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A Rain Taxonomy for Degraded Visual Environment Mitigation

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EXECUTIVE SUMMARY

This Technical Memorandum (TM) provides a description of rainfall for the purpose of degraded visual environment (DVE) mitigation. The taxonomy is based on raindrop size measurements collected around the globe and encompasses several different climate types. Included in this TM is a description of the rainfall observations considered, an explanation of methods used to process those data, and resultant metrics comprising the weather taxonomy database. For purposes of DVE mitigation, rain can be described using three categories that correspond to light, moderate, and heavy amounts of liquid water, and these are related to traditional rainfall intensity-based definitions. Each of the categories in the rain taxonomy are characterized by a unique set of raindrop sizes that can be used in simulations of electromagnetic wave propagation through a rain medium. This taxonomy defines the size distributions for light, moderate, and heavy rainfall. Light rain consists of raindrops with an average mass-weighted mean diameter (D_m) of 0.9 mm, moderate rain consists of raindrops with an average D_m of 1.1 mm, and heavy rain consists of raindrops with an average D_m of 1.6 mm. A description of the relational database containing the weather taxonomy built for DVE mitigation is provided in a companion report, "A Weather Taxonomy Database for DVE Mitigation."

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2DVD	two-dimensional video disdrometer
DVE	degraded visual environment
GPM	Global Precipitation Measurement
LWC	liquid water content
RSD	raindrop size distribution
TM	Technical Memorandum
VIS	visibility

NOMENCLATURE

a	semi-major (axis)
b	semi-minor (axis)
D	equivalent spherical diameter
D_m	mass-weighted mean diameter
i	index of the size bin
N	number of raindrops
N_T	total drop concentration
n	number of diameter bins
R	rainfall intensity
v	velocity
μ	shape parameter of the gamma distribution model
ρ_w	density of liquid water

TECHNICAL MEMORANDUM

A RAIN TAXONOMY FOR DEGRADED VISUAL ENVIRONMENT MITIGATION

1. GENERAL RAINFALL CHARACTERISITCS

Precipitation in the form of liquid water drops can be classified as either rain or drizzle based on the drop diameter. The *Glossary of Meteorology* defines raindrops as having diameters of 0.5 mm or larger, whereas water drops smaller than 0.5 mm but larger than 0.1 μm in diameter are referred to as drizzle drops.[1] Rain observed in nature has a wide range of intensities, typically ranging from 0.01 mm/hr (<0.04 in/hr) to just over 300 mm/hr (>11.8 in/hr). The vast majority of the time that rain occurs it occurs at the lower end of this range, with the median rain rate being approximately 0.8 mm/hr (fig. 1). Rainfall rates exceeding 10 mm/hr (0.4 in/hr) are not nearly as frequent or long lasting. Although weaker rainfall intensities occur for longer periods of time, there are some climates where intense rainfall is relatively more frequent (e.g., tropical climates), but the distribution of rain is always skewed toward lower intensities.

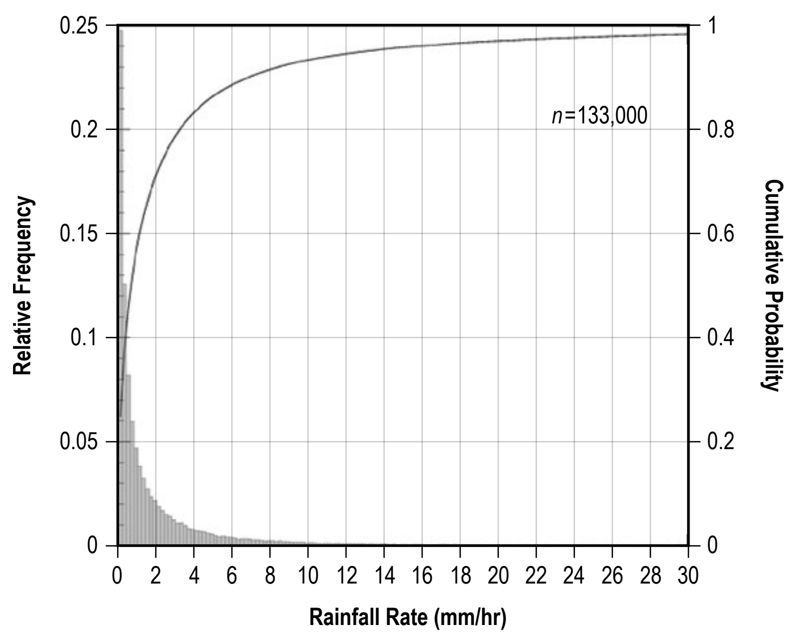

Figure 1. Distribution of rainfall intensities from 133,000 min of rainfall observations used to define the rain taxonomy described in this TM. Rain in any climate always exhibits such a skewed distribution, which indicates that low intensity rain is the most frequent type of rain observed.

1.1 Raindrop Shape

Raindrop sizes range from 0.5 mm to just under 10 mm in diameter (diameter being that of its equivalent spherical volume since raindrop shape can vary). Falling raindrops larger than 1 mm in diameter become less spherical and tend to take on a more oblate (i.e., vertically compressed) shape similar to that shown in figure 2. One of the most simplistic descriptions of raindrop shape in terms of its size is given by the length of its semi-minor, b, axis to that of its semi-major, a, axis:

$$\frac{b}{a} = 1.03 - 0.062D\,, \tag{1}$$

where $b > a$ and D is its equivalent spherical diameter in units of millimeters.[3] More detailed raindrop shape models exists that can provide a surface contour of a raindrop.[4]

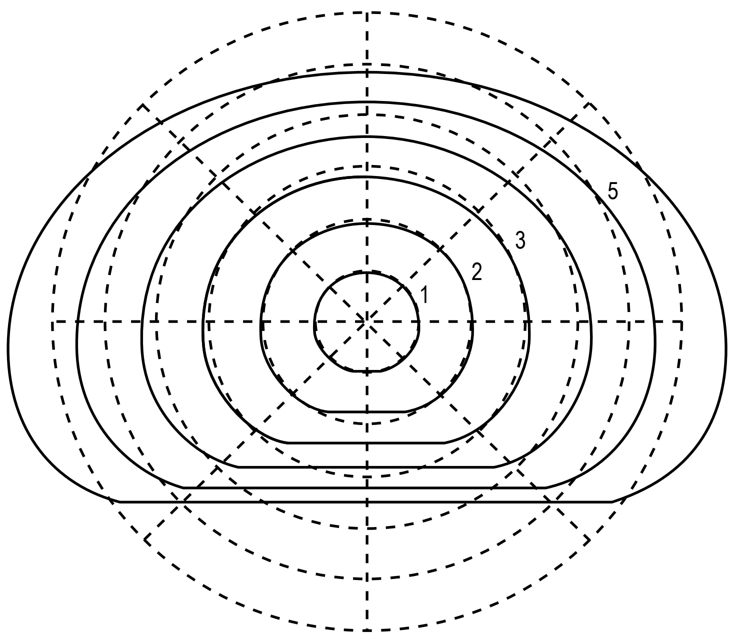

Figure 2. Shapes of falling raindrops with 1, 2, 3, 4, 5, and 6 mm diameter compared with their equivalent spherical shape.[2] Falling raindrops larger than 1 mm in diameter tend to take on a more oblate shape but with a flattened base.

1.2 Raindrop Fall Speed

Natural raindrops attain terminal fall velocities that range from 2 m/s for diameters of 0.5 mm to 7 m/s for those around 2 mm diameter and asymptotically approach 9 m/s for drops exceeding 4 to 5 mm in diameter.[5] A commonly used equation[6] for computing terminal velocity, v (m/s), of natural raindrops falling in still air as a function of equivalent spherical volume diameter, D (mm), is:

$$v = 9.65 - 10.3\exp(0.6D)\,. \tag{2}$$

It should be noted that raindrop terminal velocity increases with altitude and the result of the above equation should be adjusted accordingly with height above minimum sea level.[7]

2. CONSTRUCTION OF THE RAIN TAXONOMY

Raindrop size measurements from 14 locations encompassing eight different climates were considered (see fig. 3). These measurements were obtained using two-dimensional video disdrometers (2DVDs; cf., fig. 4) that supported NASA's Global Precipitation Measurement (GPM) Mission.[8] This type of instrument provides a measure of particle size, shape, and fall speed by employing two line-scan cameras that perpendicularly view a pair of illuminated optical planes vertically offset about 6.7 mm over a sample area of 100 cm^2. The 2DVD measures particles with a resolution of 0.2 mm for diameters as small as 0.3 mm and their associated vertical velocity to within 4% accuracy.[9] As a result, the 2DVD is commonly used as a reference for evaluating the accuracy of other disdrometers.[10–12] Hence, the taxonomy defined in this Techncial Memorandum (TM) was derived from the most comprehensive characterization of rainfall to date.

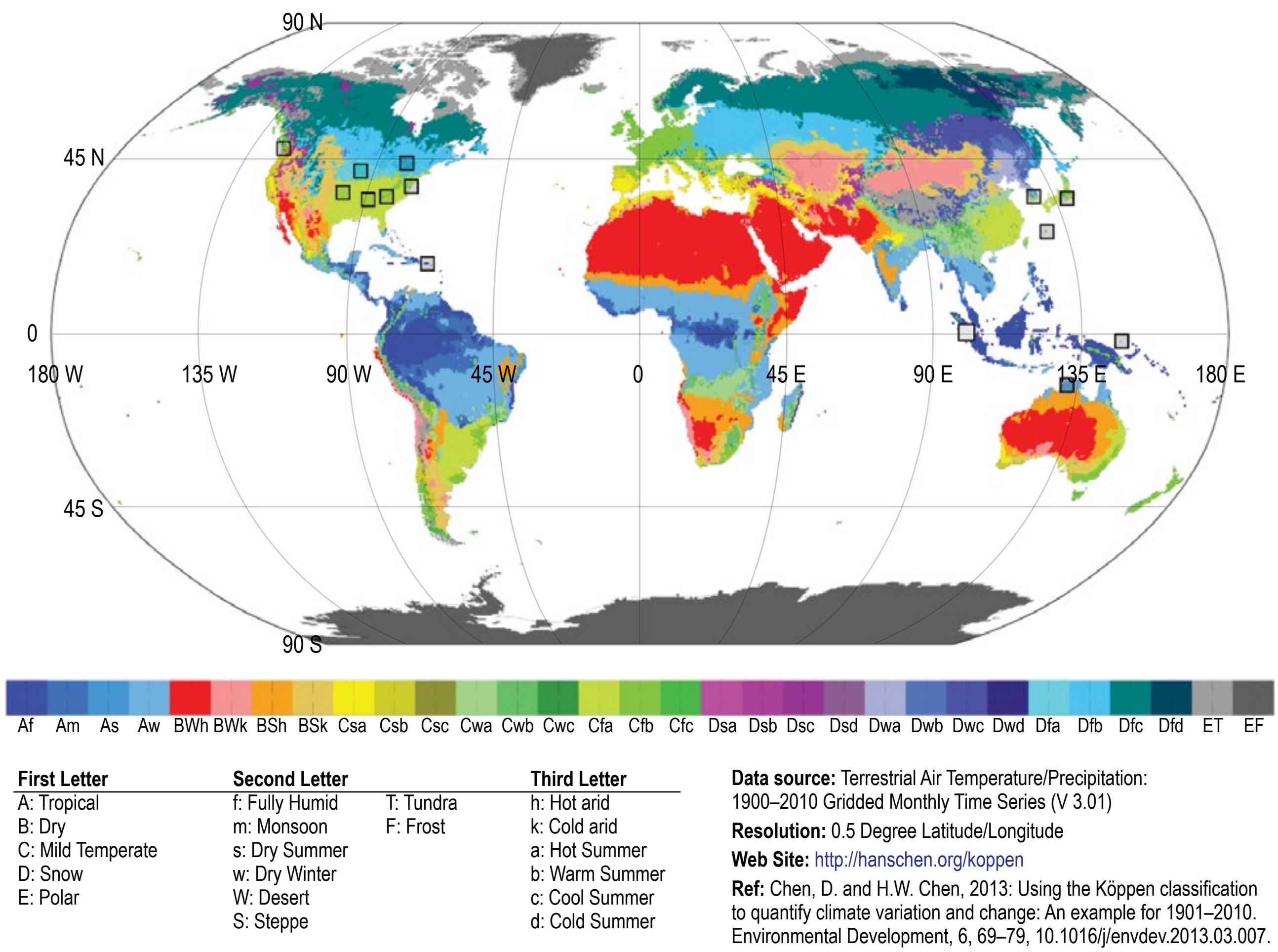

Figure 3. Map showing locations (small boxes) of 2DVD rainfall observations that were used to define the rain taxonomy. The colors represent Earth's climates according to the Köppen climate classification system.[13]

Figure 4. An example of the 2DVD (foreground—third generation compact type; background—second generation low-profile type), which is the type of disdrometer that was used to construct the weather taxonomy for rain described herein.

Table 1 provides an overview of the locations of the raindrop size measurements that were used to define the rain taxonomy described in this TM. This rain taxonomy represents the characteristics of rainfall for 8 of the 31 climate types defined in the Köppen climate classification system. The Köppen system classifies the world's climates based on temperature and precipitation[13] and is one of the most widely used climate classification schemes. From table 1 it is evident that the vast majority of the raindrop size observations were obtained in Huntsville, Alabama. Furthermore, the climate type of Huntsville (Köppen climate classification is Cfa[13]), which can be described as having mild temperatures throughout the year and being very humid with hot summers, is the most represented climate contained in this rain taxonomy since it was sampled in six different locations.

Table 1. Overview of rainfall observations used to define the rain taxonomy. The color shading corresponds to the climate classification map in figure 3.

Location	Climate (Köppen) Description	Dates of Observations	Number of 1-Minute RSDs
Huntsville, Alabama, USA	Cfa: mild temperate, fully humid, hot summer	July 2007 – December 2013	133,803
Quinault, Washington, USA	Cfb: mild temperate, fully humid, warm summer	October 2015 – January 2016	69,147
Manus Island, Papua, New Guinea	Af: tropical rainforest	December 2011 – November 2013	52,706
Koto Tabang, West Sumatra, Indonesia	Af: tropical rainforest	November 2005 – April 2007	38,711
Darwin, Australia	Aw: tropical savannah with dry winter	March 2011– November 2013	35,726
Wallops Island, Virginia, USA	Cfa: mild temperate, fully humid, hot summer	June 2012 – December 2013	33,123
Billings, Oklahoma, USA	Cfa: mild temperate, fully humid, hot summer	March 2011 – November 2013	32,675
Eastern Iowa, USA	Dfa: snow, fully humid, hot summer	April 2013 – June 2013	27,905
Daegu and Bosung, South Korea	Cwa: mild temperate with dry winter, hot summer	August 2011 – September 2015	27,700
Hiratsuka, Japan	Cfa: mild temperate, fully humid, hot summer	July 2003 – November 2003	19,857
Okinawa, Japan	Cfa: mild temperate, fully humid, hot summer	November 2003 – May 2004	14,335
Mayaguez, Puerto Rico	Am: tropical monsoon	July 2005 – January 2006	11,672
Asheville, North Carolina, USA	Cfa: mild temperate, fully humid, hot summer	April 2014 – June 2014	11,587
San Juan, Puerto Rico	Af: tropical rainforest	August 2004 – June 2005	11,333
Barrie, Ontario, Canada	Dfb: snow, fully humid, warm summer	November 2006 – May 2007; October 2011 – March 2012	9,591

Several of the 2DVD datasets, such as those from Washington, Iowa, and Ontario, were obtained for only a single season as part of a NASA GPM field campaign.[14] Hence, the information provided for those locations where only a few months of observations exist may not be as representative of all possible weather regimes occurring in their respective climates. For instance, the taxonomy may not be as representative for rain occurring in climates classified as Am, Cfb, Dfa, and Dfb as it is for those climates where at least several seasons were sampled (e.g., Af, Cfa, Cwa).

2.1 Defining the Raindrop Size Distribution

The individual raindrops measured by the 2DVD for locations in table 1 were checked to ensure that equivalent spherical diameters ranged from 0.3 to 10 mm and drop fall speeds were within ±40% of the expected terminal fall velocity,[6] which helps mitigate inclusion of non-rain particles or incorrect particle matches that can result from the 2DVD processing software.[15] Raindrops that passed these constraints were counted over 1-min intervals and apportioned into 0.2-mm-diameter-size bins to obtain a sample of the raindrop population. Each bin with rain was required to contain at least two raindrops and each 1-min sample was required to contain at least 10 raindrops total. These additional requirements facilitated a representative sample for the curve-fitting procedure used to obtain a better estimate of the 1-min raindrop population across the full spectrum of raindrop diameters while allowing a robust number of samples to define the taxonomy.

The 1-min binned raindrop observations likely do not include the full spectrum of diameters in the raindrop population falling during the 1-min sample collection due to the variability of rainfall size distributions and issues with sampling such a population using such a small measurement area (i.e., 2DVD only samples across a 10 cm × 10 cm area). Hence, to better depict the actual raindrop population, a distribution with known properties was used to define the raindrop size distribution (RSD). RSDs have been defined using either an exponential, gamma, or log-normal distribution.[16–18] Each one has its strengths and weaknesses, but raindrop populations sampled with 2DVDs have been shown to closely resemble a gamma distribution[19–21] and this is the type used to define the rain metrics of this weather taxonomy.

2.2 Model to Describe Rain: Gamma Distribution

The gamma model formulation used to define the rainfall characteristics contained within this weather taxonomy is commonly referred to as the gamma drop size distribution. It is used to compute the number of raindrops, N, of diameter D within a volume of air:

$$N(D) = \frac{N_T}{D_m} f_\mu\left(\frac{D}{D_m}\right) , \tag{3}$$

with

$$f_\mu\left(\frac{D}{D_m}\right) = \frac{(4+\mu)^{\mu+1}}{\Gamma(\mu+1)}\left(\frac{D}{D_m}\right)^{\mu} \exp\left[-(4+\mu)\frac{D}{D_m}\right] , \tag{4}$$

where N_T is the total drop concentration, D_m is the mass-weighted mean diameter, and μ is the shape parameter of the gamma distribution. These three parameters should be used within the model given by equation (3) to obtain the raindrop size distribution. Both D_m and N_T were computed from the 1-min binned raindrop samples and the μ was determined via minimizing the difference between the observed $N(D)$ and the model given by equation (3) following reference 22. This resulted in 561,616 min of rainfall (i.e., raindrop size distributions) that were used to determine the physical characteristics of different types of rain.

2.3 Definition of Rain Taxonomy Metrics

The primary metric used to define rain for this taxonomy is the liquid water content (LWC) (related to the third moment of the raindrop size distribution) which provides a measure of the mass of liquid water per unit volume of air. Hence, LWC is a metric that can be used for determining signal loss due to rain. It is defined in this taxonomy as

$$\text{LWC} = \frac{\pi\rho_w}{6}\sum_{i=1}^{50} D_i^3 N\left(D_i\right) dD_i , \tag{5}$$

where ρ_w is the density of liquid water (=10^6 g/m^3 at 4 °C) and the summation is performed over n number of diameter bins with width dD (0.2 mm bin sizes were used for the LWC reported in this taxonomy). The units of LWC used in this taxonomy are g/m^3.

The characteristics size of the RSD is given by the mass-weighted mean diameter, D_m, which is defined in this taxonomy as

$$D_m = \frac{\sum_{i=1}^{n} D_i^4 N\left(D_i\right) dD_i}{\sum_{i=1}^{n} D_i^3 N\left(D_i\right) dD_i} . \tag{6}$$

The units of D_m in this taxonomy are mm.

The total drop concentration, N_T, is defined in this taxonomy as

$$N_T = \frac{6}{\pi \rho_w} \frac{\text{LWC}}{D_m^3} \frac{\Gamma(\mu+1)}{\Gamma(\mu+4)} (4+\mu)^3 . \tag{7}$$

The units of N_T in this taxonomy are m^{-3}. This metric is commonly referenced in logarithmic units but must be in linear units when used to compute $N(D)$ in equation (3).

Visibility is another metric that is commonly used in aviation. For purposes of this taxonomy, visibility is based on 550 nm wavelength, which is that seen with the unaided human eye. Hence, visibility represents the visual range of objects seen with a contrast of 5.5% against the background horizon sky.[23] It is defined in this taxonomy as

$$\text{VIS} = \left(\frac{2.9}{3.9}\right) \frac{D_m}{1.04 \text{ LWC}} \tag{8}$$

with units of kilometers given that D_m is mm and LWC is g/m^3. This formulation is based on that given in reference 24 and assumes a Marshall-Palmer type RSD.[16]

3. TAXONOMY OF RAIN

The function of this taxonomy is to provide a comprehensive set of metrics that define physical characteristics of rainfall types observed in nature. Instead of using rain intensity to define the types of rain observed in nature, LWC was used since it provides a more robust measure of the physical rainfall characteristics and readily facilitates computations requiring signal loss through rain. This taxonomy uses similar qualitative descriptors of rainfall like those based on its intensity—light, moderate, and heavy. However, the rainfall categories used for this taxonomy are based on the LWC. These LWC categories are associated with the light, moderate, and heavy rainfall intensities defined in the *Federal Meteorological Handbook on Surface Weather Observations and Reports*,[25] which is the most commonly used definition of rain reported at airports throughout the United States. Table 2 defines these categories in terms of LWC and maps them to the commonly used rainfall intensity definitions. For example, light rainfall is defined in this taxonomy as having an LWC < 0.09 g/m^3 and that corresponds to a rainfall rate less than 2.54 mm/hr. The raindrop diameters reported in table 2 represent the average and standard deviation of D_m within a given category and cannot be used to define the bounds of all raindrop sizes within a given category. Instead, it represents characteristic raindrop sizes in each category. The visibility in table 2 was computed using the corresponding D_m and LWC via equation (8).

Table 2. Definition of rainfall types in this taxonomy with mean and standard deviation raindrop diameter.

Descriptive Rainfall Category	Defining Metric: Liquid Water Content (g/m^{-3})	Rainfall Intensity* (mm/hr)	Visibility (km)	Raindrop Diameter (D_m) ± σ_{D_m} (mm)
Light	LWC < 0.09	R < 2.54	VIS > 9.6	0.9 ± 0.3
Moderate	0.09 ≤ LWC < 0.4	2.54 ≤ R < 7.62	9.6 ≤ VIS < 2.6	1.1 ± 0.4
Heavy	LWC ≥ 0.4	R ≥ 7.62	VIS ≤ 2.6	1.6 ± 0.5

* Rain intensity definitions are based on that given by the *Federal Meteorological Handbook*.[25]

The taxonomy herein categorizes the rain using similar qualitative terms but these categories are based on a statistical analysis of raindrop size distribution measurements and therefore connects the qualitative description of rain to its quantitative-based physical characteristics. To do this, a cluster analysis was performed via the K-means technique[26] on the 1-min RSDs using the three metrics—LWC, D_m, and N_T. A random subset of 9,500 RSDs from each location was used in the cluster analysis to ensure the resultant clusters were not biased towards certain locations/climates that contained a larger sample of rainfall (e.g., Huntsville, AL and S. Korea). Figure 5 shows the resultant three clusters that correspond to the categories in terms of LWC, D_m, and N_T (i.e., a 3D RSD parameter diagram). The light rainfall category (i.e., low LWC) is comprised of small raindrops in relatively small concentrations (i.e., widely dispersed), whereas the heavy rainfall category (i.e., high LWC) contains larger and more numerous raindrops. This trend agrees with the conceptual model of rainfall types; hence, the analysis is sound and the resultant rain taxonomy correctly describes different types of rainfall observed in nature.

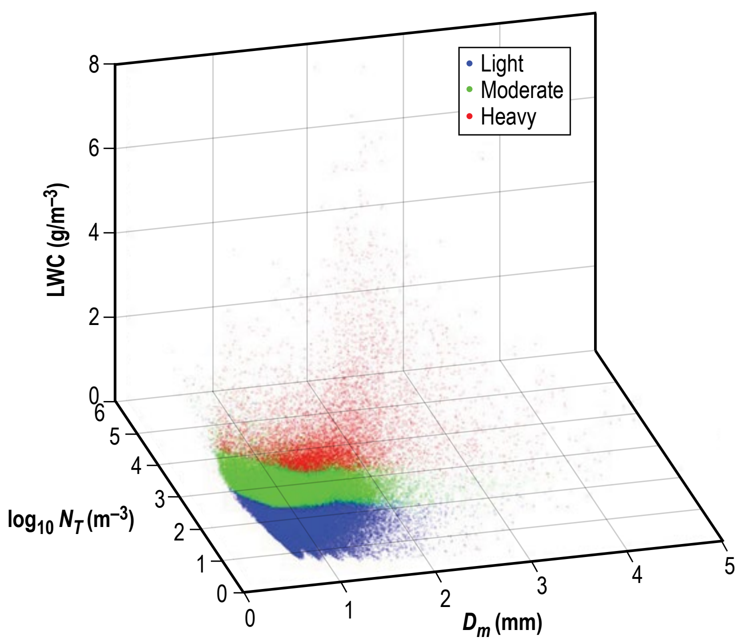

Figure 5. A 3D representation of the rain taxonomy that shows three categories of rain exhibiting different physical rainfall characteristics. This plot is in terms of the DVE rain taxonomy metrics (sec. 2.3).

A statistical summary of the rain taxonomy RSD metrics for light, moderate, and heavy rain is shown in figure 6. These distributions represent metrics describing the parameters of the raindrop size distribution model (see sec. 2.2) used to define the three categories within this rain taxonomy. The characteristic diameter shown in figure 6(a) (i.e., D_m) indicates two distinct populations—one characterized by mostly small raindrops associated with light to moderate rain and one characterized by larger drops that occur with heavy rain. As for the total raindrop concentration metric, N_T, it can span several orders of magnitude; hence, it is commonly referenced in logarithmic units. Figure 6(b) shows three distinct populations exist for N_T—one consisting of mostly

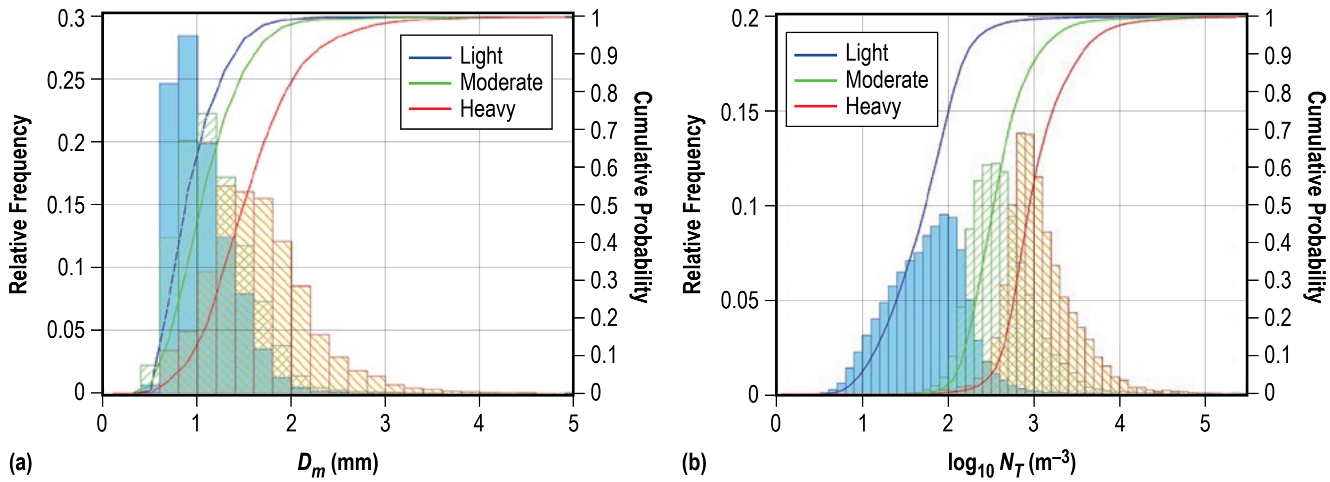

Figure 6. Distributions of RSD metrics that define the rain taxonomy for the three categories of rain: (a) Plot of D_m, which is the RSD metric that represents characteristic raindrop diameter and (b) plot of N_T, which is the RSD metric of the total raindrop concentration.

low concentrations of raindrops found with light rain, another population consisting of much higher concentrations of raindrops found with moderate rain, and one population with a very high concentration of raindrops that occurs with heavy rainfall.

Tables 3–5 contain the three RSD model parameters required to compute the raindrop size distribution given by equation (3) for light, moderate, and heavy rainfall. The tables provide a statistical desciption of LWC and representative D_m, N_T, and μ for each rain type within the taxonomy. Additional descriptive statistics for these parameters, such as mean and standard deviation for each rain type and statistics for each climate type, are contained within the companion weather taxonomy database. Some uses of the information contained within tables 3–5 can be used to perform electromagnetic propagation simulations or assess performance of sensors or rainfall simulations relative to this rain taxonomy.

Table 3. Statistical description of the raindrop size distribution model parameters for light rain defined by LWC < 0.09 g/m^3.

LWC Statistic	D_m (mm)	N_T (m^{-3})	μ
5th Percentile	0.84	26	12.6
10th Percentile	0.85	27	12.4
25th Percentile	0.86	31	12
50th Percentile	0.93	57	10.1
75th Percentile	1.03	106	7.4
90th Percentile	1.26	110	4.8
95th Percentile	1.42	111	3.8

Table 4. Statistical description of the raindrop size distribution model parameters for moderate rain defined by $0.09 \leq LWC < 0.4$ g/m^3.

LWC Statistic	D_m (mm)	N_T (m^{-3})	μ
5th Percentile	0.83	281	10.3
10th Percentile	0.9	280	8.9
25th Percentile	1.03	305	6.5
50th Percentile	1.24	328	4.3
75th Percentile	1.29	473	3.9
90th Percentile	1.32	617	3.8
95th Percentile	1.35	618	3.6

Table 5. Statistical description of the raindrop size distribution model parameters for light rain defined by $LWC \geq 0.04$ g/m^3.

LWC Statistic	D_m (mm)	N_T (m^{-3})	μ
5th Percentile	1.19	933	5.1
10th Percentile	1.35	827	4
25th Percentile	1.45	764	3.4
50th Percentile	1.56	869	3.6
75th Percentile	1.7	1,081	3.2
90th Percentile	1.99	1,550	1.8
95th Percentile	2.09	1,991	1.4

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14. ABSTRACT
This Technical Memorandum (TM) provides a description of a rainfall taxonomy that defines the detailed characteristics of naturally occurring rainfall. The taxonomy is based on raindrop size measurements collected around the globe and encompasses several different climate types. Included in this TM is a description of these rainfall observations, an explanation of methods used to process those data, and resultant metrics comprising the rain taxonomy database. Each of the categories in the rain taxonomy are characterized by a unique set of raindrop sizes that can be used in simulations of electromagnetic wave propagation through a rain medium.

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