NOTES

Experimental Verification of the Linear Relationship between IR Extinction and Liquid Water Content of Clouds

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21 March 1980 and 14 July 1980

ABSTRACT

The IR extinction of clouds has been measured with a CO_2 laster transmissometer ($\lambda = 10.6\ \mu m$). Using an established linear relationship (based on the Chýlek approximation to the Mie theory) between extinction and liquid water content, the liquid water contents of clouds varying in both droplet size and concentration have been determined. These values are compared with liquid water contents derived from simultaneous cloud collection. The agreement between the two techniques is excellent having a correlation coefficient of 0.98 and corresponding favorable 95% confidence limits. The results indicate that this technique should prove extremely useful for the field measurement of the liquid water content of clouds and fogs.

1. Introduction

Determination of the liquid water content of a cloud or fog is of considerable meteorological importance. An ideal technique would measure the liquid water content accurately over a wide range without dependence on the drop size distribution, give a rapid continuous response, and cause a minimal disturbance to the environment (Mason, 1971). Until now, there is no proven analytical method that meets the above requirements.

Recently, Chýlek (1978) derived a linear relationship, independent of the size distribution for drop radii $< 14\ \mu m$, between the liquid water content of a cloud or fog and its extinction in the infrared at $11\ \mu m$. This relationship was verified using numerical calculations by Pinnick *et al.* (1979) for 341 drop size distributions measured by impaction, holographic and light scattering techniques under various meteorological conditions. Their results suggest that the liquid water content of a cloud can be uniquely determined from measurement of CO_2 laser ($\lambda = 10.6\ \mu m$) extinction along a path in the cloud. The essential feature leading to the linear relationship is the approximation of the extinction cross section, $Q_e(x,\lambda)$ by

$$Q_e(x,\lambda) = c(\lambda)x, \tag{1}$$

where x is the droplet size parameter defined by the ratio of the particle circumference to the wavelength λ, and $c(\lambda)$ is the slope of a straight line that closely approximates the extinction efficiency curve from the Mie theory at the 10.6 μm wavelength. Upon application of this result, a linear expression between extinction σ_e and liquid water content W was obtained with the form

$$\sigma_e = \frac{3\pi c(\lambda)}{2\lambda\rho} W, \tag{2}$$

where ρ is the density of water. The derivation of this result and the conditions under which this expression is valid have been discussed by Chýlek (1978) and Pinnick *et al.* (1979).

We have compared the results of liquid water content determinations using CO_2 laser extinction measurements and simultaneous cloud-water collection and have found them to be in excellent agreement. This work is the first experimental verification of the linear relationship proposed by Chýlek (1978). The data also indicate good agreement for both polydisperse and monodisperse droplets over a wide range of liquid water contents.

2. Experiments

Clouds of known droplet radius and concentration were produced using the DRI dynamic cloud chamber.[1] The chamber is a cylindrical vessel 1.8 m in diameter and 2.5 m high with a volume of 6.6 m^3. The gradual evacuation of the chamber and cooling of the walls closely simulates the adiabatic ascent of

[1] See, for example, Dunsmore, H., and R. L. Steele, 1974: An investigation of sequence dependent effects in seeding simulated cumulus clouds. *Preprints 4th Conf. on Weather Modification*, Ft. Lauderdale, Amer. Meteor. Soc., 183–189; and Steele, R. L. and F. W. Smith, 1968: An experimental facility for simulation of adiabatic cloud processes. *Preprints First Nat. Conf. Weather Modification*, Albany, Amer. Meteor. Soc., 316–325.

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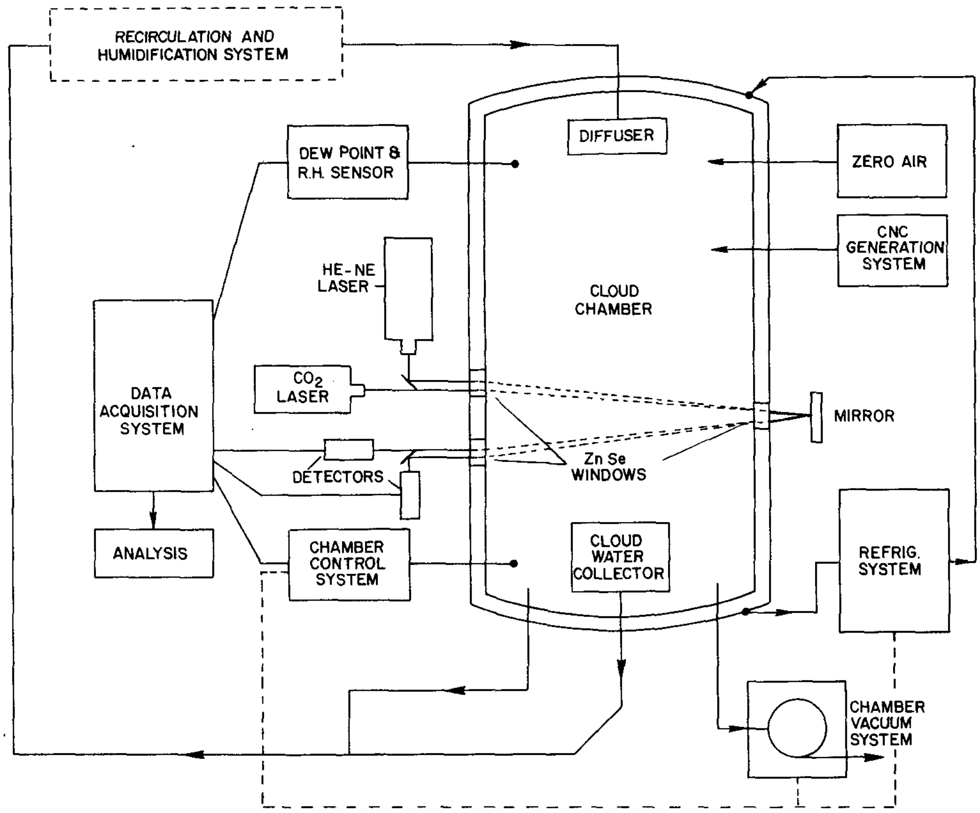

FIG. 1. Schematic of the cloud chamber. The CO_2 laser beam is approximately colinear with the HeNe beam and has a total path length of 361 cm. The cloud water collector is removed through a window on the chamber wall.

an air parcel in the atmosphere with accompanying cloud formation.

The cloud condensation nuclei (CCN) used to initiate cloud formations in the chamber were produced by atomization of saline solutions that were introduced into the chamber after drying and passing through a size discriminator (TSI 3071 Electrostatic Classifier).[2] The concentrations of the CCN in the chamber were monitored by a total particle counter (TSI 3020 Condensation Nucleus Counter).[3]

Using the above atomization technique, polydisperse droplet populations were produced by direct atomization of a sodium chloride solution, i.e., bypassing the size discriminator. The size distribution, $dN/d \log R$, of droplets generated in this manner has a maximum at $R = 0.05$ μm with a median radius of 0.065 μm and standard deviation of 1.4. Calculations based on this measured size distribution show that the fraction of droplets that grow to 14 μm in radius is less than 0.6% of the total number of droplets. Under the experimental conditions, size distributions that strongly violate the maximum radius condition (14 μm) are, therefore, not expected. For monodisperse CCN populations, alteration of the initial CCN concentration (keeping all other parameters constant) yields clouds of different drop sizes and concentrations for a given liquid water content.

The liquid water content of the cloud is measured by an absolute collector installed in the chamber. The collector consists of an aluminum cylinder 10 cm in diameter packed with glass wool and connected to the chamber sampling system as shown in Fig. 1. A measured volume (1–1.5 m^3) is sampled, the collector is removed, weighed and the liquid water content of the cloud (g m^{-3}) is calculated. The uncertainty in the measurements is approxi-

[2] For detailed analysis of the TSI 3071 Electrostatic Classifier see Knutson and Whitby (1975). It should be noted that under normal operating conditions, the aerosol output is not truly monodisperse. The output consists not only of the aerosol size of interest but also particles having two and three times the specified aerodynamic size. The ratio of aerosols to doublets is approximately 4:1 by number.

[3] A description and discussion of the TSI 3020 Condensation Nucleus counter has been presented by J. K. Agarwal, G. J. Sem and M. Pourprix in *Proceedings of the Ninth International Conference on Atmospheric Aerosols, Condensation and Ice Nuclei*, Galway, Ireland, September 1977, Pergamon Press (in press).

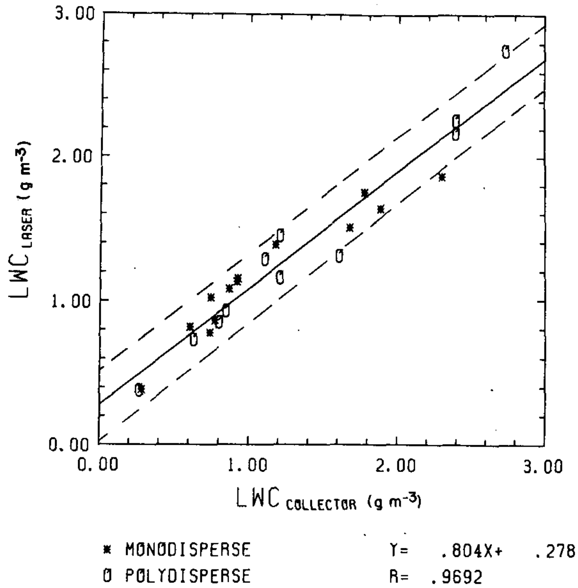

FIG. 2. Comparison of liquid water content measurements using the cloud water collector (LWC^{coll}) and the CO_2 laser transmissometer (LWC^{laser}) for both monodisperse (*) and polydisperse (O) droplet populations. There is very good agreement between the two methods. The dashed lines correspond to ±2 standard errors of the regression.

mately ±10% as determined from blank experiments. The major source of this error is in evaporative losses from the collector after cloud dissipation since the collector cannot be removed from the chamber until ambient pressure is restored. Losses during the sampling period under supersaturated conditions were found to be minimal. A second source of error is the accuracy with which the sample volume could be determined from the measured mass flow rate and the sampling time (see Fig. 1 for schematic of sampling system). The short lag time for the flow to reach a steady value, i.e., the time required for establishment of the required flow, was small compared with the total sampling period but cannot be totally ignored. Another source of error could result from the cloud being sampled at a fixed point in the chamber, since the cloud density may not be uniform along the laser path but it is unlikely that this could produce an error of more than 5%. Aside from the foregoing, small fluctuations in the laser signal were taken in account in the LWC calculations by using average values of the intensity to calculate the extinction.

The IR extinction measurements were made in the cloud chamber with a CO_2 laser transmissometer designed so as to minimize any forward-scattering effects (Deepak and Box, 1978a,b). The semi-angle of field of view is 0.05° with a total integrated path length of 361 cm leading to negligible corrections for both single- and multiple-scattering events. The system consists of an externally mounted GTE Sylvania model 941S stabilized CO_2 laser, Laser Precision RL-3610 power meter with probe and chopper, and ZnSe windows which are water insoluble and transparent in the visible and infrared. The laser power is stable to within 5% per hour and was assumed to be stable over the course of an experiment (which is nominally 8 min long). The output of the power meter is continuously displayed on a strip chart recorder which is also used to monitor the development of the cloud. When the maximum liquid water content is reached and held constant, the cloud is sampled. The simultaneous measurements from both the laser system and the collector are then compared and the correlation of the IR extinction measurements with the collected cloud water evaluated.

3. Results and discussion

In order to calculate W from Eq. (2), a value of $c(\lambda) = 0.33\ [3\pi c(2\lambda\rho)^{-1} = 1.5 \times 10^3\ \mathrm{cm^2\ g^{-1}}]$, calculated by Pinnick *et al.* (1979), was used. For water drops at $\lambda = 10.6\ \mu$m, the linear approximation is valid for all drop radii up to 14 μm. A comparison of the LWC measured by cloud collection and IR laser extinction is shown in Fig. 2. The liquid water contents ranged from 0.27 to 2.74 g m^{-3}. Under different but controlled experimental conditions in the chamber, both higher and lower liquid water contents were observed. The two methods agree remarkably well. The data were found to be normally distributed with a correlation coefficient of 0.97, a standard error of 0.14 g m^{-3} and a 95% confidence limit of ±0.28 g m^{-3}.

It is interesting to note that little difference is observed between monodisperse and polydisperse droplet distributions. (For the monodisperse droplets the correlation coefficient R is 0.96, slope = 0.68, and y intercept = 0.4. For polydisperse droplets R = 0.98, slope = 0.87 and y intercept = 0.17). The linear relationship is expected to be more significant for the polydisperse case since the approximation overestimates the exact value of Q_e at some values of x and underestimates it at others. This is the case for the large and small ends of the drop size spectrum. For the mid-range the deviations from the theoretical curve derived from Mie theory are minimized and agreement between the polydisperse and monodisperse cases is also expected.

For the case of monodisperse CCN (and subsequently a monodisperse cloud drop size distribution) knowledge of the CCN concentration and liquid water content enables one to calculate the theoretical droplet radius. These results are shown in Fig. 3. Again, the agreement is excellent, with a correlation coefficient of 0.99, standard error of 0.28

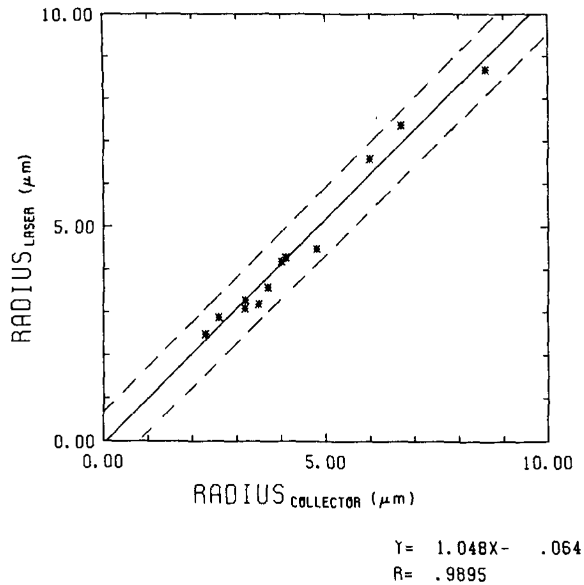

FIG. 3. Comparison of results for monodisperse cloud droplet populations. The droplet radii were from 2.3 to 8.7 μm.

μm and 95% confidence limit of ± 0.55 μm. Droplet radii varied from a low of 2.3 to a high of 8.7 μm, a large spread when one considers the agreement between the two methods. Finally, work continues to refine and utilize the laser calibration techniques. A number of other drop size distributions will also be examined over a broader range of liquid water contents.

4. Conclusion

The linear relationship as predicted by Chýlek (1978) between liquid water content and IR extinction has been experimentally verified. The results, covering a practical range of liquid water contents and droplet sizes, demonstrate that the technique is extremely promising for the real-time determination of liquid water content of clouds and fogs.

The simplicity of the experimental system should enable it to be used not only for ground but also for airborne measurements to determine path-integrated liquid water content of both clouds and fogs.

Acknowledgments. The authors gratefully acknowledge the Electric Power Research Institute who provided much of the support for this work. We also thank Dr. Gerry Jennings and Dr. Ronald Pinnick for their stimulating discussions that led to the acquisition of the laser system. Mr. Rick Purcell is also recognized for his design and construction of the cloud water collector.

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