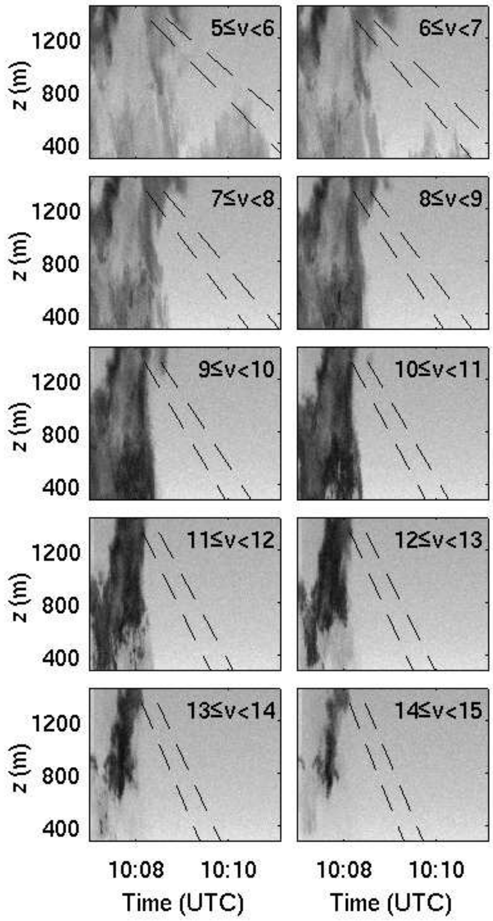

Fig. 2. Distribution of the logarithm of the signal power in time and space for different velocity intervals, where darker colors indicate more power. Also shown are lines representing the bounds of the given velocity classes.

There seems to be a downdraft (large negative vertical wind) from 600 m and upward just before 10:08 UTC, which can be concluded from the lack of slow drops and the excess of fast drops. The fact that the largest drops that generally occur in nature have terminal fall velocities in still air between 9 and 10 m s^{-1} also shows that the vertical wind is at least 5 m s^{-1} in some regions, as there is still significant power returned by drops with $14 \leq v < 15$ m s^{-1} and the power returned by drops with velocities smaller than 5 m s^{-1} is negligible. Besides the evidence of strong vertical wind, Fig. 2 shows that there is significant structure in the rain, and that this structure is different for drops with different fall velocities.

A typical operational radar has measurement volumes that are several km^3, and the typical scanning time of such radars is in the order of several minutes. Given the short duration and small spatial scales of the structures of the event presented in this paper (and convective events in general), the estimation of the rainfall intensity from operational radar data is prone to large errors (Gosset and Zawadzki, 2001; Berne and Uijlenhoet, 2005).

4 Conclusions

The study of the microstructure of rainfall is highly relevant for both society and science. Little is known about the distribution in space and time of drops with different sizes. A high-resolution Doppler radar may be used to study this microstructure as it can resolve both space (in one dimension) and time for drops with different fall velocities (and hence diameters). The conversion from Doppler spectra measured by a radar to DSDs is a non-trivial issue due to vertical wind and variations therein. For analyses of the spatial structure of rainfall, the time-height map of DSDs must be converted to a distance-height map using information about wind. Hence, good estimates of the wind field play a critical role in the analysis of the microstructure of rain using Doppler radar.

In a preliminary analysis of data collected in a convective event by a high-resolution vertically pointing Doppler radar (TARA) located at the CESAR site in The Netherlands, it has been shown that such rainfall exhibits large variations in time and space. Both horizontal and vertical wind have been shown to have important effects on the microstructure of rainfall.

This paper provides a background for the study of the microstructure of rainfall using Doppler radar. Future analyses will be done on spatial maps of DSDs derived from Doppler spectra and estimations of the wind field. These analyses will focus on the quantification of spatial variations in two dimensions of the DSD. In this framework, the alternative descriptions of rainfall microstructure suggested in the literature may be tested.

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