MetStorm
powered by DTN

Precision Storm Precipitation Analytics

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Introduction

A systematic means of providing an accurate, detailed analysis of precipitation associated with a recently occurring storm has historically been difficult to attain given the lack of reliable data. However, real-time precipitation gauge data and radar-estimated precipitation data make near real-time, systematic storm analyses possible. MetStorm integrates quality-controlled precipitation gauge data, dual-polarimetric (dual-pol) radar-estimated precipitation data, satellite-estimated precipitation data and innovative algorithms for computing precipitation analytics. Storm analyses of this nature support media inquiries, hydrologic modeling calibration and validation, flood responses, forensic cases, insurance claims, emergency management, situational awareness, and help build a storm database for use in engineering design applications.

MetStorm is a new Geographic Information System (GIS) based analysis system that produces gridded precipitation at 5-minute and/or 1-hour intervals over a specified domain (Laro, 2015; Parzybok, 2015). The relative spatial precipitation patterns are largely governed by DTN tropical weather video graphic images quantitative precipitation estimates (QPE). The POLARIS QPE is a mosaic of dual-pol radar-estimated precipitation at a spatial resolution of 250 m^2.

Meanwhile, the precipitation magnitudes of MetStorm grids are influenced by quality-controlled rain gauge data from the NWS Cooperative Observer Network (COOP) sites as well as from our strategic partner, Synoptic Data Corp. MetStorm has the ability to integrate hourly, daily, and irregularly measured precipitation data, thereby providing a high degree of gauge density for "ground truthing." Satellite data, though at a coarser spatial resolution, influences areas void of rain gauge and/or radar data. Innovative algorithms blend the precipitation estimates from the different sources into a seamless GIS grid, which provides the basis for summary statistics, maps, tables, and plots.

MetStorm was developed and is operated exclusively by DTN. The term gauge, station and site are used interchangeably in this document.

MetStorm input

MetStorm uses up to seven (7) key inputs to compute gridded precipitation across the analysis domain. Depending on data availability, MetStorm intelligently integrates the data listed in Figure 1 and described in subsequent sections.

Gauge-only

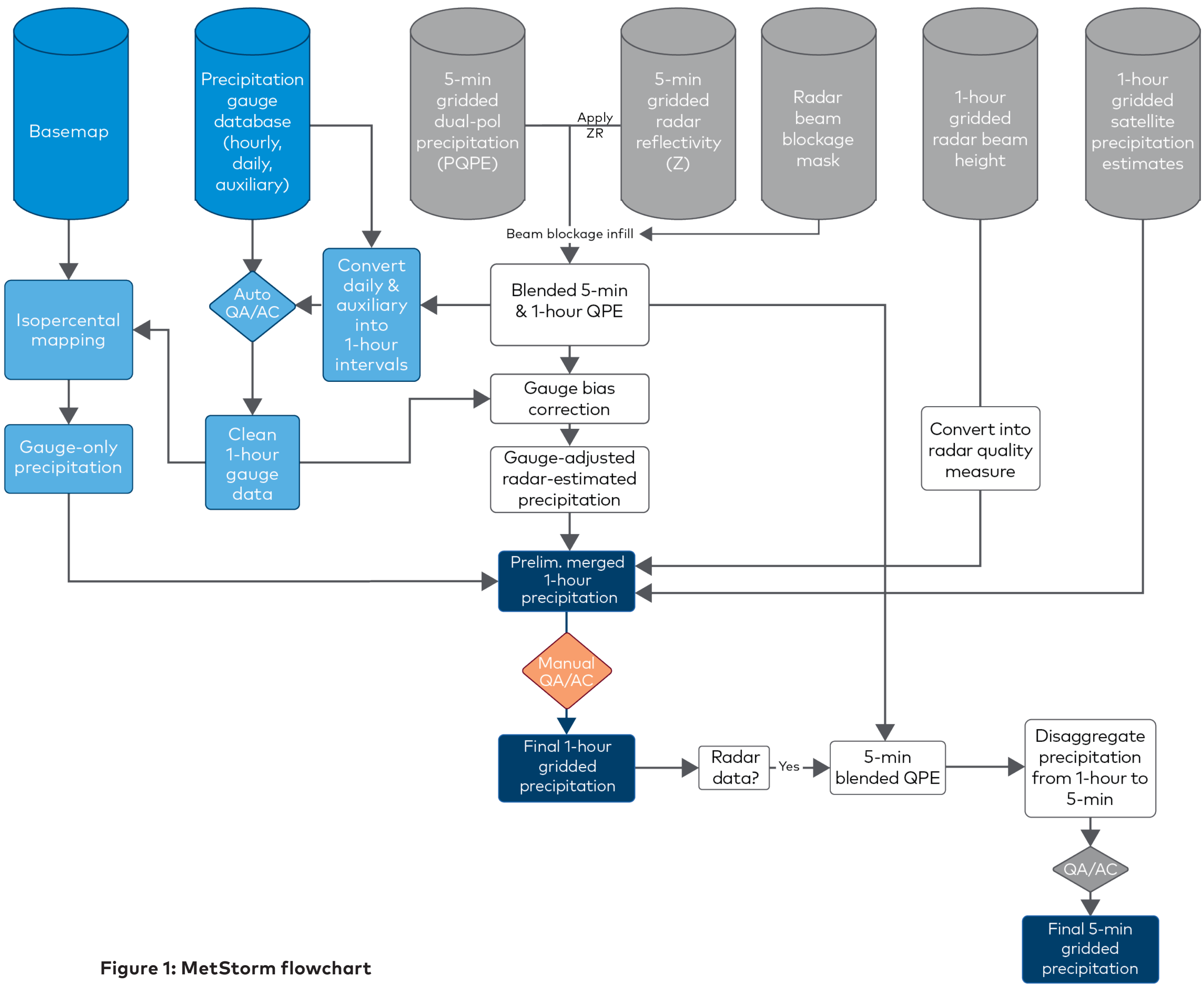

Figure 1: MetStorm flowchart

Precipitation gauge data

Measured precipitation from daily and hourly precipitation gauges are required input (Figure 2). MetStorm has the ability to utilize hourly, daily, and irregularly reported precipitation data, thereby providing a gauge density as comprehensive as possible for "ground truthing." For historical storms, gauge data is easily added manually, however, MetStorm automatically accesses quality-controlled rain gauge data for newer (post-1997) storms from our strategic partner, Synoptic Data Corp, who aggregates, quality controls and archives hourly precipitation gauge data from over 200 networks across North America. Synoptic's 1-hour precipitation data amounts to over 26,000 gauges, which are quality-checked using a multi-sensor quality assurance system designed and maintained by DTN. MetStorm also accesses data from the DTN in-house database, which is largely based on the Global Historical Climatological Network (GHCN). Spatially-based algorithms, which leverage nearby hourly gauges and radar data, convert the daily precipitation amounts into estimated hourly precipitation for use in the MetStorm precipitation analysis system.

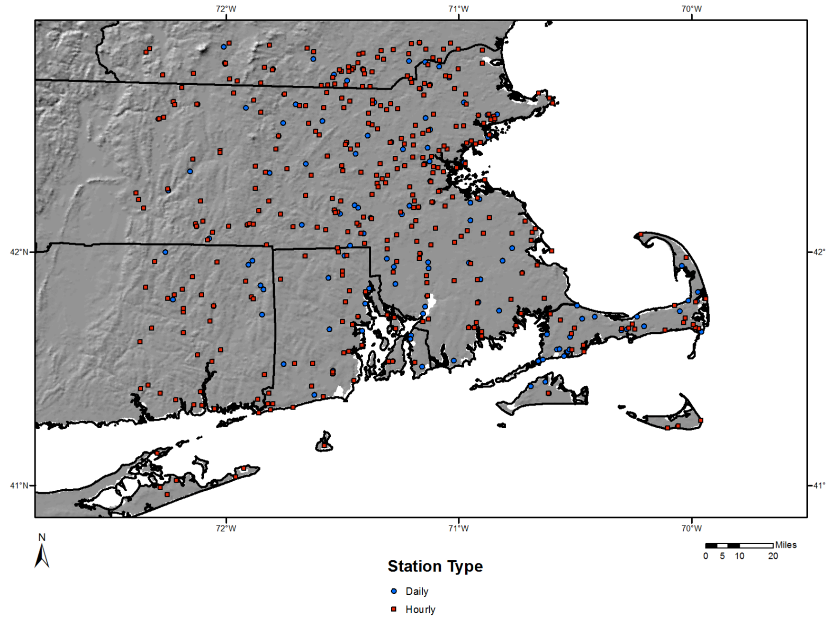

Figure 2: Sample precipitation station map for 04/01/2017 Massachusetts storm

Basemaps

Basemaps are independent grids of spatially distributed weather or climate variables that are used to govern the spatial patterns of the hourly precipitation, particularly in areas where radar is either not available or of poor quality (Figure 3). The basemap provides a stable and spatially consistent reflection of how the precipitation may fall over a region. For MetStorm analyses over complex terrain, climatological basemaps, such as PRISM mean monthly precipitation or NWS precipitation frequency grids, are often used given they resolve inherent orographic enhancement and micro-climates. Climatological basemaps in flat terrain, however, are not as effective given the weak precipitation gradients; therefore, in these cases, basemaps are often developed from pre-existing (hand-drawn) isohyetal patterns, independently-created radar-estimated storm totals, the summation of PRISM daily precipitation grids or the individual monthly (e.g., March 2013) PRISM precipitation grids available online.

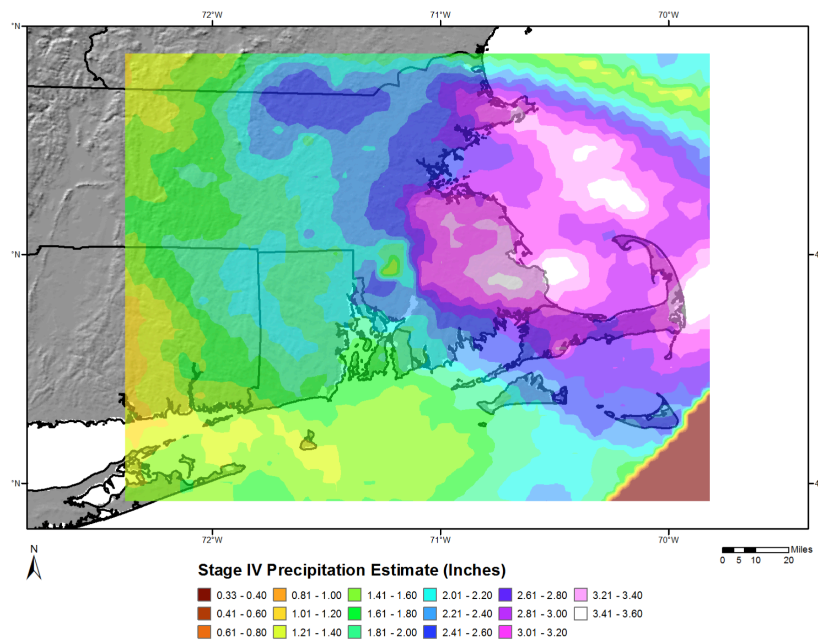

Figure 3: Sample basemap (Stage IV/Mulit-Sensor Precipitation) for 04/01/2017 Massachusetts storm

Basemap options include, but are not limited to:

- Precipitation frequency grid (e.g. NOAA Atlas 14)
- Stage IV/MPE
- PQPE sum (after initial run)
- Total storm radar reflectivity (after initial run)
- MetStormLIVE grids
- Mean annual maximum precipitation
- PRISM daily storm summation (1981-present)
- PRISM monthly precipitation (1895-present)
- PRISM mean monthly precipitation (e.g. 1971-2000, 1981-2010)
- PRISM mean annual precipitation (e.g. 1971-2000, 1981-2010)
- Digitized pre-existing isohyetal patterns
- Client-provided reanalysis data

Gridded dual-pol precipitation

MetStorm uses Quantitative Precipitation Estimates (QPE) from state-of-the-science dual-pol precipitation estimates from the DTN Polarimetric Radar Identification System (POLARIS) (Porter, et. al, 2012) (Figure 4). The POLARIS QPE grids are a mosaic of dual-pol estimated precipitation from all 143 U.S. and 30 Canadian Next Generation (NEXRAD) radar sites. Depending on the precipitation type (e.g. wet snow, light rain, heavy rain, etc.) determined by the dual-pol radar data, an optimized radar-to-precipitation rate algorithm is utilized to compute precipitation at 5-minute intervals and at a spatial resolution of 250 m^2.

Radar reflectivity

Level-II radar reflectivity is the native data provided by NEXRAD weather radars across the United States. MetStorm translates this into a rainfall rate using a standard Z-R algorithm (Figure 5). The Z-R (radar reflectivity, Z, and rainfall, R) relationship allows estimation of precipitation from reflectivity. Most current radar-derived precipitation techniques rely on a constant relationship between radar reflectivity and precipitation rate for a given storm type (e.g. tropical, convective), vertical structure of reflectivity and/or reflectivity magnitudes. This nonlinear relationship is described by Equation 1.

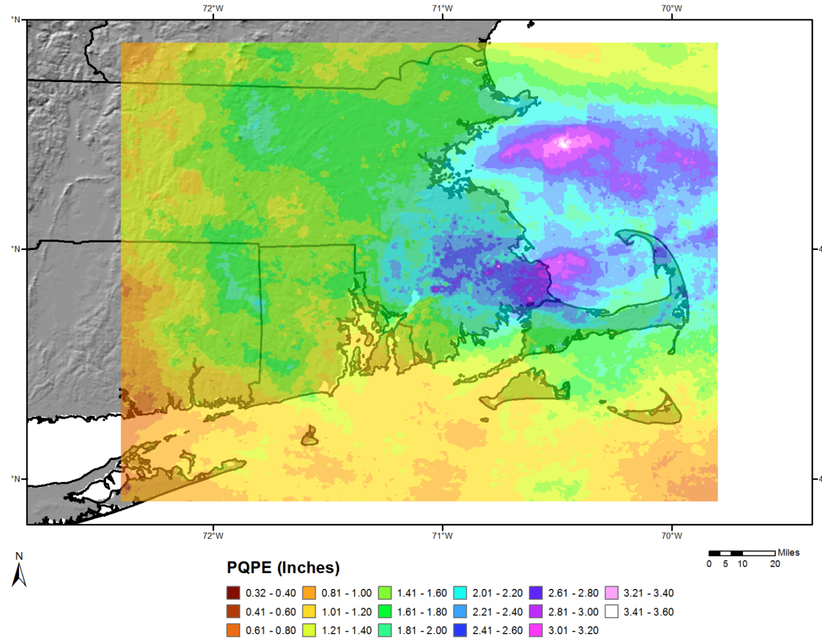

Figure 4: Sample POLARIS QPE for 04/01/2017 Massachusetts storm

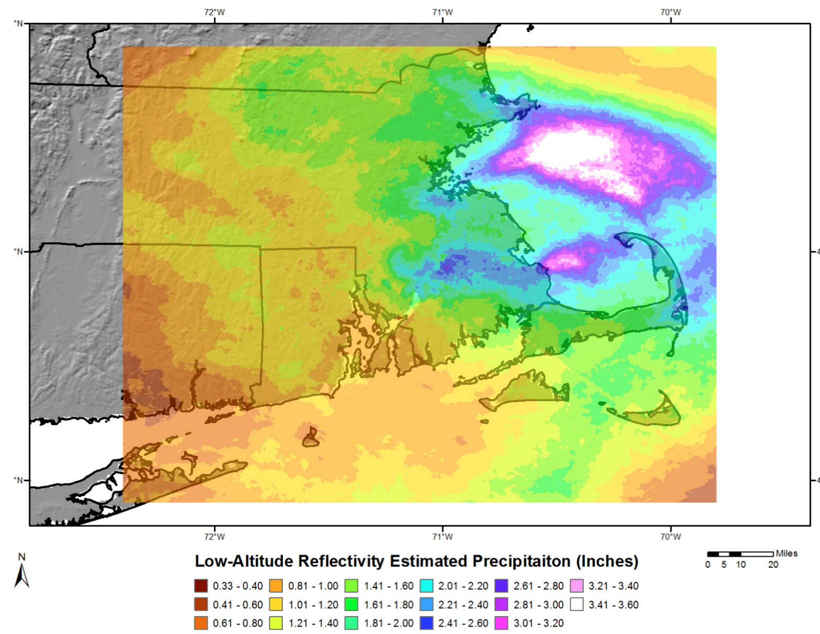

Figure 5: Sample QPE derived from traditional radar reflectivity for 04/01/2017 Massachusetts storm

$$Z = A * R^b$$

Equation 1. Z-R Relationship, where Z is the radar reflectivity (measured in units of dBZ), A is the multiplicative coefficient, R is the rainfall rate (in mm per hour), and b is the power coefficient.

Both A and b are directly related to the raindrop size distribution (DSD) and rain drop number distribution (DND) within a cloud (Martner and Dubovskiy 2005). The variability in the results of Z versus R is a direct result of differing DSD, DND and air mass characteristics (Dickens 2003). The NWS utilizes different default Z-R algorithms, depending on the precipitation-causing event, to estimate precipitation through the use of NEXRAD radar reflectivity data across the United States. (Baeck and Smith 1998). A default Z-R relationship of Z = 300R1.4 is the primary algorithm used throughout the continental U.S. by the NWS and MetStorm, but can be set to user-defined coefficients in MetStorm. Although it is widely known that purely based Z-R QPE can suffer from deficiencies that may lead to significant over or underestimation of precipitation, MetStorm uses the Z-R QPE to inform a dynamic basemap and not the Final QPE (FQPE) directly.

Beam blockage mask

Particularly in complex terrain, radar coverage is often compromised, causing areas to have poor or no radar coverage. In order to overcome this, the MetStorm Analyst will manually define areas with poor radar coverage based on a summation of radar reflectivity grids during the storms. A summation of radar grids tends to amplify the impact of terrain blockages, thereby making it clear where radar coverage is poor. The radar blocked areas are used as a mask in MetStorm (Figure 6) and infilled from neighboring, valid radar pixels. In most cases this resolves the problem, but in severe cases the blockages are so large that the infilling is not sufficient; in these situations, MetStorm instead relies on the isopercental interpolation estimates to produce a seamless transition from areas without radar to areas with adequate radar coverage.

Radar confidence

In order to quantify the quality of the radar data (both POLARIS and reflectivity) across the analysis domain, MetStorm uses the lowest altitude (above mean ground level) of the radar beam. Generally speaking, a radar beam sampling precipitation closest to the ground is more reliable. Therefore, a function between a radar weight (ranging from 0 to 1) and radar beam height is imposed to create a radar-weight grid (Figure 7); this provides MetStorm with

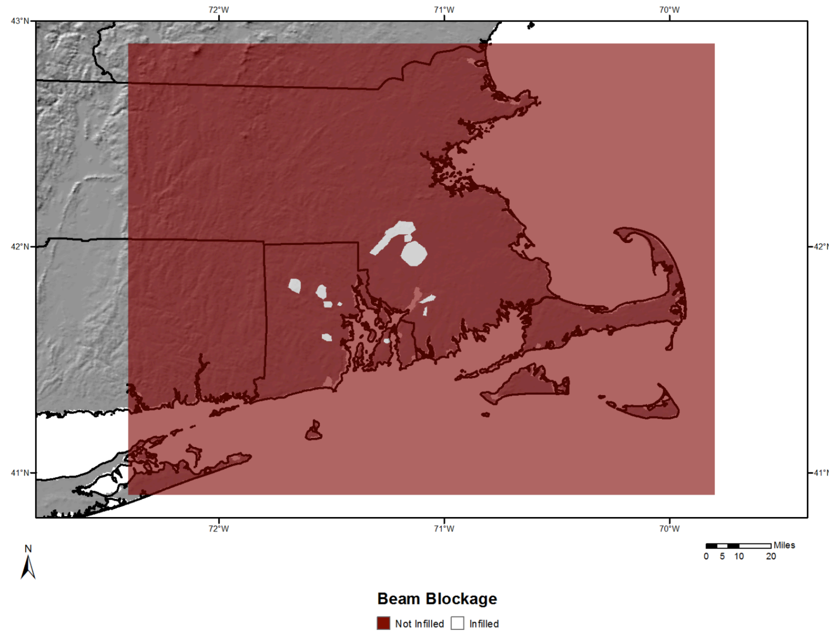

Figure 6: Sample radar beam blockage mask for area around 04/01/2017 Massachusetts storm

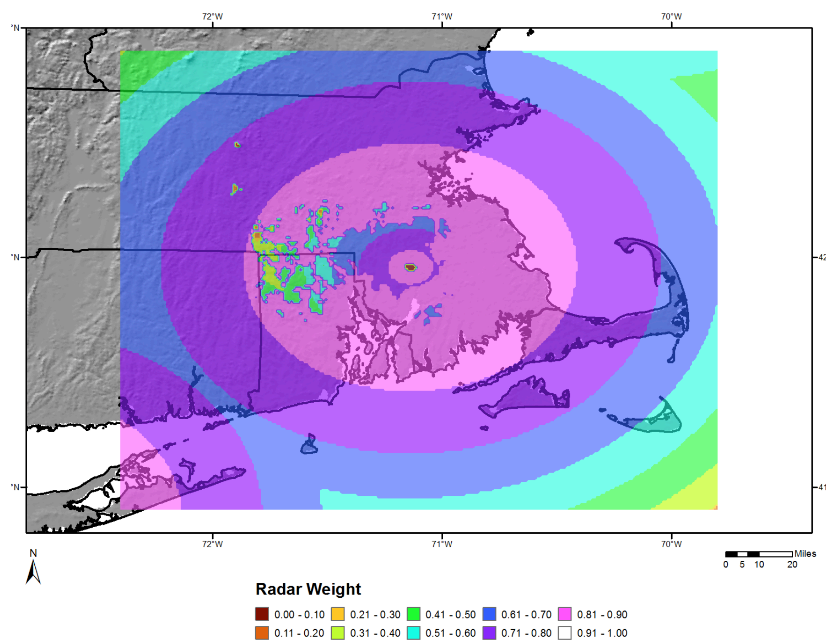

Figure 7: Sample radar weight for 04/01/2017 Massachusetts storm.

an objective means for determining where gauge-adjusted radar-estimated precipitation can be relied upon more than a purely basemap-driven interpolation of precipitation.

Satellite precipitation

Satellite-based estimates of rainfall have been used since the late 1970s, especially in areas where rain gauge or radar data are unreliable or unavailable. Similarly, MetStorm uses satellite-estimated precipitation data (Figure 8), though coarse spatial resolution (4 km2), to influence areas void of rain gauge and/or radar data. MetStorm ingests 1-hour satellite rainfall estimates known as "Hydro-Estimator" from NOAA's Center for Satellite Applications and Research (STAR). The Hydro-Estimator uses infrared (IR) satellite data from NOAA's Geostationary Operational Environmental Satellites (GOES) to estimate rainfall rates. The estimated rainfall rates are most accurate during the warm season in areas of deep convection (thunderstorms). The magnitudes of satellite rainfall are used for aiding the spatial interpolation of gauge data in MetStorm.

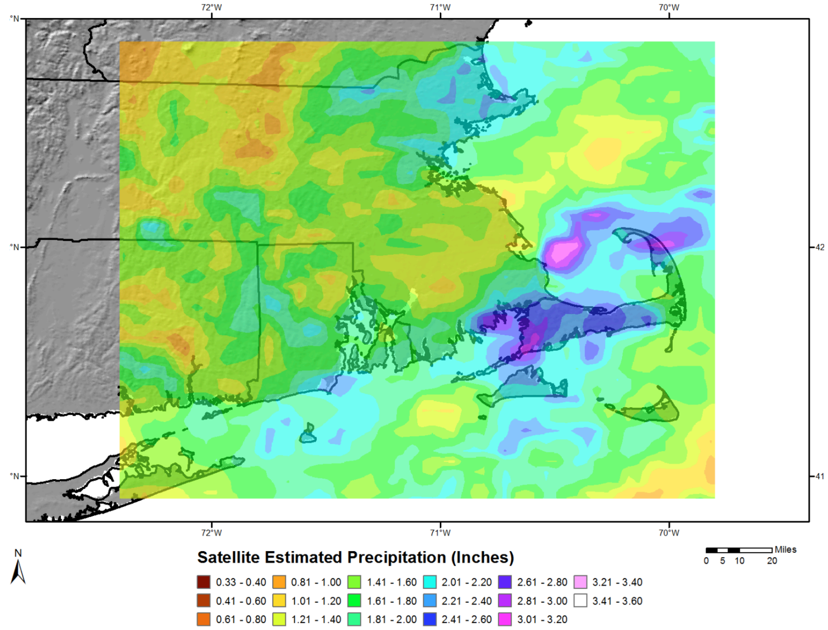

Figure 8: Sample satellite-estimated QPE for 04/01/2017 Massachusetts storm

Methods

MetStorm is designed to operate with a wide range of input data which makes it a flexible tool for producing gridded precipitation associated with very old storms (pre-1900) as well as storms that just occurred. To instill consistency among previous storm analyses conducted by others, MetStorm's logic is built on similar techniques used in the past by the U.S. Army Corps of Engineers (USACE) and others, but includes numerous improvements (see Section titled: MetStorm versus Storm Precipitation Analysis System). MetStorm intelligently integrates all available data for creating quality GIS grids of Quantitative Precipitation Estimates (QPE). At a the minimum, MetStorm requires one hourly station and a basemap to produce a series of QPE grids. However, if available, additional gauge data (of various types; see below), dual-pol radar-estimated precipitation data, traditional radar reflectivity and/or satellite data can be used to create seamless grids of QPE across varied terrain.

The nominal temporal resolution of MetStorm is 1-hour given precipitation is standardly reported in 1-hour precipitation increments. However, if radar data is available, further disaggregation down to 5-minute intervals (snapped to even 5-minute intervals, e.g. :05, :10, :15, etc.) is possible by imposing the temporal distribution of precipitation derived from radar precipitation estimates together with MetStorm's final 1-hour QPE.

Storm analysis setup and data mining

Prior to launching MetStorm, a storm domain and time period is established to ensure an adequate buffer around the storm center and timing to capture all available precipitation data. Data mining is also among the first steps of a storm analysis. Initially, MetStorm automatically extracts and reformats hourly and daily gauge data from the DTN internal database of precipitation data. This database includes records from many sources, including NCEI (formerly NCDC), GHCN, USGS, and hourly data from our real-time precipitation gauge quality control network, which is archived and made available for post-storm analyses. Our comprehensive precipitation database provides a fast and effective means for incorporating precipitation data. Otherwise, manual data mining and hand-entry of precipitation reports is a significant task for older MetStorm runs.

Although the data in DTN internal database provides much of the gauge data used, additional manual data mining is performed. Data that are acquired include auxiliary reports of the storm that may not fall into the standard reporting times. These data are found through NCEI publications, National Atmospheric Deposition Program, Clean Air Status and Trends Network, Soil Climate Analysis Network, and USGS websites. Other data, such as bucket surveys, found when researching the storm are also added.

Spatial precipitation data may also be discovered when data mining. This can range from gridded data to a scanned copy of an isohyetal map. Given the spatial data represent the entire storm period, it can be combined with a climatological basemap and be used as the storm's basemap, or in can be used in place of the climatological basemap typically used in MetStorm. In the case of isohyetal maps, the storm analyst digitizes the contours, then uses interpolation methods to create a spatially continuous map. Incorporating this spatial element in the analysis contributes greatly to the overall spatial pattern output from MetStorm.

The MetStorm system utilizes parameter files to allow the analyst to specify which options to run in MetStorm. As of the date of this publication, there are 50 parameters available. Some of these parameters include: the date and location of the storm, the data available to the storm, and various thresholds to aid in the auto quality control of the storm. Once all parameters are selected, MetStorm is launched.

MetStorm gauge types

One of the many features of MetStorm is its ability to integrate a variety of different types of precipitation gauge data. Below is a table representing the different gauge types.

Guage Type	Abbreviation	Description
Hourly	H	Hourly precipitation data
Hourly timer	HT	Hourly precipitation data used purely for timing; a nearby or co-located daily or auxiliary gauge is used to govern the magnitude
Hourly estimated	HE	Hourly station used as a true hourly, but its values are estimated based on ancillary information (e.g. weather maps, nearby hourly stations, information from daily observation forms, etc.)
Daily	D	Regularly reporting daily precipitation gauge
Auxiliary	A	Irregularly reporting precipitation gauge. Oftentimes these gauges only represent a total storm amount

Disaggregation of daily and auxiliary precipitation into hourly format

In order to obtain one hour temporal resolutions and utilize all gauge data in the creation of hourly QPE grids, it is necessary to disaggregate the daily and auxiliary precipitation observations into estimated hourly amounts. If radar data is available, its temporal distribution is used to disaggregate the daily/auxiliary precipitation into hourly estimates. However, if radar is unavailable or if coverage over a daily/auxiliary gauge is inadequate for timing, the following approach is used for that single gauge.

Disaggregation without radar data

For analyses without radar data, this process has traditionally been accomplished by distributing (temporally) the precipitation at each daily/auxiliary gauge in accordance to a single nearby hourly gauge (Thiessen polygon approach). However, this may introduce biases and not correctly represent hourly precipitation at daily/auxiliary gauges situated in-between hourly gauges. Instead, MetStorm uses a spatial approach by which the estimated hourly precipitation at each daily and auxiliary gauge is governed by a distance weighted algorithm of timing from all nearby true hourly gauges.

In order to disaggregate (i.e. distribute) daily/auxiliary gauge data into estimate hourly values, the true hourly gauge data is first evaluated and quality controlled using synoptic maps, nearby gauges, orographic effects, guage history and other documentation on the storm. Any problems with the hourly data are resolved, and when possible/necessary accumulated hourly values are distributed. If an hourly value is missing, the storm analyst can choose to either estimate it or leave it missing for MetStorm to estimate later based on other nearby hourly gauges. Hourly timer gauges can be added to represent precipitation timing in topographically complex locations, areas with limited/no hourly data or to capture localized convention. An hourly timer gauge is created by distributing the precipitation at a co-located daily gauge or by creating a completely new hourly timer gauge from other information such as inferences from COOP observation forms, METAR visibility data (if hourly precipitation isn't already available), lightning data, satellite data, or radar data. True hourly gauges can also be converted into hourly timer data, if the storm analyst determines the magnitude to be suspect, but timing to be trustworthy. Hourly timers are flagged so MetStorm only uses it for timing and not magnitude. Care is taken to ensure hourly timer gauges represent justifiably important physical and meteorological characteristics before being incorporated into the analysis. Although timer gauges provide a very important role, their use is kept to a minimum.

Using the hourly MetStorm precipitation gauges, each hourly precipitation value is converted into a percentage that represents the incremental hourly precipitation divided by the total storm precipitation of that gauge. An inverse-distance-weighting (IDW) interpolation technique is used to create hourly grids of these percents of total storm precipitation. Since the percentages typically have a high degree of spatial autocorrelation, the spatial interpolation has skill in determining the percentages between gauges, especially since the percentages are somewhat independent of the precipitation magnitude.

After the hourly percentage grids are generated and QC'ed, MetStorm converts the daily/auxiliary gauge data into incremental hourly data. The timing at each of the daily/auxiliary gauges is based on (1) the daily/auxiliary gauge observation time, (2) daily/auxiliary precipitation amount and (3) the series of interpolated hourly percentages extracted from grids.

For example, an auxiliary gauge reported 1.40" of precipitation during the storm event and is located equal distance from the three surrounding hourly recording gauges. The procedure steps are:

1. For each hour, extract the percent of total precipitation from the hourly gauge-based percentage grid at the location of the daily/supplemental gauge. In this example, assume these values are the average of all the surrounding hourly gauges.
2. Multiply the hourly percentages by the total storm precipitation at the daily/auxiliary gauge to arrive at estimated hourly precipitation at the daily/auxiliary gauge.

To ensure the daily/auxiliary accumulated precipitation is equal the daily/auxiliary observations, it is sometimes necessary to adjust the hourly percentages so they equate 100% and account for 100% of the daily observed precipitation.

This disaggregation methodology is carried out in every MetStorm analysis, regardless of radar availability. This provides reliable disaggregation at stations suffering from complete and/or poor radar coverage when operating MetStorm with radar.

Disaggregation with radar storms

When radar data is available, the disaggregation (i.e. distribution) of daily/auxiliary gauge data into estimate hourly values uses the temporal patterns of radar data. Each hourly radar-estimated precipitation value is then converted into a percentage that represents the incremental hourly precipitation divided by the radar-estimated total storm precipitation at each daily/auxiliary station. Each incremental hourly precipitation estimate is computed by multiplying the percentage by the total observed precipitation. The timing at each of the daily/auxiliary gauges is based on (1) the daily/auxiliary gauge observation time, (2) daily/auxiliary precipitation amount and (3) the hourly percentages computed from the radar-estimated precipitation grids.

Hourly precipitation grids

The observed hourly and disaggregated daily/auxiliary hourly precipitation data are spatially interpolated into hourly precipitation grids by intelligently integrating all available input data. Figure 9 shows an example of the FQPE total storm map, or a summation of all hourly FQPE grids.

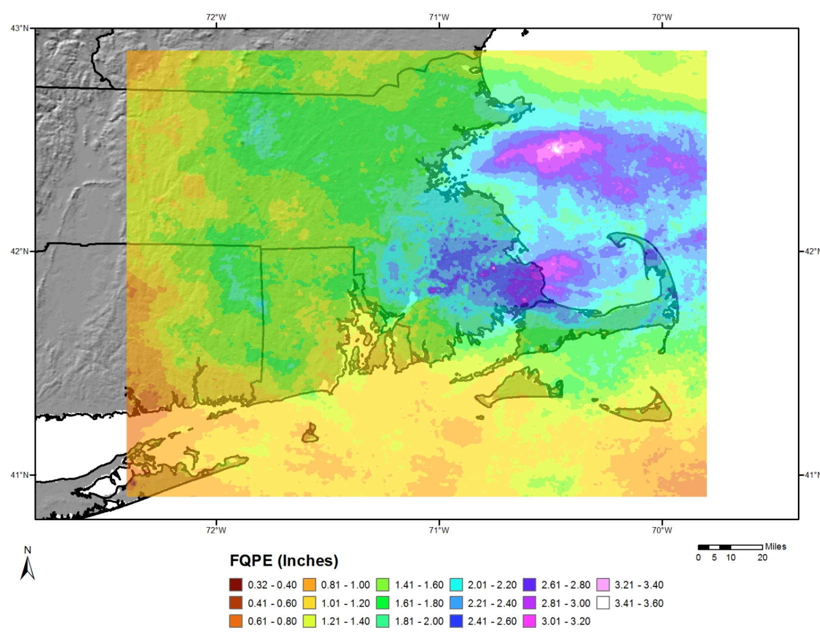

Figure 9: Sample Final QPE (FQPE) for 04/01/2017 Massachusetts storm

Isopercental approach

For storms without radar data, an isopercental approach, a variation of the climatologically-aided interpolation approach, is used to interpolate precipitation between gauged locations (Hunter 2005). As noted before, the spatial patterns of the basemap govern the interpolation between points of hourly precipitation estimates, while the actual precipitation observations govern the magnitude. This approach to interpolating point data across complex terrain is widely used and was extensively used by the NWS during their storm analysis era from the 1940s through the 1970s.

The pooled hourly precipitation gauge data are first normalized by the corresponding grid cell value of the basemap; this value is known as an isopercental. The normalization allows information and knowledge from the basemap to be transferred to the spatial distribution of the hourly precipitation. Using an IDW algorithm, the isopercentals are spatially interpolated to a grid. The resulting grid is then multiplied by the basemap grid to back out a FQPE precipitation field, where the observed precipitation magnitudes at gauge locations are maintained. This is repeated each hour of the storm and results in a complete set of FQPE precipitation grids.

Radar-based approach

The coupling of MetStorm with radar data, both dual-pol estimates and traditional radar-estimated precipitation, provides the most accurate method of spatially and temporally distributing precipitation. The spatial variability in gauge versus radar biases is accounted for through a local bias correction each hour. The radar approach involves several steps, each briefly described below. Even if radar data is available, the isopercental approach (described above) is carried out by MetStorm to address areas with poor or no radar data.

During 2011-2013 the National Weather Service deployed Dual Polarization (a.k.a. dual-pol) at all WSR-88D NEXRAD radar sites across the United States. The standard WSR-88D Doppler radar transmits and receives information horizontally, while the dual-pol transmits and receives information both horizontally and vertically which allows the radar to determine approximate sizes and shapes of objects in the atmosphere, thereby providing better estimates of radar-estimated precipitation amounts.

MetStorm utilizes dual-pol radar-estimated precipitation grids from Weather Decision Technologies' Polarimetric Radar Identification System (POLARIS) and/or quantitative precipitation estimates (QPE) from the traditional (single polarization) NEXRAD radars. The POLARIS QPE is a mosaic of dual-pol radar-estimated precipitation at a spatial resolution of 250 m^2; traditional radar data is limited to a 1 km^2 resolution.

Calculation of the 1-hour FQPE, for a given grid cell, is determined by first computing isopercentals at all gauges. The isopercental is defined as the hourly precipitation amount divided by a dynamic basemap gridcell value. The dynamic basemap is a unique basemap, created each hour, based on radar, satellite and the traditional basemap. The isopercentals are converted into a grid and then mapped back into a precipitation field, all while maintaining the observed precipitation magnitudes at gauged locations. Using radar precipitation estimates, isopercental precipitation estimates, and radar confidence, a FQPE value is computed at each gridcell. Repeating this process at each gridcell results in a seamless FQPE grid across the storm analysis domain, regardless of radar quality/confidence.

Subsequent to the creation of hourly FQPE grids, MetStorm calculates 5-minute FQPE grids. Taking available radar data, 5-minute percentages of radar estimated hourly precipitation for each gridcell is computed and then applied to the hourly FQPE grid. This processes is repeated each hour to produce 5-minute FQPE grids for the entire analysis period.

Quality control

Quality control is an on-going and critical element of a storm precipitation analysis to ensure the highest data quality and integrity. Given the plethora of data available in each storm analysis, manual inspection is required to parse through data errors such as: incorrect observation times, previously undetected accumulation periods, beam blockage issues, radar anomalies, co-located gauges with different storm total amounts, undercatch of precipitation from gauges, etc. Storm analysts also contribute to the data mining process by digitizing basemaps used in previous reports to ensure the spatial pattern matches what has been previously determined, as well as incorporating (and perhaps also digitizing) gauge data which was not included in any of the common sources readily available (see Storm Analysis Setup and Data Mining in the Methods section above). The manual quality control procedure ensures spatial and temporal patterns are both realistic and based off the best available product.

Each storm requires an analyst to complete a checklist of various QC steps, which include but are not limited to:

- Resolving any errors identified by MetStorm
    - Errors typically consist of incorrect data entry
- Verifying high hourly precipitation values
    - Based on threshold set in parameter file
    - This step resolves any accumulations found in hourly data
- Rectifying large discrepancies in radar precipitation estimates and hourly gauge precipitation estimates
- Quality controlling radar by verifying there are no beam blockages, and if there are creating a beam block mask to fill in those blockages
- Hourly quality control
    - Spatial check of precipitation pattern to identify erroneous data in each hourly time step
- Total storm quality control
    - Spatial check of precipitation pattern to identify erroneous data in the total storm grid
- Verify large differences in the station precipitation estimate and FQPE point precipitation estimate
    - This checks that any missing data were infilled properly

Before FQPE is considered final, precipitation checks are conducted to ensure the spatial patterns and magnitudes of the maximum storm intensities are consistent with any storm reports. Any erroneous data are corrected and MetStorm is re-run. Considering all of the QA/QC checks in MetStorm, it typically requires 10-20 MetStorm runs to arrive at the the final output.

Output from MetStorm has been compared with existing depth-area-duration results generated from other methods. Metstat and MGS (2018c) provided documentation that explored potential sources of differences between depth-area-duration (DAD) results computed using different methods for a project along the Trinity River in Texas for the U.S. Army Corps of Engineers. Final DAD tables and curves are influenced by methods applied in the calculation of area and estimation of precipitation depth: (i) the selection of the DAD zone; (ii) the interpolation scheme applied; (iii) use of gridded versus point data (i.e., Thiessen) approaches. Each of these potential sensitivities were evaluated through the use of a case study (Thrall, TX, September 1921) demonstrating the value of the MetStorm approach.

Our preferred method of evaluating the performance of a MetStorm analysis is through the use of jackknife error statistics. The jackknife cross-validation technique is used to evaluate the spatial interpolation technique's performance for deriving and interpolating total storm precipitation values. This method of validation resamples the data to see how the results vary with and without a specific station included in the analysis. The cross-validation results reflect the accuracy of the derivation and interpolation procedure. For each storm analysis in a study, every station is subjected to the jackknife cross validation test. The jackknife output is summarized into a mean bias and mean absolute percentage error (MAPE). The bias represents the average difference in the total storm value between the analysis (MetStorm) and the observed data; a positive bias suggests the analysis is estimating higher than the observed value of precipitation and a negative bias means the analysis is estimating lower than the observed data. Mean absolute percentage error (MAPE) is a common measure of an analysis's predictability, in this case how well MetStorm predicted the total storm precipitation at each station location (as a percentage of the observed value) in the station's absence. MAPE functions best when there are no extremes in the data, otherwise small values amplify the percentages and distort the MAPE.

As a final check when radar data and 5-minute gauge data are available, a validation can be conducted at 1-3 stations where the observed/measured precipitation is compared to the corresponding MetStorm grid cell at a 5-minute time step. By nature of the MetStorm logic, the hourly gridded precipitation equals that of the measurements, provided all of the hourly measurements were accepted and the entire storm period was captured by the measurements. For all stations, regardless of whether radar data was used, the consistency between MetStorm and the measured amounts are conveyed through a scatter plot; a perfect match is associated with a one-to-one line. Any deviations from the one-to-one line are the result of missing data, poor quality data or a combination of the two at the stations.

Deliverables

MetStorm's gridded FQPE is the basis for a variety of precipitation analytics. The complete list of potential deliverables include the following, which are described in more detail in the subsequent subsections:

- High-resolution gridded QPE
- Average Recurrence Interval (ARI) maps/grids
- Depth-Area-Duration (DAD) plots/tables
- Complete gauge data catalog
- Validation plots
- Error statistics
- Mass curve tables/plots for any location at 5-minute or 1-hour intervals
- Storm report, including the above elements plus a total storm map (Figure 10), a brief meteorological discussion and the analyst's assessment of the storm analysis reliability.

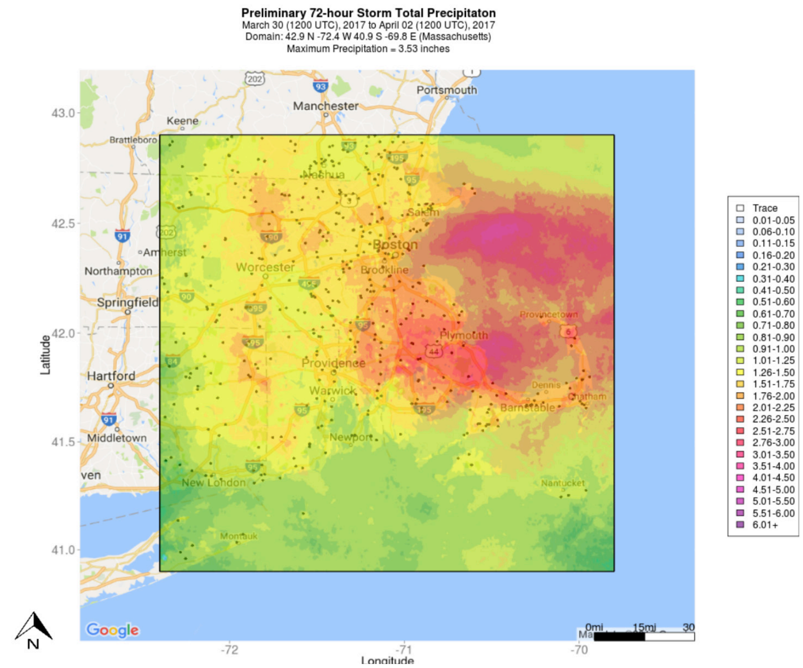

Figure 10: Sample Total Storm Map for 04/01/2017 Massachusetts storm

Precipitation grids/maps

The native output from MetStorm is gridded precipitation (QPE) at 5-minute and/or 1-hour time intervals and at spatial resolutions as fine as 250m^2. These grids precipitation serve as the basis for most of the other analytics provided in a MetStorm deliverable. The grids can be provided in a variety of customizable formats, including shapefiles, ESRI® ASCII grids or .bil files. Although MetStorm grids are in a longitude/latitude WGS84 coordinate system, they can be re-projected into other projections.

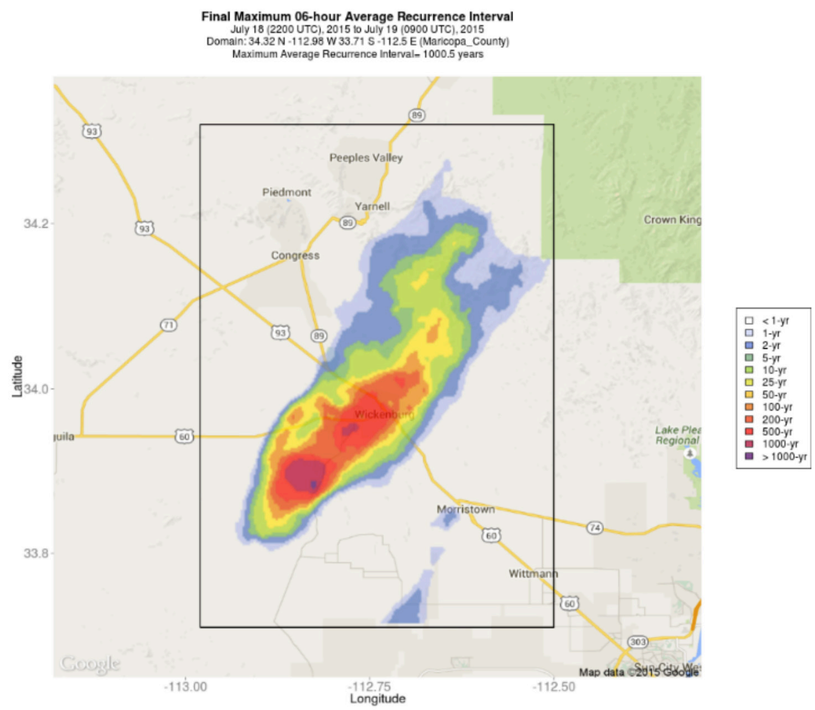

Figure 11: Sample 6-hour ARI map

Average Recurrence Interval (ARI)

The Average Recurrence Interval (ARI) of precipitation provides an objective and statistical perspective of how rare the precipitation was for a specific duration of precipitation during the storm (Figure 11). Often referred to as the "return period", the ARI represents a precipitation event (amount per unit time) as the average number of years (climatologically) between equivalent events for a specific location. An ARI of 100 years is the same as a 1% probability of an event occurring in any given year ("a 100-year event"). In fact, the MetStorm precipitation frequency graphics are also available in terms of an Annual Exceedance Probability (AEP) to more clearly communicate the equivalent probability of storm precipitation.

Precipitation frequencies have been calculated in terms of amount and duration (e.g., how often 10 inches of rain may fall in a 24 hour period). These frequencies are provided in precipitation frequency atlases such as NOAA Atlas 2 (Miller et al. 1973) and Technical Paper 40 (Hershfield 1961), but are undergoing revision at the NWS Hydrometeorological Design Studies Center (HDSC) as part of NOAA Atlas 14 (NOAA 2006-2015).

Using MetStorm's gridded FQPE, maps of ARI are generated for key durations of the storm for which NOAA Atlas 14 or client/project specific frequency data are available. These maps are made available as graphics or grids. The ARI maps effectively characterize significant precipitation allowing users to quickly ascertain areas with the most unusual precipitation.

Depth-area-duration

A depth-area-duration (DAD) analysis provides a three-dimensional perspective of a storm's precipitation: depth, area, and duration. DAD analyses are an industry-standard method to characterize precipitation of extreme events in a tabular and graphical format. The tabular format of a DAD analysis provides a convenient format for maximizing and transposing (i.e. moving) the storm precipitation characteristics from one location (in-place) to another (transposed location).

A complete DAD analysis requires hourly gridded precipitation for the entire storm period across the storm domain. Equipped with gridded hourly precipitation, a meteorological understanding of the storm and a sense of the topography and other geographic features that may have impacted the precipitation, DAD zones can be identified. The region within each DAD zone represents geographic areas that exhibit similar total storm precipitation, orographics, and storm dynamics such that all of the individual storm centers within that DAD zone could have conceivably co-occurred in time and space. The co-occurring in time and space requirement is necessary given the DAD calculations combine all of the precipitation into a single virtual storm center. The virtual single storm center concept makes the formation of DAD zones critical given the DAD table/plot will represent a storm that could physically occur. For instance, combining storm centers across an area with steep terrain (orographics) and high plains (convergence) would represent something that would not occur naturally if combined into a single storm center. The virtual single storm center concept in defining DAD zones requires the following to be true of each DAD zone:

- Similar topography and orographic enhancement
- Similar meteorological setting, dynamics and moisture sources
- Similar timing of the precipitation
- Consideration of areas with adequate station density to support reliable DAD calculations with a high degree of confidence

MetStorm's DAD code is consistent with the methodology used by the U.S. Weather Bureau, Bureau of Reclamation and World Meteorological Organization (WMO) as part of their extreme precipitation analyses (Stodt, 1995; USWB, 1946; WMO, 1969). The DAD calculations begin by masking the precipitation outside the DAD zone. For each duration, a moving sum is computed by adding up the gridded hourly QPE. Based on the range of precipitation values in the moving sum, a series of precipitation thresholds are established that span the precipitation values. For each precipitation threshold, the code determines the total area and average precipitation for all areas at and above the threshold. The computed depth-area (DA) pair is saved. This is repeated for each threshold value, including 0. The process is also repeated for all of the moving sums until a complete sample of DAs is created for all available moving sums. An example of a complete sample of DA pairs,

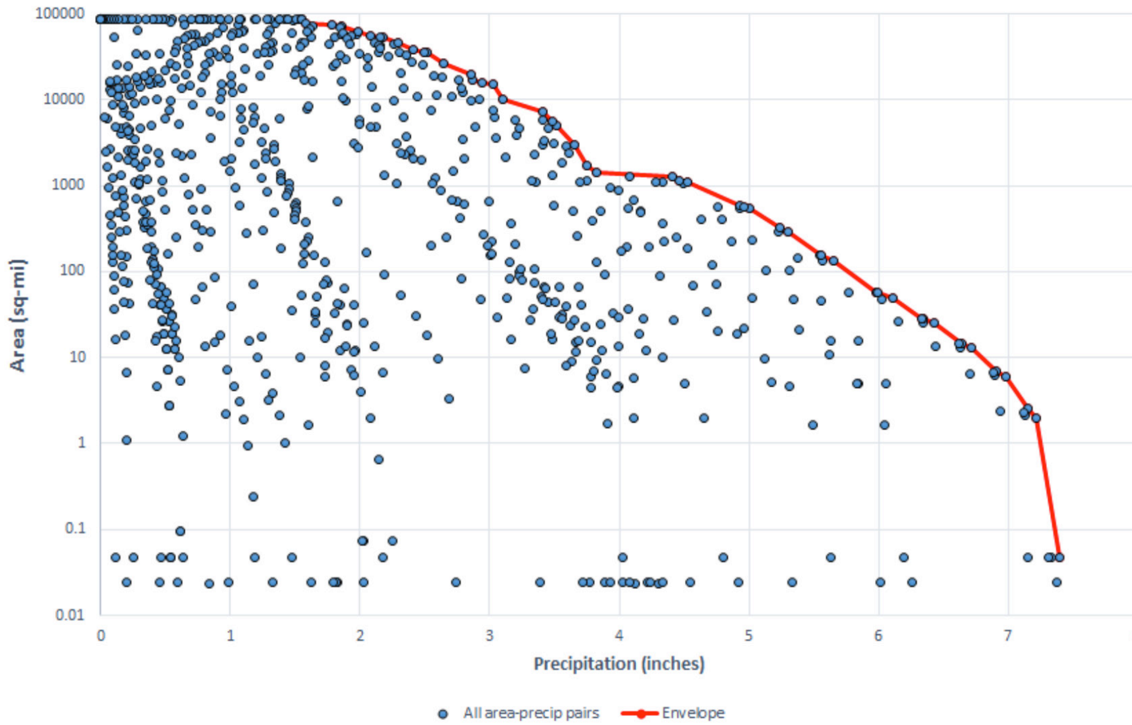

Figure 12: Depth-area plot for all precipitation-area pairs associated with a specific duration. The envelope line represents the final depth-area curve for the duration

for a specific duration (e.g. 12-hours), is illustrated in Figure 12. The enveloping curve (red line in Figure 12) represents the final DA curve for the given duration and DAD zone. A sample DAD plot is shown in Figure 13.

MetStorm operates in a geographic coordinate system based on the WGS84 datum. Although this is not an equal area projection, the spatial distortion is not a significant source of error/uncertainty for storm events in the mid-latitudes as compared to other elements of the analysis. Additionally, for convenience and consistency with most basemaps, including NOAA Atlas 14 and PRISM grids, the geographic coordinate system is a good choice for MetStorm. However, the area sizes associated with the DAD calculations are more sensitive to distortion and projection issues, therefore the DAD calculations are based on an equal area projection.

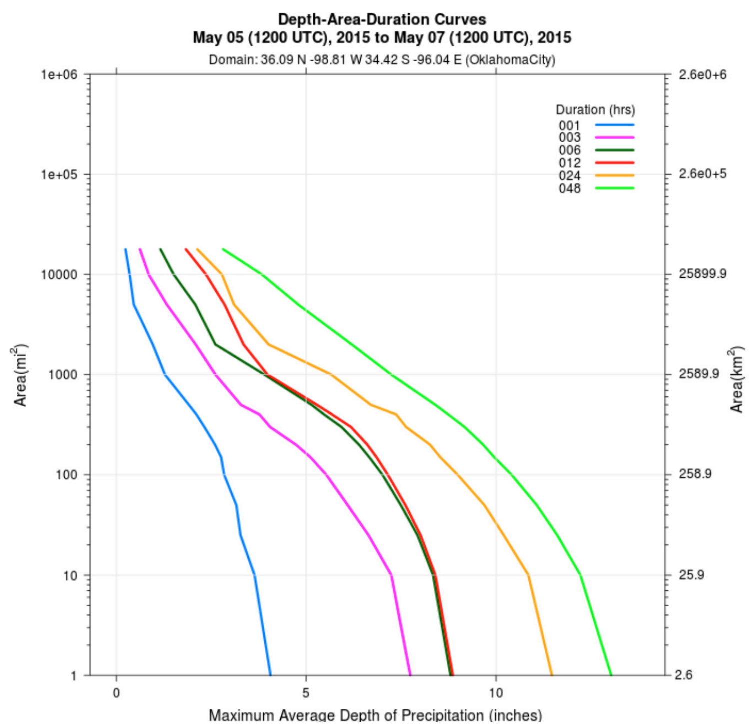

Figure 13: Sample DAD plot

Gauge catalog

A complete precipitation gauge catalog provides metadata for all precipitation gauges utilized in the analysis. The data is provided in a separate (.csv) file and/or as a table in the report. The station catalog contains the following columns of information:

- Station ID = station identification code/ number
- Station Name = Station Name
- Source = Source of data
- Lat = Latitude in decimal degrees
- Lon = Longitude in decimal degrees
- Elev = Elevation in feet above mean sea level
- Start Date-Time = First ending hour and date of precipitation (UTC)
- End Date-Time = Ending hour and date of precipitation (UTC)
- Type = Station type where H=hourly, HT=hourly timer, HE=hourly estimated, D=Daily, A=Auxiliary
- Station sum = Observed total precipitation at station
- FQPE sum = Final Quantitative Precipitation Estimate (FQPE) from MetStorm in inches

Station ID	Station Name	Source	Lat (*)	Lon (*)	Elev (ft)	Start date/time	End date/time	Type	Station sum	FQPE sum
USW0001 3988	Kansas City Downtown AP D525 MO	GHCN-WBAN	39.121	-94.597	742	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	1.22	1.20
USC00030 828	Dooneville 3 W D25 AR	GHCN-COOP	35.150	-93.967	459	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	1.19	1.17
USC00032 442	Fayetteville Day Air	CHCN-COOP	36.083	-94.167	1371	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	4.53	4.53
USC00032 444	Fayetteville Exp STN Day AR	CHCN-COOP	36.101	-94.174	1270	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	3.66	3.66
USC00348 462	Stapp CCC D25 OK	CHCN-COOP	34.750	-94.633	-999	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	0.55	0.51
USC00142 541	Emporia 1 $ Day KS	CHCN-COOP	38.386	-96.182	1077	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	2.32	2.32
USC00144 675	Le Roy Day KS	CHCN-COOP	38.080	-95.640	1004	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	2.16	2.16
USC00143 008	Garnett 1 E Day KS	CHCN-COOP	38.280	-95.218	1001	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	3.48	3.48
USC00142 622	Eureka 1 E Day KS	CHCN-COOP	37.825	-96.264	1100	1940-09-02 T 06:00:00	1940-09-06 T 05:00:00	A	1.47	1.47

Validation

A validation analysis is conducted to confirm consistency between gauges included in the analysis and the resulting MetStorm precipitation. The validation analysis compares the incremental precipitation at the finest available temporal distribution as it was measured to the final gridded MetStorm precipitation (Figure 14). By nature of MetStorm's logic, the validation demonstrates a close match to observed data; differences can be attributed to gauge malfunctions, inherent differences between the small gauge catchment area versus the much larger grid-cell average, wind drift of precipitation above the gauge, snow/hail, or radar quality (see more detailed descriptions in Gauge-FQPE Correlation Statistics section).

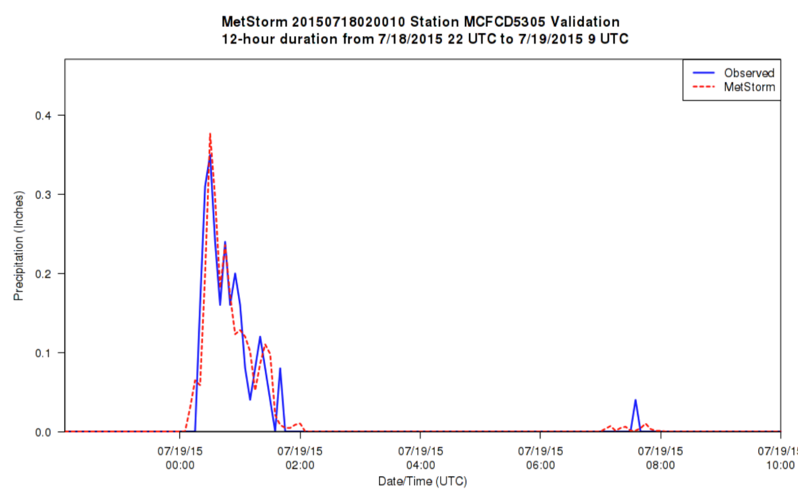

Figure 14: Sample gauge vs. MetStorm 5-minute validation

Error statistics

An important feature of MetStorm is its error statistics, which includes a jackknife cross-validation test and gauge versus FQPE comparison. The results of these tests inform the user and analyst of the uncertainty associated with the storm analysis. Oftentime, the results also help the analyst compose the "Conclusions and Confidence in Results" section in the MetStorm report.

Jackknife cross-validation

A jackknife cross-validation is used to evaluate the spatial interpolation technique's performance for deriving and interpolating total storm precipitation values. This method of validation resamples the data to see how the results vary with and without a specific station included in the analysis. The cross-validation results reflect the accuracy of the derivation and interpolation procedure. The jackknife output is summarized into a mean bias and a mean absolute percentage error (MAPE); see Equation 2.

Gauge-FQPE correlation statistics

Additionally, measured precipitation as compared to gridded MetStorm is evaluated (Figure 15). Differences between the gauge precipitation and the final QPE (FQPE) from MetStorm can be caused by a number of legitimate factors, including incomplete gauge observations, erroneous gauge data, and/or strong spatial gradients.

Comparing MetStorm FQPE to observed point precipitation depths at the gauged locations provides an objective measure of the consistency, accuracy and bias. For quality stations with complete precipitation data, the FQPE equals the observed precipitation, but less-than-perfect correlations could be the result of any number of issues, including:

- **Different observational periods**: Perhaps the largest cause of gauge versus FQPE differences is when the gauge measurement represents a period of time that is shorter than that of the storm analysis. MetStorm infills the precipitation before and after the gauge observational period, therefore computing a larger total storm precipitation value than was supplied to MetStorm.

$$\mathrm{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{O_t - M_t}{O_t}\right|$$

Equation 2. Mean Absolute Percentage Error (MAPE), where Ot is observed precipitation and Mt is MetStorm precipitation.

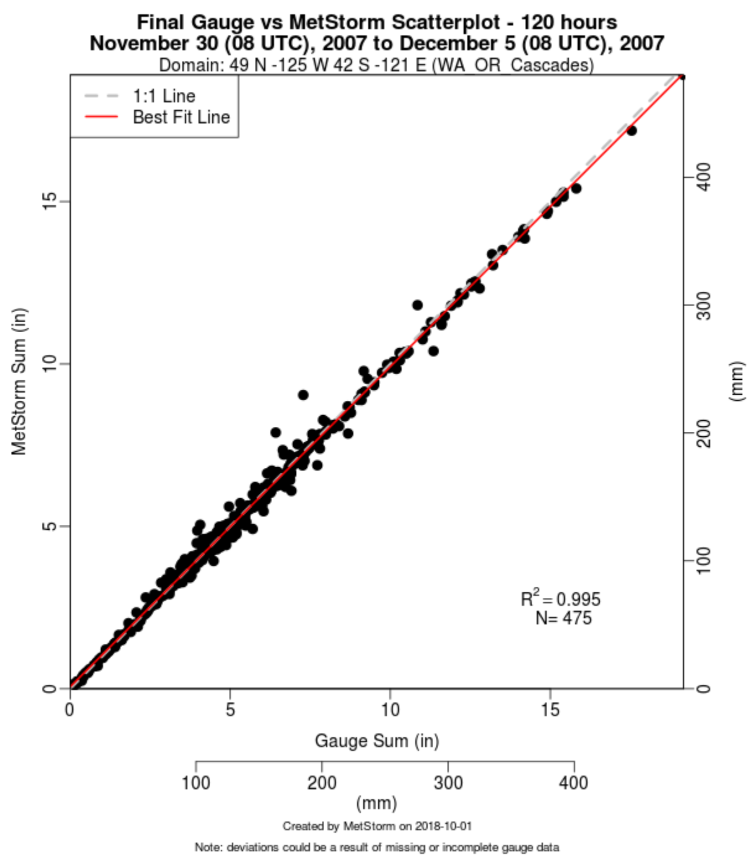

Figure 15: MetStorm's final QPE (FQPE) and radar-only QPE versus observed gauge data

- **Tight spatial precipitation gradients:** Oftentimes the spatial resolution is not sufficient to resolve point precipitation in areas with a tight spatial gradient of precipitation. The spatial resolution is dictated by the resolution of the basemap and/or radar data.
- **Hourly Quality Control:** Every hourly precipitation value in MetStorm is accompanied by a quality control flag ranging from 0 (erroneous data) to 1 (high-quality data). For a number of reasons, an individual hourly observation (or estimation if from a daily gauge), could fall below the acceptable minimum quality control flag level (usually 0.8) for inclusion in the MetStorm gridded analysis, but will remain in the original observational record for comparison. This will cause a difference between the gridded FQPE and the gauge.
- **Point versus area:** A rain gauge observation represents a much smaller area than the area sampled by the radar. The area that the radar is sampling is approximately 1 km2, whereas a rain gauge only samples an area approximately 8.0x10-9 km2. Therefore, a gridcell radar-derived precipitation value and a gauge (point) precipitation depth may vary.
- **Precipitation gauge under-catch:** Although we consider gauge data "ground truth," we recognize gauges themselves suffer from inaccuracies. Precipitation gauges, shielded and unshielded, can inherently underestimate total precipitation due to local airflow, wind undercatch, wetting, and evaporation. The general rule-of-thumb is 1% of the precipitation is lost for every 1 mph. Therefore, a 10 mph wind can cause up to 10% error (under-catch) (Guo et al. 2001, Duchon and Essenberg 2001, Ciach 2003, Tokay et al. 2010). Tipping buckets miss a small amount of precipitation during each tip of the bucket due to the bucket travel and tip time. As precipitation intensities increase, the volumetric loss of precipitation due to tipping tends to increase. Smaller tipping buckets can have higher volumetric losses due to higher tip frequencies, but on the other hand capture higher precision timing.
- **Radar Calibration:** NEXRAD radars calibrate reflectivity every volume scan, using an internally generated test. The test determines changes in internal variables such as beam power and path loss of the receiver signal processor since the last off-line calibration. If this value becomes large, it is likely that there is a radar calibration error that will translate into less reliable precipitation estimates. The calibration test is supposed to maintain a reflectivity precision of 1 dBZ. A 1 dBZ error can result in an error of up to 17% in MetStorm, using the default Z-R relationship Z=300R1.4. Larger calibration errors will result in larger MetStorm errors. However, by performing correlations each hour, the calibration issue is minimized in MetStorm.
- **Attenuation:** Attenuation is the reduction in power of the radar beams' energy as it travels from the antenna to the target and back. It is caused by the absorption and the scattering of power from the beam by precipitation. Attenuation can result in errors in reflectivity as large as 1 dBZ, especially when the radar beam is sampling a large area of heavy precipitation. In some cases, storm precipitation is so intense (>12 inches/hour) that individual storm cells become "opaque" and the radar beam is totally attenuated. Armed with sufficient gauge data, however, MetStorm will overcome attenuation issues.
- **Range affects:** The curvature of the Earth and radar beam refraction result in the radar beam becoming more elevated above the surface with increasing range. With the increased elevation of the radar beam comes a decrease in Z values due to the radar beam not sampling the main precipitation portion of the cloud (i.e. "over topping" the precipitation and/or cloud altogether). Additionally, as the radar beam gets further from the radar, it naturally samples a larger and larger area, therefore amplifying point versus area differences (described above).

- **Radar Beam Occultation/Ground Clutter:** Radar occultation (beam blockage) results when the radar beam's energy intersects terrain features. The result is an increase in radar reflectivity values that can result in higher than normal precipitation estimates where the beam meets the terrain feature and a decrease in radar reflectivity values that can result in lower than normal precipitation estimates where the beam can no longer travel. DTN processing algorithms account for these issues, and MetStorm uses GIS spatial interpolation functions to infill areas suffering from poor or no radar coverage.

- **Anomalous Propagation (AP):** AP is false reflectivity echoes produced by unusual rates of refraction in the atmosphere. WDT algorithms remove most of the AP and false echoes; however, in extreme cases the air near the ground may be so cold and dense that a radar beam that starts out moving upward is bent all the way down to the ground. This produces erroneously strong echoes at large distances from the radar. Again, equipped with sufficient gauge data, the MetStorm bias corrections will overcome AP issues.

MetStorm and its integration of multiple data sources is designed to overcome many of these shortcomings by intelligently using the strengths of all input for computing FQPE.

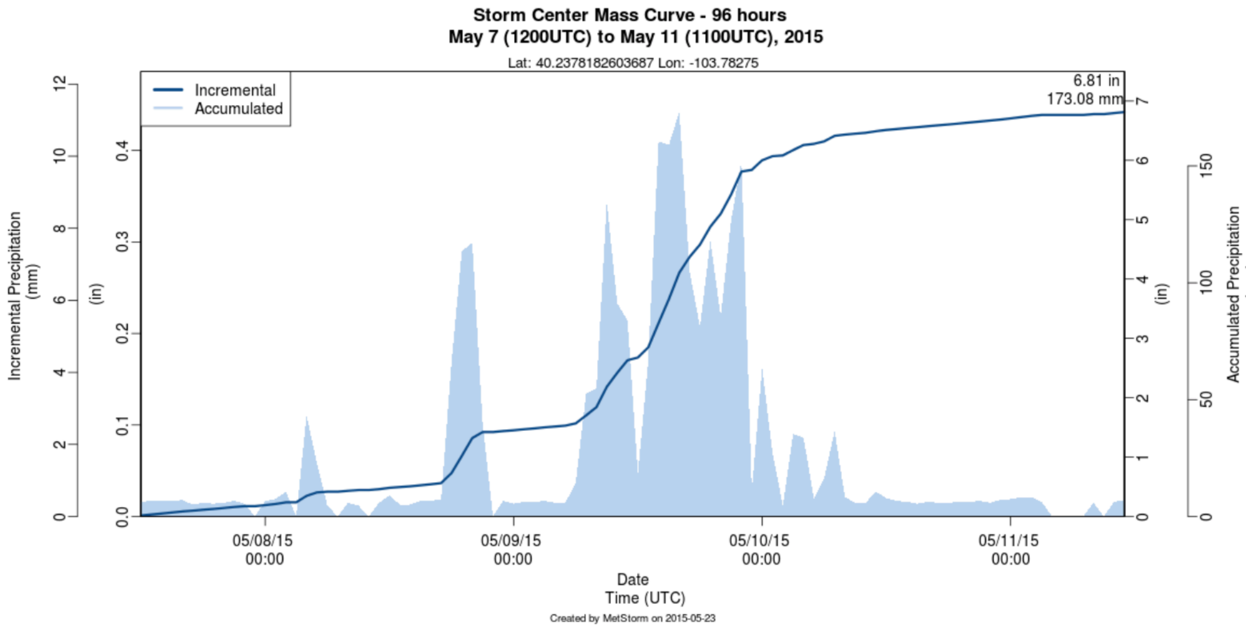

Figure 16: Sample mass curve from MetStorm

Mass curves

Mass curves provide a traditional perspective of the timing of precipitation. A common MetStorm deliverable is the mass curve for the storm center, but mass curves can be created for any location in the storm domain. MetStorm mass curve plots (Figure 16) provide both accumulated and incremental precipitation for a single location.

Storm report

A complete storm report (Figure 17) accompanies a MetStorm analysis. The report generally follows a standardized template/format, but can vary depending the on the client's needs. The report contains the following sections:

- Meteorological storm discussion
- Noteable storm reports and data sources
- ARI analysis
- Validation
- Error statistics
- Conclusions and confidence in the results
- Description of output/deliverables
- A brief summary of MetStorm
- Station catalog

Other deliverables

MetStorm output supports a wide variety of applications requiring different deliverables. Some of these additional deliverables include:

- Average basin/subbasin precipitation time series
- Storm Events Flood Model (SEFM) storm templates
- Animations
- Maps/grids of maximum precipitation intensities
- Shapefiles of total storm and/or incremental hourly precipitation
- Other customized output

STORM PRECIPITATION REPORT

Date of storm: **September 8, 2014**	Analysis duration (hours): **24**	Analysis status: **Final**	Report created: **4/12/2017**	Analyst: **KLL**
General storm location: **Maricopa County, AZ**		No. of stations used: 409	Storm type: **Local**	
Storm number: **2014090809**	MetStorm® version: **2.5**	Basemap: **CONUS 2-year, 6-hour climatological basemap**	Radar data used: **Low-altitude reflectivity from Phoenix, Arizona radar site**	
Notes:				

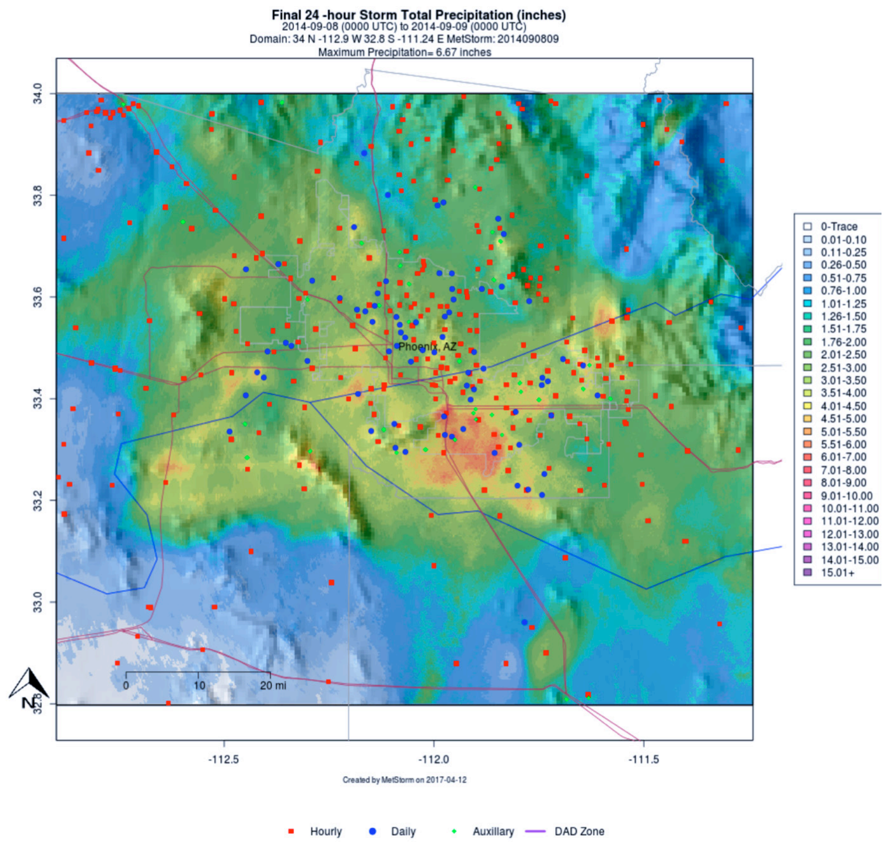

Figure 17: Sample MetStorm report cover

Version history

After the initial version of MetStorm was released, improvements and bug fixes are made when necessary. As more advances occur, improved versions may be released that will serve to improve validation and error statistics.

Version	Release date	Predominant changes/improvements
1.0	5/1/2015 - 9/10/2015	First stable release
2.0	9/10/2015 - 9/22/2016	Added logic to integrate traditional radar reflectivity; added the ability to disaggregate data into 5-minute intervals; added ability to add gauge data with varying observation times; improved integration and disaggregation of daily gauge measurements.
2.1-2.4	9/22/2016 - 4/1/2017	Various edits and improvements
2.5	4/1/2017 - 10/18/2018	Improved logic for infilling missing hourly data
2.6	10/18/2018 - 9/25/2018	Metric output options (BC-Hydro), no longer deletes auto-blacklist
2.7	9/25/2018 - 8/31/2019	Faster hourly vector processing, new beam block logic, new isolated cell removal/infilling/parameter
2.8	5/31/2019 - current	Same code as 2.7, with the exception that the database is disconnected so final storm statistics and deliverables are not automatically uploaded to postgreSQL database. This version is for use on AWS machines only in an AutoMetStorm mode.
2.9	9/1/2019 - current	MetStorm parameter file to database, added options for generating maximum x-hour grids for AEP code, added temperature/freezing level height extraction and plotting for maximum location, added logic to ensure duplicate IDs are resolved.

MetStorm versus Storm Precipitation Analysis System (SPAS)

MetStorm was originally developed to serve as a highly-detailed and precise near real-time storm precipitation analysis tool given the availability of radar, gauge, and satellite data. However, the utility of MetStorm was expanded and now serves as an improved hydro-meteorological tool for evaluating new and old (pre-radar) storms. DTN Storm Precipitation Analysis System (SPAS) has supported hundreds of storm analyses since 2003, but improved data sources and technologies motivated the development of MetStorm in 2014. Although SPAS and MetStorm utilize similar input data, MetStorm uses a different data structure and integrates more comprehensive data sources. MetStorm includes the following improvements over SPAS:

1. Unlike SPAS, which has a minimum analysis duration of 72 hours, MetStorm has no minimum duration constraint.
2. MetStorm automatically integrates precipitation gauge data from a third-party consolidated and quality-controlled precipitation database dating back to 1997 that has over 20,000 hourly observations per hour. As with SPAS, gauge data extending back to the late-1800s is available and quality controlled for older storm analyses.
3. At the onset, MetStorm utilizes quality-controlled 1-hour precipitation gauge data. Each hourly precipitation measurement is accompanied by a QC flag, both are editable by the analyst thereby providing powerful flexibility in using/excluding precipitation gauge data.
4. For storms since 2015, MetStorm utilizes mosaicked dual-pol precipitation (together with raw reflectivity) for governing the spatial precipitation patterns and relative magnitudes of precipitation. Prior to 2015, but after 1996, MetStorm utilizes radar-only precipitation estimates computed by Weather Decision Technologies' dynamic Z-R algorithm.
5. MetStorm leverages satellite-estimated precipitation in areas with limited gauge data and/or poor radar coverage.
6. The conversion of incremental hourly precipitation into hourly percentages (at hourly gauge locations) addresses missing individual hourly values better by estimating the individual hourly precipitation for all missing hours before translating into percentages.
7. Given the high-degree of uncertainty with observation times of daily precipitation measurements, MetStorm reduces this uncertainty by disaggregating the total daily precipitation into hourly precipitation based on nearby hourly gauges for the entire storm period; when observation times are critical/certain, the analyst can adjust the MetStorm input files to be consistent with 1-day totals at specific times.
8. MetStorm is more efficient and simpler to run.
9. Average Recurrence Interval analyses and maps are a standard output of MetStorm.
10. MetStorm has improved maps with transparent precipitation overlaid on detailed terrain and/or street maps (either Google® Maps or OpenStreetMap which is an open source).
11. MetStorm output is clearly named with the date/time in addition to "index hours" (e.g., 1-72).
12. Given radar data, MetStorm operates at a resolution of 250 m2 instead of 1 km2 as in SPAS.

Although the algorithm processing within MetStorm is completely different from SPAS, a comparison of individual storms indicates similar total precipitation patterns and magnitudes. Improved spatial and temporal resolution in MetStorm, however, is evident at finer scales. Figure 18 through Figure 26 show an objective and direct comparison between the output of SPAS and MetStorm for an analysis of the same storm (Wickenburg, AZ on July 18, 2015). Each analysis utilized the same rain gauge data. The maximum observed rainfall was 5.08 inches, whereas the maximum gridcell values were 5.17 inches and 5.31 inches for SPAS and MetStorm, respectively.

The comparison below shows a high degree of consistency between SPAS and MetStorm, which validates both as reliable precipitation analysis systems.

SPAS

MetStorm

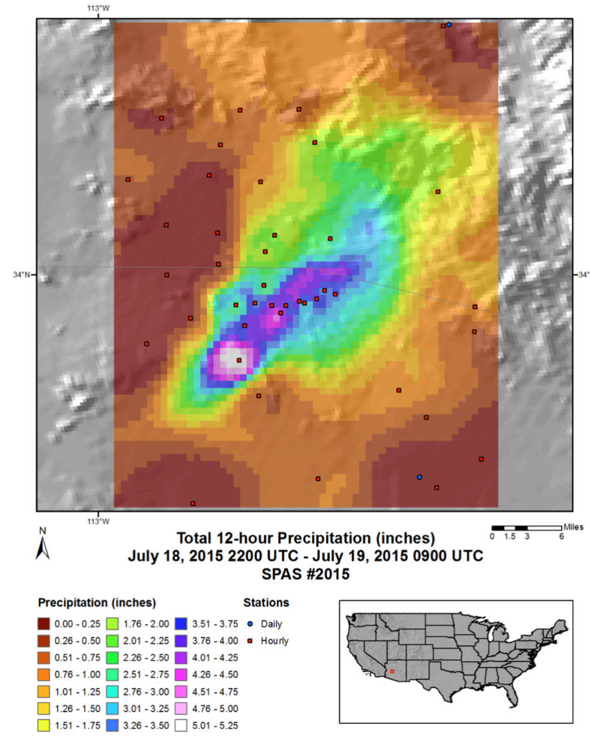

Figure 18: Sample total storm SPAS map created manually using ArcGIS. Maximum grid cell = 5.17"

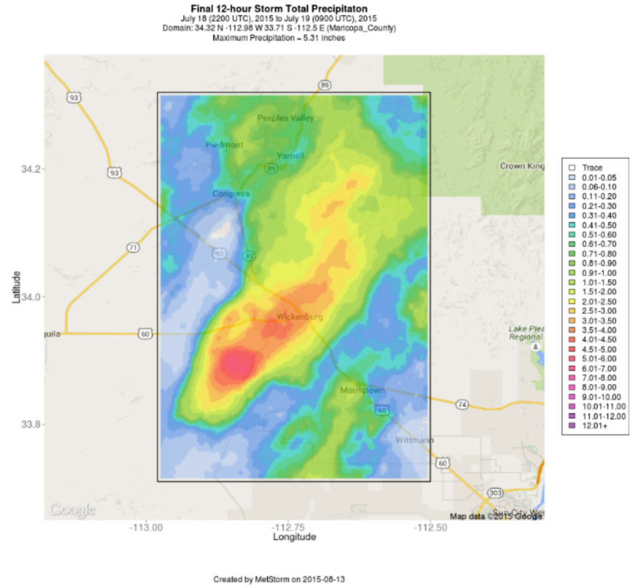

Figure 19: Sample total storm MetStorm map automatically created using Google Maps. Maximum grid cell = 5.31"

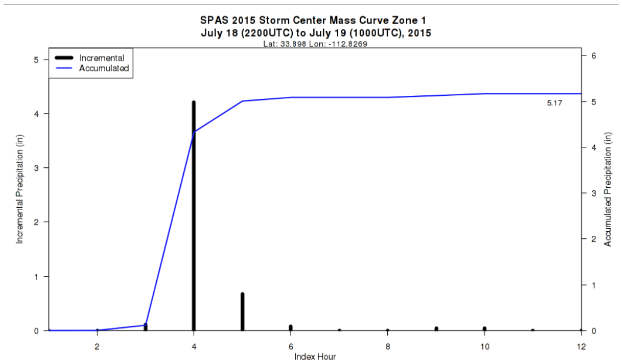

Figure 20: Sample storm-center 1-hour mass curve from SPAS

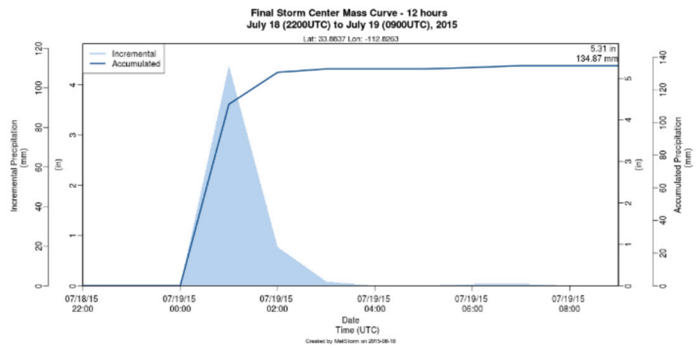

Figure 21: Sample storm-center 1-hour mass curve from MetStorm

SPAS

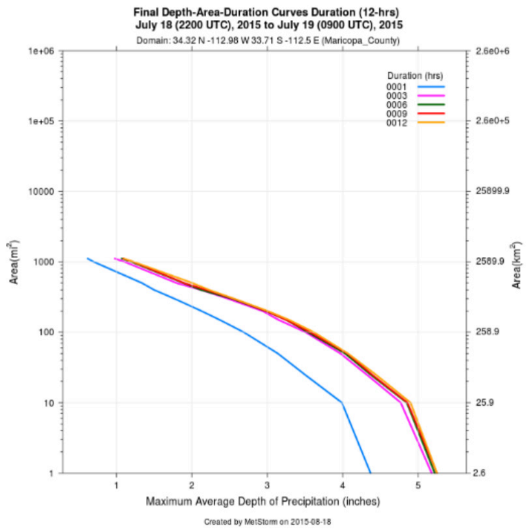

Figure 22: Sample DAD plot from SPAS

MetStorm

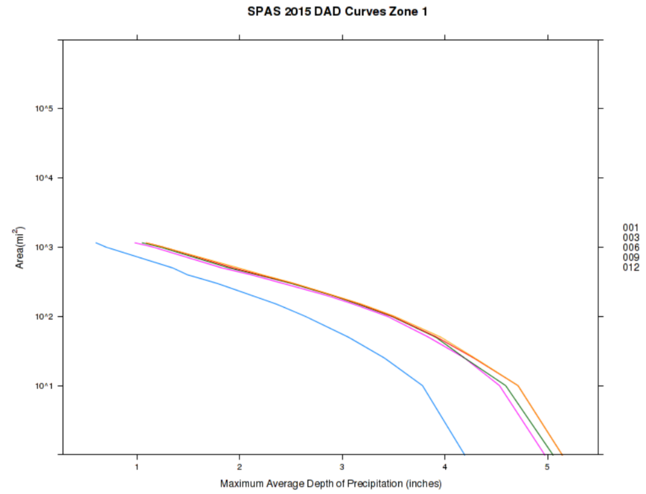

Figure 22: Sample DAD plot from MetStorm

	Duration (hours)				
Area	**1**	**3**	**6**	**9**	**12**
0.3	4.21	5.00	5.08	5.17	5.17
1	4.19	4.97	5.05	5.14	5.14
10	3.78	4.53	4.59	4.71	4.71
25	3.41	4.19	4.19	4.28	4.29
50	3.06	3.84	3.91	3.92	3.96
100	2.64	3.44	3.48	3.49	3.51
150	2.36	3.11	3.15	3.17	3.19
200	2.12	2.85	2.90	2.91	2.92
300	1.78	2.42	2.50	2.52	2.53
400	1.49	2.11	2.17	2.19	2.22
500	1.35	1.83	1.90	1.94	1.99
1000	0.70	1.16	1.23	1.26	1.26

Figure 24: SPAS DAD table in inches

	Duration (hours)				
Area	**1**	**3**	**6**	**9**	**12**
0.3	4.42	5.23	5.27	5.31	5.31
1	4.37	5.18	5.22	5.25	5.25
10	3.99	4.77	4.85	4.86	4.90
25	3.50	4.32	4.37	4.39	4.44
50	3.14	3.97	4.03	4.06	4.07
100	2.69	3.51	3.54	3.57	3.62
150	2.37	3.15	3.25	3.25	3.29
200	2.13	2.94	2.98	2.99	3.01
300	1.77	2.48	2.53	2.55	2.56
400	1.50	2.12	2.12	2.19	2.23
500	1.34	1.80	1.89	1.90	2.01
1000	0.70	1.11	1.20	1.22	1.23

Figure 25: MetStorm DAD table in inches

	Duration (hours)				
Area	**1**	**3**	**6**	**9**	**12**
0.3	5.0%	4.6%	3.7%	2.7%	2.7%
1	4.3%	4.2%	3.4%	2.1%	2.1%
10	5.6%	5.3%	5.7%	3.2%	4.0%
25	2.6%	3.1%	4.3%	2.6%	3.5%
50	2.6%	3.4%	3.1%	3.6%	2.8%
100	1.9%	2.0%	1.7%	2.3%	3.1%
150	0.4%	1.3%	3.2%	2.5%	3.1%
200	0.5%	3.2%	2.8%	2.7%	3.1%
300	-0.6%	2.5%	1.2%	1.2%	1.2%
400	0.7%	0.5%	-2.3%	0.0%	0.5%
500	-0.7%	-1.6%	-0.5%	-2.1%	1.0%
1000	0.0%	-4.3%	-2.4%	-3.2%	-2.4%

Figure 27: Percent ((MetStorm-SPAS)/SPAS) differences of DAD values. Red indicates MetStorm is lower than SPAS.

MetStorm database

We maintain a historical archive of extreme storm analytics including most of the output described above. These storm analyses are available for future use in hydrometeorological and meteorological applications, such as Probable Maximum Precipitation studies, stochastic flood modeling, hydrologic model calibration/validation, extreme precipitation risk analyses, forensic cases, insurance claims and infrastructure design/operation projects.

Beginning in 2015, DTN has been running MetStorm on noteworthy storms across the United States (Figure 27) and has already analyzed and archived 157 storms (as of April 19, 2017).

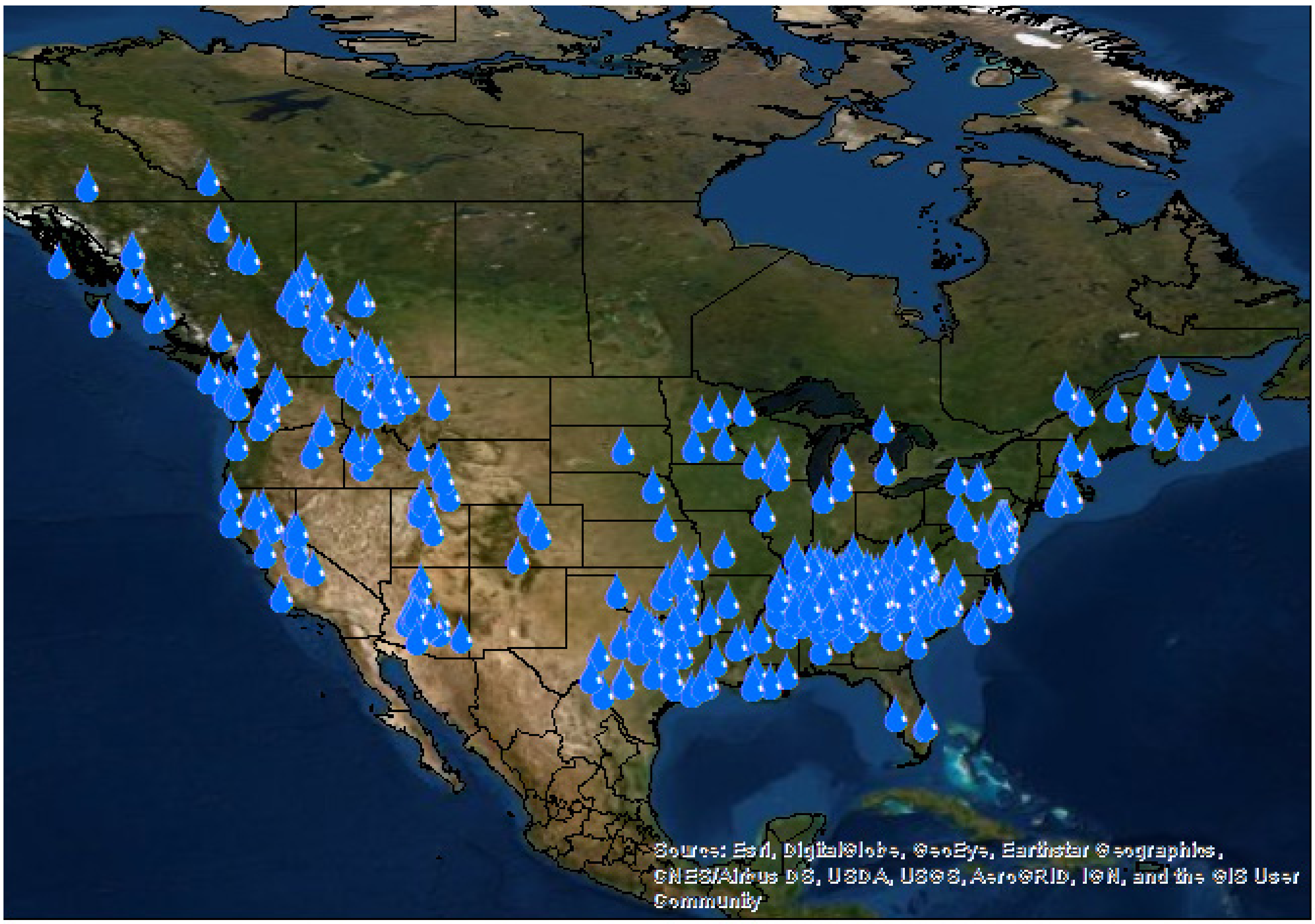

Figure 27: Locations of storms analyzed with MetStorm from January 1, 2015 through April 2020 (concurrent with the publication of this white paper). Source: http://metstat.com/solutions/MetStorm/

Summary

The use of a multi-sensor approach to analyzing storm precipitation provides the accuracy necessary for creating engineering-quality results and unique analytics, such as depth-area-duration (DAD) tables/plots and Average Recurrence Interval (ARI) maps. Emphasizing the strengths of each input variable (e.g. dual-pol QPE, radar reflectivity, gauge data) and down-weighting their weaknesses allows for precise precipitation analytics.

Analyses of such events will help build and maintain a historical archive of extreme storms for future use in hydro-meteorological applications, such as Probable Maximum Precipitation studies, stochastic flood modeling, hydrologic model calibration/validation, extreme precipitation risk analyses, forensic cases, insurance claims and infrastructure design/operation projects. MetStorm is constantly evolving and improving as new datasets, techniques, and standards of practice become available.

A near real-time version of MetStorm, known as MetStormLive, provides many of the same features, skills and innovations of MetStorm, but in a near real-time setting. MetStormLive imposes several automatic quality control measures to help provide the most accurate, near real-time QPE data available.

References

Baeck, M.L. and J.A. Smith. 1998. Rainfall Estimation by the WSR-88D for Heavy Rainfall Events. Weather and Forecasting Vol. 13, No. 2.

Ciach, G.J. 2003. Local Random Errors in Tipping-Bucket Rain Gauge Measurements. J. Atmos. Oceanic Technol. Vol. 20.

Dickens, J. 2003. On the Retrieval of Drop Size Distribution by Vertically Pointing Radar. In: American Meteorological Society 32nd Radar Meteorology Conference, Albuquerque, NM, October 2005.

Duchon, C.E., and G.R. Essenberg, 2001: Comparative Rainfall Observations from Pit and Above Ground Rain Gauges with and without Wind Shields. Water Resources Research Vol. 37, N. 12, 3253-3263.

Guo, Z., D.H. Bromwich, and J.J. Cassano, 2001: Evaluation of Polar MM5 simulations of Antarctic atmospheric circulations. Mon. Wea. Rev., (submitted).

Hendricks, A.D., Parzybok, T.W.,Laro,K.L., Mokry, W, 2015. MetStorm - Near Real-Time Storm Precipitation Analytics. Presented at GIS in the Rockies Conference, Denver, CO, September 2015.

Hershfield, D.M., 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. Weather Bureau Technical Paper No. 40, U.S. Weather Bureau, Washington, D.C.

Hunter, R.D., and R.K. Meentemeyer. 2005. Climatologically Aided Mapping of Daily Precipitation and Temperature. Journal of Applied Meteorology Vol. 44, pp. 1501-1510.

Laro, Katie and T. Parzybok. 2015: MetStorm:® Near Real-time Storm Precipitation Analytics. 11th National Hydrologic Warning Council Training Conference and Exposition. Indianapolis, Indiana. June 15-18, 2015.

Martner, B.E., V. Dubovskiy, and S.Y. Matrosov. 2005. Z-R Relations from raindrop disdrometers: Sensitivity to regression methods and DSD data refinements. In The 32nd Radar Meteorology Conference, Albuquerque, NM, 22–29 October 2005, Paper no. P14R.4. American Meteorological Society.

Miller, J.F., R.H. Frederick and R.J. Tracy, 1973. Precipitation-frequency atlas of the western United States. NOAA Atlas 2, 11 vols., National Weather Service, Silver Spring, Maryland.

NOAA National Weather Service, 2006-2015: NOAA Atlas 14 Volumes 1-10, Precipitation-Frequency Atlas of the United States. Silver Spring, MD.

Parzybok, T., N. A. Lock, C. W. Porter, K. Laro, A. D. Hendricks, and W. Mokry Jr. 2015: MetStorm:® Near Real-time Storm Precipitation Analytics Using Dual-pol Radar Data. 37th Conference on Radar Meteorology. Norman, OK. September 13-18, 2015.

Porter, C, B. C. Baranowski, B. Clarke, and B. Shaw, 2012: The Polarimetric Radar Identification System (POLARIS): Leveraging Dual-Polarized Radar Data for Real-Time Operational Applications, 92nd American Meteorological Society Annual Meeting, New Orleans, LA, January 22-26, 2012.

Stodt, R.W. (1995) Manual for automated depth-area duration analysis of storm precipitation. Department of Interior, Bureau of Reclamation, Denver, CO, November, 96 p.

Tokay, A., and P. G. Bashor, 2010: An experimental study of small-scale variability of raindrop size distribution. J. Appl. Meteor., 49, 2348–2365.

U.S. Weather Bureau (USWB) (1946) Manual for Depth-Area-Duration Analysis of Storm Precipitation. Cooperative Studies Technical Paper No. 1, U.S. Department of Commerce, Weather Bureau, Washington, D.C.

World Meteorological Organization (WMO) (1969) Manual for Depth-Area Duration Analysis of Storm Precipitation. WMO No. 237. TP.129, Geneva, 114 p.