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**BIMODAL SIZE DISTRIBUTION MODELS
FOR
FOGS AT MEPPEN, GERMANY**

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By

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RICHARD D. H. LOW**

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ERRATA FOR ASL-TR-0056

BIMODAL SIZE DISTRIBUTION MODELS FOR FOGS

AT MEPPEN, GERMANY

Page 9 Change equation (1) as follows:

$$K_{\lambda} = \pi \int_{r_1}^{r_2} r^2 n(r) Q_{\text{ext}}(m, r, \lambda) dr, \quad (1)$$

Change equation (2) as follows:

$$W = \frac{4}{3} \pi \int_{r_1}^{r_2} r^3 n(r) dr, \quad (2)$$

Page 11 Equation (3). Change numerator from r to r^{α}

Equation (5), last line:

$$(\alpha + 2) \cdots (\alpha + n) .$$

Page 14 Fourth paragraph, last line:
of (5) to solve for β

Page 21 Table 3, 6th column:
Change K'_{10} to K_{10}

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20. ABSTRACT (cont)

Six parameters are required to determine a model size distribution. It is shown that constants can be assigned to two of these parameters. Algorithms, based upon curve fits, are developed for computing the other parameters as a function of visibility.

Tables and graphs are presented which demonstrate the capability of the model to reproduce the features of the measured drop-size distributions; also included are comparisons of the derived quantities of liquid water content and infrared extinction coefficients.



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INTRODUCTION

Over the next few years, various kinds of thermal imaging and other electro-optical sensing devices will be developed and deployed as integral components of diverse types of military and civilian systems. Under limited visibility conditions, the performance of such systems may be adversely affected. The point at which this degradation becomes significant depends upon a number of factors such as the intended application, the nature of low visibility conditions, and the system itself. Both the designer and the user should be aware of the environmental limitations and should possess the tools for an assessment of the severity of these limitations. The purpose of this report is to attempt to provide such tools.

Dense haze or fog occurrences in the lower atmosphere produce sharp reduction in visibility which may persist for hours. The resulting attenuation of the electromagnetic radiation by the suspended haze and/or fog particles depends upon their number concentration, refractive index, and characteristics of the size distribution. The extinction (or conversely, transmission) property of this polydispersion is highly wavelength dependent from the visible through the infrared; such dependence appears to be strongly related to the size range as well as the shape of the size distribution.

In the past, the drop-size data found in the literature were collected, almost without exception, with mechanical impactors and reduced with the aid of a microscope.¹ The collection efficiency of these impactors drops to nearly zero for particles of $1\mu\text{m}$ to $2\mu\text{m}$ radius. While the tiny particles less than $1\mu\text{m}$ to $2\mu\text{m}$ radius may play an insignificant role in the microphysics and dynamics of cloud/fog formation, growth, and dissipation, they cannot be lightly neglected in the optics of a hazy/foggy environment. Their importance has been demonstrated by Hindman and Heimdahl.² As a result of missing the tiny particles, the drop-size spectra on the average often revealed a unimodal distribution. Past efforts in modeling a distribution of this type have been made by resorting to standard statistical functions³ without regard to optical implications of the distribution. However, with the advent of optical particle counters and the resulting finer resolution, the drop-size

¹B. J. Mason, 1971, The Physics of Clouds, Oxford University Press, 617 pages

²E. E. Hindman II and O. E. R. Heimdahl, 1977, "Submicron Haze Droplets and their Influence on Visibility in Fog," preprint, 6th Conference Inadvertent and Planned Weather Modification, Am Meteorol Soc, Boston, MA, 10-13

³N. H. Fletcher, 1962, The Physics of Rainclouds, Cambridge University Press, 386 pages

spectra on the average often do not appear to be unimodal, but unmistakably reveal a second mode in what Hindman and Heimdahl² called the haze regime.

During the past several years, a significant amount of drop-size data has been collected by the NATO countries and the United States in an effort to establish a data base for the evaluation of various types of military electro-optical systems. An analysis of these data shows that the drop-size distributions on the average are usually bimodal and their shapes vary considerably with variations in visibility (e.g., Low³). With these characteristics in mind, we have undertaken to further analyze these data and to develop more adequate haze/fog models, which are bimodal in shape and which reflect the changes in drop-size spectra with visibilities. This report represents the initial results of these investigations. In the following section, a review of the state of the art in fog modeling together with a set of criteria for the formulation of models will be presented. Next, the nature of the data used and the steps in model development are discussed. This discussion is then followed by an evaluation of model outputs and our concluding remarks in two separate sections.

BACKGROUND

Two skewed probability density functions have most often been used in the past to model haze/fog drop-size spectra, i.e., lognormal and gamma.^{3, 5, 1} There are, then, two variations of the gamma function.^{7, 8}

²E. E. Hindman II and O. E. R. Heimdahl, 1977, "Submicron Haze Droplets and their Influence on Visibility in Fog," preprint, 6th Conference Inadvertent and Planned Weather Modification, Am Meteorol Soc, Boston, MA, 10-13

³R. D. H. Low, L. D. Duncan, and Y. Y. R. Hsiao, 1979, Microphysical and Optical Properties of California Coastal Fogs at Fort Ord, ASL-TR-0034, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 22 pages

⁴N. H. Fletcher, 1962, The Physics of Rainclouds, Cambridge University Press, 386 pages

⁵A. Kh. Khrgian, Ed., 1963, Cloud Physics, Israel Program for Scientific Translations, Jerusalem, 392 pages

⁶B. J. Mason, 1971, The Physics of Clouds, Oxford University Press, 617 pages

⁷A. Kh. Khrgian and I. P. Mazin, 1952, "Distribution of Drops According to Size in Clouds," Trudy Tsen Aero Obs, 7:56-61 (English version)

⁸D. Deirmendjian, 1964, "Scattering and Polarization Properties of Water Clouds and Hazes in the Visible and Infrared," Appl Opt, 3:187-196

Of the two, the former reduced the two parameters of the function to one, and the latter added one parameter to make it a three-parameter function. Following Diermendjian's lead, Tampieri and Tomasi⁹ assembled a large amount of fog data from the literature and developed statistical models on the basis of these data. Their results show that there can be appreciable variations among fog drop-size spectra resulting from different formation processes. It may be of some historical interest to note that according to Khrgian,⁵ Levin⁶ first suggested in 1958 that the size distribution of droplets obeys the lognormal law discovered by Kolmogorov for the size of gold particles in placer deposits, but then finally settled on the gamma distribution (1958) on the basis of cloud-chamber experiments. Each function will undoubtedly have its adherents. According to Twomey,¹⁰ there appear to be no theoretical grounds for stating that haze/fog spectra should necessarily follow any or all of these distribution functions (or any other for that matter), and the problem is largely one of curve fitting.

After having examined a large set of drop-size spectra, Zevv¹¹ felt that most samples could be adequately approximated by a gamma distribution. When one inspects a large number of sample distributions as we have done, it becomes immediately apparent that no simple distribution function can reproduce all of the features exhibited by measurements. Nor is it evident that such detailed representation is necessary or desirable, considering the state of the art in aerosol sampling. In fact, having compared a number of different optical particle counters in a carefully designed laboratory investigation, Cross and Fenn,¹² showed

⁹F. Tampieri and C. Tomasi, 1976, "Size Distribution Models of Fog and Cloud Droplets in Terms of the Modified Gamma Function," Tellus, 28:333-347

⁵A. Kh. Khrgian, Ed., 1963, Cloud Physics, Israel Program for Scientific Translations, Jerusalem, 392 pages

⁶L. M. Levin, 1958, "Functions to Represent Drop-size Distributions in Clouds," Izv Geofiz Ser, 10:1211-1221 (English version)

¹⁰S. Twomey, 1977, Atmospheric Aerosols, Elsevier, NY, 302 pages

¹¹V. E. Zuev, 1970, Atmospheric Transparency in the Visible and in the Infrared, Israel Program for Scientific Translations, Jerusalem, 220 pages

¹²T. S. Cross and R. W. Fenn, Ed., 1978, OPAQUE Aerosol Counter Intercomparison, 25 April 1977--4 May 1977, AFGL-TR-78-0004, USAF Geophysics Laboratory, Hanscom AFB, MA, 56 pages

that the optical devices in current use for measuring drop-size distributions are accurate to within a factor of 2. Since the observed drop-size data are typically bimodal, it would be logical to formulate bimodal distribution functions to represent them. Of the two commonly used density functions, the gamma function is simpler to handle and its various moments can be readily generated. The bimodal feature may be easily represented by the weighted sum of the two gamma distributions.

Since there is no theoretical reason for selecting a priori a particular type of model, a set of guidelines by which the models are to be developed must be established. The guidelines are as follows:

1. The model should be as simple as practicable.
2. The model should reproduce, well within a factor of 2, the data and the derived quantities such as liquid water content and infrared extinction coefficients.
3. The fitting of the model to the measured data should not be an onerous task.

Following these guidelines, the lognormal distribution, the one-parameter gamma distribution of Khrgian and Mazin,⁷ the standard two-parameter gamma distribution, and the three-parameter distribution of Deirmendjian⁸ in two modes were each fitted to the same sets of data and carefully analyzed. The lognormal distribution gave rather inconsistent results, the one-parameter gamma distribution was consistent but not accurate enough, and the three-parameter gamma distribution was superior to either of the above, but not enough over the two-parameter gamma distribution to warrant the added burden of carrying an extra parameter. Therefore, the bimodal two-parameter gamma distribution was elected.

DATA USED FOR MODEL DEVELOPMENT

The data used for developing and fitting the model were obtained by the Atmospheric Sciences Laboratory (ASL) during an extensive field experiment at Meppen, Germany.* Ground-based measurements of haze/fog

⁷A. Kh. Khrgian and I. P. Mazin, 1952, "Distribution of Drops According to Size in Clouds," Trudy Tsen Aero Obs, 7:56-61 (English version)

⁸D. Deirmendjian, 1964, "Scattering and Polarization Properties of Water Clouds and Hazes in the Visible and Infrared," Appl Opt, 3:187-196

*A comprehensive technical report on the Meppen experiment is in preparation.

drop-size distributions were made with a Particle Measuring Systems FSSP-100 light scattering particle measurement device (commonly known as Knollenberg Counter) which measures drop sizes from 0.25 μ m to 23.5 μ m radius. The data from 22 February 1978 and 4 March 1978 were reduced to obtain an average size distribution every 5 minutes and were used for curve fitting. These two sets were chosen because of the large number of drop-size spectra collected (24 hours on 22 February and 16-1/2 hours on 4 March) as well as the broad range of visibilities encountered. Computed visibilities* ranged from 0.04 km to 2.7 km on 22 February and from 0.02 km to 7.5 km on 4 March.

In the course of analyzing this huge amount of data, we often noted that there was an apparent relationship between the ranges of visibility and the shape characteristics of a distribution. To display these characteristics, the visibility range was segmented and the mean size distributions for the various segments were computed. Mean size distributions for 22 February are shown in figure 1, and the mean size distributions for the 0- to 200-meter visibility segment for several days are shown in figure 2. Inspection of these two figures not only reveals the distinct bimodal character of the drop-size spectra but also shows that the most pronounced change with changing visibility in these spectra is manifest in the second mode.

The relative importance of the two modes can be investigated by employing some of the computations which are frequently used in assessing the degradation of an electro-optical system. These computations are liquid water content and extinction coefficient. The extinction coefficient, K_λ , at a wavelength λ is computed from

$$K_\lambda = \pi \int_{r_1}^{r_2} r^2 n(r) Q_{\text{ext}}(m, r, \lambda) dr, \quad (1)$$

where $n(r)$ is the size distribution; $Q_{\text{ext}}(m, r, \lambda)$ is the Mie extinction efficiency factor at complex refractive index m , radius r , and wavelength λ ; and r_1 and r_2 are the range of radii over which $n(r)$ is defined. Liquid water content W of the distribution is given by

$$W = \frac{4}{3} \pi \int_{r_1}^{r_2} r^3 n(r) dr, \quad (2)$$

*Throughout the paper, the values used for visibility were calculated from the drop-size distributions.

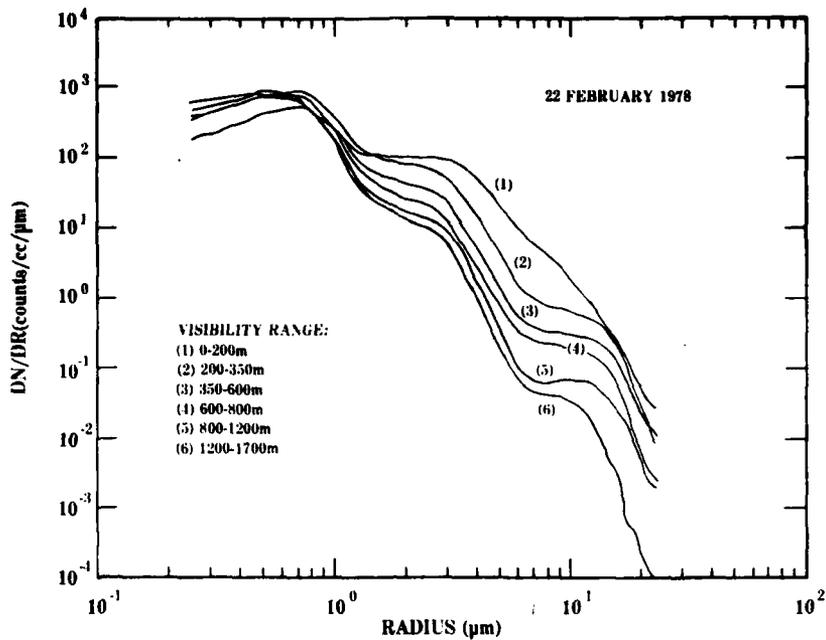


Figure 1. Mean drop-size distributions of the Meppen fog on 22 February 1978 corresponding to different visibility ranges.

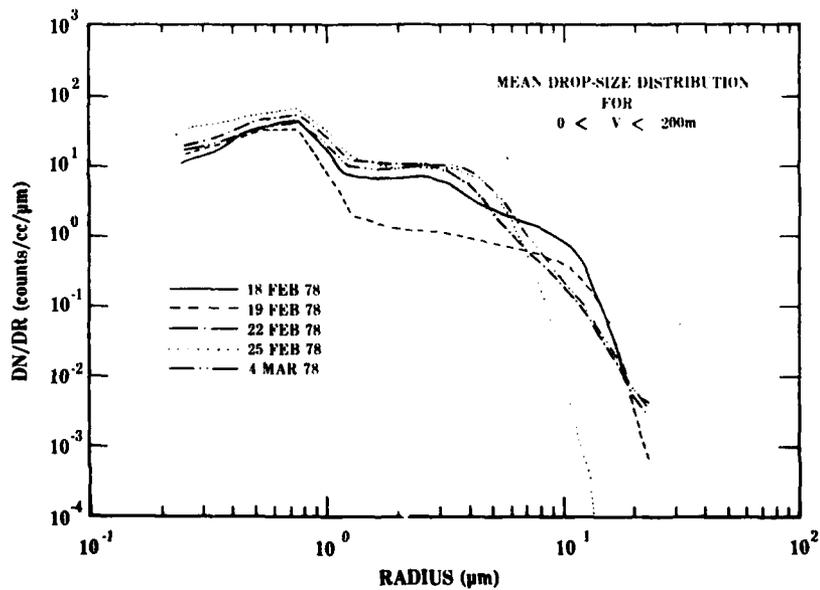


Figure 2. Mean drop-size distributions in the 0 m to 200 m visibility range on different foggy days at Meppen, Germany.

with the implicit assumption that the density (of liquid water) is unity. Now if we define $K_\lambda(r)$ to be the partial integral obtained by integrating equation (1) from r_1 to $r \leq r_2$ and let $P_1(r) = 100 k_\lambda(r)/K_\lambda$, then $P_1(r)$ is the percent of the total extinction at wavelength λ resulting from particles of sizes equal to or less than r . With a similar definition of $W(r)$ and $P_2(r)$, we have the percent of the total liquid water content up to radius r . Examples of such calculations are shown in figures 3 and 4 for visibilities of 1.95 and 0.258 km, respectively. The 10 and 90 percentile radii from a number of different visibility values are presented in table 1. These graphs show that the major contribution to both extinction and liquid water comes from the second mode of the distribution.

Fitting the Bimodal Gamma Distribution

The gamma distribution is defined by the density function

$$\Gamma(r, \alpha, \beta) = \frac{r^\alpha}{\alpha! \beta^{\alpha+1}} e^{-r/\beta} \quad (3)$$

where α and β are the two parameters subject to $\alpha = 1$ and $\beta > 0$. Published literature disagrees as to whether α is required to be an integer. Since restricting α to integer values simplifies the computations considerably, we decided to adopt this approach in our model development. The statistical moments as given by the equation

$$\mu_n(\alpha, \beta) = \int_0^\infty r^n \Gamma(r, \alpha, \beta) dr, \quad (4)$$

are

$$\begin{aligned} \mu_1(\alpha, \beta) &= \beta(\alpha + 1) \\ \mu_2(\alpha, \beta) &= \beta^2(\alpha + 1)(\alpha + 2) \\ \mu_n(\alpha, \beta) &= \beta^n(\alpha + 1)(\alpha + 2) \dots (\alpha + n). \end{aligned} \quad (5)$$

TABLE 1. TEN AND NINETY PERCENTILE RADII FOR COMPUTATION OF LIQUID WATER CONTENT AND $10_{\mu m}$ EXTINCTION COEFFICIENT. DATA IS FROM MEPPEN, GERMANY, 22 FEBRUARY 1978

Time	Visibility (km)	10th Percentile K_{10}	Lwc	90th Percentile K_{10}	Lwc
0005	1.95	0.75	0.6	12	9
0129	0.534	1.0	0.7	17.5	18.5
0216	0.407	3.5	3.0	15.0	15.0
0247	0.242	3.5	2.75	14.0	14.5
0334	1.08	1.8	1.0	14.0	14.0
0446	0.258	2.7	2.2	13.0	12.5
0527	0.172	3.0	2.5	12.0	12.0
0638	0.287	3.0	2.8	11.5	11.5
0751	0.173	3.0	2.5	12.5	12.5
0905	0.146	3.0	2.2	11.5	11.0
1018	0.529	2.6	2.0	14.5	15.0
1229	1.09	2.7	2.0	20.8	21.0
1358	0.304	3.2	2.9	17.5	18.0
1532	0.100	4.5	4.3	18.5	17.5
1626	0.090	4.6	4.5	18.0	19.0
2042	0.86	3.9	3.5	13.5	14.0
2200	0.112	3.9	3.5	10.5	10.5
2301	0.131	4.0	3.7	11.6	11.5

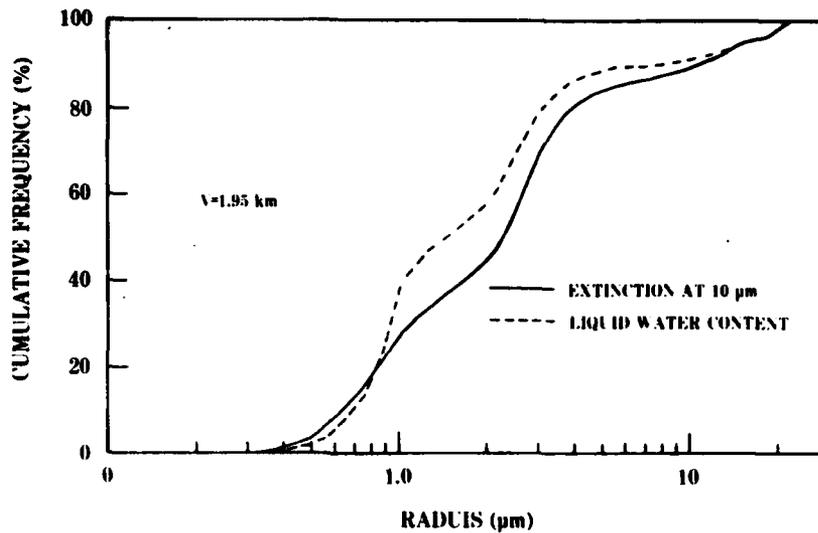


Figure 3. An example of cumulative frequency distributions of the liquid water content and the extinction coefficient at $10\mu\text{m}$ wavelength for visibility = 1.95 km. Note the relatively high percentage of sizes below the $1\mu\text{m}$ radius.

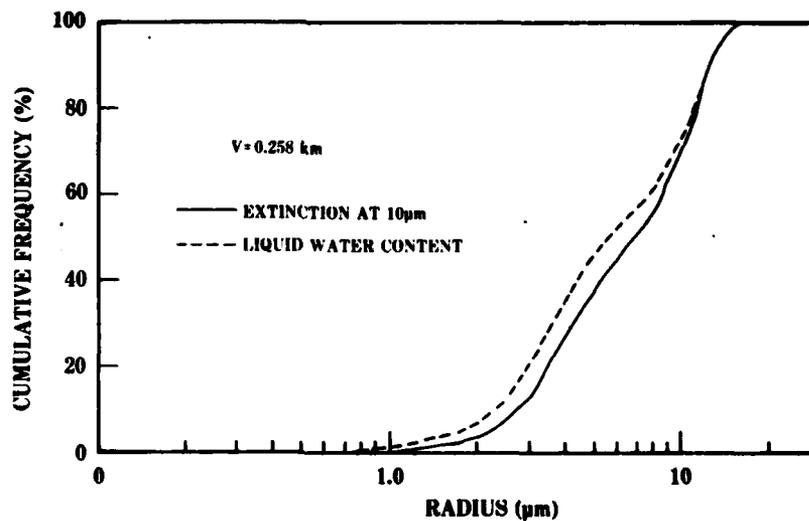


Figure 4. An example of cumulative frequency distributions of the liquid water content and the extinction coefficient at the $10\mu\text{m}$ wavelength for visibility = 0.258 km. Note the almost total absence of smaller droplets below $1\mu\text{m}$ radius.

The values of α and β are readily obtained from the first two moments,

$$\beta = \mu_2 / \mu_1 - \mu_1 \quad (6)$$

and

$$\alpha = \mu_1^2 / (\mu_2 - \mu_1^2) - 1 . \quad (7)$$

As mentioned earlier, the data are typically bimodal and should be fitted with a bimodal function. In addition, equation (3) represents a density function, while the number concentration of a drop-size distribution is significantly greater than unity. This suggests a model of the form

$$n(r) = N_1 \Gamma(r, \alpha_1, \beta_1) + N_2 \Gamma(r, \alpha_2, \beta_2) , \quad (8)$$

where N_1 , α_1 , β_1 , N_2 , α_2 , and β_2 are parameters to be determined.

Using equations (5) and (8), one obtains a set of six simultaneous nonlinear equations of degrees ranging from 2 to 12, which can be solved for the parameters of equation (8). These equations would be difficult to solve for the six unknowns. Fortunately, a simple approximate method for obtaining these parameters was found. As will be seen later, the errors resulting from the approximation must be insignificant.

An inspection of figures 1 and 2 with the basic shape of the gamma distribution in mind suggests that the contribution to $n(r)$ from $\Gamma(r, \alpha_1, \beta_1)$ comes from sizes less than about $1.5\mu\text{m}$ radius and that the contribution from $\Gamma(r, \alpha_2, \beta_2)$ comes from radii greater than $1.5\mu\text{m}$. With this in mind, each drop-size distribution was separated into two distributions with the $1.5\mu\text{m}$ radius as the separation point. (The $1.5\mu\text{m}$ separation point may be an instrument artifact according to Pinnick and Auvermann.¹³) The first and second moments and the number concentrations of particles were computed independently for each portion. The computed number of particles provides values for N_1 and N_2 . The values of α 's and β 's are obtained from equations (6) and (7) in an iterative fashion. Since equation (7) will usually not provide an integer value for α , the value so obtained is rounded to the nearest positive integer. This value of α is then substituted into the first moment equation of (6) to solve for β .

Frequency distributions of α_1 and α_2 values are shown in table 2. The table shows that 6 and 3 are the most likely values for α_1 and α_2 , respectively. Consequently, these values were selected as fixed model

¹³R. G. Pinnick and H. J. Auvermann, 1979, "Response Characteristics of Knollenberg Light-Scattering Aerosol Counters," J Aerosol Sci, 10:55-74

TABLE 2. FREQUENCY OF OCCURRENCE OF VALUES α_1 AND α_2

	Value of α_1				
	4	5	6	7	8
22 Feb 78	1	65	98	0	0
4 Mar 78	10	42	40	7	11

	Value of α_2						
	0	1	2	3	4	5	6
22 Feb 78	8	49	12	62	24	2	5
4 Mar 78	1	1	11	22	18	14	9

parameters. The β_1 values were then recomputed by using $\alpha_1 = 6$ according to the first moment equation for all cases where the original values of α_1 differed from 6. A similar recalculation of some of the β_2 values was also required. Once these computations were completed, curve fitting techniques were used to obtain equations relating N_1 , N_2 , β_1 , and β_2 to visibility.

To simplify the data handling procedure and preclude bias towards the lower visibility data, the visibility range was segmented into logarithmically equally spaced intervals and mean values were computed for each interval. The results for N_1 , β_1 , and β_2 together with the corresponding equations obtained by the least squares curve fitting technique are presented in figures 5, 6, and 7. These results indicate that N_1 , β_1 , and β_2 can be related to visibility V through the following formulas:

$$N_1 = 446 V^{-0.106} , \quad (9)$$

$$\beta_1 = 0.09 - 0.2 \log V , \quad (10)$$

and

$$\beta_2 = 0.63 V^{-0.076} . \quad (11)$$

A preliminary equation for N_2 was obtained by the least squares procedure, and simulated drop-size distributions were computed for a range of visibilities. The N_2 values were then modified to "fine tune" the model until visibilities computed from the simulated distributions agreed with the input visibilities. Figure 8 shows the results of such "fine tuning," and the equations for N_2 are given below:

$$\begin{aligned} N_2 &= 36 V^{-1} && \text{for } V < 0.5 \text{ km} \\ &= 29.4 V^{-1.11} && \text{for } V = 0.5 \text{ km} \end{aligned} \quad (12)$$

Evaluation of Model Outputs

Equations (9) through (12) together with the values $\alpha_1 = 6$ and $\alpha_2 = 3$ provide the parameters to be used in equation (8) to simulate a dropsize distribution corresponding to a given or an observed visibility. With a distribution known, it is a simple matter to compute the resulting extinction or transmission of any desired wavelength. As discussed earlier, the model is not intended to reproduce all the details of the measurements; the goal was to simulate their principal characteristics and extinction properties. An example of the model's capability to satisfy the first objective is shown in figure 9. The comparison of the measurement with simulation can be considered excellent for radii

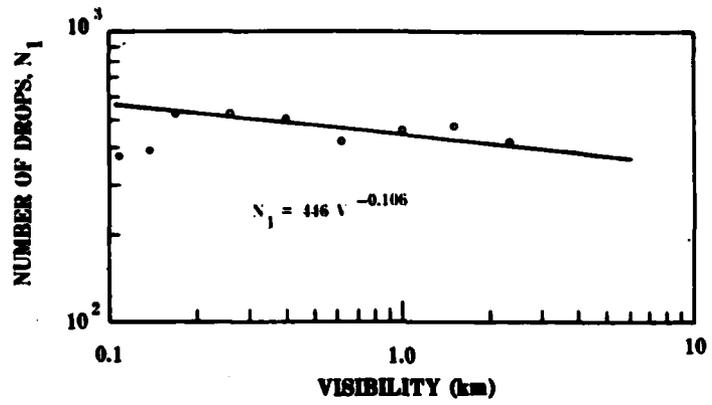


Figure 5. The number of drops in the first mode as a function of visibility in a least-squares fit.

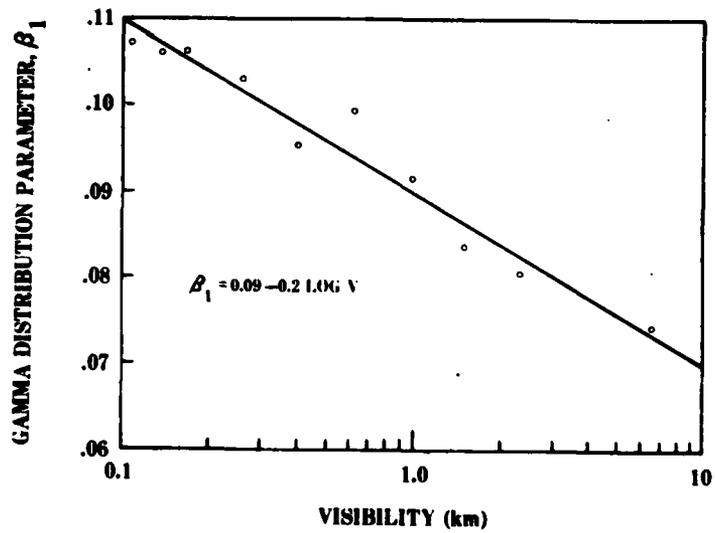


Figure 6. The gamma distribution parameter of the first mode as a function of visibility in a least-squares fit.

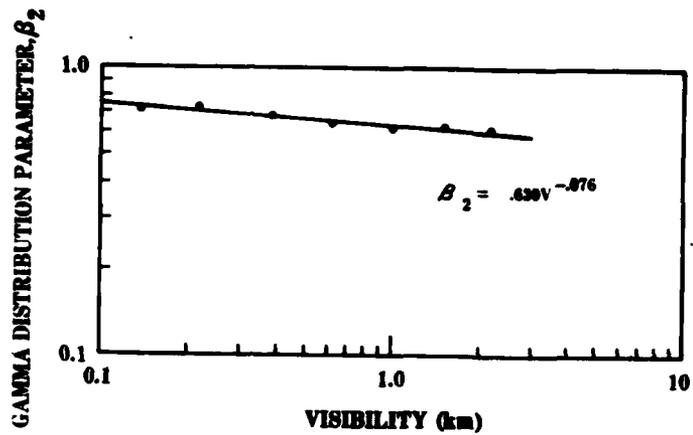


Figure 7. The gamma distribution parameter of the second mode as a function of visibility in a least-squares fit.

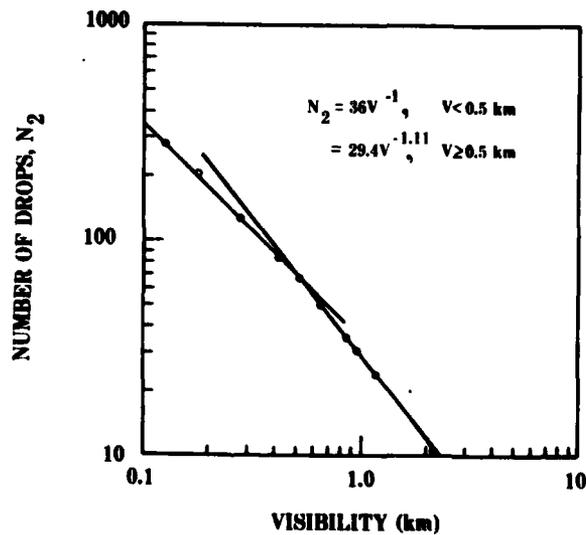


Figure 8. The number of drops in the second mode as a function of visibility in a fine-tuned least squares fit.

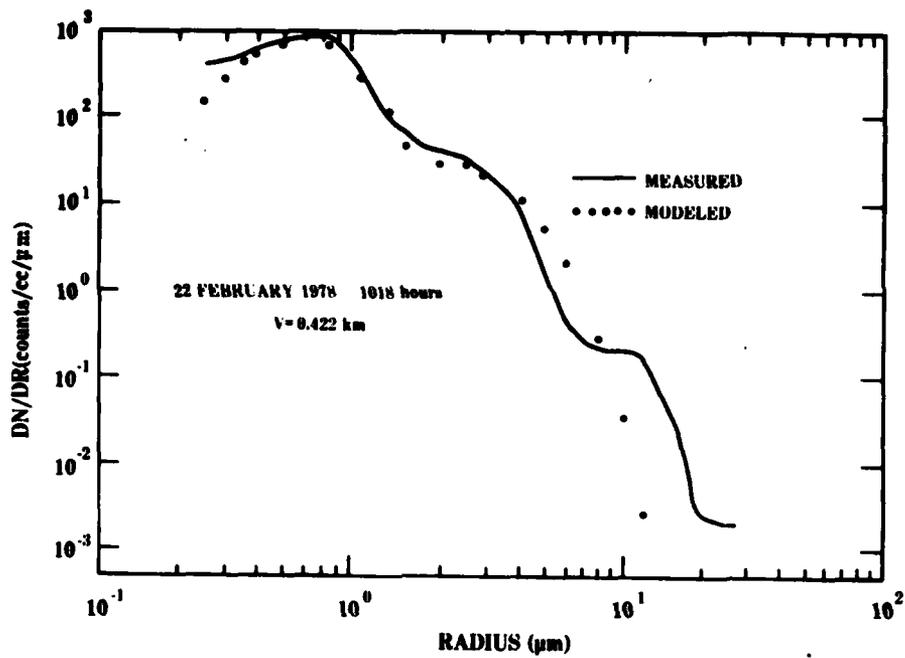


Figure 9. An example of how well the model distribution matches the observed distribution for visibility = 0.422 km.

smaller than about $10\mu\text{m}$. The model cannot reproduce the apparent third mode between $10\mu\text{m}$ and $15\mu\text{m}$ radii. This apparent third mode, which can also be seen in figure 1, appears in about one-half of the observations. This occurrence is not at all surprising, as may be deduced from a theoretical study by Neiburger and Chien.¹⁴ In this study, they succeeded in generating a bimodal drop-size distribution in the fog sector after some 50 minutes of droplet growth under the influence of droplet collision and coalescence.

Liquid water content and extinction coefficient for wavelengths of $3.8\mu\text{m}$ and $10\mu\text{m}$ computed from the model drop-size distributions were compared with those derived from corresponding measured ones of 22 February 1978 and 4 March 1978. As before, mean values for specific visibility intervals were also computed. These values are tabulated in table 3. A cursory comparison of the values of the corresponding parameters shows that deviations of the model values are on the average no greater than $\pm 15\%$ of those derived from observations--well within the measurement capability of the particle counter in current use.

Concluding Remarks and Some Observations

The methodology which has been developed and exploited in this report provides a capability to generate bimodal drop-size distributions consisting of both the haze and fog sectors commensurate with measurement data (at least in the case of the Meppen fogs) and possesses the additional capability to provide a distribution corresponding to a given or observed visibility. The model distribution so established may then be used to calculate extinction coefficients at other wavelengths.

Although the equations presented herein do not provide the parameters for depicting all types of haze/fog drop-size distributions, they are nevertheless quite adequate in representing most of the observations taken at Meppen, with the possible exception of those of 19 February 1978. It may thus be said that the approach used for modeling the Meppen fogs with a bimodal gamma distribution could be readily applied to other fog data. In concluding this report, we make a few observations about the difficulties encountered in haze/fog modeling as a result of the experiences gained in our thoroughgoing analysis of the Meppen fogs.

1. There are strong indications that, because of the continual presence of submicron-sized pollution particles which may be too tiny or may not be hygroscopic enough to grow into fog droplets, there will always be a haze regime in a fog, the magnitude of which depends upon

¹⁴M. Neiburger and C. W. Chien, 1960, "Computations of the Growth of Cloud Drops by Condensation Using an Electronic Digital Computer," Phys of Precipitation, Geophys. Monor. No. 5, Amer. Geophys. Union, Washington, DC, 191-210

TABLE 3. COMPARISON OF DERIVED QUANTITIES FROM MEASURED AND MODELED SIZE DISTRIBUTIONS. PRIMED QUANTITIES INDICATE MODELED VALUES.

Visibility	Lwc	Lwc'	K _{3.8}	K _{3.8} '	K ₁₀ '	K ₁₀ '
<u>4 March 1978</u>						
6.640	0.0004	0.0003	0.162	0.241	0.028	0.026
1.000	0.0046	0.0045	3.58	3.27	0.512	0.655
0.614	0.0087	0.0102	6.86	6.43	1.028	1.327
0.380	0.0158	0.0143	12.79	11.83	1.98	2.54
0.201	0.0410	0.0440	28.45	26.47	5.64	5.02
0.095	0.1110	0.0985	56.57	56.82	16.74	14.02
0.065	0.1750	0.1567	81.68	87.81	27.48	22.62

22 February 1978

2.300	0.0016	0.0018	0.633	1.01	0.189	0.158
1.490	0.0033	0.0031	1.395	1.85	0.453	0.364
0.980	0.0065	0.0054	2.67	3.67	0.842	0.979
0.630	0.0131	0.0101	5.27	6.37	2.02	1.31
0.390	0.0287	0.0180	9.71	10.05	4.83	2.42
0.251	0.0469	0.0313	17.01	19.18	7.64	4.29
0.160	0.0691	0.0533	29.14	31.87	11.03	7.45
0.099	0.1047	0.0949	52.59	54.88	16.29	13.50
0.064	0.2335	0.1599	72.33	89.42	38.81	23.09

the state of pollution at a locality. Therefore, one would expect to find bimodal drop-size spectra in a fog observed with an optical particle counter capable of measuring submicron-sized particles. As the fog evolves and grows, a third mode generally appears under the influence of droplet collision and coalescence. Further evidence of this may be found in Jiusto.¹⁵ Since droplet collision, collection, and coalescence are stochastic in nature,¹⁶ fog drop-size spectra may well be multimodal as noted by Eldridge.¹⁷ Our present approach merely strikes for a compromise.

2. In the absence of condensation nuclei, there would be no haze or fog at the kind of saturation and supersaturation found in the atmosphere. An abundance of nuclei of substantial sizes would form fog in a rather slightly supersaturated or barely saturated atmosphere, but the nuclei are subject to gravitational settling as well as washout. Thus, as a fog persists under a given synoptic situation for 2 or more days, one would expect that its drop-size spectra would change from day to day for the above reasons. This tendency to change may explain why the spectra of 19 February 1978, as shown in figure 2, differed considerably from the others.

3. The above observations then lead to a third one. Regardless of whether meteorological factors will or will not enter into our modeling considerations, it is imperative to have some knowledge of the pollution state such as light, moderate, or heavy pollution as well as of the abundance of cloud/fog condensation nuclei at a locality. With this knowledge, it would then become possible to refine our model categories to be suitable for use in a realistic battlefield environment.

¹⁵J. E. Jiusto, 1979, Considerations in the Optical Characterization of the Atmosphere, ASL-CR-79-0100-3, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 26 pages

¹⁶H. R. Pruppacher and J. D. Klett, 1978, Microphysics of Clouds and Precipitation, Reidel, Boston, MA, 714 pages

¹⁷R. G. Eldridge, 1966, "Haze and Fog Aerosol Distributions," J Atmos Sci, 23:605-613

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