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# Assessing the size distribution of droplets in a cloud chamber from light extinction data during a transient regime

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The paper describes a method of assessing the size distribution of fog droplets in a cloud chamber, based on measuring the time variation of the transmission of a light beam during the gravitational settling of droplets. Using a model of light extinction by floating spherical particles, the size distribution of droplets is retrieved, along with characteristic structural parameters of the fog (total droplet concentration, liquid water content and effective radius). Moreover, the time variation of the effective radius can be readily extracted from the model. The errors of the method are also estimated and fall within acceptable limits. The method proves sensitive enough to resolve various modes in the droplet distribution and to point out changes in the distribution due to diverse types of aerosol present in the chamber or to the thermal condition of the fog. It is speculated that the method can be further simplified to reach an in-situ version for real-time field measurements.



## 1. Introduction

Droplet suspension is one of the most important components of the atmosphere. Whether grouped at high altitudes (as clouds) or close to the ground level (as fog), the properties of such liquid suspensions have dramatic implications on the atmospheric conditions and, more generally, on the environment. Knowing the optical and microphysical properties of clouds and fogs proves crucial both in operational weather forecasting and in climatological analyses (Intergovernmental Panel on Climate Change, 2007). For example, it is now a widely accepted fact that atmospheric aerosols strongly influence the formation and the properties of clouds (Haywood and Boucher, 2000; Lohmann and Feichter, 2005). For this reason, much effort has been made for studying cloud droplets from the point of view of their sizes (Borrmann et al., 1994; Korolev et al., 1999; Miles et al., 2000; Mayer et al., 2004; Lasher-Trapp et al., 2005; Ramirez-Beltran et al., 2009; Alexandrov et al., 2012). Also, combining the knowledge of dimensional parameters with various information on cloud droplet concentrations (Meskhidze et al., 2005; Fountoukis et al., 2007; Pinsky et al., 2012) allows clarifying the droplet growth mechanisms and provides both useful forecasting tools and parameterization data for cloud microphysics that enters various climate models.

Equally important is the study of droplet size distributions for characterizing various types of fog. The haze and fog analysis aims of providing data necessary to model quantitatively their structural, dynamic and microphysical characteristics in order to obtain reliable forecasts (Alpert and Feit, 1990). Haze and fog predictions may significantly impact on health, commercial, industrial and military aspects in the modern society. As the size distribution of droplets in a fog is an essential aspect of such liquid suspensions in the atmosphere, various methods, both experimental (Jiusto, 1964; Rinehart, 1969) and theoretical (Tampieri and Tomasi, 1976) have been developed quite long ago. More recent approaches to this problem have led to significant increase of accuracy (Elias et al., 2009; Okuda et al., 2009). Moreover, when satellite imagery is combined with theoretical models, fog detection becomes possible over much wider areas (Cermak and Bendix, 2011). As in the case of clouds, the properties of the local atmospheric aerosol prove to be essential for establishing a given size distribution of droplets in the emerging fog (Pant et al., 2010; Yasmeen et al., 2012).

One of the basic tools used in studying both the formation and evolution of clouds and fogs is the so-called cloud chamber. Starting with the first applications as detectors for charged particles (Das Gupta and Ghosh, 1946) the use of these instruments has been extended towards meteorological studies, for which various dimensions and experimental capabilities have been designed and reported in the literature (Gollub et al., 1973; Frick et al., 1992; Khlystov et al., 1996; Wagner et al., 2011). Also, for the determination of the size spectrum of droplets formed in cloud chambers, a broad variety of methods have been used.

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The most efficient of these methods are obviously the optical-based ones, which analyze the effects of light scattering on the suspension of liquid particles in the chamber. Thus, they range from resolving the spectra of the size-dependent Doppler shifts of the scattered light due to the gravitational settling of droplets (Gollub et al., 1974) to inversion procedures of optical depth data (Hoppel et al., 1994; Arnott et al., 1997). It is worth mentioning here the ingenious and effective method of relating the extinction of a light beam, propagating through a droplet suspension, to the corresponding liquid water content (Chýlek, 1978). More precisely, the method relies on the quasi-linear behavior of the light′s efficiency for extinction in the region of small values of the size parameter of droplets, which occurs for wavelengths in the infrared range.

The present paper describes a method for estimating the size spectrum of artificial fog, which is essentially based on the correlation between the droplet size distribution and the extinction of a light beam propagating through the cloud chamber. More precisely, the focus is shifted on the transient regime following the fog formation, due to the gravitational settling of droplets. By analyzing the corresponding time dependence of the light extinction during the gradual fall of the droplets (whose speeds are size-dependent), one may resolve their various dimensional concentrations and thus may construct the whole size distribution of fog′s particles. While the method is very simple and robust by allowing rapid evaluations of the droplet distributions, it also proves sensitive enough to resolve bi-modal size spectra with good accuracy and to distinguish the influence of various types of aerosol serving as condensation nuclei. Moreover, the procedure has a clear potential of being simplified to an in-situ version suitable for various field evaluations of fog and cloud droplet size distributions.

The principle of the method and its main assumptions are detailed in the next section and the experimental setup is further described in Section 3. The various sources of errors and their quantitative evaluation are discussed in Section 4. In order to exemplify both the robustness and the sensitivity of the proposed procedure, some sample results are presented in Section 5. The analysis is finally summarized in Section 6, which is dedicated to concluding remarks.

## 2. Principle of the method

The extinction of a narrow beam of monochromatic light traveling through a polydisperse medium containing is given by the following expression (Liou, 2002):

$$I(\lambda) = I_0(\lambda)e^{-\tau(\lambda)}, \tag{1}$$

where $I$ and $I_0$ are, respectively, the measured and the emitted values of the light intensity and $\tau(\lambda)$ is the wavelength-dependent optical depth (OD) of the medium. When this medium contains a suspension of dielectric particles, OD can be expressed as the sum of their individual contributions to the extinction. This can be achieved by integrating the individual particles′ extinction cross-sections over the size distribution assumed in the given polydisperse medium (Liou, 2002):

$$\tau(\lambda) = \int_0^{r_m} \pi r^2 Q_{ext}\left(\frac{2\pi r}{\lambda}, m\right) N(r)dr, \tag{2}$$

where $Q_{ext}$ is the extinction efficiency factor (depending on the size parameter $2\pi r/\lambda$ and on the complex refraction index, $m$, of the individual particles) and $N(r)dr$ is the number of particles of radii between $r$ and $r+dr$ to be found in the unit cross-sectional area of the light beam over the whole length $L$ of its geometric path through the medium. The quantity $r_m$ defines the upper limit of the range of particles′ radii. The extinction efficiency factor is given approximately by the theory of Mie which describes the scattering of electromagnetic radiation by dielectric spheres. It is strongly dependent on the relative weight of the light absorption in the target particle, which is roughly quantified by the imaginary part of the complex refraction index.

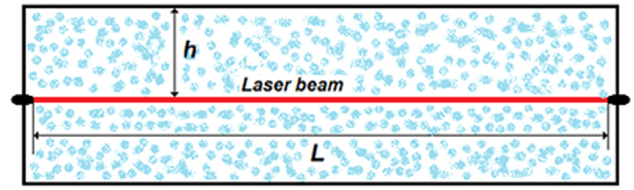


**Fig. 1.** Schematic view of the cloud chamber with geometrical parameters used in the text.

In cloud chamber experiments, one of the main parameters of interest is the volumetric distribution of droplets, $n(r)$, which is considered as position independent (an assumption that further implies an even spatial distribution of nucleation centers). This quantity is defined by writing the number of particles of radii between $r$ and $r+dr$ to be found in the unit volume as $n(r)dr$. To switch between the two forms of particle size distribution, one may note that $SN(r)dr$ is the number of particles of radii between $r$ and $r+dr$ to be found in the whole volume $L \cdot S$, which is lighted by the beam ($S$ is the cross-sectional area of the light beam and $L$ is its length across the fog, as can be seen in Fig. 1). It readily follows that $N(r) = Ln(r)$. Therefore, the OD expression of Eq. (2) changes to:

$$\tau(\lambda) = L\int_0^{r_m} \pi r^2 Q_{ext}\left(\frac{2\pi r}{\lambda}, m\right) n(r)dr. \tag{3}$$

For the normal range of cloud droplets radii and for the wavelength of the light in the beam, which is in the red part of the spectrum, the significant values of the size parameter to appear in Eq. (3) are of the order of 100, thus making the efficiency factor very close to its geometrical optics limit of 2 (Liou, 2002). Therefore, Eq. (3) can be safely simplified to:

$$\tau = 2\pi L\int_0^{r_m} r^2 n(r)dr. \tag{4}$$

In this approximate form, OD clearly becomes independent of the wavelength.

Once the fog droplets are formed in the chamber, they begin gravitational fall. In a real situation, the settling of droplets is always perturbed by various convection flows. As such motions may be very complicated and are essentially random, they will not be taken into account in the present model. More precisely, it will be assumed that the fog′s environment is *perfectly quiescent*. Even under the hypothesis of a convection-free atmosphere, the fall of a droplet may still be perturbed by its possible encounters with particles below (sedimentation effects). The main hypothesis on which the present method is founded is that each falling droplet will have no interactions with its neighbors. This assumption is obviously consistent only with low-to-moderate fog densities. In such situations, a combination of Archimedes′ force and fluid (Stokes) friction with the surrounding air quickly makes a droplet of radius $r$ to fall with the constant limit speed $\upsilon(r) = (2g/9\eta)(\rho - \rho_a)r^2$, where $\rho$ and $\rho_a$ are the densities of the liquid material of the droplet and that of the surrounding air, $g$ is the free fall acceleration and $\eta$ is the viscosity of the air at the corresponding temperature. The time needed for a droplet of radius $r$ to fall over the distance $h$ (see Fig. 1) will be then:

$$t(r) = \frac{9\eta}{2g}\frac{h}{\rho - \rho_a}r^{-2}. \tag{5}$$

Under the same hypothesis of low-to-moderate fog densities it may be assumed that a falling droplet *will not attach* smaller