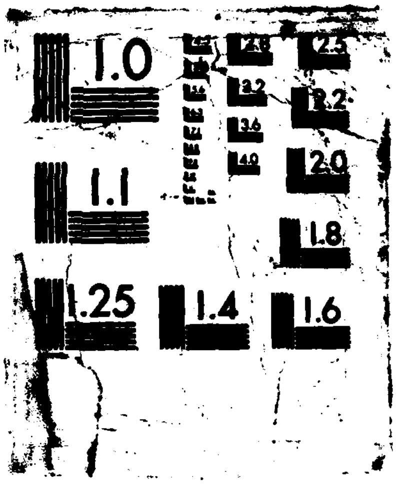
AD-A191 342 RAINFALL RATES AND DROP-SIZE DISTRIBUTIONS FOR 1/1
ENVIRONMENTAL TESTING(U) AIR FORCE GEOPHYSICS LAB
HANSCOM AFB MA P TATTELMAN 25 FEB 88 AFGL-TR-88-0046
UNCLASSIFIED F/G 4/2 NL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AD-A191 342

DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release
Distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
AFGL-TR-88-0046

5. MONITORING ORGANIZATION REPORT NUMBER(S)

DTIC
ELECTE
MAR 09 1988
S E D

6a. NAME OF PERFORMING ORGANIZATION
Air Force Geophysics Laboratory

6b. OFFICE SYMBOL *(If applicable)*
LYA

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
Hanscom AFB
Massachusetts 01731-5000

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS *(City, State, and ZIP Code)*

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62101F	6670	09	13

11. TITLE *(Include Security Classification)*
Rainfall Rates and Drop-Size Distributions for Environmental Testing

12. PERSONAL AUTHOR(S)
Paul Tattelman

13a. TYPE OF REPORT
Reprint

13b. TIME COVERED
FROM ________ TO ________

14. DATE OF REPORT *(Year, Month, Day)*
1988 February 25

15. PAGE COUNT
3

16. SUPPLEMENTARY NOTATION Reprinted from: 1988 Proceedings of the 34th Annual Technical Meeting of the Institute of Environmental Sciences, 2-6 May 1988, King of Prussia, Pennsylvania.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Rain
Military Standards
Climatic Data
Drop-Sizes
Design Information

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Rainfall rates and associated drop-size distributions are important considerations in the design and testing of most items that must operate in and withstand the effects of weather. Erosion of aerospace vehicles, triggering of impact fuses and leakage into sealed components are some examples of the many ways that rain can impact different types of hardware. To properly design and test systems and equipment for rain, appropriate intensities and associated drop-size distributions need to be determined. This paper discusses the pertinent climatic data available on rain, how they were used to derive the design values presented in MIL-STD-210C, and how to determine the appropriate intensity values for each system's intended life cycle. (Reprints)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
PAUL TATTELMAN

22b. TELEPHONE *(Include Area Code)*
617-377-2981

22c. OFFICE SYMBOL
AFGL/LYA

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

AFGL-TR-88-0040

RAINFALL RATES AND DROP-SIZE DISTRIBUTIONS FOR ENVIRONMENTAL TESTING

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Mr. Tattelman is a research meteorologist with the Atmospheric Sciences Division of the Air Force Geophysics Laboratory, Hanscom AFB, MA. He has been employed there since 1967, except from 1969 to 1971 when he served as a Weather Officer in the Navy. He received the B.S. degree in meteorology from the Pennsylvania State University in 1967 and has done post-graduate work in meteorology, statistics, and management. He is currently responsible for planning, conducting, and managing applied research programs to determine probability distributions of atmospheric conditions. Results are primarily used for the design, testing, and operation of systems affected by weather. He was chairman of the tri-service (Army, Navy, and Air Force) committee that developed MIL-STD-210C, "Climatic Information to Determine Design and Test Requirements for Military Systems and Equipment." He has published over 40 papers in applied climatology, and has provided consultation to many Federal agencies and their contractors.

Abstract

Rainfall rates and associated drop-size distributions are important considerations in the design and testing of most items that must operate in and withstand the effects of weather. Erosion of aerospace vehicles, triggering of impact fuses and leakage into sealed components are some examples of the many ways that rain can impact different types of hardware. To properly design and test systems and equipment for rain, appropriate intensities and associated drop-size distributions need to be determined. This paper discusses the pertinent climatic data available on rain, how they were used to derive the design values presented in MIL-STD-210C, and how to determine the appropriate intensity values for each system's intended life cycle.

1. Background

Records of rainfall amounts are available for thousands of locations worldwide for more than 100 years in many instances. However, data collection was oriented toward agricultural and hydrological purposes for which monthly, daily, and less commonly, 3 and 6 h totals were collected. Precipitation amounts for intervals of 3 h down to 5 min are available for many locations in the United States, but for few locations in other parts of the world. For most design considerations instantaneous rainfall rates would be more appropriate, but 1-min rates are generally considered the most practical. Much of the meager amount of data on 1-min rates was collected during special field programs conducted for limited time periods (e.g., 1-3 years). This has prompted the development of numerous models to estimate 1-min rates.

Tattelman and Grantham (1985) discuss sources of one minute data and present a survey and comparison of models for estimating one minute rates. They found six models that estimate annual rainfall-rate distributions, but only one that estimates rates on a monthly basis. Due to the importance of worst-month considerations for design and operation problems, the monthly model developed by Tattelman and Scharr (1983) was used to derive atlases of 1-min rates (Tattelman and Grantham, 1983a, 1983b).

2. Frequencies of Extreme Rainfall Rates

a. The Tattelman-Scharr Model

The T-S model is made up of six regression equations to estimate rates that are equaled or exceeded for exceedance levels (p) = 0.01, 0.05, 0.10, 0.50, 1.0, and 2.0 percent of time during a month (approximately 4.4 min, 22 min, 44 min, 3.6 hr 7.3 hr, and 14.6 hr, respectively). Information required to make the estimates for each of the six exceedance levels (p) consists of monthly mean temperature, monthly mean precipitation, number of days in the month with precipitation (based on any of three threshold values that define a rainy day), and latitude. The minimum threshold amount of precipitation to define a rainy day varies with country. Three of the most common threshold values used worldwide to define a rainy day are 0.25, 1, and 2.54 mm. The number of rainy days during the month based on each of these threshold amounts, as well as monthly precipitation and monthly mean temperature, were observed coincident with the rain-rate frequencies. The number of days per month with another frequently used threshold called a "trace" differed only slightly with the number of days equal to greater than 0.25 mm, and was not used.

The basic form of the model equation is expressed by

$$R_p = A_p + B_p T + C_p I + D_p f(L,T) \qquad (1)$$

where R_p is the estimated precipitation rate (mm/min) for exceedance level p, T is the monthly mean temperature (°F or 1.8 X °C + 32), I is a precipitation index (monthly mean precipitation divided by the monthly mean number of days with precipitation) and $f(L,T)$ is a latitude-temperature term. A_p is the constant for exceedance level p and B_p, C_p, and D_p are multiple regression coefficients for T, I, and $f(L,T)$, respectively, for exceedance level p. The term $f(L,T)$ is defined by

$$f(L,T) = \begin{cases} 0 & L \leq 23.5° \\ (L - 23.5) \times T & 23.5° < L \leq 40° \\ (40 - 23.5) \times T & L > 40° \end{cases} \quad (2)$$

where L is the latitude (degrees and tenths) of the location of interest. This term accounts for the increasing importance of temperature for estimating precipitation rates at higher latitudes.

b. Rain-Rate Atlases

During the preparation of MIL-STD-210B, the Office of the Assistant Secretary of Defense specified that the frequency of occurrence during the worst month in the severest part of the world for a climatic element should be the basis for values presented in the Standard. For rainfall and associated vertical profiles, rates occurring 0.5 percent of the time are recommended for initial design consideration in MIL-STD-210C. Rainfall rates associated with lower frequencies-of-occurrence are also provided in the standard. Rainfall rates are presented for lower frequencies than other climatic elements because high rates are quite extensive in the tropics and can be a problem in many months of the year.

Atlases of 1-min rates based on the new model were used to determine the areas in the world with the highest rainfall rates occuring 0.5, 0.1, and 0.01 percent of the time during the worst month. Although rates are generally highest in the northern hemisphere tropics, the estimated rates for two locations in northeast Brazil, Barco Do Corda and Teresina, are about the same as the rates estimated for Cherrapunji for all three frequences. The rates for this area in northeast Brazil are 0.6 mm/min (36 mm/hr), 1.4 mm/min (84 mm/hr), and 2.8 mm/min (168 mm/hr) for 0.5, 0.1, and 0.01 percent of the worst month, respectively.

Elsewhere, values in the Northern Hemisphere tropics exceed 0.4, 1.2, and 2.4 mm/min during 0.5, 0.1, and 0.01 percent of the most severe month in many areas, especially in southeast Asia. Since these rates occur over large areas in the tropics, the slightly higher rates in northeastern Brazil were used to represent the worst month/area rates in MIL-STD-210C.

3. Drop-Size Distributions

The drop-size distributions presented in MIL-STD-210B were based upon an exponential model of drop number concentrations. Numerous investigators have pointed out the inadequacies of the exponential distribution in describing observed drop-size distributions, particularly for high-intensity convective rains. Tattelman and Willis (1985) analyzed a large sample of drop-size distributions during intense rainfall collected from reconnaisance of Atlantic hurricanes/tropical storms. The data set was normalized and fit by a gamma distribution to provide a better model to determine drop-size distributions for MIL-STD-210C.

The gamma distribution function, of which the exponential is a special case, fits tropical convective rain distributions particularly well (Willis, 1984). Most functional descriptions of the size distributions of raindrops are encompassed by the following expression:

$$N(D) = N_o D^{\alpha} \exp(-\Lambda D) \quad 0 < D < D\mathrm{max}, \qquad (3)$$

which is the gamma distribution function. Here D is the drop diameter ($N(D)dD$ is the concentration of drops having diameters between D and D+dD), Λ is the slope parameter, and α is the shape parameter of the distribution. For the case where $\alpha = 0$ and $N_o = 0.08/\mathrm{cm}^4$ this reduces to the familiar Marshall-Palmer exponential distribution.

It can be shown that D_o, the median volume diameter of a distribution, is given by the approximate expression

$$D_o = \frac{3.67 + \alpha}{\Lambda} \qquad (4)$$

as long as $\alpha > -2$, and if $D_{max}/D_o > 2.5$.

The model is applied as follows: If a drop-size distribution is desired for a given liquid water content $M(\mathrm{g/m}^3)$, first compute the median volume diameter from

$$D_o = 0.1571\, M^{0.1681} \qquad (5)$$

where D_o is in cm. If the rainfall rate, R(mm/hr) is specified, compute M from

$$M = 0.062\, R^{0.913} \qquad (6)$$

Then the three parameters of the gamma distribution, Eq. (3), needed for the model are computed:

$$\Lambda = 5.5880/D_o \qquad (7)$$

$$\alpha = 2.160 \qquad (8)$$

$$N_o = \frac{512.85 M \times 10^{-6}}{D_o^4} \left(\frac{1}{D_o}\right)^{2.160} \qquad (9)$$

As an example, the equations for the drop size distributions for the three rainfall rates discussed in section 2 are:

$$36 \text{ mm/hr} \quad N(D) = 45.08 D^{2.160} \exp[-32.75D] \qquad (10)$$

$$84 \text{ mm/hr} \quad N(D) = 43.86 D^{2.160} \exp[-28.76D] \qquad (11)$$

$$168 \text{ mm/hr} \quad N(D) = 42.88 D^{2.160} \exp[-25.86D] \qquad (12)$$

where N(D) is in cm^{-4} and D in cm. Thus, to find the concentrations per m^3 in a 0.1 mm diameter size interval, N(D) in cm^{-4} must be multiplied by 1×10^4.

Greater detail on the model is provided in Tattelman and Willis (1985). This report also provides vertical profiles of rainfall rate, drop-size distribution and liquid water content up to 20km.

4. Establishing Design and Test Requirements

The appropriate values of climatic elements specified for design of equipment depend upon:

a. Areas of Exposure. This includes:

(1) Geographical locations through which it may be transported.
(2) Where it may be stored
(3) where it may be deployed
(4) how it will be transported
(5) circumstances when it will be protected from the environment.

b. Operational Requirements

It is ordinarily costly or technologically impossible to design equipment to operate under the most extreme conceivable conditions. Therefore, military planners accept equipment designed to operate for all but a certain small percentage of the time. The procuring agency is responsible for determining the operational requirements of the item or system. These requirements should then be used to determine the acceptable frequency of occurrence of a climatic element.

For rainfall MIL-STD-210C recommends *that rates associated with a frequency of* occurrence of 0.5% of the time during the worst month (about 3.5 hrs) be initially considered for design. In the case of rainfall, extreme conditions are so widespread in the rainy tropics that less extreme values associated with higher frequencies are not provided.

c. Safety and Equipment Survivability

For some material, one-time exposure to a climatic extreme can render it permanently inoperable or dangerous. For such material, long-term climatic extremes would be more appropriate for design of equipment that is not protected from the environment. Depending on the degree of the hazard, the use of the most extreme recorded value may be required. The use of these more extreme values, instead of those occurring for a percent of the time during the most severe month each year, shall be determined by the agency or department responsible for development.

5. Other Considerations

The climatic values in 210C represent free air (ambient) conditions. The conditions that an item will see depend on how the natural environment is modified by the platform on or within which the item is expected to function. Design requirements and test procedures can be established only after the platform characteristics are identified and the platform environment is defined.

Once the platform environment(s) is(are) defined, problems in designing for any of the climatic conditions will surface if they have not already done so. If design to one or more of the initially derived ambient climatic conditions proves unacceptable due to technical or cost considerations, alternatives need to be considered. Although the procuring agency establishes the requirements, the ramifications as to cost or achievability can only be evaluated after these have been factored into the design by the contractor. The procuring agency should be made aware of the problems and potential solutions. The use of alternatives, such as less extreme values associated with higher frequencies of occurrence (and reduced operational capability), must be weighed by the procuring agency.

Acknowledgement - The author is grateful to Carolyn A. Fadden for her timely typing of the manuscript.

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