Atmospheric Research 119 (2013) 13–22

Contents lists available at SciVerse ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Vertical evolution of raindrop size distribution: Impact on the shape of the DSD

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ARTICLE INFO

Article history:
Received 21 October 2010
Received in revised form 18 July 2011
Accepted 20 July 2011

Keywords:
Drop size distribution
Coalescence process
Breakup process
Coalescence efficiency
Vertical evolution of raindrop size distributions

ABSTRACT

Models of coalescence and breakup lead to equilibrium of the raindrop size distribution (DSD) after a fall through sufficient vertical height. At equilibrium, the DSD no longer evolves, and its shape is unique whatever the rain rate or Liquid Water Content (LWC). This implies that the DSD is known, to within a multiplication constant. In the past, numerous measurements using disdrometers revealed that the slope of the DSD tail is close to 20–22 cm^{-1} when equilibrium is reached, whereas models based on the Low and List experiment predict values of approximately 65 cm^{-1}. The present paper proposes a simple modification of the coalescence efficiency in the Low and List parameterization, leading to a DSD tail with a slope of 24 cm^{-1}. To evaluate the relevance of this modification, some of the DSD parameters such as slope, mean volume diameter, and the relationship between moments are calculated, and compared with experimental DSD. The modified parameterization is then used to study the evolution of an initially gamma-like DSD in a 1D vertical rain shaft.

1. Introduction

The study of the vertical evolution of raindrop size distributions (DSDs) during rainfall, from the freezing level (0C isotherm) to ground surface, is a key element to the improvement of our understanding of the microphysics of rain. In numerous domains such as remote sensing, telecommunications, soil erosion, and the study of the rain's efficiency in “washing” the atmosphere, the DSD plays an important role. Among the different processes affecting the evolution of DSD, breakup and coalescence are two of the most significant. Various models based on experimental measurements have been developed over the past 40 years. The models proposed by Low and List (1982a, 1982b) (hereinafter LL82) and McFarquhar (2004), which are both based on the same laboratory experiments, lead to an equilibrium drop size distribution (EDSD) with two or three peaks, and an exponential tail with a slope of approximately $\Lambda = 65\ cm^{-1}$. However, numerous measurements have shown that for high rain rates, close to a state of equilibrium, this slope lies between $\Lambda = 20–22\ cm^{-1}$. Hu and Srivastava (1995) and more recently Seifert et al. (2005) stated that the LL82 parameterization may underestimate the effects of coalescence and/or overestimate the breakup processes.

In the present study, the atmosphere is assumed to be quiescent and the pressure is supposed to be constant and equal to 100 kPa although a recent study (List et al., 2009a, 2009b) showed the influence of pressure on the coalescence and breakup processes and its effect on DSD. Of course, in real atmospheric conditions the situation is considerably more complex due to the presence of turbulence, strong winds and possible wind shear effects. Under these conditions, the DSD measured at ground level results from more complex mechanisms involving not only breakup and coalescence processes, but also strong turbulence and evaporation processes, leading to a high variability of the DSD as described by Uljlenhoet et al. (2003). Moreover, as explained by Sauvageot and Koffi (2000)

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0169-8095/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.atmosres.2011.07.011

the possible interaction of several neighboring rain cells with different characteristics can play an important role.

This work tries to simulate the DSD evolution from the melting layer to the ground level. The starting point of the present paper is the LL82 parameterization, in which the empirical model of coalescence efficiency (E_{coal}), given by LL82 is replaced by the Brazier-Smith et al. (1972) model. In Section 2 the main equations used to compute the vertical evolution of the DSD, in the case of a one dimensional (1D) vertical rain shaft, are presented. The EDSD are computed using both the original coalescence efficiency model, and the Brazier-Smith model. The parameters characterizing each of their features, such as the slope Λ and normalization parameters such as the mass-weighed mean diameter (D_m) and the scaling parameter for drop concentration (N_o^*), are estimated and discussed. In Section 3 we compare these parameters with those obtained from the DSD measured with a disdrometer. We show that the LL82 parameterization associated with the Brazier-Smith coalescence model (hereafter modified LL82) leads to parameters, which are in good agreement with experimental data. In Section 4, three simulations made for a 1D rain shaft are presented. The first gives general results relevant to the DSD obtained at ground level, and discusses the shape of the DSD for the case of an initially gamma-like distribution. Various comments are made concerning the use of the gamma distribution to represent the DSD. The second simulation is used to discuss the DSD shape parameter (μ), and results related to its variability (due to breakup and coalescence processes) are presented. In the last simulation we present results related to the correlation between the μ and Λ parameters, induced by breakup and coalescence, and compared with the existing model. Finally, the conclusion is given in Section 5.

2. Coalescence–breakup parameterization

2.1. Preliminary discussion

There are few parameterizations which take into account the effects of both coalescence and breakup. The Low and List parameterization (LL82b) based on their own experimental dataset (LL82a) remained the most popular for many years. A more recent parameterization, which is also based on the LL82a, was proposed by Greg M. McFarquhar (2004). Finally, recent experiments conducted by Barros et al. (2008) have assessed the parameterization used by LL82b. The following study focuses on the original parameterization described by LL82, to which some modifications (described below) have been introduced. It can be noted that the LL82 and the McFarquhar (2004) parameterizations both lead to the same slope. The LL82 parameterization, based on laboratory experiments, was developed by colliding droplets, using numerous pairs of drop diameters. The authors proposed models of fragment size distribution for filaments, sheets and disk breakup, and also proposed an empirical coalescence efficiency model. Much research have been done with this parameterization to study the evolution of DSDs (Brown, 1986, 1987, 1988; List et al., 1987; List and McFarquhar, 1990; Valdez and Young, 1985; Prat and Barros, 2007a, 2007b and others). This has led to a three-peak equilibrium distribution, called 3PED. However, as has been pointed out by several authors, the slope of the EDSD tail is close to 65 cm^{-1} when using the LL82 parameterization, which is much higher than that measured in various rainfall events near to equilibrium (Hu and Srivastava, 1995; Sauvageot and Koffi, 2000; Brown, 1997; Atlas, 2000; Hu, 1995). Hu and Srivastava (1995) provided a very detailed list of measurements for which a lower slope is obtained (20–22 cm^{-1}). They concluded that the LL82 might respectively underestimate and overestimate coalescence and breakup processes. This observation was also made by Seifert et al. (2005) who conclude “The version with breakup destroys the large raindrops too rapidly and approaches, in heavy rain, an equilibrium DSD that is not in agreement with the observations”. To test this hypothesis, in present work we propose a different model for the estimation of the coalescence efficiency (E_{coal}).

2.2. The stochastic coalescence–breakup equation

The parameterization of LL82 gives the fragment distribution function $P(m; x, y)$, which corresponds to the mean number of droplets with a mass lying in the range between m and $m+\Delta m$, produced by the collision between a pair of droplets of mass x and y. As was done by some authors, we also modify the initial formulation to take mass conservation into account, and to improve the convergence of the iterative procedure used to estimate the standard deviation of the different normal and lognormal distributions (Brown, 1986). The rate of change of the DSD due to coalescence and breakup during the fall of the raindrops is given by the stochastic coalescence/breakup equation. Using the same formalism as that proposed by List et al. (1987), of which the principle formulae are recalled for the 1D rain shaft, the drop number density is expressed by $n(m, t, z)$ for drops of mass m at time t, at a height z:

$$\frac{\partial n(m,t,z)}{\partial t} + \frac{\partial}{\partial z}(v(m)n(m,t,z)) = \int_{m/2}^{\infty}\int_{m-x}^{x} K(m;x,y)n \times (x,t,z)n(y,t,z)dydx \quad (1)$$

Where $v(m)$ *is* the vertical velocity of a droplet of mass m and is assumed to be independent of z. $K(m; x, y)$ is called the kernel, and represents the mean number of fragments, ranging in size between m and $m+dm$, produced or lost by a collision between two droplets of mass x and y:

$$K(m;x,y) = [(1-E_{coal})P(m;x,y) + E_{coal}\delta(x+y-m) - \delta(m-x)-\delta(m-y)]C(x,y) \quad (2)$$

$C(x, y)$ represents the fractional interaction rate between a drop of mass x and diameter D_x, and a drop of mass y and diameter D_y:

$$C(x,y) = \frac{\pi}{4}\left(D_x + D_y\right)^2|U|E_{colli} \quad (3)$$

E_{colli} is the collision efficiency and is equal to unity in the case of the range of raindrop diameters considered in this paper and U is the relative velocity of the two droplets.