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RAIN ATTENUATION MEASUREMENTS: VARIABILITY AND DATA QUALITY ASSESSMENT*

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Year-to-year variations in the cumulative distributions of rain rate or rain attenuation are evident in any of the published measurements for a single propagation path that span a period of several years of observation. These variations must be described by models for the prediction of rain attenuation statistics. Now that a large measurement data base has been assembled by the International Radio Consultative Committee (CCIR), the information needed to assess variability is available. On the basis of 252 sample cumulative distribution functions for the occurrence of attenuation by rain (ACDFs), the expected year-to-year variation in attenuation at a fixed probability level in the 0.1 to 0.001 percent of a year range is estimated to be 27%. The expected deviation from an attenuation model prediction for a single year of observations is estimated to exceed 33% when any of the available global rain climate models are employed to estimate the rain rate statistics. The probability distribution for the variation in attenuation or rain rate at a fixed fraction of a year is lognormal. The lognormal behavior of the variate was used to compile the statistics for variability and to establish hypothesis tests for identifying outliers - the observed sample cumulative distribution function (CDF) that deviates significantly from the expected (modeled) ACDF.

1. INTRODUCTION

A number of the published or proposed models for the prediction of the statistical distributions of attenuation by rain depend upon parameters which must be set from the measured cumulative distributions of attenuation (ACDFs). The accuracy of such a model is then dependent on the quality of the data employed for parameter estimation. In recent years, it has been fashionable to test old and new attenuation prediction procedures against measured distributions stored in one or more data banks. The question arises as to how the data entered into a data bank may be examined or tested to detect bad data, data that could cause errors in the parameters needed for the models and data that could invalidate the use of a data bank for model evaluation. In this paper, a statistical test is presented for assessing the quality of rain attenuation distribution data. It was applied to the 1988 edition of the International Radio Consultative Committee (CCIR) data banks for slant path and terrestrial path propagation [CCIR, 1988]. The results show that 47 of the 252 ACDFs in the data banks are of questionable quality.

Any statistical hypothesis test for data quality assessment requires the use of a known probability distribution for the property to be tested and a standard or expected value for the property against which the observations may be compared. The reference standard must be a

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model which provides a prediction of the ACDF for the location and propagation path of interest. In the absence of long term temporal variations in rain statistics, the best model would be the average of a set of observations spanning many years for the same location and path (i.e. frequency, path length, elevation angle, polarization). The average annual distribution would then provide the reference for comparison for each of the observed annual distributions. The model ACDF is then the long term sample mean at each probability of occurrence. Unfortunately, no long term measurements are available.

A number of attenuation prediction models have been published recently that depend only on the location of a path (the rain climate) and the specific parameters for the path [COST 205, 1985a; CCIR, 1986a; Crane and Shieh 1989; Crane, 1985a]. When the predictions of these models are compared with observations, the models all perform equally. No statistically significant differences were evident in the root mean square deviations (RMSD) between measurement and prediction when the attenuation prediction procedures were used with the same rain climate model. Therefore, any of the models could be combined with a rain climate model to provide a reference for the estimation of variability. For this paper, two different attenuation prediction models and rain climate models were utilized to provide the reference ACDFs, the improved Two-Component rain attenuation model together with the Global rain climate model (T-C & Global) [Crane and Shieh, 1989] and the current version of the CCIR rain attenuation model together with the current CCIR rain climate model (CCIR & CCIR) [CCIR, 1986b; c; d].

Prior analyses of rain rate and attenuation prediction model behavior have shown that the deviations between measurements and model predictions at fixed probability levels are lognormally distributed. Sample deviation distributions were tested against the lognormal distribution, the percent normal distribution with the measurements used as reference (the distribution recommended by the CCIR [1986a] and employed for the analysis of some of the attenuation data in the COST 205 Project [1985a]) and the percent normal distribution with the model used as reference (a distribution also employed for the analysis of COST 205 data [COST 205, 1985b]). On the basis of Chi Square tests of goodness-of-fit, the use of either percent normal distribution could be rejected at the 20 percent significance level (and at the 0.5 % significance level) and, at the 20% level, the lognormal hypothesis could not be rejected [Crane and Shieh, 1989]. All statistics were therefore calculated using the natural logarithms of the measured or modeled attenuation values. The logarithmic transformation was necessary to generate a variate with a normal distribution. With this transformation, many of the standard tools for statistical inference become available for the assessment of data quality. For ease of interpretation, the results of some of the analyses were transformed back into the linear domain and expressed as a fraction in percent.

The year-to-year variations in the rain rate and attenuation sample cumulative distribution functions (CDFs) for sites with a sufficient run of data to estimate a geometric mean CDF is considered in section 2. In section 3, the variability relative to the T-C & Global and the CCIR & CCIR models is considered and a statistical model for the year-to-year variations is presented. The use of the variability estimates to identify outliers (questionable data) is discussed in section 4. Recommendations for data bank quality control are presented in section 5.

2. STATISTICAL VARIATIONS FROM THE SAMPLE GEOMETRIC MEAN DISTRIBUTION

Earlier evaluations of rain attenuation prediction procedures have shown that the observed cumulative distributions of rain attenuation display a natural variation from one year to the next, from one site to another and from path-to-path at the same site. The cumulative distribution of the fraction of a year the measured rain attenuation value exceeds specified thresholds (ACDF) is a random variable. The meteorological conditions along a propagation path change from year-to-year and, as a result, the attenuation statistics for a path also change from year-to-year. Data from eleven of the sites listed in the CCIR data bank for slant path rain attenuation measurements have between three and five single-year ACDFs; ten of the sites have simultaneous rain rate measurements (RCDFs) for each year of observations; seven of the sites with rain rate measurement data are from a single geographical region (Europe). Figure 1 displays the standard deviations of the annual deviations of the rain attenuation (DA) and rain rate (DR) values from the sample geometric means of the annual CDFs at 0.01% of a year for each of the sites. Figure 2 presents the simultaneous DA, DR deviation pairs for each year of observation for each site. The use of the geometric mean was necessary because of the logarithmic transformation employed in the calculation of the deviations. The data in Figure 2 are from 12 GHz satellite beacon observations made in Europe [COST 205, 1985a]. This subset of the data in the CCIR data bank was chosen because the COST 205 Project subjected their data to a strict regimen of data quality control.

The observations reveal the natural variability of the attenuation and rain rate deviations from the model (geometric mean) predictions. Table 1 lists the standard deviations for the attenuation and rain rate deviations from the geometric means of the ACDFs for each site at 0.01% of a year for the eleven sites with attenuation measurements, for all the sites with rain rate measurements and for the European composite (Figure 2). The table provides the expected 90% bounds for the variability model. The bounds are values from a Chi Square probability distribution with the specified number of degrees of freedom (DoF) exceeded with probability 0.05 (lower Bound) and 0.95 (upper bound). The standard deviations for the model distributions, 0.29 (33%) for attenuation and 0.22 (24%) for rain rate, were selected to minimize the number of sites having standard deviation estimates lying outside the 90% bounds for each model. Only one site produced observed standard deviation estimates outside the model bounds (D3, Europe: an outlier). No convincing trend is evident in the observed standard deviations vs the climate model rain rates at 0.01% of a year (Figure 1). For the D2 climate region, the observed standard deviation values span all but the D3 value identified as an outlier. The simplest model, therefore, is to assume a constant variability over all climate regions. For rain attenuation, the modeled variability is the largest value that keeps all the observations above the 5% bound. Taking the one site as an outlier for both attenuation and rain rate, the rain rate variability value is the smallest that keeps the remainder of the observations within the 90% bounds (5% to 95%). The resulting model variabilities for a year of observation are plotted on Figure 1.

For attenuation by rain, the composite standard deviation for Europe was 0.31 for DA (0.25, 0.43: 10% confidence limits based on the observed composite standard deviation given in Table 2 as opposed to the 90% bounds on the variability model given in Table 1). To assist in interpreting the data, the standard deviation values were transformed to percentage by:

$$DA_{\%} = 100\,(\exp(DA_{LN}) - 1). \qquad (1)$$

The observed composite variability in rain attenuation is 37% at 0.01% of a year. For the simultaneous rain rate observations, the standard deviation of DR was 0.24 (27%). The DA and DR variations were partially correlated (Figure 2 and Table 2). The estimated correlation coefficient is 0.8. If a linear model is used to relate the deviation in the natural logarithm of attenuation from the model prediction to the deviation in the natural logarithm of rain rate from the model prediction (DA vs DR), the slope of the least-square-fit line is in close agreement with the exponent in the power law relationship between specific attenuation and rain rate when calculated for a large number of rain drop size distribution observations (slope = 1.1 and residual error = 0.23; least-square fit weighted by the relative frequency of occurrence of observations at different rain rates [Crane, 1971]) but deviates significantly from the exponent when calculated using a standard rain drop size distribution model [CCIR, 1986a]. The standard deviation of the residual error for the linear model is 0.18 (20%). The residual error represents the natural variations associated with fluctuations in the spatial extent of the region along a propagation path with rain in an equal probability model for attenuation by rain, and in measurement errors for either attenuation or rain rate.

The sample cumulative distribution functions (CDFs) for the deviations pooled from the 27 path-years of observations at the 7 European sites are presented in Figure 3. The distributions are plotted vs the expected distributions for zero mean normal processes with modeled standard deviations of 0.29 (33%) for attenuation by rain and 0.22 (24%) for rain rate. If the curve for the observed distribution lies along the 1:1 line, the observed distribution matches the assumed model distribution (lognormal distribution because the natural logarithms of the measured values are plotted). The expected 90% bounds for the ordered distributions (95% and 5%), calculated on the basis of the assumed model distributions and the number of CDFs in the data set, are also displayed in the figure. For a large number of ordered distributions (CDFs) of observed deviations, DA or DR, 90 percent of the CDFs should lie within the bounds at each probability value (variate) if the deviation processes are consistent with the assumed variability processes. Except for the single extreme negative value in either distribution (the D3 region outlier in Table 1, marked by ♦ in this figure), both CDFs lie within the 90% bounds. Therefore, the DA and DR distributions are consistent with the variability hypotheses at the 10% significance level. Different variability values could have been assumed to model both processes that would have kept all the observations within the 90% bounds but the resulting models would then have larger differences from the observations in the central region of the distributions where the observations should be better behaved statistically.

The CDFs displayed in Figure 3 are for 0.01 percent of a year. The data in the CCIR data banks have attenuation levels listed for other percentages of a year. Older versions of the data bank had entries at only a few probability levels (fractions of a year). The current edition of the data banks includes observations at more probability levels but, in some cases, the entries were obtained by interpolation from the values in the earlier editions (using straight line segments on a plot of the logarithm of the value vs the logarithm of the percentage of the year). To avoid any errors from interpolation over large differences in probability level or from the generation of correlations between values of the sampled ACDF at different probability levels, the CDFs for the reported attenuation deviations were calculated for the probability levels common to all versions of the data bank: 0.1%, 0.01% and 0.001% of a year. The resulting CDFs are displayed in Figure 4. Again, the measured deviations from the geometric mean are plotted vs the expected deviations for a lognormal process with a variability equivalent to 33%. The 90% bounds were plotted for the number of observations in the 0.01% data set (the same as for Figure 3). The deviation distribution values for the 0.1% and 0.001% probability levels all fall within the 90% bounds (see also Table 2). Because fewer path-years of data are present in the 0.1% and 0.001% CDFs, their 90% bounding curves should be spaced further apart than the bounds displayed in the figure.

Agreement between the CDFs for 0.1% and 0.001% and the 33% variability model is significant at better than the 10% level. Therefore, the observed variability is not a function of the the fraction of a year for probability levels in the 0.1% to 0.001% range. It is noted that this conclusion is contrary to the results reported by COST 205 [1985b] for the same data.

The 33% variability model for the deviations of attenuation (DA) and the 24% variability model for the deviations of rain rate (DR) observations from their sample geometric means at fixed probability levels from 0.1% to 0.001% of a year explain the data obtained in Europe and in the USA. The attenuation deviations are consistent with the 33% variability hypothesis as indicated in Table 1. For the rain rate measurements, the observed variability is significantly smaller for the sites in the USA than for the sites in Europe (16% vs 27%). To be consistent with the observations from both geographic regions, the year-to-year variation in rain rate must be close to the 24% value assumed for the variability model. The variability models for rain rate and rain attenuation therefore obtain for mid-latitude observations from 11 sites spanning latitudes from 30° to 67° encompassing 7 rain climates (Global model) and, for attenuation, elevation angles from 11° to 50° for frequencies near 12 GHz.

3. A REFERENCE FOR VARIABILITY ESTIMATION

The selection of standard deviation estimates for the characterization of variability is predicated on an assumed probability distribution for the deviations of the cumulative distributions of the measurements from their expected CDFs. The existence of a model for estimating the expected ACDF for a single year of data is necessary to calculate the observed deviations. The model used in section 2 was the geometric average ACDF. That model also assumed that the statistics of the deviations about the geometric average were stationary (ie. drawn from the same process which did vary in space or time).

Most of the measurements in the data banks are limited data sets of only one or two years duration. These observations were not used in the analysis of section 2 because insufficient data were available for a path to provide a reference distribution (sample geometric mean) for the estimate of the standard deviation. To extend the analyses to all the data in the data banks, an alternative to the geometric mean model is needed. One possibility is to employ an attenuation prediction procedure reported in the literature. Crane and Shieh [1989] found that the four best of the attenuation prediction procedures they tested provided estimates of measured ACDFs with prediction errors that did not differ significantly from each other when coupled with the same rain climate model. The prediction errors should be larger than the intrinsic year-to-year variability because the climate modeling process is relatively coarse and the point-to-path transformation procedures only approximate the complex processes that occur in nature. The estimates made by Crane and Shieh on the basis of a lognormal distribution for prediction error suggest that the model prediction errors are of the order of 0.4 (50%).

Accepting an increase in apparent variability as the penalty for using an attenuation prediction model to make the entire data base available for the estimation of variability, any one of the attenuation prediction procedures could be selected to provide the reference. The only statistically valid procedure for model selection is to pick one that does not depend on parameters set by reference to the data in the data bank. If the data were used for parameter estimation, correlations would occur between the parameters and the data in the data bank that would reduce the apparent variability. The new Two-Component model (T-C) [Crane and Shieh, 1989] was selected to provide the reference for estimating variability. The selection was based on convenience; the model was resident on the computer system used in this analysis. None of the parameters of the T-C model were set using data in the data base. The empirical parameters in the model were obtained from analyses of weather radar and rain gauge data from Massachusetts, Tennessee, West Germany and Malaysia.

The CCIR model was also selected to provide a second variability estimate for comparison. Although the model employed by the CCIR [1986b; c; d] was fit to observations in the data banks, it has been used as a comparison standard in studies by the CCIR. The parameters in the current CCIR model were obtained in three steps. The horizontal, point-to-path variations were modeled at the 0.01% probability level using a procedure recommended by Lin [1975]. The parameters for this part of the model were least-square-fit to the attenuation and rain rate observations in the CCIR terrestrial path data bank. The extension of the model to include the effects of vertical variations along a slant path was accomplished by selecting a latitude dependent rain height (parameter) for use at 0.01% of a year that best fit the attenuation and rain rate observations in the slant path data bank (1985 edition). The prediction of attenuation at probability levels different from 0.01% of a year was made using a modification to the procedure developed by Fedi [1980]. The parameters for this procedure were obtained by a least-square fit to the attenuation observations from Europe in the data bank.

Single-year data from satellite beacon observations in Europe

Deviations in attenuation and rain rate at 0.01% of a year from the Two-Component rain attenuation and Global climate model (T-C & Global) predictions were estimated for the multiple-year data employed for the analyses presented in Section 2. The results for the 27 path-years of simultaneous, single-year ACDFs and RCDFs from Europe are presented in Table 2. The standard deviations were 0.35 (42%) for DA and 0.35 (42%) for DR. The 10% confidence limits for DA enclose the 33% variability model. The DR value confidence limits do not enclose the 24% variability model estimate but do overlap the confidence limits for the DR estimate based on the sample geometric mean model. If the site identified as an outlier is not used in the analysis, the DA estimate is identical to the model prediction but the DR estimate still significantly overestimates the model prediction. For the 27 path-years of data, the results based on the use of the T-C & Global model are not significantly different from the results based on the geometric mean model (at the 10% significance level).

The CCIR slant path data bank contains 53 path-years of simultaneous, single-year ACDFs and RCDFs. The simultaneous DA and DR values for 0.01% of a year are presented in Figure 5. The observations were for frequencies in the 11.6 to 17.8 GHz range. The standard deviations were 0.31 (36%) for DA and 0.29 (34%) for DR. The DA value lies within the 10% confidence limits for the 27 path-years of data used to generate Figure 2 and the 9 path-years of data from the USA (Table 2). The 10% confidence limits on the DA estimate enclose the 33% variability model. The DR estimate also lies within the 10% limits for the American and European data but the 10% confidence limits on the DR estimate do not enclose the 24% variability model.

The DA and DR deviations plotted in Figure 5 include modeling errors, measurement errors and the expected increase in variance caused by the use of a limited number of rain climate regions. If a site is located at random within a rain climate region, a climate modeling error is generated because the RCDF is predicted to have the same distribution throughout the region but the actual CDF must vary from one region to the next. The component of the rain rate deviations at 0.01% caused by the use of a climate region model is given as a function of climate in Table 3. To estimate the RCDF deviations for the table, it was assumed that the deviations were uniformly distributed for locations selected at random within a climate zone. The limits for the uniform deviation process were taken to be the model RCDFs for the adjacent climate regions. The Global climate regions were originally defined to have the RCDFs for a region confined between the climate model RCDFs for adjacent regions (see Crane [1980] Figures 6 and 7). Climate regions B and D were subsequently subdivided because the span of the possible RCDFs was too large. If the standard deviation for the year-to-year variation process for rain rate, 0.21 (24%), is combined with the root mean square (rms) deviation for the climate estimate (0.17, Table 3), the result is a standard deviation estimate of 0.27 (31%) which lies within the 10% confidence limits for the DR estimates listed in Table 2. For the estimation of the attenuation deviations, the linear model presented in Figure 2 generates a standard deviation estimate of 0.29 (33%) which also lies within the 10% confidence limits for the DA estimates.

For the prediction of attenuation, the expected standard deviation for DA is increased relative to the standard deviation for DR. Working back through the variance estimates, only 32 percent of the observed variance in DA corresponds to the use of the Global climate region model. The remainder is due to year-to-year variations caused in part by a lack of correlation between rain rate and attenuation deviations from the model predictions (see Figure 5). Therefore, the variability model has a component that changes only with location within a climate region but not with the length of an observation period and a component with a variance inversely proportional to the length of the observing period (the year-to-year variations). The variability in DA due to the use of the Global rain climate model is 18%; the variability due to year-to-year changes on a path is 27%: for a single year of observations the two combine to produce a variability of 33%. The use of a different climate model would produce a change in the climate model component of variability. For DR, the components of the model are 17% and 24% for site-to-site and year to year respectively with the estimated variability for the combination equal to 31%.

The observed correlation between the attenuation and rain rate deviations is only 0.6 (Figure 5) yielding a significantly larger residual error for a least-square-fit linear model for the deviations from the T-C & Global predictions. The slope for the linear model is not close to the expected value for the relationship between specific attenuation and rain rate at frequencies in the 11 to 18 GHz band. The intercept value suggests a modeling error (bias) in either attenuation or rain rate (or both). When the CCIR rain attenuation model and CCIR rain climate model (CCIR & CCIR) are used, the standard deviations are even larger (Table 2), 50% for DA and 52% for DR, but the the correlation between DA and DR is also larger, 0.8, yielding a residual error of 30% which is not significantly different (at the 10% level) from the 27% residual error for the T-C and Global model. When the CCIR model is combined with the observed rain rate values at 0.01% of a year, the attenuation prediction error is 40%, a number significantly larger than the expected residual error (18%, the residual error from Figure 2) when the effects of the annual and rain climate variations are removed from the prediction process.

The cumulative distributions of deviations from rain rate model predictions at 0.01% of a year (DR) are presented in Figure 6 for both the Global and CCIR rain climate models for the 54 path-years of single-year rain rate observations from Europe in the CCIR data bank. Both models have the same average prediction error (bias). The 90% bounds for the 31% variability model were plotted after adjustment for the prediction (or measurement) bias. The Global model predictions are consistent with the variability model bounds inferred from the deviations between observation and the sample geometric mean model. For the Global rain climate model, the standard deviation is 0.29 (34%). The CCIR model predictions deviate significantly from the observations for nearly half the path-years of observations. For the CCIR rain climate model, the standard deviation is 0.42 (52%). Two conclusions may be drawn from this figure, 1) the Global rain climate regions are consistent with the observations but the Global rain rate model overestimates the observed rain rate at 0.01 percent of a year and 2) the CCIR model climate regions are not consistent with the observations, the standard deviation for DR is significantly larger than for the Global model (at the 10% significance level) and, for more than half the observations, overestimate the rain rate.

The cumulative distributions of deviations from rain attenuation model predictions at 0.01% of a year for the 54 path-years of single-year satellite beacon attenuation observations from Europe in the CCIR data bank are presented in Figure 7. In this figure, the results from the use of 3 different models are presented: the T-C attenuation prediction model with the Global rain climate model, the CCIR attenuation prediction model with the CCIR rain climate model and the CCIR attenuation prediction model with the measured cumulative rain rate distribution at 0.01% of a year. The predictions based on the use of climate models are unbiased; the predictions based on the rain rate measurements are biased. When combined with the Global rain climate model, the deviations from both The T-C and CCIR attenuation model predictions all lie within the 90% bounds for the 33% single-year variability model. When the CCIR rain climate model is used with the CCIR rain attenuation prediction model, the combination is unbiased but the deviations are significantly larger than observed when the Global climate model is employed (50% vs 36%, see Table 2). For the CCIR model combined with rain rate observations the predictions are biased but the standard deviation is only slightly larger than for the T-C and Global model (39% vs 36%) but significantly larger than expected when measurements are used to reduce the effects of climate model and year-to-year variations.

The deviations from model predictions at 0.1% and 0.001% of a year are also unbiased and consistent with the 33% variability hypothesis when the T-C and Global model is used as illustrated in Figure 8 (and Table 2). At 0.001%, the standard deviation for all the single-year ACDFs was 36%. At 0.1%, the standard deviation is 46% which is significantly larger than 33% (at the 10% significance level). At this fraction of a year, 32% of the observed deviations lie outside the 90% bounds. Four of the twelve deviation estimates that lie outside the bounds are from a single site. If the data from that site are not used in the analysis (the thin dashed curve in Figure 8), all but three of the remaining deviations lie within the bounds and the results are consistent with the 33% variability hypothesis at the 4% significance level. Therefore, observations in the 0.1% to 0.001% of a year span of probability levels may be modeled as samples from a zero mean process with a standard deviation of 0.29 (33%).

The mean square deviation (MSD) calculated for different probability levels (fractions of a year) from a single ACDF using the natural logarithms of the ratio of measured-to-modeled values of rain attenuation should have a Chi Square distribution with the number of degrees of freedom equal to the number of probability levels (if independent of each other). This result obtains because the T-C & Global prediction model is unbiased with a constant variability over the range of probability levels available for analysis. If the reported ACDF represents the observed distribution and was not constructed by interpolation from a limited number of probability levels, the observations at probability levels separated by a factor of 3 should be independent. The cumulative distributions of root mean square deviation (RMSD) values for the ACDFs in the beacon data set from Europe with three (6 path-years of data), four (23 path-years) and five (25 path-years) probability levels (DoF = degrees of freedom) are plotted in Figure 9. The probability level samples used in the computation of a RMSD value for a single ACDF was continuous over the set, 1%, 0.3%, 0.1%, 0.03%, 0.01%, 0.003%, 0.001% of a year values, used in the analysis. At 3 DoF, the RMSD value will contain between one and two of the 0.1%, 0.01% or 0.001% values assumed to be without interpolation error. At 5 DoF, the actual number of degrees of freedom may be as small as 3 due to correlations caused by interpolation if used in the preparation of the ACDF for the data bank.

The plotting scales on Figure 9 are the observed RMSDs from the T-C & Global model vs the expected value of RMSD for a Chi Square process with the indicated number of degrees of freedom and variability. Agreement obtains if the plotted values lie within the 90% bounds for the ordered distributions. The bounds are plotted for all three distributions (thin lines with the same dash coding as the plotted CDFs). Markers are placed over the RMSD values (single path measurements) that exceed the 98% bound for agreement with the 33% variability hypothesis. For 4 and 5 probability levels, with the exception of the RMSD value for one ACDF, the ordered distributions lie within the 90% bounds. These RMSD values are therefore consistent with the unbiased variability model hypothesis at the 10% significance level. The one exception can be considered an outlier. At the 10% significance level, a hypothesis test for agreement with the variability model would decide that the exception has more variability than expected and may be considered suspect (it corresponds to the single outlier evident in Figures 3 and 4). For the RMSD values with three degrees of freedom, all but 1 lie outside the 90% bounds but only 2 are above the 98% bound for a single ACDF. RMSD values for 6 of 54 ACDFs lie outside the 90% bounds for the model. All are well outside the bounds indicating that they are not consistent with the variability model or with the other observations presented in the figure and may be outliers.

Based on the beacon observations from Europe, the following conclusions may be drawn: 1) the T-C or CCIR rain attenuation models may be used as a reference for the estimation of variability if the Global rain climate model is employed as well, 2) the variability did not increase measurably with the use of an attenuation prediction model as a reference for estimating the expected long term geometric mean ACDF when compared with the predictions of the sample geometric mean calculated from a limited data set, 3) the CCIR rain attenuation model, when used with the CCIR rain climate model, is unbiased but the standard deviation of the deviations is larger than the natural variability of the rain attenuation process, 4) the increased standard deviation when using the CCIR rain climate model appears to be due to an incorrect identification of the climate regions, 5) the utilization of measured rain rate distributions produces both a bias and an increase in the standard deviation of the differences between model predictions and measurements and 6) the rain rate measurements, not the rain climate models, produce the bias evident in Figure 5.

Single-year data from all locations and types of measurements

The 31% variability model holds for the single-year rain rate observations made simultaneously with the satellite beacon measurements in Europe. However, the European data revealed a significant bias between the climate model predictions and measurements. The next question to be addressed is the consistency of the climate models when all the single-year data sets with simultaneous rain rate observations in the entire data base are employed in the analysis. Figure 10 presents the deviations between measured and modeled rain rate at 0.01% of a year for 111 path-years of data. The variability model distribution bounds are displayed together with the cumulative distributions of the deviations of measurements from the Global and CCIR rain climate model predictions. Both climate models are unbiased when compared to the larger set of data. The deviations from the Global model predictions lie within the variability model bounds for all path-years; the standard deviation of the DR values is 0.30 (35%) with confidence limits that enclose the variability model at the 10% level (Table 2). The deviations from the CCIR model predictions agree with the variability model only within the central region of the distribution (± 0.5 standard deviations). The deviations from the CCIR model display a steeper slope (larger variability) than the model predictions and are not entirely consistent with a lognormal model because, with the steeper slope, a large number of outliers would occur for a variate greater than 0.27 (one standard deviation).

The 33% attenuation variability model holds for the single-year satellite beacon observations from Europe. Figure 12 presents the deviations between measured and modeled attenuation at 0.01% of a year for 106 path-years of data from terrestrial, satellite beacon and slant path radiometer measurements at frequencies ranging from 11 to 82 GHz, latitudes from -38° to 67° north, elevation angles from 7° to 53° for slant paths, horizontal distances from 1.3 to 25 km for terrestrial paths, and vertical, horizontal and circular polarizations. The variability model distribution bounds are displayed together with the cumulative distributions of the deviations of measurements from the T-C & Global model and the CCIR & CCIR model predictions. The deviations from the T-C & Global model predictions lie within the variability model bounds for all but 6 path-years; if the 6 path-years of data are excluded, the resulting DA is 0.31 (36%) with confidence limits that enclose the variability model (Table 2). The deviations from the CCIR & CCIR model predictions agree with the variability model only within the central region of the distribution (± 0.5 standard deviations). The deviations from the CCIR & CCIR model are consistent with a lognormal model with zero bias but with a significantly higher variance. The performance of the CCIR model is better when combined with the measured rain rate values at 0.01% of a year (CCIR & meas).

The deviations of the observations from the T-C & Global model predictions were investigated at 0.1% and 0.001% of a year. At 0.1%, the deviations have zero mean and are consistent with a 33% variability model as indicated in Figure 12. At this probability level, the standard deviation of all the ACDFs is 0.39 (47%) with confidence interval bounds that do not enclose the 33% model variability. If the 5 outliers evident in the figure are not used in the analysis, the resulting standard deviation is 0.33 (39%). This standard deviation is still larger than the model estimate at the 10% significance level but is consistent with the model at the 4% level. At 0.001% of a year, the T-C & Global model is biased and the variability is significantly larger than the model estimate. For all 58 ACDFs at 0.001%, the standard deviation in DA is 0.47 (63%). If five ACDFs from a single site in the USA are removed from the data set, the resulting CDF for the attenuation deviations has a small bias (the thin dashed 0.001% curve in Figure 12) and the resulting variability is 0.43 (54%). If the 3 additional outliers that deviate markedly from the model distribution are also removed, the resulting standard deviation is 0.29 (34%). For all but 8 of the observations (outliers from 4 sites), the data are consistent with the 33% variability model.

The RMSD values have Chi Square distributions as indicated in Figure 13. Seventeen out of 93 path-years of data with four or more degrees of freedom are outside the 90% bounds for the variability model. All but 8 of the 26 RMSD values with 3 degrees of freedom lie outside the variability model bounds. The remaining 71% of the observations are consistent with the variability model at the 10% level. For 4 or more degrees of freedom, 82% of the RMSD values are consistent with the variability model and with each other (a best fit line passing through the origin would closely approximate the 1:1 line). For 3 degrees of freedom, the RMSD values are consistent with each other (lie along a straight line that passes through the origin) but with a variability model having roughly a 25 percent greater variability. Some of the observations could correspond to observations with fewer than 3 degrees of freedom. More than 40 percent of the observations are for data with probability levels greater than or equal to 0.03% of a year and none of the observations are for 0.001% of the year. For 4 degrees of freedom almost half the observations include 0.001% of a year and, for more degrees of freedom, the fraction of the observations including 0.001% of a year is even higher. The observations tend to show an increase in apparent variability with an increasing fraction of the measurements with probability levels greater than 0.1% of a year.

The single threshold for acceptance represents an approximate single ACDF hypothesis test for 4 or more probability levels (a single sample from a Chi Square distribution with 5 degrees of freedom) at a 2% significance level and may be applied without reference to any of the other RMSD values from the data bank. If the RMSD for a single-year ACDF lies above this threshold, it is considered an outlier and is suspect.

Multiple-year data sets from all locations

The single-year observations constitute only 132 of the 252 ACDFs in the combined CCIR data banks. The variability model must be extended to multiple-year ACDFs for comparison with the remainder of the observations in the data banks. The 33% variability model has two components, 0.17 (18%) due to the use of the Global climate regions and 0.27 (31%) due to the year-to-year variations at the same site. The former is fixed for a site for any length of data sequence but the latter may be reduced by combining observations from several years. The variance for the latter component is reduced by the number of years in the data sequence. To provide a composite variability model estimate, the square root of the sum of the variances for each component must be calculated. The thresholds for acceptance at the 2% significance level hypothesis test are listed as a function of the number of degrees of freedom and the number of years of observations in Table 4. For 5 DoF, the threshold for acceptance is plotted as a function of the length of the observation set in Figure 14. Nineteen of the 95 RMSD values with 5 degrees of freedom are above the 98% bound and are not consistent with the variability model.

The variability model estimate holds for integral years of observations. The rain attenuation process is assumed to be stationary over periods spanning an integral number of years but is not stationary for arbitrary duration intervals due to the seasonal nature of the rain process. Experience suggests that seasonal variations are important. Results for 18 months of observation should be different if the measurement interval spans two normally rainy seasons or two dry seasons. The 98% threshold values (the modeled RMSD value that is expected to exceed 98 percent of the observations as a result of the natural year-to-year and within climate region variations) are calculated only for integral numbers of years. In Figure 14 the calculated threshold values are connected by straight lines. RMSD estimates are plotted for all the ACDFs with 5 DoF whether for an integral number of years or not.

The RMSD observation may be scaled to the expected value for a single year of observations by adjusting the RMSD value by the variability model estimate. For two years of observations, the apparent variability must be increased by the ratio of the variability estimate for a single year to the estimate for two years. With this adjustment, the threshold for acceptance (98% threshold) value does not depend on the duration of the measurements. The scaled RMSD values for all the paths in the data bank are presented in Figure 15. The threshold for acceptance is plotted as a function of the number of degrees of freedom (DoF) associated with each RMSD value. The 2% threshold (lower bound) is also displayed on the figure. If the observations are consistent with the variability model when adjusted to an equivalent single year of observations, 2 percent of the RMSD values should lie below the 2% threshold and 2% should lie above the 98% threshold. Four of 252 values lie below the 2% threshold in agreement with the model estimates but 47 lie above the 98% threshold in clear violation of the model estimate. The large number of values above the threshold for acceptance is an indication of contributions to the observed deviations from more than just the natural site-to-site and path-to-path variability of the rain attenuation process relative to the prediction model.

4. DATA QUALITY ASSESSMENT

The model for the site-to-site and year-to-year variability for a path is based on the lognormal distribution for the deviations of measurements from the reference ACDF for a path. The deviation model is assumed to hold for all climate regions, path geometries and probability levels within the 1.0% to 0.001% of a year range. The data presented in Section 3 represent all the ACDFs in the CCIR data banks (terrestrial plus slant path). The 90% bounds on the CDFs and 98% threshold for the RMSD estimates for single ACDFs represent the expected extremes due to chance variations in climate and rain conditions on the path. Errors in assigning the climate region, measurement errors due to the operation of the equipment and errors in the statistical adjustment for missing data will create larger RMSD values. In using the observations to fix the level of variability, it is not possible to separate deviations due to natural causes or experimental error. The latter includes the effects of rain or snow on antenna components and radomes, the problems associated with receiver baseline variations due to either the receiver system or the satellite or the terrestrial transmitter system, insufficient dynamic range for the attempted measurements and delays in receiver recovery (lock) after completely losing the signal during a deep fade. Modeling errors could also contribute to significant deviations between model predictions and measurements. Considering that the geophysical effects are assumed to dominate the modeled deviation process, deviations that are significantly larger (outside the modeled bounds which explain a significant fraction of the observed deviations for a large number of propagation paths) must be due to experimental error and the ACDF producing the large deviation must be an outlier and identified as suspect.

The estimated bounds on the CDFs for deviations at fixed probability levels or for the RMSD values calculated from independent samples from each ACDF at fixed probability levels then can be used to assess data quality. Observed ACDFs yielding samples in the CDFs that lie outside the bounds should be flagged as questionable and requiring further scrutiny. Comparisons with the bounds on the sample cumulative distributions of the deviations or the RMSD values are useful only when comparing a group of observations to a model. Such comparisons are necessary to build and verify the model. After the model has been established, hypothesis tests should be conducted on each ACDF separately. Using the Global rain climate and a convenient path attenuation model to provide the reference, the observed RMSD of the ACDF from the reference ACDF should be tested using a Chi Square hypothesis test for the number of probability levels employed for the calculation of the RMSD value and the expected standard deviation of the natural variations about the model predictions (0.29 corresponding to a 33% variability when scaled to an equivalent single year of observations). Table 4 lists the threshold levels for questioning the quality of the ACDF to be tested. If the RMSD value lies below the level in Table 4, the observed RMSD is within the range expected for chance variations in the rain process and the data set should be accepted. Higher values are suspect and should be investigated further.

This data quality assessment procedure was developed for use with the T-C & Global model for generating the reference ACDF. Deviations may be generated relative to any convenient combination of rain attenuation and rain climate models. The expected variability values will change with the number of climate regions employed in the rain rate estimation model and the sophistication of the rain attenuation prediction procedure. With a large number of observed ACDFs, deviation CDFs may be constructed that display a degree of consistency between the individual deviation estimates when plotted against the predictions of standard probability models (such as normal, Figure 7, or Chi Square, Figure 9). Consistency is indicated by approximate straight line segments such as would better fit the CCIR & CCIR model displayed in Figures 7 and 11 or the approximate straight line segment through the origin that would better fit the 3 DoF curve in Figure 13. These self consistent deviation models can then be used to establish the variability value needed for the hypothesis tests.

The quality assessment procedure based on the T-C & Global model was applied to the satellite beacon observations from the USA in the CCIR data banks. Fifteen of 58 ACDFs were judged to be questionable (Table 5). One of these was identified as being caused by a transcription error when assembling the data bank [Crane, 1989]. Ten of the 15 were from observations at a single site. A closer examination of the data showed good agreement with the variability model predictions at 0.01% of the year but poor agreement when the estimated attenuation values were either relatively large (greater than 16 dB) or small (less than 4 dB). The data can be considered suspect except within the central region of the ACDFs due to a limited dynamic range for measurements. After pruning the ACDFs to correct for the dynamic range limitations, all but three of the observations from the site are consistent with the variability hypothesis. None of the three remaining outliers are for an integral number of years of observations and agreement with the model should not be expected. The net result for the USA entries in the CCIR data bank, after correction and pruning, 7 ACDFs are still outliers. Three of the outliers should not be used in model development and testing because they do not correspond to integral numbers of years of observations. The remaining 4 are also suspect and should not be used for model development or testing.

The CCIR & CCIR model was also used to produce a list of outliers for the USA. Eleven of the ACDFs were identified as outliers. The transcription error was detected. The 4 outliers that remained after the analysis reported above using the T-C & Global model were from 3 different sites. Four of the outliers from relative to the CCIR & CCIR model were from the same three sites. The details differed in that different paths were identified as outliers. Not one of the ten paths from the single site were identified as outliers. The data from that site were in the data bank when the model parameters were set. As a result, complete sets of observations from other sites within the USA were identified as outliers even though agreement was obtained relative to the geometric mean model. In this case, the data can not be considered suspect but the rain attenuation prediction procedure should be questioned.

5. RECOMMENDATIONS

A model has been developed to estimate the expected year-to-year variations in rain rate or rain attenuation at fixed probability levels. A rain attenuation prediction model is expected to predict the long term geometric mean of the cumulative distribution function for rain attenuation. The variability model describes the expected variation of observed (or predicted) cumulative distribution functions about the long term geometric mean CDF. It should be used with the rain attenuation prediction procedure to provide a more complete statistical description of the rain attenuation process.

The model predictions provide a basis for assessing data quality. Reported CDFs of rain attenuation measurements should be tested by comparison with a model prediction. The prediction should be based on the use of a rain climate model together with the rain attenuation prediction procedure. The ACDF should not be a member of the data set used to generate the parameters for the model. The RMSD value for the natural logarithms of the ratios of measured to modeled attenuation at probability levels spaced by at least a factor of three should be calculated as a test statistic. The test value should be compared with the threshold values in Table 4 to decide on the quality of the data. If the test value is less than the threshold, the data should be added to the data bank. If not, the data should be considered suspect and subjected to further scrutiny.

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Table 1 Estimated Deviations (in LN units) Relative to the Geometric Mean Model

				Rain Attenuation			Rain Rate	
	Global		DA	33% Model		DR	24% Model	
Location	Rzone	DoF	St.Dev	5%†	95%	St.Dev	5%	95%
Europe	B	2	0.18	0.07	0.50	0.18	0.05	0.37
	B1		0.33			0.37		
	D3		0.68 •			0.45 •		
	D2	3	0.13	0.10	0.47	0.14	0.07	0.35
	C		0.17			0.15		
	D1	4	0.12	0.12	0.45	0.11	0.09	0.33
	D3		0.35			0.20		
Composite (Figure 2)		20	0.31	0.21	0.36	0.24	0.16	0.27
USA	D2	2	0.08	0.08	0.50	0.23	0.05	0.37
	D2		0.19			0.12		
	D2		0.36			0.18		
	D2					0.10		
	D2*		0.59* •					
	D2		0.18					

DA = LN(Ratio of Measured to Modeled Attenuation)
DR = LN(Ratio of Measured to Modeled Rain Rate)

• Indicates the standard deviation estimate is not within the 90% bounds for the variability model.
† Chi Square bounds on the variability model for the indicated number of degrees of freedom (DoF).
* Includes a known transcription error [Crane, 1989], the following line is for the same site and path but with the error corrected.

Table 2 Residual Errors for Single-Year Data Sets

Model Data Set	# ACDFs	DA:	UC	LC	DR:	UC	LC	corr coef	RE:	UC	LC
Geometric Mean											
Europe											
0.1%	17	0.20	0.30	0.15							
		23%	35%	17%							
0.01%	27	0.31	0.43	0.25	0.24	0.33	0.19	0.82	0.18	0.25	0.14
		37%	53%	29%	27%	38%	21%		20%	29%	15%
0.001%	14	0.22	0.35	0.16							
		24%	42%	18%							
USA											
0.01%	9	0.24	0.46	0.16	0.15	0.28	0.10	0.46	0.21	0.50	0.14
		27%	58%	18%	16%	33%	11%		24%	65%	15%
T-C & Global											
Europe											
0.01%	27	0.35	0.45	0.29	0.35	0.45	0.29	0.62	0.28	0.36	0.23
(same as above)		42%	57%	33%	42%	57%	33%		32%	44%	26%
0.01%	24	0.29	0.38	0.24	0.33	0.43	0.27	0.62	0.24	0.32	0.20
(same no outlier site)		33%	47%	27%	39%	54%	31%		27%	37%	22%
0.1%	38	0.38	0.47	0.32							
(full beacon)		46%	60%	38%							
0.1%	34	0.36	0.45	0.30							
minus 1 site		44%	57%	35%							
0.01%	53	0.31	0.37	0.27	0.29	0.35	0.25	0.61	0.24	0.29	0.21
(full beacon)		36%	44%	30%	34%	42%	29%		28%	34%	23%
0.001%	39	0.31	0.38	0.26							
(full beacon)		36%	46%	30%							
All											
0.1%	113	0.39	0.44	0.35							
		47%	55%	42%							
0.1%	108	0.33	0.38	0.30							
(no outliers)		39%	47%	35%							
0.01%	106	0.39	0.44	0.35	0.30	0.34	0.27				
		47%	55%	42%	35%	41%	31%				
0.01%	100	0.31	0.35	0.28							
(no outliers)		36%	42%	32%							
0.001%	58	0.47	0.56	0.41							
		60%	74%	51%							

DA = LN(Ratio of Measured to Modeled Attenuation)
DR = LN(Ratio of Measured to Modeled Rain Rate)
corr coef = Correlation coefficient
RE = Residual error
UC, LC = 10% significance level confidence interval bounds estimated using a Chi Square distribution with the observed standard deviation estimate and the number of degrees of freedom for the set of observations.

Table 2 Residual Errors (Continued)

Model Data Set	# ACDFs	DA:	UC	LC	DR:	UC	LC	corr coef	RE:	UC	LC
CCIR & CCIR											
Europe											
0.1%	45	0.33	0.40	0.28							
(full beacon)		39%	49%	33%							
0.01%	53	0.41	0.48	0.35	0.42	0.50	0.36	0.76	0.26	0.31	0.23
(full beacon)		50%	62%	42%	52%	65%	44%		30%	37%	25%
0.001%	39	0.41	0.51	0.35							
(full beacon)		50%	66%	41%							
All											
0.1%	121	0.40	0.45	0.36							
		50%	57%	44%							
0.01%	106	0.47	0.53	0.42	0.38	0.43	0.34				
		59%	69%	52%	46%	54%	41%				
0.001%	58	0.52	0.61	0.45							
		68%	84%	57%							

DA = LN(Ratio of Measured to Modeled Attenuation)
DR = LN(Ratio of Measured to Modeled Rain Rate)
corr coef = Correlation coefficient
RE = Residual error
UC, LC = 10% significance level confidence interval bounds estimated using a Chi Square distribution with the observed standard deviation estimate and the number of degrees of freedom for the set of observations.

Table 3 Estimated Variation Due to the Use of Climate Zones

Global E[RMSD] Climate Zone	RR 0.01% (mm/h)	LNRR	Uniform Adjacent Zones		Res. Error = 0.24	
A	10	2.30	0.25	29%	0.35	42%
B1	15.5	2.74	0.25	28%	0.34	41%
B2	23.5	3.16	0.17	19%	0.29	34%
C	28	3.33	0.12	13%	0.27	31%
D1	35.5	3.57	0.16	18%	0.29	34%
D2	49	3.89	0.17	18%	0.29	34%
D3	63	4.14	0.19	21%	0.30	36%
G	94	4.54	0.13	14%	0.27	31%
E	98	4.58	0.13	14%	0.27	31%
H	147	4.99	0.23	26%	0.34	40%
B	19.5	2.97	0.46	58%	0.52	68%
D = D2	49	3.89	0.45	57%	0.51	67%
F	23	3.14	0.53	70%	0.58	79%
Rms B1->E			0.17	18%	0.29	34%

Table 4 Thresholds for Acceptance (98% Bound)

DoF	Number of Years: 1	2	3	4	5	6	7	8	
1	0.676	0.549	0.500	0.474	0.457	0.446	0.438	0.431	Standard Deviation LN(Measured to Modeled Attenuation)
2	0.574	0.467	0.425	0.403	0.389	0.379	0.372	0.367	
3	0.526	0.428	0.389	0.369	0.356	0.347	0.341	0.336	
4	0.496	0.403	0.367	0.348	0.336	0.327	0.321	0.317	
5	0.475	0.386	0.352	0.333	0.322	0.314	0.308	0.303	
6	0.460	0.374	0.340	0.322	0.311	0.303	0.298	0.293	
7	0.448	0.364	0.331	0.314	0.303	0.295	0.290	0.286	
8	0.438	0.356	0.324	0.307	0.296	0.289	0.283	0.279	
1	97%	73%	65%	61%	58%	56%	55%	54%	Standard Deviation Percent Equivalent
2	78%	60%	53%	50%	48%	46%	45%	44%	
3	69%	53%	48%	45%	43%	41%	41%	40%	
4	64%	50%	44%	42%	40%	39%	38%	37%	
5	61%	47%	42%	40%	38%	37%	36%	35%	
6	58%	45%	41%	38%	37%	35%	35%	34%	
7	56%	44%	39%	37%	35%	34%	34%	33%	
8	55%	43%	38%	36%	34%	33%	33%	32%	

Table 5 Relative Performance of the Models Employed to Study Variability

Region	Data Bank	Data Type	Atten Model	Rain Model	Avg	RMSD	# >98%	# Paths
USA	CCIR	Satellite Beacon	T-C	Global	3.4%	49.4%	15	58
			CCIR	Global	-16.2%	49.9%	14	58
			T-C	CCIR	18.0%	62.1%	25	58
			CCIR	CCIR	-5.7%	44.1%	11	58
			CCIR	Measured	-22.7%	64.7%	17	43
	Thayer School	Satellite Beacon (same as above)	T-C	Global	5.4%	40.1%	5	55
			CCIR	Global	-17.5%	48.6%	8	55
			T-C	CCIR	26.6%	58.3%	15	55
			CCIR	CCIR	-5.7%	41.7%	8	55
	Thayer School	(full set)	T-C	Global	6.6%	37.0%	7	98
			CCIR	Global	-15.6%	52.4%	18	98
			T-C	CCIR	25.6%	53.6%	23	98
			CCIR	CCIR	4.6%	48.8%	23	98
EUROPE	CCIR	Satellite Beacon	T-C	Global	4.2%	40.5%	11	85
			CCIR	Global	0.1%	49.3%	16	85
			T-C	CCIR	2.6%	50.8%	23	85
			CCIR	CCIR	-0.7%	42.4%	15	85
			CCIR	Measured	18.2%	55.2%	20	76
ASIA	CCIR	Satellite Beacon	T-C	Global	-8.3%	70.3%	4	25
			CCIR	Global	-13.6%	58.7%	3	25
			T-C	CCIR	-12.6%	110.9%	12	25
			CCIR	CCIR	-17.9%	88.9%	7	25
			CCIR	Measured	-21.0%	70.7%	5	22
global	CCIR	Radiometer	T-C	Global	-5.4%	54.0%	12	44
			CCIR	Global	-17.6%	55.2%	13	44
			T-C	CCIR	-11.0%	65.3%	19	44
			CCIR	CCIR	-23.3%	51.6%	15	44
			CCIR	Measured	-49.9%	128.7%	14	20
global	CCIR	Terrestrial	T-C	Global	-15.1%	31.5%	5	40
			CCIR	Global	-2.6%	26.3%	2	40
			T-C	CCIR	-31.1%	66.6%	21	40
			CCIR	CCIR	-6.5%	31.5%	4	40
			CCIR	Measured	6.3%	20.9%	2	39
global	CCIR	Entire	T-C	Global			47	252
			CCIR	Global			48	252
			T-C	CCIR			100	252
			CCIR	CCIR			52	252
			CCIR	Measured			58	200

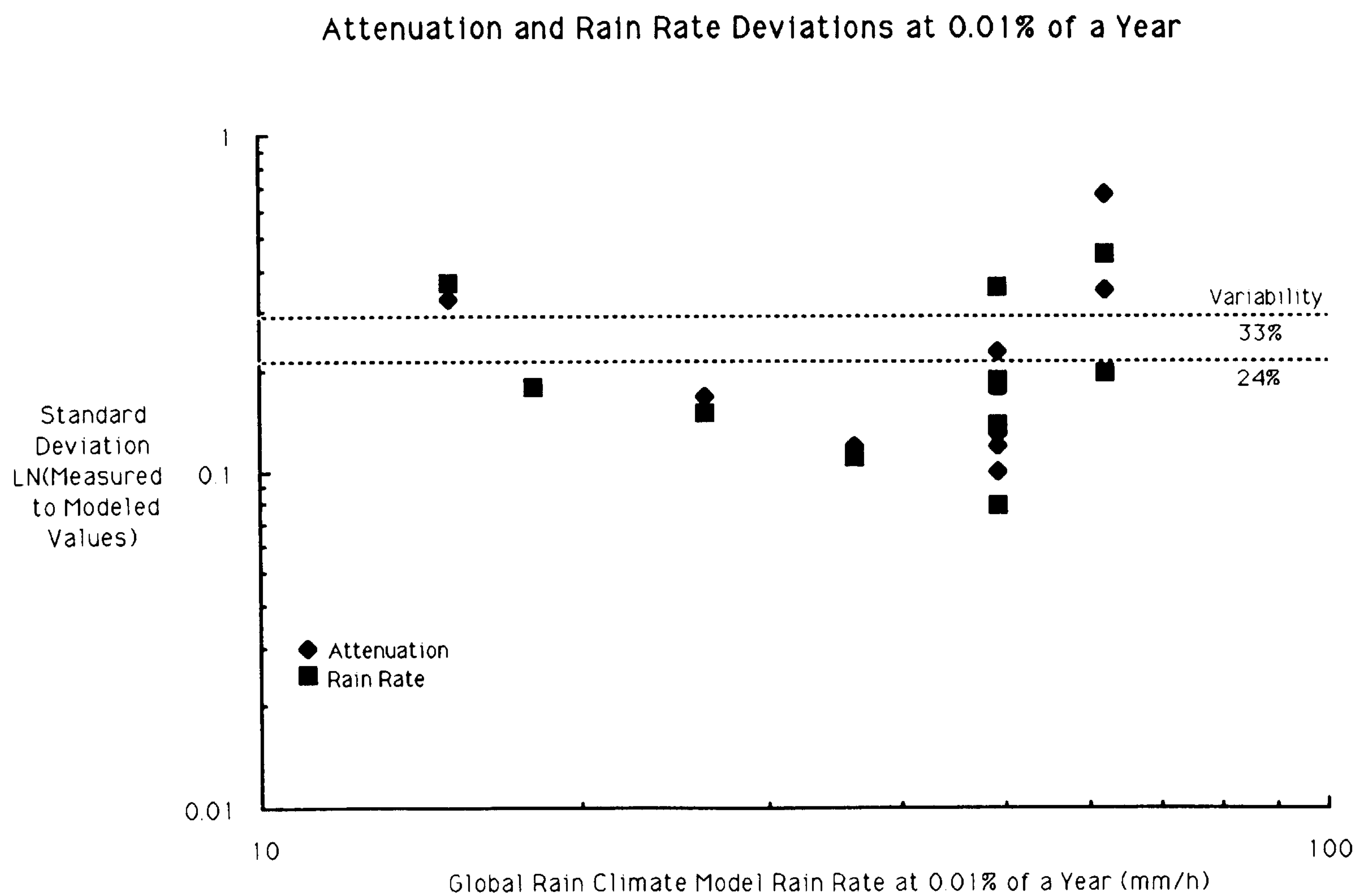

Figure 1 Standard deviation of the deviations of measured from modeled values for sites with three or more single-year sample cumulative distribution functions.

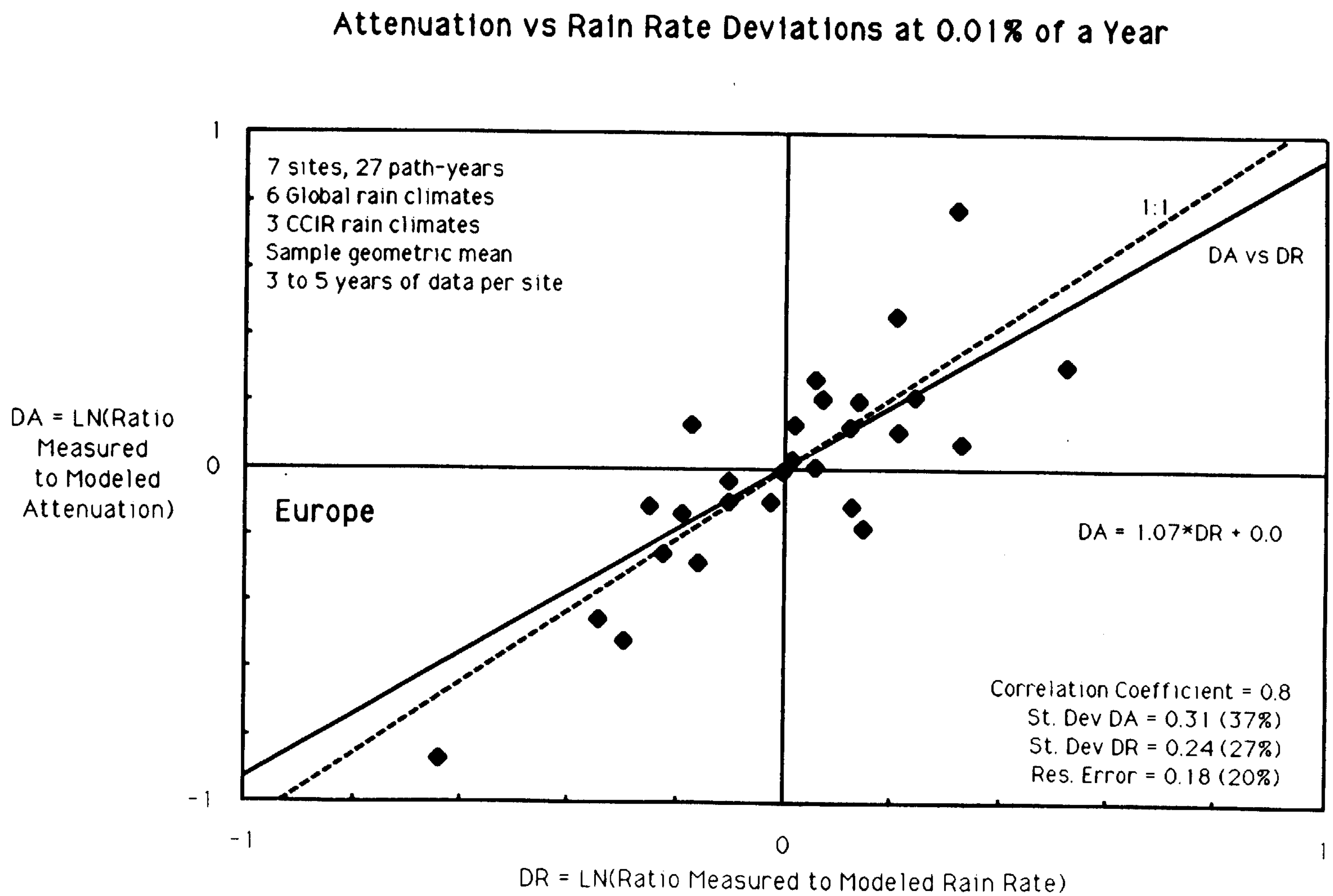

Figure 2 Rain rate and attenuation deviation pairs for sites with three or more single-year sample cumulative distribution functions.

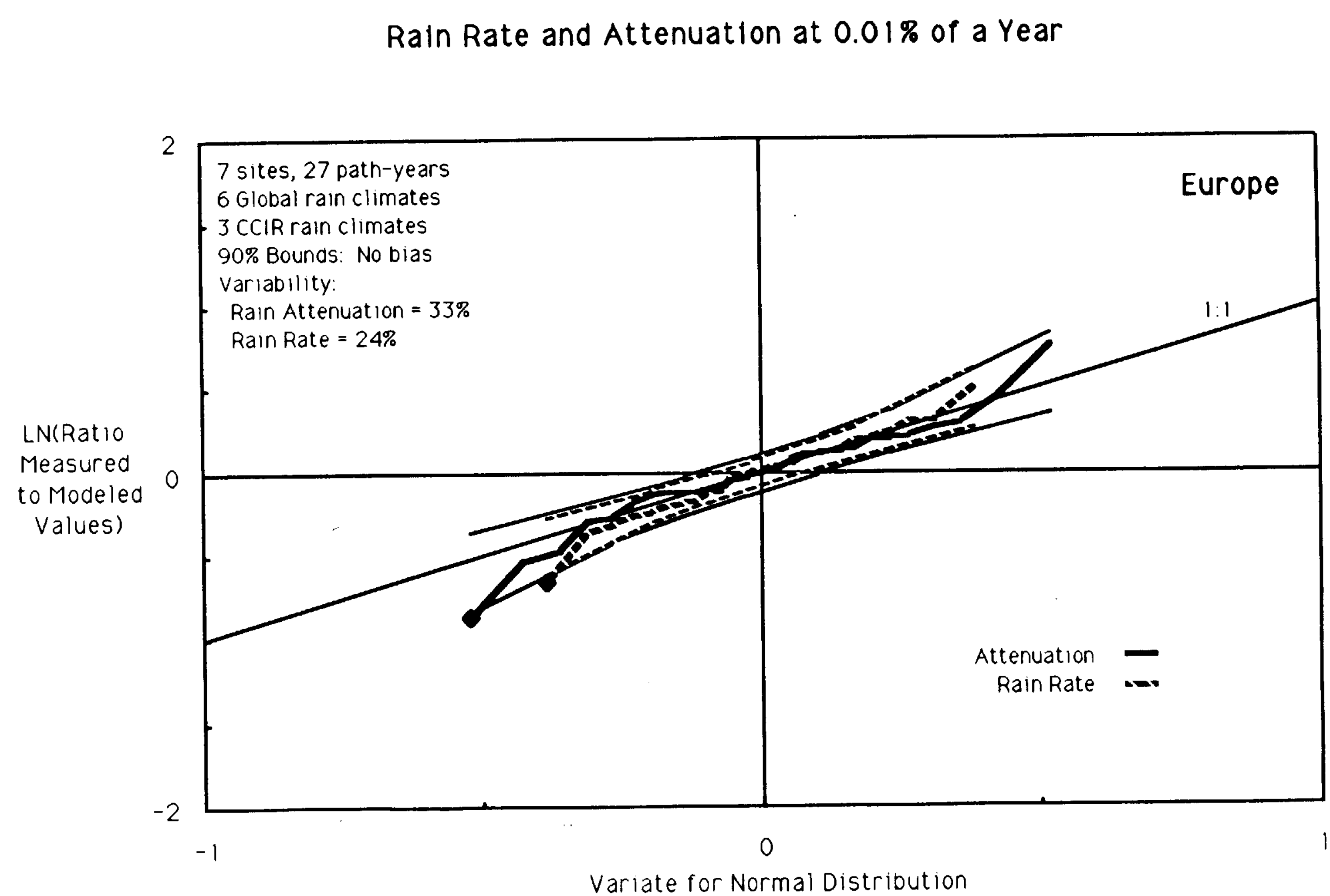

Figure 3 Cumulative distributions of deviations of measured from modeled values at 0.01% of a year for sites with three or more single-year sample cumulative distribution functions.

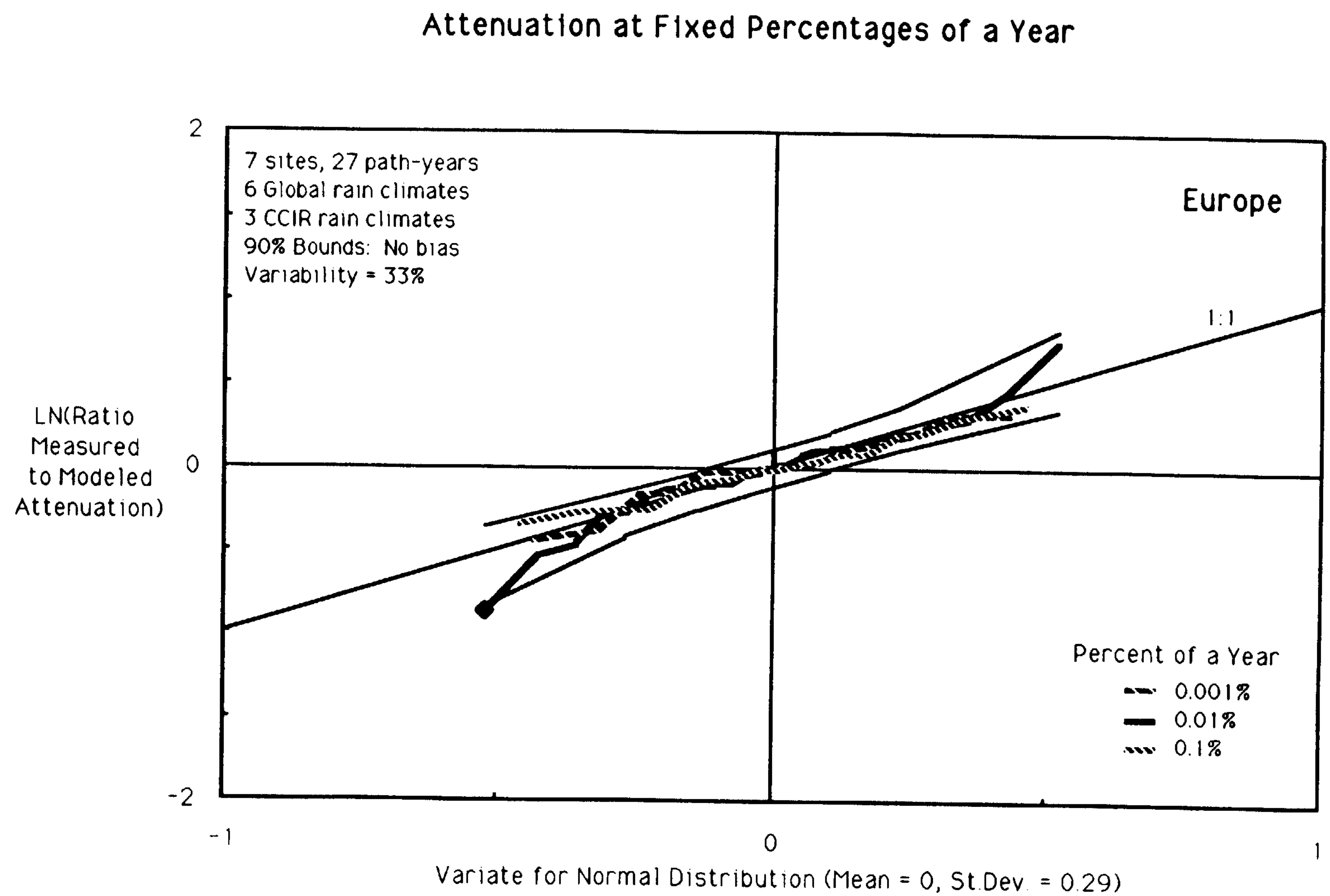

Figure 4 Cumulative distributions of deviations of measured from modeled attenuations for sites with three or more single-year sample cumulative distribution functions.

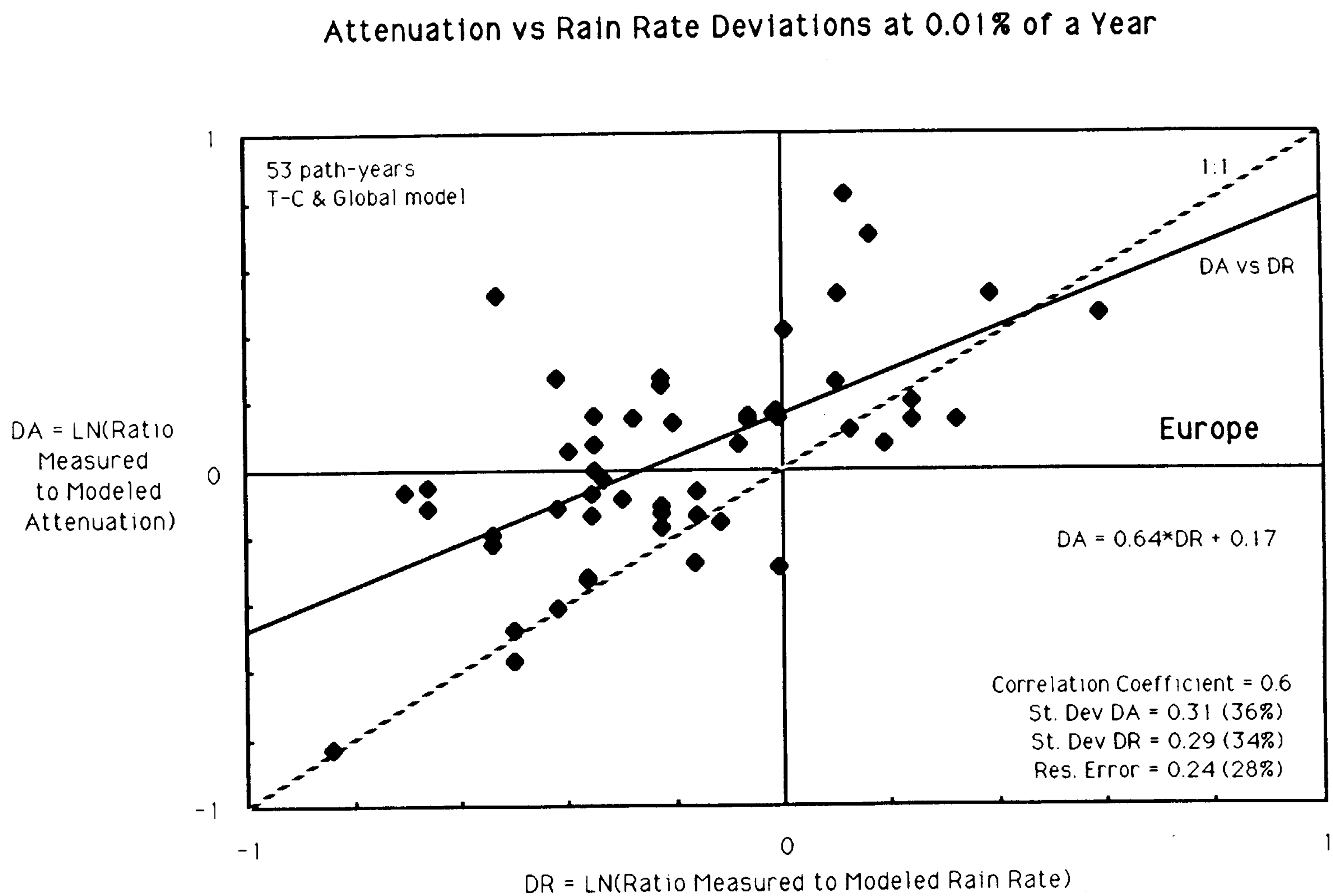

Figure 5 Rain rate and attenuation deviation pairs for single-year sample cumulative distribution functions for European satellite beacon data.

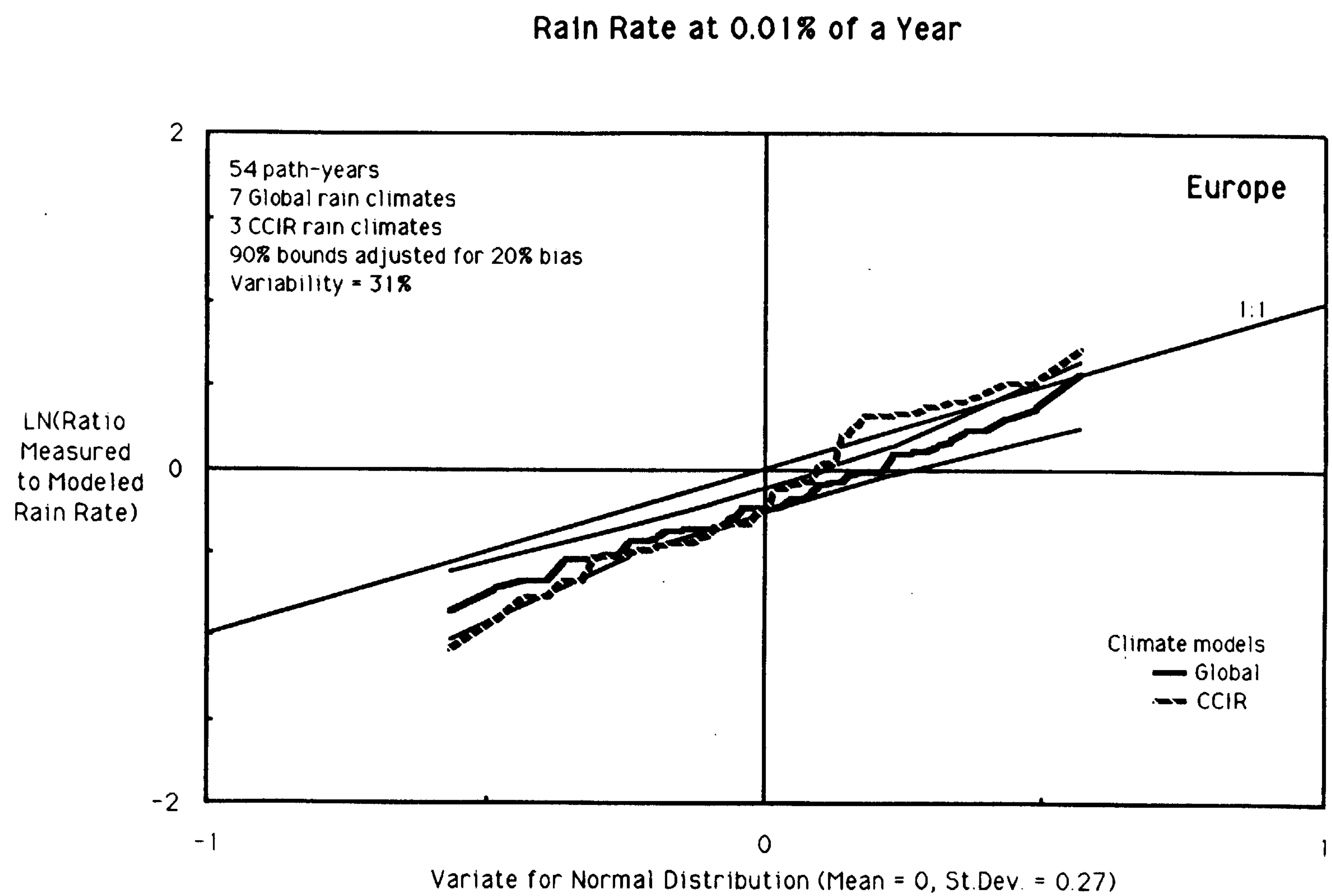

Figure 6 Cumulative distributions of deviations of measured from modeled rain rates at 0.01% of a year for single-year sample cumulative distribution functions for European satellite beacon data.

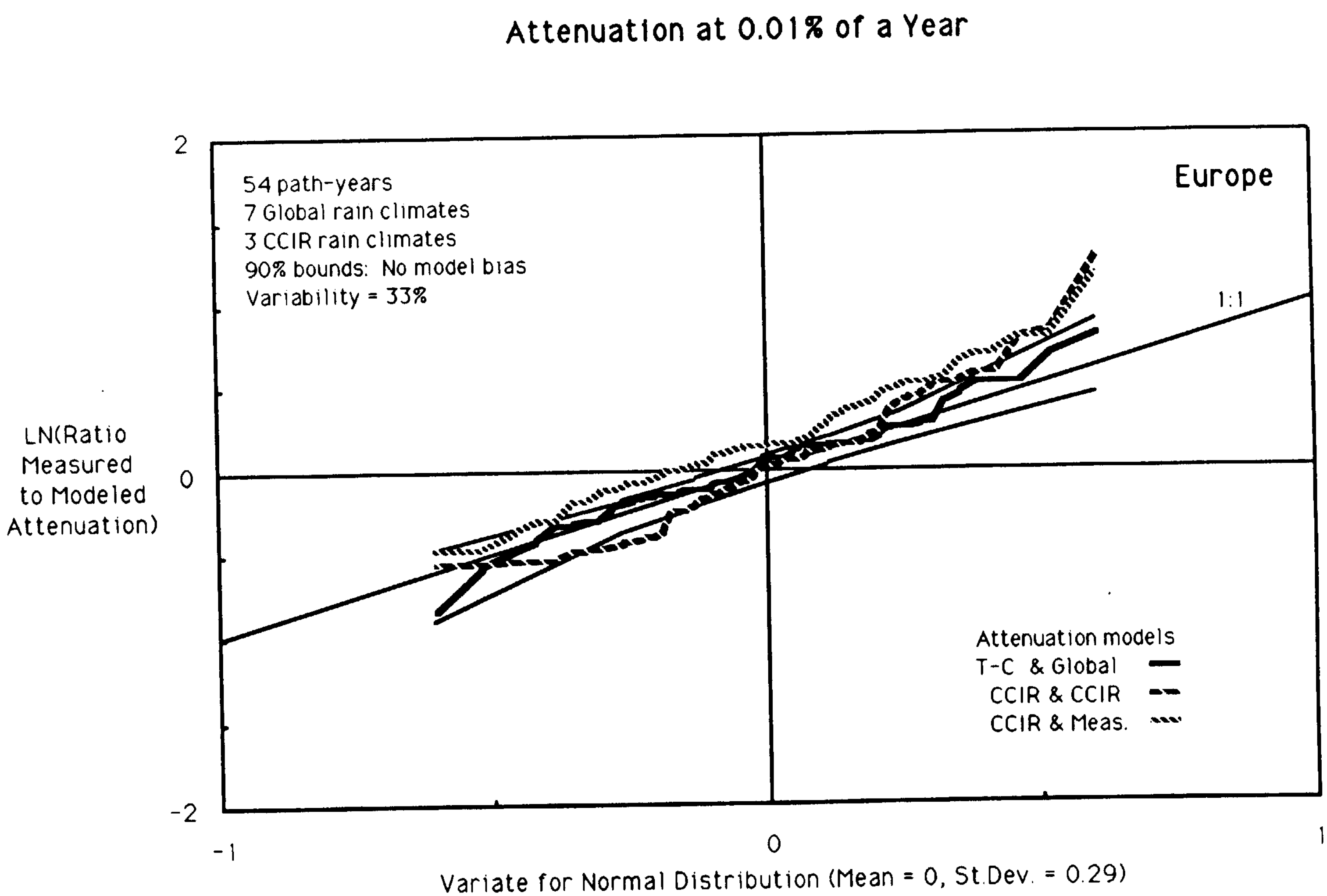

Figure 7 **Cumulative distributions of deviations of measured from modeled attenuation at 0.01% of a year for single-year sample cumulative distribution functions for European satellite beacon data.**

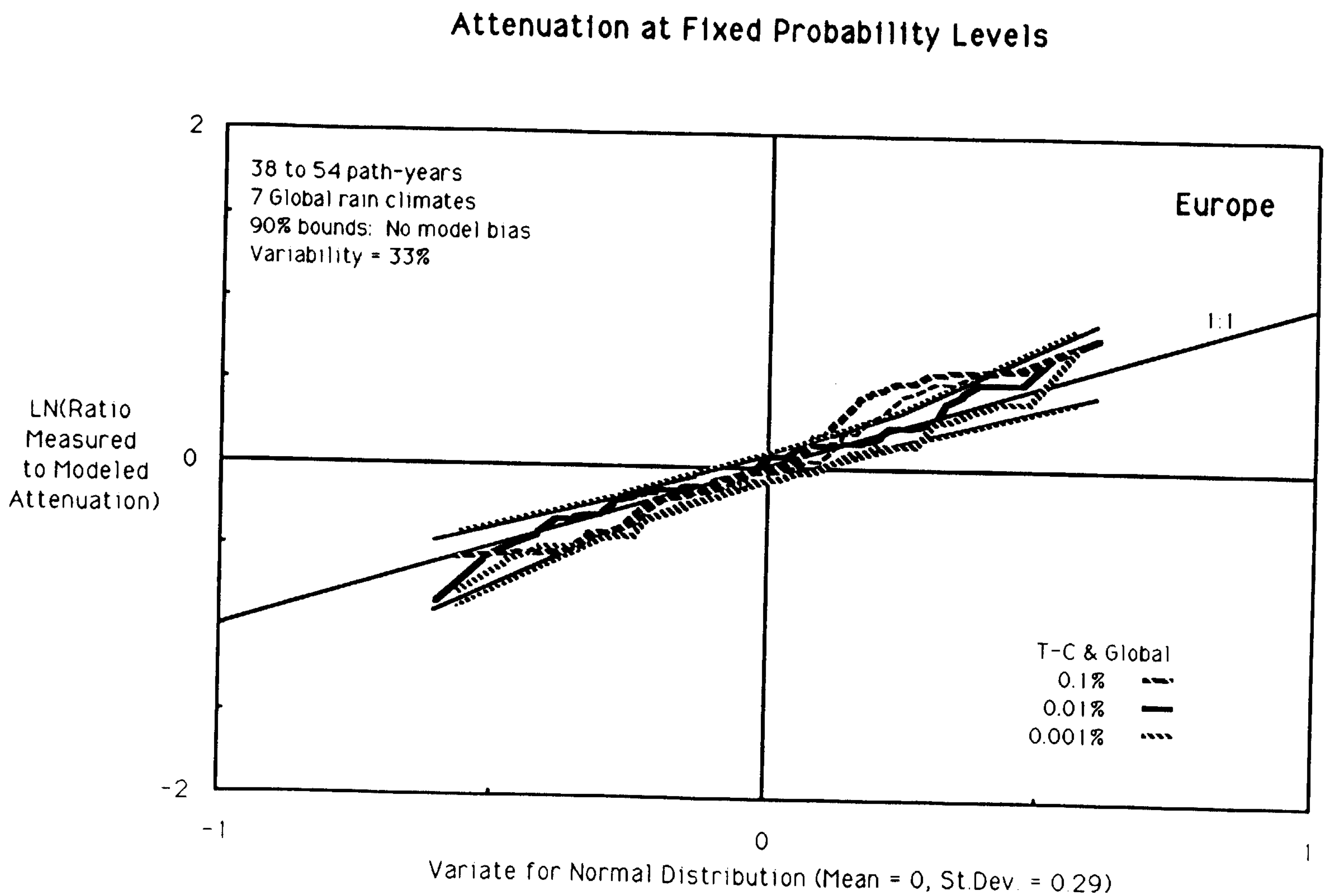

Figure 8 Cumulative distributions of deviations of measured from modeled attenuations at several probability levels for single-year sample cumulative distribution functions for European satellite beacon data.

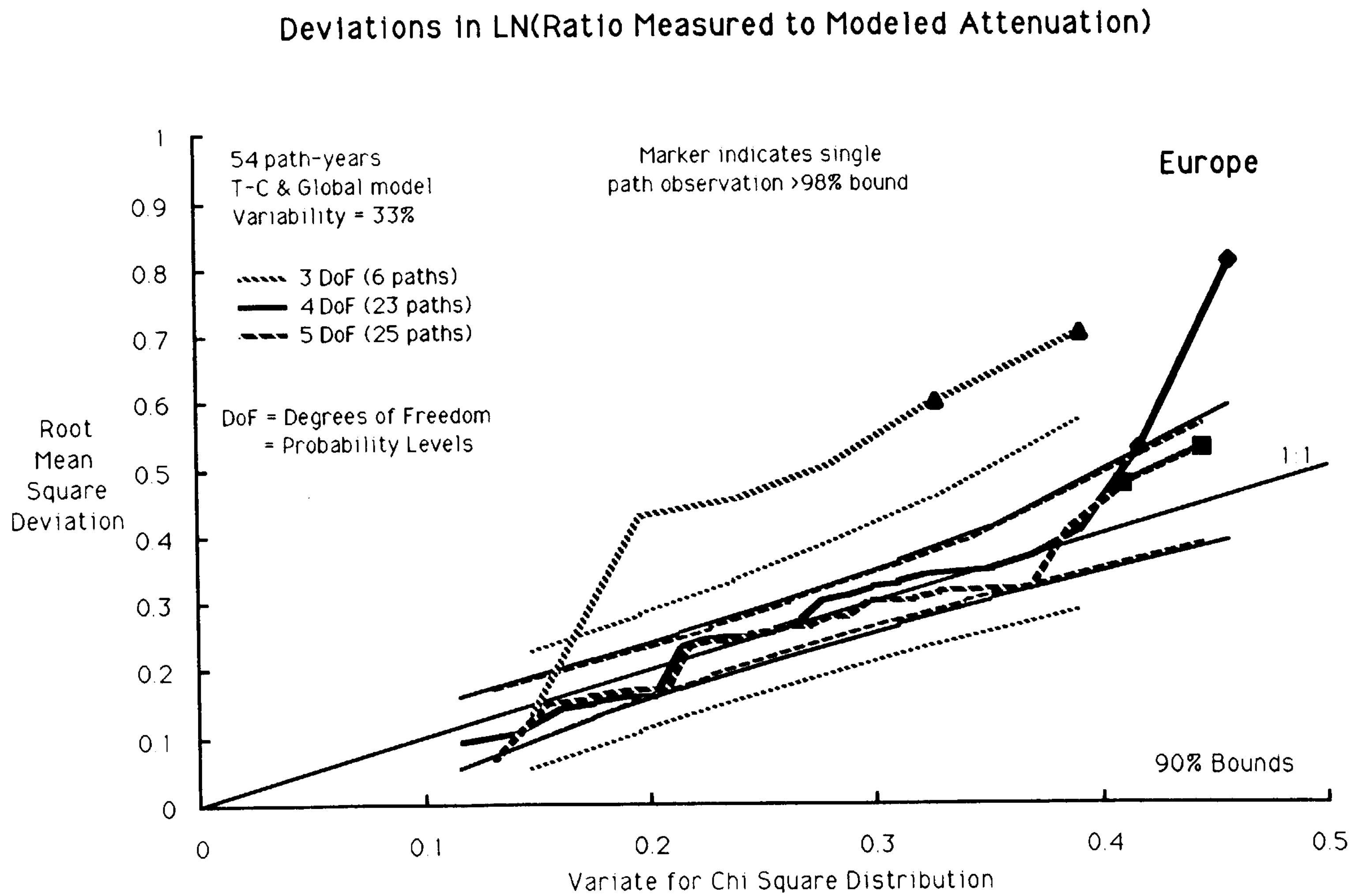

Figure 9 Cumulative distributions of the root mean square deviations of measured from modeled attenuations at several probability levels for single-year sample cumulative distribution functions for European satellite beacon data.

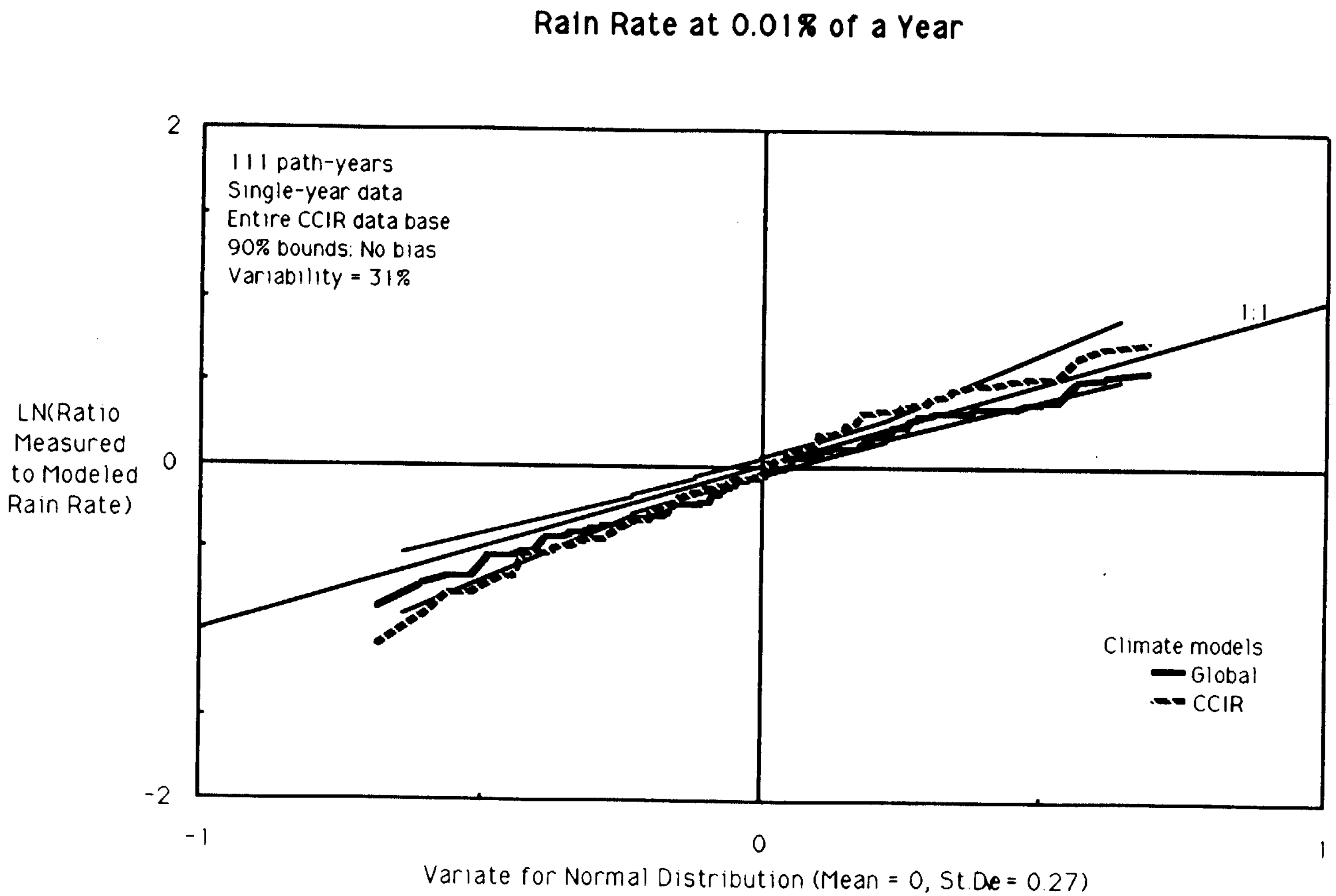

Figure 10 Cumulative distributions of deviations of measured from modeled rain rates at 0.01% of a year for single-year sample cumulative distribution functions for the CCIR data banks.

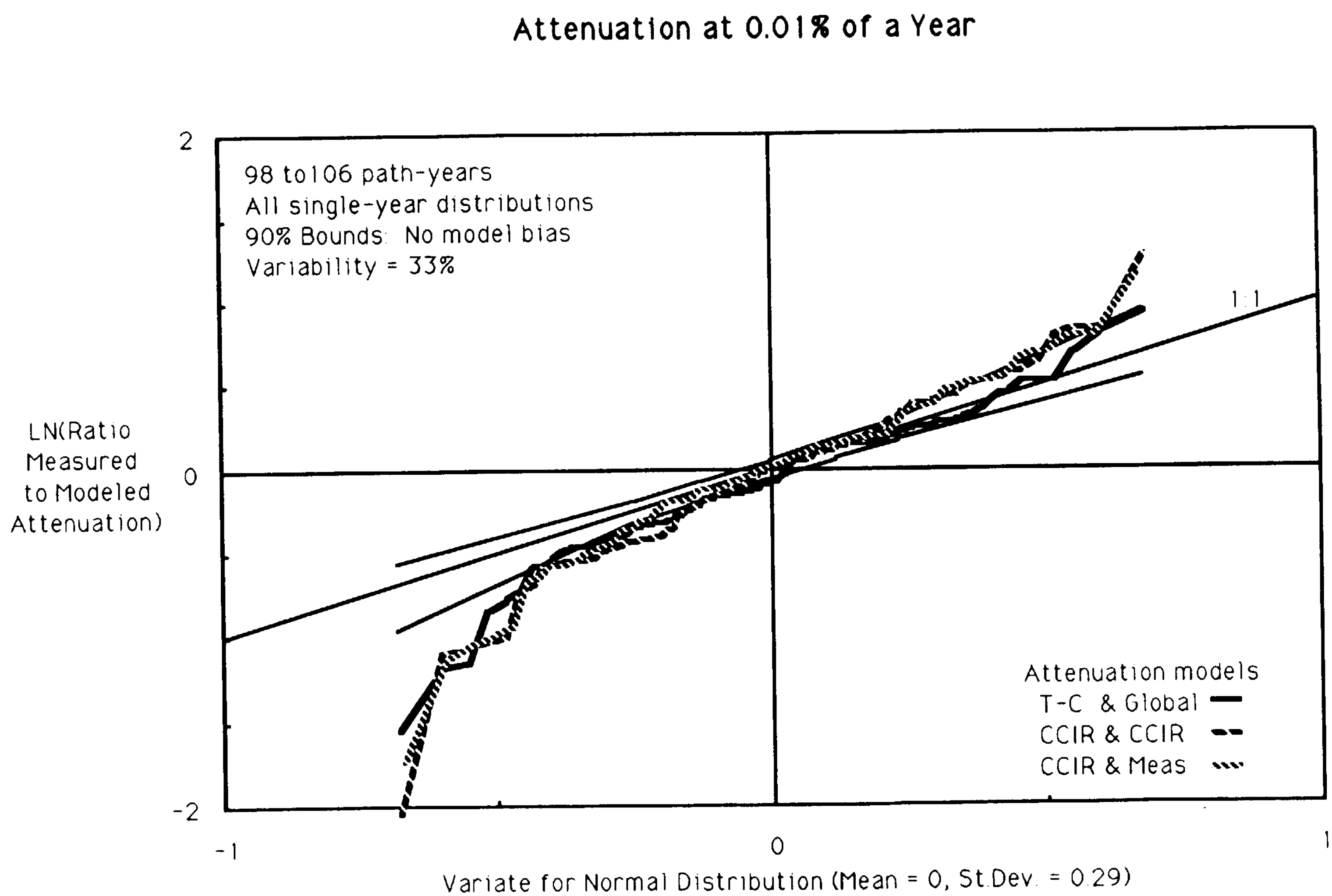

Figure 11 Cumulative distributions of deviations of measured from modeled attenuation at 0.01% of a year for single-year sample cumulative distribution functions for the CCIR data banks.

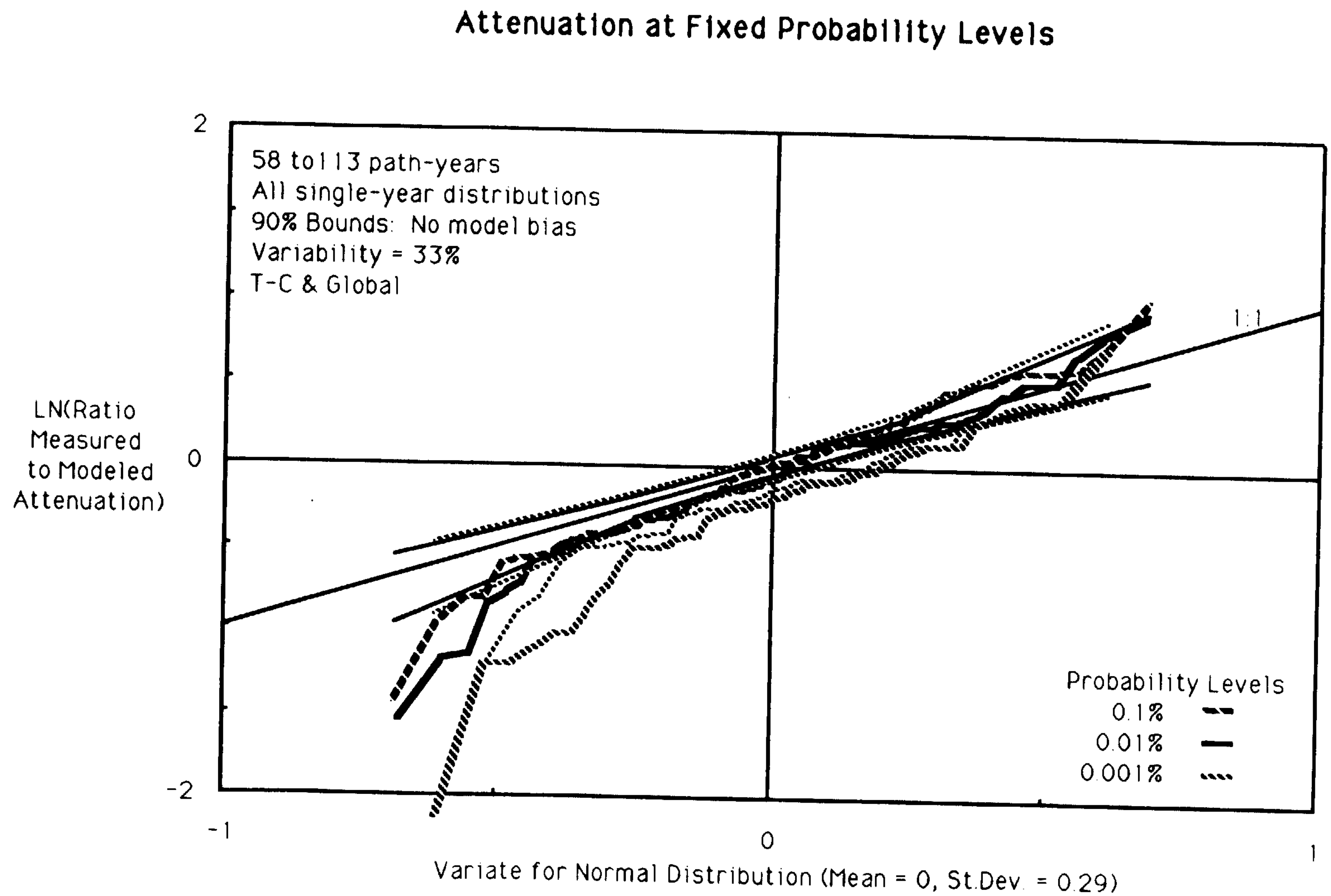

Figure 12 Cumulative distributions of deviations of measured from modeled attenuations at several probability levels for single-year sample cumulative distribution functions for the CCIR data banks.

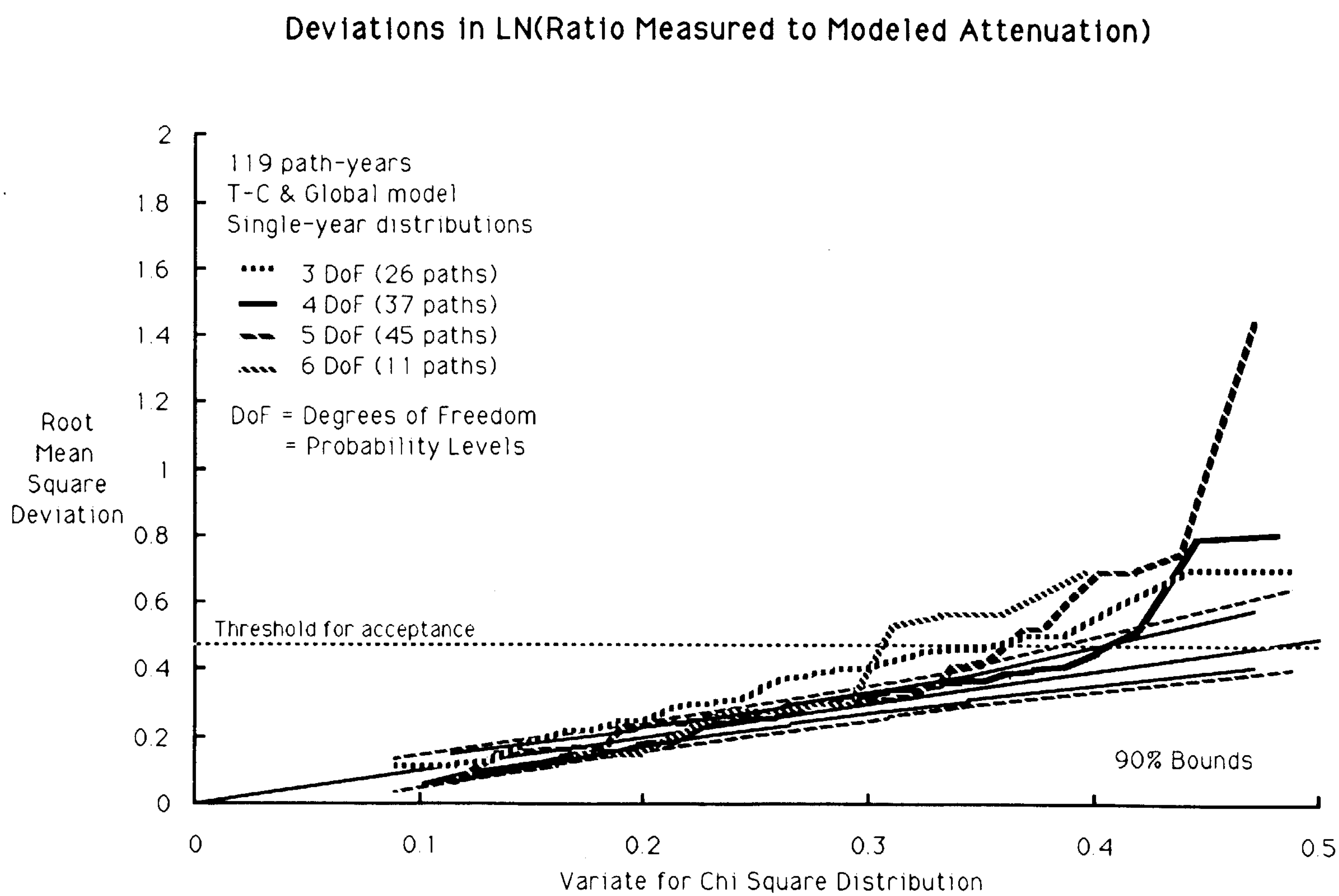

Figure 13 Cumulative distributions of the root mean square deviations of measured from modeled attenuations at several probability levels for single-year sample cumulative distribution functions for the CCIR data banks.

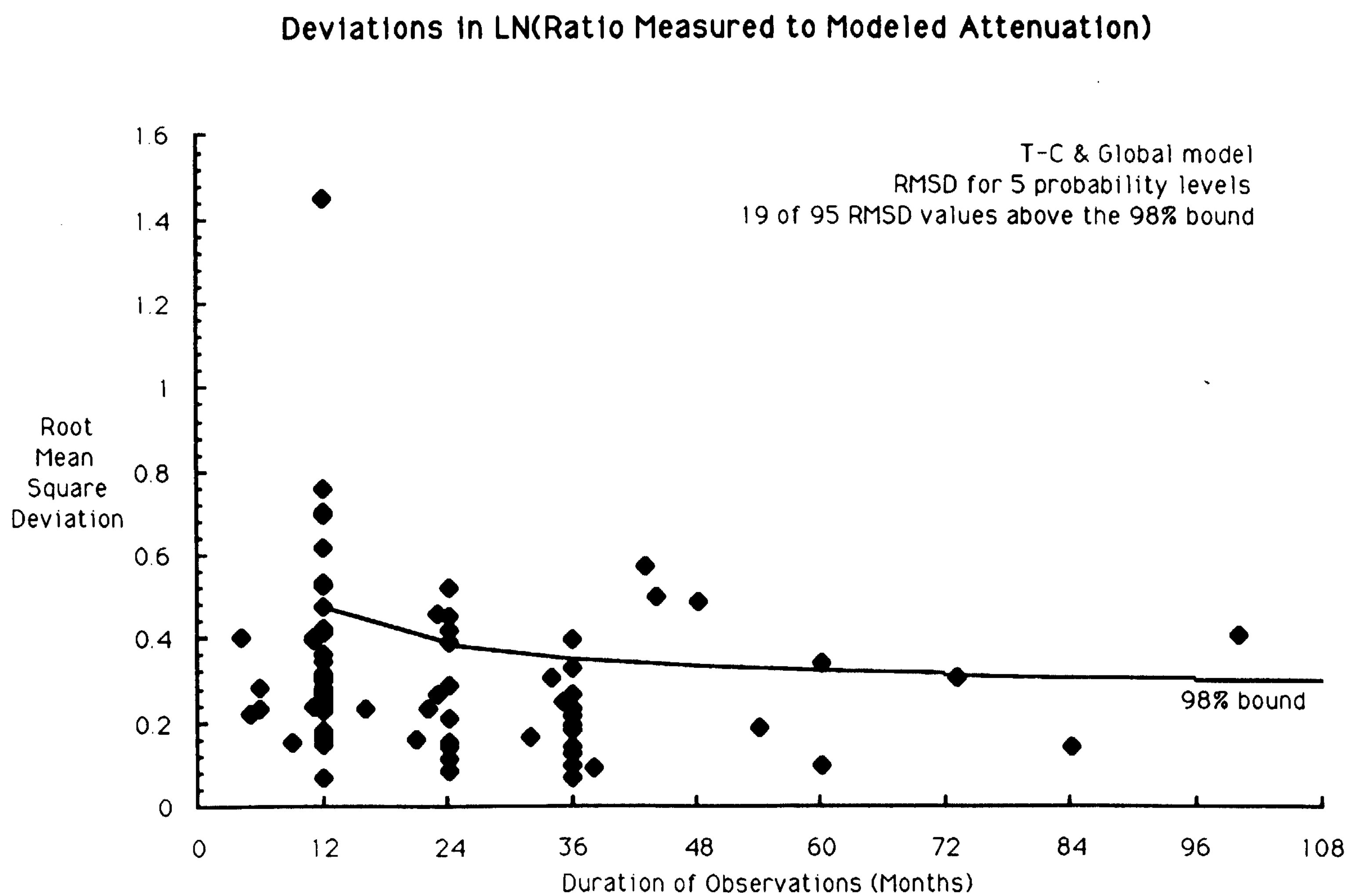

Figure 14 Root mean square attenuation deviations as a function of observation interval.

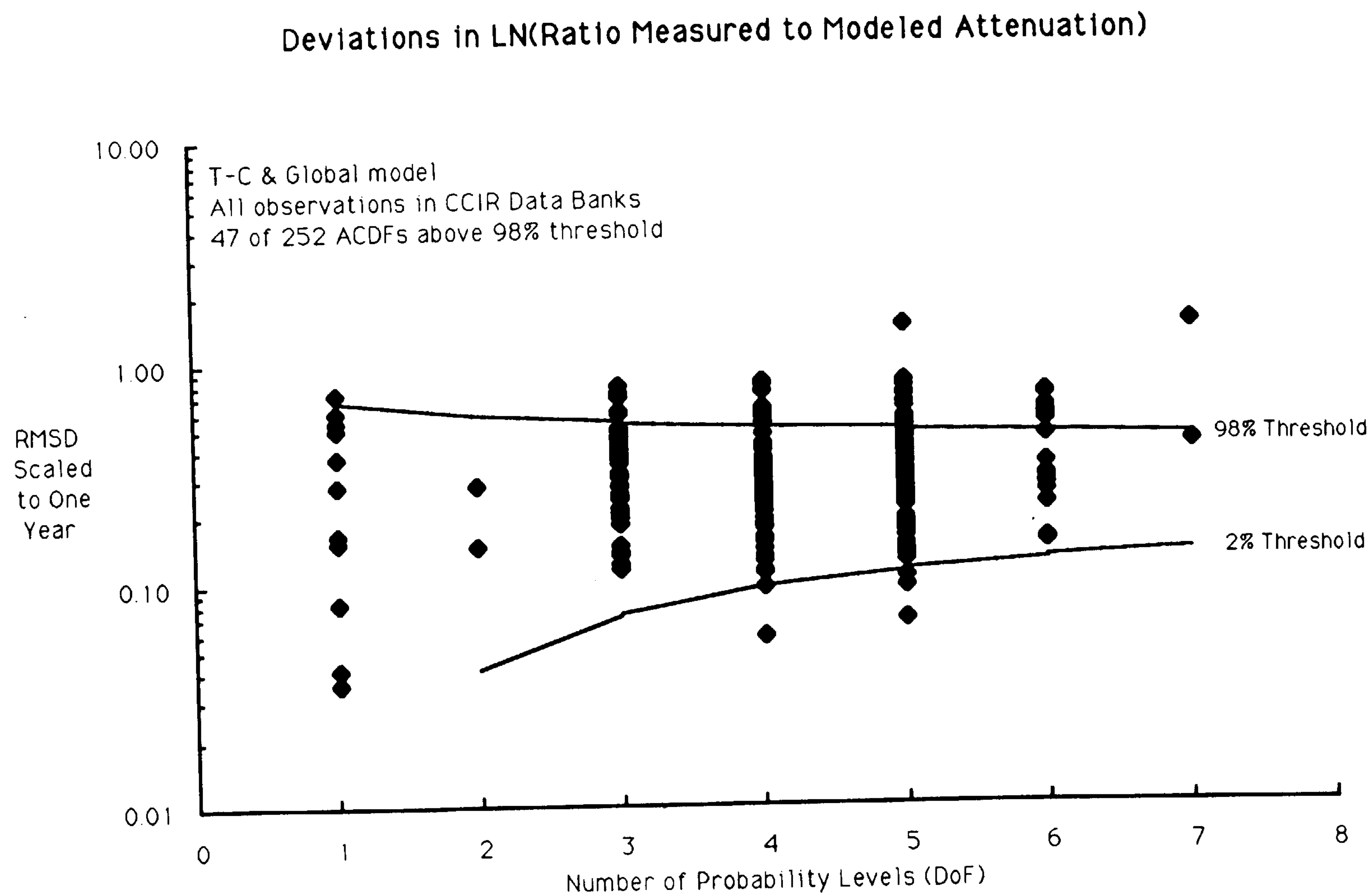

Figure 15 Root mean square attenuation deviations for the entire CCIR data base.