Enclosure 1

TOPICAL REPORT
TVA-NPG-AWA16-A

TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041, Revision 1

TOPICAL REPORT

TVA-NPG-AWA16-A

TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041, Revision 1

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SECTION A

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

March 18, 2019

Mr. Joseph W. Shea
Vice President, Nuclear Regulatory
Affairs and Support Services
Tennessee Valley Authority
1101 Market Street, LP 4A
Chattanooga, Tennessee 37402-2801

SUBJECT: FINAL SAFETY EVALUATION FOR TENNESSEE VALLEY AUTHORITY TOPICAL REPORT "TVA OVERALL BASIN PROBABLE MAXIMUM PRECIPITATION AND LOCAL INTENSE PRECIPITATION ANALYSIS CALCULATION CDQ0000002016000041," REV. 1 (EPID L-2016-TOP-0011)

Dear Mr. Shea:

By letter dated September 20, 2016 (Reference 1) and supplemented by a letter dated April 19, 2018 (Reference 2), Tennessee Valley Authority (TVA, the applicant) submitted the subject Topical Report (TR), "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041" for review. TVA revised the TR on June 22, 2018 (Reference 3) as Rev. 1. By a letter dated December 31, 2018 (Reference 4), a Nuclear Regulatory Commission (NRC) draft safety evaluation (SE) regarding our approval of this TR was provided for your proprietary review and comment. By a letter dated January 11, 2019 (Agencywide Documents Access and Management System Accession No. ML19015A016), TVA provided comments on the draft SE and confirmed it does not contain proprietary information. The NRC staff's disposition of your comments on the draft SE are discussed in Enclosure 1; the final SE is Enclosure 2.

The NRC staff has found that the subject TR is acceptable for referencing in licensing applications for TVA nuclear power plants to the extent specified and under the limitations and conditions delineated in the TR and in the enclosed final SE. The final SE defines the basis for our acceptance of the TR.

Our acceptance applies only to material provided in the subject TR. We do not intend to repeat our review of the acceptable material described in the TR. When the TR appears as a reference in licensing action requests, our review will ensure that the material presented applies to the specific plant involved. Requests for licensing actions that deviate from this TR will be subject to a plant-specific review in accordance with applicable review standards.

In accordance with the guidance provided on the NRC website, we request that TVA submit an approved version of the subject TR within 3 months of receipt of this letter. The approved version must incorporate this letter and the enclosed final SE after the title page. Also, they must contain historical review information, including NRC requests for additional information and your responses. The approved versions must include an "-A" (designating approved) following the TR identification symbol.

If future changes to the NRC's regulatory requirements affect the acceptability of this TR, TVA will be expected to revise the TR appropriately or justify its continued applicability for subsequent referencing. Licensees referencing this TR would be expected to justify its continued applicability or evaluate their plant using the revised TR.

If you have any questions, please contact Andrew Hon at 301-415-8480.

Sincerely,

Undine Shoop, Branch Chief
Plant Licensing Branch II-2
Division of Operating Reactor Licensing
Office of Nuclear Reactor Regulation

Docket Nos. 50-259, 50-260, 50-296,
50-327, 50-328,
50-390, 50-391

Enclosures:
1. Resolution of Comments from TVA
2. Final Safety Evaluation

cc: Listserv

RESOLUTION OF COMMENTS BY THE OFFICE OF NUCLEAR REACTOR REGULATION

ON DRAFT SAFETY EVALUATION FOR

TENNESSEE VALLEY AUTHORITY TOPICAL REPORT "TVA OVERALL BASIN PROBABLE

MAXIMUM PRECIPITATION AND LOCAL INTENSE PRECIPITATION

ANALYSIS CALCULATION CDQ0000002016000041"

REVISION 1

(EPID L-2016-TOP-0011)

This attachment provides the U.S. Nuclear Regulatory Commission (NRC) staff's review and disposition of the comments from Tennessee Valley Authority (TVA) on the draft safety evaluation for TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis Calculation CDQ0000002016000041, Revision 1.

Page	Line	Proposed Change / Comment	NRC Resolution of Proposed Change/Comment
1	21	Recommend deletion of *major* as used to refer to TVA dams. The term is not well defined.	The NRC staff understood the concern. The sentence in question was modified accordingly in the final SE.
2	60	Suggest inserting *upstream* to describe the watersheds depicted in Figure 2. Figure 2 does not include portions of the watersheds contributing to backwater effects downstream of the nuclear plants.	The NRC staff understood the concern. The sentence in question was modified accordingly in the final SE.

Enclosure 1

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555-0001

FINAL SAFETY EVALUATION BY THE OFFICE OF NUCLEAR REACTOR REGULATION

TOPICAL REPORT

"TVA OVERALL BASIN PROBABLE MAXIMUM PRECIPITATION AND

LOCAL INTENSE PRECIPITATION, CALCULATION, CDQ0000002016000041"

TENNESSEE VALLEY AUTHORITY

Enclosure 2

Contents

1.0 INTRODUCTION AND BACKGROUND

By letter dated September 20, 2016 (Reference 1), as supplemented (Reference 2) on April 19, 2018 and (Reference 3) on June 22, 2018, Tennessee Valley Authority (TVA, the applicant) submitted a Topical Report (TR), "TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ000002016000041" for review. The purpose of the TR is to provide Probable Maximum Precipitation (PMP) analyses for the operating nuclear plants in the Tennessee Basin. Upon the U.S. Nuclear Regulatory Commission (NRC) staff's approval, any license holder, or applicant for a license, wishing to utilize this methodology can submit a license amendment in accordance with the appropriate regulatory requirements for site specific applications which demonstrates that methodology is applicable to their site. During the review NRC staff issued Requests for Additional Information (RAIs), as discussed throughout this report. TVA responded (Reference 2) and updated the entire TR to Revision 1 (Reference 3). The focus of this evaluation and the processes and results described in this safety evaluation (SE) are related to Revision 1 of the TVA TR.

PMP is defined by the World Meteorological Organization (WMO) as "the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular time of year" (Reference 4). Operationally, when sufficient historical extreme rainfall observations are available, PMP is estimated based on a commonly used method combining storm moisture maximization, transposition (i.e., relocating patterns of storm precipitation to other areas), and envelopment (i.e., identifying maximum storm precipitation values) (Reference 3). For critical infrastructure such as dams classified as high hazard and nuclear power plants, PMP has been used as input to simulate the probable maximum flood (PMF) as a conservative design criterion.

Historically, PMP across the U.S. has been estimated primarily through work products issued by the National Weather Service (NWS) and predecessor agencies. These estimates were based on data collected over a number of decades and for a variety of extreme rainfall events. Fundamentally, PMP estimates can be classified as either *theoretical* or *operational*. Although the formal definition of PMP assumes a theoretical upper limit for precipitation, in practice a theoretical PMP cannot be directly computed or verified. Instead, most conventional PMP estimates follow an operational approach in which historical data and professional judgment may result in PMP estimates lower than the theoretical upper limit (Reference 6).

The basic approach and detailed methods used in developing operational PMP estimates have been described in numerous Hydrometeorological Reports (HMRs) published by the NWS.[1] For example, HMR 51 (Reference 5) provides generalized all-season PMP estimates for the U.S. east of the 105th meridian for drainage areas from 10 to 20,000 square miles (mi^2) and for durations of 6–72 hours. The NWS HMRs identify two types of PMP estimates: *generalized PMPs* and *individual drainage PMPs*. The PMP estimates provided in most HMRs (e.g., HMR 51) are termed "generalized estimates." In these HMRs, isolines of PMP are given on a map, allowing determination of basin-average PMP for any drainage basin. Typically, simplifying assumptions regarding the influence of topography and orographic processes were used in lieu of a detailed analysis. Other HMRs and studies produced by NWS (e.g., HMR 41 [Reference 7], HMR 46 [Reference 8], and HMR 56 [Reference 9]) provide PMP estimates for individual drainage basins that are specifically adjusted for the area and physical influences of the drainage basin under consideration. The reasons for analyzing individual drainage basins

[1] www.nws.noaa.gov/oh/hdsc/studies/pmp.html

include (1) generalized PMP studies were not available, (2) the watershed was larger in size than those covered by available generalized PMP studies, or (3) detailed studies indicated orographic effects would yield PMP estimates significantly different from those based on available generalized PMP charts (e.g., watersheds in the Appalachians).

The TVA drainage basin covers an area of approximately 41,900 mi^2 along the Tennessee River system and includes land in seven states. Figure 1 shows the TVA project domain used for the PMP development in the TR.

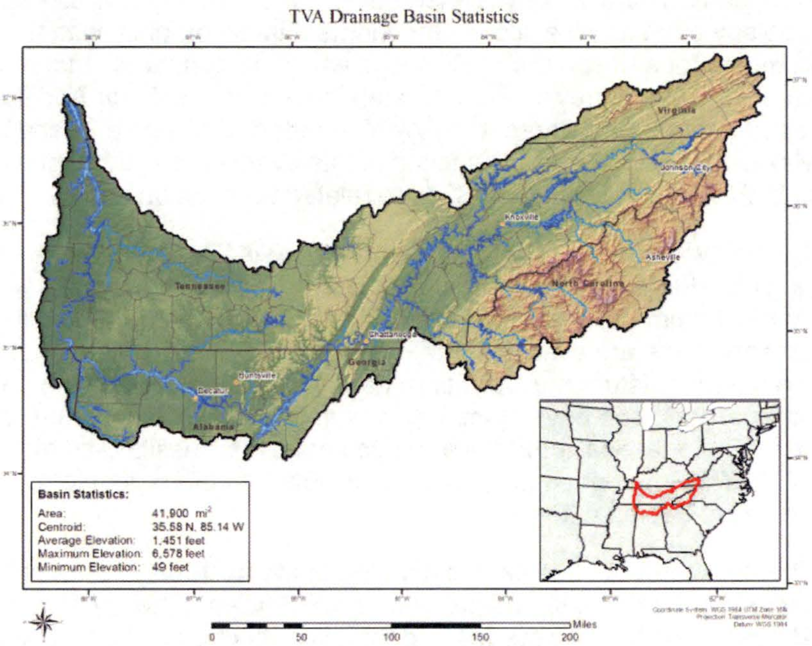

Figure 1. TVA project domain used for PMP development. (Source: TVA, 2018)

The purpose of this staff evaluation is to provide the details related to the review of the methodology and resulting precipitation values at the three operating nuclear sites located in the basin. There are TVA's three operating nuclear power plants (BFN, SQN, and WBN) in the TVA basin that provide an average of 7,800 megawatt of electricity. WBN is located upstream in the drainage basin, at Tennessee River mile 528.0 near Spring City, TN (Reference 10). SQN is located roughly 43.5 miles downstream of WBN, at Tennessee River Mile 484.5 near Soddy-Daisy, TN (Reference 11). BFN is located roughly 190.5 miles downstream of SQN, at Tennessee River Mile 294.0 near Athens, AL (Reference 12).

Figure 2 shows the location of each nuclear power plant and their respective upstream watersheds. Since all three plants are located along the same river, the contributory watershed area increases for the more-downstream locations. The WBN watershed covers 17,293 mi^2, the SQN watershed covers 20,653 mi^2, and the BFN watershed covers 27,213 mi^2.

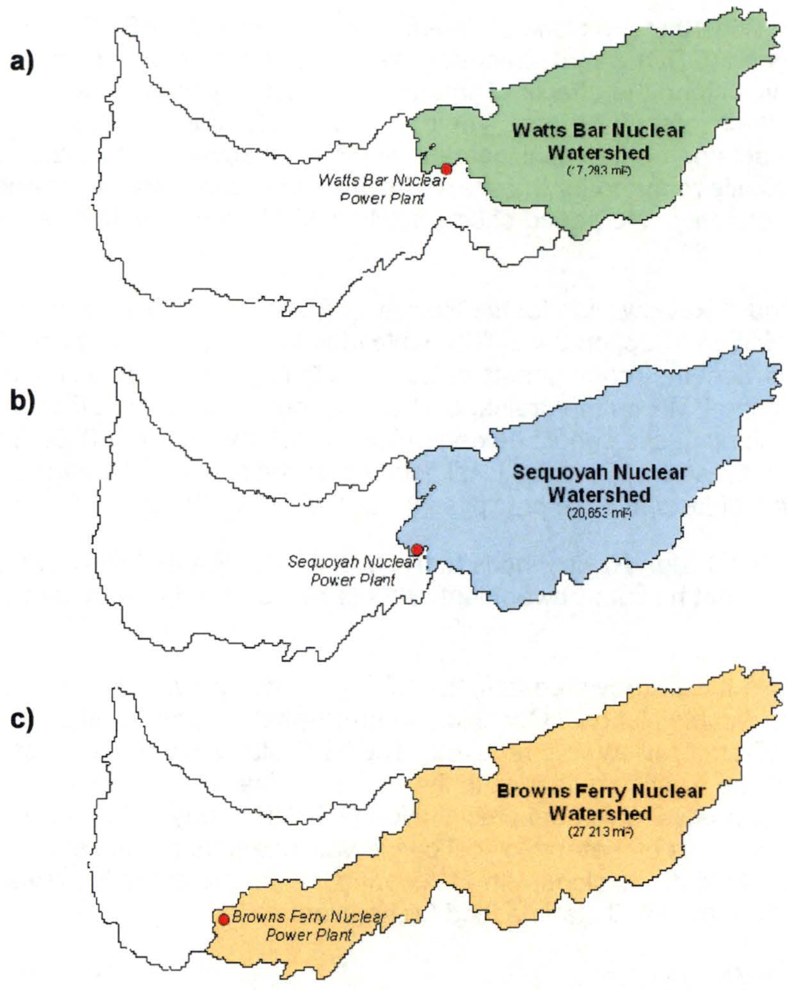

Figure 2. TVA nuclear watersheds.

The TVA drainage basin covers a topographically complex region of the southeastern U.S. The western portion, which contains relatively minor topographical relief, includes parts of the Gulf Plains and Central Plains; elevation in the western TVA drainage basin ranges from roughly 350 to 1,900 feet mean sea level (MSL). The central portion, which contains moderate topographic relief, includes parts of the Central Plains, Cumberland Plateau, and Great Valley; elevation in the central TVA drainage basin ranges from roughly 550 to 4,200 feet MSL. The eastern portion, which contains high topographic relief, includes parts of the Appalachian and Blue Ridge Mountains; elevation in the eastern TVA drainage basin ranges from roughly 850 to 6,700 feet MSL. WBN and SQN are located in the Great Valley, between the Cumberland Plateau and the Appalachian Mountains. BFN is located in the Gulf Plains.

2.0 REGULATORY EVALUATION

TVA submitted a TR that will support development of calculations to support future License Amendment Requests for revision of its operating nuclear plant design basis river and local flooding analysis, in accordance with Title 10 of the *Code of Federal Regulations* (10 CFR) Section 50.90, "Application for amendment of license, construction permit, or early site permit."

It is stated, in part, in Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, Appendix A, General Design Criterion (GDC) 2, that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as floods without loss of capability to perform their safety functions. The design bases for these structures, systems, and components shall reflect appropriate consideration of the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated.

NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition," Section 2.4.3, "Probable Maximum Flood (PMF) On Streams and Rivers," states that to meet the requirements of GDC 2 with regards to design bases for flooding in streams and rivers, the PMP on the drainage area that contributes to runoff on the stream network adjacent to the plant site should be determined. Similarly, NUREG-0800 Section 2.4.2, "Floods," states that estimates of potential local flooding on the site and drainage design should be based on estimates of local intense precipitation (LIP) or local PMP.

Regulatory Guide 1.59, "Design Basis Floods for Nuclear Power Plants," Revision 2, describes the design basis floods that nuclear power plants should be designed to withstand in accordance with GDC 2.

Since TVA's analysis in the TR deviated from the NRC guidance provided in NUREG-0800 of using the currently applicable National Oceanic and Atmospheric Administration (NOAA) NWS HMRs, a detailed NRC staff review was required. The NRC staff's review is described in this SE. There is currently no existing guidance to the staff or to licensees on how to produce or review a site specific probable maximum precipitation (SSPMP) study. Therefore, the staff reviewed the TR on the basis of meteorological conservatism and reasonableness. NRC staff subject matter experts held discussions with TVA during the course of the TR review regarding technical areas for which the NRC staff needed further clarification.

3.0 TECHNICAL EVALUATION

TVA computed PMP values across the TVA Basin (see Figure 1) using a uniform grid with a resolution of 0.025 × 0.025 degrees. A total of 17,938 grid cells were analyzed, with each grid covering an area of approximately 2.5 mi^2.

From Section 1.0 of the TR (Reference 3):

> This study provides Probable Maximum Precipitation (PMP) values for any drainage basin within the overall Tennessee Valley Authority (TVA) domain. The PMP values are valid for specific seasons based on storm type (see Section 4.5, Table 11), which is the time of the year when 100% of the PMP rainfall could occur. The PMP values are used in the computation of the Probable Maximum Flood (PMF). PMP values provided in this study are provided in place of PMP values in the four Hydrometeorological Reports (HMRs) for locations within the jurisdiction of TVA.

Since the latest HMR for the Tennessee River watershed was developed in the mid-1980s, much of the knowledge, data, and tools available now offers advantages over the NWS's HMR products. TVA identifies several issues with the HMRs, including the following:

- The limited number of analyzed storm events
- Lack of inclusion of storms that have occurred since the 1980s

- Inadequate processes used to address orographic effects
- Inconsistent data and procedures used among the HMRs
- Outdated procedures used to derive PMP (Section 1.1 of Reference 3)

As stated in Section 1.2 of the TR (Reference 3), the TVA PMP study aims to deliver reliable and reproducible PMP estimates for areas ranging from 1/3 square mile through the project domain and for durations ranging from 1 to 120 hours. In general, the TVA PMP study follows many procedures used in HMR development. Several updated procedures were also applied with consideration of meteorological and terrain interactions within the TVA drainage basin.

Consistent with the HMRs and other PMP approaches, TVA followed a storm-based approach, by which PMP is estimated based on historical storm observations. The major features of TVA's PMP estimation procedures are described in the remaining sections of this SE as follows:

- Storm selection
- Observed storm precipitation data
- Storm representative dew point selection and moisture maximization
- Dew point climatology and moisture adjustment
- Terrain adjustment using an orographic transposition factor (OTF)

Each section includes a description of TVA's submittal and the NRC staff's review findings.

NRC staff's review of the TR is site-specific and is limited to the application of aspects of the methodology and calculations of final SSPMP values that could potentially result in consequential flooding at TVA's three operating nuclear power plant sites. The NRC staff's review focuses only on assessing the adequacy of final SSPMP values given by the methodology with site-specific modifications as applied explicitly to the operating nuclear power plants with the TVA basin. The NRC staff did not assess the generic reasonableness of applying the methodologies for other sites and applications outside the watersheds directly affecting the TVA plants. Potential applications of the TR methodology for SSPMP estimates at other nuclear facility sites or watersheds, which are outside the scope of this review, would require further evaluation by NRC staff on a site-specific and case-by-case basis.

Appendix H of the TR (Reference 3) describes the use of a "PMP Evaluation Tool" to derive PMP values for watershed application. This tool is described as a Python scripting language-based tool designed to be run within the ArcGIS environment. The review of this PMP tool is outside the scope of this review of the PMP TR. Any licensee or applicant that seeks to make use of the PMP Evaluation Tool will be reviewed as part of the NRC staff's site-specific license amendment or application review.

The following SE sections describes the following topics:

- Storm Selection (Section 3.1)
- Transposition Limits (Section 3.2)
- Observed Storm Precipitation Data (Section 3.3)
- Storm Representative Dew Point Selection and Moisture Maximization (Section 3.4)
- Dew Point Climatology and Moisture Transposition Adjustment (Section 3.5)
- Terrain Adjustment using OTF (Section 3.6)
- Final PMP Results (Section 3.7)
- Limitations and Conditions (Section 4.0)

Each section includes a summary of TVA's submittal and the NRC staff's review findings.

3.1 Storm Selection

Storm selection involves the process of identifying and selecting historical storm events that are appropriate for inclusion in PMP development. This process is the essential first step in a storm-based PMP approach. The use of a particular storm for computing PMP across a region should consider the storm's transposition limits, or the geographic extent to which the storm can reasonably be applied for PMP estimation and whether it could ultimately influence the PMP values for the location being analyzed.

3.1.1 Topical Report Summary

To assess alternative PMP occurrences that may result from the variable weather patterns present in the TVA Basin, TVA evaluated three different storm types: general, local, and tropical storms. TVA associated general storms with heavy rainfall occurring over large areas and for long durations; they typically are associated with stationary or slow-moving fronts and are strongest and most active in the fall, winter, and spring (TVA's season of occurrence is September 15 through May 15). TVA associated local storms with extremely heavy rainfall occurring over small areas and for short durations; they are typically associated with severe weather systems known as mesoscale convective complexes and individual thunderstorms energized with Gulf of Mexico moisture transported into the storms by low-level jets. This storm type is most active in the warm season (TVA's season of occurrence is April 15 through October 31). TVA identified that tropical storms occurring in the TVA Basin can produce heavy rainfall from remnant tropical systems and are most active in summer and fall (TVA's season of occurrence is June 1 through October 31) (Sections 3.3 and 4.5 of Reference 3).

To develop storm-based PMP estimates, TVA first assembled a set of extreme storms identified through a review of historical storm archives and data. TVA leveraged information from previous and ongoing PMP studies, NOAA HMRs, US Army Corps of Engineers (USACE) storm studies, precipitation data from the NOAA National Centers for Environmental Information,[2] TVA rain and flood documents, and various other sources (Section 3.4.2 of Reference 3). Information about the rainfall data and data analysis is provided in Section 3.3 of this SE.

TVA identified historical extreme storms first by identifying a storm search domain (i.e., a region in which observed storm events could similarly have occurred in the TVA Basin). Through its initial search domain, TVA identified storms that could be transpositionable (i.e., reasonably relocated) to the TVA Basin and for which further analysis was needed. TVA identified the region in this study to include areas from the Canadian border to the Gulf of Mexico and from approximately 100 degrees west longitude to the Appalachians. TVA did not consider direct tropical storm landfalls as transpositionable to the TVA Basin.

TVAs identification of historically extreme storms resulted in a long-list of storms, which it subjected to additional review and refined through a series of investigations and discussions. TVA's common reasons for excluding a particular long-list storm from the analysis were that the storm was smaller than a larger nearby storm and that the storm was not transpositionable to the TVA Basin. In the end, TVA included 31 general storms, 19 local storms, and eight tropical storms on the short-storm list used for PMP development (Section 5.1 of Reference 3).

[2] Formerly (before 2015) the National Climatic Data Center.

3.1.2 NRC Staff Evaluation

The NRC staff finds the general storm selection approach to be reasonable. The staff reviewed the procedures used by TVA and found that they closely follow the HMR approach; however, the staff acknowledges that TVA developed a gridded PMP product that required high-resolution data sets and greater computational capabilities that were unavailable when the HMRs were developed. Using geographic information systems (GIS) and other resources, the transposition zones could be more easily defined based on high-resolution elevation and climatology datasets. Although these updated tools provide better accuracy and better definition of transposition zones, professional judgment is still required to assign transposition limits to each storm, as a more objective approach has not yet been developed.

Using data collected from the USACE Black Book (Reference 14), NRC staff analyzed the long-list storms to assess how close the USACE-reported observed precipitation characteristics were to the final TVA PMP values. The staff used a similar process to evaluate all USACE Black Book storms. The staff found that several storms (four long-list storms and three USACE Black Book storms) were identified that were near the PMP but were excluded from the final PMP short-storm list without clear justification. As a result, the staff issued RAI #2 (Reference 13) to request further explanation for excluding those storms. TVA provided the requested information related to each of the excluded storms and the reason for the exclusions. The staff found TVA's justification for excluding all seven storms in question to be reasonable.

3.2 Transposition Limits

As documented in NOAA HMR 51 (Reference 3), storm transposition is defined as "relocating isohyetal patterns of storm precipitation within a region that is homogenous relative to terrain and meteorological features important to the particular storm rainfall under concern."

3.2.1 Topical Report Summary

Given the variable weather patterns and topography across the TVA Basin, TVA subjected all storms to a transposition process. TVA defined transposition limits broadly across four transposition zones shown in Figure 3, with TVA's professional judgment being used to develop custom transposition limits for specific storms. TVA stated that these four zones are predominantly separated based on topography and climatology. TVA made decisions as to where to move specific storms based on the storm type, seasonality, isohyetal patterns, and moisture source.

Additional details on TVA's storm transpositioning process can be found in Section 4.3 of the TR (Reference 3).

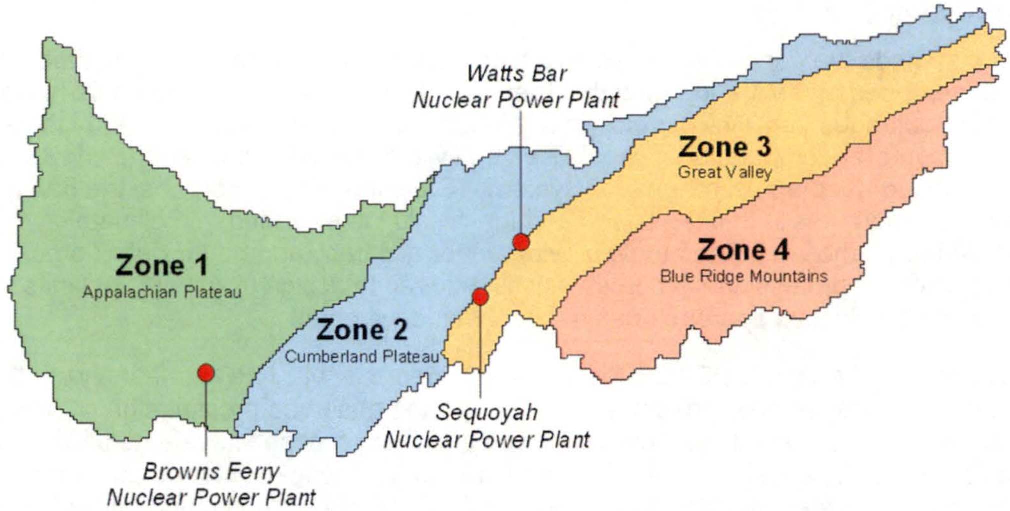

Figure 3. TVA drainage basin transposition zones.[3]

3.2.2 NRC Staff Evaluation

Based on the NRC staff's review of information provided in response to RAI #1 (Reference 13), the staff found that the majority of storms included transposition limits that conform to the TVA Zone boundaries; however, four storms contained custom transposition limits that did not conform to the TVA Zone boundaries. Consequently, the staff issued RAI #10 to seek justification for imposing custom transposition limits. In response to RAI #10 (Reference 13), TVA provided justification for imposing these custom transposition limits. Although staff found the justification for imposing latitudinal transposition limits for two storms to be reasonable, the staff needed additional information to justify the other two storms. With respect to TVA's decision to exclude two tropical storms from the protected region of the watershed based on the Tropical Storm Remnant 0.24 L-Cv contour developed by Schaefer et al. (Reference 4), TVA clarified that the L-Cv contour was used to inform transposition limits, but that the limits were ultimately informed by differences in the meteorological and topographical environments between the original storm center locations and the sheltered region of the TVA Basin. The references to the Tropical Storm Remnant 0.24 L-Cv contour were removed, as discussed in the response to RAI #10 (Reference 13). These clarifications were reflected in the final revised TR version. Therefore, the staff found TVA's justification for imposing custom transposition limits to be reasonable.

TVA's PMP calculation based on general, local, and tropical storm typing was considered reasonable by NRC staff due to the varying storms types commonly occurring in the TVA basin. The staff also found TVA's selection and application of transposition limits reasonable. Therefore, the staff found TVA's PMP calculation process and its selection of storms reasonable.

[3] Zone naming based on Section 4.3 of the topical report (TVA, 2018)

3.3 Observed Storm Precipitation Data

The observed storm precipitation data quantify the temporal and spatial distribution of rainfall for historical storms. Such data are typically quantified in the form of Depth-Area-Duration (DAD) data and presented as DAD curves or tables. A DAD value is expressed as a depth of precipitation occurring over a given area for a specified duration.

Following a storm-based approach, TVA further processed these observed data to estimate the maximum rainfall that could have occurred for that storm under an assumption of increased moisture availability and storm transposition.

3.3.1 Topical Report Summary

TVA analyzed all short-list storms included for PMP development using a suite of computer scripts called the Storm Precipitation Analysis System (SPAS). SPAS provided spatial and temporal characteristics for each storm using gridded storm analysis techniques. SPAS was originally developed in 2002 and provides DAD values for storm analyses. It uses precipitation gauge records and radar rainfall estimates with a base map interpolation approach to generate spatial and temporal rainfall information at high resolution. Using data from the location of maximum storm precipitation, TVA developed mass curves to show temporal rainfall distribution and characterize storms on a temporal basis. A more detailed description of the SPAS data sources and procedures used by TVA is available in Appendix G of the TVA TR (Reference 3).

In some cases, a single storm event may produce rainfall across wide areas and produce significant rainfall events that are separated in time or space. Using professional judgment, TVA geographically separated such storms into multiple storm centers represented by separate DAD tables. In these cases, the SPAS number (i.e., the unique SPAS-analyzed storm identification number) remained the same in TVA's analysis, but TVA categorized the separate storm centers into different "zones" and analyzed them as individual events.

3.3.2 NRC Staff Evaluation

ENERCON provides safety-related products and services to the nuclear power industries. The ENERCON quality assurance program is comprised of the Quality Assurance (QA) Manual and the associated implementing procedures. The quality assurance program meets the following requirements:

- Title 10 Part 50 Appendix B and Title 10 Part 21 of the Code of Federal Regulations: QA requirements of the U.S. Nuclear Regulatory Commission for safety applications
- ANSI [American National Standards Institute] N45.2-1977 and NQA-1-2008 / NQA-1a-2009: QA program standards endorsed by the US Nuclear Regulatory Commission as acceptable methods for meeting the requirements of 10 CFR 50 Appendix B.

ENERCON applied their quality assurance program to SPAS for the purpose of dedicating the software for use in a nuclear licensing action.

NRC staff completed an inspection of the SPAS software from November 14-18, 2016, in order to assess ENERCON's compliance with provisions in 10 CFR Part 50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants." The initial NRC inspection report (Reference 16) provided a notice of nonconformance, finding that ENERCON failed to verify the processing of radar data input into SPAS. A subsequent response to the

NRC inspection report (Reference 17) alleviated these concerns for using SPAS results in an NRC licensing action. This inspection specifically evaluated ENERCON's implementation of quality activities associated with the commercial grade dedication of the SPAS 9.5 and 10.0 software.

NRC staff did not review the raw or quality-controlled data used for the TR storms and instead reviewed the final DAD results. For historical storms previously evaluated in the Black Book (Reference 14), staff compared the SPAS DAD against the USACE DAD and found TVA's DAD data to be reasonable.

NRC staff reviewed the separation of single storm events into multiple storm centers and found TVA's treatment to be acceptable. In addition, the transposition limits applied to each storm center were found to be reasonable. Overall, staff found TVA's storm precipitation data to be reasonable.

3.4 Storm Representative Dew Point Selection and Moisture Maximization Using In-Place Maximization Factor

Storm representative dew point data are often used as a surrogate to estimate the theoretical atmospheric moisture supply (i.e., precipitable water) available during historical storm events. Although many factors contribute to a precipitation event, moisture availability is a critical component. It was used in the HMRs for maximizing an observed storm event by increasing the observed dew point temperature to a theorized maximum value based on dew point temperature climatology. TVA used a similar storm maximization process. This section describes the process TVA used to analyze storm representative dew point temperature and perform moisture maximization.

3.4.1 Topical Report Summary

For each short-list storm, TVA estimated the storm representative dew point using either surface dew point or sea surface temperature (SST) data. To identify the storm's moisture source, TVA used the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)[4] model for storms occurring in 1948 or later. TVA stated that HYSPLIT computes moisture travel paths using three-dimensional wind speed data from archived data sets; TVA ran HYSPLIT using reanalysis data[5] (available since 1948). For storms occurring before 1948, TVA selected moisture sources based on meteorological information available (e.g., daily weather maps) or historical storm assessments (e.g., NWS documents). Based on the identified moisture source region, TVA selected a set of suitable stations for determining the storm representative dew point. Since heavy precipitation is assumed to correspond to periods of high moisture availability, TVA selected data corresponding to high dew point or SST. In general, TVA selected these data during periods before significant rainfall occurred and at locations upwind of the storm center and outside the rainfall region.

For a storm with a land-based moisture source, TVA computed a storm representative dew point based on weather station observations of dew point temperatures. While the HMRs computed a 12-hour persisting dew point temperature, TVA computed a maximum average dew point. For each storm evaluated, TVA computed the maximum 6-, 12-, or 24-hour average dew point, with local storms generally using 6- or 12-hour values and general/tropical storms using

[4] http://ready.arl.noaa.gov/HYSPLIT.php, accessed 6/27/2018

[5] https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html, accessed 6/27/2018

12- or 24-hour values. Typically, TVA averaged data from multiple stations to provide a more reliable spatial representation of dew point.

For a storm with a sea-based moisture source, TVA computed a storm representative dew point based on average daily SST observations because dew point observations are typically not available over water. These SST observations are typically taken aboard moving vessels.

For two historical storms, TVA stated that sufficient data were not available to compute storm representative dew point temperatures. In these cases, TVA converted historical 12-hour persisting dew point temperatures from the USACE Black Book (Reference 14) to maximum average dew point temperatures using a heuristic estimate developed during previous SSPMP analyses. TVA made heuristic adjustments to one general storm and one local storm whereby the 12-hour persisting dew point was converted to a maximum average dew point using a + 2 °F and + 7 °F adjustment, respectively.

For all storms, TVA rounded the storm representative dew point to the nearest 0.5°F. For additional information on TVA's storm representative dew point determination process, see TR Section 4.1.2 (Reference 3).

Following traditional PMP calculation procedures, TVA performed moisture maximization, which is defined by WMO (Reference 4) as "the process of adjusting observed precipitation amounts upward based on the hypothesis of increased moisture inflow to the storm." TVA calculated the storm maximization using the In-Place Maximization Factor (IPMF). TVA limited IPMF values to a maximum of 1.5, which was largely consistent with the HMRs; a minimum IPMF of 1.00 is possible. Since the IPMF is a factor applied to the storm itself, the value remains constant regardless of where the storm is transpositioned.

To maximize the storm, TVA used dew point climatology for storms with land-based moisture sources, whereas SST climatology was used for storms with sea-based moisture sources.

The IPMF is calculated according to Eq. (1):

$$IPMF = \frac{PW_{Max,Srep,SE}}{PW_{Storm,Srep,SE}} \qquad (1)$$

where

> $PW_{Max,Srep,SE}$ = the precipitable water calculated using the 100-year recurrence interval dew point (or +2σ SST) at the storm representative dew point location from the storm elevation to the top of the atmosphere.
>
> $PW_{Storm,Srep,SE}$ = the precipitable water calculated using the storm representative dew point (or SST) at the storm representative dew point location from the storm elevation to the top of the atmosphere.

TVA estimated precipitable water depths based on the relationship between dew point and precipitable water provided in the HMR 55A precipitable water tables (Reference 18). TVA rounded dew points (or SSTs) to the nearest 0.5°F. TVA used the storm elevation for both the numerator and the denominator in the IPMF calculation and it used the elevation at the storm center location rounded to the nearest 100 feet (or nearest 500 feet for elevations above 5,000 feet MSL).

For additional information on TVA's moisture maximization process, see TR Section 5.1.1 (Reference 3).

3.4.2 NRC Staff Evaluation

NRC staff found TVA's use of maximum average dew points (instead of 12-hour persisting dew points) to be a reasonable departure from the HMRs. Also, the staff found TVAs use of HYSPLIT in determining moisture inflow trajectories and identifying moisture source locations to be reasonable.

NRC staff issued RAI #2 (Reference 13) to ask TVA to provide the observed hourly dew point data sheets for all short-list storms. This information helped staff review and understand the raw data used to develop storm representative dew points for all storms. RAI #13 (Reference 13) was issued asking TVA to clarify the duration analyzed for the Warner Park, TN, storm representative dew point; TVA verified that a 12-hour duration was used.

As a part of its assessment, the staff reviewed the rainfall mass curves, HYSPLIT trajectories, and storm representative dew point information that TVA provided in response to RAI #1 and RAI #2 (Reference 13). Staff independently evaluated these features to assess the reasonableness of TVA's application and found them to be acceptable.

NRC staff's review of this information revealed that, for some storms, TVA's original storm representative dew point selection used dew point data that were observed at locations far upwind of the storm center and during time frames in which significant rainfall had already occurred. The staff found that conducting the analysis in this way could inadequately represent the storm characteristics and (in these cases) result in PMP underestimation (a higher storm representative dew point will result in a lower IPMF value), since the relatively higher moisture observed could not have induced the observed rainfall. The staff performed sensitivity analysis, which revealed moderate increases in PMP when alternative, more physically justified storm representative dew points were used for these storms. Consequently, RAI #11 (Reference 13) was issued asking TVA to provide justification and correction of the selected dew point values. In response to RAI #11, TVA corrected the storm representative dew point values for four controlling storms to adopt NRC's values and recomputed the general and tropical PMPs (see Section 4.1.2 of Reference 3). Staff found TVA's remaining storm representative dew point values to be reasonable. After confirming the reasonableness of TVA's dew point climatology values (see SE Section 3.5 for more information), staff found TVA's IPMF values to be reasonable.

3.5 Dew Point Climatology and Moisture Transposition Adjustment

Using dew point climatology data for storm adjustment offers a method to increase a storm's observed DAD from an observed measure of storm moisture availability (i.e., storm representative dew point) to a reasonable upper limit of moisture availability (e.g., 100-year recurrence interval dew point climatology). Since historical events often occur when moisture availability is below maximum levels, a conventional HMR assumption is that more rainfall could occur if more moisture is available. By using dew point climatology data, the increased rainfall production can be quantified through storm moisture maximization.

The HMRs used a moisture transposition adjustment process to estimate the difference in maximum moisture available to a storm when it is moved from the in-place moisture source location to a transpositioned moisture source location. A similar storm maximization process was used by TVA.

3.5.1 Topical Report Summary

Dew Point Climatology

To estimate a "maximized" level of moisture that could have been available to a storm and to compare moisture availability across wide areas in transpositioning storms, TVA developed climatologies of dew point temperature and SST. TVA's process of computing dew point climatology involved several steps, which included calculating annual maximum dew points for each calendar month, performing frequency analysis, and conducting spatial interpolation and manual smoothing.

Historically, the HMRs used monthly maximum 12-hour persisting dew point temperatures to maximize storms. In this study, TVA produced monthly dew point climatologies for the 100-year recurrence interval of the annual maximum series data for individual stations. TVA developed these climatologies for storms with land-based moisture sources for 6-, 12-, and 24-hour durations using the NOAA TD3505 Integrated Surface Data set. For storms with sea-based moisture sources, TVA used monthly SST climatologies for two standard deviations above the mean SST. For both the land-based dew point climatologies and SST climatologies, TVA produced maps using manual smoothing of point-based climatologies.

TVA's climatological maximum dew point and SST maps are provided in Appendix C of the TR. For additional information on TVA's dew point climatology development and application processes, see TR Sections 4.1 and 4.2 (Reference 3).

Moisture Transposition Adjustment

When moving a storm from its originally observed location to a new location using storm transposition, TVA accounted for changes in moisture availability by using the moisture transposition factor (MTF). The MTF represents the ratio between the maximized moisture available at the storm transposition dew point location and the moisture available at the storm representative dew point location. TVA based its precipitable water estimates on the 100-year recurrence interval dew point (or +2σ SST) rounded to the nearest 0.5°F. MTF values above and below 1.00 are possible, and TVA placed no limits on the calculation.

TVA calculated the MTF according to Eq. (2):

$$MTF = \frac{PW_{Max,ST,SE}}{PW_{Max,SRep,SE}} \tag{2}$$

where

$PW_{Max,ST,SE}$ = the precipitable water calculated using the 100-year recurrence interval dew point (or +2σ SST) at the storm transposition dew point location from the storm elevation to the top of the atmosphere.

$PW_{Max,SRep,SE}$ = the precipitable water calculated using the 100-year recurrence interval dew point (or +2σ SST) at the storm representative dew point location from the storm elevation to the top of the atmosphere.

TVA rounded the dew points (or SSTs) to the nearest 0.5°F. TVA used the storm elevation for both the numerator and the denominator in the MTF calculation and rounded the elevation at the storm center location to the nearest 100 feet (or nearest 500 feet for elevations above 5,000 feet MSL).

For a few storms, TVA modified the MTF application. Since precipitation frequency data were not available for three general storms from Texas, TVA did not calculate an OTF (see SE Section 3.6). Instead, TVA modified the MTF values to include an elevation-based vertical adjustment to account for the elevation-based differences in moisture availability between the storm center location and the target grid locations. In addition, the MTF for the Holt, MO, local storm was set to 1.00 because TVA concluded moisture availability would not increase in moving from west to east.

For additional information on TVA's moisture transposition adjustment process, see TR Section 5.1 (Reference 3).

3.5.2 NRC Staff Evaluation

NRC staff found TVA's use of 100-year recurrence interval dew point climatologies based on station annual maximum series data to be a reasonable departure from the HMRs.

The NRC staff issued RAI #4 (Reference 13) asking TVA to provide a copy of the digital dew point climatology GIS data layers used for PMP development. Staff reviewed the dew point climatology data provided by TVA in response to RAI #1 and RAI #4 and independently evaluated these features to assess the reasonableness of TVA's application. The staff's primary climatology-related concern with TVA's original TR was the use of a data set (NOAA TDL [Techniques Development Laboratory]) that was not quality controlled for land-based dew point temperatures although a higher quality-controlled dataset was available (NOAA TD3505).

Based on the NRC staff's independent analysis results that suggested higher PMP values would result from using NOAA TD3505 data, the staff issued RAI #12 (Reference 13) requesting that updated dew point climatologies be developed using the NOAA TD3505 data set and applied to the general, local, and tropical PMPs. In response to RAI #12, TVA updated the TR and its dew point climatology using the NOAA TD3505 data set with data available through 2017 (see Section 4.1.1 of Reference 3). The staff compared TVAs initial submittal using NOAA TDL data to TVA's final dew point climatologies and found that TVA's updated dew point climatology was more reliable and yielded higher PMP values.

3.6 Terrain Adjustment using Orographic Transposition Factor

The use of terrain adjustment also is necessary when a historical storm is transpositioned from its original location to a point of interest for PMP development. Several different approaches have previously been used in hydrometeorological studies to quantify a terrain transposition adjustment, with a common goal of accounting for how differences in topography or orographic effects may influence PMP.

3.6.1 Topical Report Summary

TVA used an OTF to account for terrain adjustments. Use of this method represents a major departure from the HMR's process-based methodology and philosophy.

The calculations described in SE Sections 3.4 and 3.5 represent processes similar to those used in the HMRs in which an observed precipitation event is (1) moisture maximized using the IPMF and (2) geographically transpositioned (on a latitude-longitude plane) using the MTF. Although it captures spatial variation in moisture, the MTF may not adequately capture the effects of terrain—hence the need for a terrain adjustment. Some NOAA HMRs account for terrain effects on PMP adjustment using the Storm Separation Method, whereas previous PMP studies use the barrier adjustment factor (BAF). For this study, TVA used the OTF.

TVA computed the OTF by assessing the relationship between precipitation frequency depths at the target and source locations. TVA collected precipitation frequency data from Volumes 2, 8, and 9 of NOAA Atlas 14 (Reference 19; Reference 20, Reference 21, respectively). For General and Tropical storms (except the three Texas storms), TVA calculated the OTF using a linear regression developed based on 24-hour precipitation frequency depths for various recurrence intervals (10 to 1,000 years). For the three Texas storms, since NOAA Atlas 14 precipitation frequency depths were not available, TVA uniformly set the OTF to 1.00.

TVA fitted the NOAA Atlas 14 values to a linear regression line, shown in Eq. (3), to estimate *m* and *b*:

$$P_{Atlas14,Site} = m^{*}P_{Atlas14,SC}+b \qquad (3)$$

where

$P_{Atlas14,Site}$ = target grid point rainfall frequency depth (in.) across various selected durations and return periods from Atlas 14.

$P_{Atlas14,SC}$ = storm center grid point rainfall frequency depth (in.) across various selected durations and return periods from Atlas 14.

m = slope.

b = intercept (in.).

TVA then used the linear relationship determined through the target-source regression fit in Eq. (3) to determine the orographically adjusted rainfall for all grid points based on the SPAS-analyzed in-place rainfall using Eq. (4):

$$P_{TVA,Site} = m^{*}P_{TVA,SC}+b \qquad (4)$$

where

$P_{TVA,Site}$ = orographically adjusted rainfall (in.) at the targeted grid point.

$P_{TVA,SC}$ = SPAS-analyzed in-place rainfall (in.).

m = slope from Eq. (4).

b = intercept (in.) from Eq. (4).

Rearranging Eq. (4) yields the OTF, as shown in Eq. (5):

$$OTF = \frac{P_{TVA,Site}}{P_{TVA,SC}} = m + \frac{b}{P_{TVA,SC}} \qquad (5)$$

Since NOAA Atlas 14 values (and hence OTF values) show discrepancies across some volume boundaries, TVA adjusted the raw general and tropical storm OTF calculations throughout the southwest portion of the TVA Basin to uniformly set all OTF values to a single value based on what was considered a representative location.

For the calculation of LIP at the three nuclear power plant sites, TVA followed a different OTF calculation approach, which has been used in other recent PMP studies. Rather than performing linear regression, TVA calculated the OTF using the ratio between the target and source 6-hour, 100-year recurrence interval precipitation frequency depth. In addition, since PMP values in parts of the TVA Basin would otherwise exceed world record rainfall values, TVA set the OTF to 1.00 for the Simpson, KY, storm and added a vertical elevation component to the MTF calculation.

From Section 5.1.1.5 of the TR (Reference 3):

> For the development of the LIP values at SQN and WBN, the OTF adjustment was not used for the Simpson, KY July 1939 storm (the OTF was set to 1.00). Instead, an adjustment using the HMR standard vertical evaluation (approximately 0.8% per 100 feet difference) was applied as part of the MTF process to account for differences in elevation between the source storm location and the nuclear site. In addition, the 6-hour 100-year precipitation frequency climatology was used in the OTF calculations for all storms used in the LIP analysis. This replaced the use of the linear fit method used in the OTF calculations for all other grids within the TVA domain. This was done based on discussion with the NRC to better align with current OTF calculation processes utilized since the completion of this study. The result was a transposition factor of 1.06 between the Simpson, KY storm center and the SQN and WBN sites. This approach was a more conservative application to the Simpson, KY July 1939 storm transposition than the normalized OTF approach applied to the PMP calculations. This adjustment had no effect on the BFN location because the Simpson, KY July 1939 storm is not transpositionable to that location. In addition, the Smethport, PA July 1942 storm was not transpositionable to the SQN, WBN, or BFN locations and therefore no other adjustments were applied to that storm for LIP considerations.

The OTF calculation using the 100-year recurrence interval ratio is shown in Eq. (6):

$$OTF = \frac{P_{Atlas14,100\text{-}y,Site}}{P_{Atlas14,100\text{-}y,SC}} \tag{6}$$

For additional information on TVA's terrain adjustment process, see TR (TVA, 2018), Sections 3.5, 5.1, and 5.5.4.

3.6.2 NRC Staff Evaluation

Despite the NRC staff's concerns regarding the lack of a physical basis for the OTF and its high sensitivity to the internal variability of Atlas 14, the staff found TVA's final SSPMP results to be adequate for application to the three operating TVA nuclear power plant sites. The staff made this determination following its detailed review of TVA's OTF calculations, modifications included in the revised TR, and review of sensitivity analyses.

The NRC staff issued RAI #6 (Reference 13), which asked TVA to provide justification for applying sizable reductions in OTF in transpositioning some example storms across orographically similar zones. The examples cited in the RAI were the Warner, OK, and Fall River, KS, storms for which OTF values in TVA Zone 1 were approximately 0.80 and 0.75, respectively; these represented large decreases, although the storm centers shared similar orographic and climatologic characteristics with Zone 1. In addition, OTF values for the Smethport, PA, storm were much lower than expected, although the OTF values had been manually adjusted using normalization. In response to RAI #6, TVA provided meteorological reasoning for why OTF values varied for the examples cited. To better understand the sensitivity of OTF, the staff conducted independent evaluation using the conventional BAF-based approach. Overall, the staff considers the OTF to be a highly uncertain and sensitive adjustment for PMP calculation purposes, particularly in relatively non-orographic regions (e.g., western parts of the TVA drainage basin). However, given that the OTF-based SSPMP values were similar to the estimated BAF-based SSPMP values for the three nuclear power plant watersheds, the staff found TVA's use of OTF for the three nuclear power plants to be adequate for the purposes of the TVA TR.

The NRC staff issued RAI #7 (Reference 13), which asked TVA to provide justification for including significant OTF reductions for two local storms. In the original TR (Reference 1), TVA included normalization adjustments to the Smethport, PA, and Simpson, KY, OTF values whereby all OTF values were decreased proportionally, so that the maximum OTF for any grid in the TVA Basin was 1.00. This effectively decreased all OTF values for both storms by over 50%. In response to RAI #7, TVA revised the TR to address this concern by updating the LIP calculation for the three nuclear power plant sites to include Simpson, KY, OTF values of 1.00 and elevation-adjusted MTF values. Since the Smethport, PA, storm was not transpositioned to any of the nuclear power plant sites, TVA did not change its OTF calculation. Staff found TVA's final LIP calculation at the three nuclear power plant sites to be reasonable and these changes were included in an update to the TR.

The NRC staff issued RAI #8 (Reference 13), which asked TVA to justify the use of NOAA Atlas 14 for calculating the OTF and for using the best fit linear trend method in lieu of the 100-year recurrence interval ratio method for calculating the OTF. In response to RAI #8, TVA provided additional details related to NOAA Atlas 14 and its use in computing OTF values. Although staff remains concerned with some technical details of using NOAA Atlas 14 values for PMP application, the NOAA Atlas 14 data represent the best-available public data and are reasonable for use. TVA also implemented changes in how the OTF was calculated for LIP at the three nuclear power plants, choosing to use the 100-year recurrence interval ratio method instead of the best fit linear trend method. Consequently, staff found TVA's calculation of OTF using NOAA Atlas 14 to be reasonable for the purposes of the TVA TR.

The NRC staff issued RAI #9 (Reference 13), which asked TVA to explain some OTF calculation inconsistencies identified during the review of TVA files. In response to RAI #9, TVA confirmed that the inconsistencies identified were not problematic and were the results of manual adjustments to the OTF calculation in portions of the TVA Basin to correct two features. One manual adjustment ensured that OTF values remained consistent along the border between NOAA Atlas 14 Volume 2 and Volume 9. The other adjustment ensured that OTF values in the complex terrain near the Georgia–North Carolina border resembled the underlying topography and that they were reasonable given disparities between the two volumes. Staff found TVA's explanations reasonable.

Altogether, the NRC staff found TVA's final OTF-based SSPMP values to be adequate for the general and tropical PMP and for the LIP of the three nuclear power plants.

3.7 Final Probable Maximum Precipitation Results

Following the PMP development and calculation approaches described above, TVA produced final, gridded PMP depths for general, local, and tropical PMP. The results are provided in Appendix A of the TR (Reference 3) and include a 72-hour, 17,306-mi^2 WBN basin-averaged General and Tropical PMP of 12.57 inches and 10.50 inches, respectively. Compared with the HMR 41 June 72-hour, 7,980-mi^2 PMP of 17.05 inches, these values are 26.3% and 38.4% lower, respectively. This (and additional) summary information is provided in Section 5.8 of the TR.

A separate LIP calculation specific to the three nuclear power plants was also conducted by TVA. Compared with the local PMP, the site-specific LIP calculations included a unique treatment of the Simpson, KY, storm as described in Section 3.6 of this SE and Section 5.1.1.5 of the TR (TVA, 2018). While the local PMP provides localized, small-scale PMP estimates across the TVA Basin, nearly all data provided is outside the scope of the NRC's review, as stated in Section 3.0; instead, the LIP depths provide site-specific calculations relevant for on-site flooding at each of TVA's three operating nuclear power plants which may result from LIP over the powerblock. The final 1-hour, 1-mi^2 LIP depths were 11.60, 13.81, and 13.81 inches at BFN, WBN, and SQN, respectively. Additional information is provided in Section 5.4.4 of the TR.

Section 5.6.1 of the TR (Reference 3) describes a PMP evaluation tool which is used to summarize SSPMP values for specified watersheds in the TVA drainage basin. The functionality of this PMP evaluation tool is outside of the scope of the NRC's review for TVA's TR. It is anticipated that TVA will use the tool for future hydrological modeling work submitted to NRC and the tool would be reviewed by the NRC staff at that time.

4.0 LIMITATIONS AND CONDITIONS

The scope and NRC staff review of the TR is limited to the evaluation of PMP depths calculated in the TR (Reference 3) that are relevant to potential flooding at the operating nuclear plants in the TVA basin. Any nuclear power plant wishing to utilize the methodology discussed in this SE must submit a license amendment under 10 CFR 50.90 for site-specific review of any amendment or application. As part of the amendment or application to utilize this methodology, any licensee or applicant needs to fully explain and validate the approach and methods used in developing the PMP values. Any PMP values not relevant to the operating TVA reactors are not subject to NRC approval under this review. As stated in Section 6.0 of the TR (Reference 3):

> [The TR] provides PMP values which can be used to support a license amendment request to perform an assessment of river flooding effects and local intense precipitation effects at the operating nuclear plant sites in the Tennessee Basin. NRC review of this report is applicable only to these effects and their impact on these three sites.

TVA did not include examples or illustrations to address how the gridded-precipitation values derived in the TR will be applied during future surface hydrology evaluations. Therefore, the staff did not review the aforementioned PMP evaluation tool and its use in the hydrologic analysis of the TVA nuclear sites. An NRC staff review of TVA's PMP evaluation tool may be performed during the subsequent LAR hydrologic reviews.

5.0 CONCLUSION

Following detailed review and discussion with TVA and a subsequent update to the PMP calculation, NRC staff found TR TVA-NPG-AWA16 (Reference 3) to provide reasonable estimates of PMP for operating nuclear power plants in the TVA basin.

The storm-specific DAD data, transposition limits, IPMF values, MTF values, and OTF values used as input to the PMP evaluation tool were reviewed and deemed adequate for use in TVA's subsequent hydrological modeling work related to PMP. The PMP evaluation tool was not assessed within the scope of the NRC staff's review and would require subsequent review and approval. The NRC staff concludes that the TR PMP estimates, when correctly applied, will contribute to the assurance that the three TVA operating plants will maintain compliance with requirements in 10 CFR 50 Appendix A, GDC 2, governing that structures, systems, and components important to safety shall be designed to withstand the effects of natural phenomena such as floods without loss of capability to perform their safety functions. Therefore, the NRC staff finds the TR PMP estimates acceptable, with the above noted limitations and conditions, for compliance with the NRC regulations.

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Principal Contributor: K. Quinlan

Date: March 18, 2019

SECTION B

TOPICAL REPORT

TVA-NPG-AWA16-A

TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis, Calculation CDQ0000002016000041, Revision 1

Portions of this document contain Proprietary Information. Specifically, the information in Section B, Appendix H, Attachment 1, "SPAS Hourly Rainfall ASCII Grids," is considered proprietary. When separated from Section B, Appendix H, Attachment 1, this document is decontrolled.

TVA NUCLEAR CALCULATION COVERSHEET / CTS UPDATE

REV 0 EDMS/RIMS NO.	CTS TYPE:	EDMS TYPE:	EDMS ACCESSION NO (N/A for REV. 0)
B41160321001	Calculation	CALCULATIONS (NUCLEAR)	B41 180620 002

Calc Title: TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis

	ORG	PLANT	BRANCH	NUMBER	CUR REV	NEW REV
CALC ID	NUC	GEN	CEB	CDQ0000002016000041	000	001

CTS UPDATE ONLY ☐
(Verifier and Approval Signatures Not Required)

NO CTS CHANGES ☐
(For calc revision, CTS has been reviewed and no CTS changes required)

UNIT (check one)	SYSTEMS	UNIDS
0 ☒, 1 ☐, 2 ☐, 3 ☐	0 0 0	N/A

ECP, N/A	APPLICABLE DESIGN DOCUMENT(S)	CLASSIFICATION
SQN 23628, WBN 66358	N/A	E

QUALITY RELATED?	SAFETY RELATED? (If yes, QR = yes)	UNVERIFIED ASSUMPTION	SPECIAL REQUIREMENTS AND/OR LIMITING CONDITIONS?	DESIGN OUTPUT ATTACHMENT?	SAR/TS and/or ISFSI SAR/CoC AFFECTED
Yes ☒ No ☐	Yes ☒ No ☐	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☐ No ☒	Yes ☒ No ☐

CALCULATION NUMBER REQUESTOR	PREPARING DISCIPLINE	VERIFICATION METHOD	NEW METHOD OF ANALYSIS
Name: Anubhav Gaur PHONE: 405-722-7693	C	Design Review	☒ Yes ☐ No

PREPARER (PRINT NAME AND SIGN)	DATE	CHECKER (PRINT NAME AND SIGN)	DATE
Bill Kappel [signature]	6/18/2018	Doug Hultstrand [signature]	6/19/2018
VERIFIER (PRINT NAME AND SIGN)	DATE	APPROVAL (PRINT NAME AND SIGN)	DATE
Doug Hultstrand [signature]	6/19/2018	for B. Simril / [signature]	6/20/18

STATEMENT OF PROBLEM/ABSTRACT

This calculation describes the work performed to calculate the Probable Maximum Precipitation for any location within the overall Tennessee Valley Authority (TVA) basin and Local Intense Precipitation (LIP) at BFN, SQN, and WBN sites. This report describes an overview of the work performed and the results of the PMP values for all locations within the TVA region. The report outlines the process, data, and methods used to analyze storms and develop the PMP values. Results and background data are provided and discussed, along with comparisons to previous PMP work in the region. Relevant background data, input calculation, and reference materials are included in various appendices.

This calculation contains electronic attachments and must be stored in EDMS/ECM as an Adobe.pdf file to maintain the ability to retrieve the electronic attachments. computer files are stored in Filekeeper under the reference number noted on the Storage Information Sheet.

This calculation will support development of calculations to support License Amendment Requests for revision of the Watts Bar, Sequoyah, and Browns Ferry Nuclear Plant design basis river and local flooding analysis. This calculation will also support revisions to the Flood Hazard Re-evaluation Reports (FHRR) for each site. This calculation will support a re-evaluation of flood mechanism parameters to demonstrate the river and local flooding mechanisms are bounded as documented in the FHRR and Focused Evaluations for SQN, WBN, and BFN.

Revision 1 of this calculation incorporated TVA responses to NRC Requests for Additional Information TVA Licensing Letter CNL-18-044, dated April 19, 2018.

MICROFICHE/EFICHE Yes ☐ No ☒ FICHE NUMBER(S) N/A

TVA NUCLEAR CALCULATION COVERSHEET / CTS UPDATE

CALC ID	ORG	PLANT	BRANCH	NUMBER	REV
	NUC	GEN	CEB	CDQ0000002016000041	001

BUILDING	ROOM	ELEVATION	COORD/AZIM	FIRM
NA	N/A	N/A	N/A	ENERCON

CATEGORIES

KEYWORDS (A-add, D-delete)

ACTION (A/D)	KEYWORD	A/D	KEYWORD
A	Fukushima		
A	Probable Maximum Flood		
A	Beyond Design Basis		
A	Concrete		
A	PMF		

CROSS-REFERENCES (A-add, D-delete)

ACTION (A/D)	XREF CODE	XREF PLANT	XREF TYPE	XREF NUMBER	XREF REV
A	S	GEN	CALC	CDQ0000002015000034	0
A	S	GEN	CALC	CDQ0000002015000035	0
A	S	GEN	CALC	CDQ0000002016000044	0
A	S	GEN	CALC	CDQ0000002017000070	0
A	S	GEN	CALC	CDQ0000002017000055	0
A	S	GEN	CALC	CDQ0000002017000056	0
A	S	GEN	CALC	CDQ0000002017000057	0
A	S	GEN	CALC	CDQ0000002017000058	0
A	S	GEN	CALC	CDQ0000002017000059	0
A	S	GEN	CALC	CDQ0000002017000060	0
A	S	GEN	CALC	CDQ0000002017000061	0
A	S	GEN	CALC	CDQ0000002017000062	0
A	S	GEN	CALC	CDQ0000002017000064	0
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A	S	GEN	CALC	CDQ0000002017000072	0

CTS ONLY UPDATES:
Following are required only when making keyword/cross reference CTS updates and page 1 of form NEDP-2-1 is not included:

PREPARER (PRINT NAME AND SIGN)	DATE	CHECKER (PRINT NAME AND SIGN)	DATE

PREPARER PHONE NO.	EDMS ACCESSION NO.

TVA NUCLEAR CALCULATION COVERSHEET / CTS UPDATE

CALC ID	ORG	PLANT	BRANCH	NUMBER	REV
	NUC	GEN	CEB	CDQ0000002016000041	001

BUILDING	ROOM	ELEVATION	COORD/AZIM	FIRM
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CATEGORIES

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A	Fukushima		
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A	Concrete		
A	PMF		

CROSS-REFERENCES (A-add, D-delete)

ACTION (A/D)	XREF CODE	XREF PLANT	XREF TYPE	XREF NUMBER	XREF REV
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A	S	GEN	CALC	CDQ0000002017000078	0

CTS ONLY UPDATES:
Following are required only when making keyword/cross reference CTS updates and page 1 of form NEDP-2-1 is not included:

PREPARER (PRINT NAME AND SIGN)	DATE	CHECKER (PRINT NAME AND SIGN)	DATE
PREPARER PHONE NO.	EDMS ACCESSION NO.		

TVA NUCLEAR CALCULATION RECORD OF REVISION	
Calculation Identifier. CDQ0000002016000041	
Title	TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis
Revision No.	DESCRIPTION OF REVISION
0	Initial Issue: 112 Pages SAR and ISFSI SAR for BFN, SQN, and WBN have been reviewed by Karen Carboni and this revision of the calculation has no impact. Tech Specs and ISFSI CoC have also been reviewed and determined not to be affected. This is a beyond design basis calculation for BFN, SQN, and WBN. However, this calculation is a safety-related calculation and may be used to update design basis.
1	This Calculation contains 340 Pages The SAR and ISFSI SAR and Tech Specs and ISFSI CoC for BFN, SQN and WBN have been reviewed. Since the PMP defined in this calculation supports a proposed change to the WBN and SQN design basis and will be submitted to the NRC for prior review under the License Amendment Request (LAR) process, the SARs for WBN and SQN are affected. Additionally, the ISFSI SAR and ISFSI CoC for WBN and SQN are potentially affected but cannot be fully evaluated until the flooding simulation calculations are completed. Since this calculation is beyond design basis for BFN, the FSAR/Tech Specs/ISFSI SAR/ISFSI CoC for BFN are not affected. However, this calculation is safety-related and design verified and can be used later to support a BFN LAR without need for any revision to this calculation. Furthermore, this calculation does not authorize a change to plant(s) and any modifications made to the plant(s) will require a review of the SAR and ISFSI SAR and Tech Specs and ISFSI CoC to be performed at that time. Reviewed By- Ilya Lyubich / Ilya Lyubich 6/14/18

TVA NUCLEAR CALCULATION VERIFICATION FORM

Calculation Identifier CDQ000002016000041 Revision 001

Method of verification used:				
1. Design Review	☒			
2. Alternate Calculation	☐	Verifier	Doug Hultstrand	Date 06/18/2018
3. Qualification Test	☐			

Comments:

I have reviewed and verified all methods and calculations used on the development of the Probable Maximum Precipitation (PMP) and Local Intense Precipitation (LIP) values provided in this report. All Storm Precipitation Analysis System (SPAS) data used to define the PMP and LIP values have been verified as appropriate. All calculations on each storm spreadsheet have been reviewed for accuracy and all calculations are correct. Each value and calculation was checked individually on each storm spreadsheet. This verification process has shown that all data used are accurate and the resulting PMP and LIP values are correct as provided.

TVA NUCLEAR COMPUTER INPUT FILE

STORAGE INFORMATION SHEET

Document CDQ0000002016000041	Rev. 001	Plant: GEN	

Subject:

TVA Overall Basin Probable Maximum Precipitation and Local Intense Precipitation Analysis

☐ Electronic storage of the input files for this calculation is not required. Comments:

☒ Input files for this calculation have been stored electronically and sufficient identifying information is provided below for each input file. (Any retrieved file requires re-verification of its contents before use.)

The following files are electronically stored in TVA FILEKEEPER (FILEKEEPER # 345223 thru 345266 & 345268 thru 345272) and are also listed in Appendix H.

1. **PMP_Evaluation_Tool (Folder)** (345269)
   - Input (Folder)
     - DAD_Tables.gdb (ArcGIS File Geodatabase)
       • Contains the DAD tables for each analyzed storm
     - Storm_Adj_Factors.gdb (ArcGIS File Geodatabase)
       - General (Feature Dataset)
         • Contains the Total Adjustment Factor feature classes for each analyzed general storm
       - Local (Feature Dataset)
         • Contains the Total Adjustment Factor feature classes for each analyzed local storm
       - Tropical (Feature Dataset)
         • Contains the Total Adjustment Factor feature classes for each analyzed tropical storm
     - Non_Storm_Data.gdb (ArcGIS File Geodatabase)
       • Contains the spatial grid network feature classes
     - Script (Folder)
     - PMP_Tools.tbx (ArcGIS Toolbox)
       - Contains the following Script Tools (Python):
         • Basin PMP Evaluation Tool

2. **SPAS Hourly Rainfall ASCII Grids (Folder)** (Proprietary**** 345223 through 345266 ****Proprietary)
This folder contains Individual files representing each SPAS Storm Analysis gridded hourly rainfall data used in this study in ASCII format. All rainfall depths are in inches.

3. **TVA - SPAS Mass Curve Data (Folder)** (345271)
This folder contains individual files representing each SPAS Storm Analysis mass curve at each storm center. This contains three sub-folders, one for General storm type, one for Local storm type, and one for Tropical storm type. SPAS gridded rainfall data used in this study are in ASCII format. All rainfall depths are in inches and time increments are in hours.

4. **TVA_Sample_Basins (Folder)** (345272)

5. **PMP Evaluation Tool Description and Usage Rev1.pdf** (345268)

6. **Readme.txt** (345270)

☐ Microfiche/eFiche

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Appendices

List of Figures

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List of Acronyms

AWA	Applied Weather Associates
COCORAHS	Community Collaborative Rain, Hail, and Snow Network
DA	Depth Area
DAD	Depth-Area-Duration
DD	Depth-Duration
EPRI	Electric Power Research Institute
F	Fahrenheit
FERC	Federal Energy Regulatory Commission
GIS	Geographic Information Systems
GRASS	Geographic Resource Analysis Support System
HMR	Hydrometeorological Report
HYSPLIT	Hybrid Single Particle Lagrangian Integrated Trajectory Model
IPMF	In-place Maximization Factor
LIP	Local Intense Precipitation
mb	Millibar
MCC	Mesoscale Convective Complex
MCS	Mesoscale Convective System
MEC	Mesoscale Embedded Convection
MLC	Mid Latitude Cyclone
MTF	Moisture Transposition Factor
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Center for Environmental Prediction
NESDIS	National Environmental Satellite, Data, and Information Service
NEXRAD	Next Generation Weather Radar
NOAA	National Oceanic and Atmospheric Association
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PRISM	Precipitation-Elevation Regressions on Independent Slopes Model
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
PW	Precipitable Water
RAWS	Remote Automated Weather Station
SPAS	Storm Precipitation Analysis System
SST	Sea Surface Temperature
TAF	Total Adjustment Factor
TVA	Tennessee Valley Authority

TP-40	Technical Paper 40
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WMO	World Meteorological Organization

1.0 Introduction

This study provides Probable Maximum Precipitation (PMP) values for any drainage basin within the overall Tennessee Valley Authority (TVA) domain. The PMP values are valid for specific seasons based on storm type (see Section 4.5, Table 11), which is the time of the year when 100% of the PMP rainfall could occur. The PMP values are used in the computation of the Probable Maximum Flood (PMF). PMP values provided in this study are provided in place of PMP values in the four Hydrometeorological Reports (HMRs) for locations within the jurisdiction of TVA. These are HMR 41 (Schwartz, 1965), HMR 45 (Schwartz, 1969), HMR 47 (Schwartz, 1973), and HMR 56 (Zurndorfer et al., 1986).

Detailed review of the methods, data, and results was completed in two phases as part of this project. During the development of the PMP values, an independent review board consisting of a hydrologist (Dr. Mel Schaefer) and meteorologist (Dr. Barry Keim) were involved in review of methods and data and provided recommendations and review of results and documentation. In addition, several TVA personnel assisted in the review process. Subsequent to completion of the PMP development, results and documentation were submitted to the Nuclear Regulatory Commission (NRC) for review and acceptance for use in supporting licensing basis amendment requests for TVA's Browns Ferry, Sequoyah, and Watts Bar nuclear power plants.

The NRC audit review process was extensive and detailed. Several rounds of Information Needs and Requests for Additional Information (RAI) occurred over the two year period. In response to the NRC review, adjustments were made to the dew point climatological data, treatment of two important storms with respect to Local Intense Precipitation (LIP) analysis, and adjustments of the storm representative dew point values to four controlling storms. Each of these adjustments have been incorporated in the PMP database and results of Revision 1 of this report along with appropriate discussion included in this documentation.

1.1 PMP Background

Definitions of PMP are found in most of the HMRs issued by the National Weather Service (NWS). The definition used in the most recently published HMR is "theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location at a certain time of the year" (HMR 59, p.5) (Corrigan et al., 1999). Since the mid-1940s or earlier, several government agencies have developed methods to calculate PMP for various regions of the United States. The NWS (formerly the U.S. Weather Bureau), the U.S. Army Corps of Engineers (USACE), and the U.S. Bureau of Reclamation have been the primary agencies involved in this activity. PMP values presented in their reports are used to calculate the PMF, which, in turn, is often used for the design of significant hydraulic structures. It is important to remember that the methods used to derive PMP and the hydrological procedures that use the PMP values need to adhere to the requirement of being "physically possible." In other words, various levels of conservatism and/or extreme aspects of storms that could not physically occur in a PMP storm environment should not be used to produce combinations of storm characteristics that are not physically consistent in determining PMP values or for the hydrologic applications of those values.

The generalized PMP studies currently in use in the conterminous United States include HMRs 49 (1977) and 50 (1981) for the Colorado River and Great Basin drainage; HMRs 51 (1978), 52 (1982), and 53 (1980) for the U.S. east of the 105th meridian; HMR 55A (1988) for the area between the Continental Divide and the 103rd meridian; HMR 57 (1994) for the Columbia River Drainage; and HMRs 58 (1998) and 59 (1999) for California (Figure 1). In addition to these HMRs, numerous Technical Papers and Reports address specific subjects concerning precipitation (e.g. NOAA Tech. Report NWS 25, 1980; and NOAA Tech. Memorandum NWS HYDRO 45, 1995). Topics include maximum observed rainfall amounts for various return periods and specific storm studies. Climatological atlases (e.g. Technical Paper No. 40, 1961; NOAA Atlas 2, 1973; and NOAA Atlas 14, 2004-2013) are available for use in determining precipitation return periods. A number of site-specific, statewide, and regional studies (e.g. Tomlinson et al., 2002; Tomlinson et al., 2003; Tomlinson et al., 2008; Tomlinson et al., 2009; Tomlinson et al., 2010; Tomlinson et al., 2011; Kappel et al., 2012; Kappel et al., 2013; Tomlinson et al., 2013; Kappel et al., 2014) augment generalized PMP reports for specific regions included in the large areas addressed by the TVA HMRs 41, 45, 47, and 56 and general NWS HMRs 49, 51, 55A, and 57. Recent site-specific PMP projects completed within the domain have shown significant errors and outdated procedures used to estimate PMP values. These include a subjective application of methods to derive PMP values which cannot be reproduced, a methodology to address the effects of topography which cannot be reproduced, a lack of analyzed storm events, a lack of explanation and backup documentation, an inaccurate methodology to maximize storms, and an outdated storm analysis dataset. PMP results from this study provide values that could be used in place of those derived from HMRs 41, 45, 47, and 56.

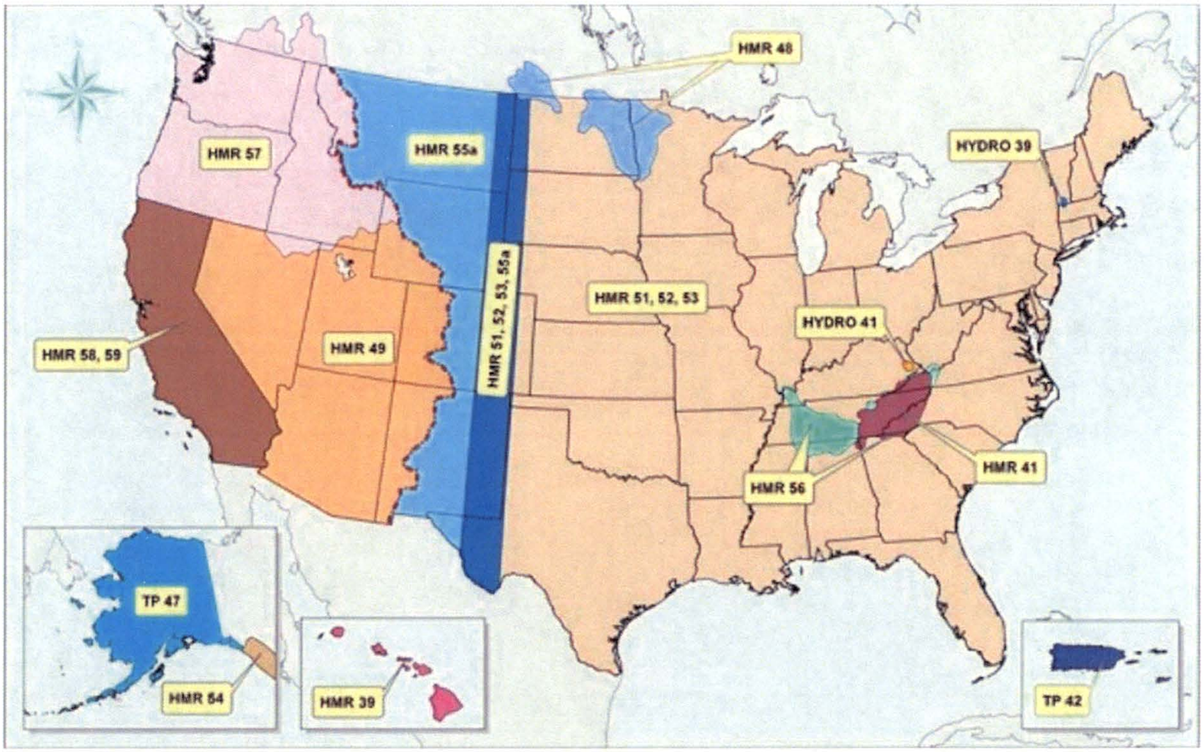

Figure 1 Coverage of National Weather Service Hydrometeorological Reports

TVA is included within the domain covered by HMR 41, HMR 45, HMR 47, and HMR 56. These HMRs provide PMP values for various area sizes and duration within the TVA domain and employ various techniques and data sets that are inconsistent between them. The TVA domain contains many diverse topographic and climatological regions. These include the Appalachian Plateau on the western portions, the Cumberland Plateau in the middle, and the Appalachian Mountains/Blue Ridge to the east. In between are several areas which are sheltered from major inflow of moisture and exhibit rain shadow effects compared to the surrounding higher elevations (Figure 2). Within the TVA domain, climate and terrain vary greatly. Because of the distinctive climate regions and significant topography, the development of PMP values must account for the complexity of the meteorology and terrain throughout the region. This project incorporated the latest methods, technology, and data to address these complexities. Several major issues have been identified with the procedures used in the HMRs to developed PMP values. Important among these are the limited number of analyzed storm events, no inclusion of storms that have occurred since the 1980s, inadequate processes used to address orographic effects, inconsistent data and procedures used among the HMRs, and the outdated procedures used to derive PMP.

Previous site-specific, statewide, and regional PMP projects completed by AWA provide examples of PMP studies that explicitly consider the unique topography of the area being studied, and characteristics of historic extreme storms over meteorologically and topographically similar regions surrounding the area. The procedures incorporate the most up-to-date sets, techniques, and applications to derive PMP. Each of these PMP studies have received extensive review and the results have been used in computing the PMF for the watersheds. This study follows similar procedures employed in those studies while making improvements where advancements in computer-aided tools and transposition procedures have become available.

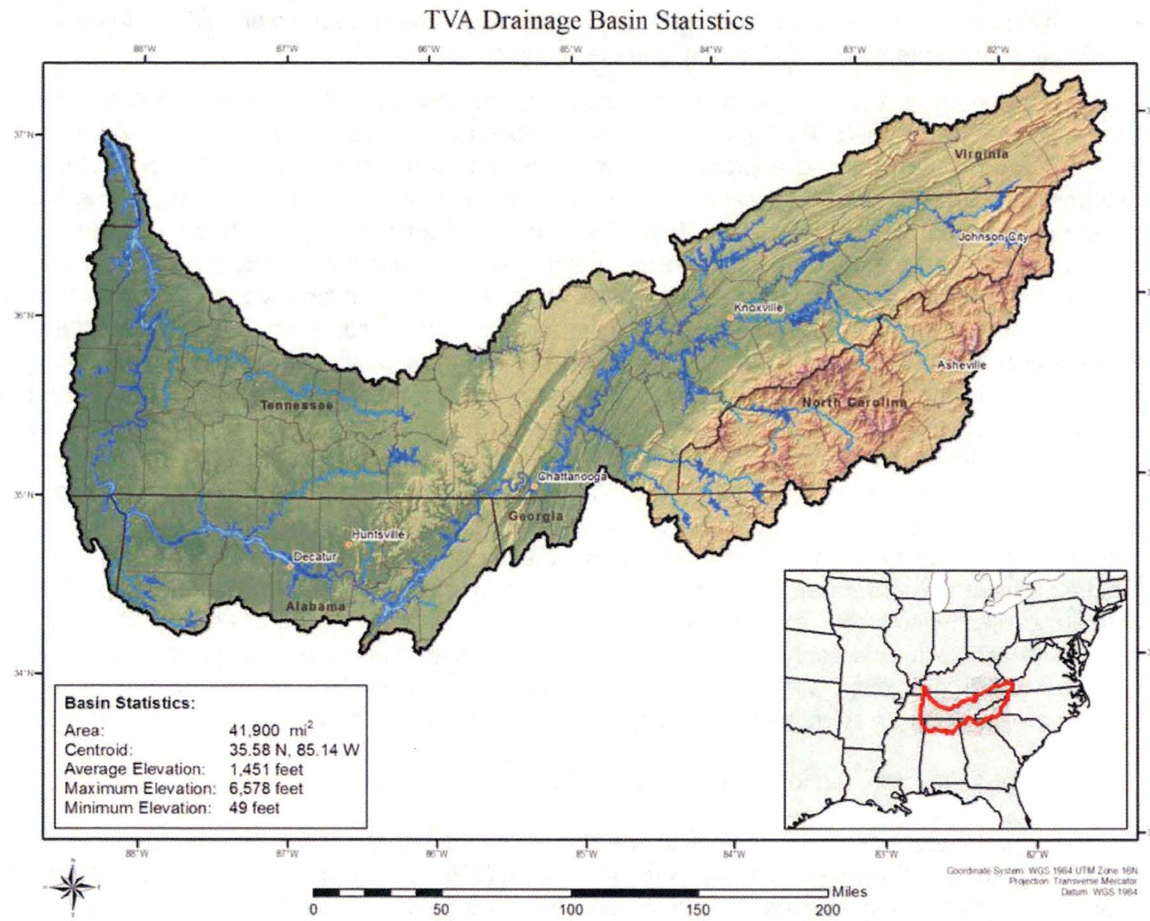

Figure 2 TVA project domain used for PMP development

1.2 Study Objective

This study determines reliable and reproducible estimates of PMP values for use in computing the PMF for various watersheds within the overall project domain. This includes all area sizes from as small as 1/3rd-square mile through the total project domain and for durations ranging from 1-hour through 120-hours. The most reliable methods and data available were used and updates to methods and data used in HMRs were applied where appropriate. Additional adjustments to methods and data resulting from interaction with the NRC during the review and RAI process were applied.

1.3 Study Approach

The approach used in this study followed procedures used in the development of the HMRs, with updated procedures used where appropriate. This includes updates AWA implemented in several recently completed

PMP projects as well as updates developed during this study. These updated procedures were applied with a consideration for meteorology and terrain, and their interactions within TVA.

A goal of this study was to maintain as much consistency as possible with the general methods used in recent HMRs, the WMO Manual for PMP (2009), and the previous PMP studies completed by AWA. AWA developed PMP following a storm based approach, which utilized actual storm data from PMP-type storms to derive deterministic PMP values. Deviations were incorporated when justified through developments in meteorological analyses and available data. The approach identifies major storms that occurred within the region. Each of the main storm types which produce extreme rainfall were identified and investigated. The main storm types analyzed include general storms, tropical storms, and local storms. The moisture content of each of these storms is maximized to provide worst-case rainfall estimation for each storm at the location where it occurred. Storms were then transpositioned to each grid point which exhibit similar topography and meteorological conditions. Adjustments were applied to each storm as it was transpositioned to each grid point to represent what amount of rainfall that storm would have produced at the new location, versus what it produced at the original location. These adjustments were combined to produce the total adjustment factor (TAF) for each storm for each grid point. The TAF is a product of the in-place maximization factor (IPMF), the moisture transposition factor (MTF), and the orographic transposition factor (OTF). Note, that the OTF was originally developed to quantify the effects of topography on rainfall in mountainous terrain. However, the procedure used in the determination of the OTF is valid in all regions where reliable precipitation frequency data are available and is therefore used to quantify the effects of topography and elevation differences between any two locations. In this study, the OTF is calculated for both orographic and non-orographic regions. For consistency with previous PMP calculations, the use of the acronym OTF is continued in this study, but the factor is also known as a storm transposition factor, as orographic effects are not a pre-requisite in the process.

$$\text{Total Adjustment Factor} = \text{IPMF} * \text{MTF} * \text{OTF} \qquad \text{Equation 1}$$

Advanced computer-based technologies, Weather Service Radar WSR-88D NEXt generation RADar (NEXRAD), and the Storm Precipitation Analysis System (SPAS) were used in the storm analyses along with new meteorological data sources. New technology such as HYSPLIT model trajectories (Draxler and Rolph, 2010) and data were incorporated into the study when they provided improved reliability, while maintaining as much consistency as possible with previous studies. An example is the updated maximum dew point climatology used in the IPMF and MTF calculations.

For some applications such as storm maximization, storm transpositioning, defining PMP by storm type, and combining storms to create a PMP design storm, this study applied standard methods presented in previous publications (e.g. WMO Operational Hydrology Reports 1986, 2009), while for other applications, new procedures were developed. Moisture analyses have historically used monthly maximum 12-hour persisting dew point values. For this project, an updated dew point climatology developed in previous studies representing the 100-year recurrence interval value of the annual maximum series data from individual stations was used. This was developed to represent the average of the 100-year values for the 6-, 12-, and 24-hour duration periods. These data were was used to better represent the atmospheric moisture for rainfall durations associated with the different storm types that affect TVA. These recurrence interval durations better represent available atmospheric moisture used to maximize individual storms versus the persisting dew point process employed in the HMRs. The updated dew point climatology values replaced the 12-hour maximum persisting dew point values used in the HMRs. The resulting storm representative dew point values better represent the available atmospheric moisture that actually contributed to each storm's rainfall production. The maximum dew point climatologies used the most up-to-date periods of record, adding over 40 years of data to the datasets used in previous climatologies. In addition, for storms where the moisture source region originated over the ocean, a sea surface temperature (SST) climatology was used as a surrogate for surface based dew points. This followed the same procedure as described in HMR 57 and HMR 59, as well as in previous and ongoing AWA PMP studies.

Environmental Systems Research Institute's ESRI ArcGIS Desktop GIS software (ESRI, 2012) was extensively used to evaluate topography and climatological datasets; analyze spatial relationships; store, organize, and process the large amounts of spatial data; design, implement, and execute the PMP database; and provide visualization and mapping support throughout the process. The Storm Precipitation Analysis System (SPAS) used gridded storm analysis techniques to provide both spatial and temporal analyses for extreme rainfall storm events (see Appendix G for a complete description of SPAS).

1.4 PMP Analysis Grid Setup

A uniform grid covering the PMP project domain provides a spatial framework for the analysis. The PMP grid resolution for this study was 0.025 x 0.025 decimal degrees (dd), or 90 arc-seconds, using the Geographic Coordinate System spatial reference with the World Geodetic System of 1984 datum used for quantifying spatial information. This resulted in 17,938 grid cells with centroids within the domain as shown in (Figure 3). Each grid cell has an approximate area of 2.5-square miles. The grid network placement is essentially arbitrary. However, the placement was oriented in such a way that the grid cell centroids are centered over whole number coordinate pairs and then spaced evenly every 0.025 dd. For example, there is a grid cell centered over 35° N and 88° W with the adjacent grid point to the west at 35° N and 88.025° W. As an example, the PMP analysis grid over the Watauga basin is shown in Figure 4.

90 Arc-second PMP Analysis Grid Network
TVA Drainage Basin

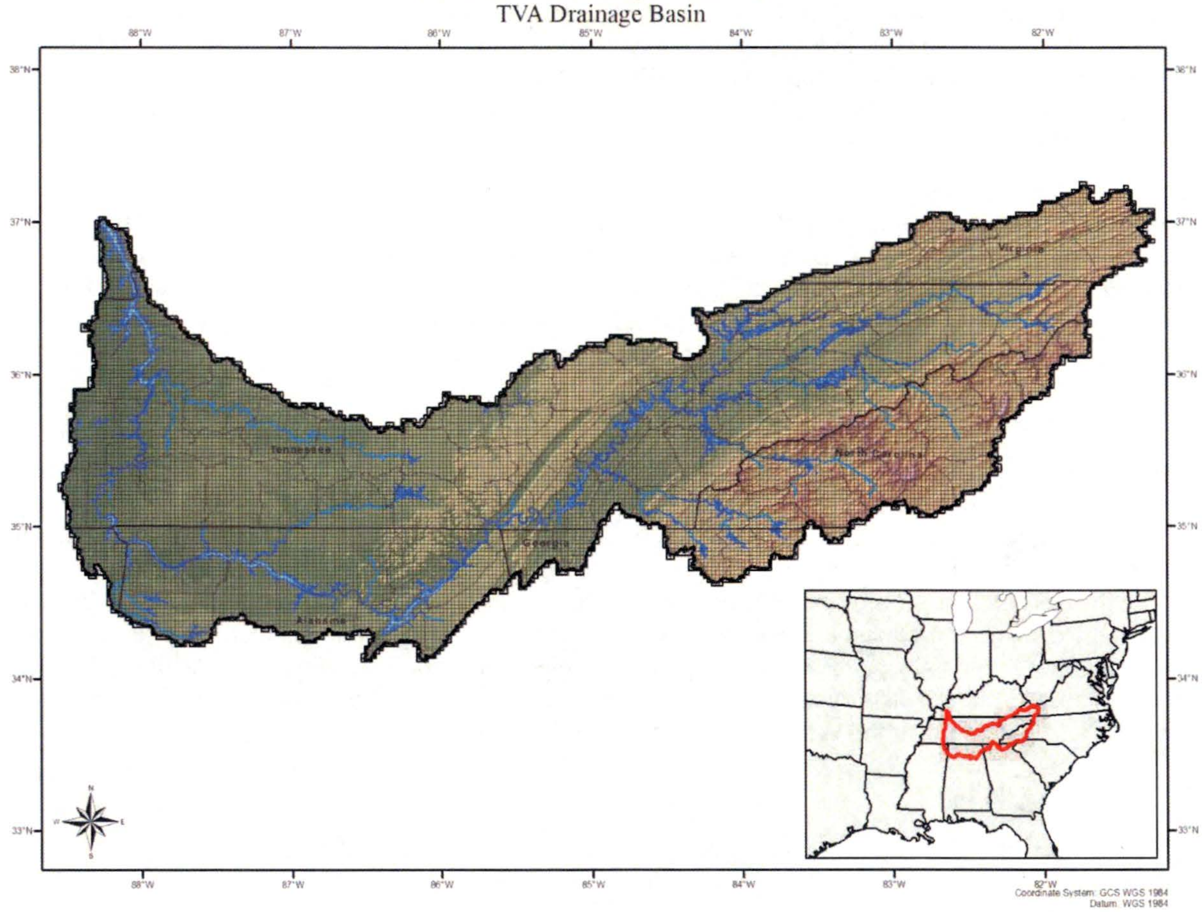

Figure 3 PMP domain with grids used in the PMP development showing the entire TVA domain

Watauga Drainage Basin - 465 sqmi
PMP Analysis Grid Network

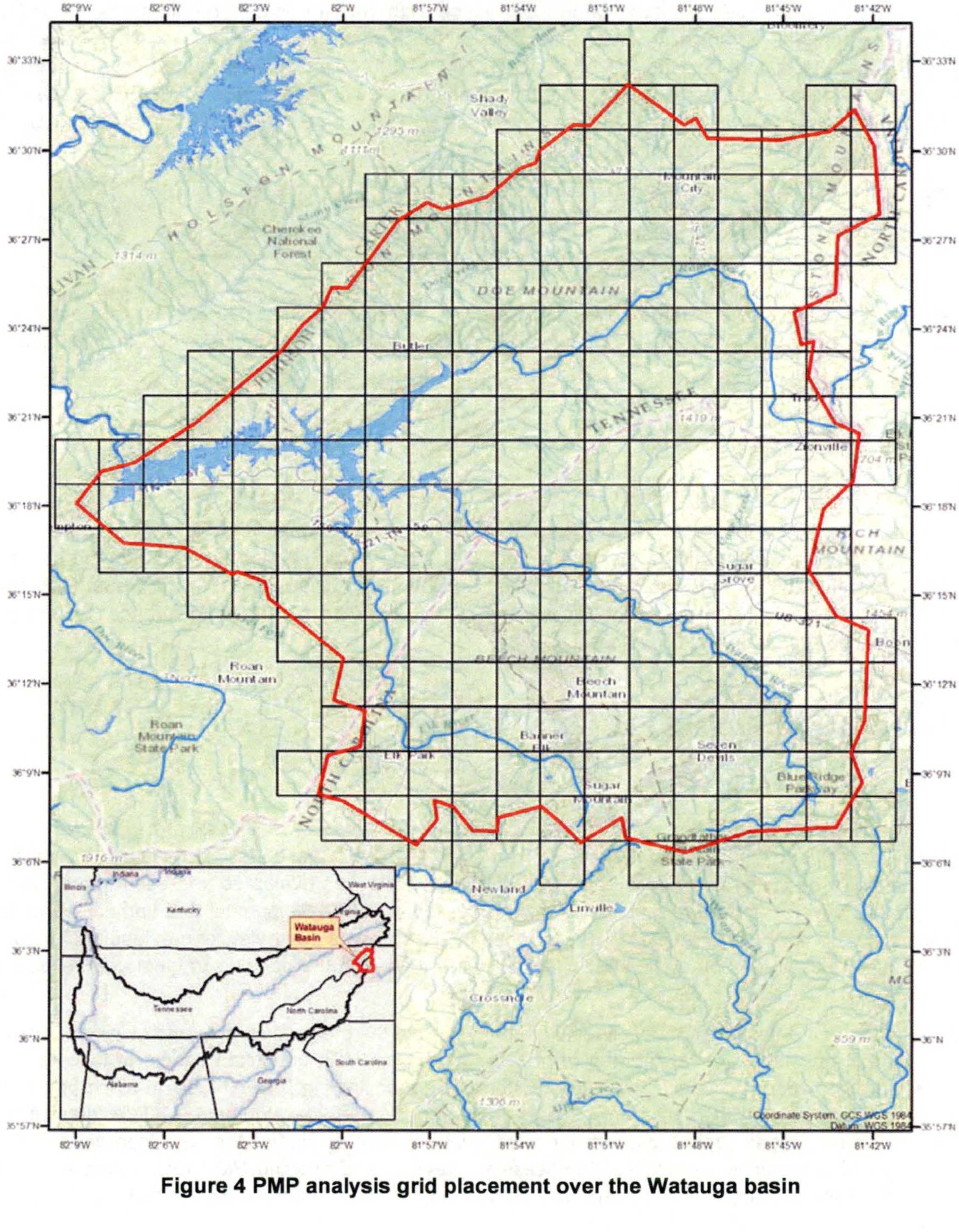

Figure 4 PMP analysis grid placement over the Watauga basin

1.5 Quality Assurance

This calculation is classified as safety-related and is performed in accordance with ENERCON's Quality Assurance Program (QAP), which is in compliance with the applicable requirements of NQA-1 and 10CFR50, Appendix B, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants," and reflects the guidance of ANSI/ASME N45.2-1977, "Quality Assurance Program Requirements for Nuclear Facilities," and applicable "daughter" standards of ANSI/ASME N45.2. ENERCON QA Program, including software controls, are reviewed by Nuclear Procurement Issues Committee (NUPIC), the organization that represents all nuclear utilities, including TVA.

Computer programs used in the calculation are identified below:

- ArcGIS for Desktop Version 10.2 by ESRI
- Storm Precipitation Analysis System (SPAS) Version 10.0 by AWA.

Software programs were commercially dedicated in accordance with ENERCON Corporate Standard Procedure s(CSPs) 7.01 and 3.09. Commercial Grade Dedication process includes two key elements-,

Technical Evaluation, which ensures that the software or service is specified correctly.

Acceptance Testing, which provides reasonable assurance that the software or service to be used meets the specified requirements.

Together, the Technical Evaluation and Acceptance Testing constitute dedication.

ENECON CSP 7.01 applies the requirements of 10CFR21, the guidance of EPRI NP-5652, TR-102260, and TR-1025243 as well as NRC Generic Letters 89-02 and 91-05. It also incorporates the standards found in NQA-1-2008 / NQA-1a-2009, including Subpart 2.7, "Quality Assurance Requirements for Computer Software for Nuclear Facility Applications", and Subpart 2.14, "Quality Assurance Requirements for Commercial Grad Items and Services".

2.0 Overview of Project Phases

2.1 Review of Previous PMP Work

The initial process in the development of PMP values for TVA was to review all previous PMP work in the region. This included extensive analysis of HMRs 41, 45, 47, 51, 52, and 56 for data and techniques applicable to the study. In addition, storm data from each of these HMRs was evaluated and used in this study where appropriate. Several storms were identified that were used in PMP development that had not previously been analyzed in other AWA PMP studies. Also included in this step was the review of previous and ongoing AWA PMP studies (e.g. Tomlinson et al., 2013, Kappel et al., 2014, and the ongoing Virginia and Texas statewide PMP studies).

Several important datasets and processes were derived from the previous studies and utilized in this analysis. This included gaining an understanding of how the previous HMRs quantified effects of topography, where storms were allowed to influence PMP, which storms were controlling PMP values, in-place maximization of various storms, identification of storm events to be considered, development of TVA precipitation, and treatment of antecedent and subsequent rainfall. Work completed during the development of the various HMRs was of high quality. In addition to assessing previous and ongoing PMP work relevant to this study, AWA had extensive discussion with various TVA personnel to gain understanding of historic rainfall over the domain, effects of flooding, seasonality of events, operational procedures, and analyze various data sets available from TVA.

2.2 Storm Search and Storm List Development

Identification of various storms which could potentially affect PMP values at any point within the domain analyzed was a critical step in the process. This study followed the storm based approach to calculate deterministic PMP values. Therefore, proper identification and inclusion of all required storms was an ongoing task throughout the entirety of the study. Storms used for PMP development in the relevant HMRs and previous and ongoing AWA PMP studies were queried to derive an initial list of PMP-type rainfall events to consider for further analysis. Analysis of each storm was completed to determine whether it should be included in further evaluation (see Section 3.4 for a description of these methods). Extensive discussions with TVA and Review Board personnel also helped to determine the final list of storms used for PMP development. A summary of Review Board comments and conclusions is provided in Appendix K.

2.3 SPAS Storm Analysis

Each of the storms identified as being needed for PMP development were required to be fully analyzed using the SPAS program (Parzybok and Tomlinson, 2006). Appendix G provides a detailed description of SPAS. SPAS analyses were required for each storm because the PMP development used in this calculation required gridded, hourly rainfall information. These data were not available for the storms previously used in the HMRs and therefore a SPAS analysis of these events was required.

2.4 Storm Maximization and Storm Adjustments

All storms used for PMP development were maximized in-place where the storm occurred and then adjusted to be representative of how the rainfall would accumulate had the storm occurred in the TVA study area instead of its original location. The process of relocating a storm from its original location to the new location and adjusting for difference in moisture and topography is known as transpositioning. The transposition of storms was done on a grid-cell by grid-cell basis for those grid-cells in the TVA study area where the storm was determined to be transpositionable. This was a three step process which involved maximizing each historical storm in-place, mathematically transposing each historical storm to each grid-cell in a transpositionable zone in the TVA study area, and accounting for differences in available atmospheric moisture and differences in topographic effects. Storms used in previous AWA PMP studies had previously been maximized in-place. Storms that had not been previously analyzed by AWA required a new in-place maximization analysis. Each of the procedures above will be explained in greater detail in the following sections. Figure 5 displays the major steps involved in the development of the PMP values derived during this study and includes a reference to the section of this calculation, which provides a description of the process.

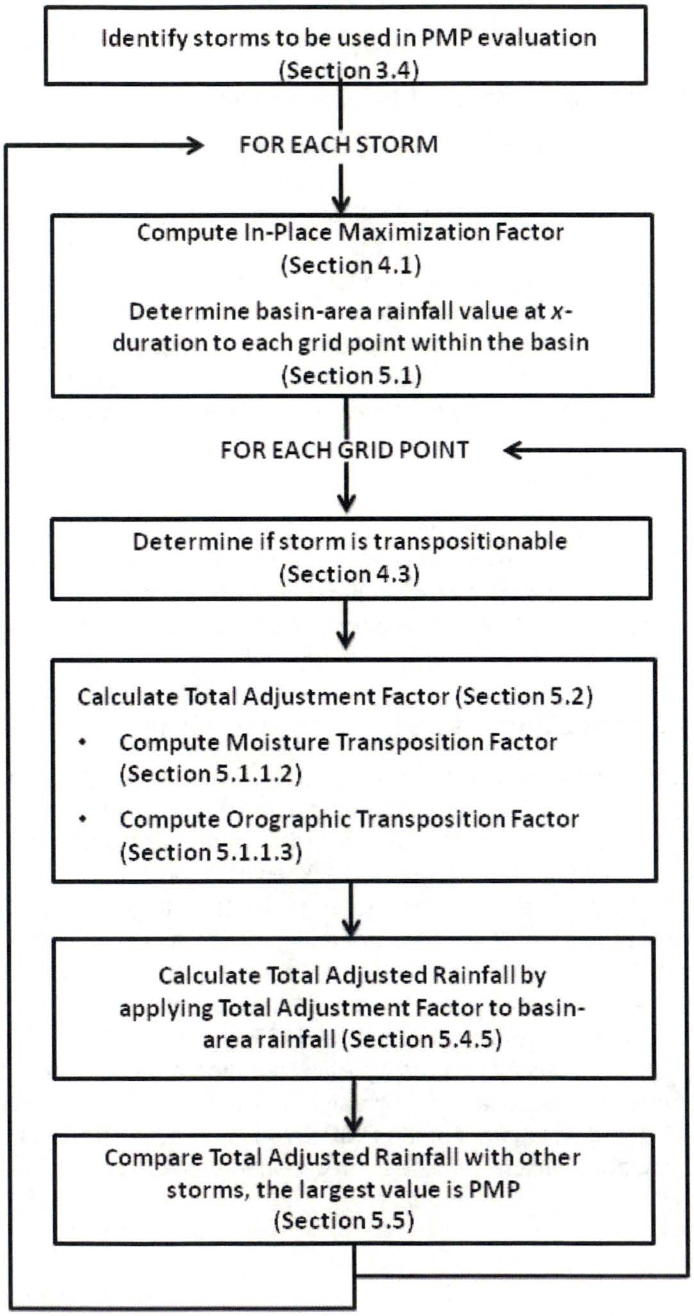

Figure 5 Steps used to calculate PMP at any location within TVA. The section describing each process is listed after each step.

2.5 Development of PMP and TVA Precipitation

PMP values were calculated using the largest of the resulting adjusted storms at each grid point at each duration. This process resulted in a large amount of data that required proper storage and organization. Excel data sets were made for each storm and scripts were utilized in GIS to store, query, and manipulate the data. This information was used to calculate the PMP and TVA precipitation values.

2.6 Procedures to Utilize the PMP Data for PMF Development

It was important that users of the PMP and TVA precipitation values understand how those data were derived, the assumptions and sensitivities involved, and how to utilize the PMP values to derive the Probable Maximum Flood (PMF) and other relevant hydrologic data. Extensive discussion took place with TVA personnel and the Review Board to ensure adequate understanding of the database, PMP and TVA precipitation development, and how to apply the data to produce the information required for hydrologic analysis.

3.0 Methods

3.1 TVA Precipitation Climatology

This section describes the general weather patterns and climate of the TVA region and how they relate to the development of PMP for this project. Figure 6 displays the PRISM annual maximum precipitation for the 30- year climatological period of 1981-2010 (PRISM, 2014). Figure 7 shows the NOAA Atlas 14 24-hour 100-year recurrence interval precipitation (Bonnin et al., 2006 and Perica et al., 2013) for TVA and surrounding regions. Data from these sources were utilized in storm adjustments and helped determine where to use individual storms for PMP development. Note that the NOAA Atlas 14 data are based on an all-season, annual maxima data series where the precipitation maxima may be from several different storm types occurring during various seasons of the year. This mixed population effect is addressed by using 6-hour duration precipitation frequency relationships to represent accumulation that were controlled by local storms. Likewise, use of the 24-hour precipitation frequency relationships represent general storms and tropical storm accumulations. This addresses the effect of mixed populations for those storm types. The assumption is that precipitation data which are used to develop the recurrence interval data at the 6-hour duration would have been from local storms and similarly, the data used to develop the 24-hour recurrence interval data would have come from general storms during the winter through spring and tropical storms in the summer through early fall. AWA recognizes that there is likely influence from non-PMP storm type(s) in the precipitation frequency climatologies used. However, by placing more emphasis on the rarer frequencies (i.e. 100-year through 1,000-year) the storm events controlling those values should be the same as the storms used in the PMP development.

Author's of the HMRs which utilized the Storm Separation Method (SSM) recognized the utility of using precipitation frequency climatologies to understand and quantify the effects of topography on rainfall (e.g. HMR 55A Section 6.3 and 6.4). This relationship between precipitation frequency climatology and terrain is also recognized in the WMO PMP Manual (WMO, 1986 pg. 54 and by the Australian Bureau of Meteorology (Section 3.1.2.3 of Minty et al., 1996). Although the orographic effects at a particular location may vary from storm to storm, the overall effect of the topographic influence (or lack thereof) is inherently included in the climatology of precipitation that occurred at that location, assuming that the climatology is based on storms of the same type.

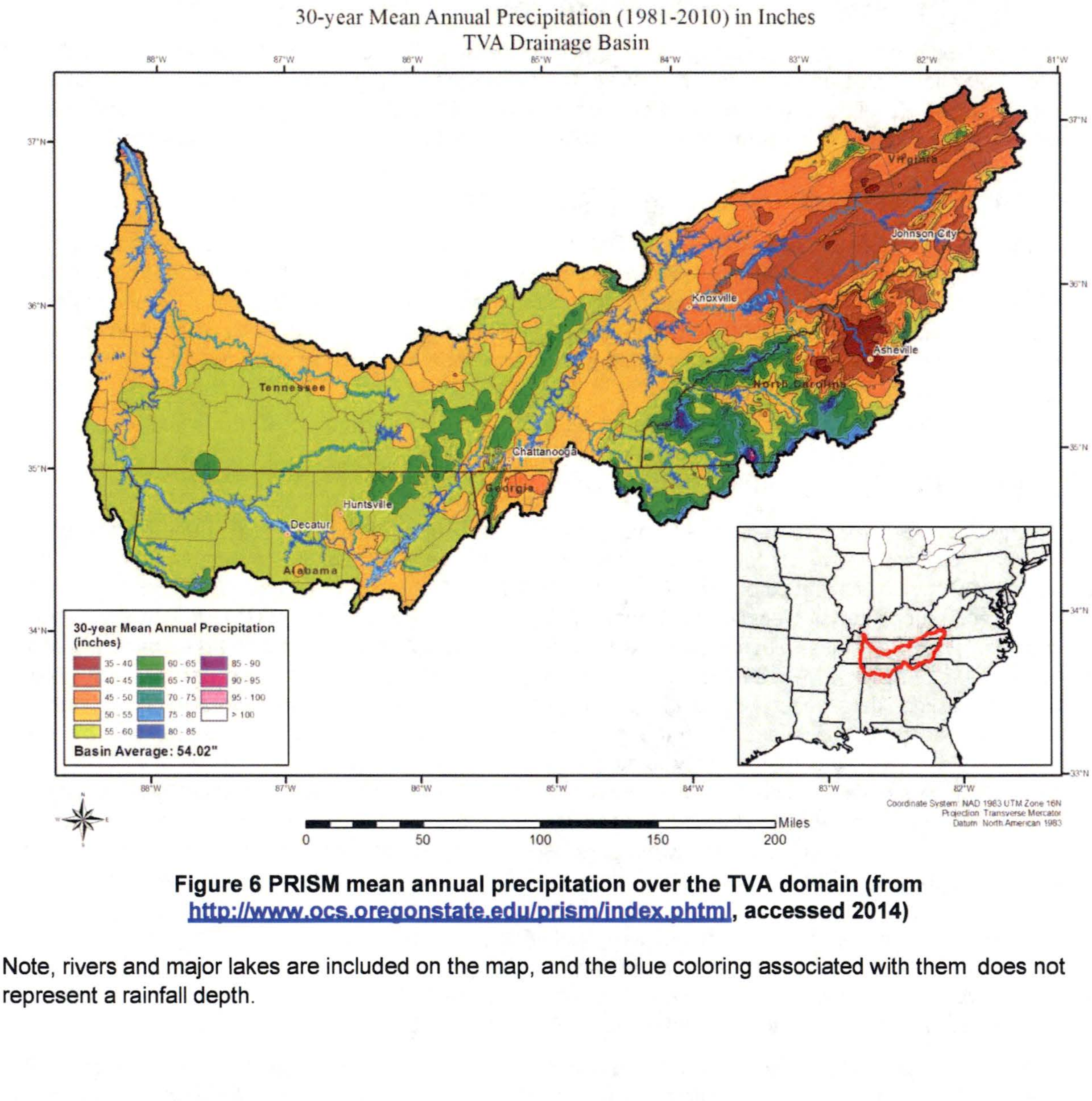

Figure 6 PRISM mean annual precipitation over the TVA domain (from http://www.ocs.oregonstate.edu/prism/index.phtml, accessed 2014)

Note, rivers and major lakes are included on the map, and the blue coloring associated with them does not represent a rainfall depth.

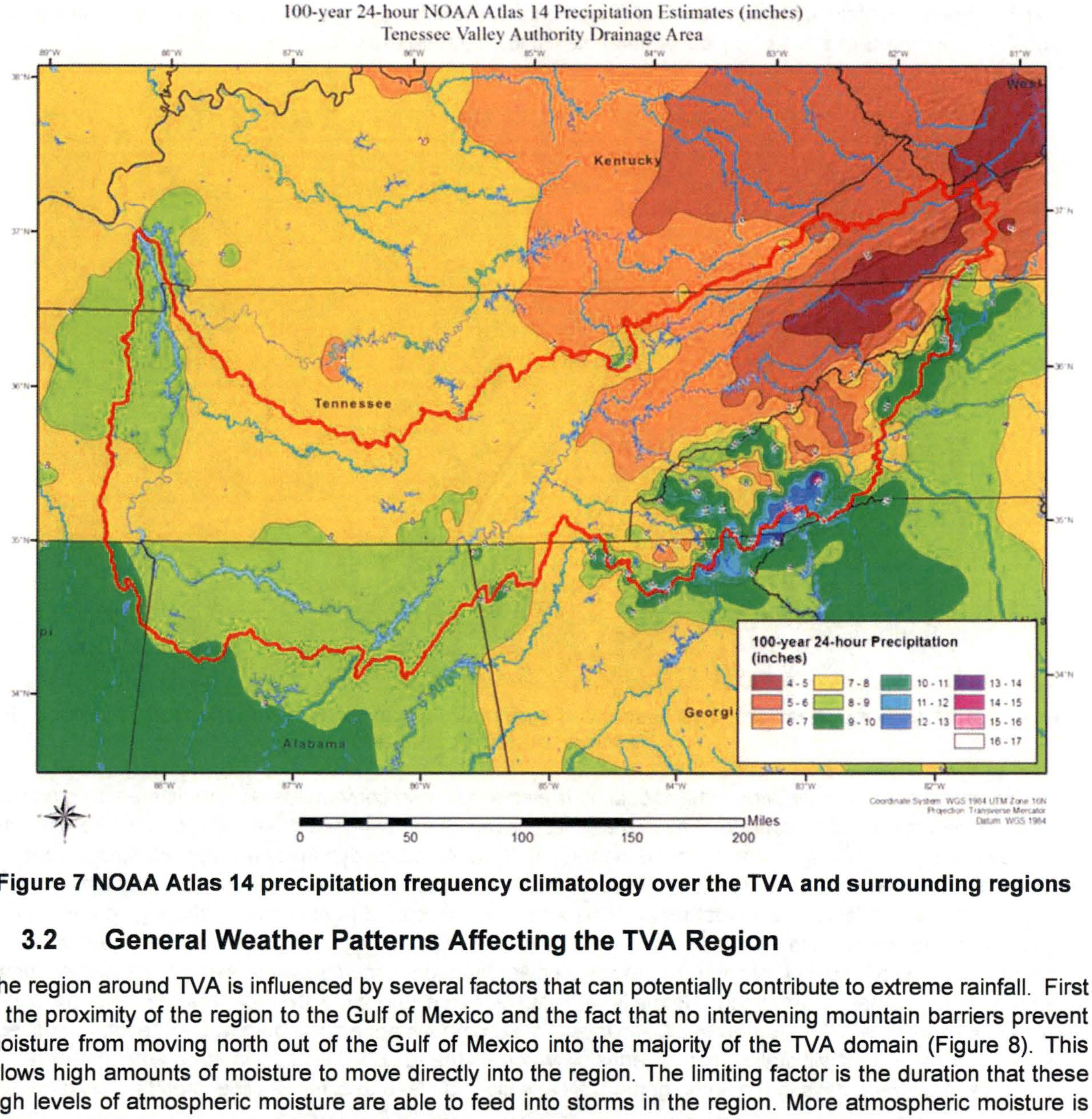

Figure 7 NOAA Atlas 14 precipitation frequency climatology over the TVA and surrounding regions

3.2 General Weather Patterns Affecting the TVA Region

The region around TVA is influenced by several factors that can potentially contribute to extreme rainfall. First is the proximity of the region to the Gulf of Mexico and the fact that no intervening mountain barriers prevent moisture from moving north out of the Gulf of Mexico into the majority of the TVA domain (Figure 8). This allows high amounts of moisture to move directly into the region. The limiting factor is the duration that these high levels of atmospheric moisture are able to feed into storms in the region. More atmospheric moisture is available over the more southern and western regions of the basin compared with the northern and eastern portions of the basin. Because of the movement and strength of the upper level winds in the region, storm patterns generally do not stay fixed over any location for long periods. Therefore, the synoptic situations which produce high levels of atmospheric moisture moving into the region, most often from the Gulf of Mexico, are generally transient and limit the magnitude of rainfall. However, PMP-type rainfall occurs during situations where the storm movement is blocked or slow and allowed to concentrate heavy rainfall for extended durations over the same region. In addition, topography plays a significant role in the spatial distribution of rainfall, as well as the magnitude of rainfall. Higher elevations generally act to enhance rainfall production and therefore exhibit higher rainfall values. Conversely, sheltered valleys and regions in general downwind locations (eastern and northern sides of major barriers) exhibit lower rainfall values.

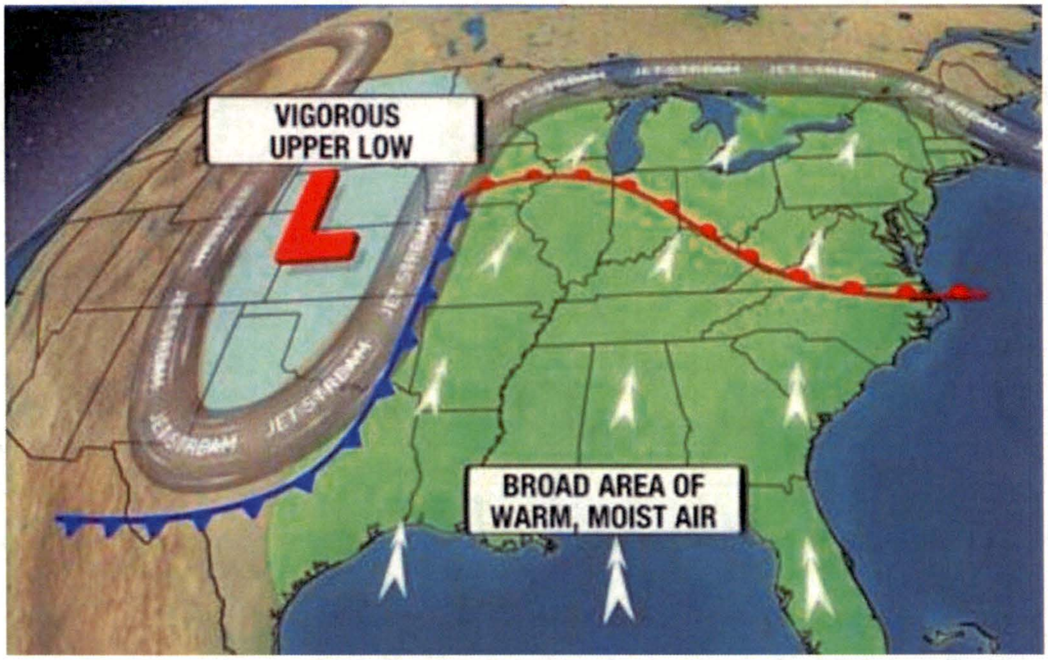

Figure 8 Locations of surface features associated with moisture advection from the Gulf of Mexico into TVA and surrounding regions

Rising motions through the atmospheric column is also required to convert available moisture into precipitation. Rising motions (or lift) required to convert these high levels of atmospheric moisture into rainfall on the ground is provided in several ways in and around the region. Synoptic storm dynamics are very effective in converting atmospheric moisture into rainfall on the ground. These are most often associated with fronts which affect the region. Numerous large scale weather systems with their associated fronts traverse the region throughout the year, with the fewest and weakest occurring in summer. The fronts (boundaries between two different air masses) can be a focusing mechanism providing upward motion in the atmosphere. These are often locations where heavy rainfall is produced. Normally, a front will move through with enough speed that no one area receives excessive amounts of rainfall. However, in extreme instances, the pattern can become blocked and some of these fronts will stall or move very slowly across the region. This allows large amounts of rainfall to continue for several days in the same general area, which can lead to extreme widespread flooding.

Another mechanism which creates lift in the region is heating of the surface and lower atmosphere by solar radiation. This creates warmer air below colder air resulting in atmospheric instability and leads to rising motions. This will often form ordinary afternoon and evening thunderstorms. However, in unique circumstances, the instability and moisture levels in the atmosphere can reach very high levels and stay over the same region for an extended period of time. This can lead to intense thunderstorms and very heavy rainfall. If these storms are focused over the same area for a long period, flooding rains can be produced. This type of storm produces some of the largest point rainfall amounts recorded, but often do not affect larger areas with extreme rainfall amounts. Therefore, this scenario is common in spring and summer and is often responsible for PMP-like events over small areas.

A final mechanism for heavy rainfall is associated with remnant tropical systems which affect portions of the TVA domain on rare occasions. The lift associated with such storms is a combination of convective process and topographic lift. More details on the PMP storm types which produce PMP level rainfalls in and around the basin are given in Section 3.3.

3.2.1 Air Mass Types Effecting the TVA Region

Weather patterns in the region are characterized by passages of fronts with differing air masses that lead to rapid changes in temperature along this boundary, and that produce rainfall caused by uplift along the front. Fronts are most prevalent in the fall, winter, and spring, with more stagnant patterns common from late spring through early fall.

There are several air mass types that affect the weather and climate of the region and produce heavy rainfall (Figure 9). The continental polar (cP) air mass, with origins from the arctic regions of Canada, is most common during winter. This air mass is often associated with a strong cold front passage and stratiform snowfall events. When this air mass type arrives, it often collides with a more humid air mass from warmer regions to the south. Low pressure (rising air) often results, and when combined with strong winds aloft, can produce extreme rainfall. However, this air mass type is often highly modified by the time it reaches the southern half of the TVA basin, as it travels a great distance from its original source and is significantly modified by the underlying landscape.

The second type of air mass observed in the region is maritime polar (mP) which originates in the Gulf of Alaska and Pacific Ocean. This air mass often arrives on strong winds from the west and northwest, but is usually devoid of significant amounts of low-level moisture because it has traveled across several mountain ranges. This storm type often produces precipitation when low-level moisture flowing north from the Gulf of Mexico can replenish atmospheric moisture enough to produce heavy rainfall. If the storm system stalls over the region, flood producing rains can result. This storm type can occur any time of year, but is most common from fall through late spring.

Another type of air mass which affects the region and produces rainfall originates from the Gulf of Mexico and can contain copious amounts of atmospheric moisture in a conditionally unstable atmosphere. This type of air mass is called maritime tropical (mT). This type of air mass is most directly responsible for producing heavy rainfall in the region when interacting with a front, which provides the needed uplift. Often, the front is located over the basin, allowing high amounts of moisture to stream in from the south, where it is then lifted, resulting in widespread rainfall. The release of the conditional instability in the atmosphere provides a very efficient mechanism to convert atmospheric moisture to rain on the ground. This can be enhanced by elevation changes in the underlying topography. If this pattern is able to remain in place for an extended period and to continue to draw in Gulf of Mexico moisture, flooding can result. This storm type is most common from early fall to late spring.

In rare cases, this type of pattern can include moisture from a decaying tropical system that had previously made landfall along the Gulf Coast states. This scenario has led to the most extreme rainfall events in the historical record for durations of 24-hours and less in the southern and eastern portions of the TVA basin.

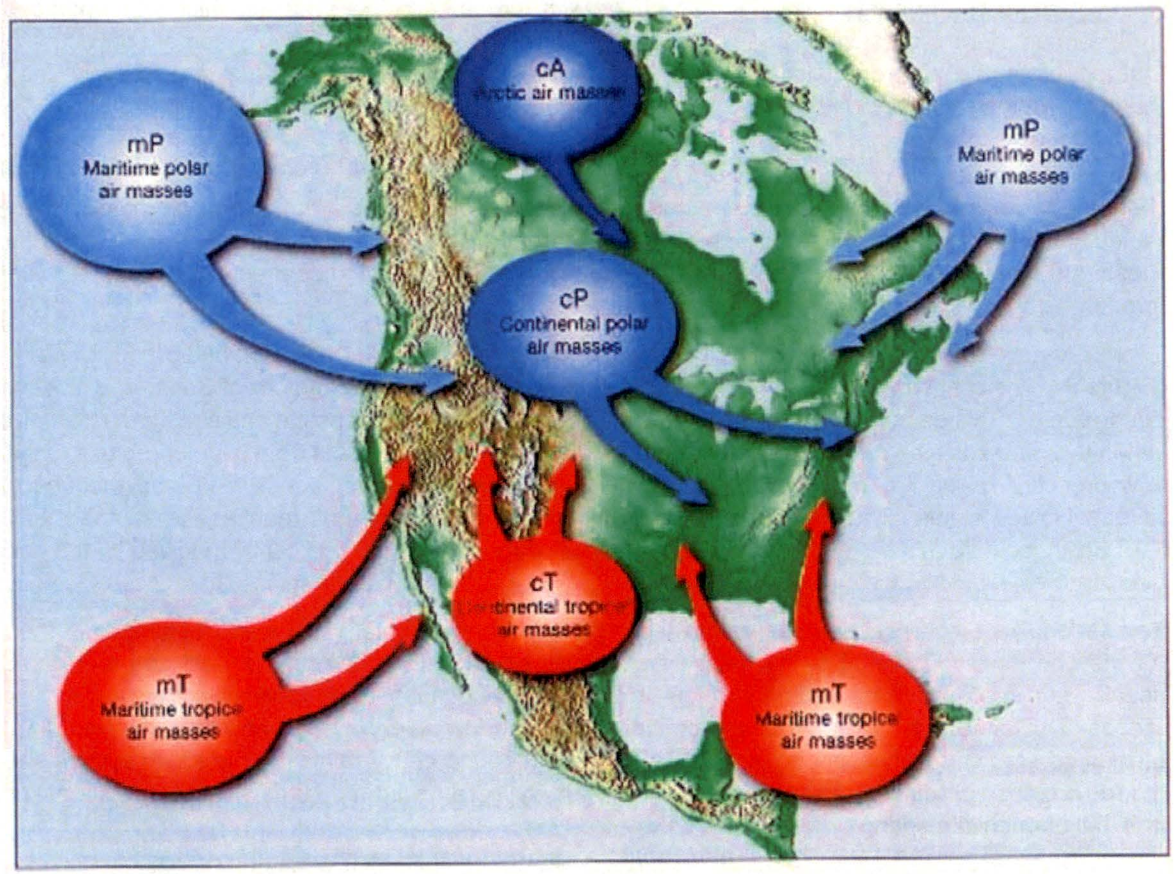

Figure 9 Air mass source regions affecting the TVA region (from therunningscientist.blogspot.com, accessed 2014)

3.3 PMP Storm Types

The TVA region has very active and varied weather patterns throughout the year. Consequently, heavy rainfall events covering both short and long durations are common. By far, the largest amount of moisture available for rainfall over the region comes from the Gulf of Mexico. The major types of extreme rainfall events in the region are produced by synoptic events/fronts (termed general storms), individual thunderstorms and Mesoscale Convective Systems (MCS) (termed local storms), and remnant tropical systems, which have made landfall along the Gulf of Mexico or from the Atlantic Ocean. A detailed discussion of TVA rainfall patterns which lead to significant flooding can be found in "Floods and Flood Control" TVA Technical Report 26 (TVA, 1961).

3.3.1 General Storms

The polar front and jet stream, which separate cool, dry Canadian air to the north, from warm, moist air to the south, is often a cause of heavy rainfall over large areas and long durations. This boundary provides large amounts of energy and strong storm dynamics to the atmosphere as fronts move through the region. These features are strongest and most active over the area during fall, winter, and spring. A common type of storm occurrence with the polar front is an overrunning event. Frontal overrunning occurs when warm, humid air carried northward around the western edge of the Bermuda High circulation encounters the frontal zone and is forced to rise over the cooler, drier air mass to the north of the front. This forced ascent condenses atmospheric moisture in the air mass, forming clouds and producing precipitation while releasing latent heat. This process most often results in widespread rainfall over longer durations, but can also help enhance convection. Air that arrives at the frontal location is conditionally unstable, where the lower layers are much warmer and more humid than the air above. This conditionally unstable air mass needs a mechanism to initiate lift to begin energy release, leading to more instability and further lift. The forced ascent over the polar front initiates the lifting of the moist air mass, release of its energy, and initiates the conversion of the atmospheric moisture to rainfall.

A stationary or slow moving polar front located within the TVA basin will often provide the mechanism necessary for this warm, humid air mass to release its convective potential. When this occurs, rainfall is produced, sometimes associated with pockets of convection and extremely heavy rainfall. The pockets of heavy rain are usually associated with a minor wave riding along the frontal boundary, called a shortwave. These are not strong enough to move the overall large scale pattern, but instead add to the storm dynamics and energy available for producing rainfall.

This type of storm environment (synoptic frontal) will usually not produce the highest rainfall rates over short durations, but instead leads to flooding situations as moderate to heavy rain falls over the same regions for an extended period of time. In addition, this scenario can occur in succession with only a few dry days in between and therefore enhance runoff on a previously saturated basin.

3.3.2 Local Storms (Thunderstorms and Mesoscale Convective Systems)

Thunderstorms and Mesoscale Convective Systems (MCSs) are capable of producing extreme amounts of rainfall for short durations and over small area sizes, generally 12 hours or less over area sizes of 500-square miles or less. The current understanding of MCS type storms has progressed tremendously with the advent of satellite technology starting in the 1970s and early 1980s. The current name of MCS was first applied in the late 1970s to these type of "flood producing", strong thunderstorm complexes (Maddox, 1980). Mesoscale systems are so named because they are small in areal extent (10s to 100s of square miles), whereas synoptic storm events are 100s to 1,000s of square miles. MCSs also exhibit a distinctive signature on satellite imagery where they show rapidly growing cirrus cloud shields with very high cloud tops. Furthermore, the high level cloud shield associated with MCSs usually take on a nearly circular pattern about the size of the state of Iowa with constantly regenerating thunderstorms fed by a low-level-jet (LLJ) bringing an inflow of atmospheric moisture (Figure 10).

The vast majority of MCSs have distinctive features and evolve in a standard pattern. A typical MCS begins as an area of thunderstorms over the western High Plains or Front Range of the Rocky Mountains. As these storms begin to form early in the day, the predominantly westerly winds aloft move them in a generally eastward direction. As the day progresses, the rain-cooled air below and around the storms begins to form a mesoscale high pressure area. This mesoscale high moves along with the area of thunderstorms. During nighttime hours, the MCS undergoes rapid development as it encounters increasingly warm and humid air from the Gulf of Mexico, usually associated with the LLJ 3,000-5,000 feet above the ground. The area of thunderstorms will often form a ring around the leading edge of the mesoscale high and continue to intensify, producing heavy rain, damaging winds, hail, and/or tornadoes. An MCS will often remain at a constant strength as long as the LLJ continues to provide an adequate supply of moisture. Once the mesoscale environment begins to change, the storms weaken, usually around sunrise, but may persist into the early daylight hours. MCSs are included in the more general definition of Mesoscale Convective Complexes (MCCs), which include a wider variety of mesoscale sized storm systems, such as squall lines and MCSs that do not fit the strict definition of size, duration, and/or appearance on satellite imagery. MCSs primarily form during the warm season (April through October) around the TVA basin region. Many of the storms previously analyzed by the USACE and NWS Hydrometeorological Branch in support of pre-1979 PMP research have features that indicate they were most likely MCCs or MCSs. However, this nomenclature had not yet been introduced into the scientific literature, nor were the events fully understood. For TVA basin, pure MCS storms are most important for PMF level flood events for basins generally below 500-square miles. In addition, convection similar to this storm type can occur within an overall synoptic frontal event. This can lead to intense areas of embedded heavy rainfall within the overall lighter rainfall pattern. This combination of synoptic and convective storm types is very important for determining PMP values for many areas within TVA.

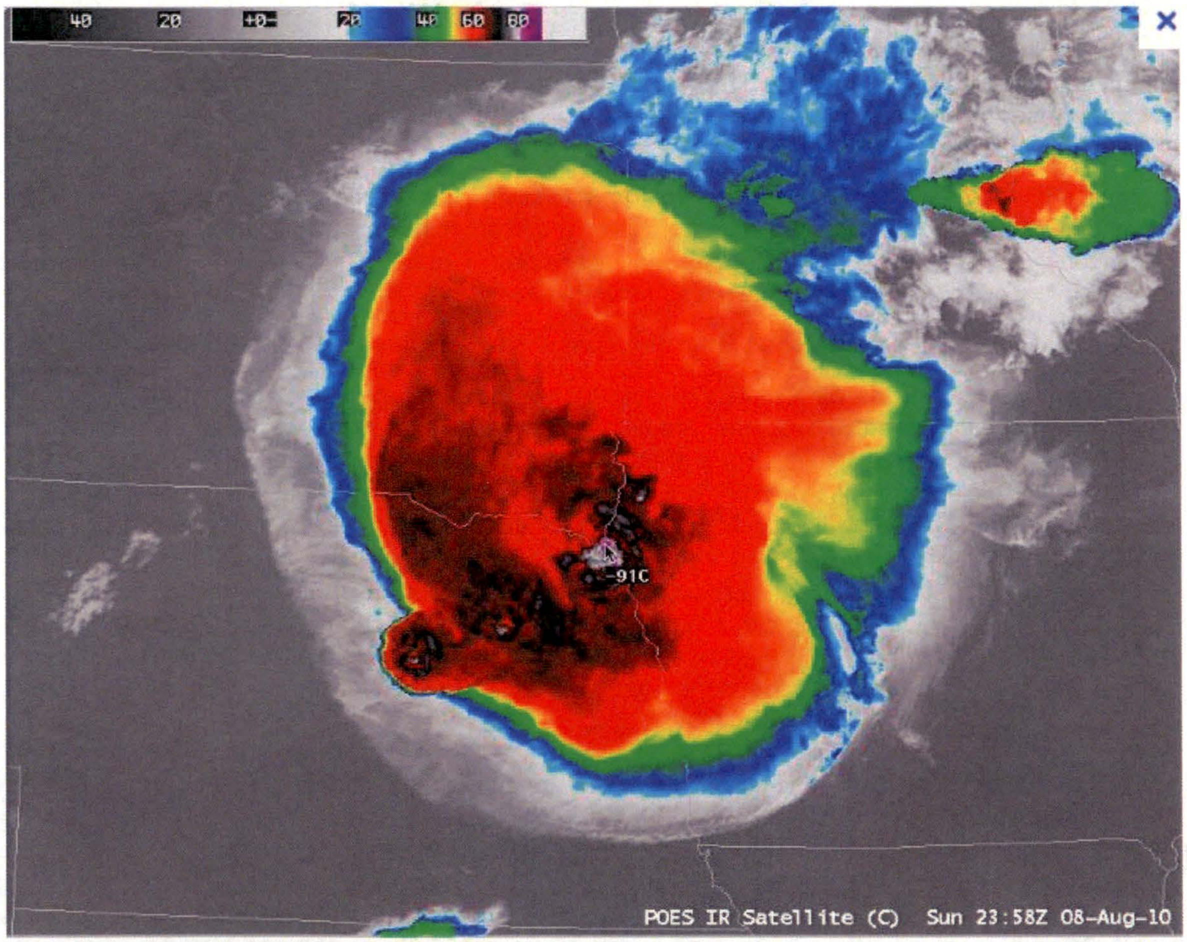

Figure 10 Color enhanced infrared satellite image of an MCS. Note the circular structure, very cold cloud tops at the center (red, black, and center white colors), and a size similar to the state of Iowa.

3.3.3 Tropical Storms

In rare cases, remnant tropical systems can directly affect the region. However, by the time these reach the TVA domain, they have lost most of the closed circulation and pure tropical characteristics because they have moved far enough away from the energy source in the Gulf of Mexico, and the low level circulations have been altered by interaction with land. However, the remnant air mass from a tropical system can add high levels of moisture and potential convective energy to the atmosphere, while circulations associated with the original tropical system continue to persist at diminished levels within the atmosphere. When these systems move slowly over a region, large amounts of rainfall can be produced both in convective bursts and over longer durations. These types of storms are dependent on the warm waters and proper atmospheric conditions to be prevalent over the Gulf of Mexico and therefore generally occur from June through November.

3.3.4 Hybrid Storms

It is very common for the largest rainfalls that affect the TVA region to incorporate characteristics of more than one storm type described in the previous sections. A common scenario includes a frontal boundary stalled out over the region that becomes a focusing mechanism as tropical moisture moves north from the Gulf of Mexico. The energy associated with the high levels of moisture and latent heat release is then focused along the frontal boundary and the rainfall mechanisms are enhanced. This can cause widespread heavy rainfall or local bursts of intense convection. If this scenario is positioned over the same region for an extended period, very high rainfall amounts can result. Another common scenario is associated with remnant outflow boundaries and moisture from decaying MCSs interacting with a frontal boundary to re-generate enhanced convection along that boundary, then continuing to "train" thunderstorms along that boundary for an extended period of time. This storm type contains characteristics of both synoptic frontal storms and intense convection. Generally, this type of storm lasts for a duration of at least 24 hours, but includes periods of intense rainfall for shorter durations. The bursts of rainfall are associated with strong imbedded convective cells within the overall storm environment that produce large amounts of rain over smaller areas within the larger storm environment.

3.4 Extreme Storm Identification

3.4.1 Storm Search Domain

A comprehensive storm search was conducted during previous and ongoing AWA PMP studies. Many of these storms could be transpositioned to the TVA region (e.g. Tomlinson et al., 2011; Kappel et al., 2012; Tomlinson et al., 2013; Kappel et al., 2014; Texas and Virginia-in progress as of April 2015). Analyses have been completed for these extreme rainfall storms that have occurred in meteorological and topographically similar regions, where extreme rainfall storms similar to those that could occur over some part of the TVA domain have been observed. The region considered for PMP development covered the United States from the Canadian border (areas below 2,000 feet in elevation) south to the Gulf of Mexico and from approximately 100°W eastward to the eastern foothills of the Appalachians (Figure 11). This limit of 2,000 feet to the west of TVA was chosen because within this region storms of similar meteorology and topography have been observed. In addition, direct coastal hurricane landfalls were not included in this analysis as this storm type would not occur at any location within TVA without significant modification. Therefore, the coastal rains that occur in these situations are not deemed transpositionable to the TVA region. Instead, the remnant moisture associated with those storms could affect the region as discussed in Section 3.3.3. The large storm search domain guaranteed a large enough area was analyzed to capture all significant storms that could potentially influence the final PMP values.

This region included areas that were later determined as none transpositionable to any point within with TVA PMP domain, but were initially included to ensure all potential storms which could influence PMP values were explicitly evaluated. Those storms and their limits of transpositionability were not known explicitly until extensive analysis was completed. Therefore a large region of potential storms was used in the storm search. Table 1 lists the storms which were included in the initial storm list using the large storm search domain. Each storm was evaluated further to derive the short list of storms used for PMP development.

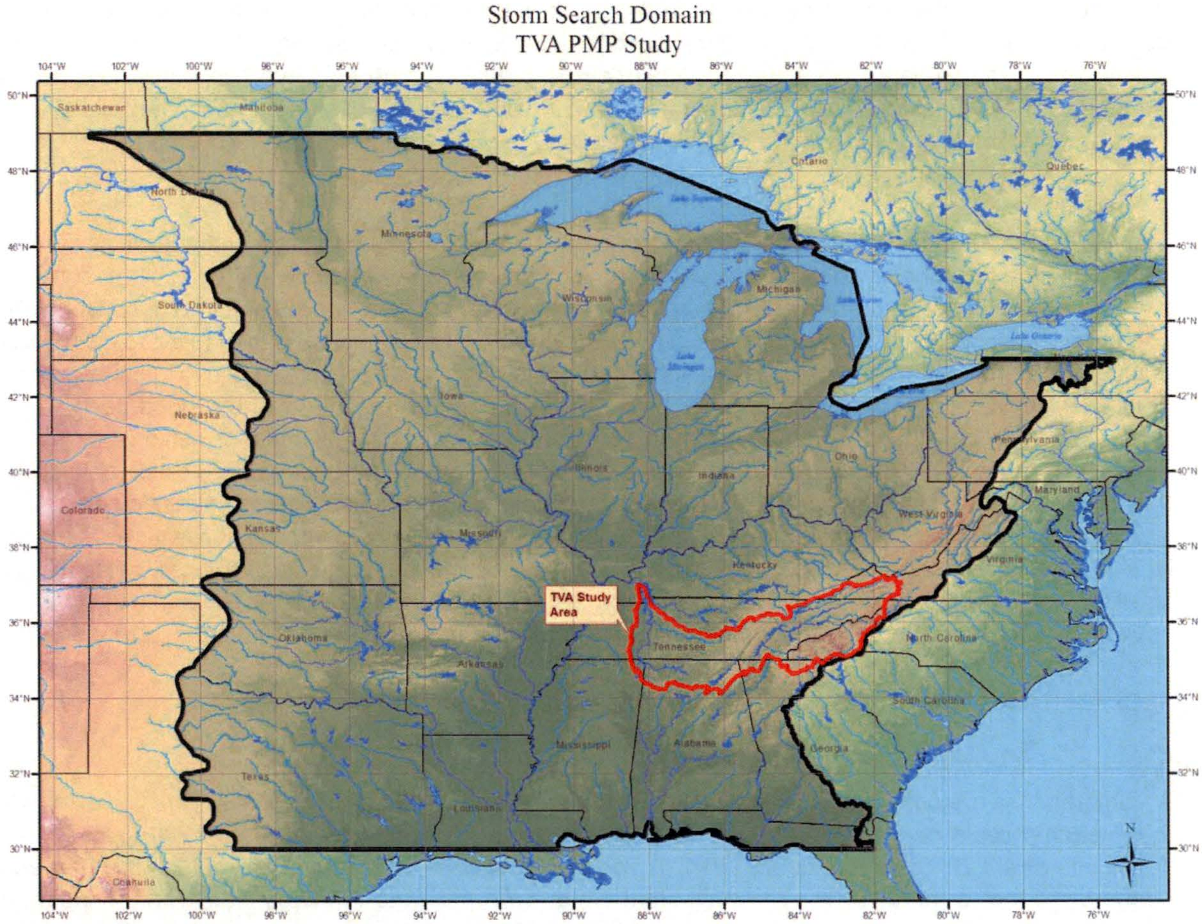

Figure 11 TVA storm search domain

3.4.2 Storm Search Sources

The storm list development for this study utilized previous storm search domains to identify all storms that could potentially affect PMP values in this project domain. The list included all storms identified in the various HMRs, which occurred in meteorological and topographical regions similar to the TVA region. Previous storm searches used in AWA PMP studies were used and the storm lists from those studies updated through December of 2014. Further searches were conducted from additional sources listed below:

- Cooperative Summary of the Day / TD3200 through 2013. These data are published by the National

Climatic Data Center (NCDC).
- Hourly Weather Observations published by NCDC, U.S. Environmental Protection Agency, and Forecast Systems Laboratory (now National Severe Storms Laboratory).
- Hydrometeorological Reports
- TVA rain and flood reports and documentation
- Corps of Engineers Storm Studies (USACE, 1973)
- Other data published by state climate office
- American Meteorological Society journals
- Previous PMP and storm analyses
- Concurrent PMP studies
- Various weather books
- Data from supplemental sources, such as Community Collaborative Rain, Snow, and Hail Network (CoCoRaHS), Weather Underground, Forecast Systems Laboratories, RAWS.

3.4.3 Storm Search Method

The initial search began with identifying hourly and daily stations that have reliable rainfall data within the storm search domain. These stations were evaluated to identify the largest precipitation totals for various durations associated with each storm type; general, tropical, and local storms. Other reference sources such as HMRs, USGS reports, NWS reports, and climate center reports were reviewed to identify dates with large rainfall amounts for locations within the storm search domain. The initial threshold for storms to make the initial list of significant storms (referred to as the long storm list) were rainfall values that exceeded the 100-year recurrence interval value for specified durations at the station location.

The resulting long storm list was extensively quality controlled to ensure that only the highest storm rainfall values for each event were selected. Storms were then grouped by storm type, storm location, and duration for further analysis. Table 1 lists the storms on the long list of storms.

These storms were plotted in a GIS format to better evaluate the spatial coverage of the events throughout the region. From this initial long storm list, the potential storms to analyze list was derived. This list was developed after extensive discussions internally with AWA, with the Review Board, and representatives from TVA. Development of the list also included investigations of which storms were important for PMP development in previous AWA and HMR PMP studies. Each storm was investigated for references in both published and unpublished (NWS offices, USGS reports, other local Flood Reports, HMRs, AMS journals, etc.) to determine its significance in the storm and flood history of TVA and surrounding regions.

Table 1 Initial List of Storms Analyzed for PMP Development

Storm Name	State	Lat	Lon	Year	Month	Day
LARRABEE	IA	42.8608	-95.5453	1891	9	10
PHILLIPSBURG	MO	37.5500	-92.7833	1895	12	16
GREELEY	NE	41.5500	-98.5333	1896	6	4
EUTAW	AL	32.7833	-87.8333	1900	4	15
WOODBURN	IA	41.0120	-93.5991	1903	8	24
BONAPARTE	IA	40.7667	-91.7500	1905	6	10
AUSTIN	MS	34.6500	-90.4667	1906	11	17
MEEKER	OK	35.5034	-96.9028	1908	10	19
GOLCONDA	IL	37.3693	-88.4843	1910	10	3
BELLEFONTAINE	OH	40.3670	-83.7670	1913	3	23
COOPER	MI	42.3764	-85.6103	1914	8	31
GRANT CITY	MO	40.4875	-94.4111	1922	7	9
JOHNSON CITY	TN	36.3000	-82.2667	1924	6	13
NEOSHO FALLS	KS	38.0820	-95.7010	1926	9	12
BOYDEN	IA	43.1900	-96.0100	1926	9	17
JEFFERSON PLAQ	LA	29.8548	-89.9905	1927	4	12
THOMASVILLE	AL	31.9167	-87.7500	1928	6	1
FAIRFIELD	TX	31.7250	-96.1650	1932	9	2
MILLRY	AL	31.6333	-88.3167	1934	11	19
HERNANDO	MS	34.8240	-89.9937	1935	1	18
MELVILLE	LA	30.6931	-91.7440	1935	5	2
SIMMESPORT	LA	30.9830	-91.8000	1935	5	16
GREENVILLE	KY	37.2253	-87.1577	1935	6	20
NEWCOMERSTOWN	OH	40.2723	-81.6060	1935	8	6
LOCK NO2	AL	32.1333	-88.0333	1938	4	5
CROSSVILLE	TN	35.9500	-85.0333	1938	5	22
KOLL	LA	30.3574	-92.7448	1938	8	12
SIMPSON	KY	37.6681	-83.3702	1939	7	4
GRANT TOWNSHIP	NE	42.2400	-96.5900	1940	6	3
INDEX	AR	33.5471	-94.0419	1940	6	30
MT MITCHELL	NC	35.7453	-82.2679	1940	8	11
BLUE RIDGE DIVIDE	NC	35.1540	-82.9940	1940	8	29
HALLETT	OK	36.2000	-96.6000	1940	9	2
HEMPSTEAD	TX	30.1333	-96.1333	1940	11	22
DAVIS	OK	34.5046	-97.1197	1941	9	30
WARNER	OK	35.4900	-95.3100	1943	5	6
MOUNDS	OK	35.8770	-96.0610	1943	5	16
SILVER LAKE	TX	32.6700	-95.5960	1943	6	5
GLENVILLE	WV	38.9343	-80.8375	1943	8	4

Table 1 Initial List of Storms Analyzed for PMP Development (continued)

Storm Name	State	Lat	Lon	Year	Month	Day
STANTON	NE	41.8670	-97.0500	1944	6	10
VAN	TX	32.3333	-95.7000	1945	3	28
COLLINSVILLE	IL	38.6717	-89.9800	1946	8	12
COLE CAMP	MO	38.4600	-93.2027	1946	8	12
HOLT	MO	39.4528	-94.3422	1947	6	18
WICKES	AR	34.3032	-94.3383	1947	8	27
SPARTA	TN	35.9167	-85.4667	1949	6	4
TVA	TN			1949	6	15
TVA	TN			1949	10	30
DUMONT	IA	42.7519	-92.9755	1951	6	25
COUNCIL GROVE	KS	38.6600	-96.4900	1951	7	9
MCMINNVILLE	TN	35.6833	-85.8000	1952	6	13
KELSO	MO	37.1906	-89.5495	1952	8	11
CAMP POLK	LA	31.0667	-93.2000	1953	4	23
HARRISONBURG DAM	LA	31.7667	-91.8167	1953	5	11
SEQUATCHIE	TN	35.1167	-85.6000	1954	8	8
GOOSE ROCK	KY	37.1000	-83.7167	1956	6	21
COVE CREEK	NC	35.6000	-83.0167	1956	6	30
CLINGMANS DOME	TN	35.5630	-83.4980	1957	1	27
COLUMBIA	TN	35.5330	-87.0167	1960	6	16
DAHLONEGA	GA	34.5500	-84.0667	1960	7	26
OAK RIDGE	TN	35.9333	-84.3167	1960	8	10
BIRMINGHAM	AL	33.5612	-86.7531	1961	2	19
IDA GROVE	IA	42.3167	-95.4667	1962	8	30
ROSEDALE	TN	36.2333	-84.2833	1965	7	24
FRANKFORT	AL	34.5833	-87.8333	1968	9	16
BURNSVILLE	TN	34.8410	-88.3140	1973	3	14
DUNLAP	TN	35.3333	-85.2833	1982	8	17
CHATTANOOGA	TN	35.0377	-85.2017	1994	2	14
ANTREVILLE	SC	34.3000	-82.6000	1995	8	26
ELIZABETHON	TN	36.3487	-82.2107	1998	1	8
CHATTANOOGA	TN	35.0377	-85.2017	1998	4	22
CLINTON	TN	36.1070	-84.1267	2002	3	20
ELIZABETHON	TN	36.3487	-82.2107	2003	11	19
ONEONTA	AL	33.9000	-86.5000	2011	9	5
PENSACOLA	FL	30.3258	-87.4089	2012	6	8
VALLEY	TN			2013	1	13
BANKHEAD NF	TN	35.2310	-87.2600	2013	7	4
EAST TENNESSEE	TN			2013	7	8

3.4.4 Developing the Short List of Extreme Storms Used for PMP Development

A multiple step process was followed to determine a list of storms that was comprehensive enough to ensure that major events were identified, while eliminating smaller events that would not be significant for determining PMP values at any area size or duration after standard adjustments were applied.

Several steps were completed to compare the magnitude of each potential storm with the magnitude of other storms being considered. These comparisons were completed by storm type and by comparing storms which occurred in similar regions. This helped eliminate several storms which occurred in the same climate region but were of significantly lower magnitude compared with others of the same duration in similar locations. The remaining storms were further investigated using various flood reports, discussions with personnel familiar with the storm events, and examination of the synoptic environment surrounding the event. Finally, storms which were controlling of PMP values in HMRs 41, 45, 47, 51, 52, 56, and/or previous AWA PMP studies were included. The storms which made it through these final evaluations were placed on the short storm list (Tables 2-4 and Figures 12-15). Each of these storms was analyzed (or re-analyzed in the case of HMR storms) with SPAS and considered to potentially affect PMP values for one or more grid points analyzed in this study.

This list contained all the storms analyzed by AWA for this study, a total of 58 individual SPAS depth-area-duration (DAD) zones. Ultimately, only a small subset of these short list storms control PMP values, with most providing support for the PMP values. The reason more storms were analyzed than was ultimately required to derive the PMP values, was to ensure no storms were omitted which could have affected PMP values after all adjustment factors were applied. The magnitude of the adjustment factors is unknown at the beginning of the process. In other words, a storm with large point rainfall values may have a relatively small total adjustment factor, while a storm with a relatively smaller but significant rainfall value may end up with a large total adjustment factor. The combination of these calculations may provide a total adjusted rainfall value for the smaller rainfall event that is greater than the larger rainfall event after all adjustments are applied.

Figures 12 through 15 display the locations of all the storms used for PMP development. Figure 12 shows the location of the general storms on the short storm list, while Figure 13 shows the locations of all the local/MCS storms, Figure 14 display the tropical storms, and Figure 15 shows the locations of all storms. Table 2 lists the general storms, Table 3 lists the local/MCS storms, and Table 4 lists the tropical storms.

Table 2 Short storm list used for PMP Development-general storms. Maximum Total Storm Rainfall is the location with the largest rainfall accumulation for the total storm duration.

SPAS_ID	NAME	STATE	LAT	LON	YEAR	MONTH	DAY	MAXIMUM 6-HOUR RAINFALL	MAXIMUM 24-HOUR RAINFALL	MAXIMUM TOTAL STORM RAINFALL
SPAS_1305_1	ELBA	AL	31.3625	-86.1208	1929	3	12	10.64	20.08	29.73
SPAS_1428_1	FAIRFIELD	TX	31.6792	-96.1292	1932	9	2	10.04	18.58	19.58
SPAS_1195_2	PADDY MOUNTAIN	WV	39.0208	-78.5625	1936	3	16	2.78	5.94	8.32
SPAS_1311_1	MCKENZIE	TN	36.4375	-87.9125	1937	1	5	4.04	6.33	22.60
SPAS_1346_1	BLUE RIDGE DIVIDE	NC	35.0375	-83.0792	1940	8	29	9.37	13.30	14.09
SPAS_1430_1	HEMPSTEAD	TX	30.1292	-96.0542	1940	11	22	8.85	18.88	21.29
SPAS_1431_1	WARNER	OK	35.4792	-95.3292	1943	5	6	10.09	17.77	25.24
SPAS_1433_1	COLLINSVILLE	IL	38.6708	-90.0042	1946	8	12	6.40	13.10	19.07
SPAS_1435_1	HARRISONBURG DAM	LA	31.7875	-91.8167	1953	5	11	9.43	18.02	25.35
SPAS_1278_1	MADISONVILLE	KY	37.3458	-87.4958	1964	3	8	3.90	8.71	11.53
SPAS_1312A_1	ROLLINS BRANCH	NC	37.7375	-81.5958	1964	9	28	4.47	7.12	9.22
SPAS_1312A_2	ROSMAN	NC	35.1458	-82.8042	1964	9	28	7.23	13.94	17.86
SPAS_1183_1	EDGERTON	MO	40.4125	-95.5125	1965	7	18	12.06	18.59	20.76
SPAS_1181_1	GLADEWATER	TX	32.8029	-94.7050	1966	4	27	9.17	14.53	25.28
SPAS_1380_1	BURTON DAM	GA	34.7958	-83.6958	1967	8	22	5.79	12.64	18.42
SPAS_1357_1	GLEN	MS	34.8375	-88.3958	1973	3	14	4.78	10.36	12.15
SPAS_1362_1	COEBURN	VA	37.2792	-81.8042	1977	4	2	3.92	12.21	15.66
SPAS_1362_2	ROBBINSVILLE	VA	35.3208	-83.6875	1977	4	2	3.95	5.41	9.21
SPAS_1227_1	LOUISVILLE	MS	33.1042	-88.7500	1979	4	12	9.32	20.06	22.07
SPAS_1219_1	BIG FORK	AR	35.8708	-92.1208	1982	12	1	6.75	14.58	15.92
SPAS_1376_1	LIBERTY	KY	37.2625	-84.9708	1984	5	7	5.24	7.08	9.62
SPAS_1206_1	BIG RAPIDS	MI	43.6125	-85.3125	1986	9	9	4.69	9.86	13.18
SPAS_1277_1	GILBERTSVILLE	KY	36.9958	-88.2625	1989	2	12	5.14	9.41	13.20
SPAS_1286_1	AURORA COLLEGE	IL	41.4575	-88.0699	1996	7	16	14.77	18.05	18.13
SPAS_1244_1	LOUISVILLE	KY	38.1000	-85.6700	1997	2	28	5.42	10.94	13.51
SPAS_1048_1	HOKAH	MN	43.8125	-91.3625	2007	8	18	7.86	7.86	20.33
SPAS_1228_1	FALL RIVER	KS	37.6300	-96.0500	2007	6	30	9.12	14.91	25.50
SPAS_1242_1	ALLEY SPRING	MO	37.1150	-91.4450	2008	3	17	6.18	13.32	15.10
SPAS_1218_1	DOUGLASVILLE	GA	33.8700	-84.7600	2009	9	19	17.36	22.82	25.37
SPAS_1218_2	LA FAYETTE	GA	34.7700	-85.2600	2009	9	19	11.84	15.99	19.61
SPAS_1208_1	WARNER PARK	TN	36.0611	-86.9056	2010	4	30	15.31	18.39	19.71

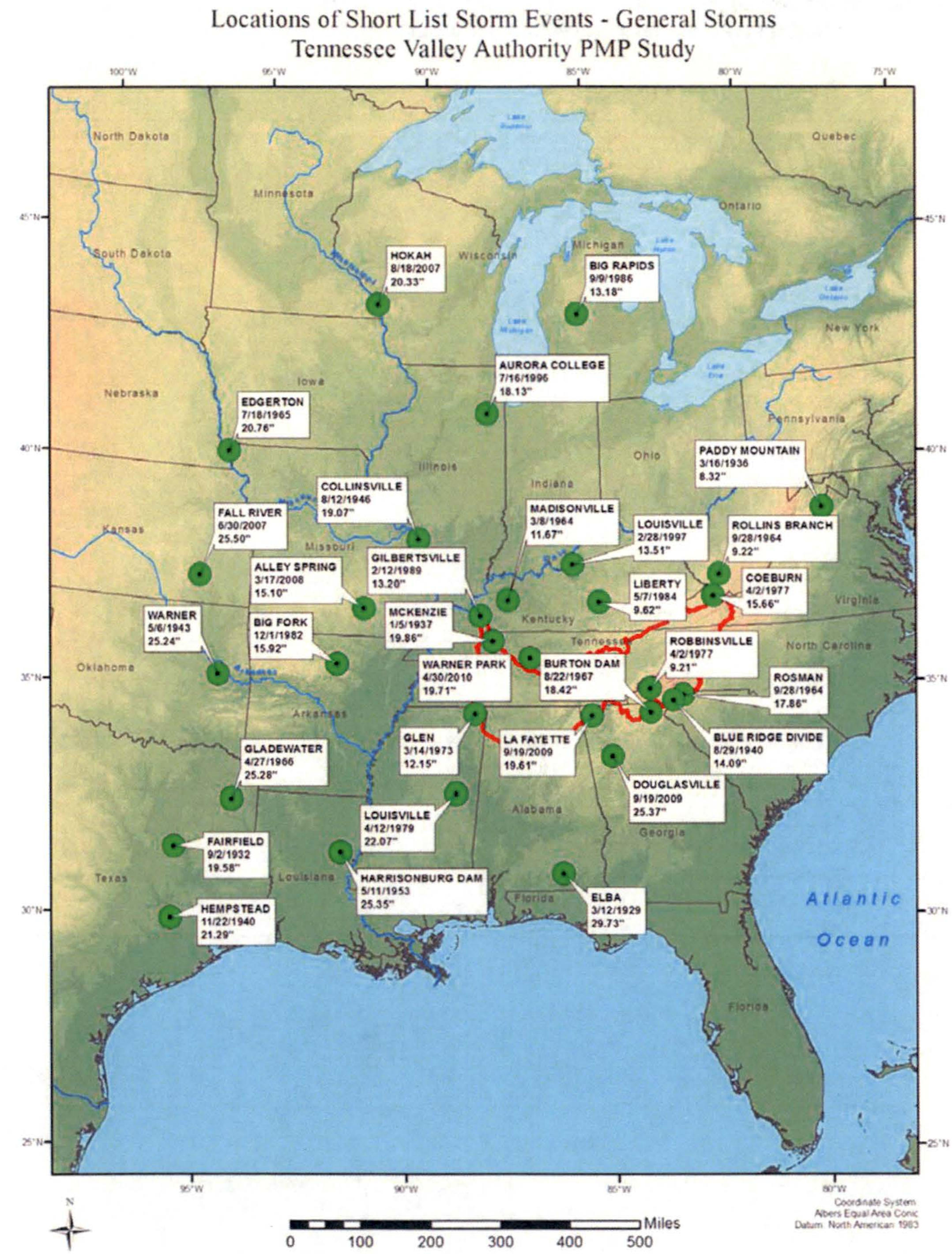

Figure 12 Locations of general storms in relation to TVA

Table 3 Short storm list used for PMP Development-local storms

SPAS_ID	NAME	STATE	LAT	LON	YEAR	MONTH	DAY	MAXIMUM 6-HOUR RAINFALL	MAXIMUM 24-HOUR RAINFALL	MAXIMUM TOTAL STORM RAINFALL
SPAS_1426_1	COOPER	MI	42.3708	-85.5875	1914	8	31	13.39	13.39	13.39
SPAS_1343_1	JOHNSON CITY	TN	36.3042	-82.0625	1924	6	13	14.48	16.20	16.14
SPAS_1427_1	BOYDEN	IA	43.1958	-95.9958	1926	9	17	18.61	24.22	24.22
SPAS_1344_1	SIMPSON	KY	38.1042	-83.2958	1939	7	4	20.31	20.82	20.82
SPAS_1429_2	HALLETT	OK	36.2458	-96.6125	1940	9	2	18.42	24.00	24.00
SPAS_1345_1	SMETHPORT	PA	41.8271	-78.2771	1942	7	17	13.06	34.91	34.91
SPAS_1432_1	MOUNDS	OK	35.8458	-96.0708	1943	5	16	16.23	17.34	19.27
SPAS_1434_1	HOLT	MO	39.4542	-94.3292	1947	6	18	13.01	13.13	17.62
SPAS_1031_1	PRAGUE	NE	41.3583	-96.8794	1959	8	1	7.07	10.43	11.27
SPAS_1030_1	DAVID CITY	NE	41.2132	-97.0710	1963	6	24	13.98	15.98	15.98
SPAS_1226_1	COLLEGE HILL	OH	40.0854	-81.6479	1963	6	3	11.50	19.16	19.39
SPAS_1402_1	LITTLE BARREN	TN	36.3625	-83.7208	1965	7	24	8.17	10.62	11.00
SPAS_1402_2	ROSEDALE	TN	36.1792	-84.2292	1965	7	24	12.31	13.09	13.32
SPAS_1209_1	WOOSTER	OH	40.9146	-81.9729	1969	7	4	8.95	14.67	14.95
SPAS_1034_1	ENID	OK	36.3805	-97.8683	1973	10	10	11.22	19.02	19.45
SPAS_1035_1	FOREST CITY	MN	45.2394	-94.5404	1983	6	20	8.35	13.89	17.00
SPAS_1210_1	MINNEAPOLIS	MN	44.8895	-93.4021	1987	7	23	11.24	11.55	11.55
SPAS_1220_1	DUBUQUE	IA	42.4400	-90.7500	2011	7	27	10.90	15.14	15.14
SPAS_1296_1	DULUTH	MN	47.0200	-91.6700	2012	6	19	6.56	10.57	10.73

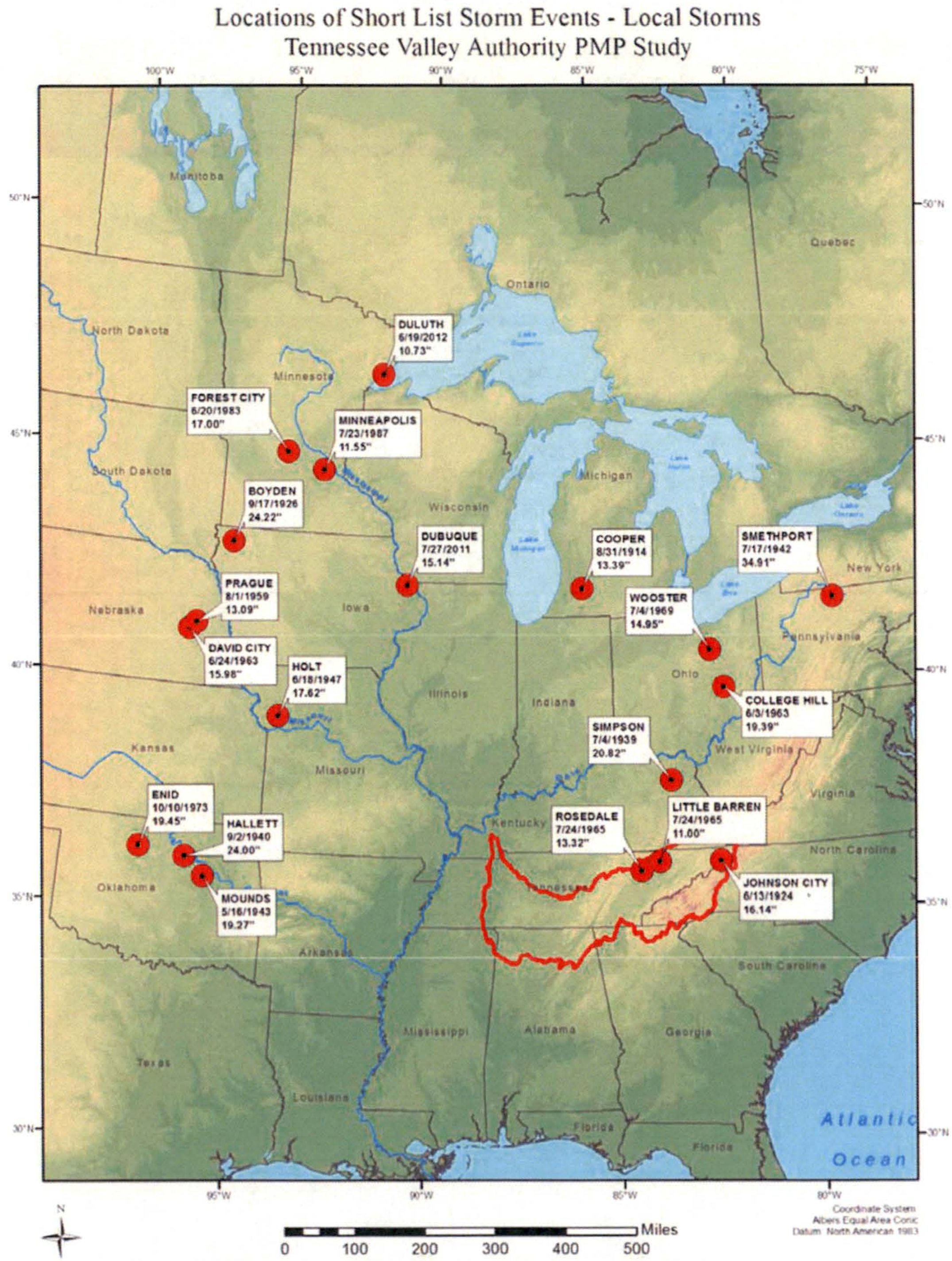

Figure 13 Locations of local storms in relation to TVA

Table 4 Short storm list used for PMP Development-tropical storms

SPAS_ID	NAME	STATE	LAT	LON	YEAR	MONTH	DAY	MAXIMUM 6-HOUR RAINFALL	MAXIMUM 24-HOUR RAINFALL	MAXIMUM TOTAL STORM RAINFALL
SPAS_1299_1	ALTA PASS	NC	35.8792	-81.8708	1916	7	13	8.67	23.15	24.90
SPAS_1342_1	MT MITCHELL	NC	36.2875	-81.4792	1940	8	11	7.70	13.71	20.27
SPAS_1312B_1	DEKALB	MS	32.7458	-88.6542	1964	10	4	2.96	3.67	3.67
SPAS_1312B_2	ROSMAN	NC	35.1375	-82.8375	1964	10	4	10.27	16.77	17.53
SPAS_1276_1	WELLSVILLE	NY	42.0375	-78.0708	1972	6	18	5.70	11.08	18.78
SPAS_1317_1	AMERICUS	GA	32.0958	-84.2292	1994	7	4	12.76	21.20	28.09
SPAS_1275_1	MONTGOMERY DAM	PA	40.6450	-80.3850	2004	9	18	5.70	8.79	8.79
SPAS_1182_1	LARTO LAKE	LA	31.2200	-92.1300	2008	9	1	11.34	16.55	23.31

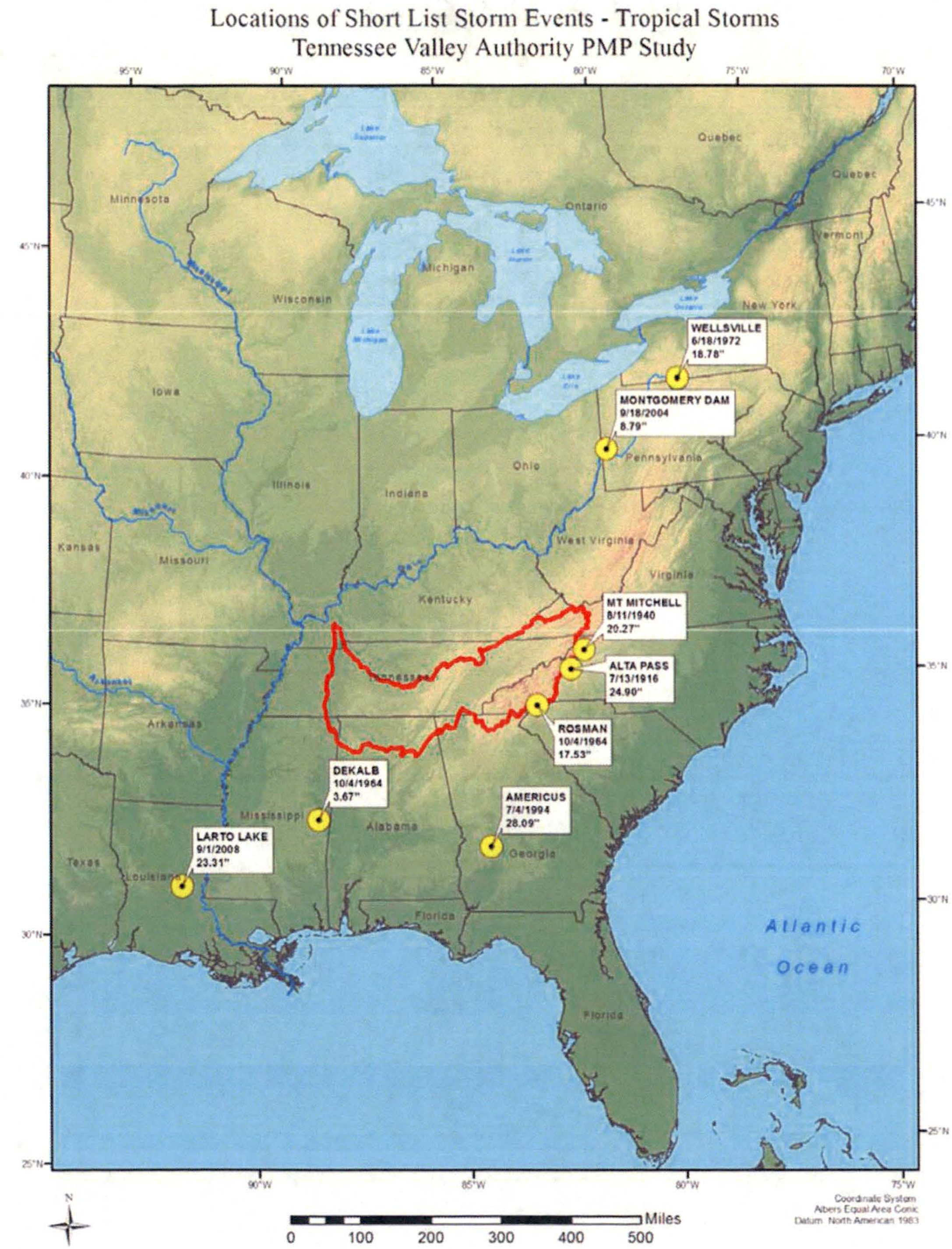

Figure 14 Locations of tropical storms in relation to TVA

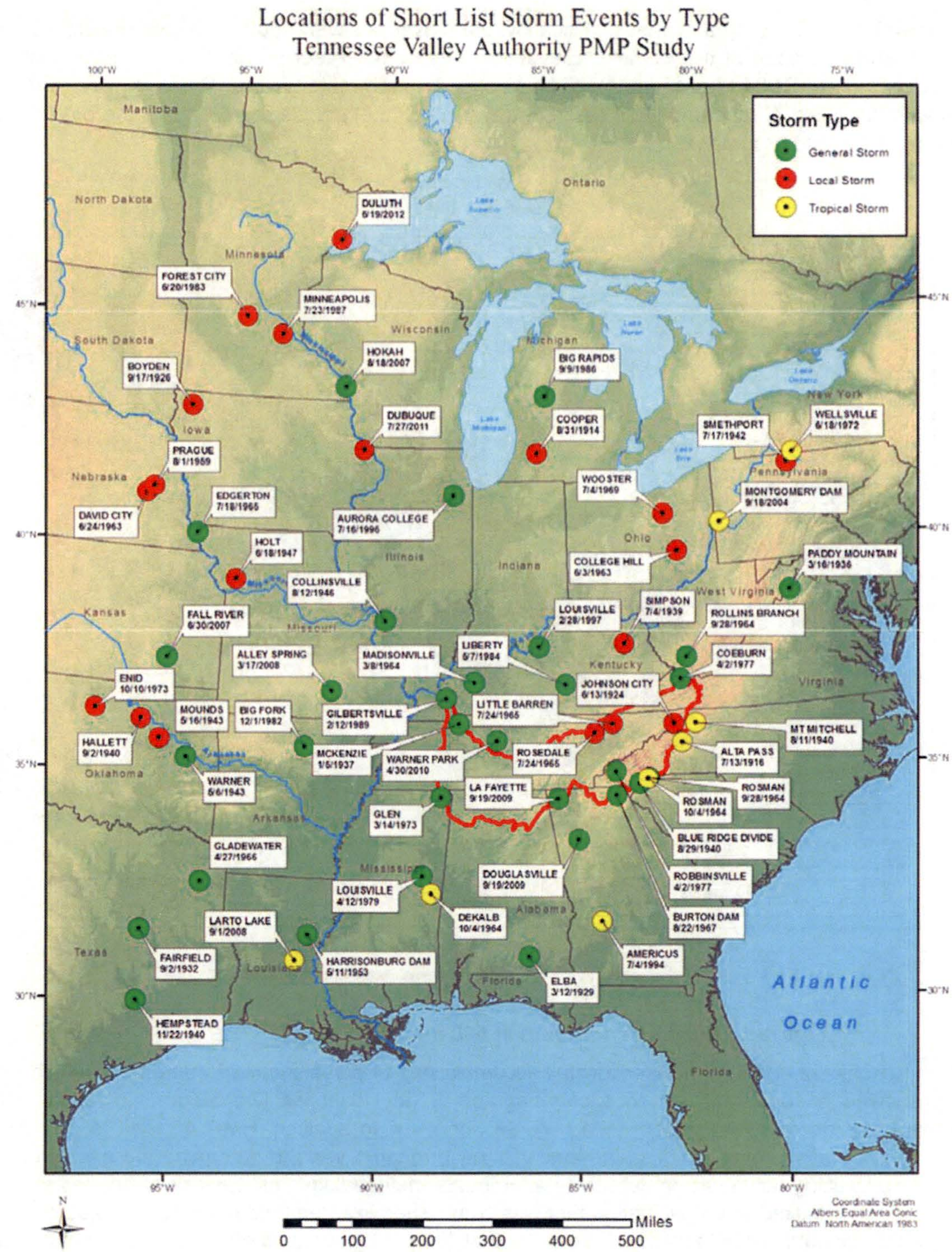

Figure 15 Locations of all short list storms in relation to TVA-by storm type

3.5 Discussion of Topographic Effects on Rainfall

Terrain within the TVA region varies significantly, often over relatively short distances (Figure 16), particularly in the eastern portions of the domain. Elevations vary from 49 feet at the Tennessee/Kentucky border at Kentucky Dam, to 6,684 feet at the top of Mt Mitchell in northwestern North Carolina. Previous TVA HMRs dealt with the effect of topography in different ways. Each method tried to delineate the overall domain into non-orographic and orographic.

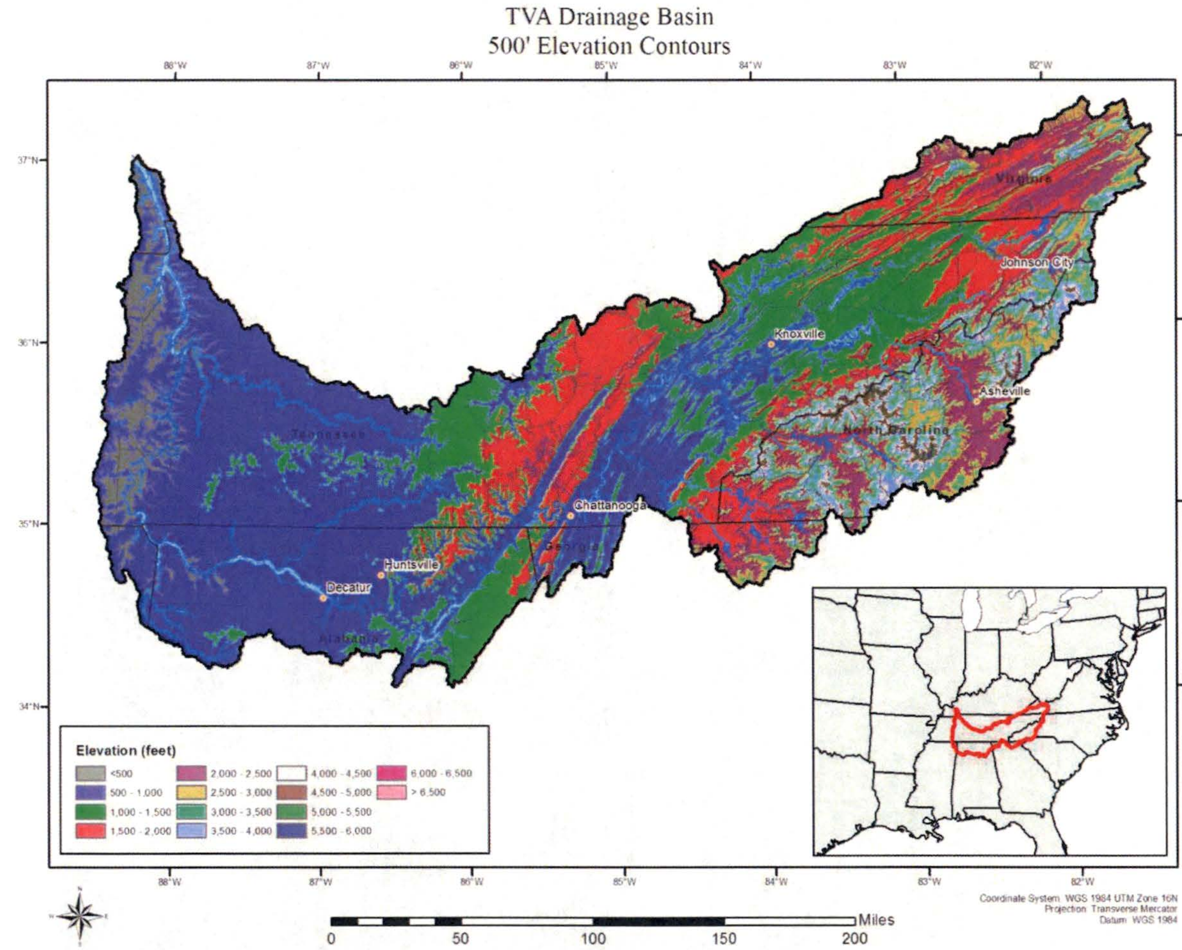

Figure 16 Elevation contours at 500 foot intervals across the TVA region

HMR 41 (Schwarz, 1965) compared rainfall accumulations of actual storms to determine which areas of the basin showed a consistent influence of topography. They identified two orographic rainfall patterns, an upstream and downstream pattern (HMR 41 Section 4-A). In addition, HMR 41 tried to use climatological evaluations of rainfall over various timescales (1 day through 1 year) to determine the effects of topography on rainfall. Utilizing actual storm data is an appropriate methodology, but the lack of gridded storm data and low resolution resulted in an evaluation that was over generalized and did not properly capture the effects of topography spatially. HMR 41's conclusion was that "no net topographic effect on volume is therefore used" (HMR 41 Page 59).

HMR 45 (Schwarz, 1969) noted that short duration rainfalls did not show a discernible correlation with topography (HMR 45 Page 5). However, they noted longer duration events (longer than a few hours) began to exhibit effects of topography stating that "effects of upslope and broad-scale sheltering are clearly indicated" (HMR 45 Page 12). HMR 45 split up the TVA domain into "rough" and "smooth" areas and applied adjustments to PMP based on this categorization. HMR 45 used rainfall climatology to help define topographic effects on rainfall, continuing the storm based methodology. Again, like HMR 41, they recognized that topography does have an effect on PMP rainfall, but did not have a robust process to quantify these effects. Therefore, the application of "rough" and "smooth" over generalized the process.

HMR 47 (Schwarz, 1973) utilized the highest monthly values as guides to defining orographic effects. Wind inflow directions were considered important. They determined meteorological factors were more important than orographic factors (HMR 47 Page 8), but they decided to incorporate a correction factor to address orographics. This correction factor was assumed to be evened out over large basins by considering some areas would see an increase and others a decrease.

HMR 56 (Zurndorfer et al., 1986) identified various regions within the overall basin that were considered influenced by topography, either enhanced or sheltered. Investigation of rainfall center verses elevation showed no strong relationship and they determined that the effect of topography should not be overemphasized in short duration rainfall (HMR 56 Section 2.1.3). HMR 56 also used mean annual precipitation patterns to derive a ratio of orographic influence termed the Broadscale Orographic Factor (HMR 56 3.4.1).

All TVA HMRs employed varying methods to evaluate the effects of topography on rainfall. Each recognized this was a significant aspect of PMP development. Each used storm data and climatological data to help delineate regions of influence and to quantify the effects. In addition, consideration was given to wind inflow direction and its interaction with topography. All of these components are included and utilized in AWA's process of evaluating and quantifying the effects of topography on rainfall. This is accomplished through the use of OTF calculations and how those are derived. The difference is the OTF, along with hourly gridded rainfall data from SPAS analyses, is able to evaluate and quantify these variations over a much more refined scale both spatially and temporally.

3.5.1 Topographic Effects on PMP Rainfall

The varying terrain within the TVA region (Figure 16) results in both increasing rainfall on upwind locations and decreasing rainfall over downwind locations. Because the PMP-design storms are required to replicate physically possible events, the effects of terrain on rainfall magnitude and spatial distribution must be accounted for. To account for the enhancements and reductions of precipitation by terrain features (called orographic effects), explicit evaluations were performed using precipitation frequency climatologies. These included NOAA Atlas 14, Volume 2 (Bonnin et al., 2006) and NOAA Atlas 14, Volume 9 (Perica et al., 2013). In addition, the regional precipitation frequency climatology analysis completed concurrently with this PMP calculation (TVA Calculation No. RSOGENROGCDX0003262016000087, R0) were evaluated by AWA. These data helped define the transposition zones used and other information relevant to storm calculations.

The NOAA Atlas 14 climatologies were used to derive the OTFs for each grid point for each storm. This approach is similar to that used in the TVA HMRs and in HMRs 55A, 57 and 59 for the mountainous western United States. The process used in the TVA HMRs was described in Section 3.4. HMRs 55a, 57, and 59 used the SSM to quantify orographic effects in topographically significant regions. In contrast to the SSM methodology, the OTF procedure is significantly more objective and reproducible. In Appendix I, a detailed example of the subjectivity and issues associated with the SSM is provided. In Appendix I, AWA tried to replicate the SSM process and data using information provided in HMRs 55A, 57, and 59 during a site-specific PMP study conducted in the coastal mountains of Southern California (Tomlinson et al., 2011). Results of that analysis explicitly showed that the SSM method is not reproducible and is highly subjective.

3.5.2 Quantification of Orographic Effects on PMP Rainfall

Orographic effects on rainfall are explicitly captured in climatological analyses that use precipitation data from historical record of rainfall events over a given region. These historical rainfall amounts include precipitation that would have accumulated without topography together with the amount of precipitation that accumulated because of the effects of topography, both at and surrounding a given observation site. Orographic effects produce both enhanced rainfall (on elevated windward terrain) and decreased rainfall (on lower leeward terrain and in protected valleys). Although the orographic effects at a particular location may vary from storm to storm, the overall effect of the topographic influence is inherently included in the climatology of precipitation that occurred at that location, assuming that the climatology is based on storms of the same type.

For TVA, extreme storm events (PMP-type storms) include local storms (both individual thunderstorms and MCSs), general storms, and remnant tropical systems. Thunderstorms/MCSs are the primary controlling storm type of the precipitation frequency climatology at durations of 6 hours or less, while the general and tropical storms are responsible for the precipitation frequency climatology values for durations of 24 hours and greater. Hence, climatological analyses of the rainfall data associated with these storm types adequately reflects the differences in topographic influences at different locations when evaluated by storm type and duration.

Procedures used in this study account for orographic effects by determining differences between the climatological information at the in-place storm location and the individual grid point being evaluated. This is a departure from the methods used in the TVA HMRs and the SSM used in HMRs 55A, 57, and 59. The method used in the TVA HMRs is oversimplified and does not adequately capture the spatial variability associated with varied topography, while the SSM used in the other HMRs is highly subjective and is not reproducible.

The OTF process used in this study (as well as all AWA PMP studies where topography plays a role in rainfall spatial distribution and magnitude) reduces the amount of subjectivity involved and provides a dataset which is reproducible. By evaluating rainfall values for a range of recurrence intervals at both locations, a relationship between the two locations was established. For this study, gridded precipitation frequency climatologies from NOAA Atlas 14, Volume 2 (Bonnin et al., 2006) and NOAA Atlas 14, Volume 9 (Perica et al., 2013) were used to develop the rainfall frequency relationships and quantify orographic effects.

The precipitation frequency estimates utilize information from the mean annual maximum grids developed using the Oregon State University Climate Group's PRISM system to help spatially distribute the values between observational data locations (Perica et al., 2011, 2013). PRISM is a peer-reviewed modeling system that combines statistical and geospatial concepts to evaluate gridded rainfall with particular effectiveness in orographic areas (Daly et al., 1994, 1997). The precipitation frequency estimates used in this study implicitly express orographic controls through the adoption of the PRISM system (Perica et al., 2011, 2013). A major component of the OTF process is the assumption that the relationship between precipitation frequency values in areas of similar meteorology and topography (transpositionable regions) are a reflection of all precipitation process, including the difference in orographic effect between the two locations being compared. It is also assumed that the influence of terrain is a primary contributing factor to the variability in the relationship between precipitation climatology values at two distinct point locations where terrain is a major influence on precipitation amounts and spatial distributions.

The orographically adjusted rainfall for a storm at a target (grid point) location may be calculated by determining the relationship between the precipitation frequency data series at the source storm location (i.e. the location where the historic storm occurred) and the corresponding data series at the target location. For the transposition of a single grid point at a given duration, the orographic relationship is defined as the linear relationship of the precipitation frequency values, at that duration, over a range of recurrence intervals between the source and target locations. This study evaluated the trend of precipitation frequency estimates through the 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-year average recurrence intervals. The relationship between the target and the source can be expressed as a linear function with P_i as the independent variable and P_o as the dependent variable as shown in Equation 2.

$$P_o = mP_i + b \qquad \text{Equation 2a}$$

$$OTF = P_o/P_i = m + b/P_i \qquad \text{Equation 2b}$$

where,

P_o	=	orographically adjusted rainfall (in.)
P_i	=	SPAS-analyzed in-place rainfall (in.)
m	=	slope of least squares line
b	=	origin offset (in.)

Equation 2a provides the orographically transpositioned rainfall depth, as a function of the in-place rainfall depth. The in-place rainfall depth used to calculate the orographically transpositioned rainfall corresponds, in duration, to the precipitation frequency datasets used (i.e., 6-hour for local storms and 24-hour for general and tropical storms). To express the orographic effect as a ratio, or OTF, the orographically adjusted rainfall (P_o) is divided by the original source in-place rainfall depth (P_i) (Equation 2b). It is assumed the orographic effect for a given transposition scenario is the same for all durations analyzed. Therefore, the 6-hour OTF determined for local storms, or the 24-hour OTF determined for general and tropical storms, is applied for all other analyzed durations for the given storm type.

The orographic relationship can be visualized by plotting the estimate precipitation depths for selected recurrence intervals for the grid point at the source location on the *x*-axis and the depths for the grid point at the target location on the *y*-axis and drawing a best-fit linear line among the seven return frequency depth points. The linear line shows the general relationship between the precipitation frequency values at the grid point location and the values at the in-place storm grid point location. At the 10- to 1,000-year recurrence intervals, the coefficient of determination (*R-squared*) for the least squares trend line is consistently very close to 1.00 indicating the goodness-of-fit of the statistical model (see Figure 26). An example of the determination of the orographic relationship and development of the OTF is given in Section 6.5.4.

4.0 Data Analysis Activities

AWA performed the data analysis activities described below to calculate the PMP values. Most of the process follow standard HMR procedures, with enhancements applied where data and current understanding of meteorology allow.

4.1 Storm Maximization

Storm maximization is the process of increasing rainfall associated with an observed extreme storm under the potential condition that additional moisture could have been available to the storm for rainfall production. This is accomplished by increasing the dew points (or Sea Surface Temperatures (SSTs) when dew points are not available) to some climatological maximum and calculating the rainfall amounts that could potentially have been produced if those increased amounts of moisture would have been available. It is assumed that adding additional moisture to the storm environment would not alter the storm dynamics (i.e. the processes in the atmosphere that convert available moisture into precipitation). This assumption is considered valid up to an increase of 50%. This follows standard HMR procedures of limiting the moisture maximization to 50% or less (e.g. HMR 51 Section 3.2.2). The maximum dew point values provided in the maximum average (average of maximum values) dew point climatologies are for the 1,000mb level, so these values are adjusted to the elevation of the storm location. This is done to remove the amount of moisture associated with the 1,000mb maximum dew point that would not be available at the storm elevation. Both the storm representative dew point and the maximum average dew point need to represent moisture in the atmospheric column above ground level, i.e. the storm location elevation.

An additional consideration is usually applied that selects the climatological maximum dew point value for a date 15 days towards the warm season (season of higher maximum average dew point/SST climatology values) from the date that the storm actually occurred. This procedure assumes that the storm could have occurred with the same storm characteristics 15 days earlier or later in the year when maximum average dew points are higher and hence, more moisture would be available for rainfall production. This assumption follows HMR guidance and is consistent with procedures used to develop PMP values in all the current HMR documents (e.g. HMR 51 Section 2.3.4) and in the WMO Manuals for PMP (1986, 2009) as well as all AWA PMP studies. There are rare occasions when this 15-day adjustment is not applied. This occurs when the synoptic weather patterns that produced the rainfall are of such a unique nature that they would not have occurred 15 days further towards the warm season.

The maximization factor depends on the determination of storm representative dew points, along with maximum historical dew point values. The magnitude of the maximization factor varies depending on the values used for the storm representative dew point and the maximum dew point. Holding all other variables constant, the maximization factor is smaller for higher storm representative dew points as well as for lower maximum dew point values. Likewise, larger maximization factors result from the use of lower storm representative dew points and/or higher maximum dew points. The magnitude of the change in the maximization factor varies depending on the dew point values. For the range of dew point values used in most PMP studies, the maximization factor for a particular storm will change about 5% for every 1°F difference between the storm representative and maximum dew point values. The same sensitivity applies to the transposition factor, with about a 5% change for every 1°F change in either the in-place maximum dew point or the transposition maximum dew point.

For example, consider the following generic case:

Storm representative dew point:	75°F	Precipitable water:	2.85"
Maximum dew point:	79°F	Precipitable water:	3.44"

Maximization factor = 3.44"/2.85" = 1.21

If the storm's representative dew point were 74°F with precipitable water of 2.73", Maximization factor = 3.44"/2.73" = 1.26 (an increase of approximately 5%)

If the maximum dew point were 78°F with precipitable water of 3.29",

Maximization factor = 3.29"/2.85" = 1.15 (a decrease of approximately 5%)

4.1.1 Use of Dew Point Temperatures

HMR and WMO procedures for storm maximization use a representative storm dew point as the parameter to represent available moisture to a historic storm (SSTs are used as a surrogate when the moisture source region is represented by the Ocean). Storm precipitation amounts are maximized using the ratio of precipitable water for the maximum average dew point to precipitable water for the observed storm representative dew point.

Maximum dew point climatologies are used to determine the maximum atmospheric moisture that could have been available. Prior to the mid-1980s, maps of maximum dew point values from the *Climatic Atlas of the United States* (EDS, 1968) were the source for maximum dew point values. For the region covered by HMR 49, HMR 50 (Hansen and Schwartz, 1981) provided updated dew point climatologies. HMR 55A contained updated maximum dew point values for a portion of United States from the Continental Divide eastward into the Central Plains. HMR 57 updated the 12-hour persisting dew points values and added a 3-hour persisting dew point climatology. The regional PMP study for Michigan and Wisconsin produced dew point frequency maps representing the 50-year recurrence interval. This study was conducted using an at-site method of analysis with L-moment statistics. The Review Committee for that study included representatives from NWS, FERC, Bureau of Reclamation, and others. They agreed that the 50-year recurrence interval values were appropriate for use in PMP calculations. For the Nebraska state-wide study, the Review Committee and FERC Board of Consultants agreed that the 100-year recurrence interval dew point climatology maps were appropriate because their use added a layer of conservatism over the 50-year return period and the additional 15 years of hourly data allowed for a robust 100-year recurrence interval statistical analysis. This has subsequently been employed in all PMP studies completed by AWA. This study is again using the 100-year recurrence interval climatology constructed using dew point data. Under the review and RAI process, extensive discussion took place between TVA and the NRC regarding the adequacy of the dew point climatology. TVA agreed that updates were warranted to include several recent years of data as well as further enhanced quality NCEI hourly dew point climatologies. AWA completed an update to the previous dew point climatology database to include data through 2017 from the NCEI TD3505 hourly dew point database. In revision 1 of this report, the NCEI TD3505 database replaced AWA's previous dew point database used in revision 0 of this report. Figure 17 displays the difference in the updated dew point climatology versus the previous version for the month of July at the 6-hour duration. All dew point climatology maps used in this study are provided in Appendix C. The updated dew point climatology was utilized to complete the storm adjustments and develop PMP values.

Percent Difference from Original
6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F) - TVA v2
July

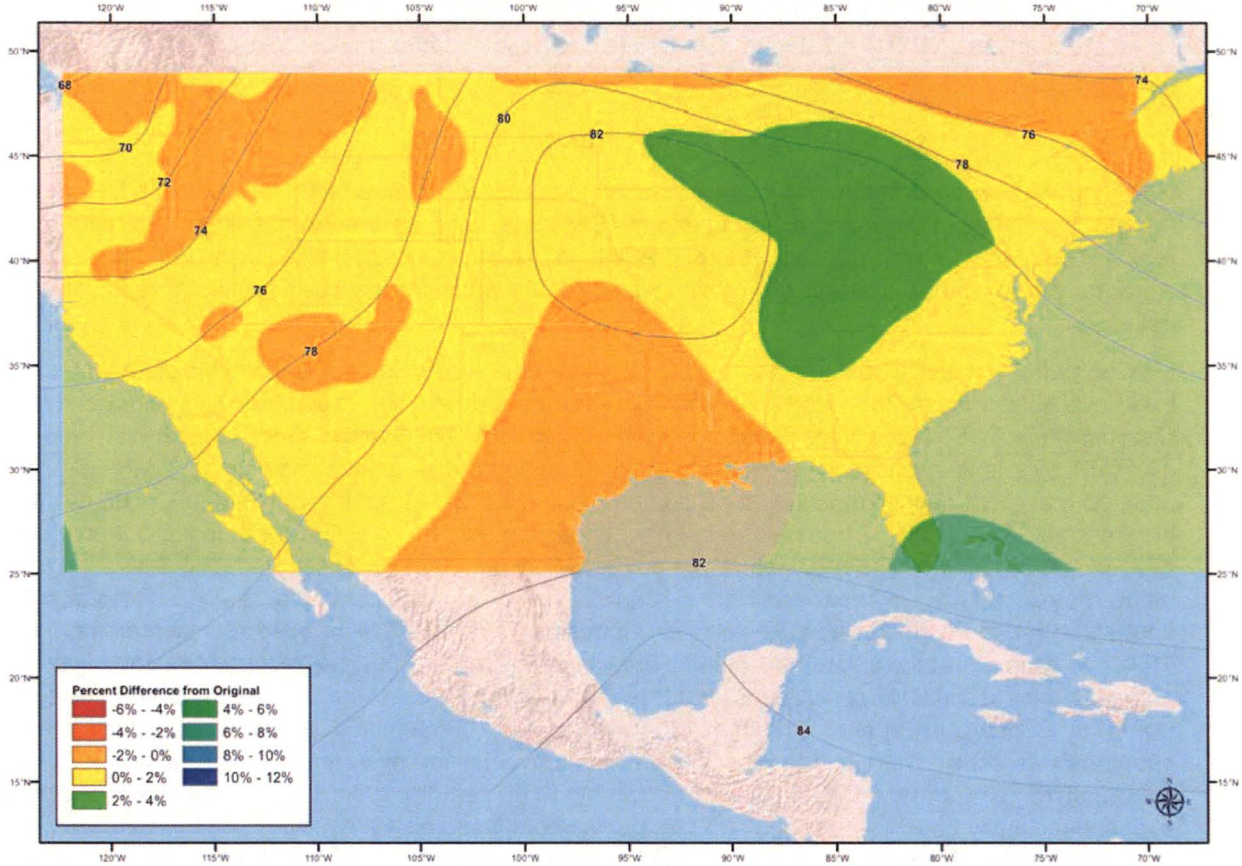

Figure 17 Percent change from July 6-hour maximum dew point utilized in the revision 0 report.

4.1.2 Storm Representative Dew Point Determination Process

For storm maximization, average dew point values for the duration most consistent with the actual rainfall accumulation period for an individual storm (i.e. 6-, 12-, or 24-hour) were used to determine the storm representative dew point. To determine which time frame was most appropriate, the total rainfall amount was analyzed. The duration closest to when approximately 90% of the rainfall had accumulated was used to determine the duration used, i.e. 3-hour, 6-hour, 12-hour, or 24-hour.

The storm representative dew point was investigated for each of the storm events analyzed during this study. Once the general upwind location was determined, the hourly surface observations were analyzed for all available stations within the vicinity of the inflow vector. From these data, the appropriate durational dew point value was averaged for each station (6-, 12-, or 24-hour depending on the storm's rainfall accumulation). These values were then adjusted to 1,000mb (approximately sea level) and the appropriate storm representative dew point and location were derived. The line connecting this point with the storm center location (point of maximum rainfall accumulation) is termed the moisture inflow vector. The information used and values derived for each storm's moisture inflow vector are included in Appendix F.

The HYSPLIT model developed by the NOAA Air Resources Laboratory (Draxler and Rolph, 2010) was used during the analysis of each of the rainfall events included on the short storm list when available (1948-present). Use of a trajectory model provides increased confidence in determining moisture inflow vectors and storm representative dew points. The HYSPLIT model trajectories have been used to analyze moisture inflow vectors in other PMP studies completed by AWA over the past several years. During these analyses, the model trajectory results were verified and the utility explicitly evaluated (e.g. Tomlinson et al., 2006-2013, Kappel et al., 2012-2014).

In determining the moisture inflow trajectory, the HYSPLIT model was used to compute the trajectory of the atmospheric moisture inflow associated with the storm's rainfall production, both location and altitude, for various levels in the atmosphere. The HYSPLIT model was run for trajectories at several levels of the lower atmosphere to capture the moisture source for each storm event. These included 700mb (approximately 10,000 feet), 850mb (approximately 5,000 feet), and storm center location surface elevation. For the majority of the analyses, a combination of all three levels was determined to be most appropriate for use in evaluation of the upwind moisture source location.

It is important to note that the resulting HYSPLIT model trajectories are only used as a general guide to evaluate the moisture source for storms in both space and time. The final determination of the storm representative dew point and its location is determined following the standard procedures used by AWA in previous PMP studies and as outlined in the HMRs and WMO manuals (WMO, 2009).

The process involves deriving the average dew point (or SST) values at all stations with dew point (or SST) data in a large region around the HYSPLIT inflow vectors. Values representing the average 6-, 12-, and 24-hour dew points or daily SST are analyzed in Excel spreadsheets. The appropriate duration representing the storm being analyzed is determined and data are plotted for evaluation of the storm representative dew point (or SST). This evaluation includes an analysis of the timing of the observed dew point (or SST) values to ensure they occurred in a source region where they would be advected into the storm environment at the time of the rainfall period. Several locations are investigated to find values that are of generally similar magnitude (within a degree or two Fahrenheit). Once these representative locations are identified, an average of the values to the nearest half degree is determined and a location in the center of the stations is identified. This becomes the storm representative dew point (or SST) value and the location provides the inflow vector (direction and distance) connecting that location to the storm center location. This follows the approach used in HMR 51 Section 2, HMR 55A Section 5, and HMR 57 Section 4, with improvements provided by the use of HYSPLIT and updated maximum dew point and SST climatologies. Appendix F of this report contains each of the HYSPLIT trajectories analyzed as part of this study for each storm (when used).

During the NRC review of revision 0 of this report, the NRC questioned several key storm representative dew points used in previous AWA studies in regard to timing and location. As a result of these questions, AWA adopted the NRC determined storm representative values for the four storms shown below in Table 5 in revision 1 of this report.

Table 5 Storms and storm representative dew points that were updated based on NRC evaluations

Storm Name	SPAS Number	Storm Type	Storm Representative Dew Point (Td) (deg F)		Difference (R0 – R1))
			Rev. 0 T_d	Rev. 1 T_d	
Big Rapids, MI	SPAS 1206	General	70.5	68.5	+2
Warner Park, TN	SPAS 1208	General	75	74	+1
Wellsville, NY	SPAS 1276	Tropical	72.5	70.5	+2
Americus, GA	SPAS 1317	Tropical	76	74.5	+1.5

4.1.3 Storm Representative Dew Point Determination Example

As an example, Figure 18 shows the HYSPLIT trajectory model results used to analyze the inflow vector for the Madisonville, KY March, 1964 (SPAS 1278) storm. HYSPLIT trajectories showed a general inflow from the Gulf of Mexico flowing north, then northeast into the storm and along the frontal boundary. The turning of the moisture in a clockwise direction was around the western edge of the general high pressure located to the east of the Atlantic (the Bermuda High). This is a common scenario for heavy rains over the region, where moisture is drawn up around the western edge of high pressure from the Gulf of Mexico and forced to lift over a frontal system stalled over the TVA region and then further enhanced by topography of the Appalachian Mountains. In this case, surface dew point values were analyzed for a region starting at the storm center and extending southward to the Gulf of Mexico and from Texas eastward to Georgia/Florida/South Carolina. All the HYSPLIT inflow vectors showed a south to southeast inflow direction from the storm center over Kentucky (the most common for TVA general storms). The air mass source region supplying the atmospheric moisture for this storm was located over southern Texas/Louisiana/Mississippi/Alabama 24-36 hours prior to the rainfall occurring over Tennessee and Kentucky. Surface dew points were analyzed over this source region, ensuring that the dew point observations were located outside of the area of rainfall to avoid contamination of the dew points by evaporating rainfall. Figure 19 displays the stations analyzed and their representative 24-hour average dew point values. The region encircled in red is considered the moisture source region for this storm.

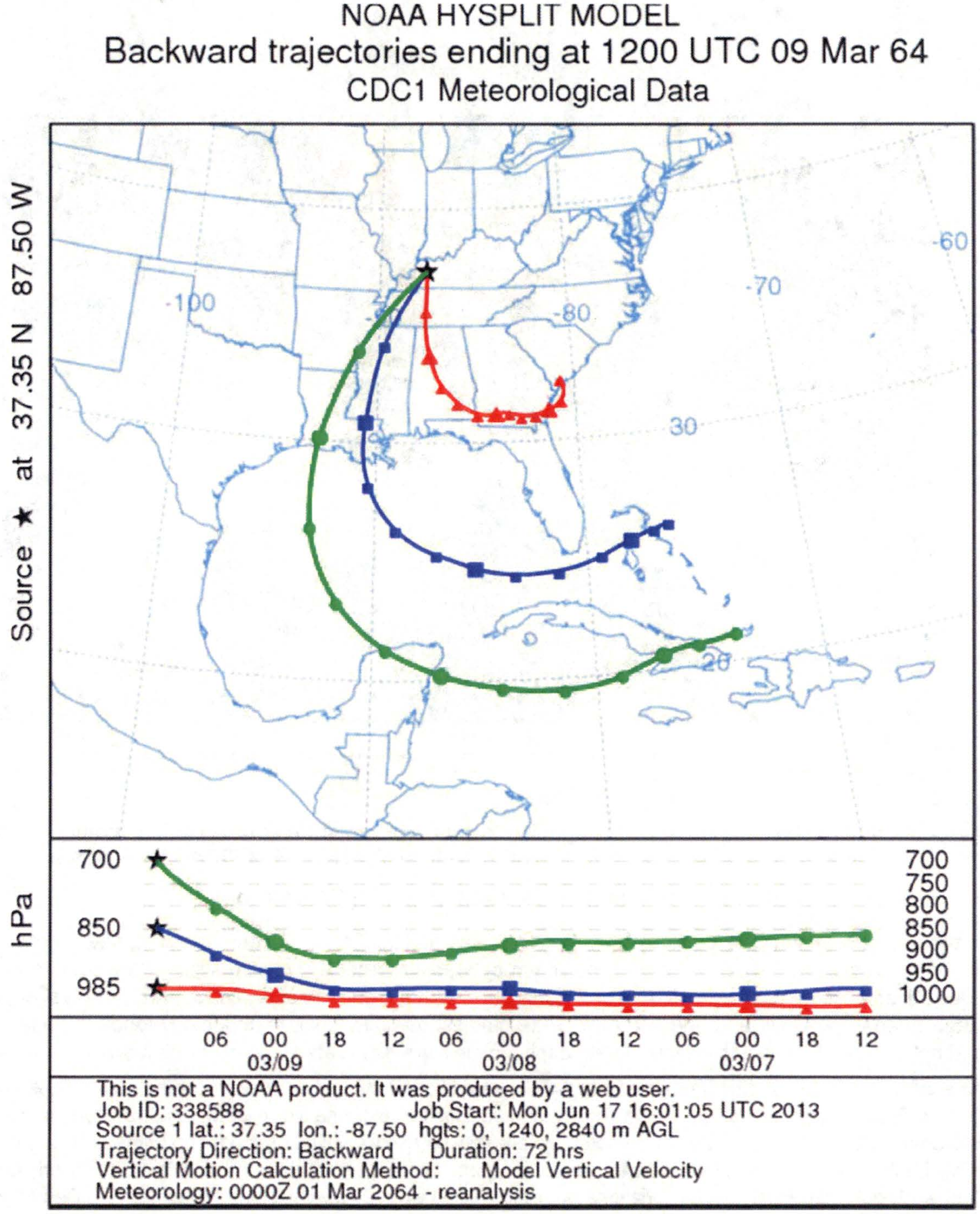

Figure 18 HYSPLIT trajectory model results for the Madisonville, KY March, 1964 (SPAS 1278) storm

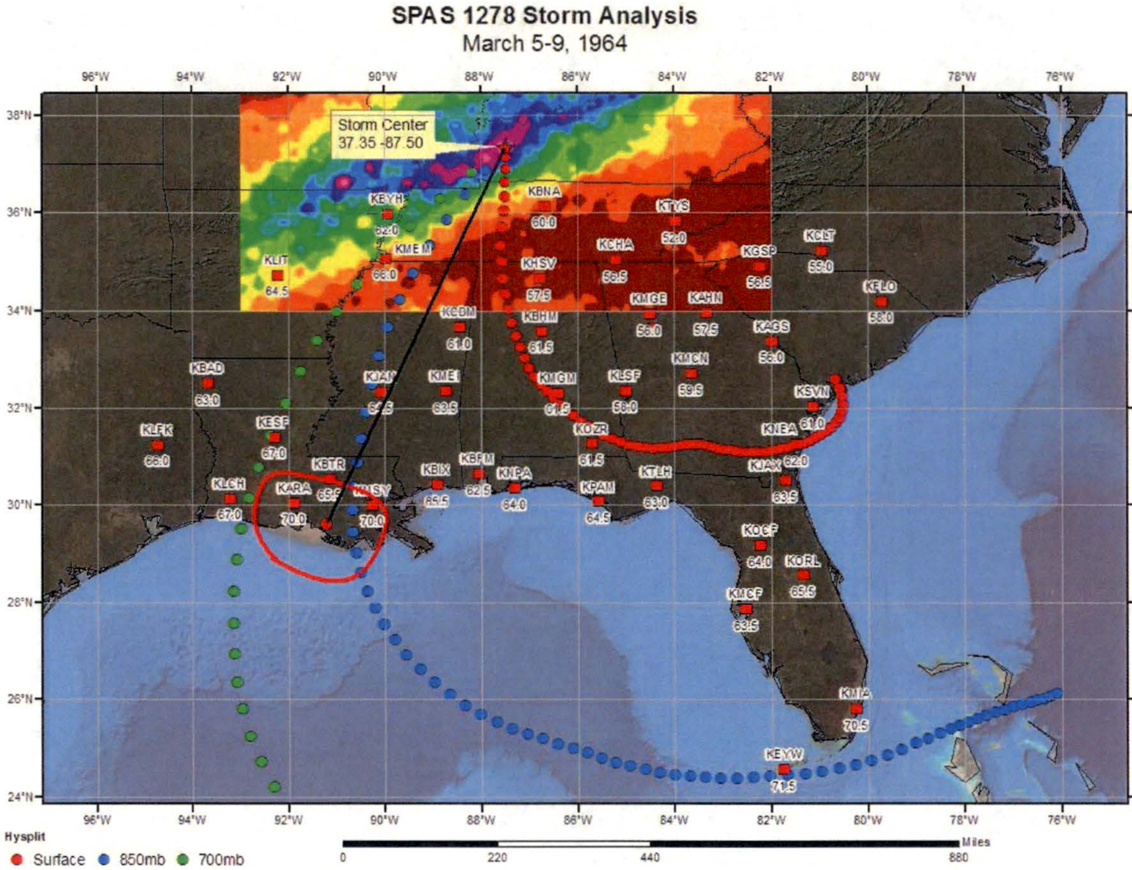

Figure 19 Surface stations, 24-hour average dew points, and moisture source region, along with HYSPLIT trajectory model results for the Madisonville, KY March, 1964 (SPAS 1278) storm

4.1.4 Rationale for Using Average Dew Point Climatology

In previous storm analyses performed by the NWS and the USACE, a 12-hour persisting dew point was used for both the storm representative and maximum dew points. The 12-hour persisting dew point is the value equaled or exceeded at all observations during the 12-hour period (e.g., WMO 2009). However, as was established in previous and ongoing AWA PMP studies, this dew point methodology tends to underestimate and not accurately reflect the available atmospheric moisture associated with the rainfall event.

An excellent example of this (from the Nebraska statewide PMP study, but relevant for the storm types that affect TVA) is illustrated by the David City, NE 1963 storm. During this extreme storm event, a narrow tongue of moisture was advected into the region by strong southeasterly flow on a low-level jet during a short time period. Most of the rain with this event (approximately 15 inches) accumulated in less than 6 hours. For this storm, hourly dew point data were collected from several locations near the rainfall event. These included Omaha, NE; Des Moines, IA; Topeka, KS; and Kansas City, MO. Following standard procedures for determining storm representative dew point location, it was determined that Topeka, KS and Kansas City, MO were the two stations that best represented the air mass that produced the extreme rainfall. Using hourly dew point data for these two stations clearly showed that use of 6-hour average dew point values better represented the atmospheric moisture available to the storm event than did use of 12-hour persisting dew point values. The 6-hour average dew point representing the moisture in the air mass associated with the rainfall was 71.5°F at Kansas City, MO and 71°F at Topeka, KS. Using these dew point values, a 1,000mb 6-hour average dew point of 73.5°F was determined for Kansas City, MO and a dew point of 73°F was determined for Topeka, KS. Using the NWS approach, the 12-hour persisting dew point is 63°F (65°F at 1,000mb) at Kansas City, MO and 66°F (68°F at 1,000mb) at Topeka, KS for an average 12-hour persisting 1,000mb adjusted value of 66.5°F (Table 6).

Table 6 Comparison of 6-hour average storm representative dew point vs. 12-hour persisting storm representative dew point for David City, NE, June 1963 (SPAS 1030)

Observed Dew Point Values for David City, NE 1963																								
Kansas City, MO																								
Hour	00Z	01Z	02Z	03Z	04Z	05Z	06Z	07Z	08Z	09Z	10Z	11Z	12Z	13Z	14Z	15Z	16Z	17Z	18Z	19Z	20Z	21Z	22Z	23Z
Dew Point	58	61	62	62	63	63	63	64	66	68	69	71	72	72	72	71	71	69	68	67	67	67	67	67
												Air Mass Supplying Rainfall Event												
12-Hour Persisting Td 63 (65 reduced to 1000mb)												12 Hour Persisting Td Timeframe												
6-Hour Average Td 71.5 (73.5 reduced to 1000mb)												6 Hour Average Td timeframe												
Topeka, KS																								
Hour	00Z	01Z	02Z	03Z	04Z	05Z	06Z	07Z	08Z	09Z	10Z	11Z	12Z	13Z	14Z	15Z	16Z	17Z	18Z	19Z	20Z	21Z	22Z	23Z
Dew Point	61	62	64	65	65	65	66	66	67	68	69	72	71	71	71	70	70	70	69	70	69	68	66	69
												Air Mass Supplying Rainfall Event												
12-Hour Persisting Td 66 (68 reduced to 1000mb)												12 Hour Persisting Td Timeframe												
6-Hour Average Td 71 (73 reduced to 1000mb)												6 Hour Average Td timeframe												

The 12-hour persisting dew point analysis included dew point values from a 6-hour period not associated with the rainfall. The hourly dew point value that provides the 12-hour persisting dew point occurred outside of the rainfall period after adjustment for advection time from the dew point observing station to the storm location.

4.1.5 Rationale for Adjusting HMR 51 Persisting Dew Point Values

In cases where updated average storm representative dew point values could not be calculated because of a lack of hourly dew point observations (generally storms occurring prior to 1948), an adjustment factor was applied to provide consistency in storm maximization while utilizing the updated dew point climatology. The adjustment factor was determined using the same procedure used in the FERC Michigan/Wisconsin and subsequent AWA PMP studies.

Results from the dew point analyses showed reasonably consistent results for local/MCS and general storms for differences between the older method for determining 12-hour persisting storm representative dew points and the approach using average storm representative dew points. The following discussion from the FERC Michigan/Wisconsin report addresses these differences:

The average difference between dew points for the synoptic storms was five degrees less than that for the MCS storms. This may be attributed to the greater homogeneity of inflow moisture associated with the synoptic events. With most of the modern MCS storms, limited-area, short-duration pockets of relatively moist air were found within the inflow moisture at one or two locations. The analyses may indicate that for MCS events, bubbles of extremely moist air interact with storm catalysts to create extreme rainfall events of short duration. A warm humid air mass over a broad area with small moisture gradients more aptly describes the synoptic inflow moisture. Several stations within the air mass may have the same or similar dew points. Much smaller variations in dew points along the inflow moisture vector are expected.

Large spatial and temporal variations in moisture associated with MCS-type storms are not represented well with 12-hour persisting dew points, especially when only two observations a day are available. Average dew point values, temporally consistent with the duration of the storm event provide a much improved description of the inflow moisture available for conversion to precipitation. The more homogeneous moist air masses associated with synoptic storms result in smaller differences between average and persisting values.

This analysis has provided correlations between 12-hour persisting storm dew points and average storm dew points for both MCS and synoptic storms. Despite the small sample size, the consistent results tend to support the reliability of the analysis. However, the small sample size has been considered in making recommendations for adjusting the old storm representative dew points for use in determining PMP estimations. The eight degree difference for MCS-type storms has been decreased to five degrees to provide a conservative adjustment. A similar consideration is made for synoptic-type storms. The three-degree difference is decreased to two degrees to provide a conservative adjustment. The adjusted representative storm dew points are used with the new maximum average dew point climatology to maximize storms.

Similar analyses were completed during the Nebraska, Ohio, and Wyoming statewide PMP studies. These analyses investigated additional storms specifically relevant to each region. Results of these analyses confirmed what has been found in previous studies, with an average difference of 7°F between the average and 12-hour persisting dew points for local/MCS storms, and an average difference of 2°F for general storms. Therefore, results of the more recent analyses were very consistent with the FERC Michigan/Wisconsin regional PMP study. This validated the process of adjusting the 12-hour persisting dew points to achieve compliance with using the average dew point climatology when explicit average dew point values could not be calculated for a given storm. This adjustment was only required for a limited number of storms where average storm representative dew point values were not able to be calculated because sufficient hourly dew point observations were generally not available prior to 1948.

4.2 Use of Sea Surface Temperatures

Dew point observations are not generally available over ocean regions. When the source region of atmospheric moisture feeding an extreme rainfall event originates from over the ocean, a substitute for dew points observations is required. The NWS adopted a procedure for using SSTs as surrogates for dew point data. The value used as the maximum SST in the PMP calculations is determined using the SSTs two standard deviations warmer (+2-sigma) than the mean SST. This provides a value for the maximum SST that has a probability of occurrence of about 0.025 (i.e. about the 40-year recurrence interval value).

HYSPLIT trajectory model provides detailed analyses for determining the upwind trajectories of atmospheric moisture that was advected into the storm systems. Using these trajectories, the moisture source locations are determined. This is especially helpful over ocean regions where surface data are lacking to help with guidance in determining the moisture source region for a given storm. The procedures followed are similar to the approach used in HMR 59. However, by utilizing the HYSPLIT model trajectories, much of the subjectivity is eliminated. Further, details of each evaluation can be explicitly provided and the results are reproducible. These trajectories extend over cooler coastal ocean currents to the warmer regions of the ocean that provide the atmospheric moisture that is later converted to rainfall by the storm system. SSTs for in-place maximization and storm transpositioning follow a similar procedure to that used with land based surface dew points. Use of the HYSPLIT trajectory model provides a significant improvement in determining the inflow wind vectors compared to older methods of extrapolating coastal wind observations and estimating moisture advection from synoptic features over the ocean. This more objective procedure is especially useful for situations where a long distance is involved to reach warmer ocean regions.

Timing is not as critical for inflow wind vectors extending over the oceans since SSTs change very slowly with time compared to dew point values over land. What is important is the changing wind direction, especially for situations where there is curvature in the wind fields. Any changes in wind curvature and variations in timing are inherently captured in the HYSPLIT model re-analysis fields, thereby eliminating another subjective parameter. Timing of rainfall is determined using the rainfall mass curves from the region of maximum rainfall associated with a given storm event. The location of the storm representative SST was determined by identifying the location where the SSTs are generally changing less than 1°F in an approximate 1° x 1° latitude and/or longitude distance following the inflow vector upwind. This is used to identify the homogeneous (or near homogeneous) region of SSTs associated with the atmospheric moisture source for the storm being analyzed. The value from the SST daily analysis for that location is used for the storm representative SST. The storm representative SST becomes a surrogate for the storm representative dew point in the maximization procedure.

The value for the maximum SST was determined using the mean +2-sigma (two standard deviations warmer than the mean) SST for that location. SSTs were substituted for dew points in this study for several storms where the inflow vector originated over the Atlantic Ocean. The storm spreadsheets presented in Appendix F list the moisture source region for each storm and whether dew points or SSTs were used in the maximization calculations. For storm maximization, the value for the maximum SST is determined using the mean +2-sigma SST for that location for a date two weeks before or after the storm date (which ever represents the climatologically warmer SST period). Storm representative SSTs and the mean +2-sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology values in the maximization and transpositioning procedure. Figure 20 is an example of a daily SST map used to determine the storm representative SST for the Mt. Mitchell, NC August, 1940 (SPAS 1342) storm event.

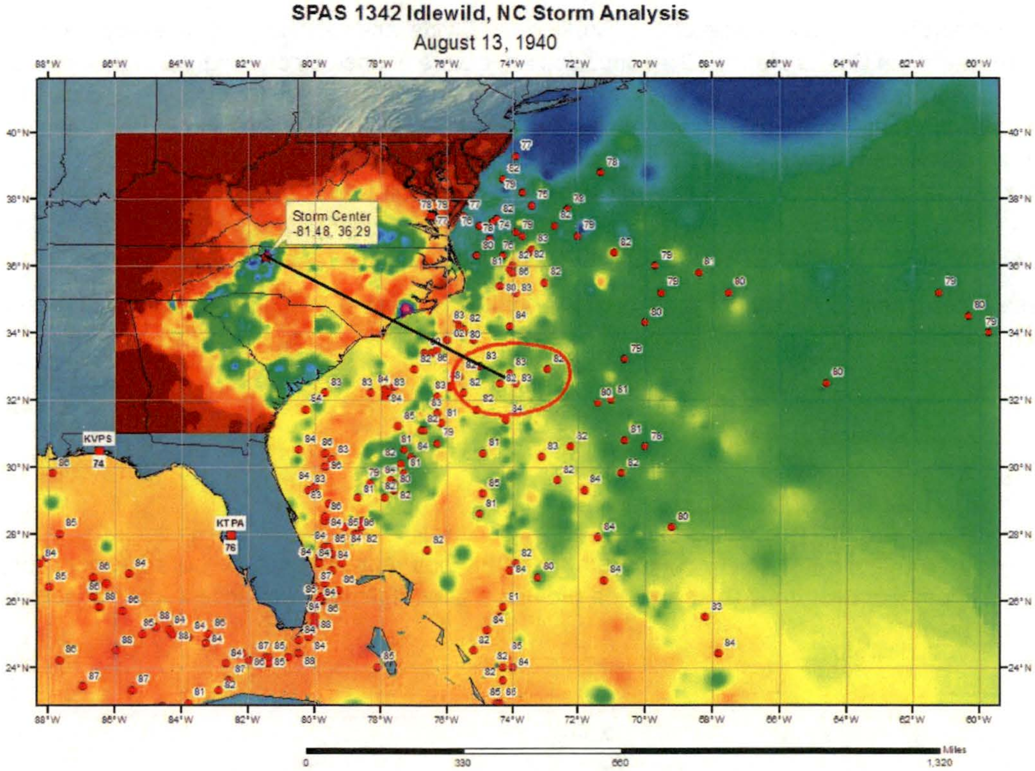

Figure 20 Daily SST observations used to determine the storm representative SST value for the Mt Mitchell, NC August, 1940 (SPAS 1342) storm

Storm representative SSTs and the mean +2 sigma SSTs are used in the same manner as storm representative dew points and maximum dew point climatology in the maximization and transpositioning procedure.

4.3 Storm Transpositioning

Extreme rain events in a meteorologically homogeneous region surrounding a location are a very important part of the historical evidence on which a PMP estimate for that location is based. Since most locations have a limited period of record for rainfall data, the number of extreme storms that have been observed over a location is limited. Historic storms that have been observed within similar meteorological and topographic regions are analyzed and adjusted to provide information describing the storm rainfall as if that storm had occurred over the location being studied. Transfer of a storm from where it occurred to a location that is meteorologically and geographically similar is called storm transpositioning. The underlying assumption is that storms transposed to the location could have occurred under similar meteorological conditions. To properly relocate such storms, it is necessary to address issues of similarity as they relate to meteorological conditions, moisture availability, and topography. In this study, adjustment factors used in transposing a storm are quantified by using the OTFs and MTFs as discussed in Section 4.

The search for extreme rainfall events identified storms that occurred throughout a large region extending from the Midwest through the northern Plains and Great Lakes, to the Appalachians and south to the Gulf Coast (see Figure 11). This region was considered meteorologically and geographically similar to one or more locations within the TVA domain.

The storms on the eastern side of the Continental Divide are supplied with low-level atmospheric moisture primarily from the Gulf of Mexico. Transposition limits were defined by dividing the region into four transposition zones. Each transposition zone was delineated after careful consideration of a combination of criteria including; physiographic provinces (defined by the USGS); climatological zones defined by NCDC; and the Köppen classification, variations in topography, variations in precipitation frequency climatology, variations in mean annual precipitation, and ecological regions. The climatic regions that were defined in the regional precipitation frequency analysis for the TVA study area (TVA Calculation No. RSOGENROGCDX000326201600087, R0) were also evaluated as delineation criteria.

These criteria helped identify regions of similar meteorology and topography. Four transposition zones were defined as follows (Figure 21):

1) Appalachian Plateau
2) Cumberland Plateau
3) Great Valley
4) Blue Ridge Mountains

It is recognized that these boundaries are not discrete boundaries in nature, but transitional zones. However, for the purpose of this study, these zones provide a good estimation of acceptable transpositionable extents for each storm.

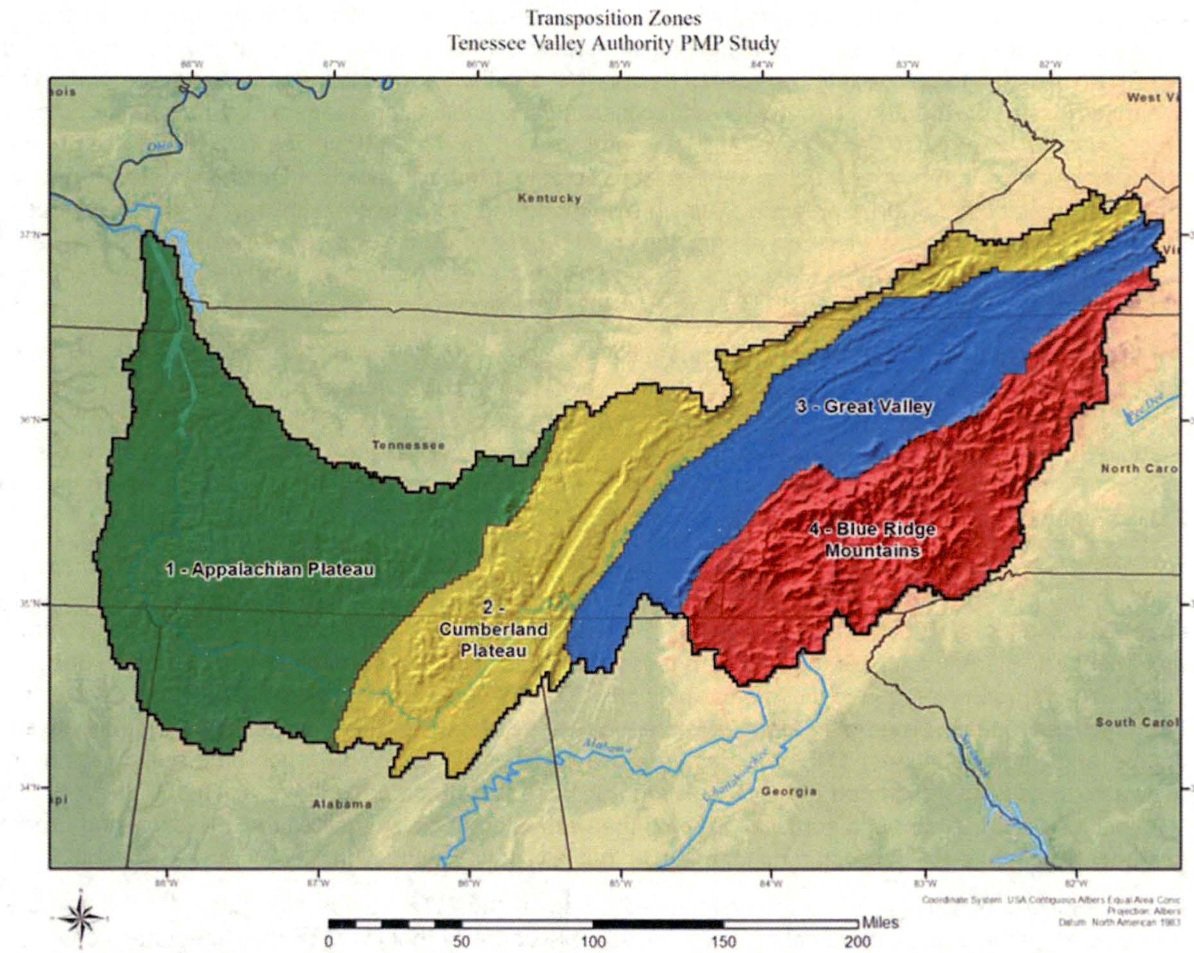

Figure 21 Transposition zones used to define transposition limits for individual storms

The 58 SPAS DAD zone centers on the short storm list were individually evaluated to determine their unique transposition limits. Initially, general transposition limits were placed on all storms and their individual DAD zones based on subjective judgments of the meteorology associated with each, the moisture source regions, and the interaction with topography at the original location versus other areas being considered for transpositioning. Initial results were presented at the several Review Board meetings and the limits were refined during the meeting held September 18-19, 2014. During the meetings, extensive discussions with all members present took place to explicitly define transposition limits for each of the 58 SPAS DAD zones. Each storm's meteorological characteristics were evaluated, including the storm type, the seasonality, the storm isohyetal patterns, and the storm's moisture source. These factors were evaluated for each storm to provide reasoning as to where the storm could be transpositioned. Each storm was assigned to one or more of the transposition zones across the study domain. It should be noted that conservative transposition limits were employed (i.e., moving storms to larger regions than may be justified) unless there was justification for a more refined analysis. This is because the transposition process involves some subjectivity and although it produces a binary answer (either a storm is transpositionable to a point or not), in actuality, there are gradients in meteorology that need to be considered.

Initial transposition limits were assigned with the understanding that additional refinements would take place as the data were run through the PMP evaluation process. Numerous sensitivity runs were performed using the PMP database to investigate the results based on the initial transposition limits. Several storms were re-evaluated based on the results that showed inconsistencies and/or unreasonable values when compared to other storms, precipitation frequency climatology, world record rainfall, PMP values in the area, and other storm analyses. Although somewhat subjective, decisions to adjust the transposition limits for a storm were based on the understanding of the meteorology which resulted in the storm event, similarity of topography between the two locations, access to moisture source, seasonality of occurrence, and comparison to other similar storm events. Appendix E provides a description of the iterations and adjustments that were applied during each PMP version to arrive at the final values.

For all storms, the IPMF does not change during this process. The MTF and OTF change as a storm is moved from its original location to a new location. Further, because the MTF represents the horizontal difference in available moisture between the original location and the new location (i.e. no elevation difference component is applied when used with the OTF), this factor does not vary as much as the OTF across the region. Generally, most MTFs result in less than a +/-10% change. Therefore, the largest contributing factor to the variation of PMP over a specific area in the transposition process is the OTF.

Extensive evaluations were completed to try and quantify how much of the MTF was already accounted for, if at all, in the OTF process. It is not straightforward to separate the purely orographic component driving the spatial distribution of the precipitation frequency climatology (used to calculate OTF) from other components that might be inherent, such as changes in atmospheric moisture. An approach taken to analyze and quantify these non-orographic components was to apply the "OTF" calculation process to NOAA-Atlas 14 precipitation frequency data in non-orographic regions where the change in elevation and terrain is negligible between the source and target locations. OTF calculations were done using locations in non-orographic regions of the Midwest where it was assumed the OTF was 1.00 or close to 1.00. Most of the resulting OTFs were indeed 1.00 or close to 1.00, although some were larger than expected. This suggested that there are non-orographic components captured, albeit with a minor effect on rainfall spatial distribution.

If the variations of OTF values closely matched those of the MTF values calculated for the same storm transposition, then it could be concluded with reasonable certainty that the OTF was adequately capturing the MTF. However, because of the internal variability of the precipitation frequency data even in seemingly homogenous regions, and the inability to isolate a specific atmospheric component that mirrors the spatial distribution of the dew point climatology, no definitive conclusion was able to be reached. It is likely that the OTF does account for some of the moisture differences between two locations, however the amount is unknown and would potentially differ for each discrete storm event. Because we are quantifying moisture and orographic effects for storms of the rarest occurrence, it is expected the moisture associated with them to also be of similar rarity. Utilizing an explicit analysis related to extreme moisture conditions (i.e. the 100-year recurrence interval climatology) more accurately reflects the unique characteristics of a given storm event. In addition, the calculation of the MTF allows the atmospheric component to be evaluated discretely of the orographic component, which is useful in determining the storm's transposition limits. If future investigations into the MTF show that a correction should be applied, this will allow for that correction to be executed in a straightforward, quantifiable manner. It is recognized that there is uncertainty that a portion of the atmospheric component expressed by the MTF may also be accounted for within the OTF factor. However, until it can be adequately quantified, the approach of including the MTF should remain.

The spatial variations in the OTF were useful in making decisions on transposition limits for a storm. Values larger than 1.50 for a storm's maximization factor exceed reasonable limits. In these situations, changing a storm by this amount is likely also changing the storm characteristics. The same concept applies to the OTF.

OTF values greater than 1.50 indicate that the transposition limits for a given storm to a given grid point need further evaluation. Mapping the OTF and MTF values across the region provided visual guidance to aid with defining transposition zones. This allowed areas of excessively large transposition factors (i.e. greater than 1.50) to be identified and evaluated further to determine transpositionability. Therefore, storms were re-evaluated for transpositionability in regions which result in an OTF greater than 1.50. In some high elevation locations where there was a lack of extreme rainfall data and the OTF was greater than 1.50. In these situations where storms were used in regions where the OTF was greater than 1.50, a cap of 1.50 was applied to be consistent with the IPMF cap. This followed the same process as described in HMR 51 (Section 2.3) and in the Arizona (2013) and Wyoming (2014) statewide PMP studies.

In addition to this, information included in TVA Calculation No.RSOGENROGCDX000326201600087, R0 were initially investigated to determine whether information from that analysis could help inform the transposition evaluation process. Although data from that analysis were supportive of transposition limits applied, they were ultimately not relied upon or used to define transposition limits. Instead, all final transposition limits followed guidelines from the HMRs, AWA analyses, and discussions with the review board and were related to the variations in meteorology and topography within the region.

From these analyses, refinements such as limiting a storm's transposition location using an elevation constraint or by an OTF amount were applied where appropriate and supported by data analyses. An example of the Smethport, PA July, 1942 (SPAS 1345) storm is provided. This storm occurred on the west side of the Appalachians of north central Pennsylvania at an elevation of 2,200 feet. The storm is only transpositionable to the western side of the Appalachians, the side on which it occurred, and within the foothill and mountainous regions (see HMR 52 Figure 26, Tomlinson et al., 2013, and Smith et al., 2011). Elevation, terrain, synoptic meteorology, moisture source, storm type, and distance are examined to further refine the transposition limits. Figure 22 shows the OTF values for the storm across the TVA domain. In this scenario, in the regions where this storm is considered transpositionable (all of Zone 4) there are many locations where OTF values are above 1.50. This results from both moving this storm a long distance from its location in north central Pennsylvania to the TVA region (nearly 6° of latitude), and the associated differences in precipitation frequency climatology between the two regions. This is combined with the more extreme topography over the eastern region of the TVA domain (Zone 4). Therefore, a limitation of the OTF in areas where the value is 1.50 or higher is required. This is because increasing the storm by more than 50% would significantly alter its dynamics, violating the definition of transpositionability.

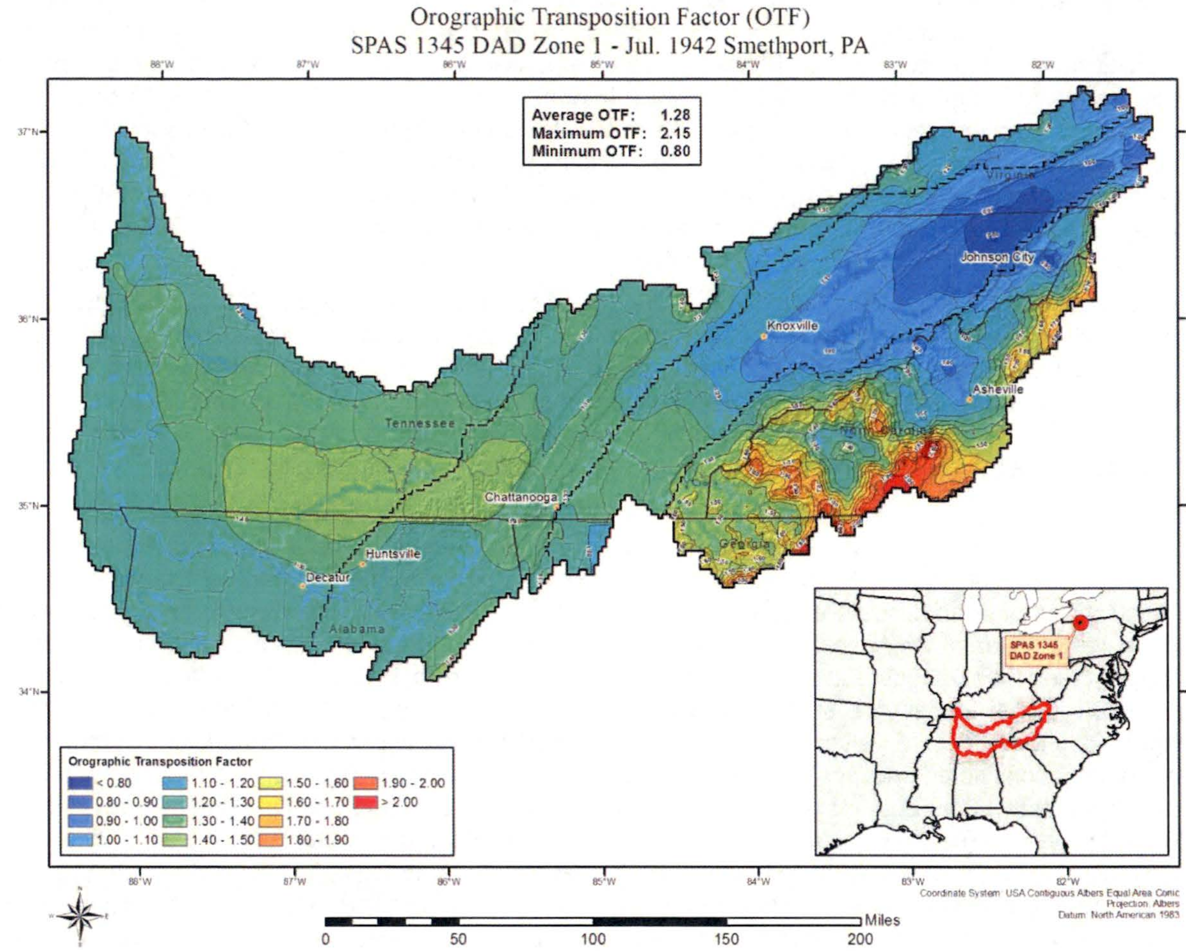

Figure 22 Orographic Transposition Factors for Smethport, PA July, 1942, SPAS 1345

4.4 Antecedent Rainfall Investigations

Antecedent rainfall is an important aspect for defining the overall flood response of a given location to PMP. Investigations were undertaken in the TVA HMRs (e.g. HMR 56 Section 7.3.3) to try and define what amount of rainfall and how long of a recharge period is required, yet is still physically possible, before and after the PMP rainfall. AWA investigated the storms on the initial storm list (see Table 1) to determine which storms exhibited characteristics of back-to-back extreme rainfalls over the same area. This followed the same general investigations as were done in the TVA HMRs. Less extreme rainfalls can and have followed each other over the same area in the past (e.g. Mounds and Warner, OK May 1943 and Rosman, NC Sept-Oct 1964), but this may not be the case for PMP level rainfall.

Several problems were identified in reviewing these antecedent storm analyses. First, the assumption is being made that back-to-back non-PMP storms occur in the same fashion as would be expected with an antecedent extreme rainfall (e.g. a 500-year recurrence interval event or half PMP three days prior to PMP) and a subsequent PMP event. The amount of time it would take the atmosphere to recharge both the moisture levels and the required storm dynamics at sufficient levels to produce PMP rainfall is unknown. Further, the combined events investigated are independent events which add to the rarity of the occurrence of the combined back-to-back storm event. Finally, antecedent rainfall analyses are not included in most HMRs (e.g. HMR 49, HMR 51, HMR 52, HMR 55A, HMR 57, HMR 59) because the magnitude of an antecedent storm is a hydrologic consideration. Specifically, the antecedent storm is often a requirement from the governing regulatory agency which is intended to set antecedent watershed conditions and initial reservoir levels prior to the occurrence of the PMP. Therefore, a deterministic antecedent storm with so much uncertainty can be excessively conservative based on storm history and the fact that rainfall events of half PMP followed by PMP have not been observed. Because of this, significant assumptions are being made that analog storms of much lesser magnitude are representative of that scenario.

Because of these issues and unknowns, AWA recommends not using antecedent rainfall conditions to define the hydrologic conditions prior to and subsequent to the PMP rainfall. Instead, because the hydrologic conditions (reservoir operations, pool levels, soil moisture, etc.) are better known and defined, it is recommended that those data be used to set the antecedent and subsequent conditions related to the PMP.

4.5 Seasonality Development

Investigations on the seasonality of occurrence of each storm type were part of this calculation. AWA investigated seasonality for local/MCC storms, general storms, and tropical storms. AWA relied extensively on the evaluations of seasonality that were part of TVA Calculation No. RSOGENROGCDX0003262016000087, R0 in regards to a statistical analysis of when major rainfall events occurred throughout the TVA domain. During that analysis, storms were classified similarly but that analysis split general storms into two categories, Mid Latitude Cyclone (MLC) and Mesoscale Storm with Embedded Convection (MEC). For PMP purposes, the local storm category included the MEC storm type and the general storm included the MLC. Those investigations resulted in a set of data which clearly showed strong seasonality by storm type. Table 7 provides results of that work for MLC storms, Table 8 provides results for Tropical Storms, Table 9 provides results for MECs, and Table 10 provides results for Local Storms. AWA used this information, as well as the storm data used for PMP development and consideration of meteorology which would create each storm type to develop the recommended seasonality. The time frame presented in Table 11 are the periods when 100% of PMP could reasonably be expected to occur by storm type.

Table 7 Seasonal limits for MLCs (from TVA Calculation No. RSOGENROGCDX0003262016000087, R0)

Seasonal Limits for 100% PMP – Mid-Latitude Cyclones		
Criteria	**Start Date**	**End Date**
25 Rarest Storm Events	October 1	April 30
25 Rarest Storm Events plus 2-Week Buffer	Mid-September	Mid-May
5th and 95th Percentile for Storms with 15 or More Stations Exceeding 10-Year Event (68 Storm Events)	October 1	April 30

Table 8 Seasonal limits for Tropical Storms (from TVA Calculation No. RSOGENROGCDX000326201600087, R0)

Seasonal Limits for 100% PMP – Tropical Storm Remnants		
Criteria	**Start Date**	**End Date**
25 Rarest Storm Events	Mid-June	Mid-October
25 Rarest Storm Events plus 2-Week Buffer	June 1	October 31
5th and 95th Percentile for Storms with 14 or More Stations Exceeding 10-Year Event (61 Storm Events)	Late-June	Mid-October

Table 9 Seasonal limits for MECs (from TVA Calculation No. RSOGENROGCDX000326201600087, R0)

Seasonal Limits for 100% PMP – Mesoscale Storms with Embedded Convection		
Criteria	**Start Date**	**End Date**
25 Rarest Storm Events	May 1	September 30
25 Rarest Storm Events plus 2-Week Buffer	Mid-April	Mid-October
5th and 95th Percentile for Storms with 4 or More Stations Exceeding 10-Year Event (46 Storm Events)	Mid-April	Early-October

Table 10 Seasonal limits for Local Storms (from TVA Calculation No. RSOGENROGCDX000326201600087, R0)

Seasonal Limits for 100% PMP – Local Storms		
Criteria	**Start Date**	**End Date**
25 Rarest Storm Events	Mid-May	Mid-October
25 Rarest Storm Events plus 2-Week Buffer	May 1	October 31
5th and 95th Percentile for 40 Rarest Storms based on estimated Annual Exceedance Probabilities	June 1	Late-September

Table 11 Recommended seasonality by PMP storm type

Storm Type	Season of Occurrence 100% PMP
General Storms	September 15 through May 15
Tropical Storms	June 1 through October 31
Local Storms	April 15 through October 31

The recommended dates reflect the meteorological timeframe when each storm type could occur, the statistical analysis completed in TVA Calculation No. RSOGENROGCDX000326201600087, R0, and a conservative buffer applied to each side similar to the two-week adjustment that is applied during the maximization process.

5.0 Results

5.1 Development of PMP Values

Gridded PMP depths were calculated by comparing the total adjusted rainfall values for all transpositionable storm events over each grid point and taking the largest value. In this process, all transpositionable storms are considered independently at each grid point for the analyzed duration and area size. This approach provides a site-specific calculation for each grid point across the analysis domain. During this process, durational envelopment occurs because the largest PMP depth for a given duration is identified after analyzing all the transpositionable storms for each grid point at each location for each duration at the area size(s) specific to the basin being analyzed. In addition, several storms can control the PMP depth for a given basin at various grid points and/or durations. This is similar to the HMR process of envelopment, which encompasses several different storms for each area size.

The adjusted rainfall at a grid point, for a given storm event, was determined by applying a total adjustment factor (TAF) to the SPAS analyzed DAD value corresponding to the given area size (in square miles) at the appropriate duration. The TAF is the product of the three separate storm adjustment factors; the IPMF, the MTF, and the OTF. These calculations were completed for all storms for every grid point analyzed over the entire domain and are described in the following sections. Several storms have multiple centers analyzed. Each SPAS DAD zone was considered as independent events for the purpose of PMP calculation. In total, there were 58 separate events analyzed; 19 local storms, 31 general storms, and 8 tropical storms.

An Excel spreadsheet with storm adjustments was produced for each of the analyzed events. These spreadsheets are designed to perform the calculation of each of the three adjustment factors, along with the final TAF. The spreadsheet format allows for the large number of calculations to be performed correctly and consistently in an efficient template format. In addition to the IPMF, MTF, and OTF calculations, a Boolean transpositionability flag for each grid point is stored within the spreadsheets, allowing a conditional statement to determine if the given storm is transpositionable to the grid point based on pre-determined criteria (see Section 4.3). Information such as precipitation climatological values, coordinate pairs, grid point elevation values, equations, and the precipitable water lookup table remain constant from storm to storm and remain static within the spreadsheet template. The spreadsheet contains a final adjusted rainfall tab with the adjustment factors, including the TAF, listed for each grid point. For each storm, this table was exported to a GIS feature class to be used as input for the PMP Evaluation Tool, a scripted GIS tool that automates the calculation and production of PMP gridded datasets. At any point in the future, new storm feature classes could be added, removed, or edited.

The PMP Evaluation Tool accesses the storm TAF feature classes and the corresponding DAD tables for each of the storm events as input, along with a basin outline feature layer as a model parameter. The PMP Evaluation Tool then calculates and compares the total adjusted rainfall for each transpositionable storm at each grid point within the statewide analysis domain and determines the PMP depth for each duration separately for both storm types. The durations calculated for general and tropical storms PMP were 1-, 6-, 12-, 24-, 48-, 72-, 96-, and 120-hours. The durations calculated for local/MCC storms PMP were 1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hours.

5.1.1 Available Moisture at Source and Target Locations

The available atmospheric moisture, in terms of precipitable water depth, must be determined for the storm center location to calculate both the IPMF and MTF. The IPMF is determined by taking the ratio of the maximum precipitable water depth at the storm representative dew point location to the storm representative precipitable water depth at the same point location. The MTF is determined by taking the ratio of the maximum precipitable water depth at the transposition dew point location to the maximum precipitable water depth at the storm representative dew point location. Identification of storm representative dew point values and locations are described in Section 4.1.3. Note that in the final total adjustment factor calculation, the climatological maximum precipitable water depth at the storm center is used in both the numerator of the IPMF and denominator of the MTF, and is ultimately cancelled out of the equation, mathematically having no impact on the total adjustment factor. However, it is still important to calculate the storm center precipitable water, and the MTF and IPMF individually, so that the proportion of each component can be quantified for transparency and quality/error control purposes.

The precipitable water depth is obtained from a lookup table stored within the storm adjustment spreadsheets. The lookup table is a digital version of the precipitable water table found in Appendix C of HMR 55A with dew point temperatures every ½ °F through the entire atmospheric column required to represent the amount of precipitable water available for rainfall production (sea level through 30,000 feet).

To determine the temperatures to use from the precipitable water lookup table, GIS was used to extract the values from the appropriate monthly climatological maximum dew point raster files at the appropriate duration. ArcGIS was used to extract the dew point temperatures to point features stored within shapefiles. For each storm there was a point feature at the storm center, and a series of 17,938 point features across the TVA domain at the .025 x .025 dd resolution. Before the dew point extraction, each of these point features were shifted a distance in the *x* and *y* direction equivalent to the moisture inflow vector components for the given storm. This allows for the extraction of dew point temperatures that are representative of the moisture source location. The monthly maximum average dew point temperature values were linearly interpolated between the bounding monthly values according to the temporal transposition date. The moisture inflow vectors and temporal transposition date for each storm are in Appendix F.

The precipitable water was calculated for each event within the storm adjustment spreadsheet, for the storm center grid cell, and each of the target grid cells within the project domain using the lookup table with the storm center elevation. Storm center elevations were rounded to the nearest 100 feet, or nearest 500 feet for elevations above 5,000 feet, to coincide with the values in the precipitable water lookup table.

As described in the previous section, the precipitable water depths are adjusted for elevation. This is done by determining the precipitable water depth present in the atmospheric column (from sea level to 30,000 feet) and subtracting the precipitable water depth that would be present in the atmospheric column between sea-level and the surface elevation at the storm location using Equation 3.

$$W_p = W_{p,30,000'} - W_{p,elev} \qquad \text{Equation 3}$$

where,

W_p	=	precipitable water above the storm location (in.)
$W_{p,30,000'}$	=	precipitable water at 30,000' elevation (in.)
$W_{p,elev}$	=	precipitable water at storm surface elevation (in.).

5.1.1.1 In-Place Maximization Factor

In-place storm maximization is applied for each storm event using the methods described in Section 4.1. Storm maximization is quantified by the IPMF using Equation 4.

$$IPMF = \frac{W_{p,max}}{W_{p,rep}}$$ Equation 4

where,

$W_{p,max}$ = precipitable water for the maximum dew point (in.)

$W_{p,rep}$ = precipitable water for the representative dew point (in.)

5.1.1.2 Moisture Transposition Factor

The change in available atmospheric moisture between the storm center location and the basin target grid point is quantified as the MTF. This MTF represents the change due to horizontal distance only and is calculated at the storm center elevation. The change due to vertical displacement is quantified inherently within the OTF, described in the next section; the MTF is strictly a horizontal adjustment. The MTF is calculated as the ratio of precipitable water for the maximum dew point at the target grid point location to precipitable water for the storm maximum dew point at the storm center location as described in Equation 5.

$$MTF = \frac{W_{p,trans}}{W_{p,max}}$$ Equation 5

where,

$W_{p,trans}$ = precipitable water at the target location (in.)

$W_{p,max}$ = precipitable water at the storm center location (in.)

5.1.1.3 Orographic Transposition Factor

Section 3.5 provides details on the methods used in this study to define the orographic effect on rainfall. The OTF is calculated by taking the ratio of transposed rainfall to the in-place rainfall (Equation 6).

$$OTF = \frac{P_o}{P_i}$$ Equation 6

where,

P_o	=	orographically adjusted rainfall (in.)
P_i	=	SPAS-analyzed in-place rainfall (in.)

The orographically adjusted rainfall is determined by applying the functions in Equations 2a and 2b to SPAS-analyzed rainfall depth for the appropriate duration (24-hour for general storm and 6-hour for local storm events).

$$P_o = mP_i + b$$ Equation 2a

$$OTF = P_o/P_i = m + b/P_i$$ Equation 2b

where,

P_o	=	orographically adjusted rainfall (in.)
P_i	=	SPAS-analyzed in-place rainfall (in.)
m	=	least squares slope
b	=	origin offset (in.)

5.1.1.4 OTF Adjustment for NOAA Atlas 14 35°N Discontinuity

The majority of the PMP analysis domain is covered by NOAA Atlas 14 Volume 2 (2004). However, the areas south of 35° N latitude, Mississippi, Alabama, and Georgia, are covered by NOAA Atlas 14 Volume 2 (2013). There are discontinuities in precipitation depths between these two volumes. From NOAA Atlas 14 Volume 4 (2013, p.19); "Precipitation frequency estimates for each NOAA Atlas 14 volume were computed independently using all available data at the time. Some discrepancies between volumes at project boundaries are inevitable and they will generally be more pronounced for more rare frequencies."

The discontinuities in precipitation vary with recurrence interval and duration and are reflected in the OTF calculated for each storm which is transpositioned between the two volumes. Adjustments were made to the OTF for each storm to correct for these discontinuities. The OTF quantifies the effect of terrain between two locations on rainfall accumulation. The terrain in the western portion of the project domain does not vary significantly, therefore, the OTF should reflect small variations because of terrain over this region. Of the two NOAA Atlas 14 volumes, Volume 2 was determined to be most representative and applicable to the western portion of the study area. Volume 9 showed variation and characteristics that were not representative to the underlying terrain. This was based on the meteorologically unrealistic spatial gradients of precipitation frequency values in areas where there is no meteorological process that would cause such variations. This was most acute in north eastern Mississippi and north eastern Alabama, which was generally considered non-orographic. Therefore, the OTF values for the discontinuous grid points under the non-orographic portions of Volume 2 (south of 35° N) were adjusted to be consistent with the OTF from a grid point in Volume 9 (north of 35° N) that is determined to be representative to the entire region.

A similar process was employed over north western Georgia within the 6-hour and 24-hour precipitation climatology. The area over the Appalachian region of northern Georgia exhibited unrealistic gradients between the NOAA Atlas 14 volumes covering each region within the 6-hour precipitation climatology, which was used for local storm OTF calculations. The local storm OTF adjustment area over northern Georgia is highly orographic. Assigning a constant OTF over this region would not be sufficient to capture the topographic controls on rainfall. Therefore, a weighted adjustment based on the surface elevation was also applied to the local storm OTF adjustments over this region

5.1.1.5 OTF Calculations for Smethport, PA and Simpson, KY

The Smethport, PA July, 1942 and Simpson, KY July, 1939 storms were transposed to the orographic regions of the project area; Smethport to zone 4 and Simpson to zones 2, 3, and 4. The resulting OTF in these areas was greater than one due to the relationship to the precipitation climatology at the storm center locations and the grid points each storm was transpositioned too. Each of these events produced rainfall accumulations that were assumed to approach the upper limit of what was possible for the associated meteorological conditions. In the case of Smethport, this produced a world record rainfall at 4.5 and 6 hours. In addition, the highest rainfall accumulations were not recorded in standard rain gauges, but instead were collected during bucket surveys after the storm had occurred. Further, very little to no hourly data were available. Therefore, significant subjective decisions were made to determine rainfall accumulations for durations less than 3 hours for Simpson, KY and less than 4 hours for Smethport, PA. Initial adjustment of these storms to various locations within TVA resulted in unreasonable total adjustment values for many locations. This resulted in total adjusted rainfall values that were much greater than world record rainfalls and produced anomalous patterns when plotted against the world record rainfall curve (Figure 23).

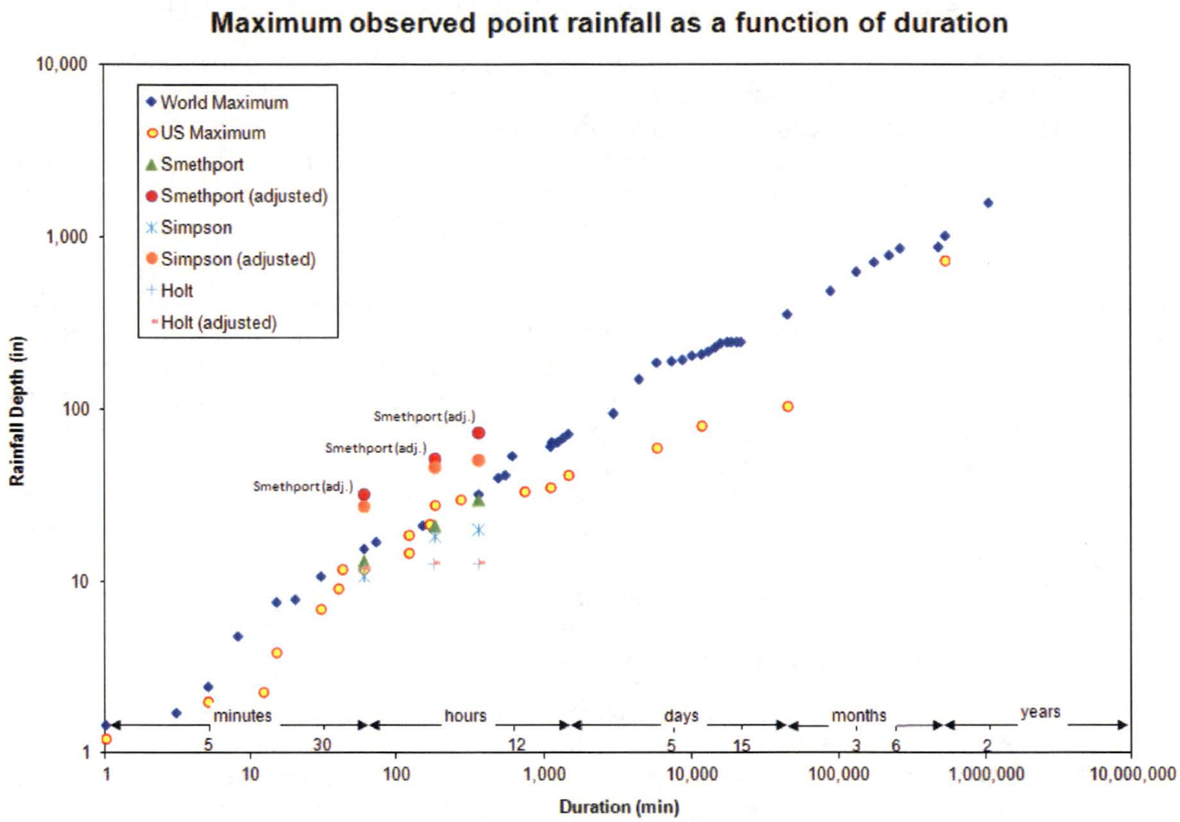

Figure 23 Comparison of total adjusted values of the Smethport, PA, Simpson, KY, and Holt, MO storms without constraint compared to the world record rainfalls.

Although the values were unreasonably high, what the values should be is unknown. Therefore, because of these extreme rainfall accumulations and the uncertainty involved in the data, extensive discussions took place with the review board and TVA personnel regarding the use of these storms, explicitly related to their total adjustments. Although subjectivity was involved in the decisions on how to adjust these storms, meteorological reasoning and comparisons against similar storms were utilized as much as possible.

Evaluations of the meteorological pattern associated with both events were considered and discussed in detail (see daily weather maps in Appendix F and metrological description by Eisenlohr in USGS Water Supply Paper 1134-B, 1952). It was determined that the factors leading to extreme levels of moisture and instability combined with terrain influences were similar to what could occur over the eastern foothills and mountainous terrain in the TVA basin. Because of the similarity to the meteorological conditions and terrain, it was determined to be unreasonable to further adjust the events upward based on the OTF. For the Smethport, PA July, 1942 storm specifically, this was most pronounced because the storm was already moved far from its original location and therefore at the edge of reasonable transposition limits. This distance of transposition from north to south further increased the total adjustment of the storm because of the increase in dew point climatology between the two locations. However, the meteorology of the two events is not adequately reflected in the north to south gradient of dew point climatology. This is because the low-level moisture inflow for both storms was from the west/northwest and localized sources. This is related to the flow of moisture in a clockwise fashion around the Bermuda High to the east. This is also evidenced by the storm representative dew point determination which showed in both cases the storm representative locations were to the west/northwest of each storm center. This westerly flow of low-level moisture was very important in both cases in producing extreme rainfall accumulations because this resulted in optimal moisture interaction with terrain forcing. This same flow pattern would be required in the TVA basin for this storm interaction to take place.

The result of these analyses and discussions resulted in a consensus decision that it was not reasonable to apply a further increase in magnitude due to topographical influence. To account for this, the OTF factors for these events were normalized to a maximum of 1.00. This was accomplished by applying a reduction factor to each target grid point based on the ratio of the originally calculated OTF at that grid point to the highest calculated OTF from all grid points. The resulting normalized OTF provides a spatial distribution based on the precipitation climatology without increasing rainfall unrealistically.

For the development of the LIP values at SQN and WBN, the OTF adjustment was not used for the Simpson, KY July 1939 storm (the OTF was set to 1.00). Instead, an adjustment using the HMR standard vertical evaluation (approximately 0.8% per 100 feet difference) was applied as part of the MTF process to account for differences in elevation between the source storm location and the nuclear site. In addition, the 6-hour 100-year precipitation frequency climatology was used in the OTF calculations for all storms used in the LIP analysis. This replaced the use of the linear fit method used in the OTF calculations for all other grids within the TVA domain. This was done based on discussion with the NRC to better align with current OTF calculation processes utilized since the completion of this study. The result was a transposition factor of 1.06 between the Simpson, KY storm center and the SQN and WBN sites. This approach was a more conservative application to the Simpson, KY July 1939 storm transposition than the normalized OTF approach applied to the PMP calculations. This adjustment had no effect on the BFN location because the Simpson, KY July 1939 storm is not transpositionable to that location. In addition, the Smethport, PA July 1942 storm was not transpositionable to the SQN, WBN, or BFN locations and therefore no other adjustments were applied to that storm for LIP considerations.

5.1.2 Special Transposition Cases

There were three general storms used in this study that occurred over Texas where NOAA Atlas 14 precipitation frequency climatology is not available. Therefore, the standard process of comparing NOAA Atlas 14 precipitation estimates at two locations could not be used for these storms to produce OTF values over the TVA project area. However, since these storms were only transposed to non-orographic portions of the TVA basin, the OTF adjustment was not critical and instead was set to 1.00. Alternatively, a vertical component was included in the MTF to account for the changes in moisture availability between the target grid point and the storm center based on elevation differences between to two locations.

The final unique transposition case is the treatment of the Holt, MO June 1947 storm. Review of the MTF for this storm led to a further evaluation of the synoptic meteorology associated with the event and the availability of moisture during June and July over western Missouri versus areas where the storm was transpositionable in the TVA basin. The daily weather maps for the storm are included in Appendix F and a discussion of the storm event can be found in Lott (1954). These investigations showed that moisture availability would not be expected to increase going west to east in this case. Therefore, the MTF was set to 1.00, with the assumption that the moisture component was being adequately accounted for with the OTF adjustment. Setting the MTF to 1.00 produced adjusted rainfall values which were reasonable compared to expected limits and in agreement with the other controlling storms for the short duration small area PMP.

5.2 Total Adjusted Rainfall

The TAF is a product of the linear multiplication of the IPMF, MTF, and OTF. The TAF is a combination of the total moisture and terrain differences on the SPAS analyzed rainfall after being maximized in-place and then transpositioned to the target grid point.

$$TAF = IPMF * MTF * OTF$$ (from Equation 1.1)

The TAF, along with other data relevant to each grid point, is exported and stored within the storm's adjustment factor feature class. The feature class includes a spatial component, a point feature at each grid cell centroid, and a table component as shown in Figure 24. For each feature, the table stores the grid point ID, the storm ID, the latitude and longitude coordinate pair, the transposition zone number, the elevation (in feet), the storm adjustment factors, and the transpositionability flag. For a grid point, the total adjusted rainfall depths for all storms transpositionable to that grid point are compared and the largest is stored as the PMP depth for that grid point location. It is important to understand that PMP depths are calculated for specific area sizes and are a representation of average PMP over that area size for a given duration and are not point rainfall values. *Therefore no areal reduction factors should be applied to the calculated PMP depths.* The depth-area relationships in the PMP values are directly related to the gridded SPAS analyses from the controlling storm events.

SPAS_1208_1

OBJECTID *	CNT	STORM	LON	LAT	ZONE_	ELEV	IPMF	MTF	OTF	TAF	TRANS	Shape *
1	1	1208_1	-86.525	34.125	2	1,001	1.16	1.07	1.04	1.29	1	Point
2	2	1208_1	-86.500	34.125	2	850	1.16	1.07	1.04	1.29	1	Point
3	3	1208_1	-86.475	34.125	2	948	1.16	1.07	1.04	1.29	1	Point
4	4	1208_1	-86.150	34.125	2	1,132	1.16	1.07	1.04	1.29	1	Point
5	5	1208_1	-86.125	34.125	2	1,070	1.16	1.07	1.04	1.29	1	Point
6	6	1208_1	-86.100	34.125	2	1,102	1.16	1.07	1.04	1.29	1	Point
7	7	1208_1	-86.525	34.150	2	932	1.16	1.07	1.04	1.29	1	Point
8	8	1208_1	-86.500	34.150	2	984	1.16	1.07	1.04	1.29	1	Point
9	9	1208_1	-86.475	34.150	2	827	1.16	1.07	1.04	1.29	1	Point
10	10	1208_1	-86.450	34.150	2	833	1.16	1.07	1.04	1.29	1	Point
11	11	1208_1	-86.150	34.150	2	1,181	1.16	1.07	1.04	1.29	1	Point
12	12	1208_1	-86.125	34.150	2	1,079	1.16	1.07	1.04	1.29	1	Point
13	13	1208_1	-86.100	34.150	2	1,063	1.16	1.07	1.04	1.29	1	Point
14	14	1208_1	-86.075	34.150	2	1,066	1.16	1.07	1.04	1.29	1	Point
15	15	1208_1	-86.050	34.150	2	1,043	1.16	1.07	1.04	1.29	1	Point
16	16	1208_1	-86.500	34.175	2	909	1.16	1.07	1.04	1.29	1	Point
17	17	1208_1	-86.475	34.175	2	909	1.16	1.07	1.04	1.29	1	Point
18	18	1208_1	-86.450	34.175	2	791	1.16	1.07	1.04	1.29	1	Point
19	19	1208_1	-86.425	34.175	2	889	1.16	1.07	1.04	1.29	1	Point
20	20	1208_1	-86.150	34.175	2	1,070	1.16	1.07	1.04	1.29	1	Point
21	21	1208_1	-86.125	34.175	2	1,079	1.16	1.07	1.04	1.29	1	Point
22	22	1208_1	-86.100	34.175	2	1,024	1.16	1.07	1.04	1.29	1	Point
23	23	1208_1	-86.075	34.175	2	1,056	1.16	1.07	1.04	1.29	1	Point
24	24	1208_1	-86.050	34.175	2	1,056	1.16	1.07	1.04	1.29	1	Point
25	25	1208_1	-86.025	34.175	2	997	1.16	1.07	1.04	1.29	1	Point
26	26	1208_1	-86.500	34.200	2	968	1.16	1.07	1.04	1.29	1	Point
27	27	1208_1	-86.475	34.200	2	702	1.16	1.07	1.04	1.29	1	Point
28	28	1208_1	-86.450	34.200	2	948	1.16	1.07	1.04	1.29	1	Point
29	29	1208_1	-86.425	34.200	2	794	1.16	1.07	1.04	1.29	1	Point

1 (0 out of 17938 Selected)

SPAS_1208_1

Figure 24 Example of a storm adjustment factor feature class table

5.3 TVA Precipitation

TVA precipitation was first described and evaluated as part of HMR 41 (HMR 41 Page 6 "Relation of probable maximum to TVA precipitation). The development of TVA precipitation continued to be applied in the subsequent TVA HMRs. TVA precipitation is derived by simply not maximizing each storm in-place, but applying all other adjustments. During this calculation, AWA followed the same process in that TVA precipitation was completed by removing the IPMFs from all storms. A separate database of TVA precipitation was then derived once the IPMFs were removed.

5.4 Local Intense Precipitation Background

The Local Intense Precipitation (LIP) event is a distinct flooding mechanism that consists of heavy rainfall centered upon the plant site itself. As per guidance contained in NUREG/CR-7046 (NRC, 2011), the LIP is considered to include the 1-hour, 1-mi^2 PMP. The PMP from 1- through 6-hours at 1-mi^2 were determined using the same storm based approach used in this study to derive PMP values. For durations of less than 1-hour, the 5-, 15-, and 30-minute ratios provided in HMR 52, Figures 36-38 (NOAA, 1982), can be utilized.

During this storm based process to develop the LIP specific to each TVA nuclear site, AWA analyzed the PMP database to derive the values over the grid point representing the site location. These LIP values derived specifically deemed to be transpositionable to each site through evaluations described in Section 4.3.

AWA is not providing the hyetograph and incremental depths from the second hour to the sixth hour, but recommends those be based on NUREG/CR-7046 (Attachment B, NRC, 2001) or other relevant temporal distribution deemed appropriate by the hydrologist.

Section 5.2 of ANSI/ANS-2.8-1992 (ANS, 1992) indicates that parameters of the PMP should be determined by a meteorological study utilizing a storm based approach. The World Meteorological Organization (WMO) Manual for PMP determination (WMO, 1986; WMO, 2009) recommends this same approach. Improvements were employed as described in this calculation as part of the overall development of PMP for the entire TVA region. An evaluation of the storms used in the development of PMP is described in Section 3.4. The largest of these events, which were judged to be transpositionable to each site, were controlling of the LIP at 1- through 6-hours.

5.4.1 Local Intense Precipitation Evaluation Approach

The storm based approach utilizes actual data from rainfall events which have occurred over each site and in regions transpositionable to each TVA Nuclear site. These rainfall data are derived following the PMP development used in this study. The resulting 1- through 6-hour 1-mi^2 PMP values derived in this analysis are used at each nuclear site within TVA by using the PMP Evaluation Tool and database to derive the 1- through 6-hour 1-mi^2 PMP values specific to each location.

Information is included in this report detailing the storms used, how they were analyzed, and how the LIP values were derived. Data from each individual storm event evaluated are included in Appendix F and information regarding the dew point climatologies used to maximize the storms is included in Appendix C.

5.4.2 Assumptions and Justification

There are no assumptions in the development of the LIP values that require verification. Justified assumptions used in this report include:

1. This study assumes that if an appropriate set of storm events have been identified, analyzed, and maximized; they will represent the meteorological environment associated with the 1- through 6-hour, 1-mi^2 PMP accumulations for each TVA nuclear site. This assumption is required when using a storm based approach to derive deterministic PMP values. This same assumption is employed in HMR-51 and HMR-52 (NOAA, 1978; NOAA, 1982).
2. The assumption is made that if additional atmospheric moisture had been available, the storm would have maintained the same efficiency for converting atmospheric moisture to rainfall, in accordance with HMR guidelines (NOAA, 1978; NOAA, 1982). The ratio of the maximized rainfall amounts to the actual rainfall amounts would be the same as the ratio of the precipitable water (the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels in the atmosphere) in the atmosphere associated with each storm. This assumption is required to complete the storm maximization process when using surface dew points to represent a saturated atmosphere. The actual amount of atmospheric moisture available to the LIP/PMP is not known and therefore the assumption of a fully saturated atmosphere allows the maximization calculation to be possible.
3. Changes in climate that will occur in the region are adequately accounted for by the rarity of the resulting PMP and LIP values. Further, changes in climate which have occurred during the past 100 years are captured in the storm record and rainfall data used in this analysis and, therefore, represent any changes that would be expected during the useful lifetime of the values. Therefore, no adjustment is made to account for potential changes in climate during the useful lifetime of the values. This mirrors HMR 51 (NOAA, 1978) and the WMO guidance (WMO, 2009).

Instances of other meteorological judgment inherent to the deterministic process of developing PMP are specifically noted throughout this calculation.

5.4.3 Local Intense Precipitation Development

HMR 51, HMR 52, and HMR 56 cover large domains and were produced 30- to 40-years ago. Therefore generalization and conservatism were necessarily employed in the development of their respective PMP values that do not necessarily reflect the site-specific characteristics at each TVA nuclear site. This resulted in PMP values which were influenced by storms not appropriate for each site and/or do not include recent storms and meteorological advances. Because of this, accurate values as can be derived using this site-specific storm based approach employed in this study.

To correct for these issues, AWA has employed a current understanding of meteorology and updated data and storm databases that are specifically relevant to each location. This included explicitly evaluating storms which are directly transpositionable to each site, updating the storm database, and updating the storm adjustments. In addition, the understanding of the meteorology of these events has advanced significantly since HMR 51, HMR 52, and HMR 56 were published. These corrections and the updated storm database were employed in this study.

5.4.4 Local Intense Precipitation Results

The results from this analysis provided the 1- through 6-hour, 1-mi^2 LIP values for each TVA nuclear site. These data represented the upper limit of rainfall that could be expected to occur over the site. The large domain analyzed, the number of extreme storm events analyzed, and the maximization/transposition of those extreme rainfall events provide the necessary combination of rainfall parameters so that the results represent the LIP for each location. Note, the unique treatment of the Simpson, KY July 1939 storm at the SQN and WBN locations as discussed in Section 5.1.1.5. Tables 12-14 provide the LIP values for each TVA nuclear site analyzed.

Table 12 Site-specific LIP values for Browns Ferry

Browns Ferry Reactor - 1 mi^2 TVA LIP (inches) 34.703641° N, 87.119009° W					
1-hour	2-hour	3-hour	4-hour	5-hour	6-hour
11.60	16.42	21.45	25.59	25.94	26.45

Table 13 Site-specific LIP values for Watts Bar

Watts Bar Nuclear Plant - 1 mi^2 TVA LIP 35°36'10.430"N, 84°47'24.267"W					
1-hour	2-hour	3-hour	4-hour	5-hour	6-hour
13.81	20.17	23.44	24.05	24.64	25.21

Table 14 Site-specific LIP values for Sequoyah

Sequoyah Nuclear Plant - 1 mi^2 TVA LIP 35°13'35.65"N, 85°05'28.17"W					
1-hour	2-hour	3-hour	4-hour	5-hour	6-hour
13.81	20.17	23.44	24.05	24.64	25.21

Extreme rainfall events that can produce 1- through 6-hour, 1-mi^2 PMP values were evaluated for each TVA nuclear site. These storms were maximized in place and transpositioned to each site following procedures described in this calculation. The largest of these events defined the LIP values. This study was performed to avoid inappropriate conservatism, apply the most up-to-date data and meteorological methods, and to determine appropriate, data-based, and physically possible LIP/PMP values for each site. All LIP/PMP-type rainfall events in the region as described in Section 3.4 were evaluated to ensure storms with the highest accumulation of rainfalls over short durations and small area sizes were analyzed.

5.5 Sample Calculations

The following sections provide sample calculations for the storm adjustment factors for the Warner Park, TN April 30-May 2, 2010 (SPAS 1208) general storm event when transposed to 35.625° N, 82.625°W (grid point #9,910). The target location is near Asheville, NC approximately 240 miles to the east of the storm center location at an elevation of 2,129 feet. (Figure 25). This event produced nearly 20 inches of rain and flooding across middle and western Tennessee.

May 2010 Warner Park, TN Transposition to Grid Point #9,910 [35.625° N, 82.625°W]
TVA PMP Study

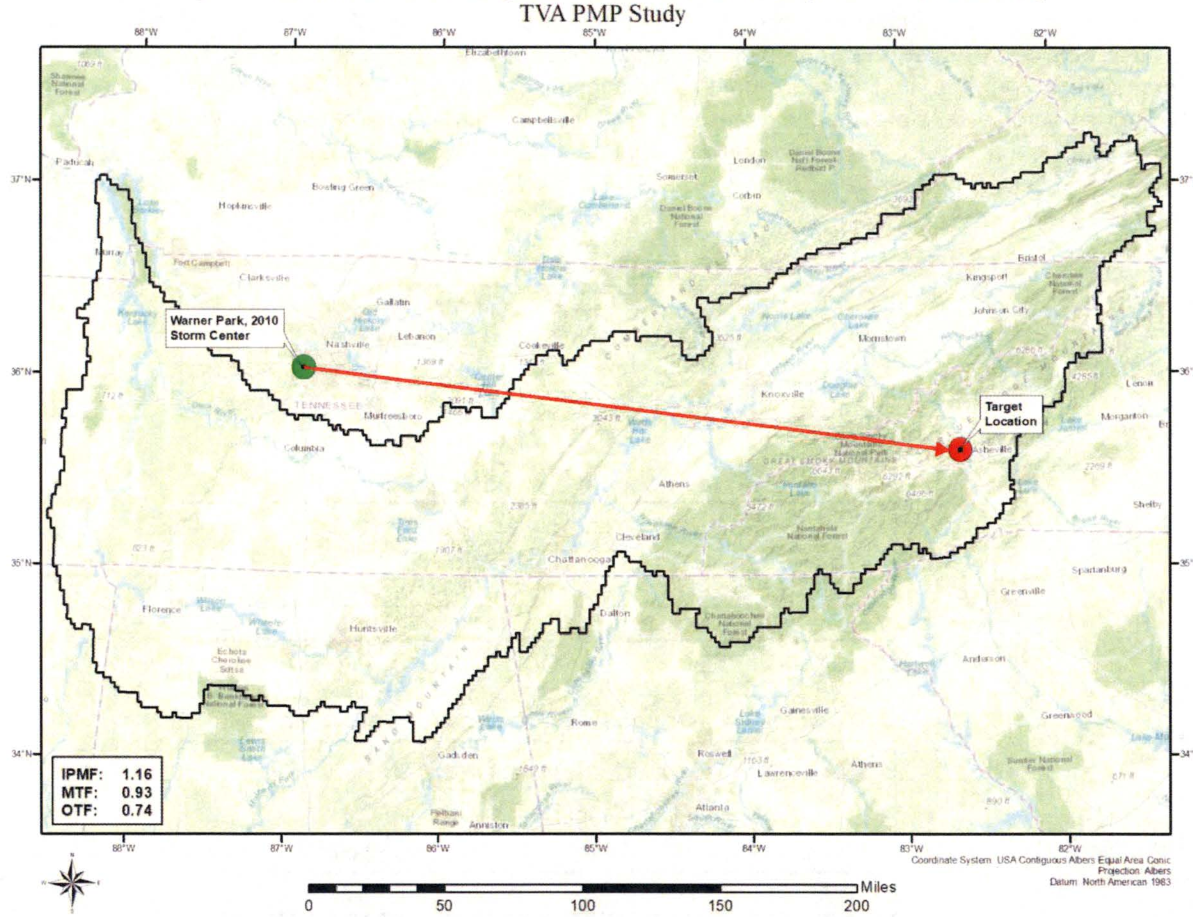

Figure 25 Transposition of Warner Park, TN April-May, 2010 (SPAS 1208) to grid point #9,910.

5.5.1 Example of Precipitable Water Calculations

Using the storm representative dew point temperature and storm center elevation as input, the precipitable water lookup table returns the depth, in inches, used in Equation 3. The storm representative dew point temperature is 74.0°F at the storm representative dew point location 360 miles south-southwest of the storm center (see Appendix F for the detailed storm maximization and analysis information). The storm center elevation is approximated at 600 feet at the storm center location of 36.06° N, 86.91° W. The storm representative available moisture ($W_{p,\ rep}$) is calculated using Equation 3:

$$W_{p,rep} = W(@74.0°)_{p,30,000'} - W(@74.0°)_{p,600'}$$

or,

$$W_{p,rep} = 2.73'' - 0.15''$$

$$W_{p,rep} = 2.580''$$

The storm occurred at the end of April and was adjusted 15 days toward the warm season to a temporal transposition date of May 15th. The September climatological 100-year maximum 24-hour average dew point at the storm representative dew point location is 77.0°F at the in-place elevation of 600 feet. The in-place climatological maximum available moisture ($W_{p,\,max}$) is calculated using Equation 3:

$$W_{p,max} = W(@77.0°)_{p,30,000'} - W(@77.0°)_{p,600'}$$

$$W_{p,max} = 3.140'' - 0.16$$

$$W_{p,max} = 2.980''$$

The climatological maximum available moisture was determined for the target grid point. The September climatological 100-year maximum 24-hour average dew point for the target grid point location using the 360 miles south-southwest offset is 75.5 °F at the elevation of 600 feet[1]. The horizontally transpositioned climatological maximum available moisture ($W_{p,\,trans}$) is calculated.

$$W_{p,trans} = W(@75.5°)_{p,30,000'} - W(@75.5°)_{p,600'}$$

$$W_{p,trans} = 2.920'' - 0.155''$$

$$W_{p,trans} = 2.765''$$

5.5.2 In-place Maximization Factor

Using Equation 4:

$$IPMF = \frac{W_{p,max}}{W_{p,rep}}$$

$$IPMF = \frac{2.980}{2.580''}$$

[1] Although the elevation at grid cell #9,910 is at 2,100 feet, the elevation of the storm center is used to remove the vertical component of the moisture transposition which will be included in the orographic transposition factor.

$$IPMF = 1.155$$

5.5.3 Moisture Transposition Factor

Using Equation 5:

$$MTF = \frac{W_{p,trans}}{W_{p,max}}$$

$$MTF = \frac{2.765''}{2.980''}$$

$$MTF = 0.928$$

5.5.4 Orographic Transposition Factor

Table 15 gives an example of 24-hour rainfall frequency values at both the Warner Park, TN May 2010 storm center location (source) grid point, and the target grid point location used to determine the orographic relationship. The storm center at the source location is the grid-cell with the greatest precipitation for the total storm duration.

Table 15 10-year through 1,000-year NOAA Atlas 14 rainfall frequency depths for the storm center and target locations

	24-hour Rainfall Frequency Depths (in)						
	10 year	25 year	50 year	100 year	200 year	500 year	1000 year
SOURCE (X-axis)	5.01	5.89	6.61	7.35	8.12	9.18	10.00
TARGET (Y-axis)	3.81	4.51	5.06	5.61	6.18	6.92	7.47

When the precipitation recurrence interval values are plotted (Figure 26), a least squares trend line can be constructed to provide a visualization of the relationship between the rainfall frequency values at the source and target locations. In this example, the values for the source grid point nearest the Warner Park, TN, May 2010 storm center are plotted on the *x*-axis while the target values for the target grid point are plotted on the *y*-axis.

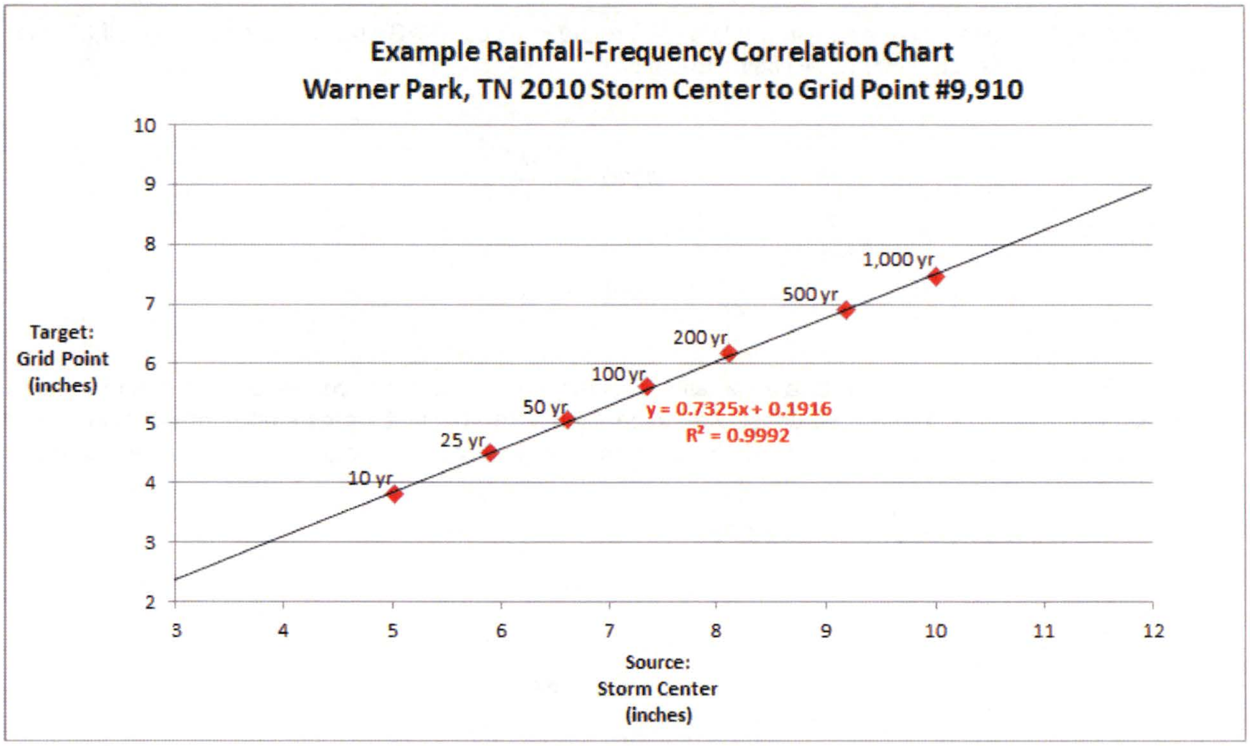

Figure 26: Precipitation recurrence interval values at the source and target locations with a least square trend line

The orographically adjusted rainfall at the target location can be computed using the equation of the trend line in slope-intercept form.

$$y = mx + b \qquad \text{Equation 7}$$

The slope, *m* represents the direct relationship between the source and target points. The y-intercept, *b*, adjusts for disproportionality between the source and target locations within precipitation frequency datasets. The equation for the Warner Park, TN May 2010 24-hour orographically adjusted rainfall transpositioned to the target grid point, using the linear relationship shown in Figure 26 is:

$$y = 0.73x + 0.19$$

The maximum SPAS analyzed 24-hour point rainfall value of 18.39" is entered as the *x* value to compute the target *y*-value, or orographically adjusted rainfall (P_o) of 13.61".

$$P_o = 0.73(18.39) + 0.19$$

$$P_o = 13.61''$$

The ratio of the orographically adjusted rainfall (P_o) to the in-place SPAS analyzed 24-hour rainfall (P_i) is the orographic transposition factor (OTF) using Equation 6:

$$OTF = \frac{13.61''}{18.39''}$$

$$OTF = 0.74$$

The OTF at grid #9,910 is 0.74, or a 26% rainfall decrease from the storm center location due to terrain and elevation effects. The OTF is then considered to be a temporal constant for the spatial transposition between that specific source/target grid point pair, for that storm only, and can then be applied to the other durations for that storm.

5.5.5 Total Adjustment Factor

$$TAF = IPMF x MTF x OTF$$

$$TAF = 1.076 \text{ x } 0.974 \text{ x } 0.740$$

$$TAF = 0.78$$

The total adjustment factor for Warner Park, TN (SPAS 1210) when moved to the grid point at 35.625° N, 82.625° W, representing storm maximization and transposition, is 0.78. This is an overall decrease of 22% from the original SPAS analyzed in-place rainfall. The TAF can then be applied to the DAD value for a given area size and duration to calculate the total adjusted rainfall. If the total adjusted rainfall is greater than the depth for all other transpositionable storms, it becomes the PMP depth at that grid point for that duration.

5.6 PMP Calculation Process

To calculate PMP, the TAF for each storm must be applied to the storm's SPAS analyzed DAD value for the area size and duration of interest to yield a total adjusted rainfall value. The storm's total adjusted rainfall value is then compared with the adjusted rainfall values of every storm in the database transpositionable to the target grid point. This process must be repeated for each of the 17,938 grid points within the statewide domain and for each duration for each storm type.

5.6.1 PMP Evaluation Tool

For this study, a scripted GIS-based tool was developed to aid in calculating gridded PMP values, producing final output datasets, evaluating modeling sensitivities, and quality control/error checking. The Basin PMP Evaluation Tool is a Python-based script designed to run within the ArcGIS environment. The tool provides gridded PMP values at a spatial resolution of 90 arc-seconds (equivalent to .025 x .025 dd) for a specific area size. The tool can be used to calculate PMP values for local storm types at the 1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hour durations and for general and tropical storm types at the 1-, 6-, 12-, 18-, 24-, 48-, 72-, 96-, and 120-hour durations. There is a separate script contained within the overall database which is used to calculate the TVA Precipitation separate from the PMP. A description of TVA Precipitation is provided in Section 5.3 and the resulting TVA Precipitation maps are provided in Appendix B.

While the script performs many tasks, its primary purpose is to iterate through both the storm list and the grid points over the project domain comparing each, and creating output based on the maximum values. To accomplish this, several functions and layers of nested iterative loops are used.

The tool accesses spatial input data from three file geodatabases: DAD_Tables.gdb, which holds the SPAS-analyzed DAD tables for each storm; Storm_Adj_Factors.gdb, which holds the total adjustment factors for each storm; and Non_Storm_Data.gdb, which holds the grid network data for the project domain. There is also a folder with a metadata template to be applied to the output.

SPAS DAD tables and adjustment factors can be added, removed, or edited within these databases. This is important if it becomes necessary to add a new storm to the analysis in the future or make adjustments to an existing storm. A new storm addition should follow the analysis procedures used on the existing storms in the database as much as possible to ensure consistency. In this event, PMP would need to be re-calculated to determine if the added or revised storm changes PMP.

5.7 PMP Evaluation Tool Description and Usage

The PMP Evaluation Tool provided with this study uses a Python-based script designed to run within the ArcGIS environment. ESRI's ArcGIS 10.x (or later) software (ESRI, 2012) is required to run the tool and it is recommended that the user have a basic familiarity with the operation of this software. The tool provides gridded PMP values at a spatial resolution of 90 arc-seconds (equivalent to .025 x .025 dd) for a user-designated drainage basin or area at user-specified durations.

5.7.1 File Structure

The tool, source script, and all input data are stored within the 'PMP_Evaluation_Tool' project folder. The file and directory structure within the 'PMP_Evaluation_Tool' folder should be maintained as it is provided – as the script will locate various data based on its relative location within the project folder. If the subfolders or geodatabases within are relocated or renamed, then the script must be updated to account for these changes.

The file structure consists of only three subfolders: Input, Output, and Script. The 'Input' folder contains all input GIS files (Figure 27). There are three ArcGIS file geodatabase containers within the 'Input' folder: DAD_Tables.gdb, Storm_Adj_Factors.gdb, and Non_Storm_Data.gdb. The DAD_Tables.gdb contains the DAD tables (in file geodatabase table format) for each of the 58 SPAS analyzed storm DAD zones. The Storm_Adj_Factors.gdb contains a feature class for each analyzed event and stores the adjustment factors for each grid point as a separate feature. These feature classes are organized into feature datasets, according to storm type (General, Local, and Tropical). The storm adjustment factor feature classes share their name with their DAD Table counterpart. The naming convention is SPAS_XXXX_Y, where XXXX is the SPAS storm ID number and Y is the DAD zone number. Finally, the Non_Storm_Data.gdb contains spatial data not directly relating to the input storms: Grid_Points, a point feature class, and Vector_Grid, a polygon feature class representing the grid cells for each of 17,938 grid points.

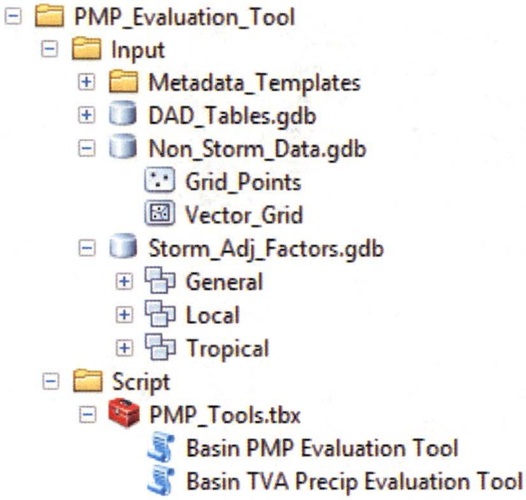

Figure 27 PMP tool file structure

The 'Script' folder contains an ArcToolbox called PMP_Tools.tbx.The toolbox contains a Script Tool called 'Basin PMP Evaluation Tool' that is used to calculate basin PMP. There is a second Script Tool called 'Basin TVA Precip Evaluation Tool' that is used to calculate basin TVA Precipitation.

ArcCatalog should be used for viewing the GIS tool file structure and interacting with the input and output geospatial data and metadata. A typical operating system's file browser does not allow access to the geodatabase containers and cannot be used to directly run the tool.

5.7.2 Python Script

Due to the large number of storm datasets and grid points within the project domain, a scripted process is necessary to compare each value efficiently and accurately for a given area of interest and make the necessary calculations. ArcGIS has adopted the Python scripting language as the viable option for compiling powerful geoprocessing operations as clearly and concisely as possible.

The Python scripts are imported and stored internally within the Script Tools and can be exported to .py files within ArcGIS Catalog. A hardcopy version of the code is given in Appendix D. The Python code can be opened and edited within any text editor. The python script uses the arcpy, arcpy.management, and arcpy.conversion modules. After the input parameters are provided, the script runs the pmpAnalysis() three times, once for each storm type. To shorten and simplify the code, repeatable functions are designed and called within the code when needed. Within the broader pmpAnalysis() function, several smaller functions are called to perform various tasks:

createPMPfc()	Creates the PMP_Points feature class to store vector (point) results
getAOIarea()	Calculates the area of the input basin
dadLookup()	Gets the DAD value for the current storm based on basin area

updatePMP()	Writes the largest adjusted rainfall value (PMP) to the PMP_Points feature class
outputPMP()	Produces output PMP raster files for each duration and applies metadata to output GIS files

There is extensive documentation within the code in the form of '# comments'. These comments provide guidance toward its functionality and describe the code.

While the script performs many actions, its primary purpose is to iterate through both the storm list and the grid points within the area of interest (AOI), comparing each, and creating output based on the maximum values. To accomplish this, several layers of nested iterative "for" loops are used.

The following high-level algorithm broadly describes the script process:

- Calculate Basin Area (in mi^2)
- For each Storm Type (general, tropical, and local)
    - For each duration
        - For each storm in database
            - Lookup storm's depth-area-duration (DAD) value for basin size
            - For each grid point in basin
                - Calculate total adjusted rainfall (TAR) by multiplying DAD value by total adjustment factor for the grid point
                - If TAR > PMP, the TAR becomes the new PMP value for that grid point
    - Create Point feature class for the storm type
    - Create raster GRID files for each duration
    - Attach metadata to each output file

5.7.3 Usage

The 'PMP_Evaluation_Tool' Script Tool within the PMP_Tools.tbx ArcToolbox opens and runs the script within the ArcGIS environment. The Script Tool has validation code that allows the user to override the basin area and provide input for the PMP area to be analyzed. In addition to running as a standalone tool, the script tool can be incorporated into Model Builder or be called as a sub-function of another script. The 'PMP_Evaluation_Tool' project folder should be stored locally at a location that can be accessed (both read/write) by ArcGIS desktop.

5.7.3.1 Input Parameters

The tool requires several parameters as input to define the area and durations to be analyzed. The first parameter required by the tool dialogue is a feature layer, such as a basin shapefile or feature class, designed to outline the area of interest for the PMP analysis. The basin shapefile must have a map surface projection spatial reference, with units of either feet or meters (e.g. Universal Transverse Mercator or State Plane). If the feature layer has multiple features (or polygons), the tool will use the combined area as the analysis region. Only the selected polygons will be used if the tool is run from the ArcMap environment with selected features highlighted. If the basin shapefile extends beyond the project analysis domain, only the grid cells within the domain will be analyzed, although the PMP depths will be calculated for the area of the entire basin.

The dialogue also requires the path of the 'PMP_Evaluation_Tool' and an 'Output Folder' path which provide the tool with the location of the input geodatabases and the location to write the output geodatabases, respectively. Figure 28 shows the input dialogue window.

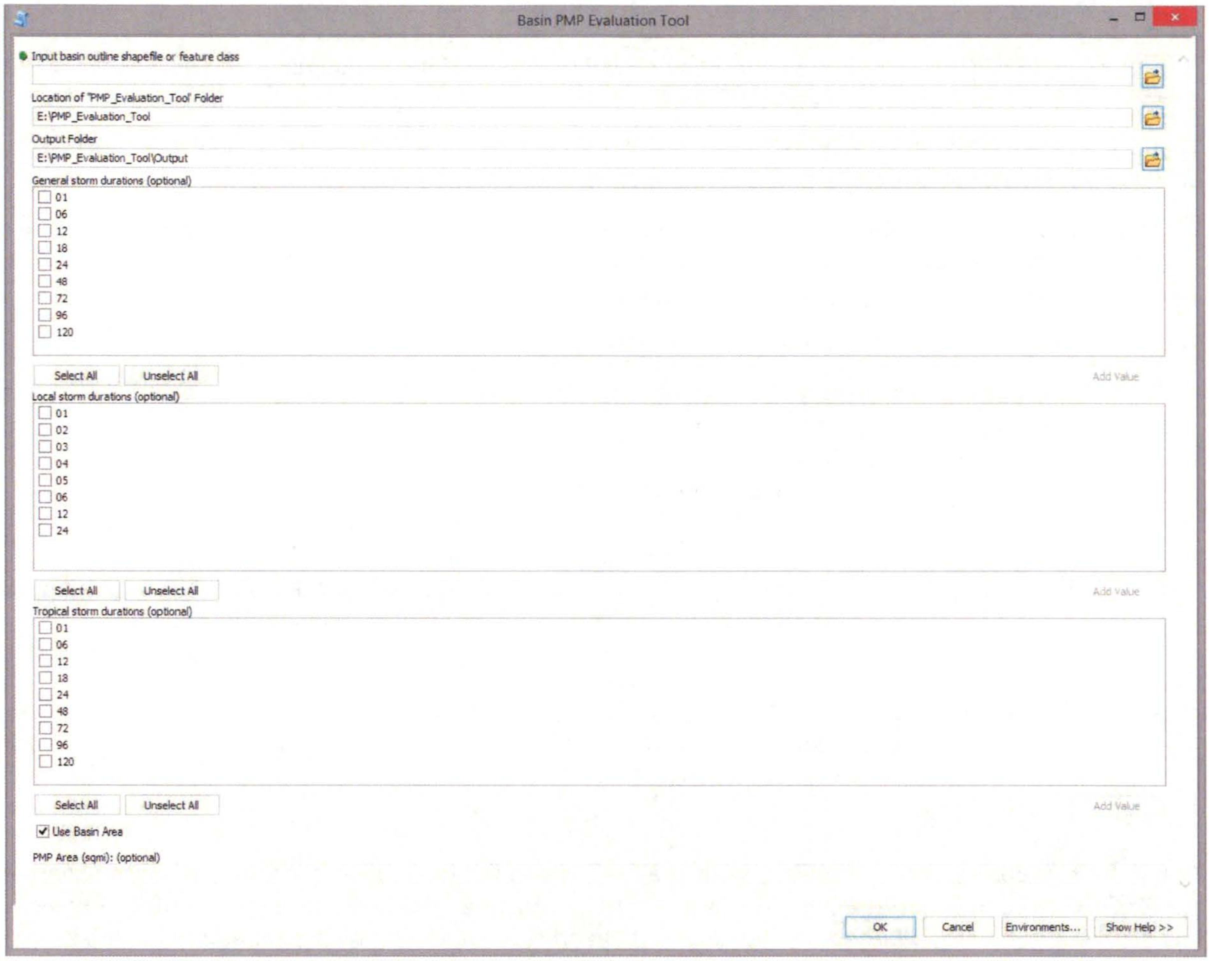

Figure 28 The PMP Evaluation Tool input dialogue

5.7.3.2 Tool Output

Once the tool has been run, the output folders and geodatabases will be populated with the model results (Figure 29). The GIS files can then be brought into an ArcMap, or other compatible GIS environment, for mapping and analysis. The tool is set to have overwrite capabilities; if output data exists, it will be overwritten the next time the tool is run. Output data should be moved to an alternate permanent storage location before the tool is run again, if the user wants the output data to be preserved.

For each storm type, the output is organized within file geodatabases and named according to the analyzed PMP area. An output geodatabase named "PMP_21.gdb" holds PMP values for a 21 square-mile basin. Each file geodatabase contains a feature class which stores each grid point centroid within the basin as a separate feature. Each feature has a field for the grid ID, latitude, longitude, analysis zone, elevation, PMP (for each duration), and the contributing storm ID. The PMP GRID files are also stored within the file geodatabase. The naming convention for the GRID files is T_XX_YYYYY, where T is the storm type (L for local convective and G for general), XX is the duration in hours, and YYYYY is the analyzed area size. For example, a GRID named

"G_06_00021" would be the 21-square mile 6-hour general storm PMP. An example of the output file structure is shown in Figure 29.

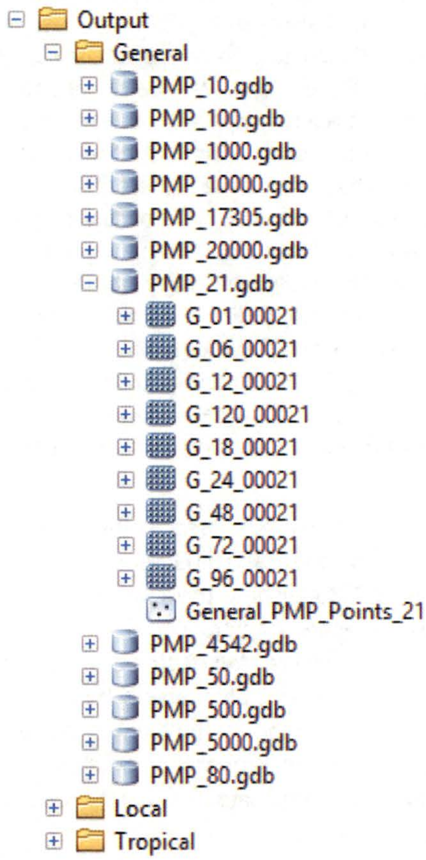

Figure 29 Example of the PMP Evaluation Tool output file structure

Full descriptions of each field are provided in the metadata for each GIS dataset.

5.7.3.3 GIS Dataset Metadata

Comprehensive metadata have been included for every data element within the project folder. The metadata were compiled using the Federal Geographic Data Committee (FGDC) .xml format standard and are attached to each GRID file. The metadata can be viewed in ArcCatalog under the description tab (the FGDC metadata style may need to be enabled under ArcCatalog 'options' for proper viewing). The output metadata originates from templates stored within each storm type's 'Metadata_Templates' sub-folder within the 'Input' folder.

5.8 PMP Sensitivity and Comparisons

The PMP and intermediate data produced for this study were rigorously evaluated throughout the process. ArcGIS was used as a visual and numerical evaluation tool to assess gridded values to ensure they fell within acceptable ranges and met test criteria. Comparisons of the PMP values against the 100-year recurrence interval values were made to ensure all PMP values were at least two times as large. In addition, comparisons of the PMP values were made against the Annual Exceedance Probability data produced in TVA Calculation No. RSOGENROGCDX0003262016000087, R0. These comparisons demonstrated that the PMP values were generally greater than a 1:100,000 AEP. Many iterations of maps were produced that helped identify potential issues with calculations, transposition limits, DAD values, or storm adjustment values. The maps also helped to define storm characteristics and transposition limits as discussed previously. As expected, several different storms controlled PMP values at various durations and area sizes. In some instances, a discontinuity of PMP depths between adjacent grid point locations resulted. This occurs when a transposition zone bisects an area of interest. In these cases, storms that are transpositionable to one transposition zone may not be transpositionable to the other. Therefore, different storms are affecting adjacent grid points and often result in a shift in values over a short distance. This occurs because of the requirement to assign specific transposition limits to each storm that result in a storm being either transpositionable to a grid point or not, with no allowance for gradients of transpositionability. In reality, there would be some transition for a given storm, but the process and definition of transpositionability does not allow for this. However, it is important to note that these discontinuities make little difference in the overall basin average PMP values for most basins and is only seen when analyzing data at the highest resolution (e.g. individual grid points). This issue could potentially have the most significant effect for small basins where there are a small number of grid points representing the drainage and therefore, each grid point value would have an exaggerated effect on the basin average PMP.

Figures 30- 32 display sample basin PMP maps used in this evaluation for 6-hour local storm at the 10-square mile area size, 72-hour general storm at 10,000-square miles, and 48-hour tropical storm at 1,000-square miles, respectively. Figures 33-35 display the controlling storms by storm type across the entire domain. Often a transposition zone is entirely controlled by a single storm. However, in some cases, more than one storm can produce similar adjusted rainfall depths and control within a single zone. In zones 2 and 3 in Figure 34 and zone 4 in Figures 33 and 35 there is more than one storm controlling PMP. This is caused when two storms produce total adjusted rainfall values that are similar and the controlling storm can alternate based on small fluctuations in the orographic or moisture adjustment factors (OTF and MTF). Because these alternations only occur when adjusted rainfall values are very close for both storms, there is no noticeable variation in the final PMP values.

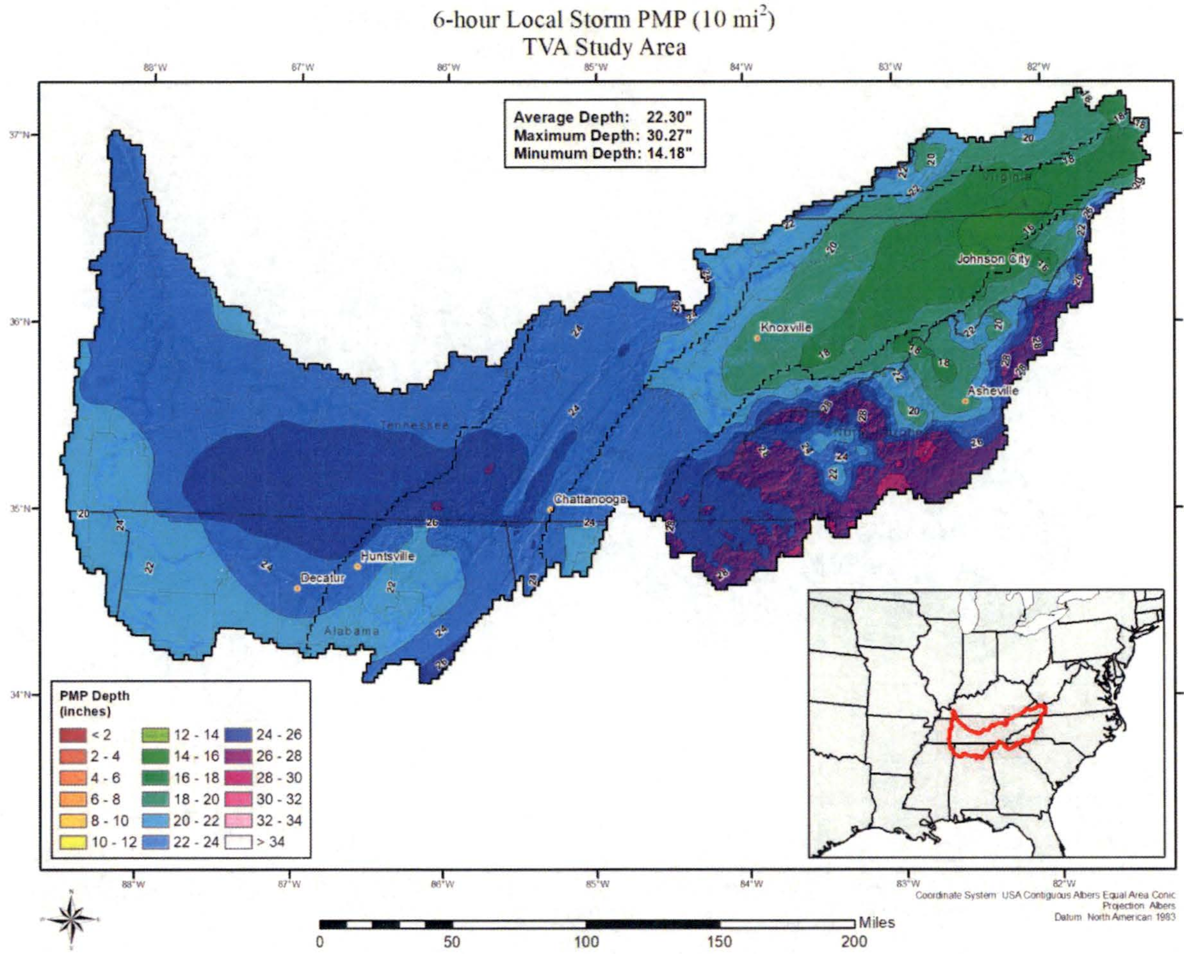

Figure 30 TVA project domain map of the 6-hour, 10-square mile PMP values derived from local/MCC storms

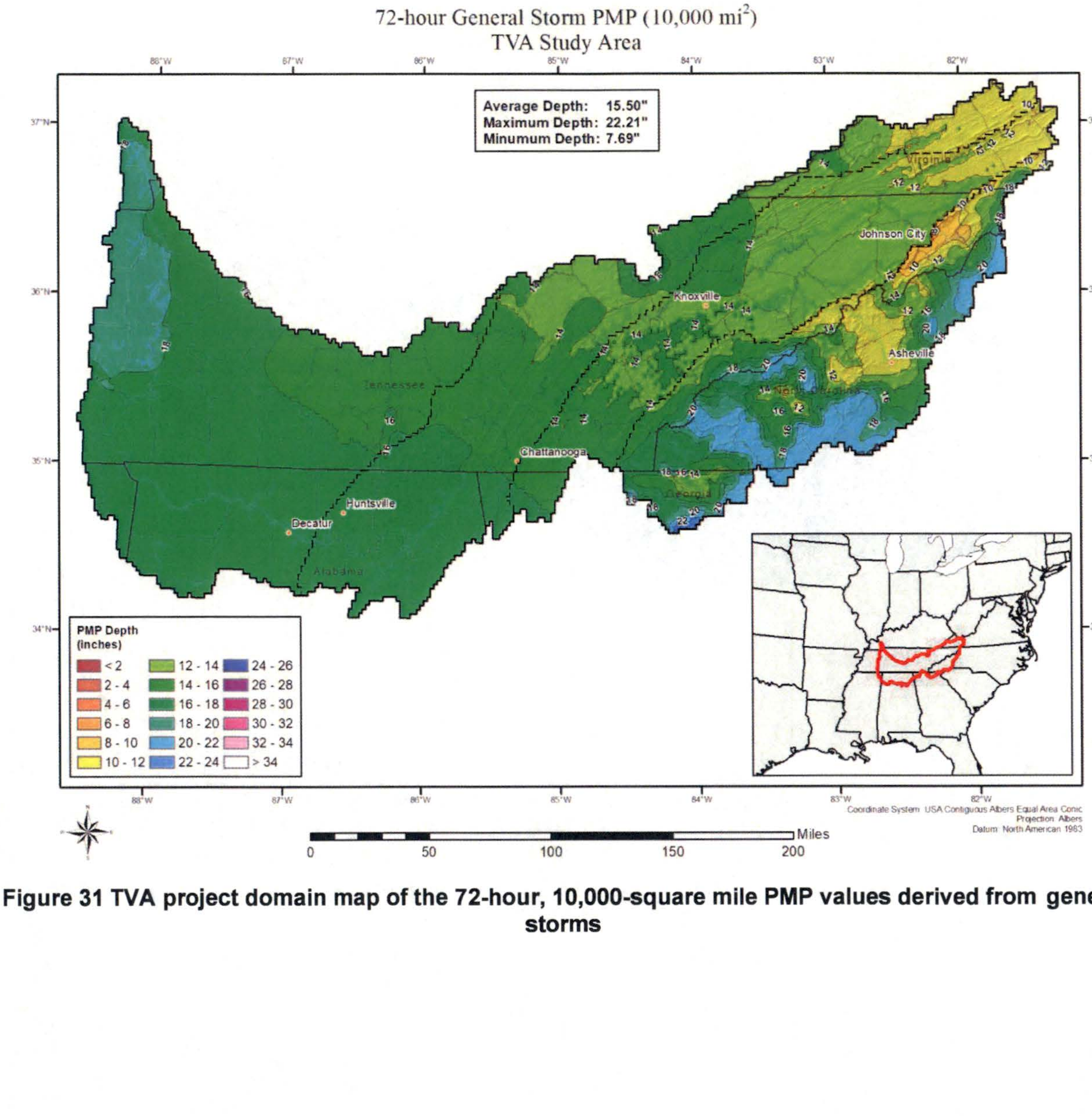

Figure 31 TVA project domain map of the 72-hour, 10,000-square mile PMP values derived from general storms

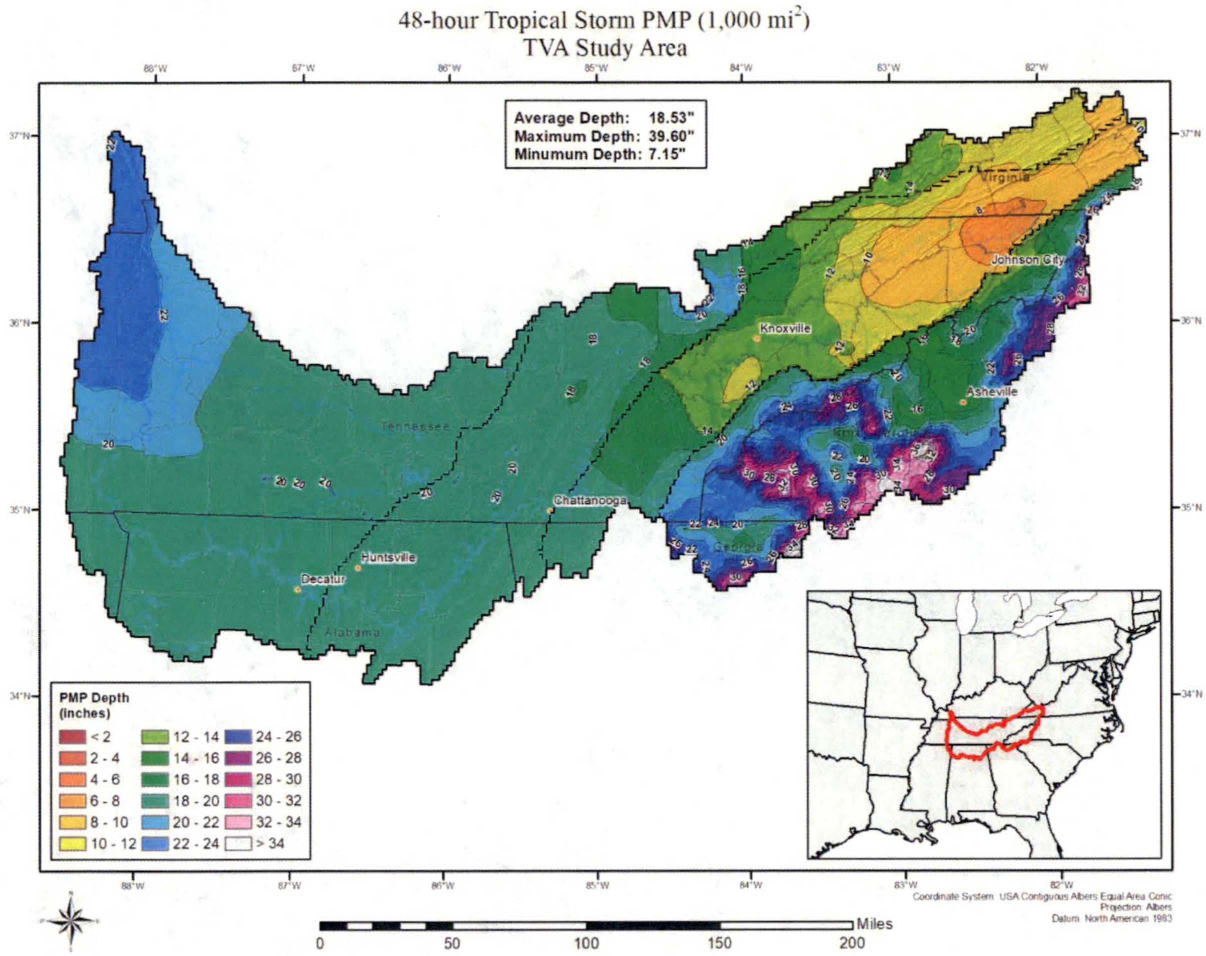

Figure 32 TVA project domain map of the 48-hour, 1,000-square mile PMP values derived from tropical storms

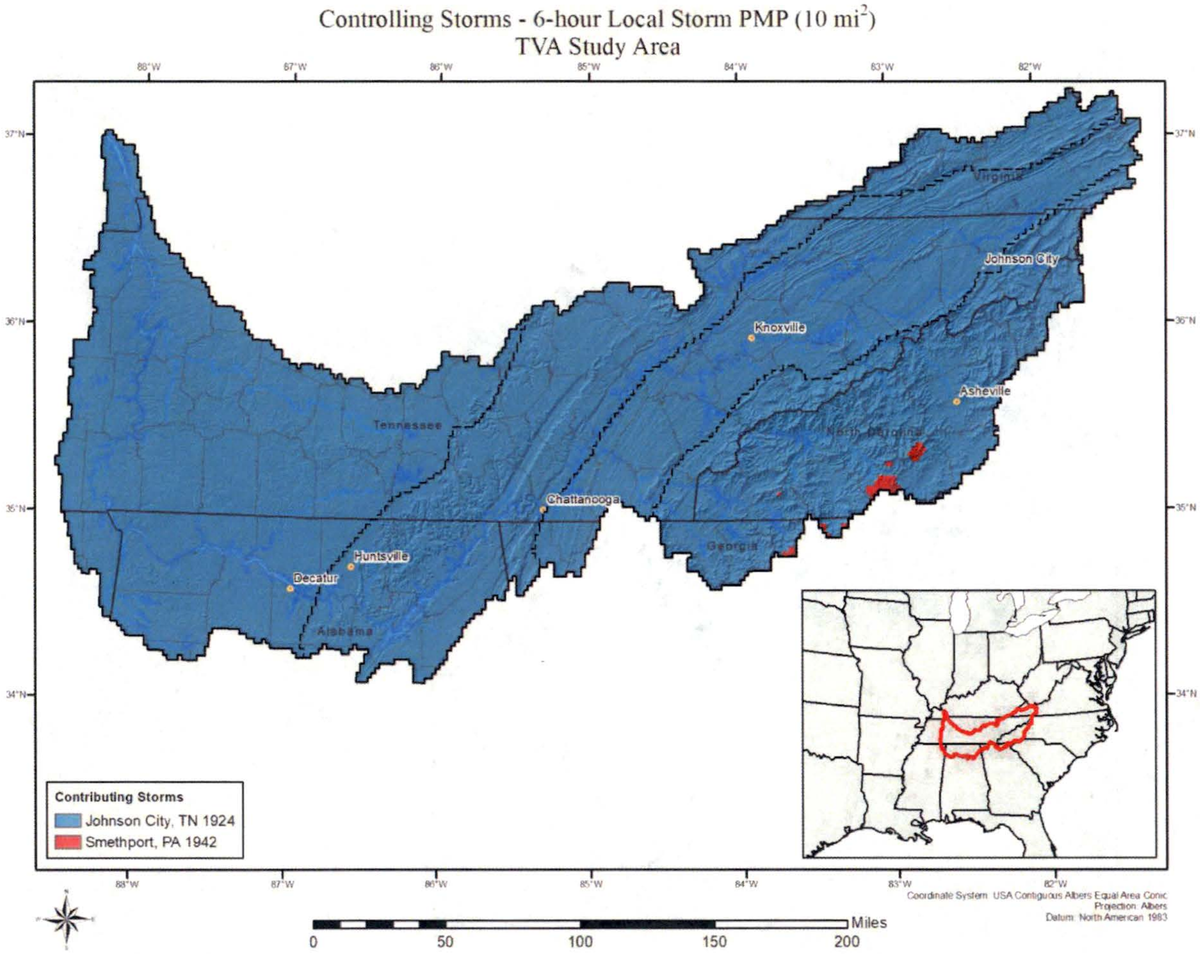

Figure 33 TVA project domain map of the 6-hour, 10-square mile local/MCC PMP controlling storms

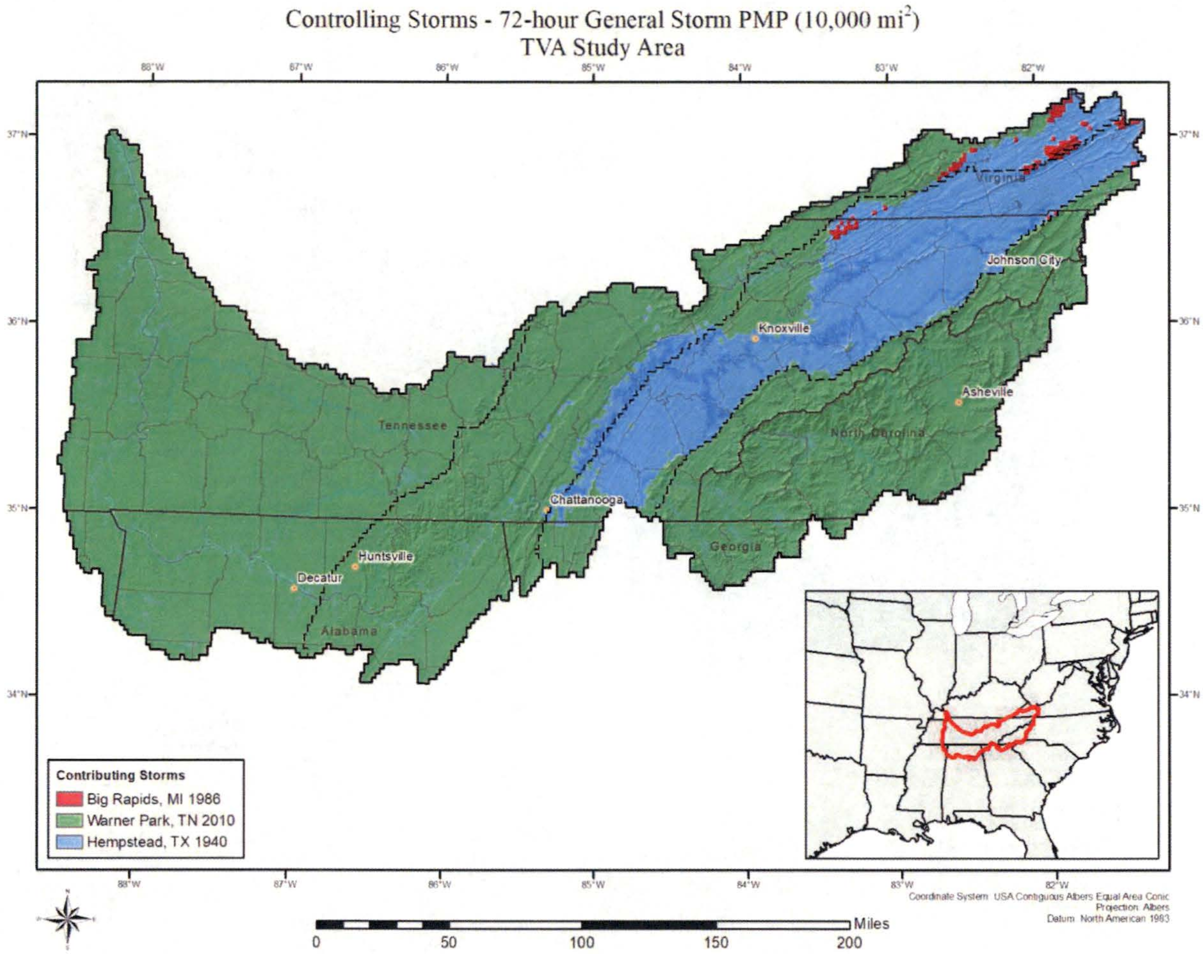

Figure 34 TVA project domain map of the 72-hour, 10,000-square mile general storm PMP controlling storms

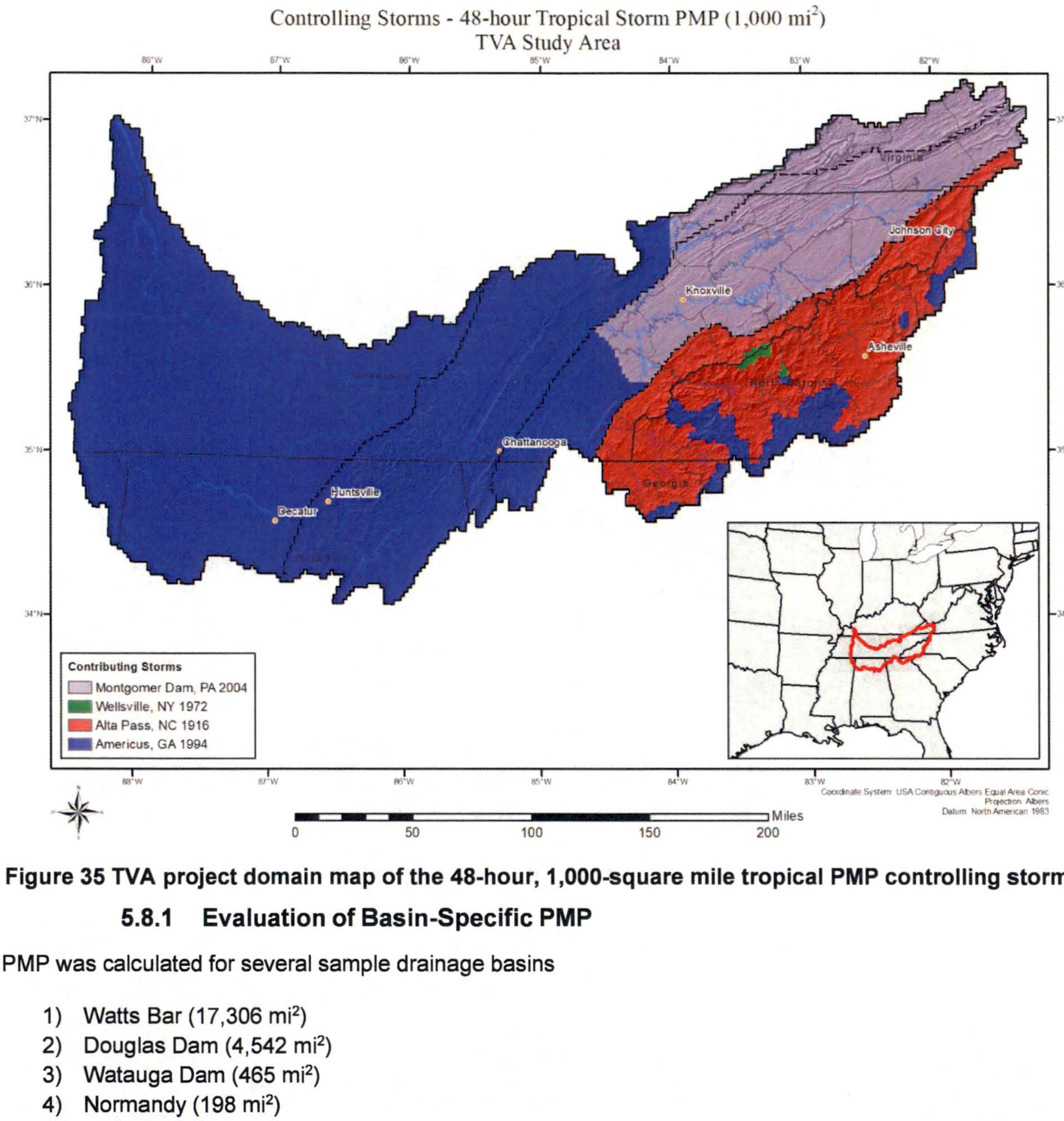

Figure 35 TVA project domain map of the 48-hour, 1,000-square mile tropical PMP controlling storms

5.8.1 Evaluation of Basin-Specific PMP

PMP was calculated for several sample drainage basins

1) Watts Bar (17,306 mi^2)
2) Douglas Dam (4,542 mi^2)
3) Watauga Dam (465 mi^2)
4) Normandy (198 mi^2)
5) East Fork (80 mi^2)
6) North Fork (22 mi^2)

The basin locations are shown in Figure 36.

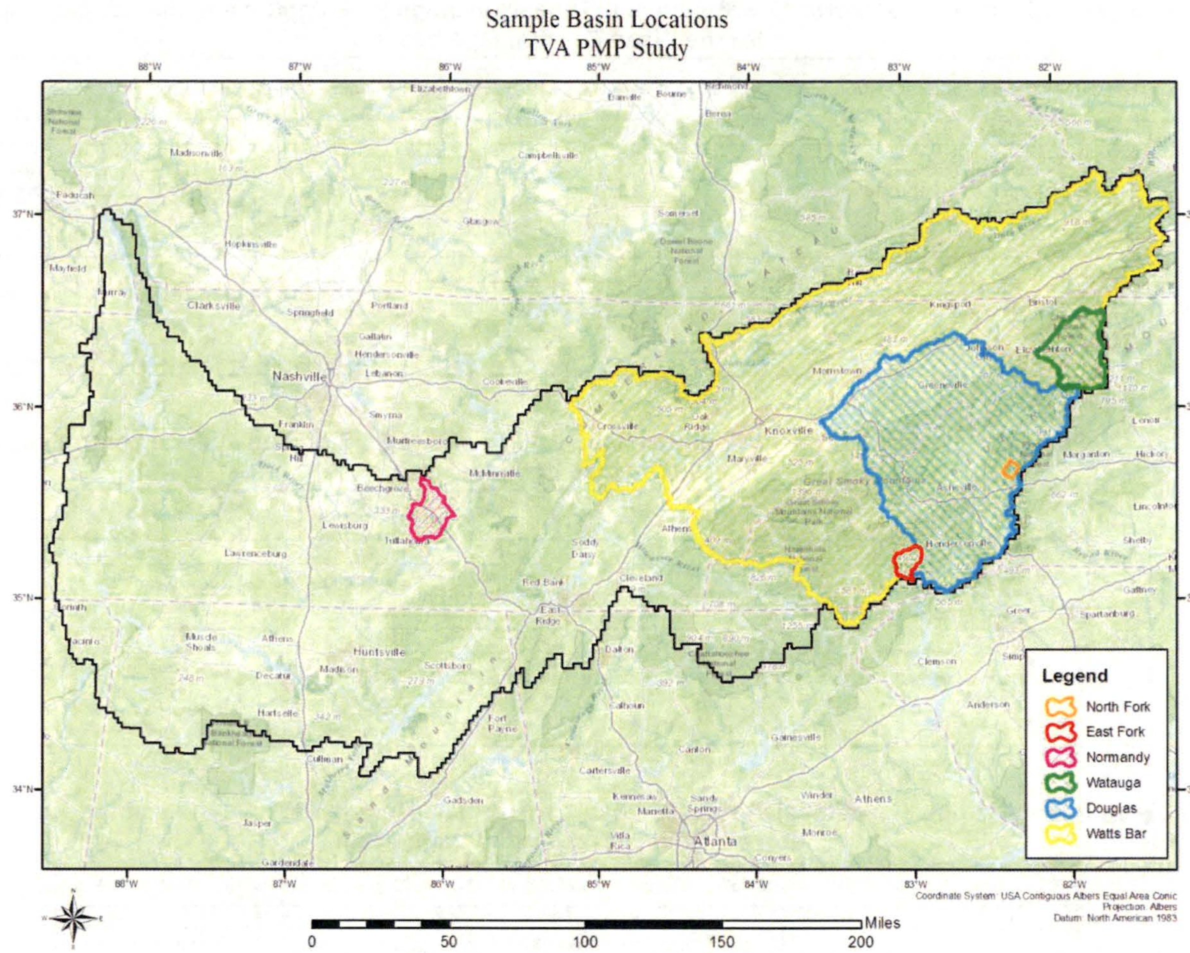

Figure 36 Sample basin locations

The PMP Evaluation Tool was used to calculate gridded PMP values for each test basin. The PMP values are summarized. General and Tropical storm PMP was calculated for the Watts Bar, Douglas, and Watauga basins (Tables 16-18). Local storm PMP was calculated for the Normandy, East Fork, and North Fork basins (Tables 19-22).

Table 16 General and tropical storm 17,306-square mile basin average PMP depths and the controlling storms for the Watts Bar drainage basin

		1-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)	48-hour PMP (in)	72-hour PMP (in)	120-hour PMP (in)
General	PMP (in)	0.88	3.21	6.04	8.33	11.96	12.57	12.80
	Source Storm(s)	Gladewater, TX 1966 Warner Park, TN 2010 Madisonville, KY 1964 Warner, OK 1943	Gladewater, TX 1966 Warner Park, TN 2010	Gladewater, TX 1966 Warner Park, TN 2010 Hempstead, TX 1940	Warner Park, TN 2010 Alley Spring, MO 2008 Hempstead, TX 1940	Big Rapids, MI 1986 Warner Park, TN 2010 Hempstead, TX 1940	Big Rapids, MI 1986 Warner Park, TN 2010 Hempstead, TX 1940	Big Rapids, MI 1986 Warner Park, TN 2010 McKenzie, TN 1937 Hempstead, TX 1940
Tropical	PMP (in)	0.84	3.99	6.50	8.51	9.52	10.50	11.60
	Source Storm(s)	Montgomery Dam, PA 2004 Americus, GA 1994	Montgomery Dam, PA 2004	Montgomery Dam, PA 2004	Montgomery Dam, PA 2004 Alta Pass, NC 1916	Montgomery Dam, PA 2004 Wellsville, NY 1972 Americus, GA 1994	Montgomery Dam, PA 2004 Wellsville, NY 1972 Americus, GA 1994	Montgomery Dam, PA 2004 Wellsville, NY 1972 Americus, GA 1994

Table 17 General and tropical storm 4,542-square mile basin average PMP depths and the controlling storms for the Douglas drainage basin

		1-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)	48-hour PMP (in)	72-hour PMP (in)	120-hour PMP (in)
General	PMP (in)	1.59	5.72	9.78	11.75	15.87	16.48	16.57
	Source Storm(s)	Warner Park, TN 2010 Hempstead, TX 1940 Warner, OK 1943	Warner Park, TN 2010 Hempstead, TX 1940	Warner Park, TN 2010	Warner Park, TN 2010 Alley Spring, MO 2008 Hempstead, TX 1940	Warner Park, TN 2010 Hempstead, TX 1940	Warner Park, TN 2010 Hempstead, TX 1940	Warner Park, TN 2010 Hempstead, TX 1940
Tropical	PMP (in)	1.41	6.02	8.61	10.96	13.91	15.68	16.24
	Source Storm(s)	Montgomery Dam, PA 2004 Americus, GA 1994	Montgomery Dam, PA 2004 Americus, GA 1994	Montgomery Dam, PA 2004 Alta Pass, NC 1916	Montgomery Dam, PA 2004 Alta Pass, NC 1916	Montgomery Dam, PA 2004 Wellsville, NY 1972 Americus, GA 1994	Montgomery Dam, PA 2004 Wellsville, NY 1972 Americus, GA 1994	Montgomery Dam, PA 2004 Wellsville, NY 1972 Americus, GA 1994

Table 18 General, tropical and local storm 465-square mile basin average PMP depths and the controlling storms for the Watauga drainage basin

		1-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)	48-hour PMP (in)	72-hour PMP (in)	120-hour PMP (in)
General	PMP (in)	3.30	12.40	15.77	17.04	20.11	20.48	20.48
	Source Storm(s)	Warner Park, TN 2010	Warner Park, TN 2010	Warner Park, TN 2010	Warner Park, TN 2010 Douglasville, GA 2009	Warner Park, TN 2010	Warner Park, TN 2010 Douglasville, GA 2009	Warner Park, TN 2010 Douglasville, GA 2009
Tropical	PMP (in)	3.09	10.18	13.13	19.91	23.53	26.73	27.27
	Source Storm(s)	Wellseville, NY 1972 Americus, GA 1994	Montgomery Dam, PA 2004 Wellseville, NY 1972 Americus, GA 1994	Montgomery Dam, PA 2004 Wellseville, NY 1972 Americus, GA 1994	Alta Pass, NC 1916	Wellseville, NY 1972 Alta Pass, NC 1916	Wellseville, NY 1972 Americus, GA 1940	Wellseville, NY 1972 Americus, GA 1940

		1-hour PMP (in)	2-hour PMP (in)	3-hour PMP (in)	4-hour PMP (in)	5-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)
Local	PMP (in)	4.99	9.99	13.03	15.42	15.64	15.91	17.46	17.84
	Source Storm(s)	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924

Table 19 General, tropical and local storm 198-square mile basin average PMP depths and the controlling storms for the Normandy drainage basin

		1-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)	48-hour PMP (in)	72-hour PMP (in)	120-hour PMP (in)
General	PMP (in)	4.05	14.26	17.55	18.47	21.19	21.92	23.02
	Source Storm(s)	Warner Park, TN 2010 Hempstead, TX 1940	Warner Park, TN 2010	Warner Park, TN 2010	Warner Park, TN 2010	Warner Park, TN 2010 Douglasville, GA 2009	Warner Park, TN 2010 Liberty, KY 1984	Liberty, KY 1984
Tropical	PMP (in)	3.76	11.24	14.43	18.68	21.97	25.52	25.92
	Source Storm(s)	Americus, GA 1994	Americus, GA 1994	Montgomery Dam, PA 2004	Americus, GA 1994	Americus, GA 1994	Americus, GA 1994	Americus, GA 1994

		1-hour PMP (in)	2-hour PMP (in)	3-hour PMP (in)	4-hour PMP (in)	5-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)
Local	PMP (in)	6.75	13.48	17.60	20.91	21.21	21.63	23.81	24.24
	Source Storm(s)	Mounds, OK 1943	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924

Table 20 Local storm 80-square mile basin average PMP depths and the controlling storms for the East Fork drainage basin

		1-hour PMP (in)	2-hour PMP (in)	3-hour PMP (in)	4-hour PMP (in)	5-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)
Local	PMP (in)	8.11	16.18	21.13	25.14	25.42	26.05	29.03	29.17
	Source Storm(s)	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924

Table 21 Local 22-square mile basin average PMP depths and the controlling storms for the North Fork drainage basin

		1-hour PMP (in)	2-hour PMP (in)	3-hour PMP (in)	4-hour PMP (in)	5-hour PMP (in)	6-hour PMP (in)	12-hour PMP (in)	24-hour PMP (in)
Local	PMP (in)	7.72	15.40	20.10	23.92	24.21	24.80	27.65	27.72
	Source Storm(s)	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924	Johnson City, TN 1924

5.8.2 Comparison of the PMP Values with Precipitation Frequency Values

The ratio of the 10-square mile 24-hour PMP to 24-hour 100-year return period rainfall amounts is generally expected to range between two and four. These investigations have been used as a sensitivity of the PMP values in all current HMRs (e.g. HMR 51 Section 3.1, bullet f). In the two most recent HMRs, values as low as 1.7 and as high as 5.5 for regions east of 117° W are found in HMRs 57 and 59 (Hansen et al., 1994, Corrigan et al., 1999). Further, as stated in HMR 59 "*...the comparison indicates that larger ratios are in lower elevations where short-duration, convective precipitation dominates, and smaller ratios in higher elevations where general storm, long duration precipitation is prevalent*" (Corrigan et al., 1999, p. 207).

For this study, the 24-hour 10-square mile PMP was compared directly to the NOAA Atlas 14 100-year 24-hour precipitation frequency values on a grid-by-grid basis for the entire analysis domain using a GIS. The comparison was presented as a percent of PMP and ratio of PMP to precipitation/rainfall, and was determined for each grid point. Average zonal statistics were summarized for each transposition zone. Table 22 provides the statistics for the comparison with NOAA Atlas 14 100-year 24-hour precipitation frequency depths. The PMP to 100-year return period precipitation ratios vary from 3.1 to 3.4 and are in reasonable proportion expected for the study area.

Table 22 Comparison of the 24-hour 10-square mile PMP with 100-year 24-hour precipitation values

Gridded Average by Transposition Zone					
ZONE	NAME	24hr 10mi² Local PMP (inches)	100yr 24hr Precip (inches)	100yr 24hr Precip Percent of PMP	Ratio of PMP to 100yr 24hr Precip
1	Appalachian Plateau	26.04	8.07	31%	3.2
2	Cumberland Plateau	25.32	7.50	29%	3.4
3	Great Valley	21.78	6.06	28%	3.6
4	Blue Ridge Mountains	27.04	8.06	29%	3.4

5.8.3 Annual Exceedance Probability of Short List Storms

Annual Exceedance Probabilities were estimated for each storm's unadjusted maximum rainfall using the NOAA Atlas 14 precipitation frequency climatologies. The AEPs were calculated at the 6-hour duration for local storms and the 24-hour and 72-hour durations for general and tropical storms. The SPAS analyzed maximum rainfall at the storm center location was compared to the NOAA Atlas precipitation values obtained from the Precipitation Frequency Data Server (PFDS) at the same location. The AEP was estimated by locating the SPAS analyzed rainfall depth on the range of precipitation values reported on the PFDS and linearly interpolating between the two bounding average recurrence intervals. The reciprocal of the return period is the AEP. NOAA Atlas 14 provides precipitation estimates up to the 1,000-year average recurrence interval. In many cases, the return period for many of the analyzed storms was beyond 1,000-years. When this occurred, the AEP was expressed as < 0.10%. Three storms centers occurred in Texas where there is no NOAA Atlas 14 data available. For these events, the TP-40 and Southern Regional Climate Center precipitation frequency climatologies were used, although they are limited to the 100-year recurrence interval. Table 23 lists the AEP for each local storm, Table 24 lists the AEP for each general storm, Table 25 lists the AEP for each tropical storm, and Table 26 lists the AEP for the three Texas storm centers.

Table 23 Annual Exceedance Probability for local storms

NAME	STATE	LAT	LON	YEAR	MONTH	DAY	MAX_PPT	NOAA Atlas 14 AEP (6hr)
COOPER	MI	42.3708	-85.5875	1914	8	31	13.39	< 0.10%
JOHNSON CITY	TN	36.3042	-82.0625	1924	6	13	16.14	< 0.10%
BOYDEN	IA	43.1958	-95.9958	1926	9	17	24.22	< 0.10%
SIMPSON	KY	38.1042	-83.2958	1939	7	4	20.82	< 0.10%
HALLETT	OK	36.2458	-96.6125	1940	9	2	24.00	< 0.10%
SMETHPORT	PA	41.8271	-78.2771	1942	7	17	34.91	< 0.10%
MOUNDS	OK	35.8458	-96.0708	1943	5	16	19.27	< 0.10%
HOLT	MO	39.4542	-94.3292	1947	6	18	17.62	< 0.10%
PRAGUE	NE	41.3583	-96.8794	1959	8	1	13.09	0.41%
DAVID CITY	NE	41.2132	-97.0710	1963	6	24	15.98	< 0.10%
COLLEGE HILL	OH	40.0854	-81.6479	1963	6	3	19.39	< 0.10%
LITTLE BARREN	TN	36.3625	-83.7208	1965	7	24	11.00	< 0.10%
ROSEDALE	TN	36.1792	-84.2292	1965	7	24	13.32	< 0.10%
WOOSTER	OH	40.9146	-81.9729	1969	7	4	14.95	< 0.10%
ENID	OK	36.3805	-97.8683	1973	10	10	19.45	< 0.10%
FOREST CITY	MN	45.2394	-94.5404	1983	6	20	17.00	0.10%
MINNEAPOLIS	MN	44.8895	-93.4021	1987	7	23	11.55	< 0.10%
DUBUQUE	IA	42.4400	-90.7500	2011	7	27	15.14	< 0.10%
DULUTH	MN	47.0200	-91.6700	2012	6	19	10.73	0.10%

Table 24 Annual Exceedance Probability for general storms

NAME	STATE	LAT	LON	YEAR	MONTH	DAY	MAX_PPT	NOAA Atlas 14 AEP (24hr)	NOAA Atlas 14 AEP (72hr)
ELBA	AL	31.3625	-86.1208	1929	3	12	29.73	0.21%	< 0.10%
PADDY MOUNTAIN	WV	39.0208	-78.5625	1936	3	16	8.32	1.46%	0.93%
MCKENZIE	TN	36.4375	-87.9125	1937	1	5	19.86	3.56%	0.15%
BLUE RIDGE DIVIDE	NC	35.0375	-83.0792	1940	8	29	14.09	0.37%	1.08%
WARNER	OK	35.4792	-95.3292	1943	5	6	25.24	< 0.10%	< 0.10%
COLLINSVILLE	IL	38.6708	-90.0042	1946	8	12	19.07	0.11%	< 0.10%
HARRISONBURG DAM	LA	31.7875	-91.8167	1953	5	11	25.35	0.14%	0.19%
MADISONVILLE	KY	37.3458	-87.4958	1964	3	8	11.67	0.51%	0.40%
ROLLINS BRANCH	WV	37.7375	-81.5958	1964	9	28	9.22	0.12%	0.12%
ROSMAN	NC	35.1458	-82.8042	1964	9	28	17.86	0.12%	0.11%
EDGERTON	MO	40.4125	-95.5125	1965	7	18	20.76	< 0.10%	< 0.10%
BURTON DAM	GA	34.7958	-83.6958	1967	8	22	18.42	1.31%	1.12%
GLEN	MS	34.8375	-88.3958	1973	3	14	12.15	0.47%	0.72%
COEBURN	VA	37.2792	-81.8042	1977	4	2	15.66	< 0.10%	< 0.10%
ROBBINSVILLE	VA	35.3208	-83.6875	1977	4	2	9.21	20.46%	5.99%
LOUISVILLE	MS	33.1042	-88.8875	1979	4	12	22.07	< 0.10%	< 0.10%
BIG FORK	AR	35.8708	-92.1208	1982	12	1	15.92	< 0.10%	< 0.10%
LIBERTY	KY	37.2625	-84.9708	1984	5	7	9.62	0.90%	0.58%
BIG RAPIDS	MI	43.6125	-85.3125	1986	9	9	13.18	0.11%	< 0.10%
GILBERTSVILLE	KY	36.9958	-88.2625	1989	2	12	13.20	0.33%	0.12%
AURORA COLLEGE	IL	41.4575	-88.0699	1996	7	16	18.13	< 0.10%	< 0.10%
LOUISVILLE	KY	38.1000	-85.6700	1997	2	28	13.51	< 0.10%	< 0.10%
HOKAH	MN	43.8125	-91.3625	2007	8	18	20.33	0.85%	1.67%
FALL RIVER	KS	37.6300	-96.0500	2007	6	30	25.50	< 0.10%	< 0.10%
ALLEY SPRING	MO	37.1150	-91.4450	2008	3	17	15.10	< 0.10%	< 0.10%
DOUGLASVILLE	GA	33.8700	-84.7600	2009	9	19	25.37	< 0.10%	< 0.10%
LA FAYETTE	GA	34.7700	-85.2600	2009	9	19	19.61	< 0.10%	< 0.10%
WARNER PARK	TN	36.0611	-86.9056	2010	4	30	19.71	< 0.10%	< 0.10%

Table 25 Annual Exceedance Probability for tropical storms

NAME	STATE	LAT	LON	YEAR	MONTH	DAY	MAX_PPT	NOAA Atlas 14 AEP (24hr)	NOAA Atlas 14 AEP (72hr)
ALTA PASS	NC	35.8792	-81.8708	1916	7	13	24.90	< 0.10%	< 0.10%
MT MITCHELL	NC	36.2875	-81.4792	1940	8	11	20.27	0.12%	< 0.10%
DEKALB	NC	32.7458	-88.6542	1964	10	4	3.67	98.31%	> 100 %
ROSMAN	NC	35.1375	-82.8375	1964	10	4	17.53	< 0.10%	< 0.10%
WELLSVILLE	NY	42.0375	-78.0708	1972	6	18	18.78	< 0.10%	< 0.10%
AMERICUS	GA	32.0958	-84.2292	1994	7	4	28.09	< 0.10%	< 0.10%
MONTGOMERY DAM	PA	40.6450	-80.3850	2004	9	18	8.79	< 0.10%	< 0.10%
LARTO LAKE	LA	31.2200	-92.1300	2008	9	1	23.31	0.40%	0.18%

Table 26 Annual Exceedance Probability for Texas storms

NAME	STATE	LAT	LON	YEAR	MONTH	DAY	24-hr DAD	72-hr DAD	TP-40 24hr 100yr	TP-40 AEP	SRCC 24hr 100yr	SRCC AEP
GLADEWATER	TX	32.8029	-94.7050	1966	4	27	14.53	21.04	10.00	< 1.0%	9.80	< 1.0%
HEMPSTEAD	TX	30.1292	-96.0542	1940	11	22	18.88	21.29	12.00	< 1.0%	11.50	< 1.0%
FAIRFIELD	TX	31.6792	-96.1292	1932	9	2	18.58	19.58	10.40	< 1.0%	9.90	< 1.0%

5.8.4 Comparison of PMP Values with Previous PMP Values

Previous PMP values in HMR 41 and HMR 56 are unable to accurately account for the effect of terrain and do not provide analysis specific to these sites as was done in this study. This study employs a variety of improved methods when compared to previous HMRs studies including a far more robust storm analysis system with a higher temporal and spatial resolution; improved dew point and precipitation climatologies that provide an increased ability to maximize and transpose storms; gridded PMP calculations which result in higher spatial and temporal resolutions; and a greatly expanded storm record. Because of the number and degree of changes from these past studies, there is limited usefulness in making direct PMP comparisons. Furthermore, due to the generalization of the regionally-based HMR studies, comparisons to the detailed gridded PMP of this study can vary greatly over short distances. However, comparisons were made for sensitivity purposes.

Figure 37 shows the locations of six test basins where PMP was calculated and compared with previous PMP estimates. The PMP values from this study were compared with HMR 56 for the Watauga (Table 27) and Normandy (Table 28) basins and compared with special wide-area cases June 7980 and March 21400 for the Douglas (Table 29) and Watts Bar (Table 30) basins.

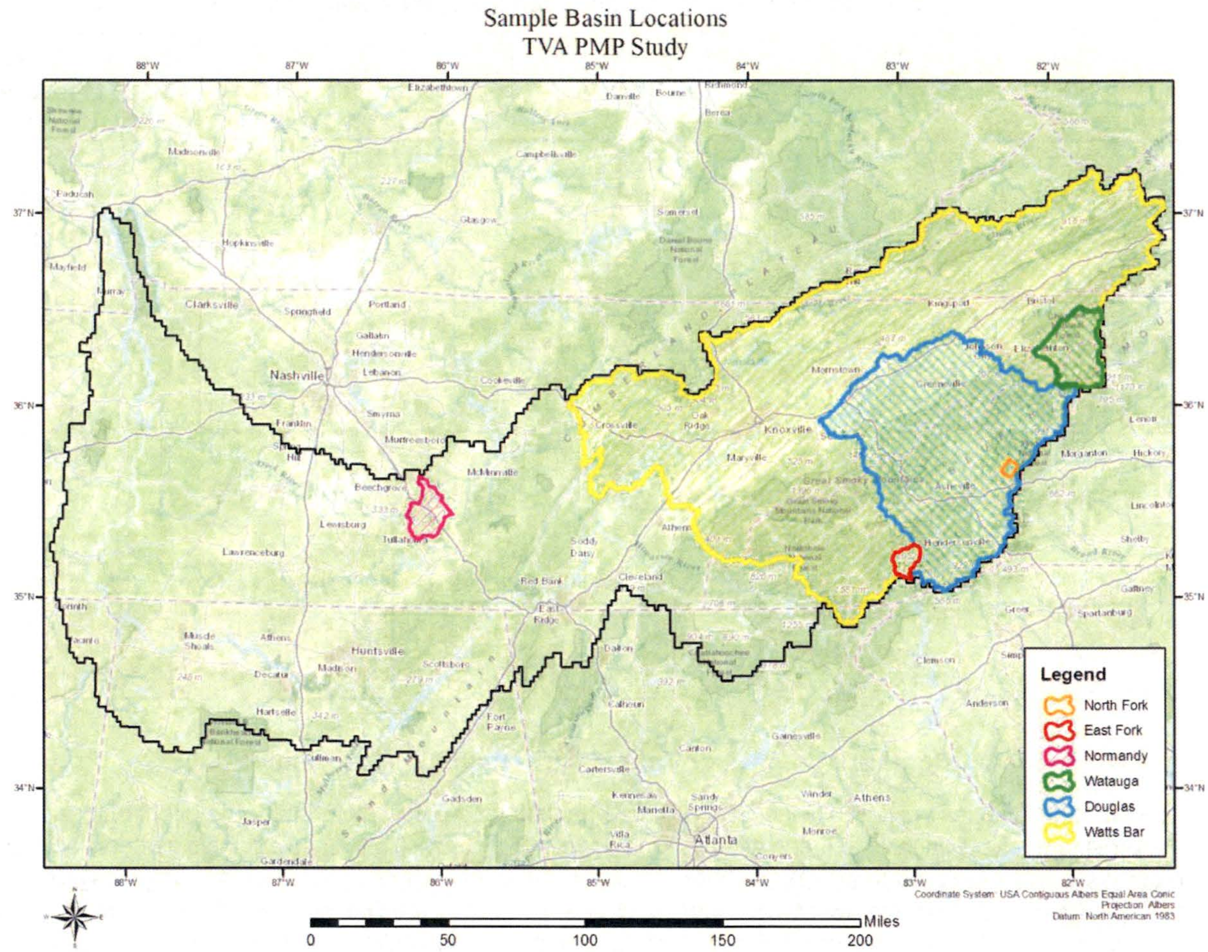

Figure 37 Locations of basins used for PMP comparisons

Table 27 Comparison of Watauga basin average PMP to HMR 56

	Watauga Basin Average PMP (inches)					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
HMR 56 PMP	**14.95**	**18.29**	**20.27**	**21.68**	**25.08**	**27.08**
General Storm PMP	12.40	15.77	**16.62**	**20.11**	20.48	20.48
Tropical Storm PMP	10.18	13.13	16.02	19.91	**23.53**	**26.73**
Local Storm PMP	**15.91**	**17.46**	-	17.84	-	-
	Percent Change from HMR 56					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
General Storm Change	-17.1%	-13.8%	**-18.0%**	**-7.2%**	-18.3%	-24.4%
Tropical Storm Change	-31.9%	-28.2%	-21.0%	-8.2%	**-6.2%**	**-1.3%**
Local Storm Change	**6.4%**	**-4.5%**	-	-17.7%	-	-

Table 28 Comparison of Normandy basin average PMP to HMR 56

	Normandy Basin Average PMP (inches)					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
HMR 56 PMP	**17.84**	**21.39**	**23.47**	**24.94**	**28.48**	**30.55**
General Storm PMP	14.26	17.55	**18.23**	18.47	21.19	21.92
Tropical Storm PMP	11.24	14.43	16.64	18.68	**21.97**	**25.52**
Local Storm PMP	**21.63**	**23.81**	-	**24.24**	-	-
	Percent Change from HMR 56					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
General Storm Change	-20.0%	-18.0%	**-22.3%**	-26.0%	-25.6%	-28.3%
Tropical Storm Change	-37.0%	-32.5%	-29.1%	-25.1%	**-22.9%**	**-16.5%**
Local Storm Change	**21.3%**	**11.3%**	-	**-2.8%**	-	-

Table 29 Comparison of Douglas basin average PMP to June 7980 and March 21400

	Douglas Basin Average PMP (inches)					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
June 7980 PMP	**5.54**	**8.37**	**10.32**	**11.71**	**15.20**	**17.25**
March 21400 PMP	**5.45**	**8.29**	**10.21**	**11.73**	**15.34**	**17.45**
General Storm PMP	5.72	**9.78**	**10.93**	**11.75**	**15.87**	**16.48**
Tropical Storm PMP	**6.02**	8.61	10.15	10.96	13.91	15.68
	Percent Change from June 7980					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
General Storm Change	3.2%	**16.9%**	**5.9%**	**0.3%**	**4.4%**	**-4.5%**
Tropical Storm Change	**8.7%**	2.9%	-1.6%	-6.5%	-8.4%	-9.1%
	Percent Change from March 21400					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
General Storm Change	4.9%	**18.0%**	**7.1%**	**0.2%**	**3.5%**	**-5.5%**
Tropical Storm Change	**10.5%**	3.9%	-0.6%	-6.6%	-9.3%	-10.2%

Table 30 Comparison of Watts Bar basin average PMP to June 7980 and March 21400

	Watts Bar Basin Average PMP (inches)					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
June 7980 PMP	**5.40**	**8.20**	**10.14**	**11.54**	**15.00**	**17.05**
March 21400 PMP	**4.83**	**7.50**	**9.33**	**10.75**	**14.19**	**16.17**
General Storm PMP	3.21	6.04	7.04	8.33	**11.96**	**12.57**
Tropical Storm PMP	**3.99**	**6.50**	**8.08**	**8.51**	9.52	10.50
	Percent Change from June 7980					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
General Storm Change	-40.5%	-26.4%	-30.6%	-27.9%	**-20.3%**	**-26.3%**
Tropical Storm Change	**-26.1%**	**-20.7%**	**-20.3%**	**-26.2%**	-36.5%	-38.4%
	Percent Change from March 21400					
	6-hour	12-hour	18-hour	24-hour	48-hour	72-hour
General Storm Change	-33.5%	-19.5%	-24.5%	-22.6%	**-15.7%**	**-22.2%**
Tropical Storm Change	**-17.4%**	**-13.3%**	**-13.4%**	**-20.8%**	-32.9%	-35.1%

5.9 Assumptions

In the process of deriving site-specific PMP values, various assumptions were made and explicit procedures were adopted for use. Additionally, various parameters and derived values were used in the calculations. It is of interest to assess the sensitivity of PMP values to assumptions that were made and to the variability of parameter values.

5.9.1 Assumptions

The following verified assumptions were used in this calculation.

1) This calculation assumes that if an appropriate set of storm events has been identified, analyzed, and maximized, they will represent the meteorological environment associated with the PMP for any location within the overall basin and the Local Intense Precipitation (LIP) at any nuclear site. This assumption is validated by including a large enough set of PMP-type and LIP-type storms to ensure no storms which could have potentially affected PMP or LIP values after all adjustments were applied, were left out of the analysis. This same assumption is made in HMR 51.

2) It is assumed that storms transposed to the any grid point in the TVA domain could have occurred over the area under similar meteorological conditions. This decision is made using scientific judgment related to the storm type, season of occurrence, similarity of topography between the original locations and the new location, and experience analyzing past storms. Parameters used in screening for transpositionability include not moving storms across the Appalachian crest, employing a +/- 1,000 foot limitation between the original storm location and the basin centroid or site location, and limiting the north/south region of transposition to approximately +/- 6° longitude. Note that judgment is still employed for storms that are questionable following these guidelines so that conservatism is applied when a storm potentially affecting PMP is near one of these boundaries. This follows the same guidance provided in HMR 51 Section 2.4.2.

3) It is assumed that the cool-season PMP values are considered and analyzed as a rain-on-snow scenario where some amount of rainfall accumulates when snow is on the ground and are combined with a given amount of snow melt to derive the total runoff associated with a cool-season PMP rainfall.

4) The atmospheric air masses that provide moisture to both historic storms and the PMP storm are assumed to be saturated through the entire depth of the atmosphere and to contain the maximum moisture possible based on the surface dew point. This assumes moist pseudo-adiabatic temperature profiles for both the historic storms and the PMP storm. In addition, it is assumed that the maximum amount of moisture the atmosphere can hold is available to the PMP storm. This follows the same guidance provided in HMR 51 and WMO Manual for PMP.

5) The assumption is made that if additional atmospheric moisture had been available, the storm would have maintained the same efficiency for converting atmospheric moisture to rainfall. The ratio of the maximized rainfall amounts to the actual rainfall amounts would be the same as the ratio of the precipitable water (the total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels in the atmosphere) in the atmosphere associated with each storm. For this analysis, the assumption of no change in storm efficiency is accepted, following HMR and WMO assumptions.

6) The climatological maximum dew point for a date 15 days towards the warm season from the date that the storm actually occurred is applied in the storm maximization process. This procedure assumes that the storm could have occurred 15 days earlier or later in the year when maximum dew points (and moisture levels) are higher. This assumption follows HMR guidance and is consistent with procedures used to develop PMP values in all the current HMR documents (e.g., HMR 51, Section 2.3 Reference 1; HMR 59, Section 4.2, Reference 5; and WMO, as well as all AWA PMP studies.)

7) Changes in climate that will occur in the region are adequately accounted for by the rarity of the

resulting PMP and LIP values. Further, changes in climate which have occurred during the past 150 years are captured in the storm record and rainfall data used in this analysis and therefore represent any changes that would be expected during the useful lifetime of the values. Therefore, no adjustment is made to account for potential changes in climate. This follows the same guidance provided in the HMRs and WMO Manual for PMP of assuming no climate change the process.

5.10 Recommendations for Application

5.10.1 Site-Specific PMP Applications

Site-specific PMP values provide rainfall amounts for use in computing the Probable Maximum Flood (PMF). This study addressed several issues that could potentially affect the magnitude of the PMP storm over any drainage basin within the project area covering the TVA region. It is important to remember that the methods used to derive PMP and subsequently the methods used to derive the PMF from those data, adhere to the caveat of being "physically possible" as described in the definition of PMP (see Section 1.1). In other words, various levels of conservatism and/or extreme aspects of storms that would not occur/co-occur in a PMP storm environment should not be compounded to generate unrealistic results in either the PMP values or the hydrologic applications of those values to derive the PMF.

The storm search process and selection of storms analyzed in this study only considered events that occurred over areas that are both meteorologically and topographically similar to locations within the overall project domain. Each storm type (local/MCS and general) that occurs in the overall project domain was analyzed. Therefore, results of this study should not be used for watersheds where meteorological and/or topographical parameters are different from those found within the project domain without further evaluation.

5.10.2 Antecedent Precipitation

The lack of explicit data from which to derive conclusions regarding the amount of antecedent precipitation and the timeframe between this and the PMP results leads us to not recommend it in PMF development. Instead, AWA recommends that antecedent conditions of a given location are set using hydrological and operating rules, which have a greater foundation in data and analysis from which to draw conclusions and set appropriate guidelines.

5.10.3 Climate Change Assumptions

The effect of climate change on the number and intensity of extreme rainfall events in the state of TVA is unknown as of the date of this report.

With a warming of the atmosphere, there can potentially be an increase in the available atmospheric moisture for storms to convert to rainfall (e.g. Kunkel et al., 2013). However, storm dynamics play a significant role in that conversion process and the result of a warming or cooling climate on storm dynamics is not well understood. A warmer or cooler climate may lead to a change in the frequency of storms and/or a change in the intensity of storms, but there is no definitive evidence to indicate the trend or the magnitude of potential changes.

It is recognized that the climate is in a constant state of change and there is uncertainty whether the state will be wetter or drier, warmer or colder, and/or experience more or less extreme precipitation events with any quantitative and statistically significant certainty, particularly for the region specific to this study. The PMP values derived in this study have a useful life between 30 to 50 years before they would require re-evaluation. In general, most projected changes that *may* occur within the Earth's climate system would be unlikely to significantly affect the project's PMP related hydrology beyond the bounds of the PMP/PMF values derived from this project. Therefore, this study has continued the practice of assuming no climate change, as climate trends are not considered when preparing PMP estimates (WMO, Section 1.1.1).

6.0 Summary and Conclusions

This calculation provides PMP values which can be used to support a license amendment request to perform an assessment of river flooding effects and local intense precipitation effects at the Browns Ferry, Sequoyah, and Watts Bar nuclear plant sites. NRC review of this report is applicable only to these effects and their impact on these three sites. The PMP values calculated during this study incorporated storms through 2014, thereby most recent HMRs. State-of-the-science meteorology was applied in all aspects of PMP development. This included the following:

- Use of HYSPLIT trajectory models to help determine moisture inflow regions
- Use of NEXRAD weather radar in quantifying rainfall accumulations in space and time as well as magnitude
- Employing GIS extensively to display, sort, and store storm information and derive PMP values on a high resolution grid.
- Providing a methodology to explicitly quantify the effect of topography on rainfall, both enhancement and reduction, and analyze those data on a fine resolution which explicitly captures the spatial variations created by the widely varying topography of the region.
- Detailed analysis of each storm's transpositionability to each grid point within the overall TVA domain was evaluated during this study. Refinements to HMR transposition limits were employed were data and meteorological understanding allowed.

As with all previous AWA studies and in the HMRs, a storm based approach was utilized to calculate the PMP values. This study therefore followed the same basic procedures as were utilized in the HMRs to derive PMP. That involved identifying the storm types which could produce PMP rainfall, maximizing those storms in-place, then transpositioning those storms to appropriate locations throughout the TVA domain.

The following are the main conclusions from this study:

- HMR values are outdated. This study provided updated PMP values as an alternative to HMRs 41, 45, 47, 56, as well as 51 and 52 PMP values.
- The most recent storm used to derive PMP values in HMR 51 occurred in 1972. The most recent storm used in HMR 56 occurred in 1982. This study updated the storm database to include storms through 2014.
- HMRs 41, 45, 47, 56, as well as 51 and 52 did not use computer based technologies in the storm analyses procedures. This study used computer technology and GIS to more accurately analyze storm rainfall patterns and implement the spatially distributed PMP values.
- HMRs 51, 52, and 55A did not have weather radar to help spatially distribute rainfall among rain gauge locations. SPAS storm analyses incorporates this information when available to provide the most advanced spatial representation of rainfall storm patterns possible.
- Understanding of meteorological processes, interactions, and storm patterns have advanced greatly since the publication of HMRs 41, 45, 47, 56, as well as 51 and 52. Satellite and radar technology have greatly added to the understanding of storm patterns over the last 40 years. This study incorporated the state-of-the-science understanding and technology associated with analyzing extreme rainfall events.

- HMRs 51 and 52 provide generalized and smoothed values over a large geographic domain that covers the United States east of the 105th meridian and to a lesser extent HMRs 41, 45, 47, and 56 suffer from the same problem. This calculation considered characteristics specific to grid points within the overall TVA domain, and produced PMP values that explicitly considered the meteorology of the PMP storm type.
- The transposition limits of the Smethport, PA July 1942 storm, which produced the 4- and 6-hour world record rainfall, were explicitly evaluated on a grid point basis. The refined transposition limits used in this calculation result in lower values compared to the HMRs for locations where the Smethport storm apparently influenced PMP values in those HMRs beyond reasonable transposition limits. Smoothing of the PMP/LIP isolines in HMRs 51 and 52 necessarily had to encompass the Smethport maximized in-place rainfall far beyond its explicit transposition limits. Note, Section 3.2.4 of HMR 51, p.28 states that they "slightly undercut" the maximized 6-, 12-, and 24-hour values by up to 7% to avoid "excessive envelopment of all other data in a large region surrounding the Smethport location." This over envelopment effect extended well beyond the intended transposition limits of the Smethport storm because the PMP/LIP isolines required smoothing and fitting over surrounding regions.
- Each storm's inflow vector was re-evaluated and combined with an updated set of dew point climatologies and when necessary, updated storm representative dew point values were used for the in-place maximization and transposition factors. The HYSPLIT trajectory model was used to evaluate moisture inflow vectors for storms on the short storm list. Trajectory models were not available in HMR studies. Use of HYSPLIT allowed for a high degree of confidence when evaluating moisture inflow vectors and storm representative dew points.
- Several storms have been analyzed and included in this analysis that were not included in the HMRs. This provided a higher level of confidence in the final PMP values. This expanded data set used to derive values includes a large number of recent storms where weather radar data were available.
- The calculation provided adjustments for storm elevation through all elevations and terrain classifications, whereas HMRs 41, 45, 47, and 56 used generalized terrain classification and HMRs 51 and 52 made no explicit adjustment for elevation. This adjustment depends on the elevation of the historic storm's maximum rainfall location and therefore varies from storm to storm.
- Storms analyzed by the NWS/USACE which occurred prior to 1948 and used 12-hour persisting dew points in the storm maximization process were adjusted so that the updated dew point climatology could be utilized consistently. For thunderstorms and MCC storm events, 7°F was added to the NWS/USACE storm representative dew point. This was done to adjust for using average dew point values for varying durations vs. 12-hour persisting dew point values. Recent evaluations of 12-hour persisting storm representative dew points showed those used HMRs underestimated the storm representative dew point values.

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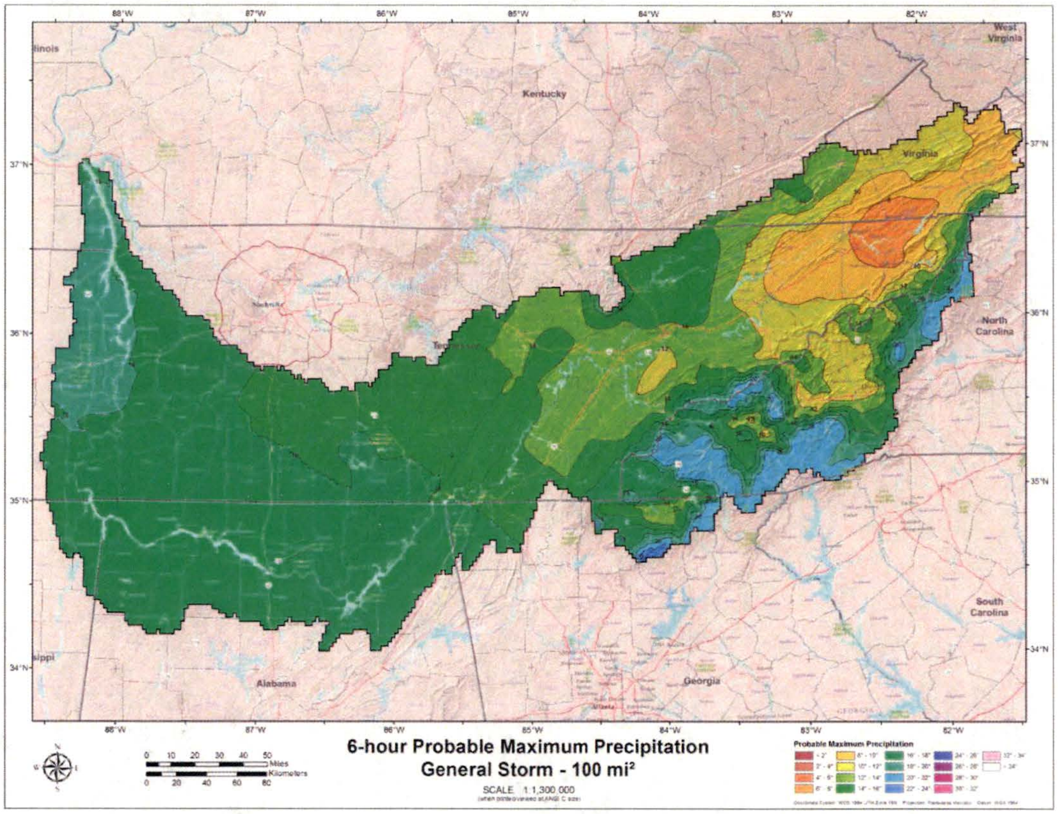
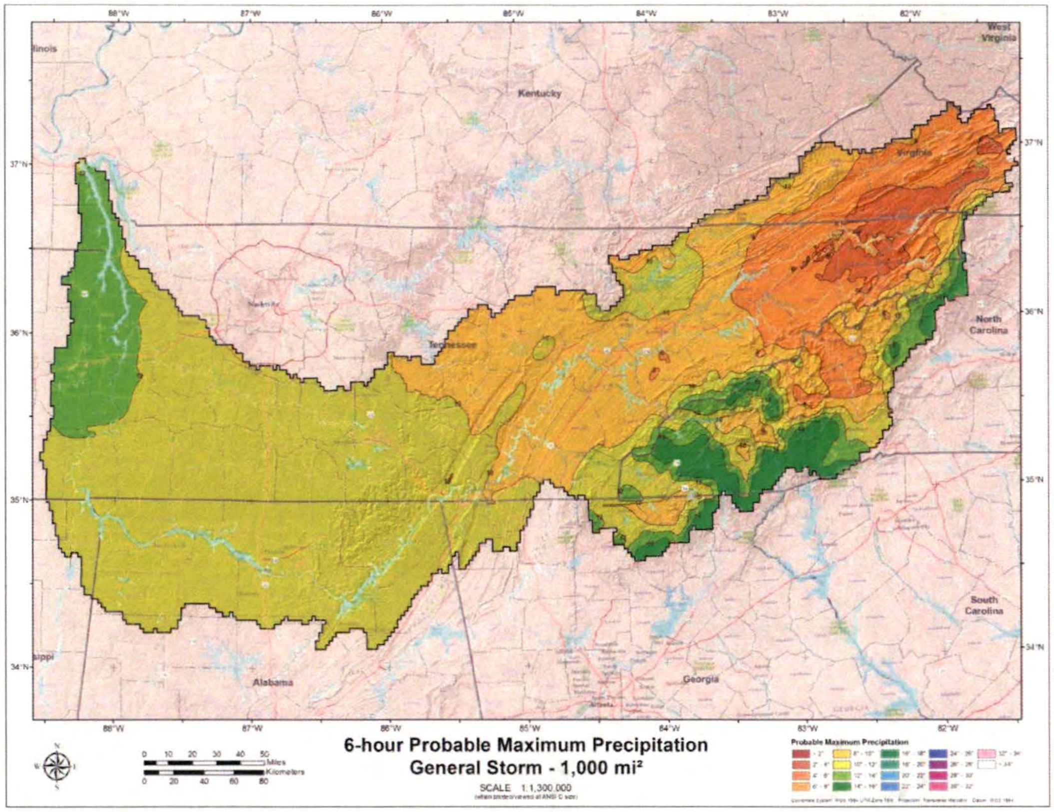
APPENDIX A - Probable Maximum Precipitation Maps

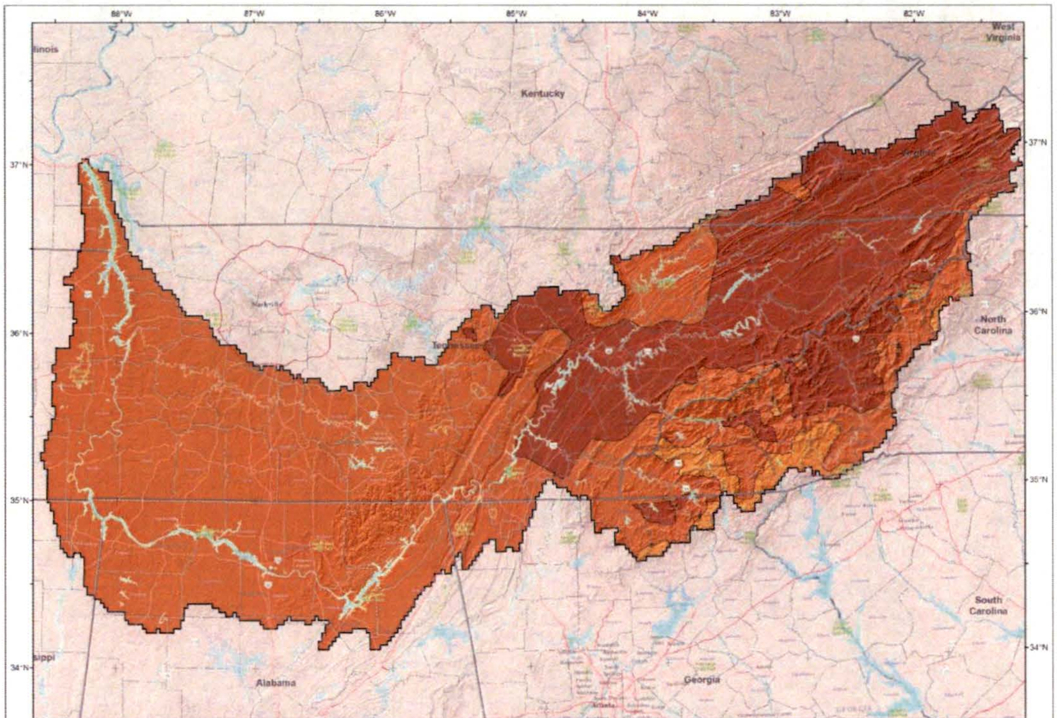
General Storm



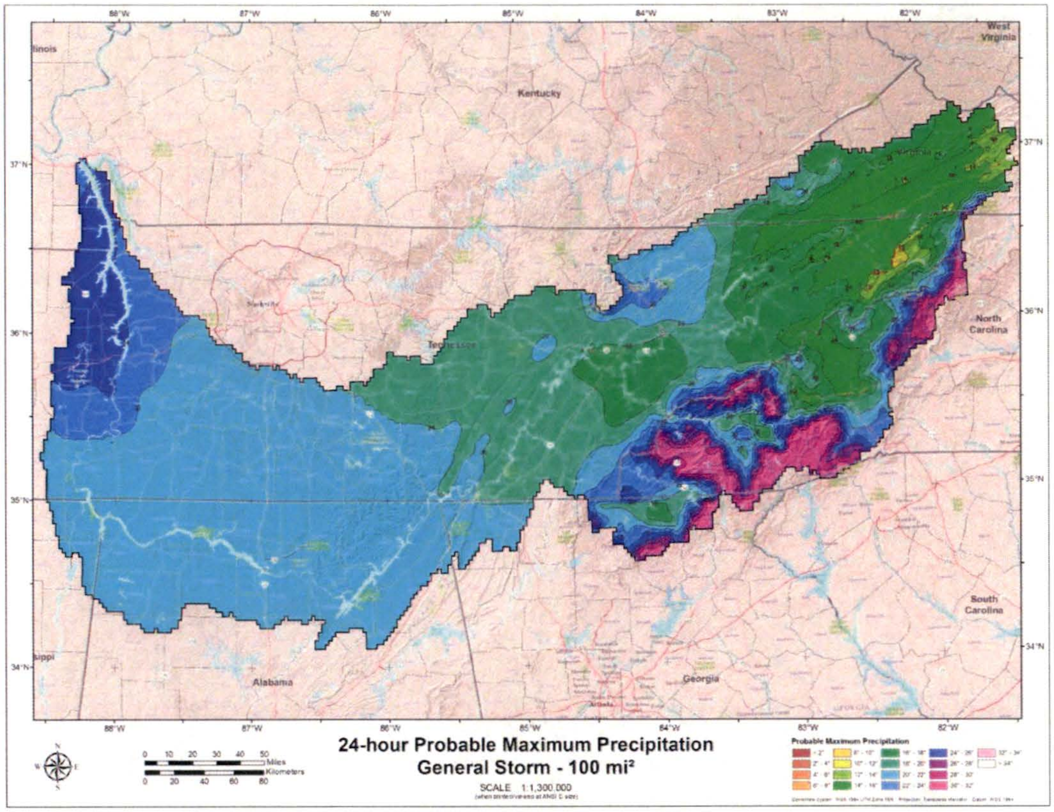
Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Alabama
Georgia
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
6-hour Probable Maximum Precipitation
General Storm - 100 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation



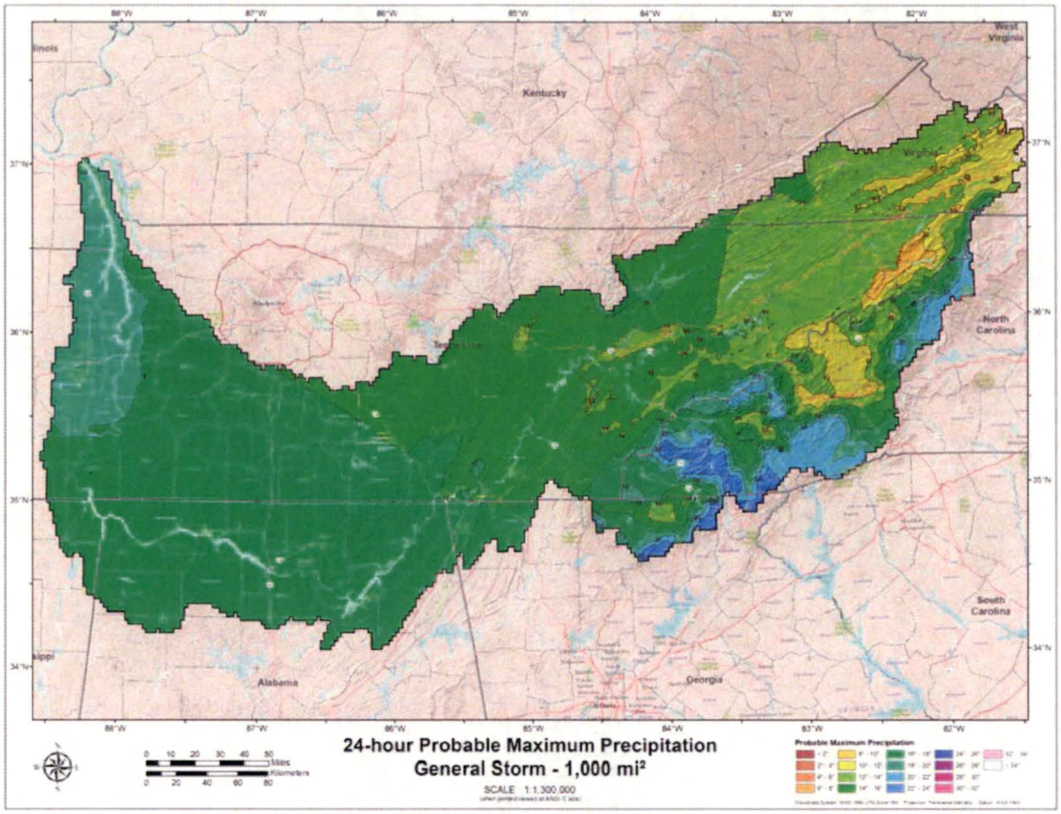
6-hour Probable Maximum Precipitation
General Storm - 1,000 mi²



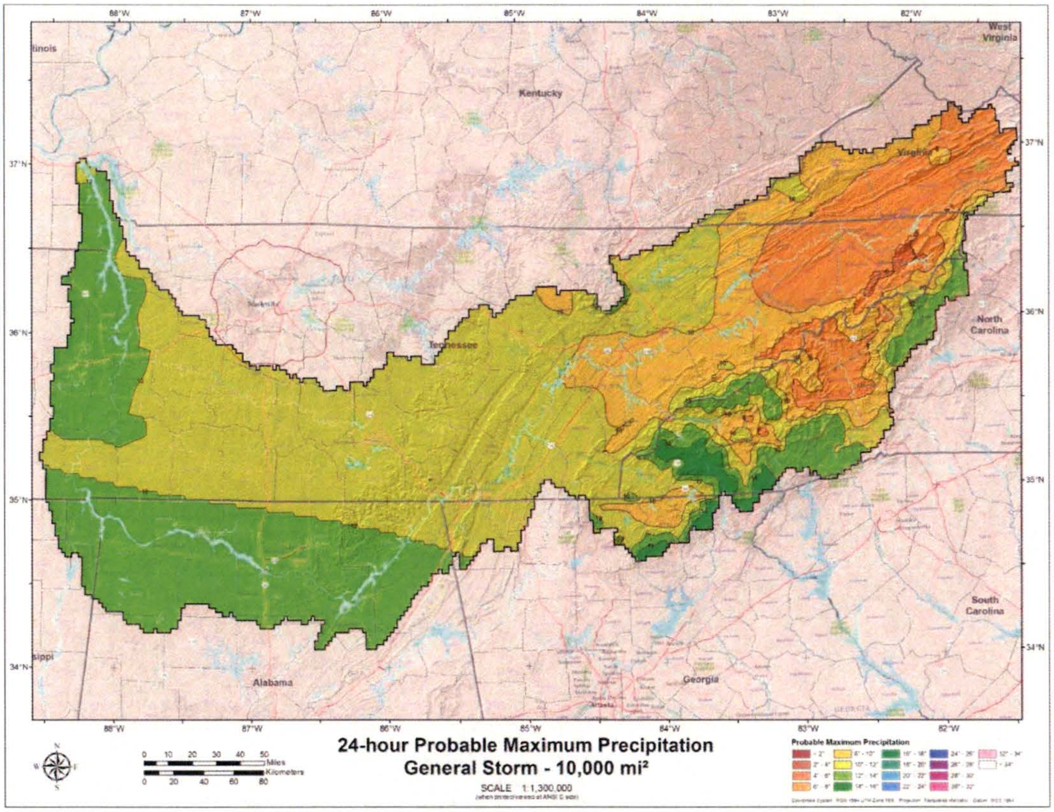
6-hour Probable Maximum Precipitation
General Storm - 10,000 mi²
SCALE 1:1,300,000



Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
24-hour Probable Maximum Precipitation
General Storm - 100 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

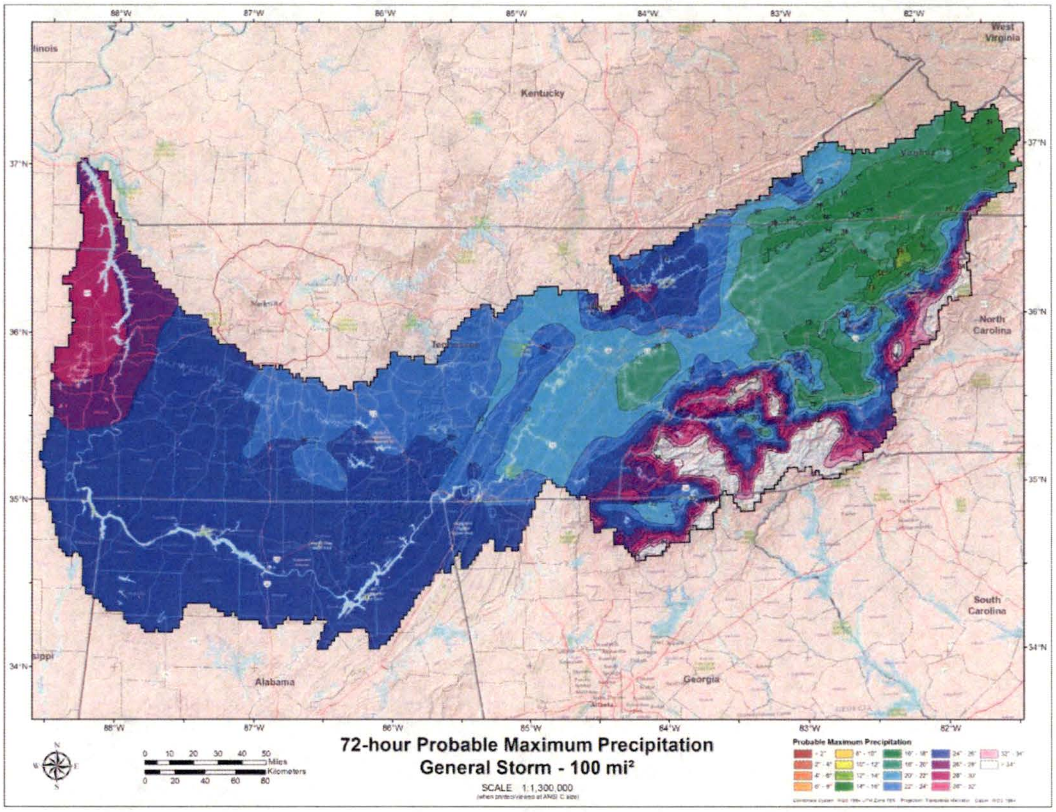


West Virginia
Kentucky
Virginia
North Carolina
South Carolina
Georgia
Alabama
24-hour Probable Maximum Precipitation
General Storm - 1,000 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

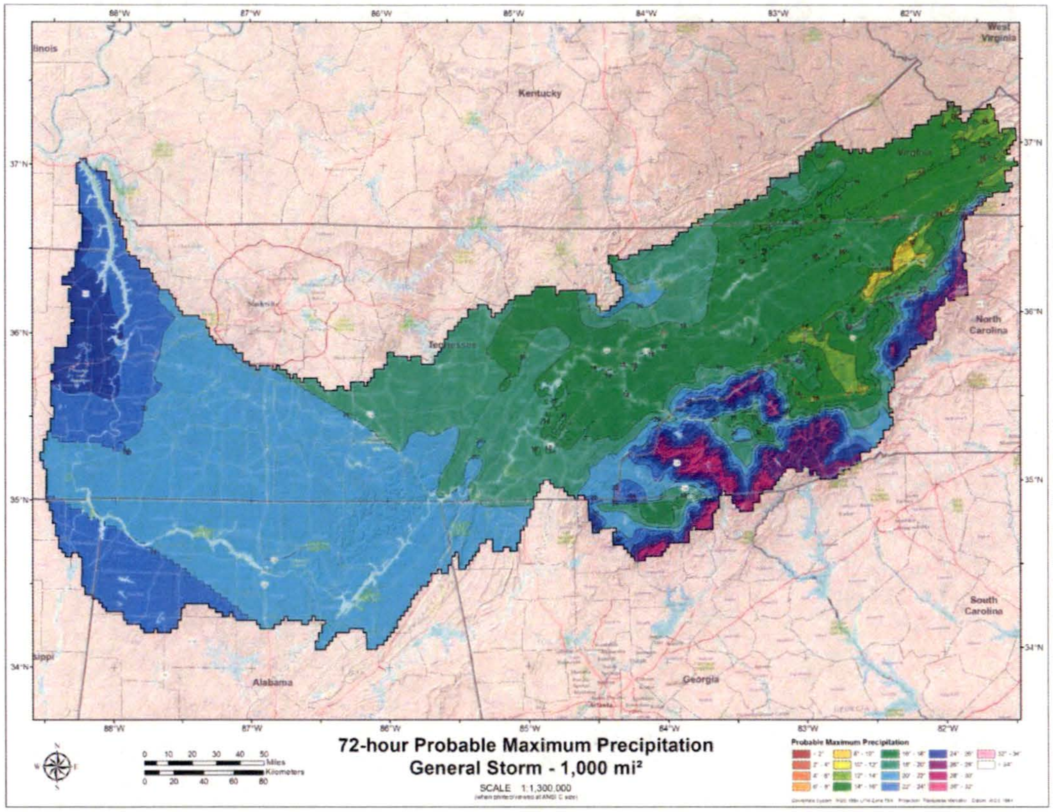

24-hour Probable Maximum Precipitation
General Storm - 10,000 mi²
SCALE 1:1,300,000
Kentucky
Tennessee
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
Probable Maximum Precipitation

CALCULATION SHEET

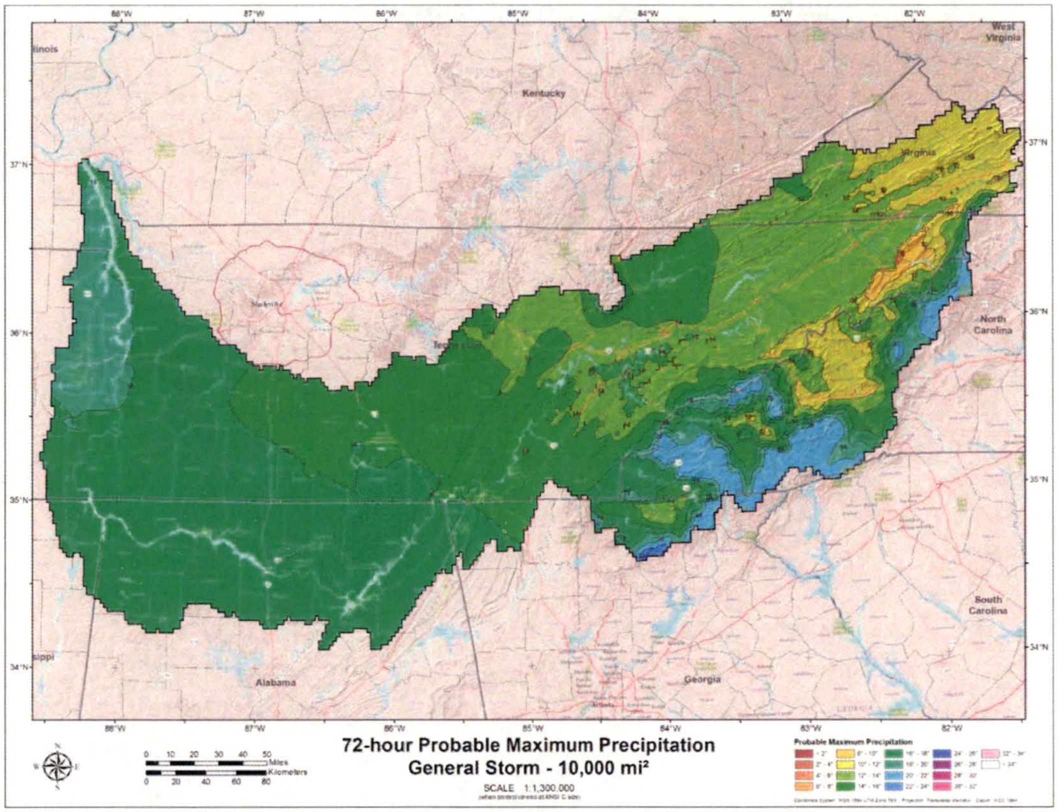
Calculation Title: Appendix A – Probable Maximum Precipitation Maps	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: A9



72-hour Probable Maximum Precipitation
General Storm - 100 mi²
SCALE 1:1,300,000

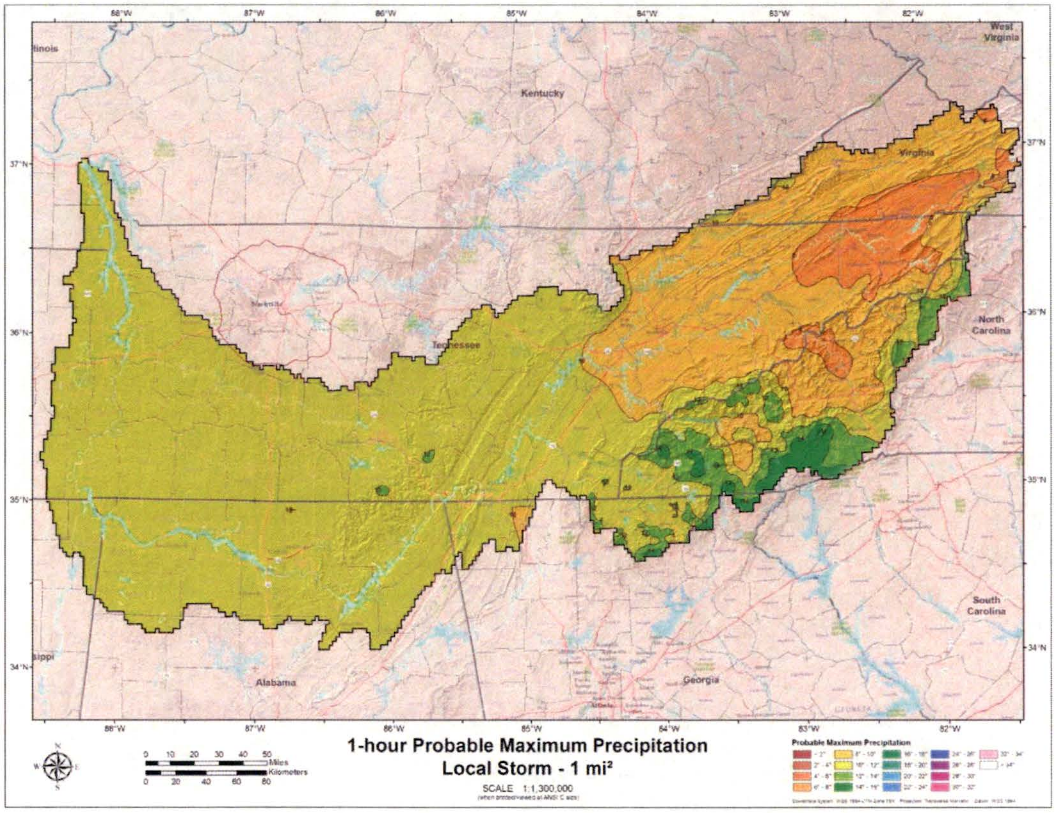


Kentucky
Virginia
West Virginia
Illinois
Tennessee
North Carolina
South Carolina
Alabama
Georgia
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
72-hour Probable Maximum Precipitation
General Storm - 1,000 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

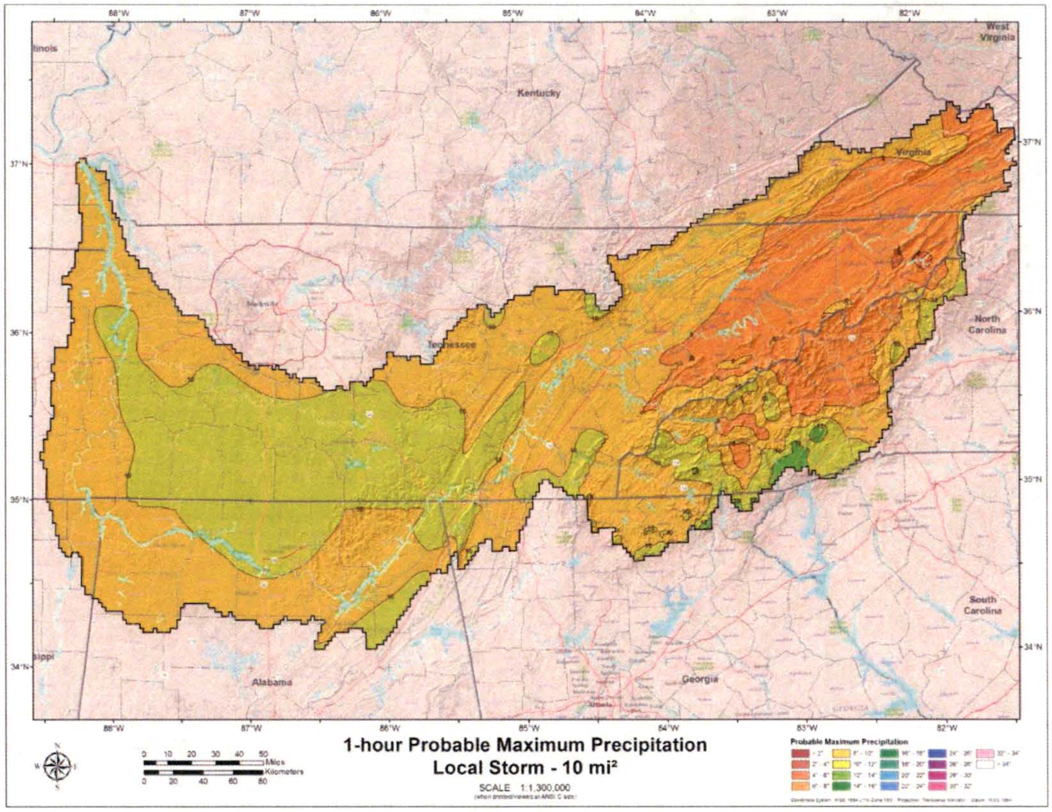


72-hour Probable Maximum Precipitation
General Storm - 10,000 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation
Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
Miles
Kilometers

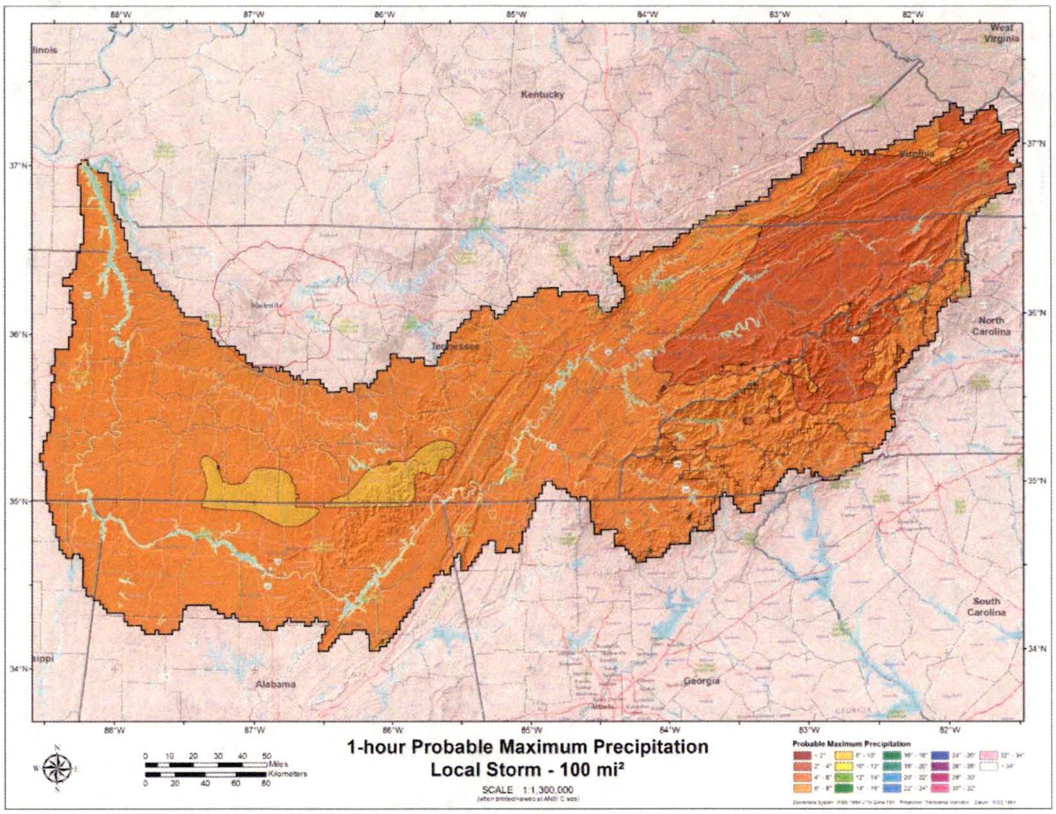
Local Storm



88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
Illinois
Kentucky
West Virginia
Virginia
Tennessee
North Carolina
South Carolina
Alabama
Georgia
1-hour Probable Maximum Precipitation
Local Storm - 1 mi²
SCALE 1:1,300,000
Miles
Kilometers
0 10 20 30 40 50
0 20 40 60 80
Probable Maximum Precipitation

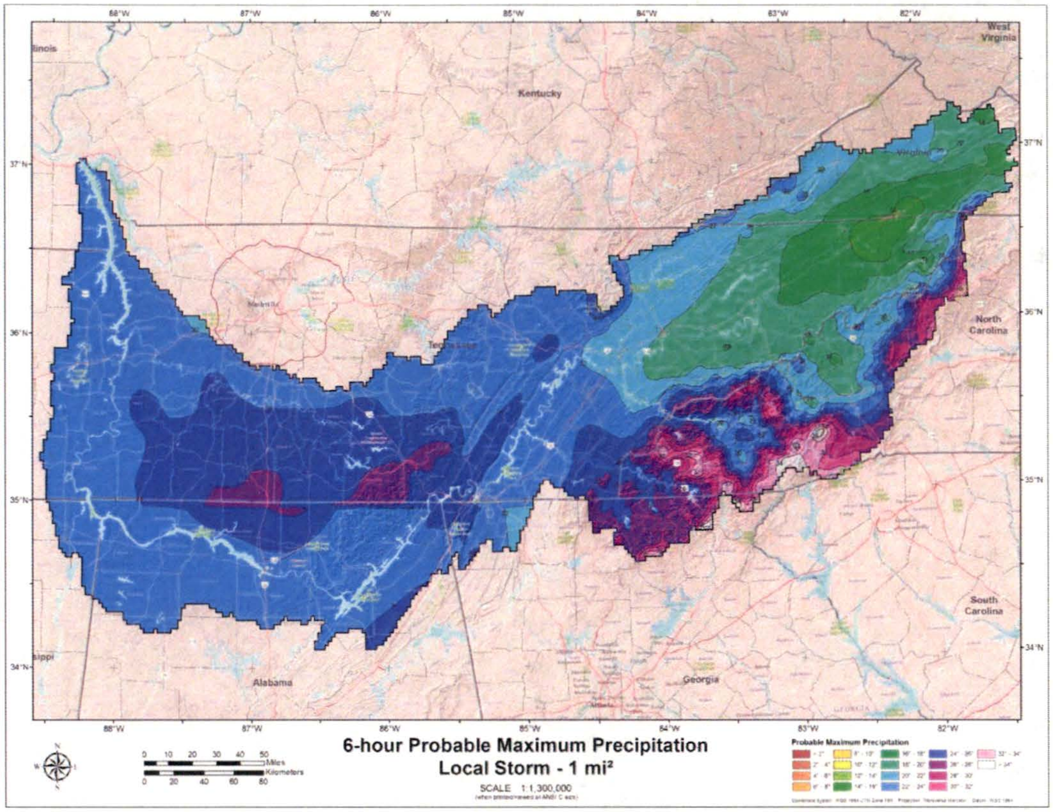


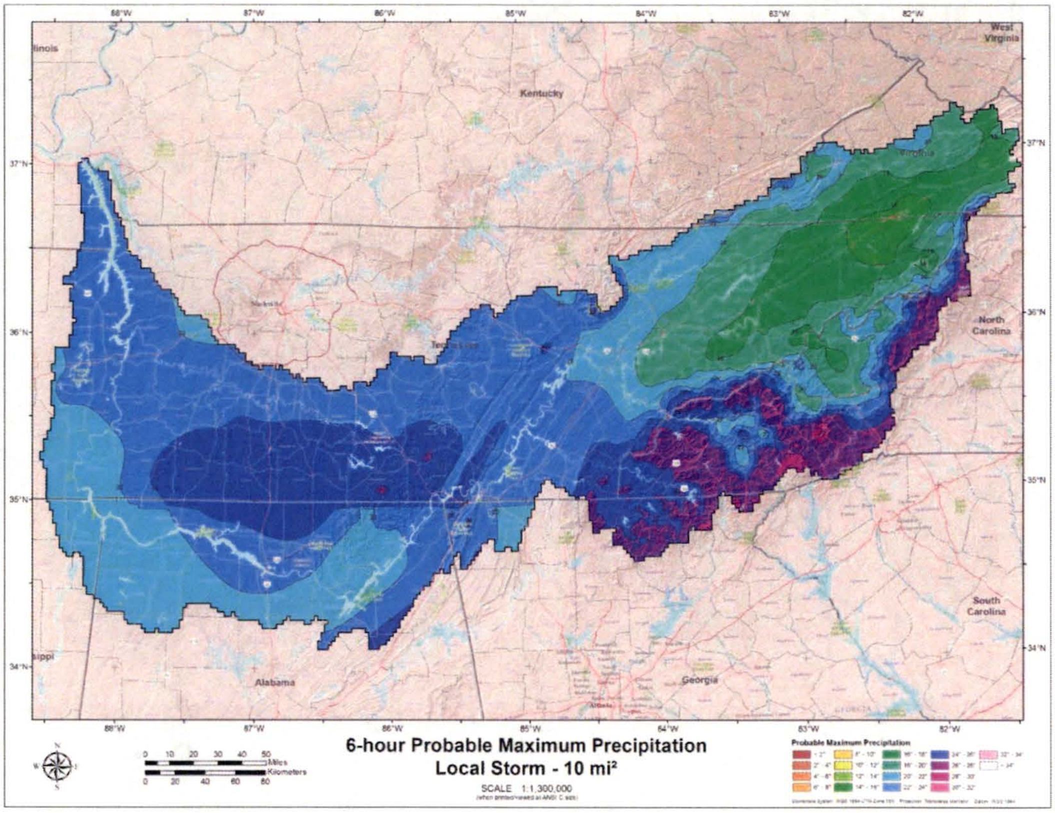
Kentucky
Virginia
West Virginia
Tennessee
North Carolina
South Carolina
Alabama
Georgia
1-hour Probable Maximum Precipitation
Local Storm - 10 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation



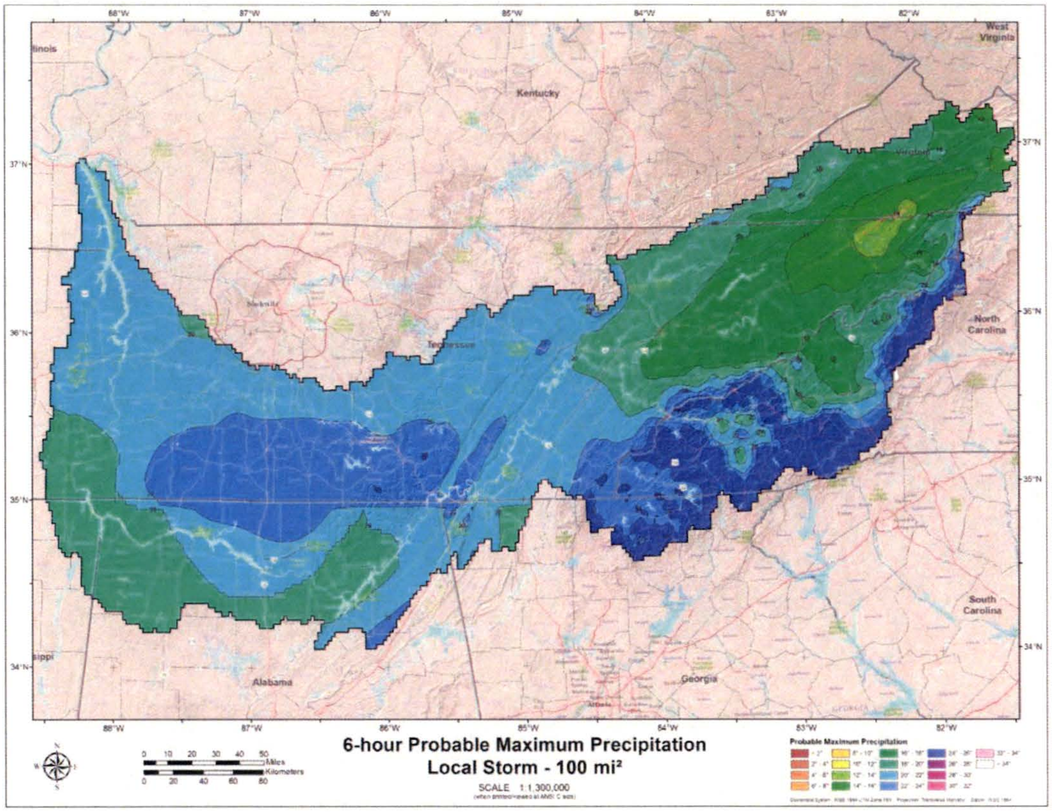
1-hour Probable Maximum Precipitation
Local Storm - 100 mi²
SCALE 1:1,300,000

CALCULATION SHEET			
Calculation Title: Appendix A – Probable Maximum Precipitation Maps	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: A16

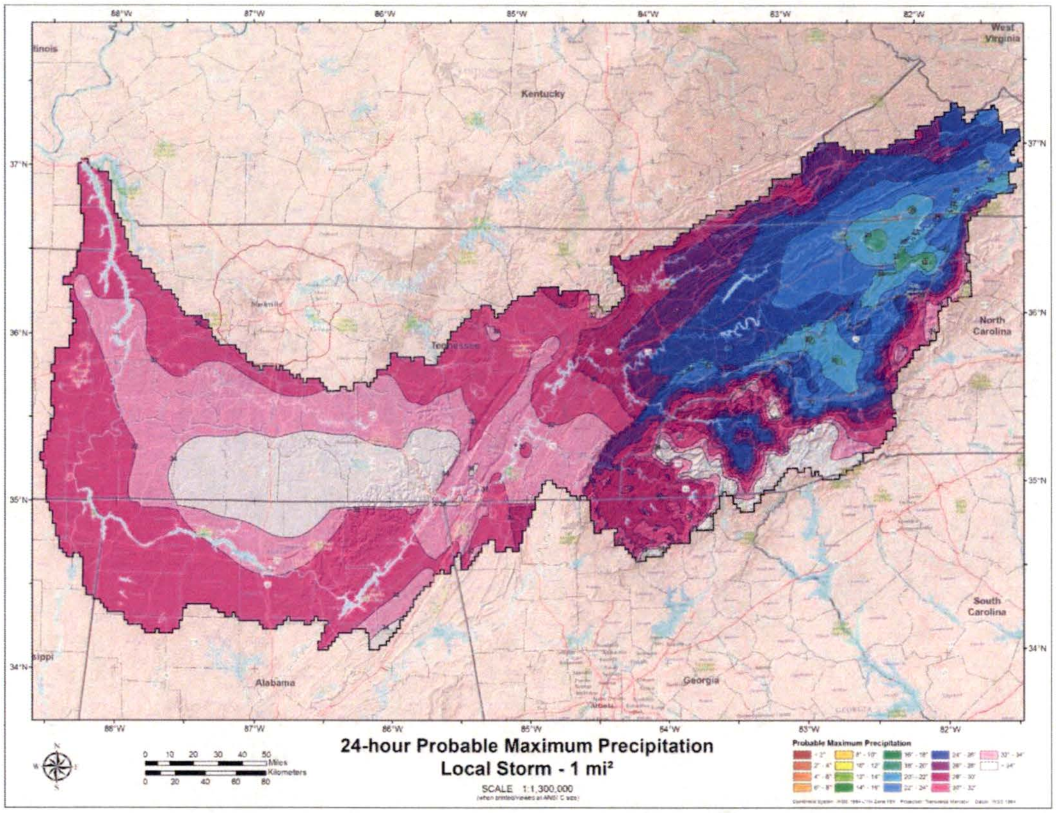




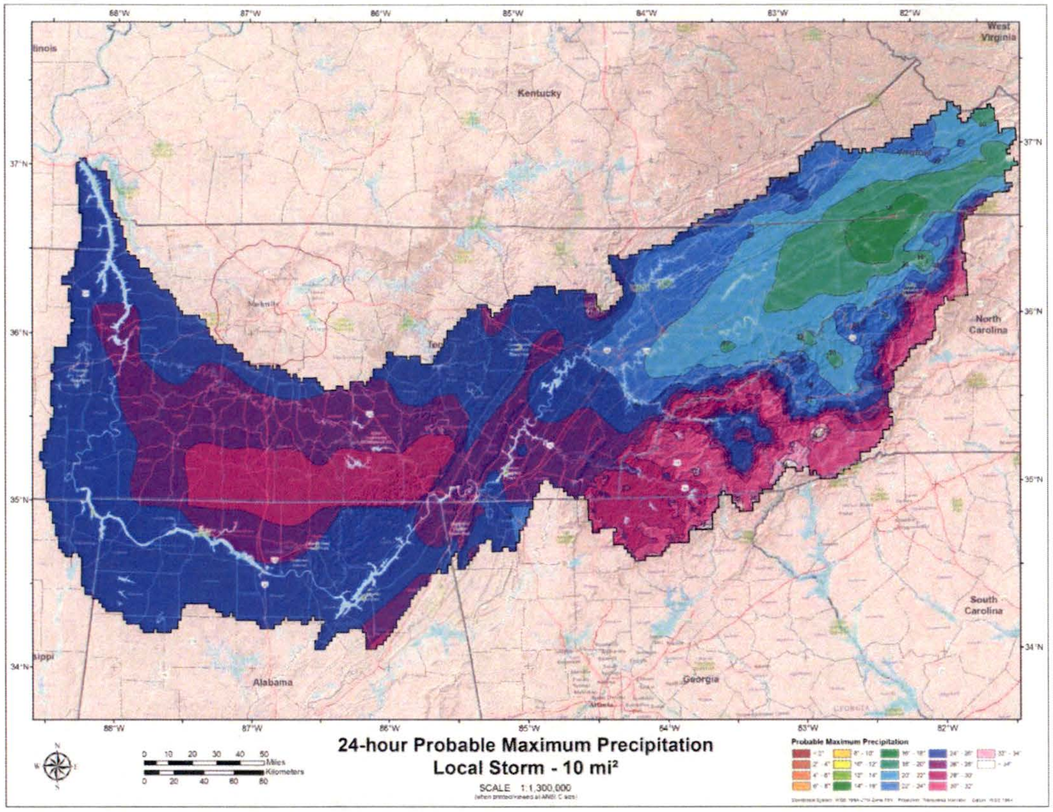
6-hour Probable Maximum Precipitation
Local Storm - 10 mi²
SCALE 1:1,300,000
Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
Probable Maximum Precipitation



Kentucky
West Virginia
Virginia
North Carolina
Tennessee
South Carolina
Alabama
Georgia
6-hour Probable Maximum Precipitation
Local Storm - 100 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation

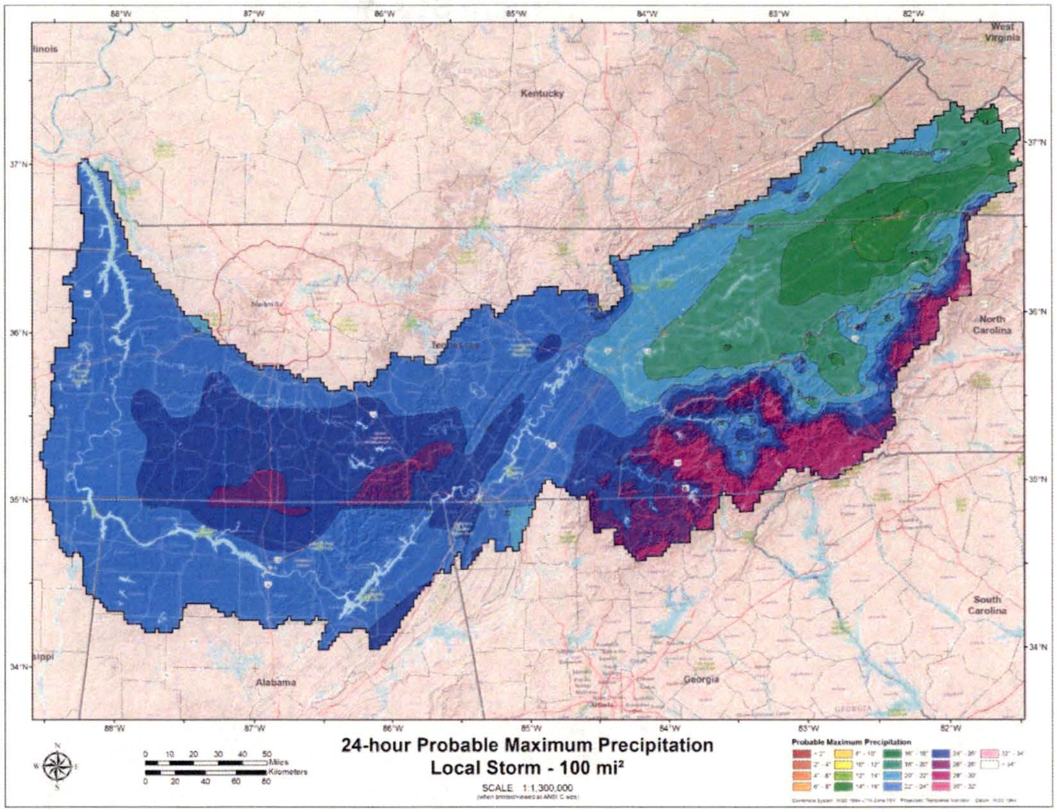


Kentucky
Tennessee
North Carolina
South Carolina
Alabama
Georgia
West Virginia
24-hour Probable Maximum Precipitation
Local Storm - 1 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation



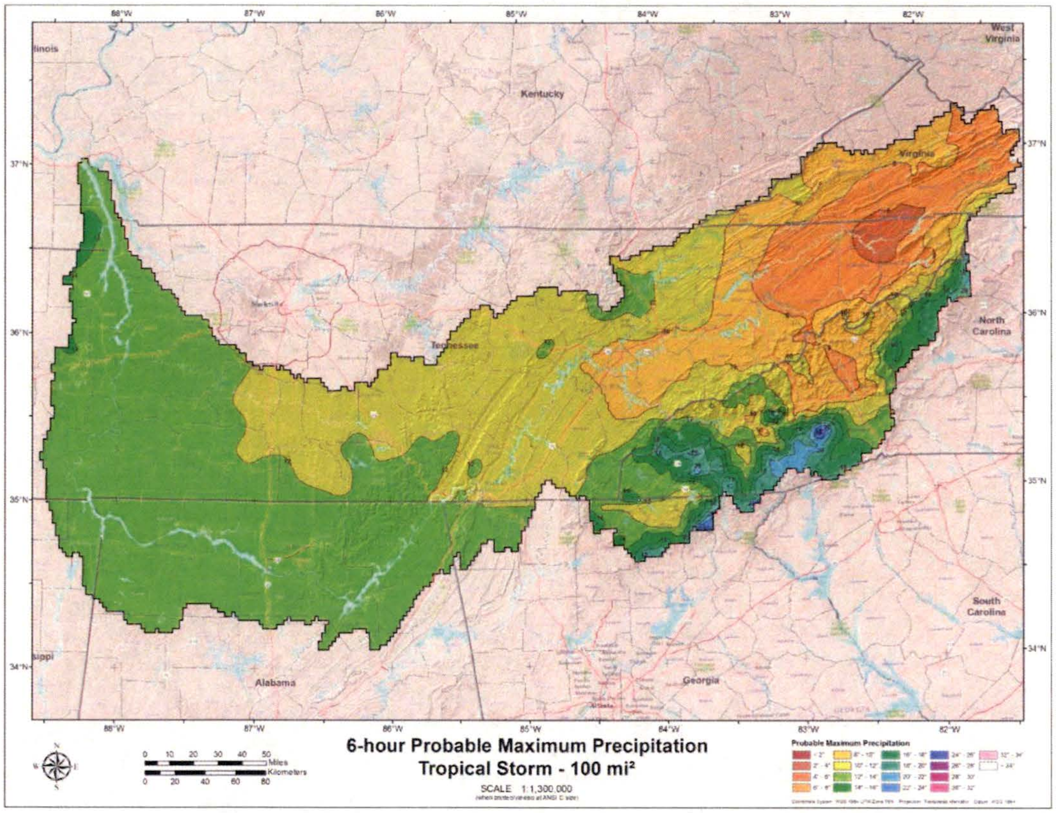
24-hour Probable Maximum Precipitation
Local Storm - 10 mi²

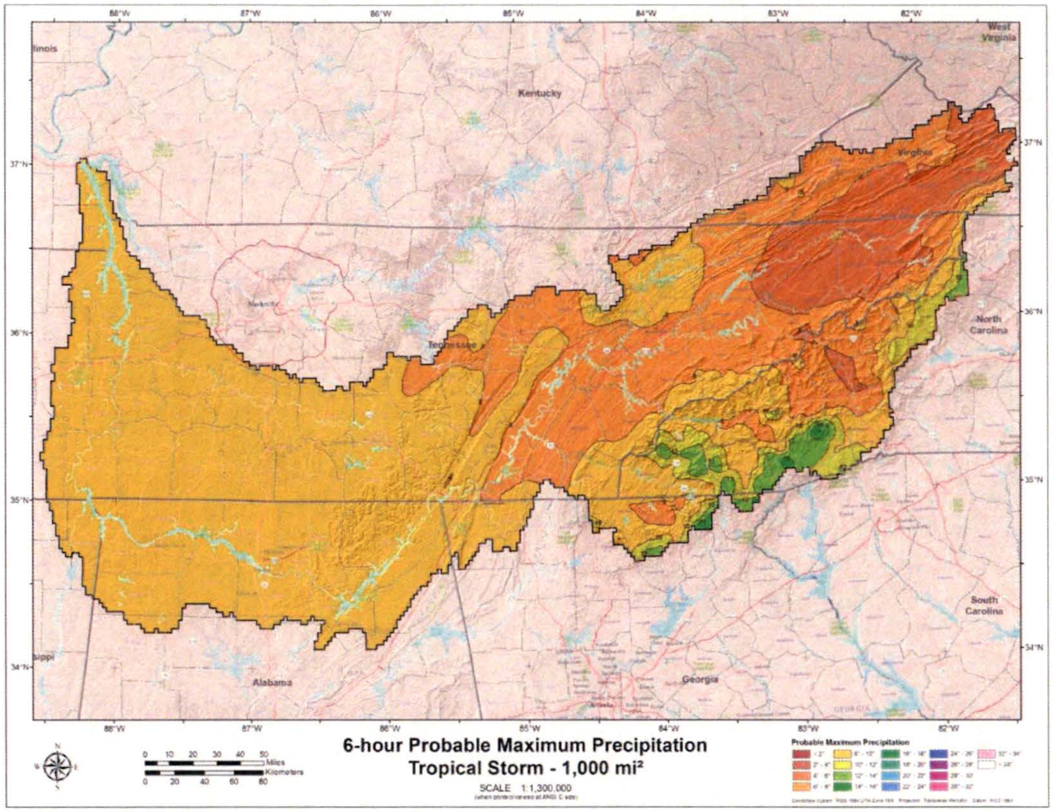
SCALE 1:1,300,000


Kentucky
Tennessee
North Carolina
South Carolina
Georgia
Alabama
West Virginia
24-hour Probable Maximum Precipitation
Local Storm - 100 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

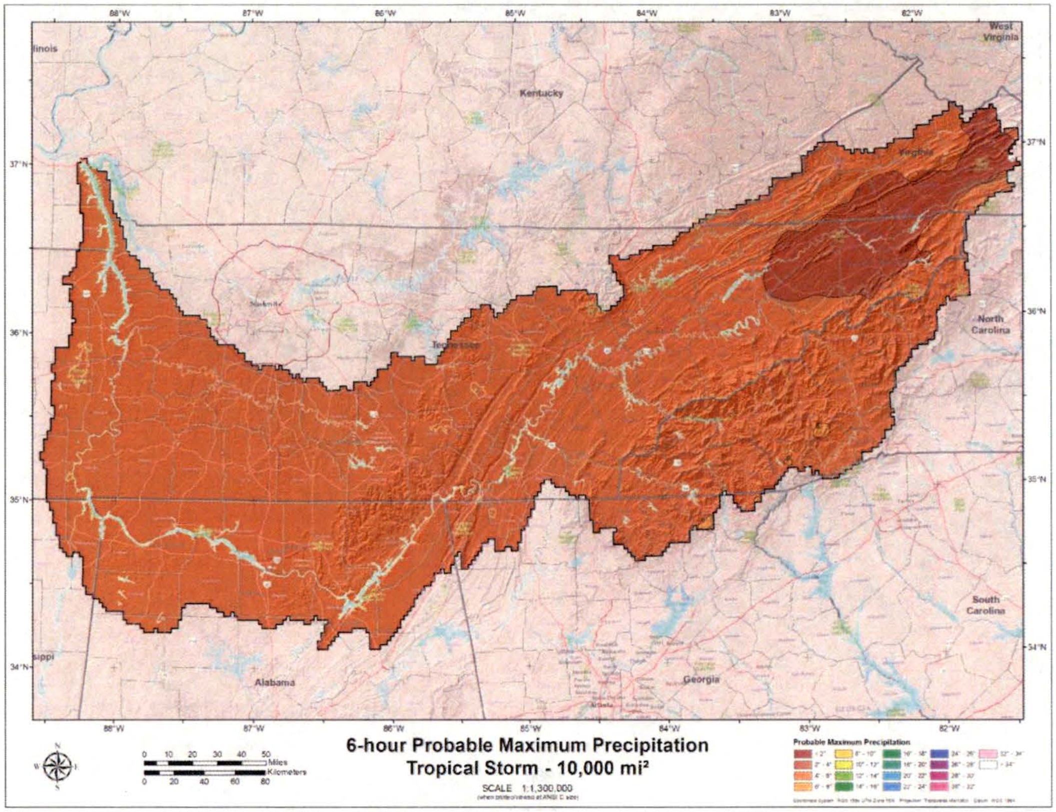
Tropical Storm

CALCULATION SHEET			
Calculation Title: Appendix A – Probable Maximum Precipitation Maps	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: A23

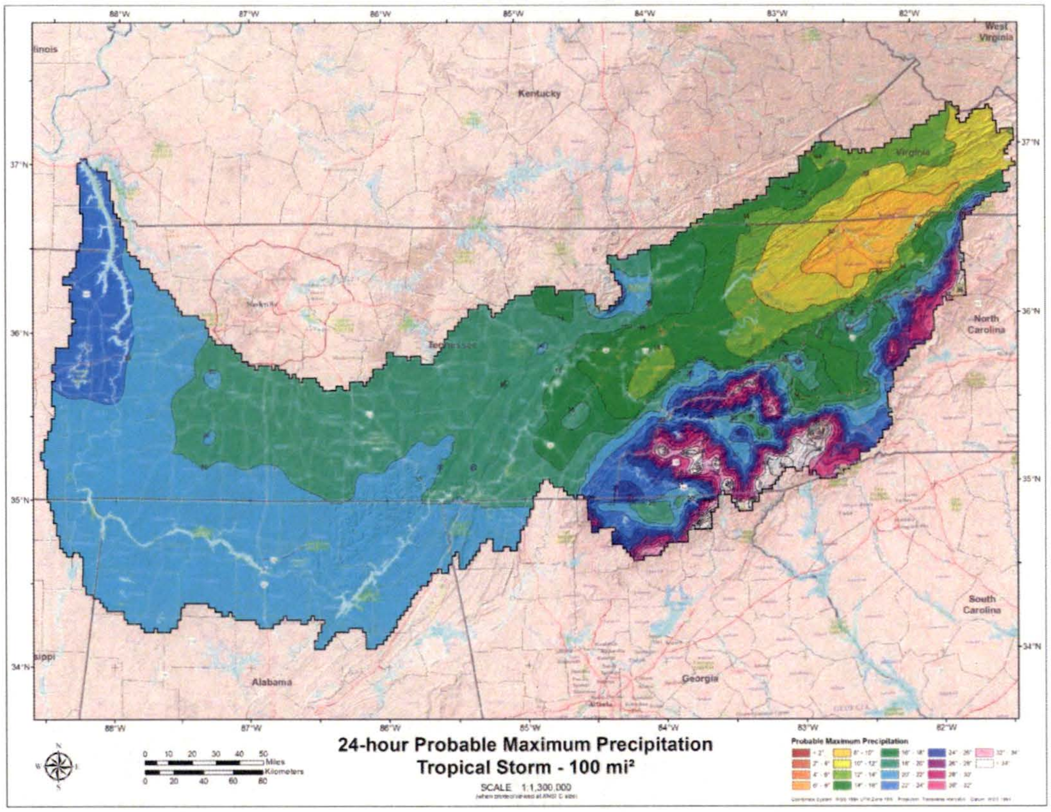




Kentucky
Virginia
West Virginia
Tennessee
North Carolina
South Carolina
Georgia
Alabama
6-hour Probable Maximum Precipitation
Tropical Storm - 1,000 mi²
SCALE 1:1,300,000

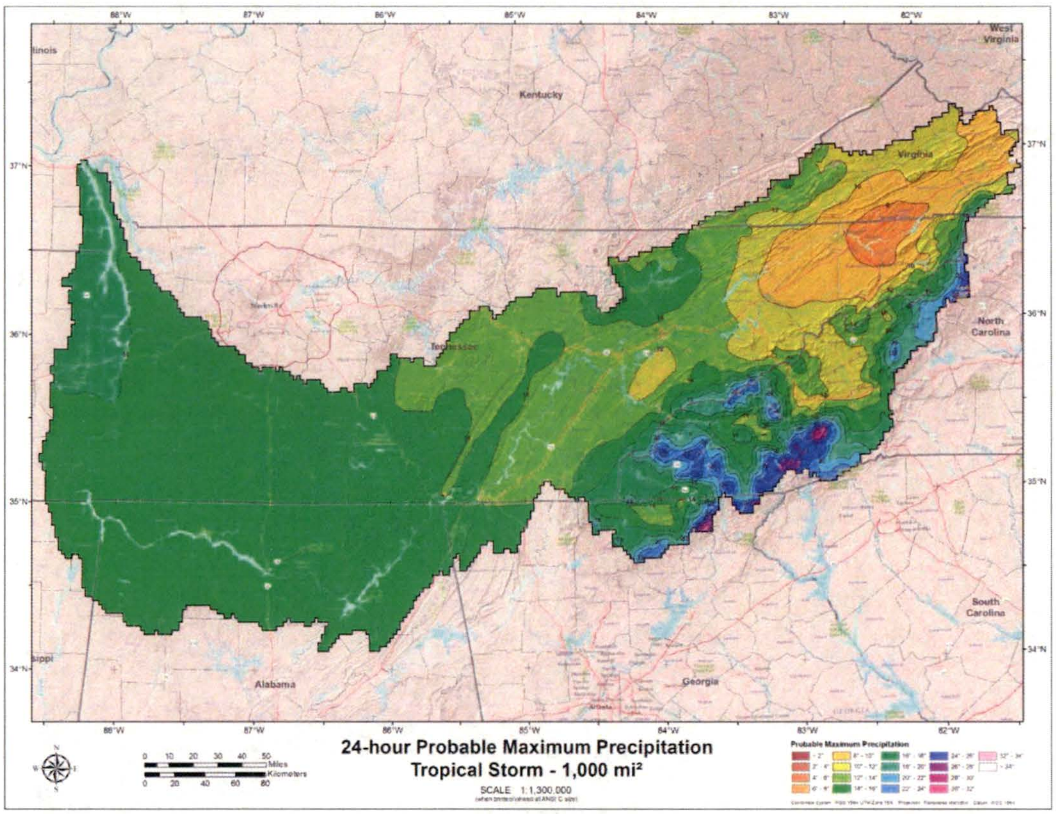


6-hour Probable Maximum Precipitation
Tropical Storm - 10,000 mi²
SCALE 1:1,300,000
Kentucky
Tennessee
Virginia
North Carolina
South Carolina
Georgia
Alabama
West Virginia
Probable Maximum Precipitation

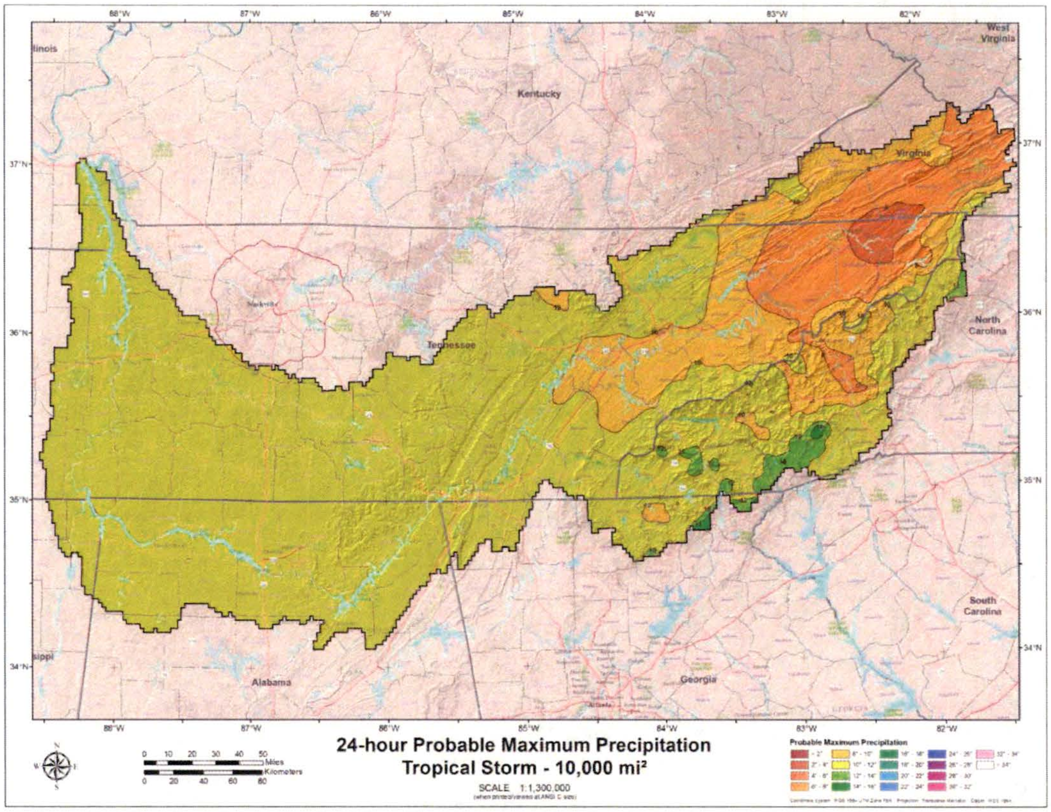


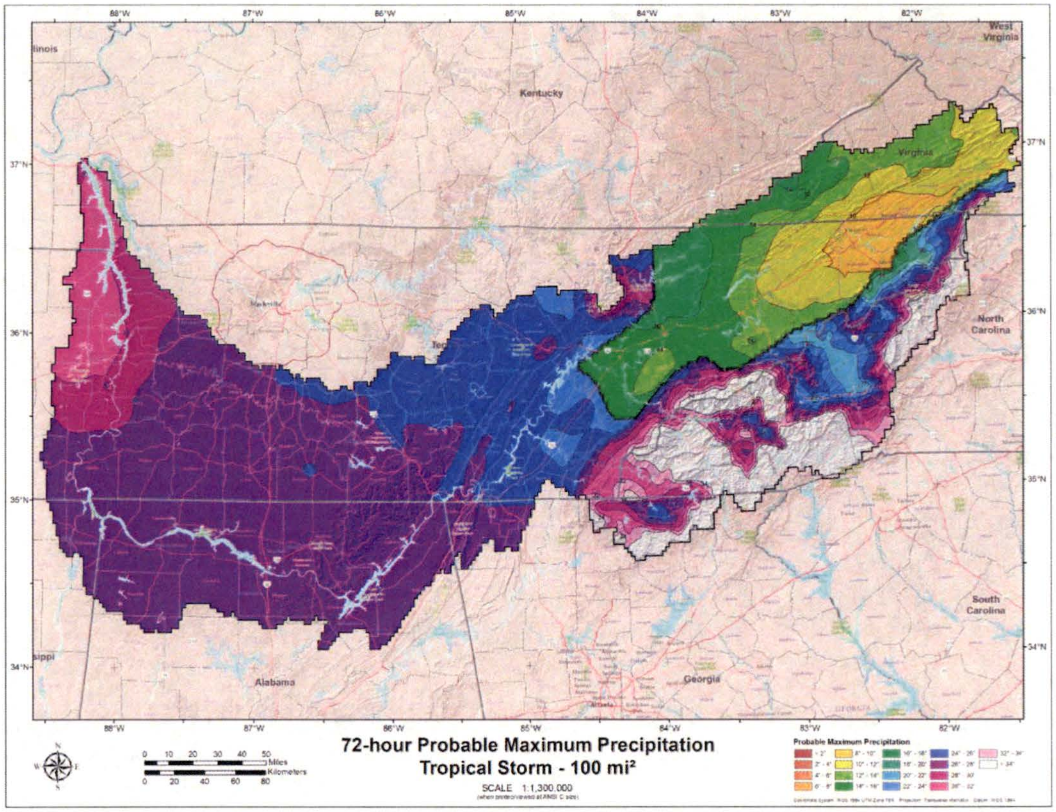
Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Tennessee
Alabama
Georgia
Illinois
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
Miles
Kilometers
24-hour Probable Maximum Precipitation
Tropical Storm - 100 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation

TVA	CALCULATION SHEET		
Calculation Title: Appendix A – Probable Maximum Precipitation Maps	Calculation No.: CDQ000002016000041	Rev. No.: 001	Sheet: A27

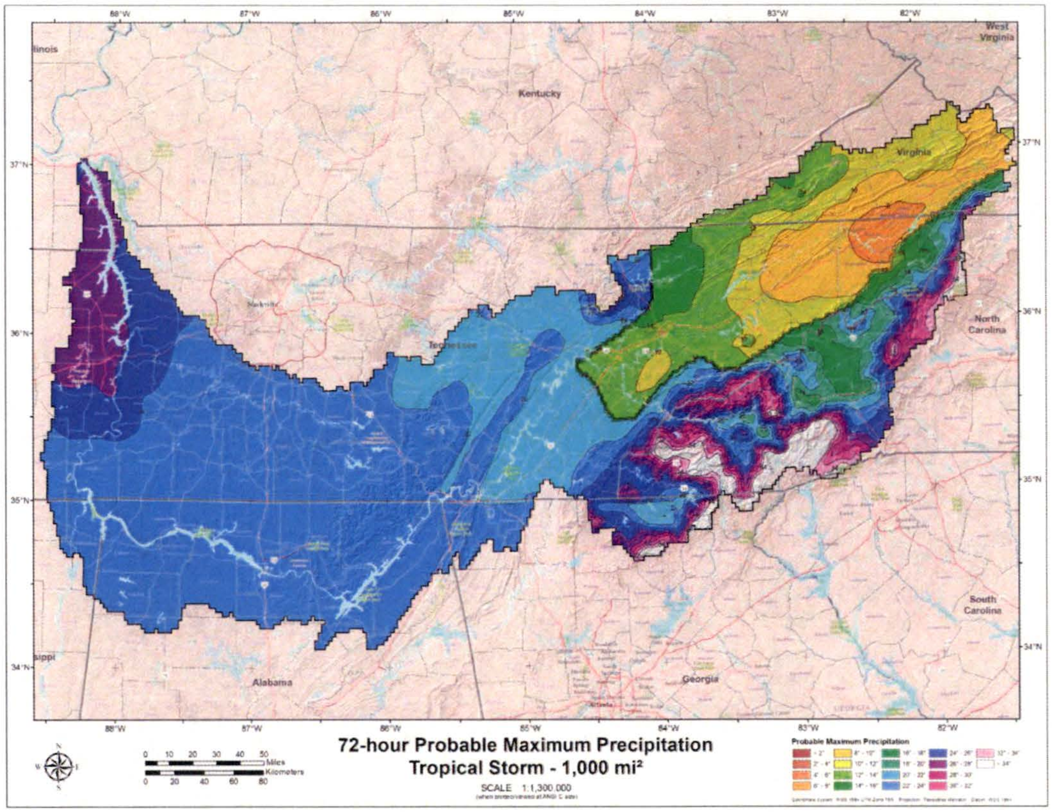


CALCULATION SHEET			
Calculation Title: Appendix A – Probable Maximum Precipitation Maps	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: A28





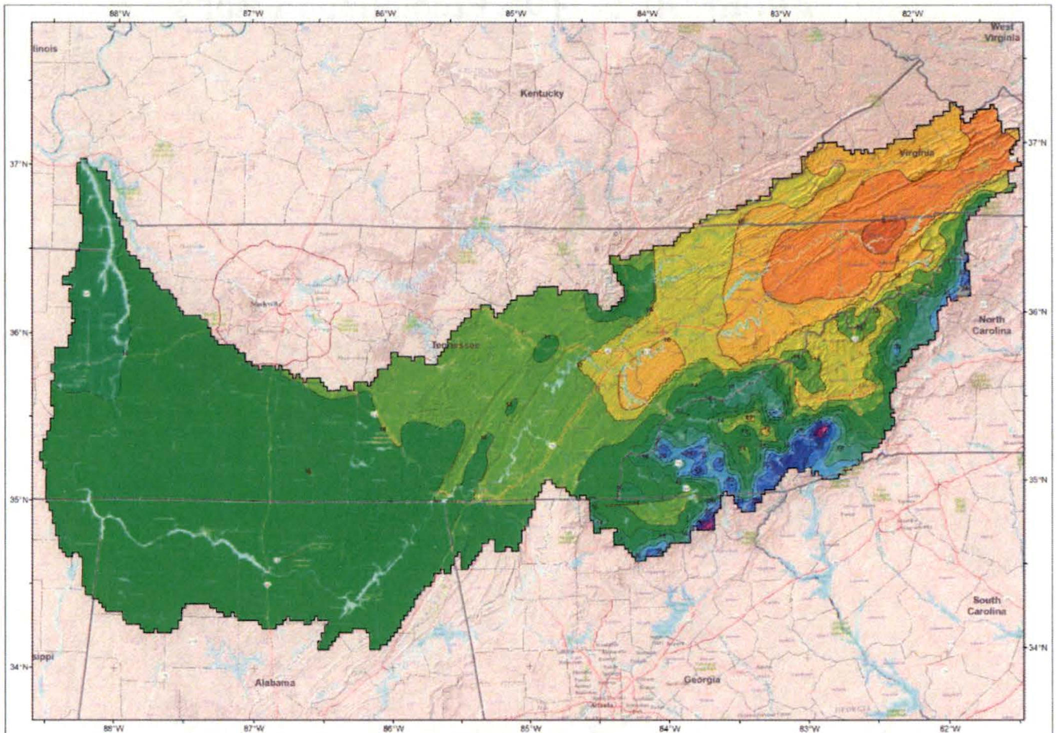
Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
Illinois
72-hour Probable Maximum Precipitation
Tropical Storm - 100 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation



Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Tennessee
Alabama
Georgia
72-hour Probable Maximum Precipitation
Tropical Storm - 1,000 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

CALCULATION SHEET

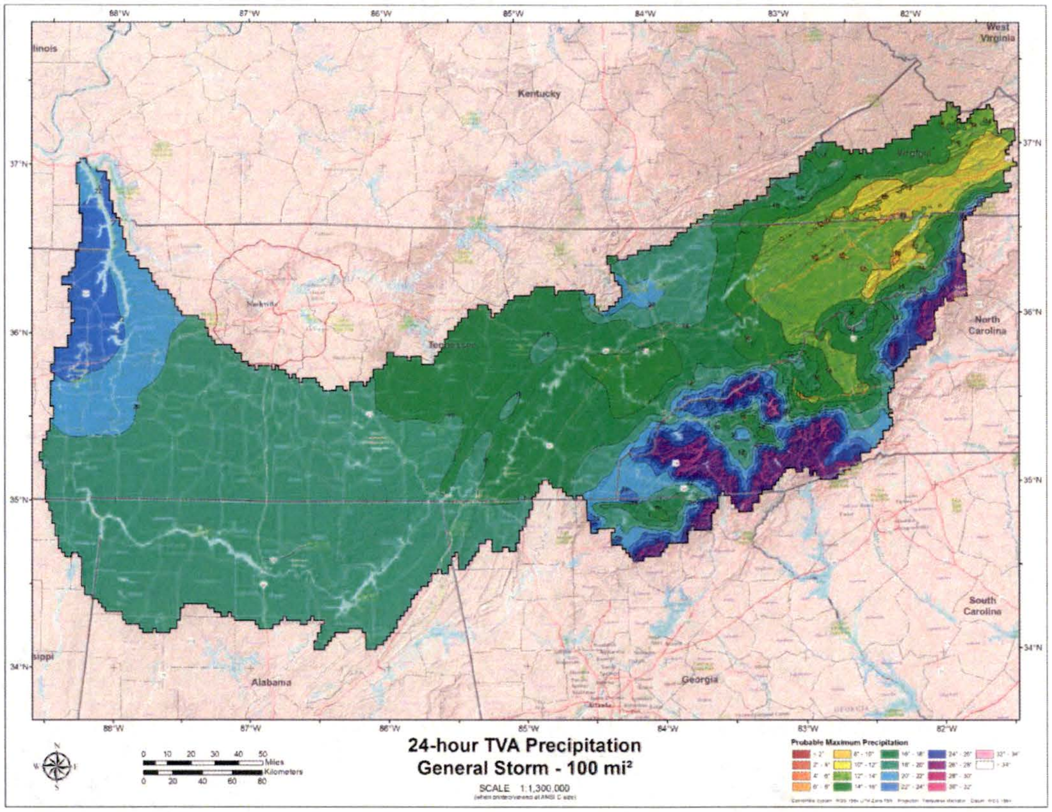
Calculation Title: Appendix A – Probable Maximum Precipitation Maps	Calculation No.: CDQ000002016000041	Rev. No.: 001	Sheet: A31



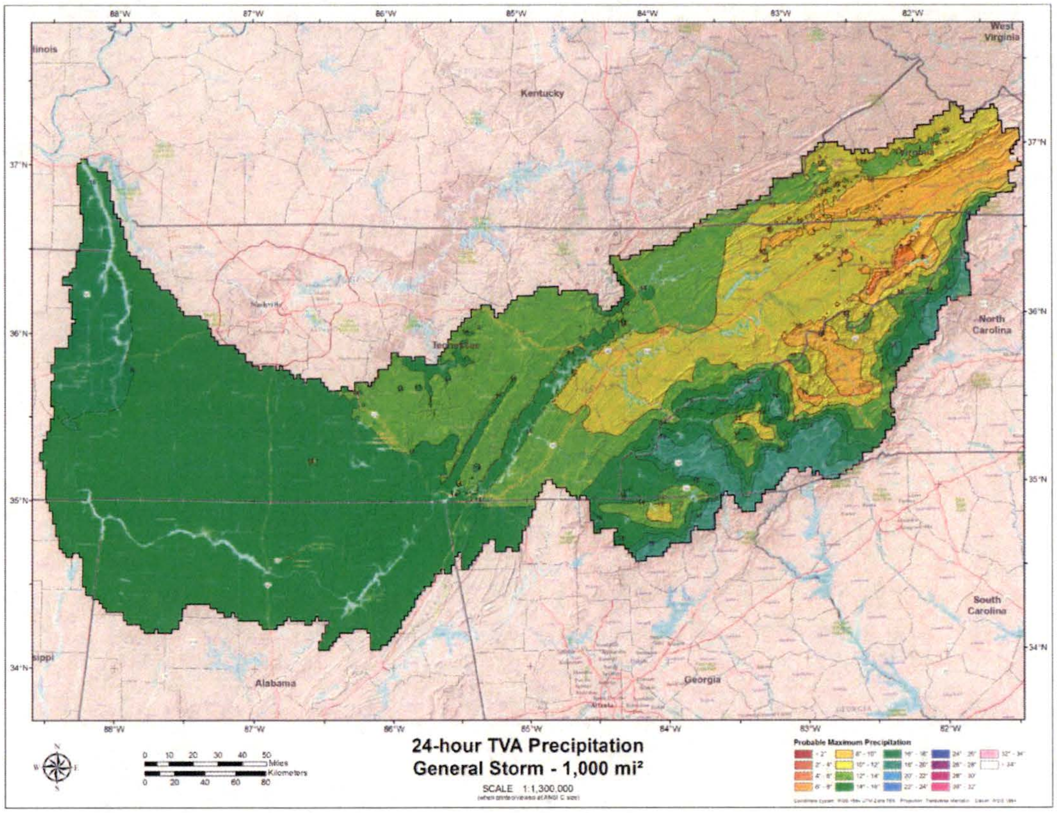
72-hour Probable Maximum Precipitation
Tropical Storm - 10,000 mi²
SCALE 1:1,300,000

APPENDIX B - TVA Precipitation Maps

General Storm



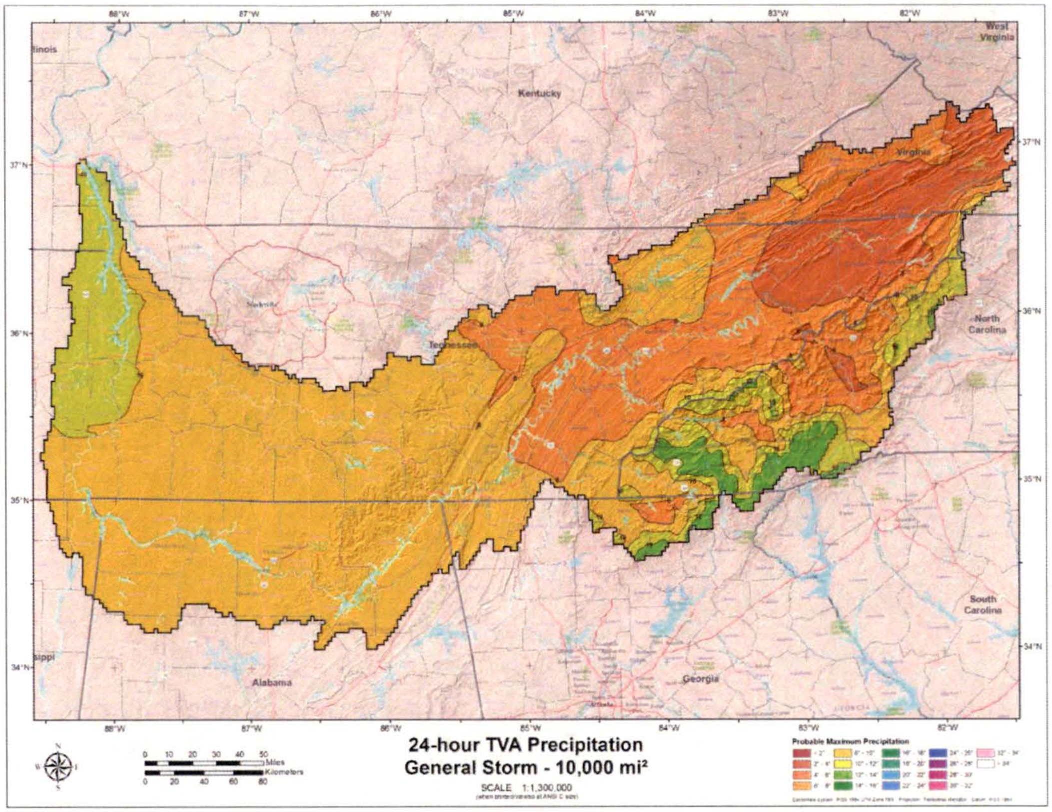
Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Tennessee
Alabama
Georgia
Nashville
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
0 10 20 30 40 50 Miles
0 20 40 60 80 Kilometers
24-hour TVA Precipitation
General Storm - 100 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation

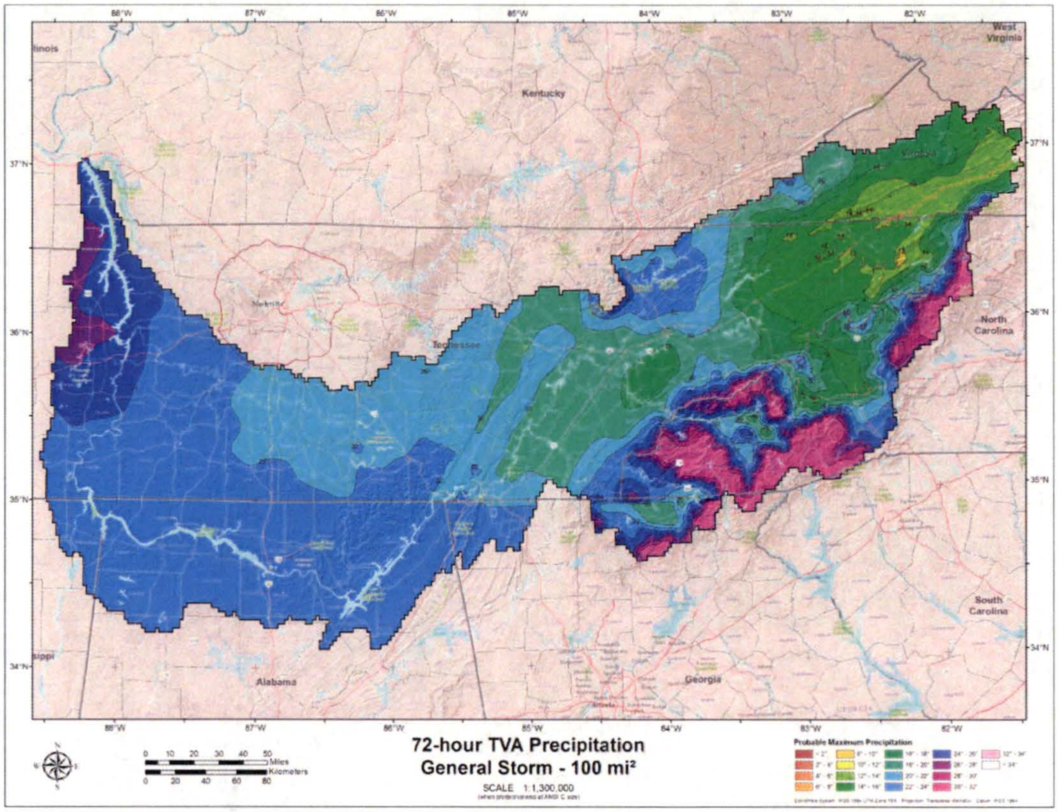


Kentucky
West Virginia
North Carolina
South Carolina
Alabama
Georgia
Tennessee
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
24-hour TVA Precipitation
General Storm - 1,000 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

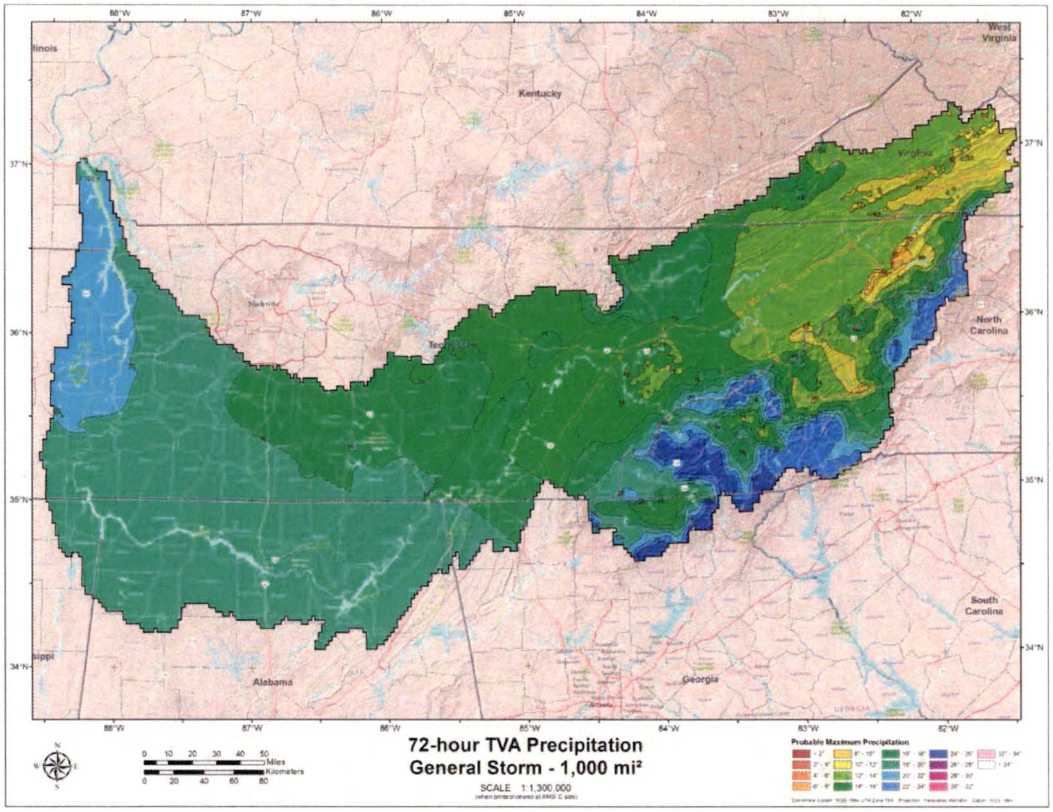
CALCULATION SHEET

Calculation Title: Appendix B – TVA Precipitation Maps	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: B5

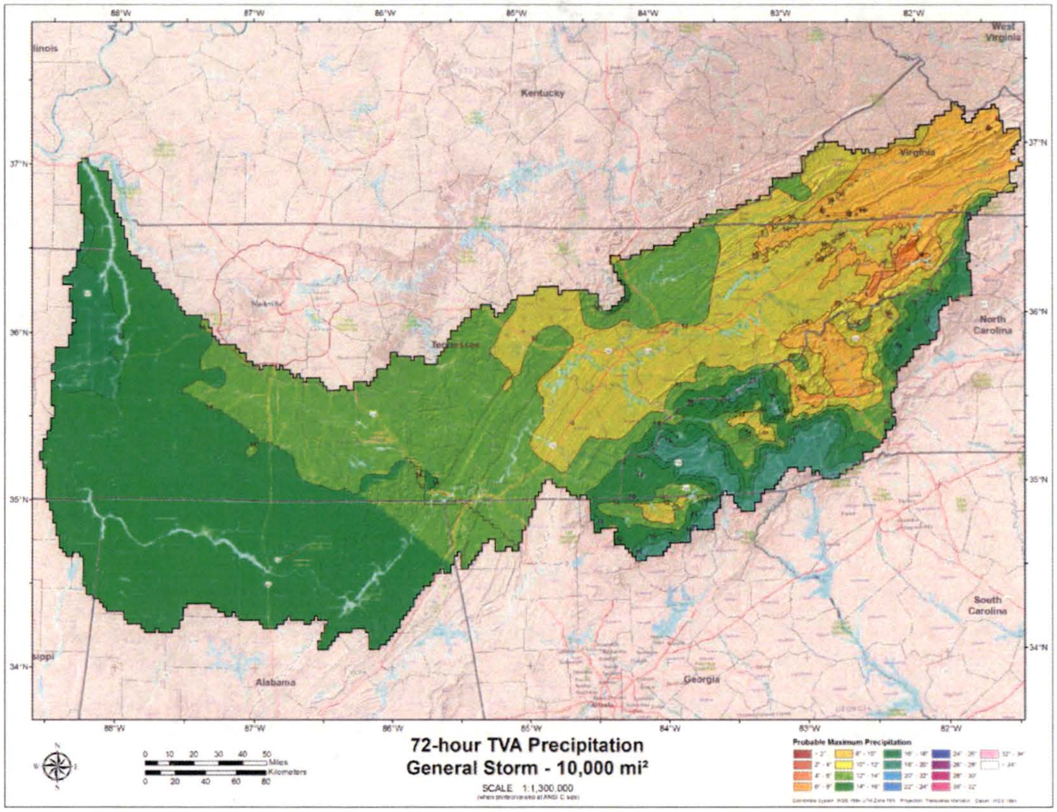




Kentucky
Tennessee
North Carolina
South Carolina
Alabama
Georgia
West Virginia
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
72-hour TVA Precipitation
General Storm - 100 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

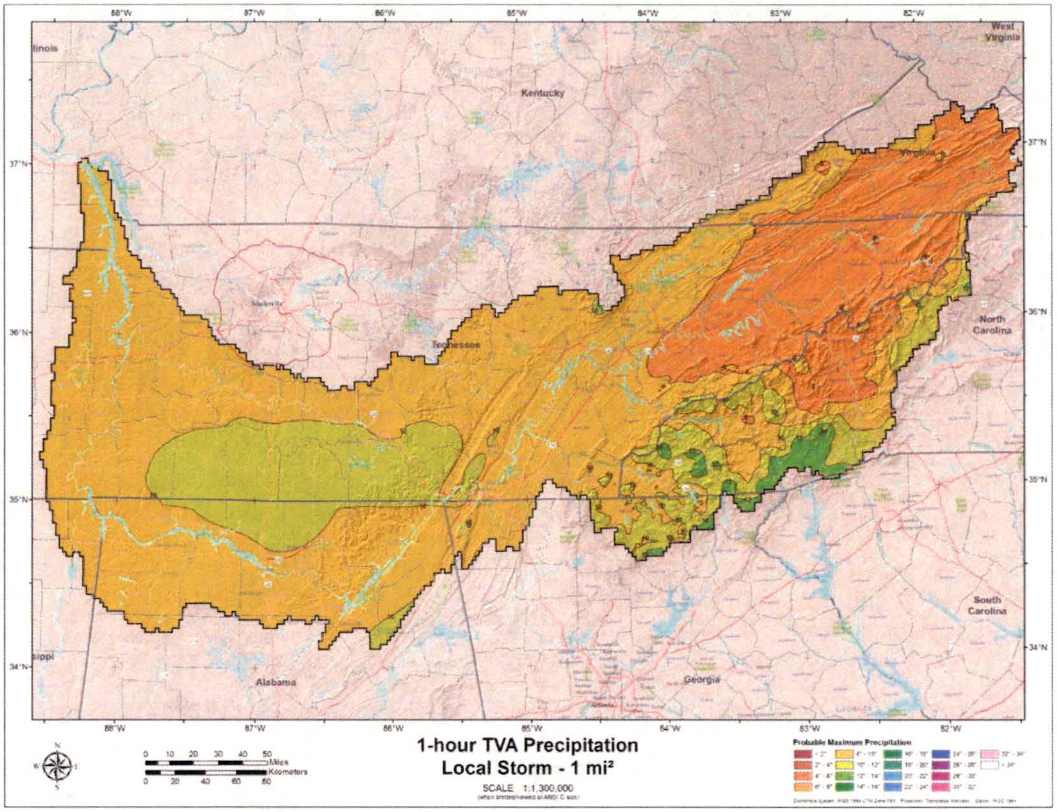


72-hour TVA Precipitation
General Storm - 1,000 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation
Miles
Kilometers
0 10 20 30 40 50
0 20 40 60 80
N
S
E
W
Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N

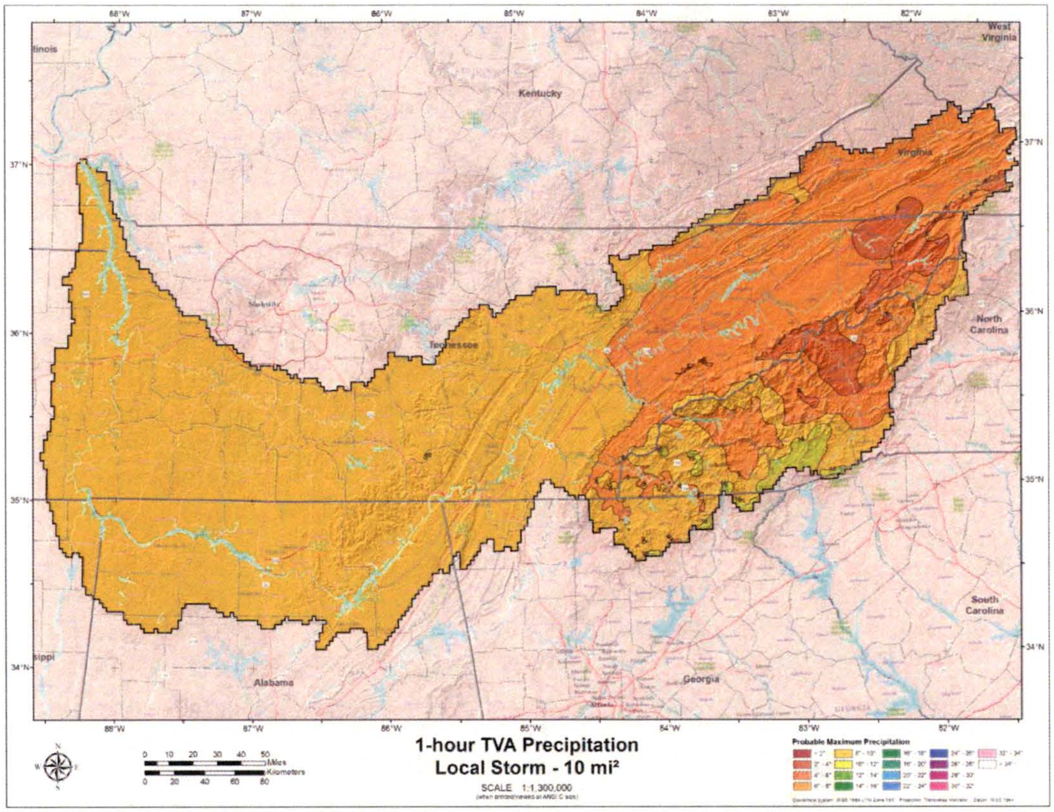


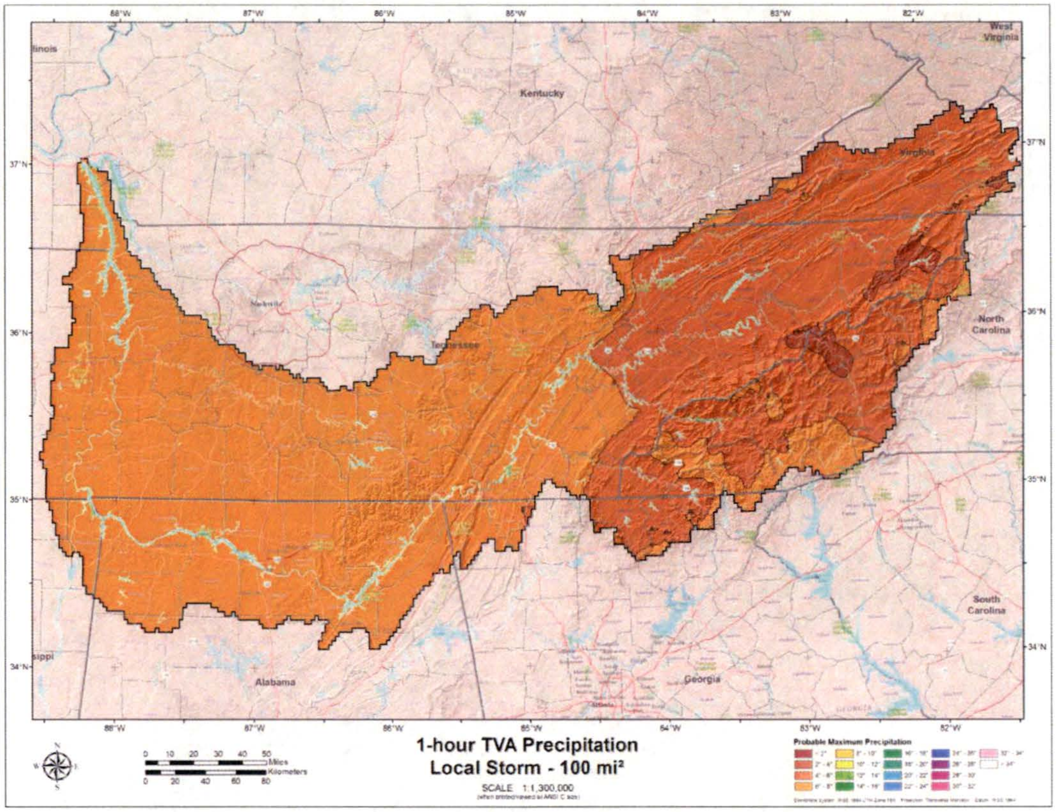
Kentucky
Virginia
West Virginia
Tennessee
North Carolina
South Carolina
Alabama
Georgia
88°W
87°W
86°W
85°W
84°W
83°W
82°W
37°N
36°N
35°N
34°N
72-hour TVA Precipitation
General Storm - 10,000 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation

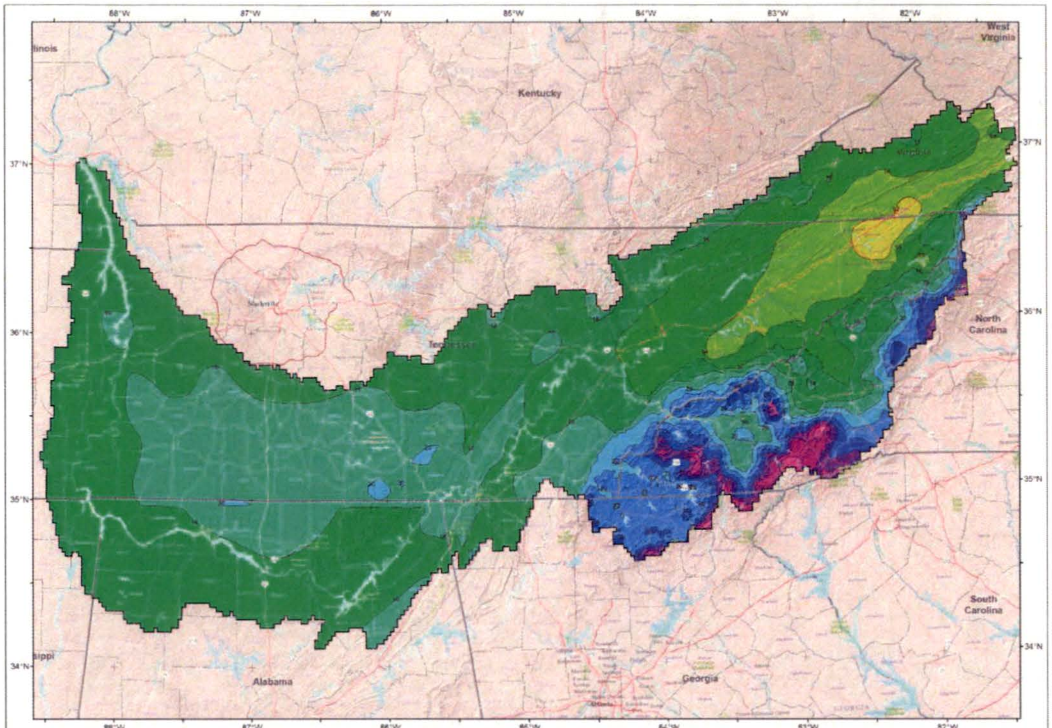
Local Storm



1-hour TVA Precipitation
Local Storm - 1 mi²
SCALE 1:1,300,000
Kentucky
Tennessee
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
Probable Maximum Precipitation

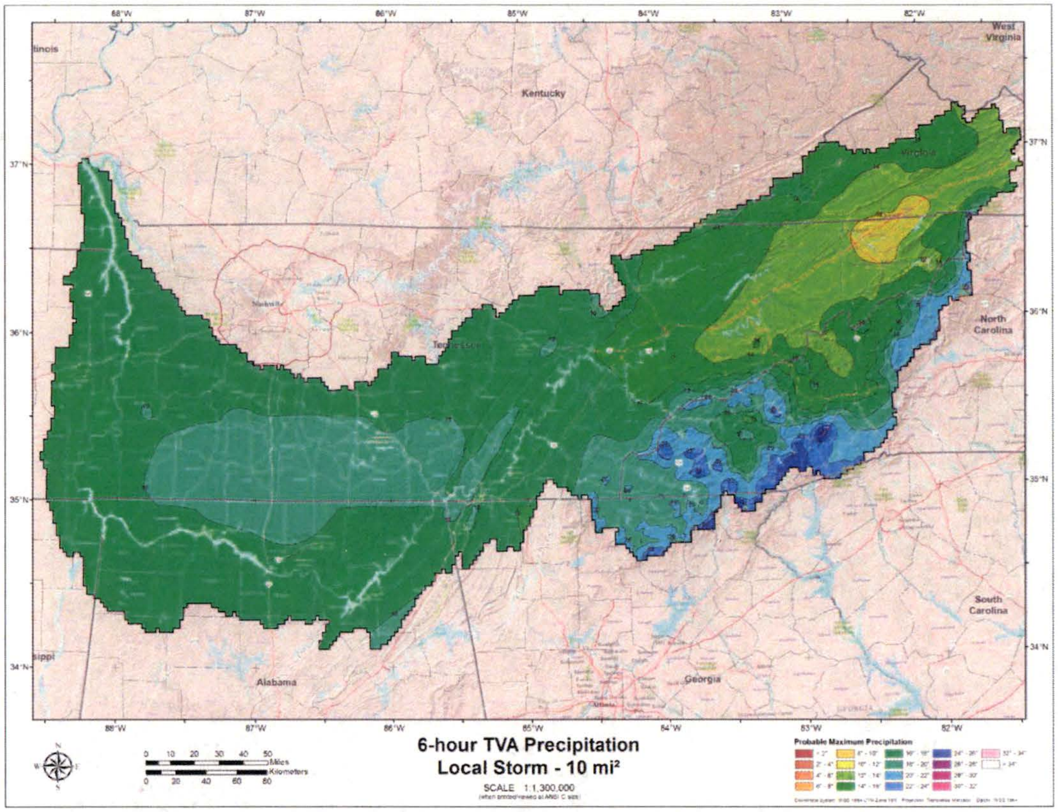

Kentucky
Virginia
West Virginia
Tennessee
North Carolina
South Carolina
Georgia
Alabama
1-hour TVA Precipitation
Local Storm - 10 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation


Kentucky
Virginia
West Virginia
Tennessee
North Carolina
South Carolina
Alabama
Georgia
1-hour TVA Precipitation
Local Storm - 100 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation

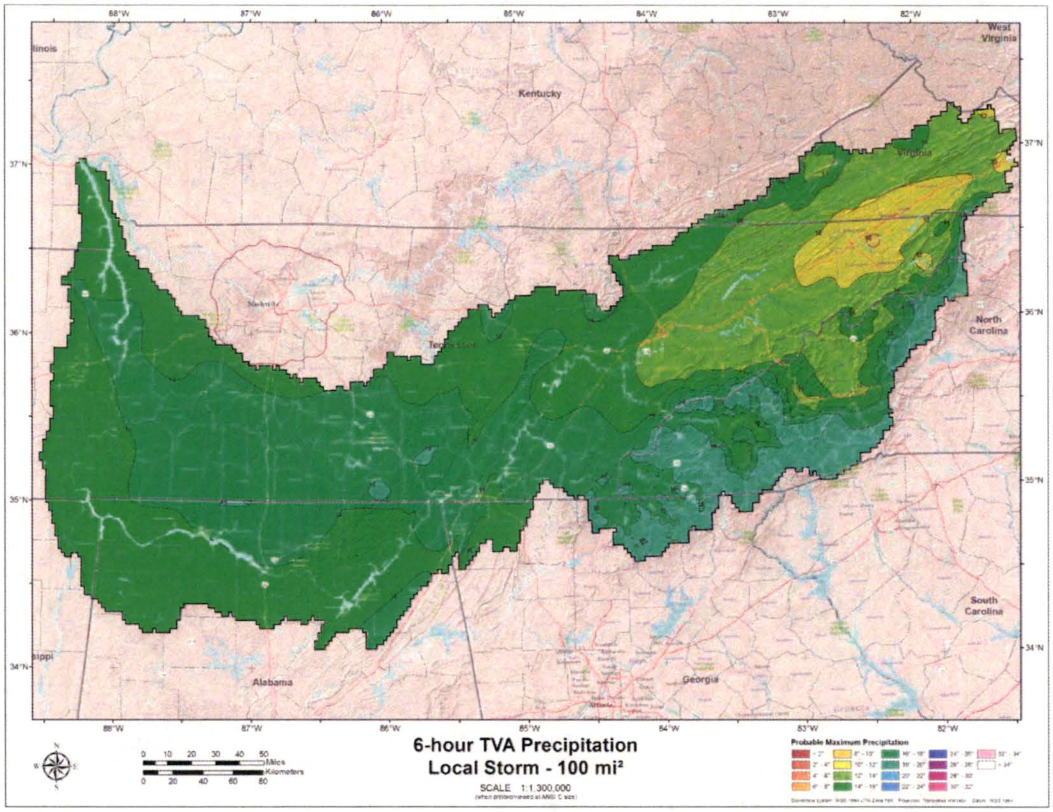


6-hour TVA Precipitation
Local Storm - 1 mi²

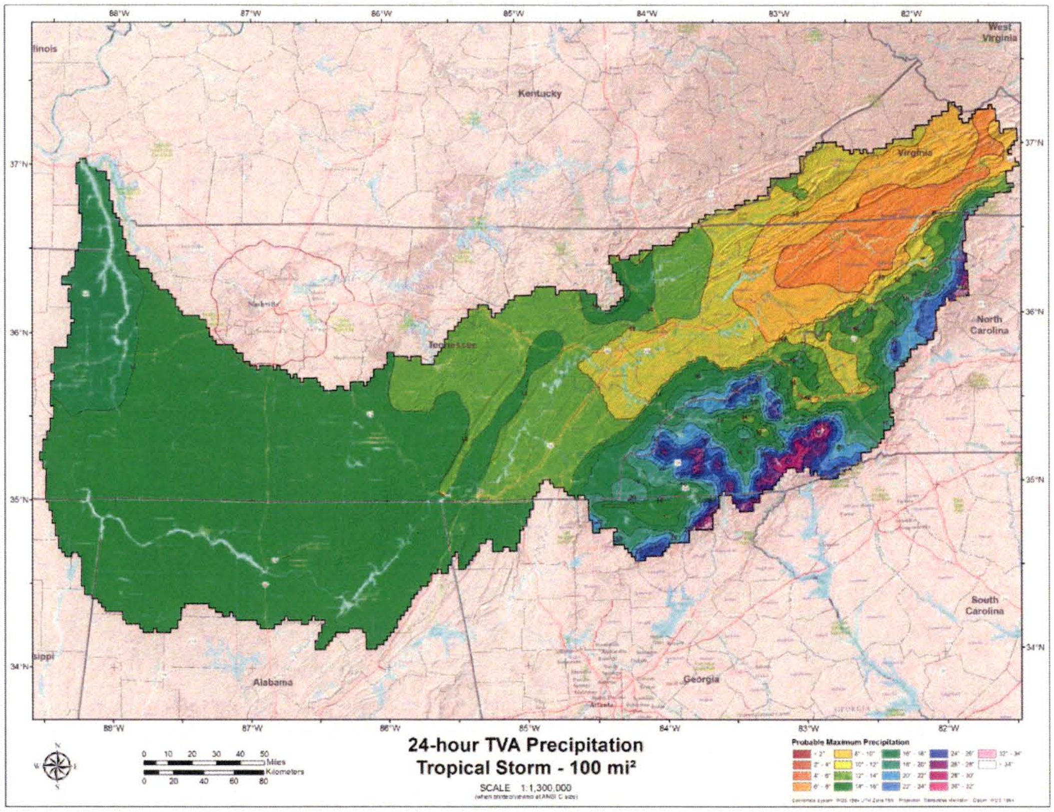
SCALE 1:1,300,000

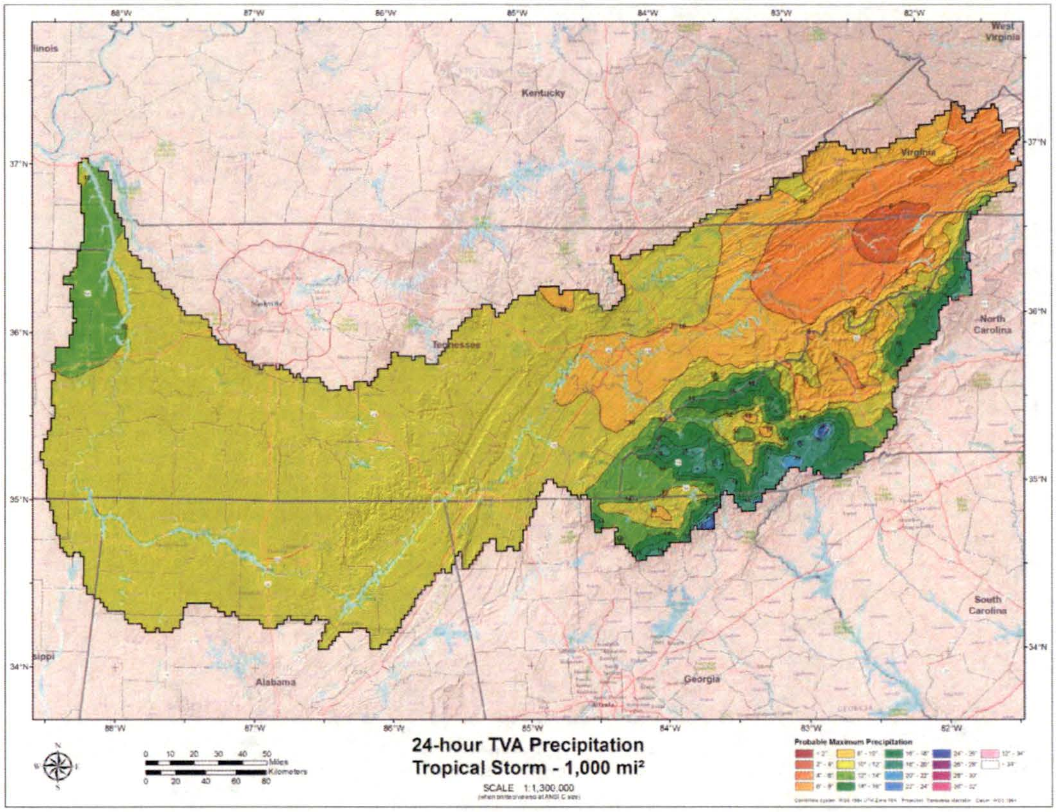


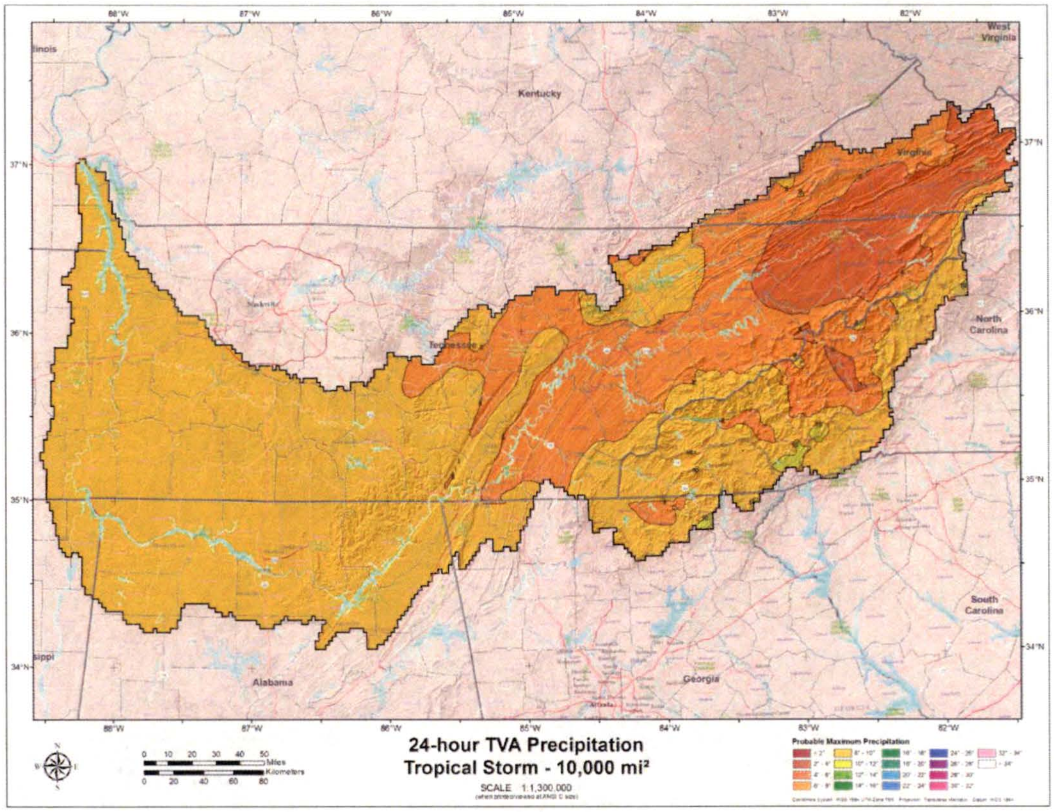
6-hour TVA Precipitation
Local Storm - 10 mi²


Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
6-hour TVA Precipitation
Local Storm - 100 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation

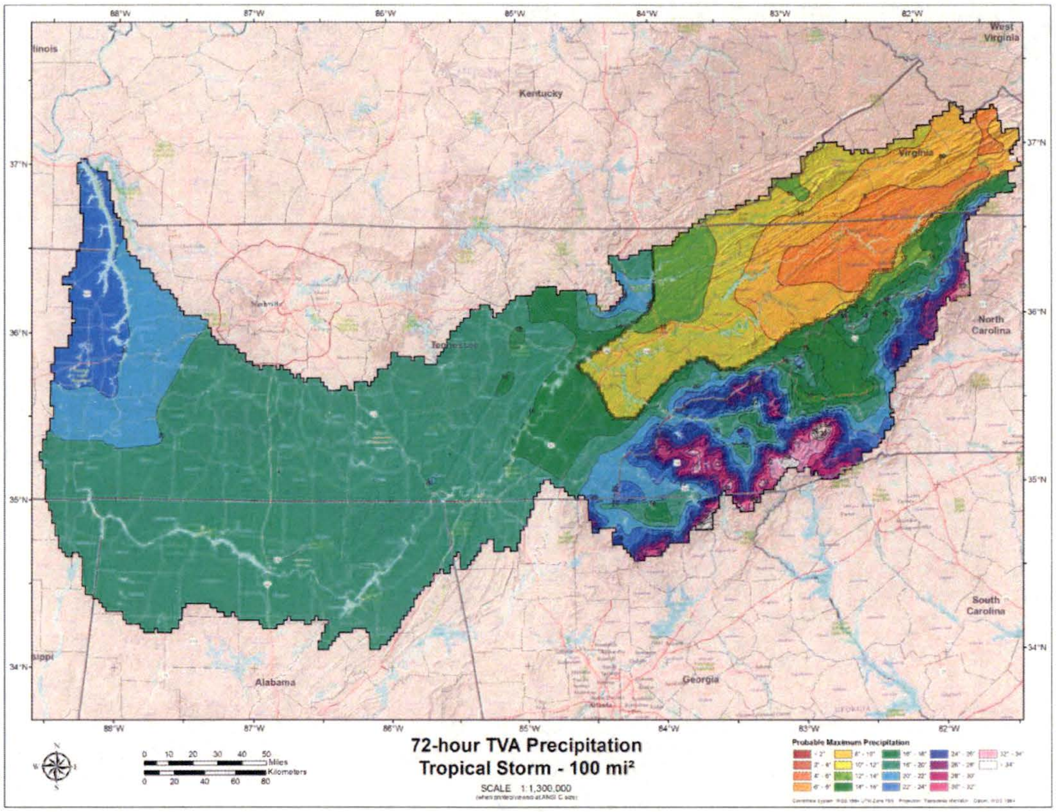
Tropical Storm

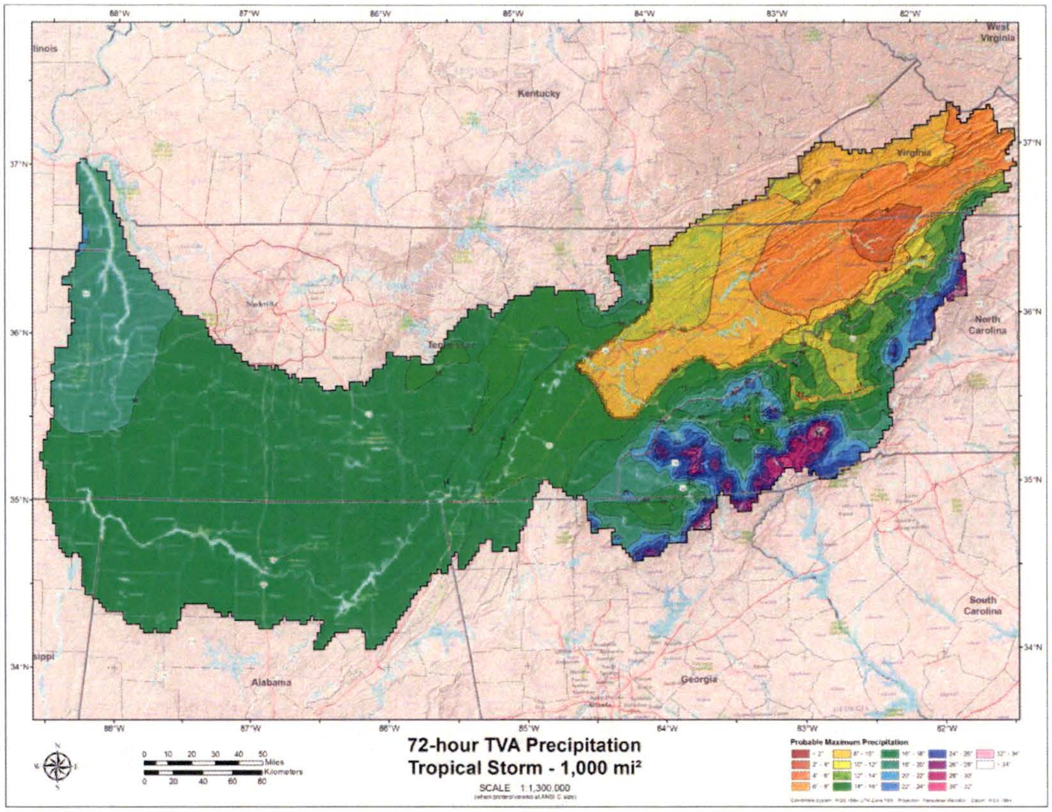

Kentucky
Virginia
West Virginia
Tennessee
North Carolina
South Carolina
Georgia
Alabama
Illinois
24-hour TVA Precipitation
Tropical Storm - 100 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation
Miles
Kilometers

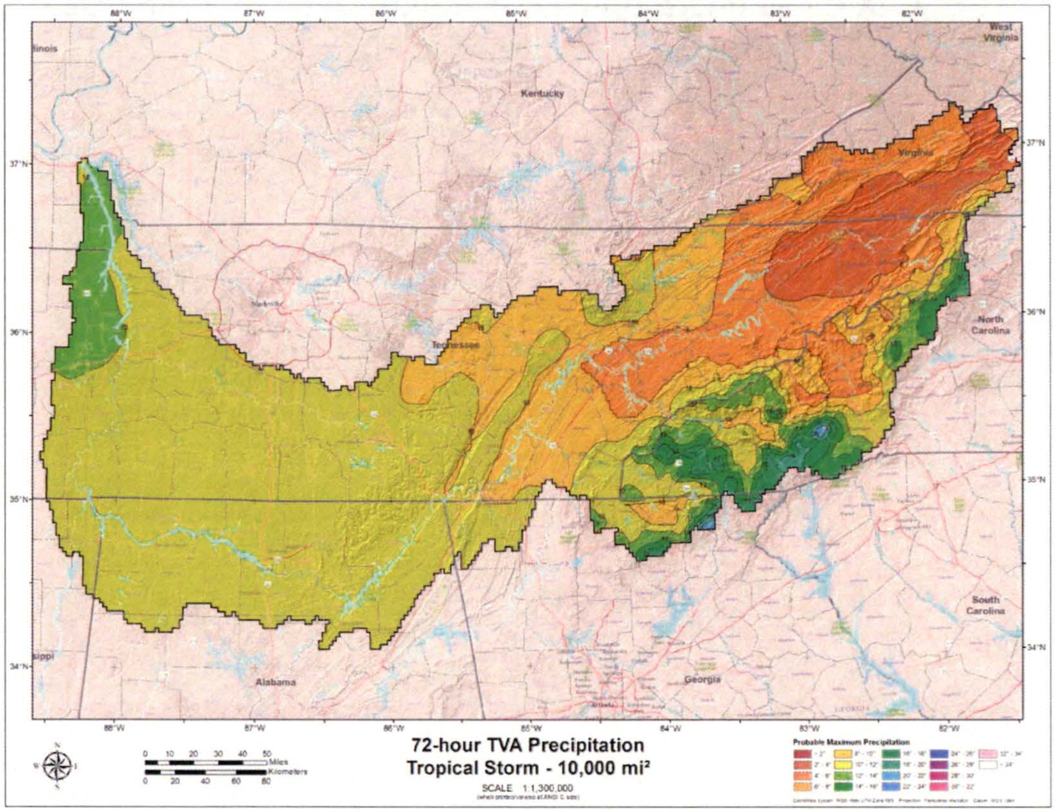

Kentucky
Virginia
West Virginia
Tennessee
North Carolina
South Carolina
Alabama
Georgia
24-hour TVA Precipitation
Tropical Storm - 1,000 mi²
SCALE 1:1,300,000
Miles
Kilometers
Probable Maximum Precipitation


West Virginia
Kentucky
Virginia
Tennessee
North Carolina
South Carolina
Georgia
Alabama
24-hour TVA Precipitation
Tropical Storm - 10,000 mi²
SCALE 1:1,300,000

CALCULATION SHEET			
Calculation Title: Appendix B – TVA Precipitation Maps	Calculation No.: CDQ000002016000041	Rev. No.: 001	Sheet: B20




Kentucky
Virginia
West Virginia
North Carolina
South Carolina
Georgia
Alabama
72-hour TVA Precipitation
Tropical Storm - 1,000 mi²
SCALE 1:1,300,000
Probable Maximum Precipitation
Miles
Kilometers



72-hour TVA Precipitation
Tropical Storm - 10,000 mi²
SCALE 1:1,300,000
Kentucky
Tennessee
Virginia
North Carolina
South Carolina
Georgia
Alabama
West Virginia
Probable Maximum Precipitation

APPENDIX C – Climatological Maximum Dew Point and Sea Surface Temperature Maps

The 100-year maximum dew point climatology was developed using the NCEI TD 3405 database, accessed from the following sources:

ISD:

National Center for Environmental Information (NCEI) Integrated Surface Database (ISD), https://www.ncdc.noaa.gov/isd. Accessed January 2018.

DS3505:

National Center for Environmental Information (NCEI) Surface Data Hourly Global (DS3505), https://www7.ncdc.noaa.gov/CDO/cdopoemain.cmd?datasetabbv=DS3505&countryabbv=&georegionabbv=&resolution=40. Accessed January 2018.

6-Hour, 100-year Recurrence Interval Dew Point Maps

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
January

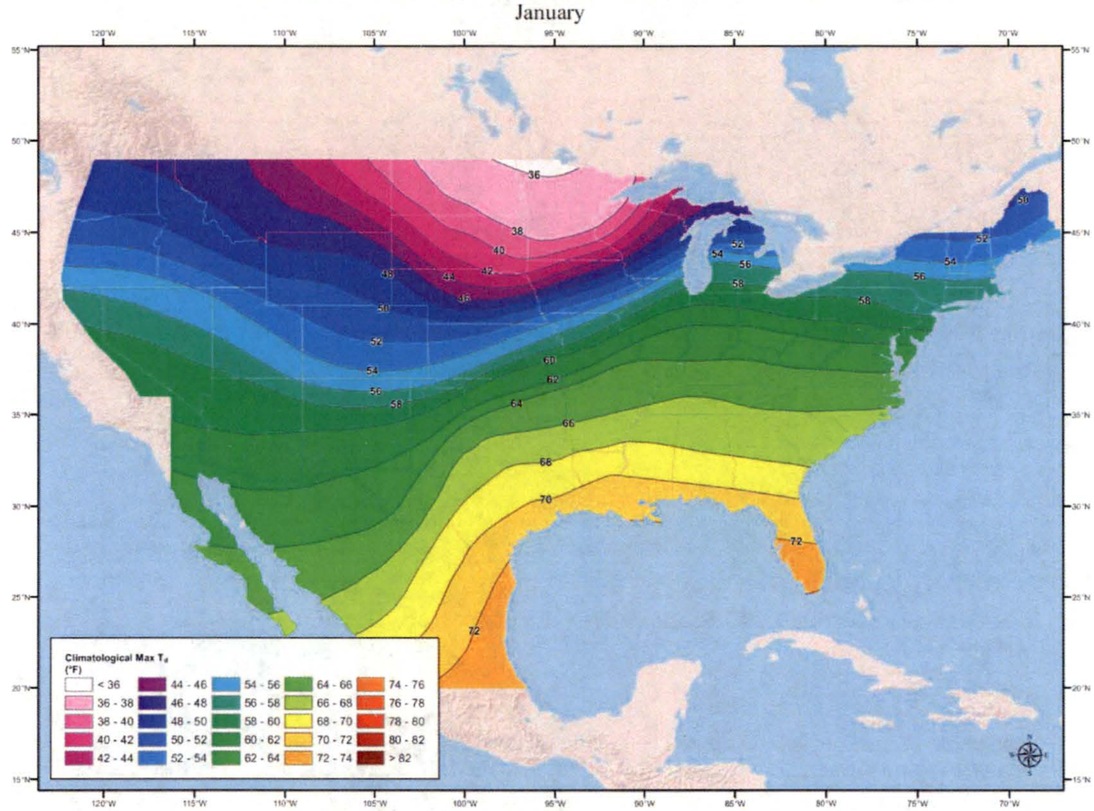


Figure C.1 January 6-hour 100-year maximum dew point climatology

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
February

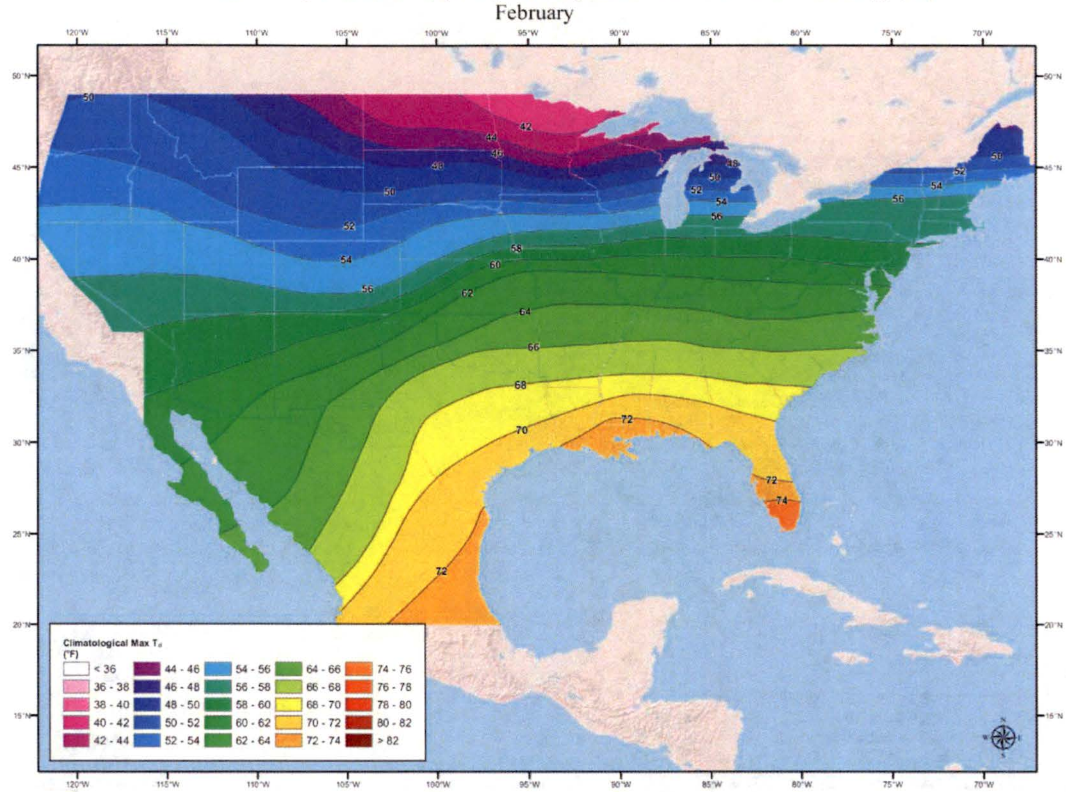


Figure C.2 February 6-hour 100-year maximum dew point climatology

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
March

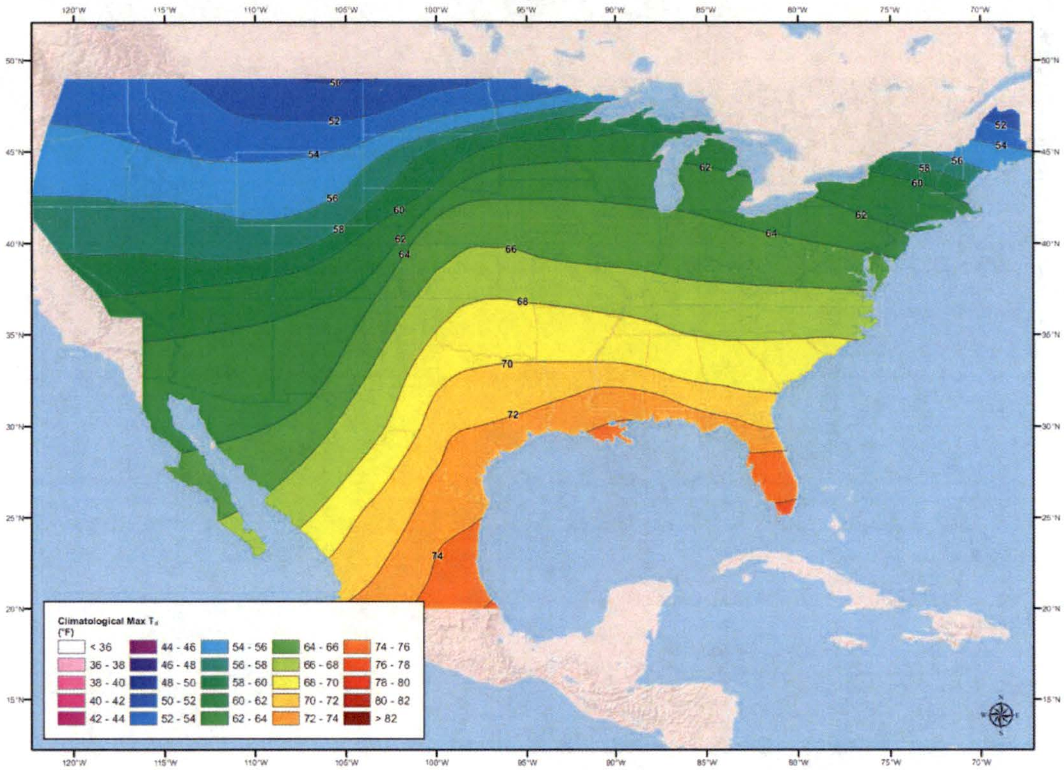


Figure C.3 March 6-hour 100-year maximum dew point climatology

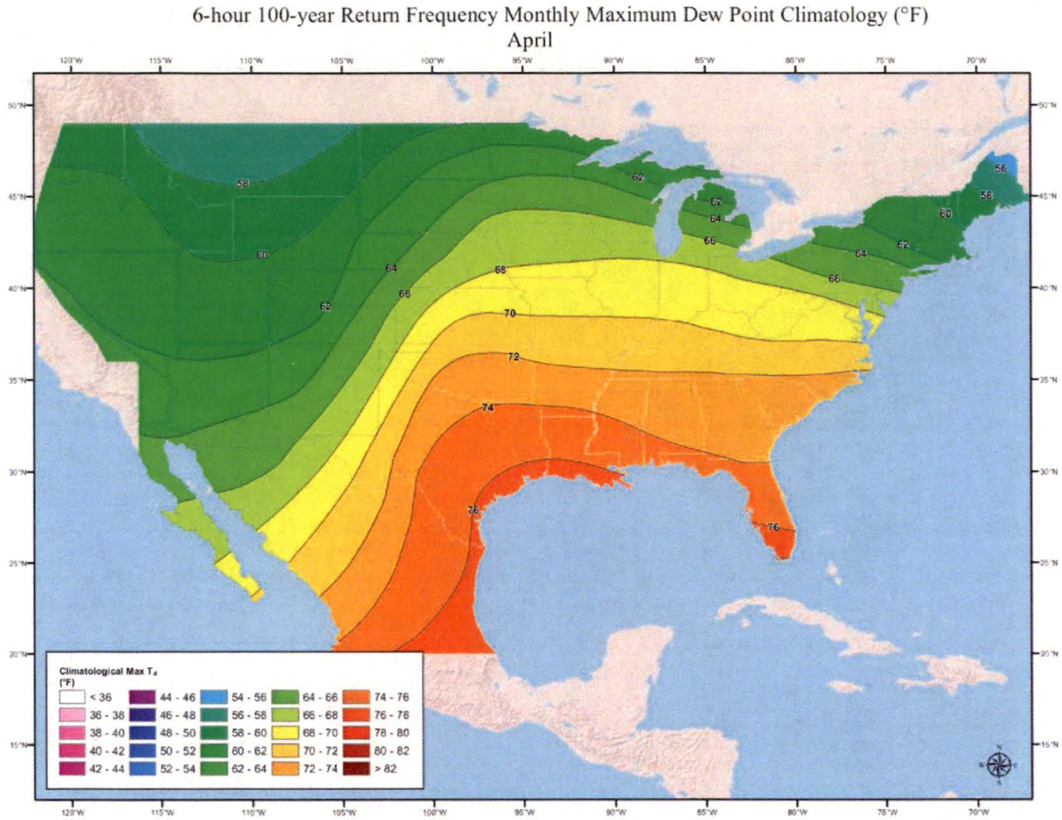


Figure C.4 April 6-hour 100-year maximum dew point climatology

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
May

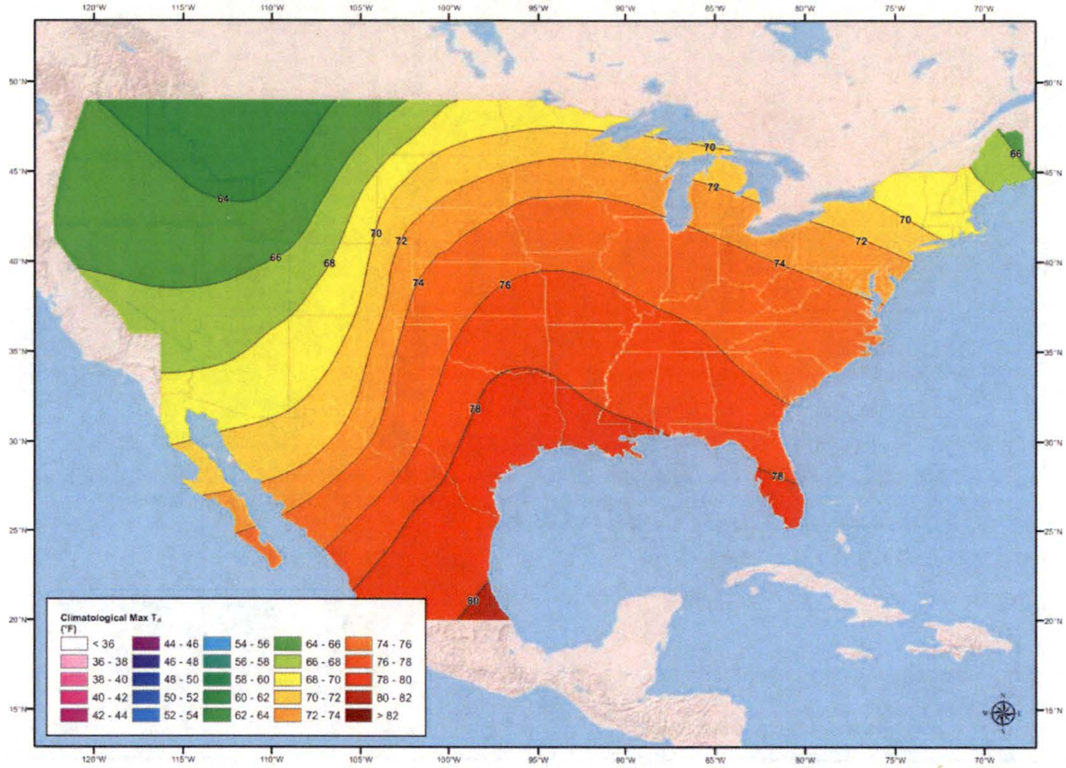


Figure C.5 May 6-hour 100-year maximum dew point climatology

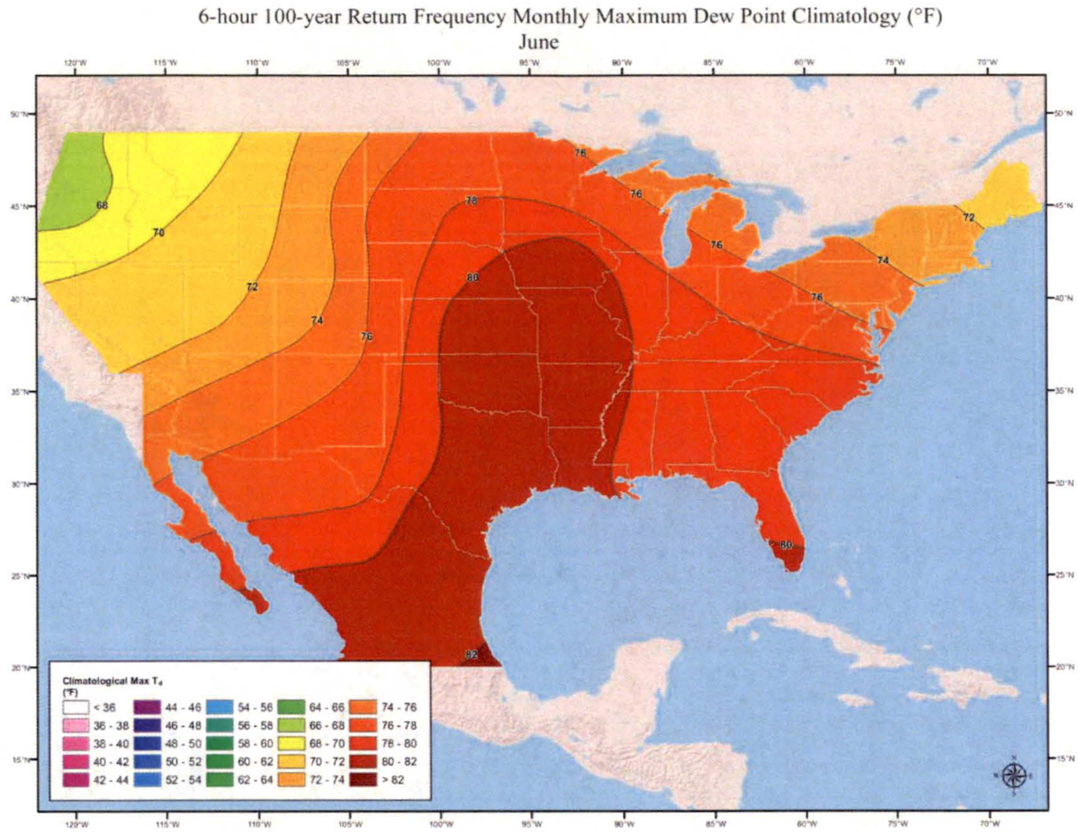


Figure C.6 June 6-hour 100-year maximum dew point climatology

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
June

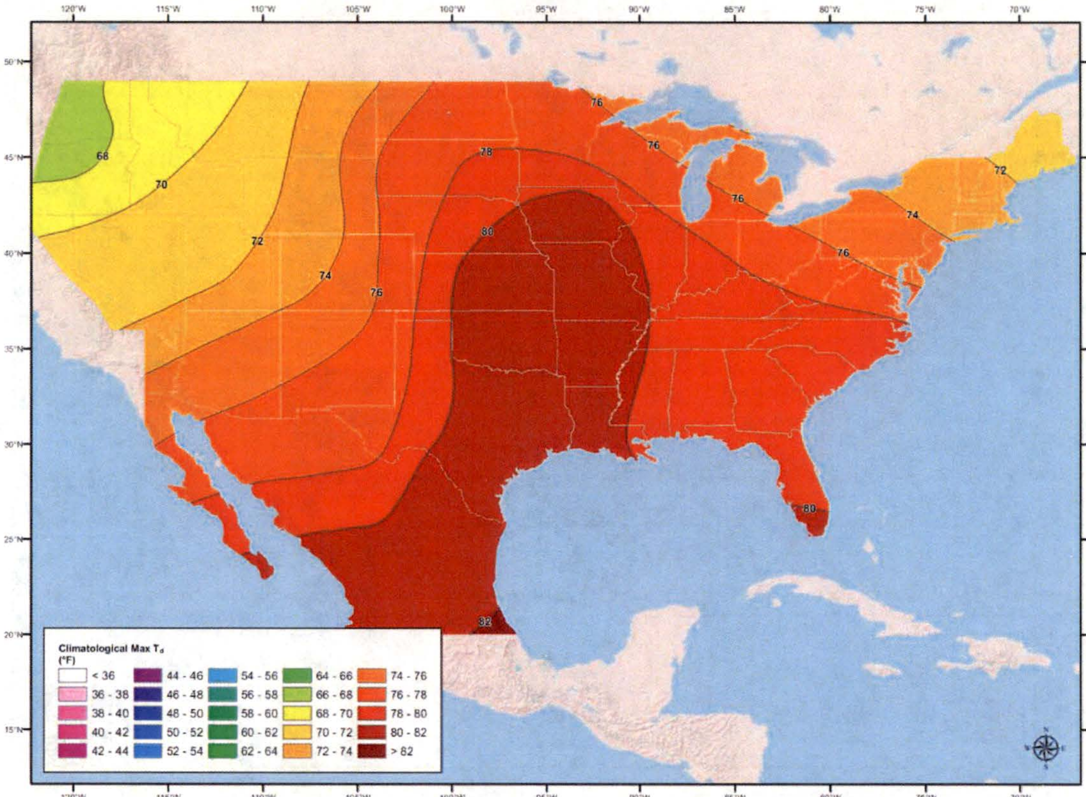


Figure C.7 July 6-hour 100-year maximum dew point climatology

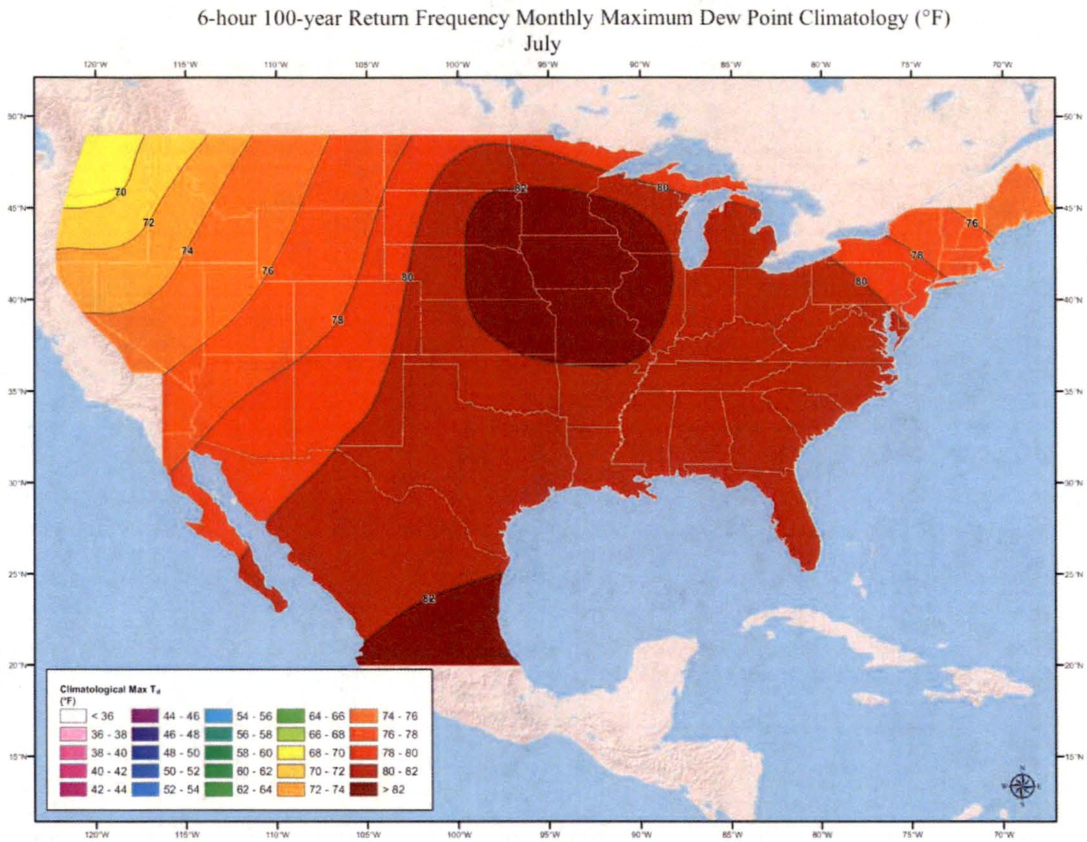


Figure C.8 August 6-hour 100-year maximum dew point climatology

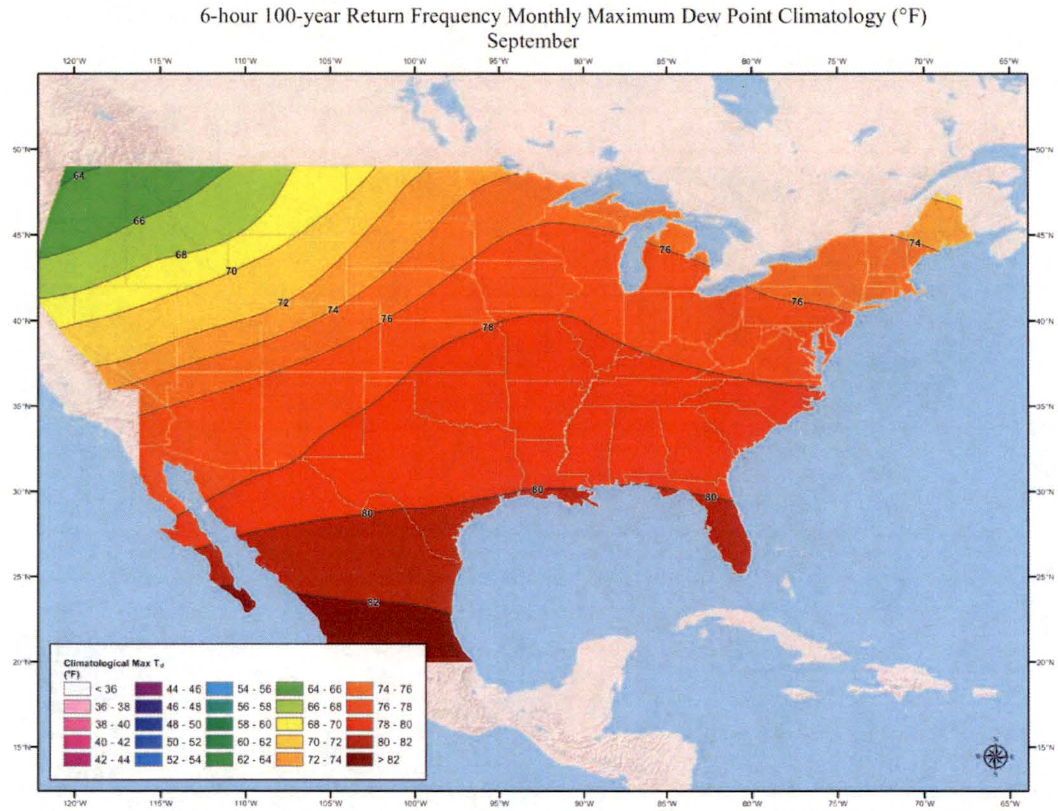


Figure C.9 September 6-hour 100-year maximum dew point climatology

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
October

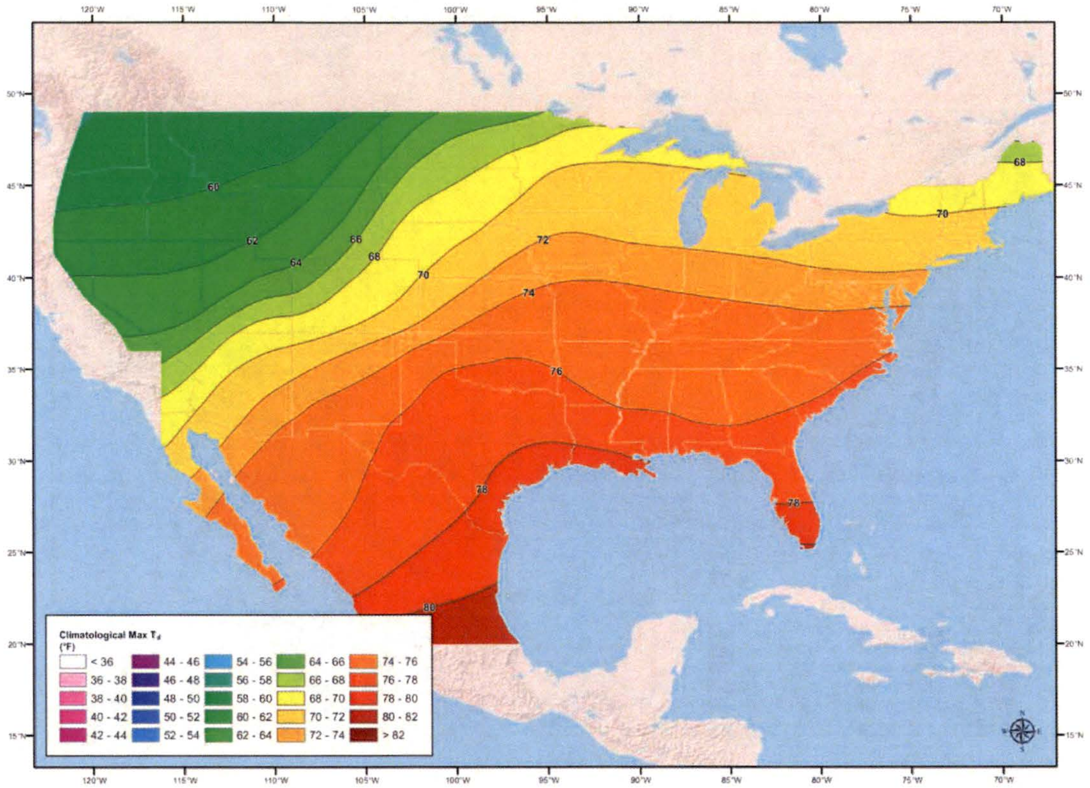


Figure C.10 October 6-hour 100-year maximum dew point climatology

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
November

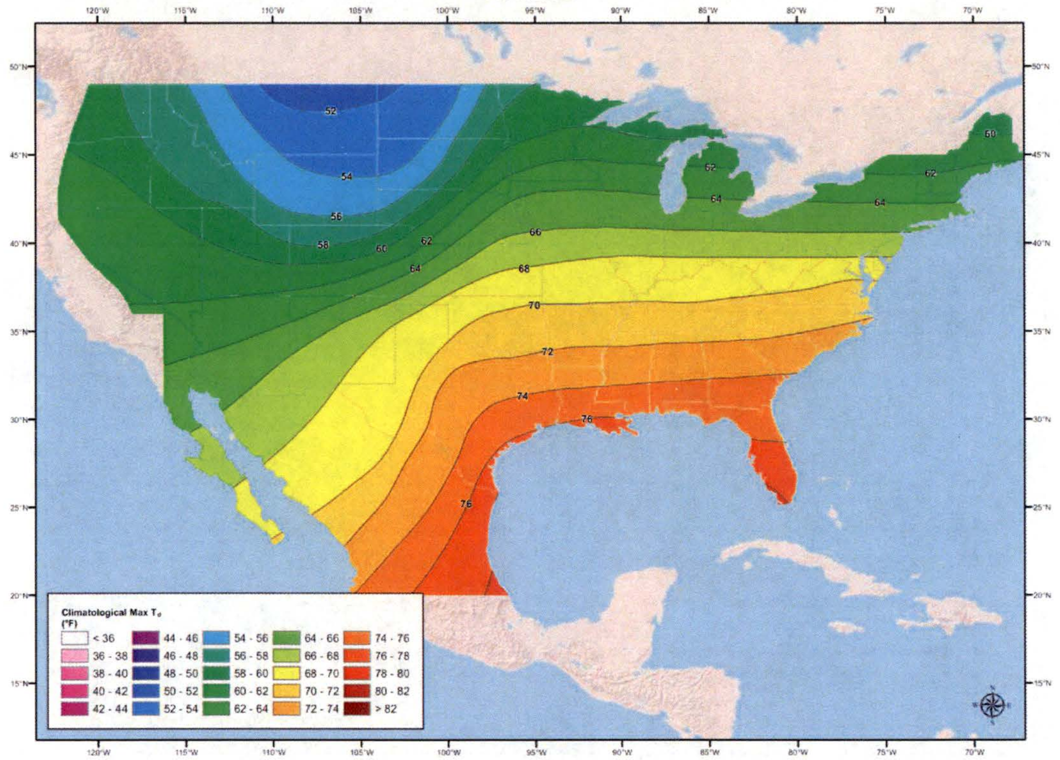


Figure C.11 November 6-hour 100-year maximum dew point climatology

6-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
December

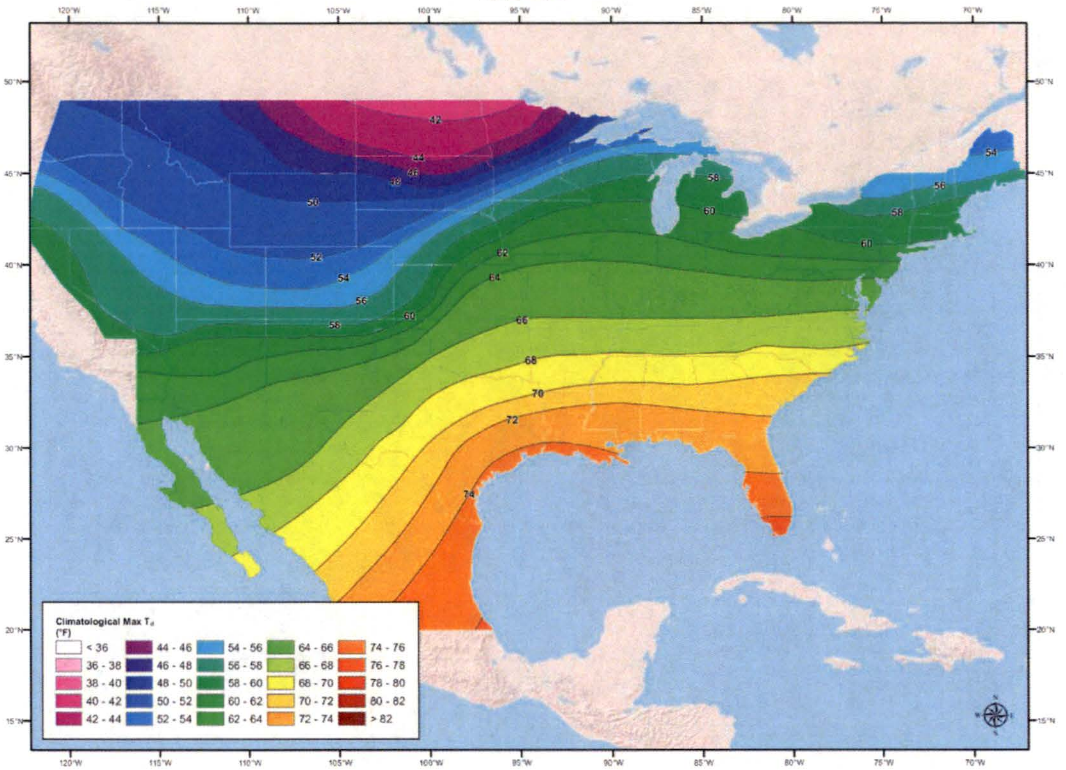


Figure C.12 December 6-hour 100-year maximum dew point climatology

12-Hour, 100-year Recurrence Interval Dew Point Maps

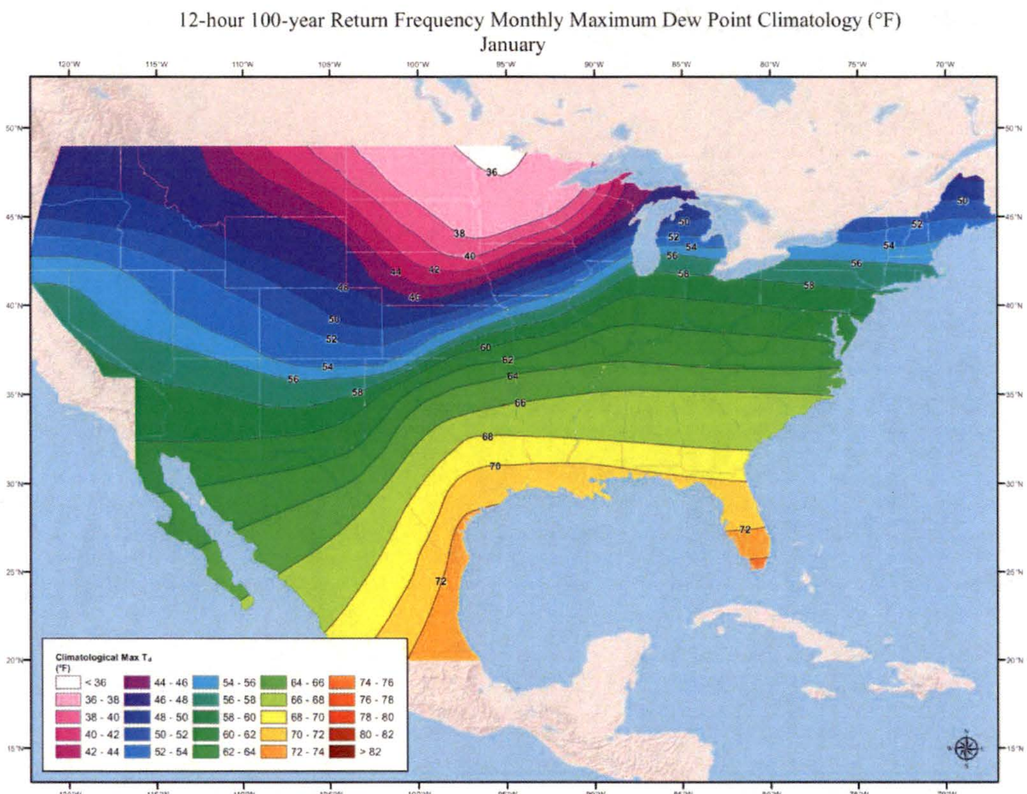


Figure C.13 January 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
February

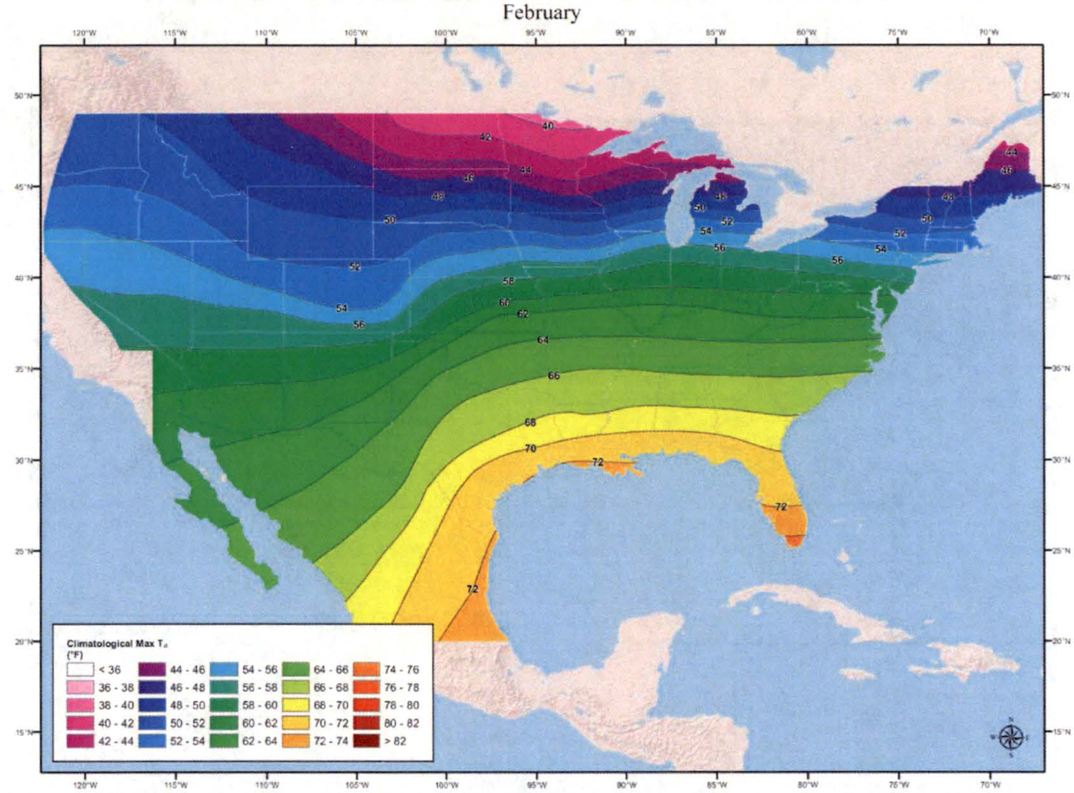


Figure C.14 February 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
March

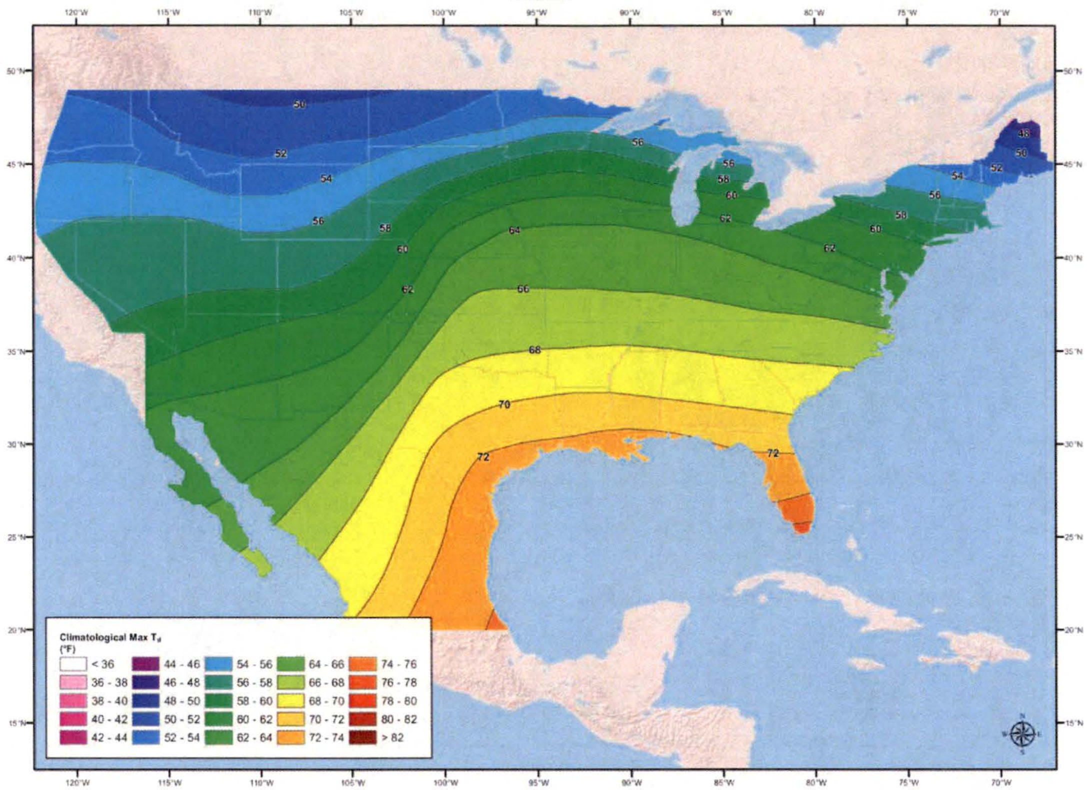


Figure C.15 March 12-hour 100-year maximum dew point climatology

CALCULATION SHEET			
Calculation Title: Appendix C – Climatological Maximum Dew Point and Sea Surface Temperature Maps	Calculation No.: CDQ000002016000041	Rev. No.: 001	Sheet: C20

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
April

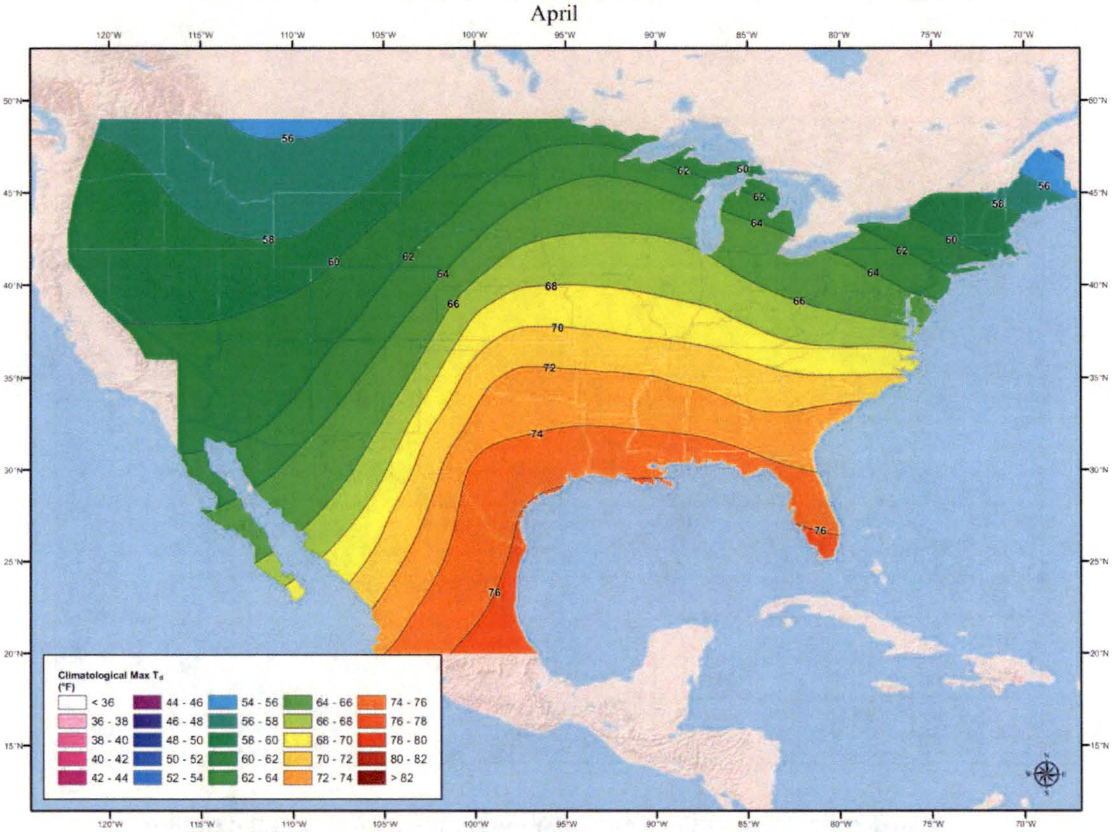


Figure C.16 April 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
May

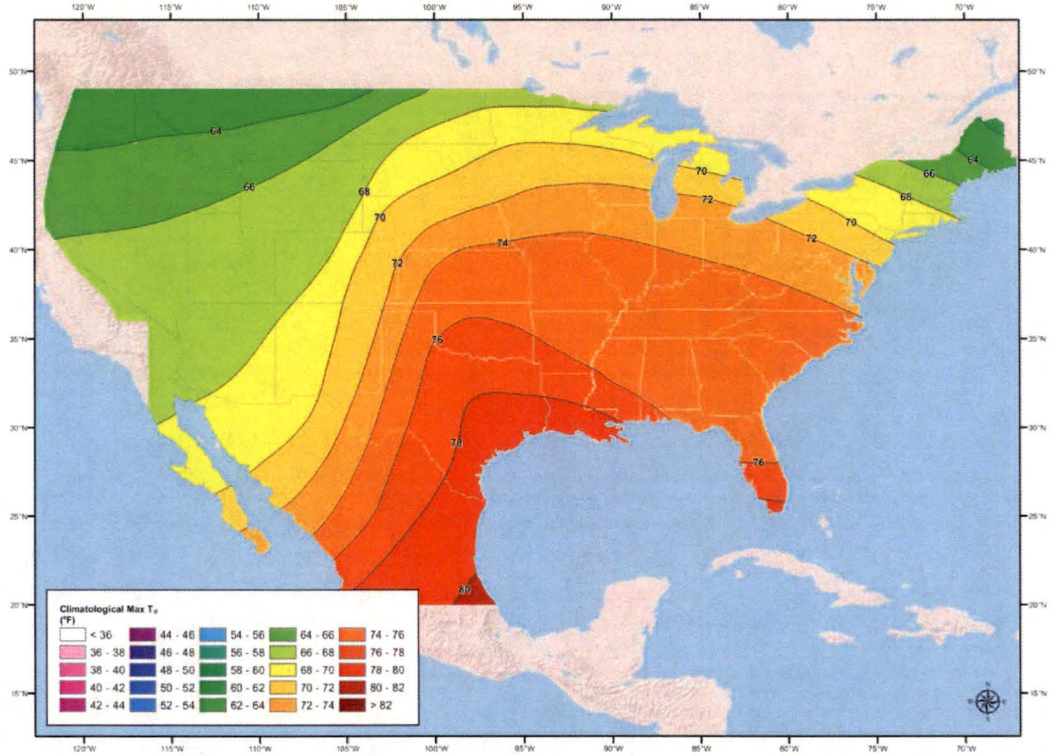


Figure C.17 May 12-hour 100-year maximum dew point climatology

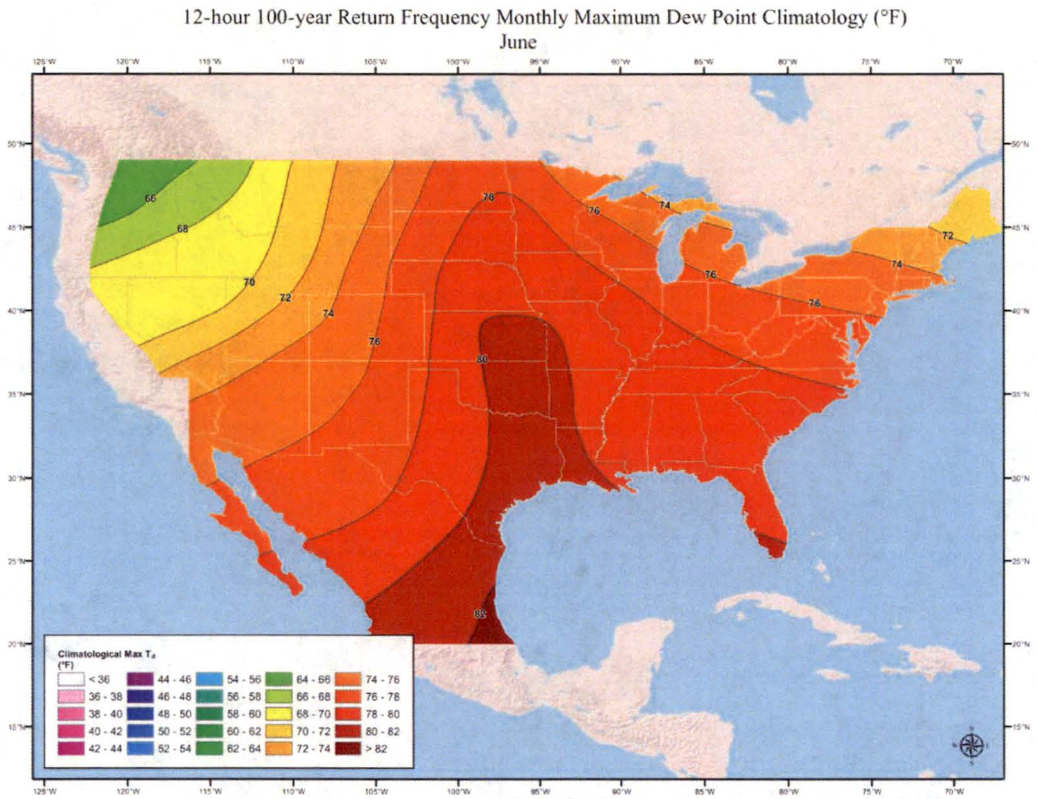


Figure C.18 June 12-hour 100-year maximum dew point climatology

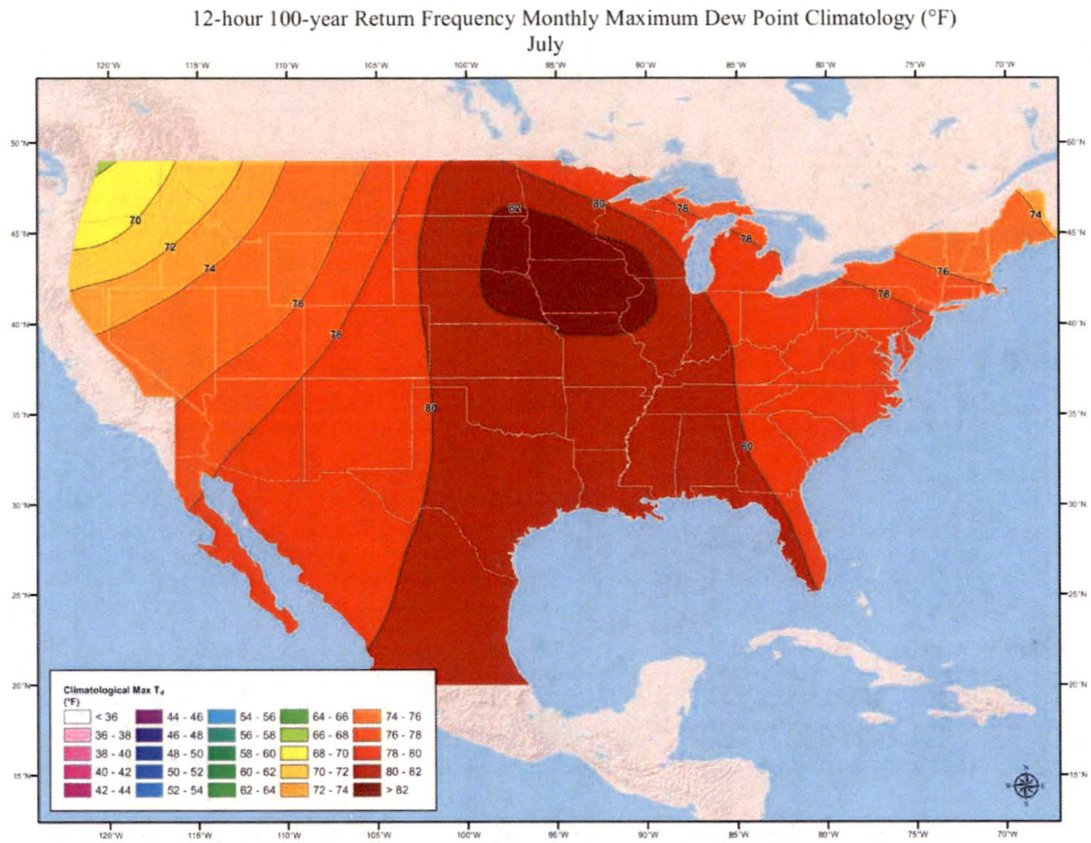


Figure C.19 July 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
August

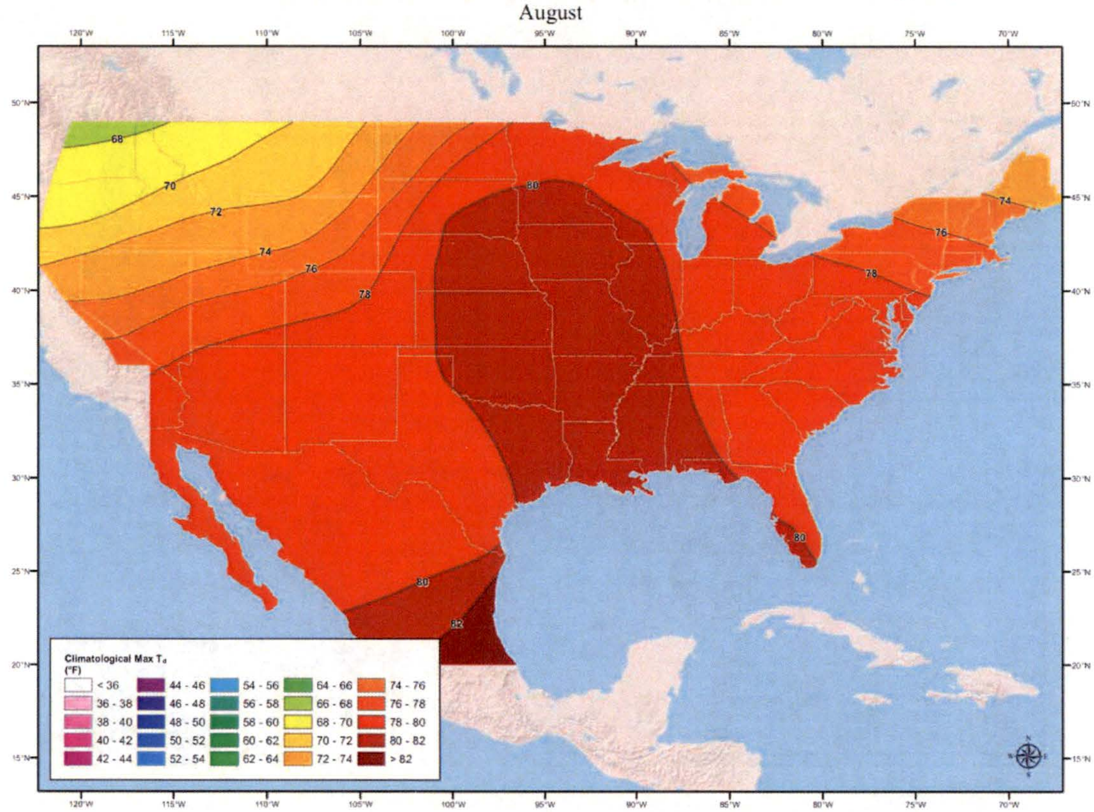


Figure C.20 August 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
September

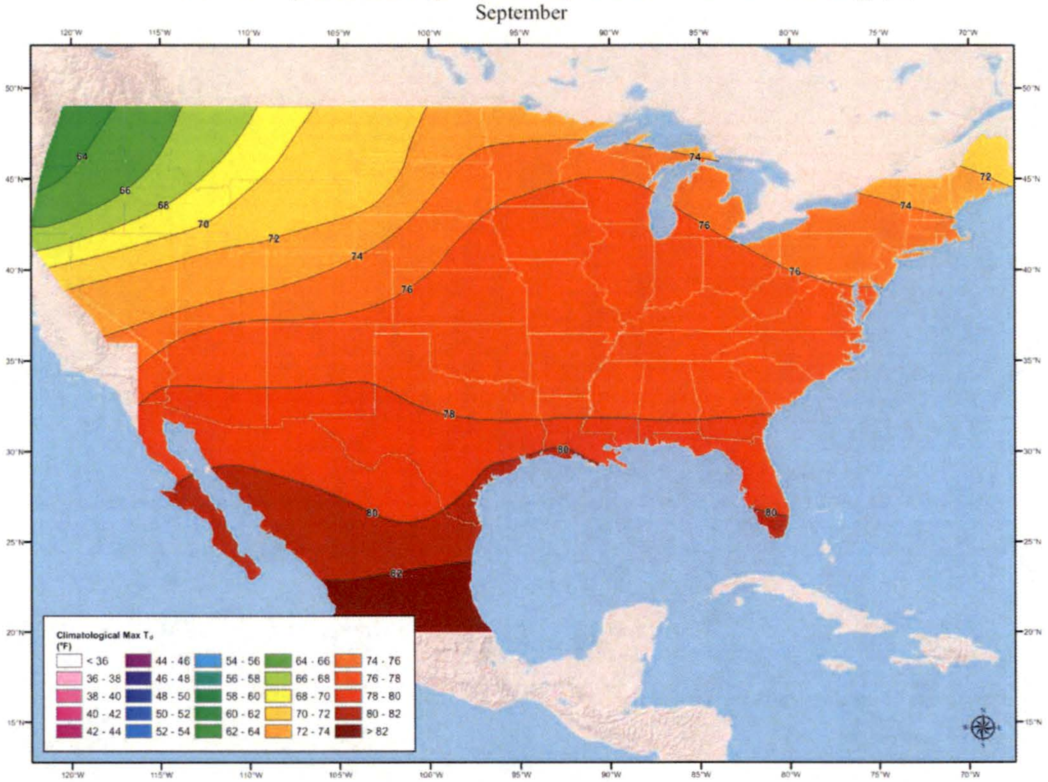


Figure C.21 September 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
October

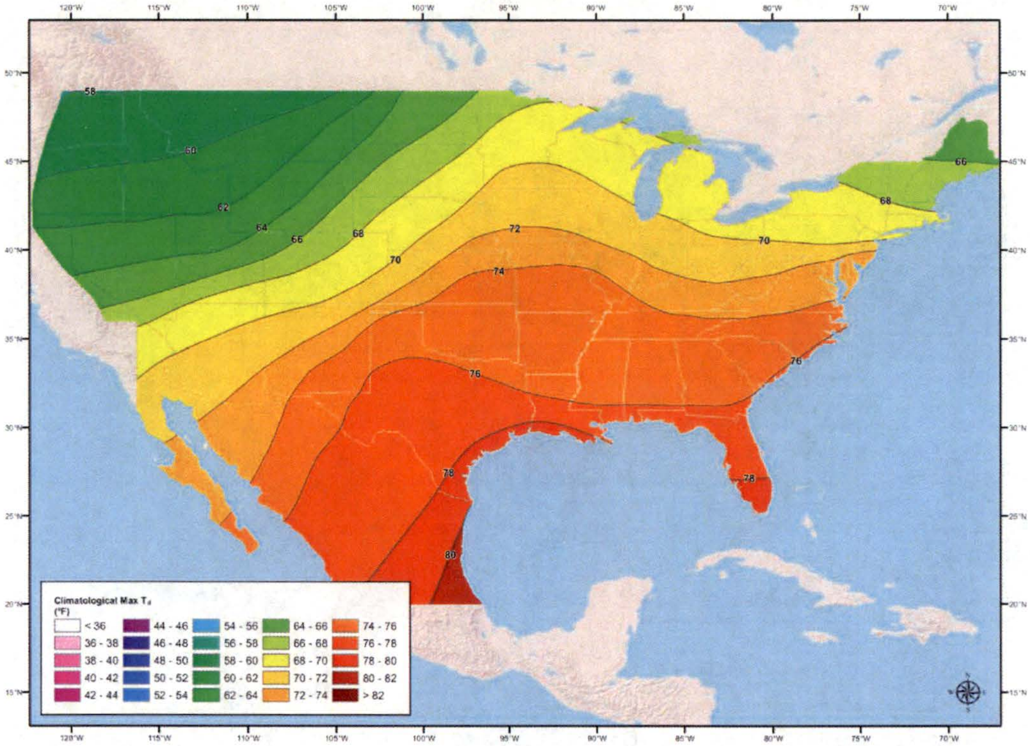


Figure C.22 October 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
November

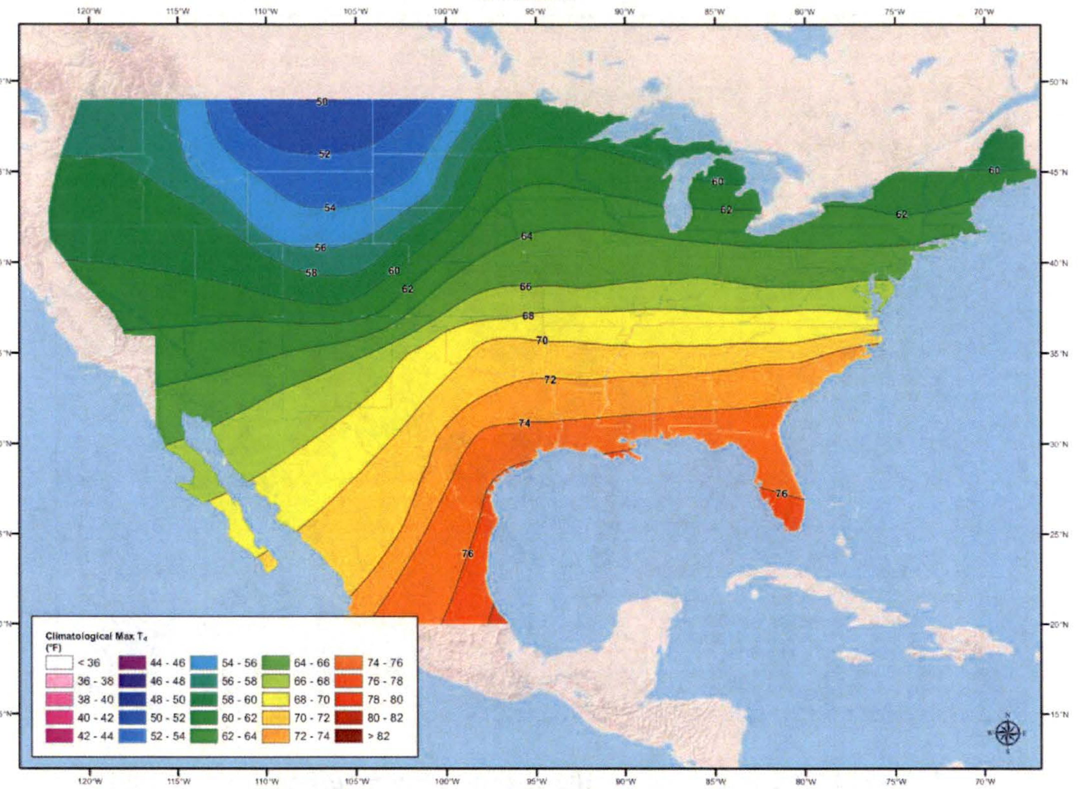


Figure C.23 November 12-hour 100-year maximum dew point climatology

12-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
December

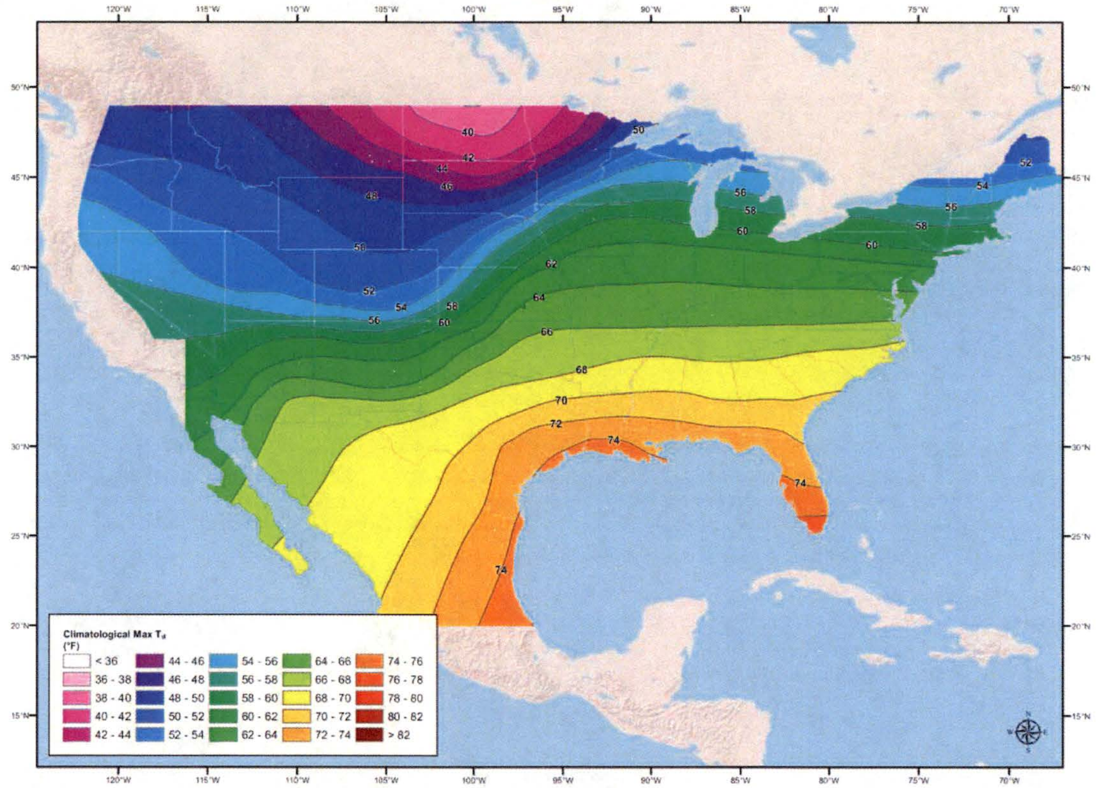


Figure C.24 December 12-hour 100-year maximum dew point climatology

24-Hour, 100-year Recurrence Interval Dew Point Maps

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
January

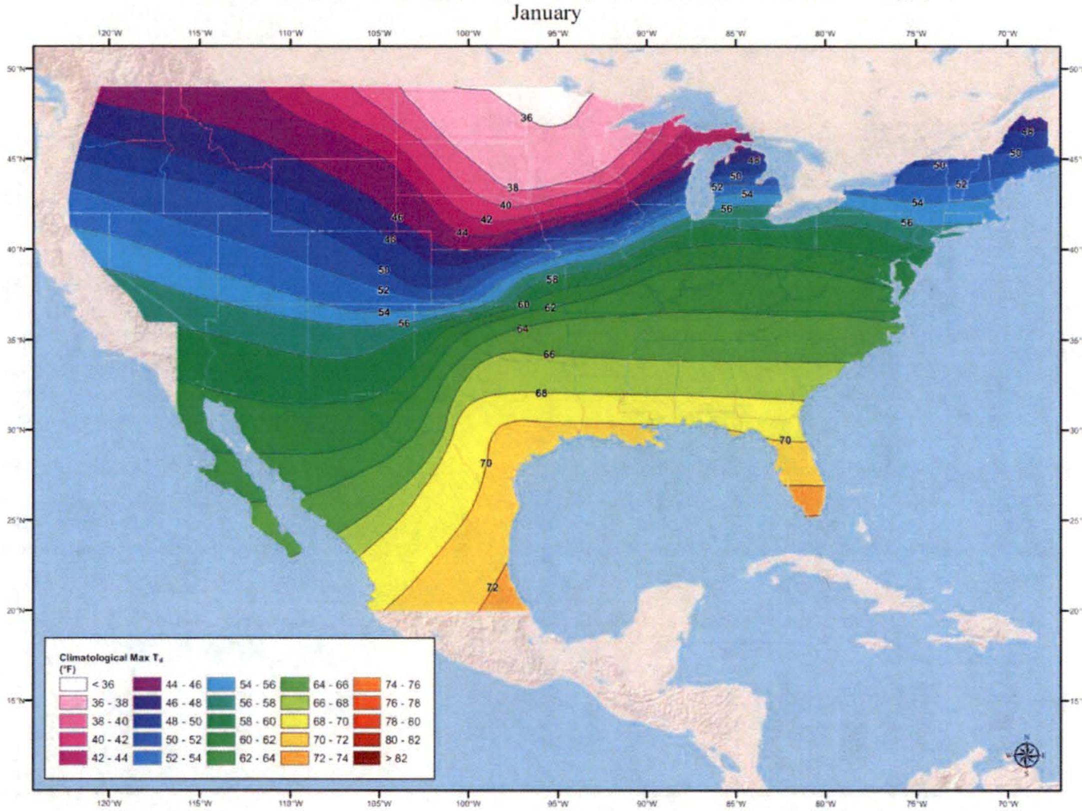


Figure C.25 January 24-hour 100-year maximum dew point climatology

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
February

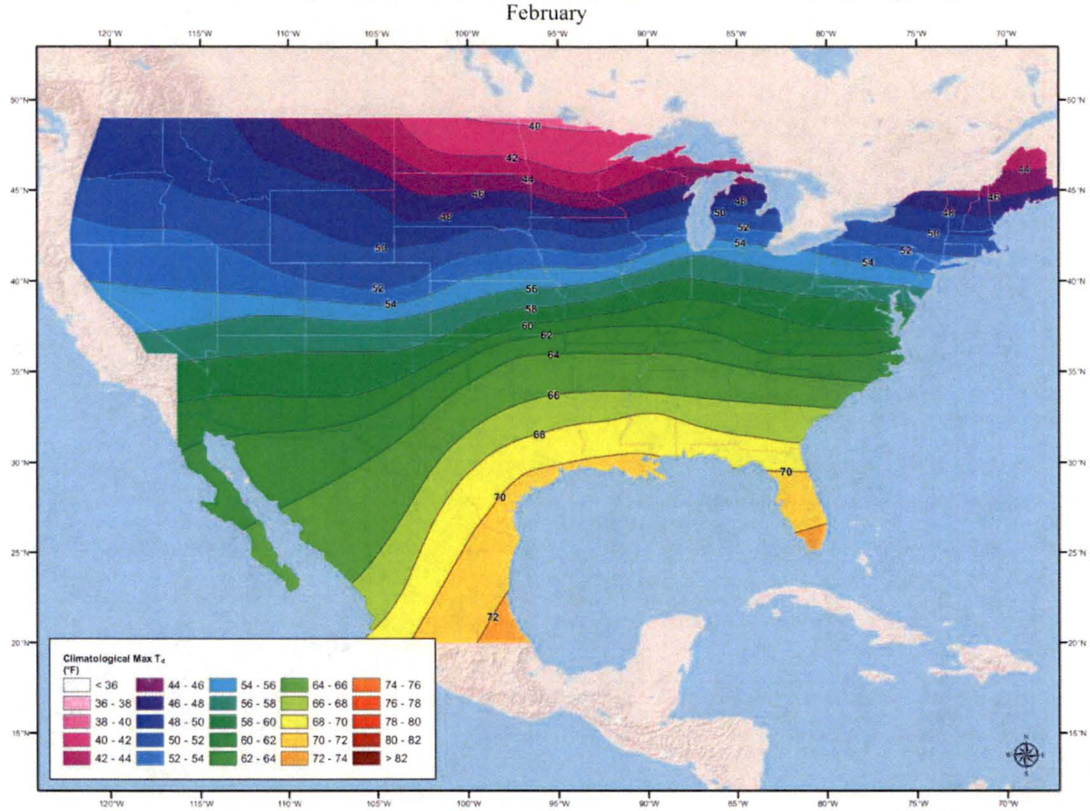


Figure C.26 February 24-hour 100-year maximum dew point climatology

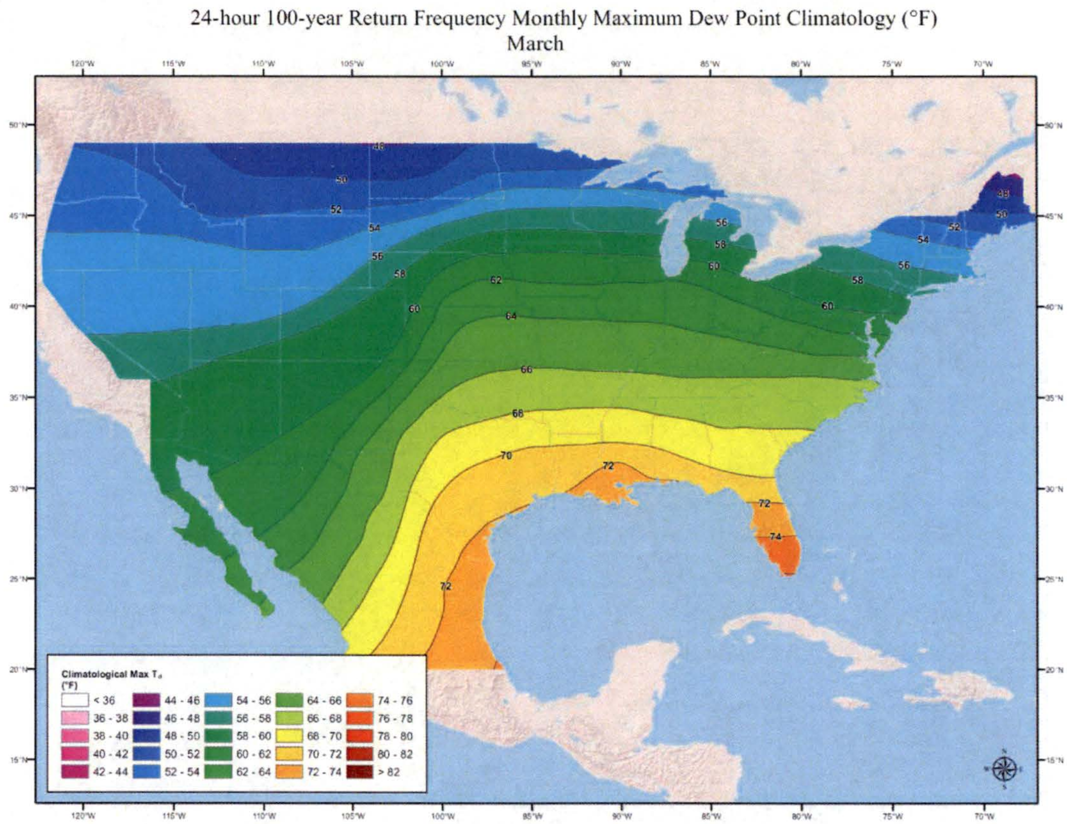


Figure C.27 March 24-hour 100-year maximum dew point climatology

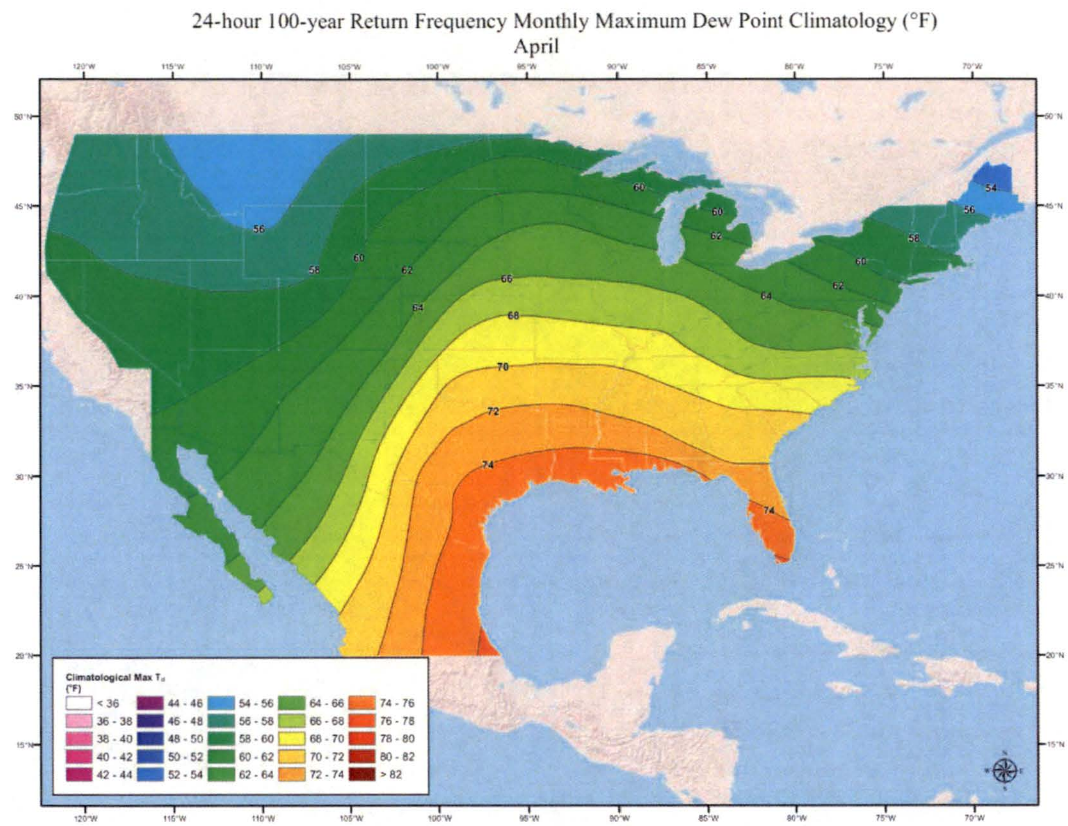


Figure C.28 April 24-hour 100-year maximum dew point climatology

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
May

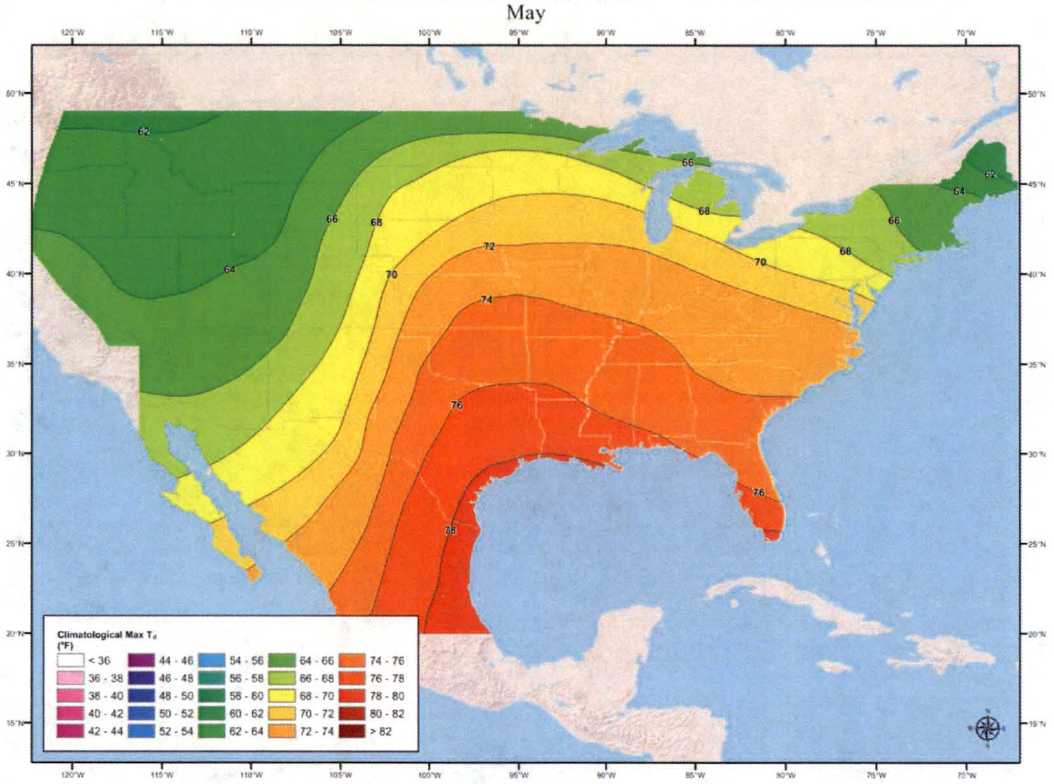


Figure C.29 May 24-hour 100-year maximum dew point climatology

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
June

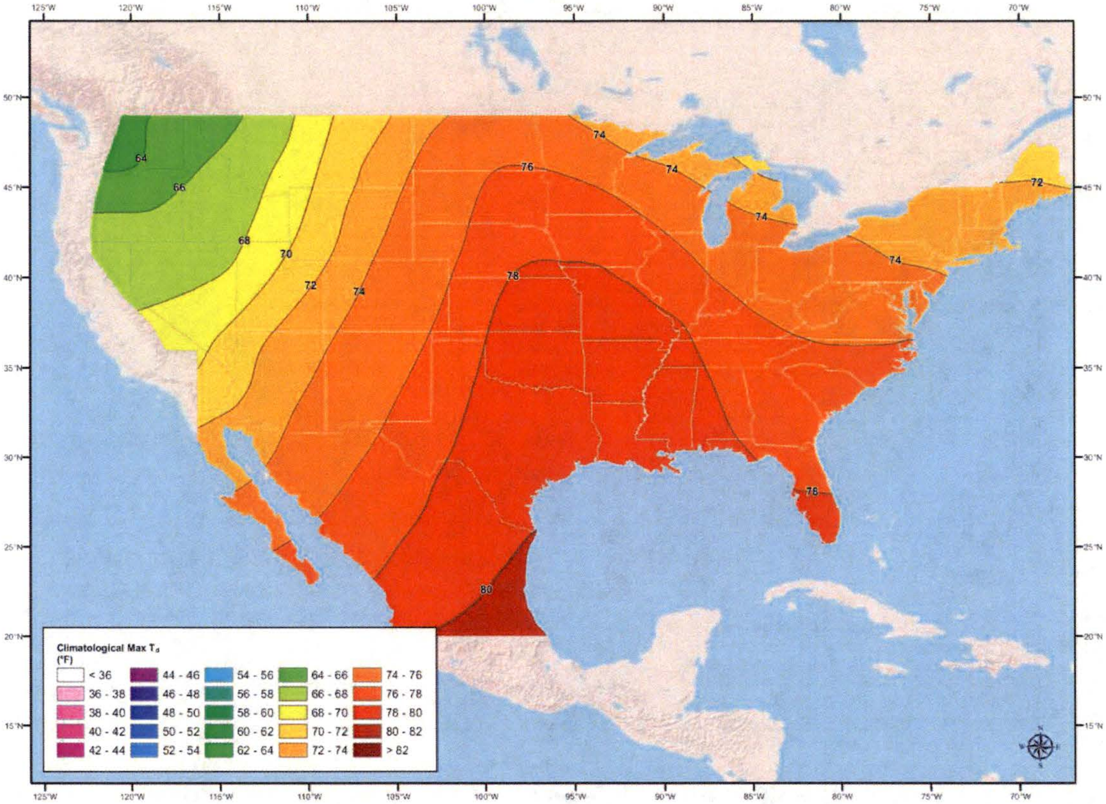


Figure C.30 June 24-hour 100-year maximum dew point climatology

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
July

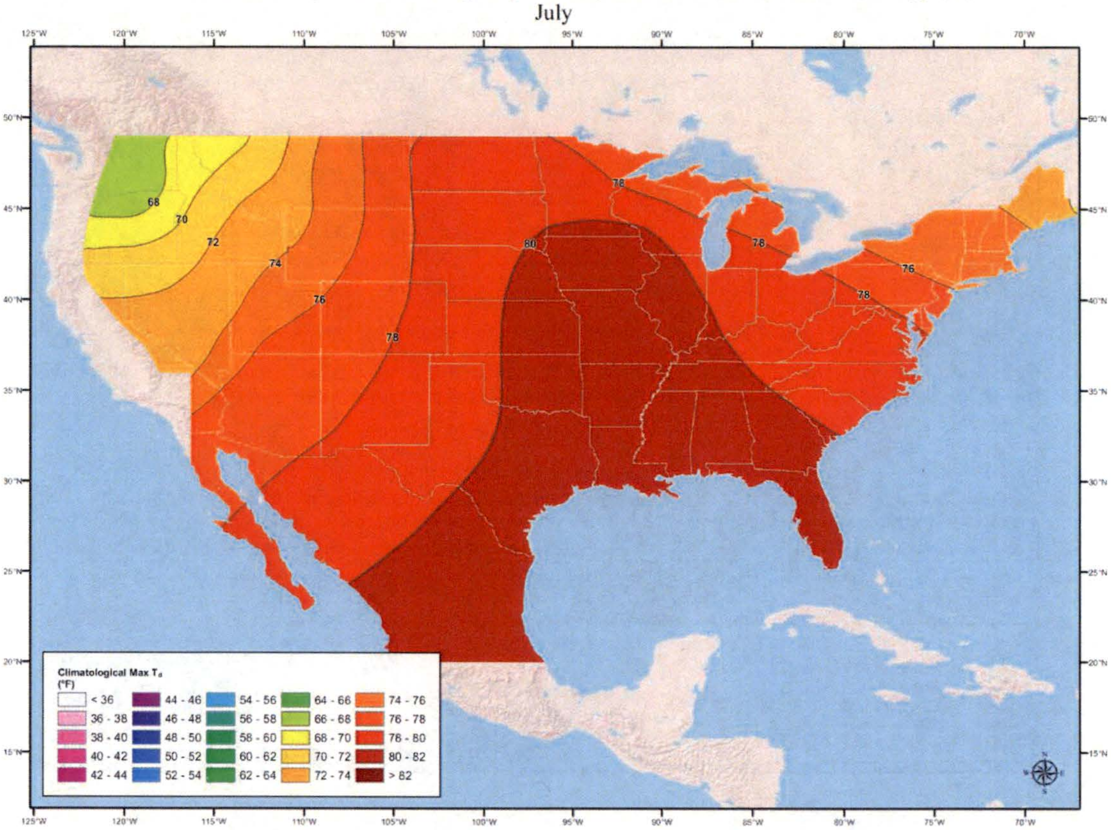


Figure C.31 July 24-hour 100-year maximum dew point climatology

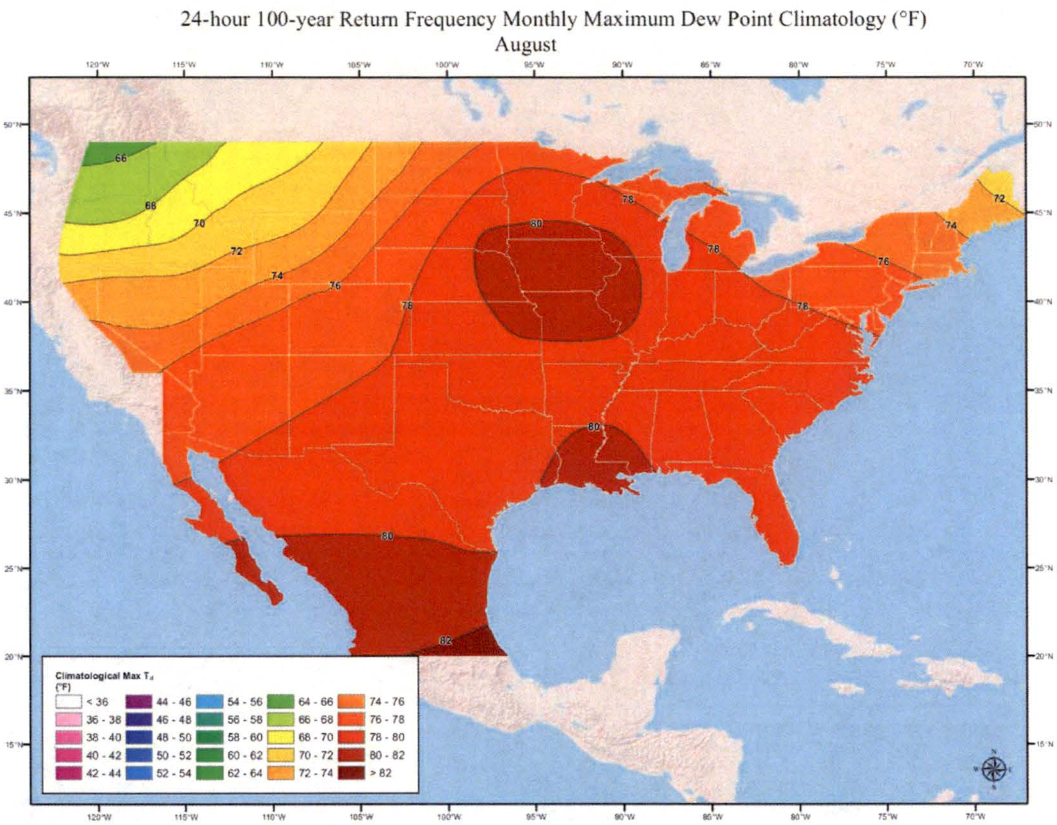


Figure C.32 August 24-hour 100-year maximum dew point climatology

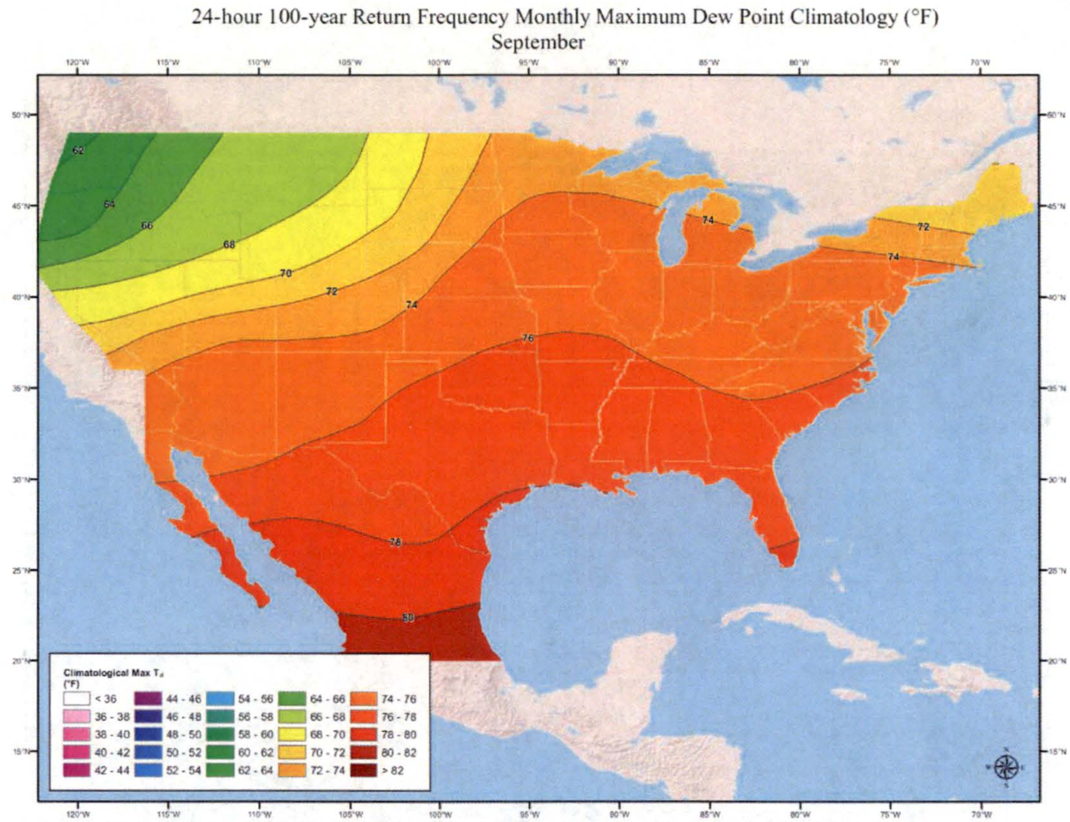


Figure C.33 September 24-hour 100-year maximum dew point climatology

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
October

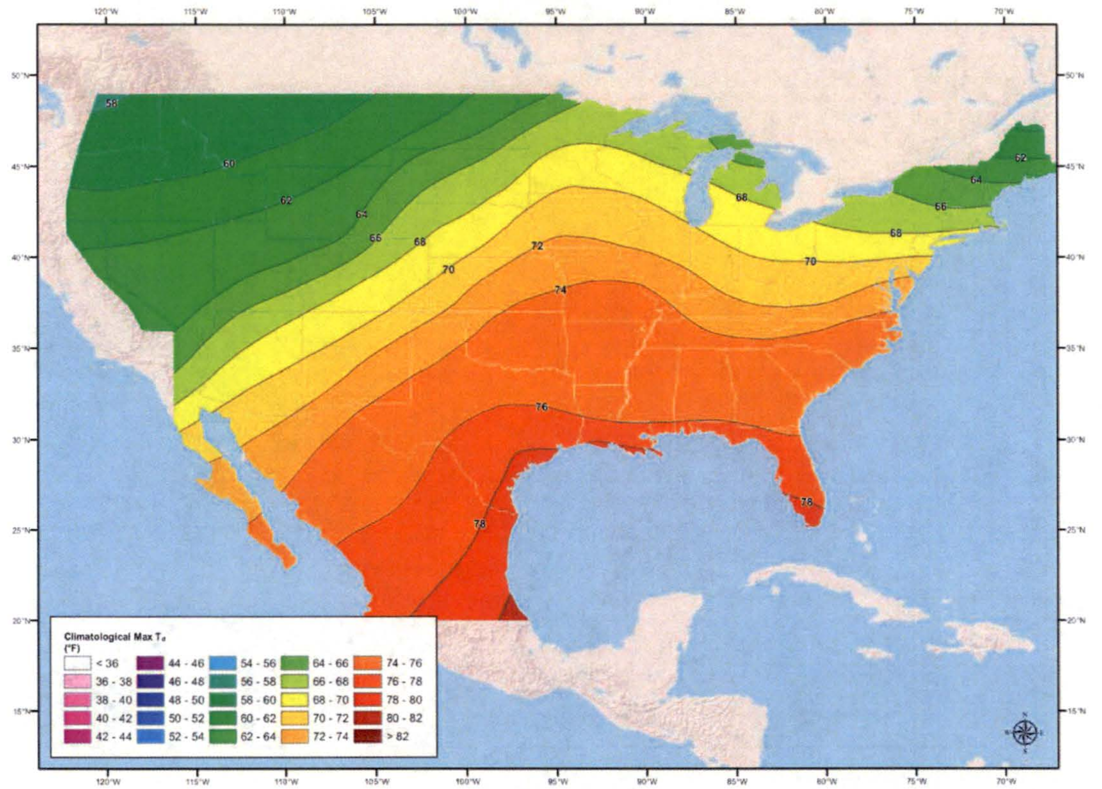


Figure C.34 October 24-hour 100-year maximum dew point climatology

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
November

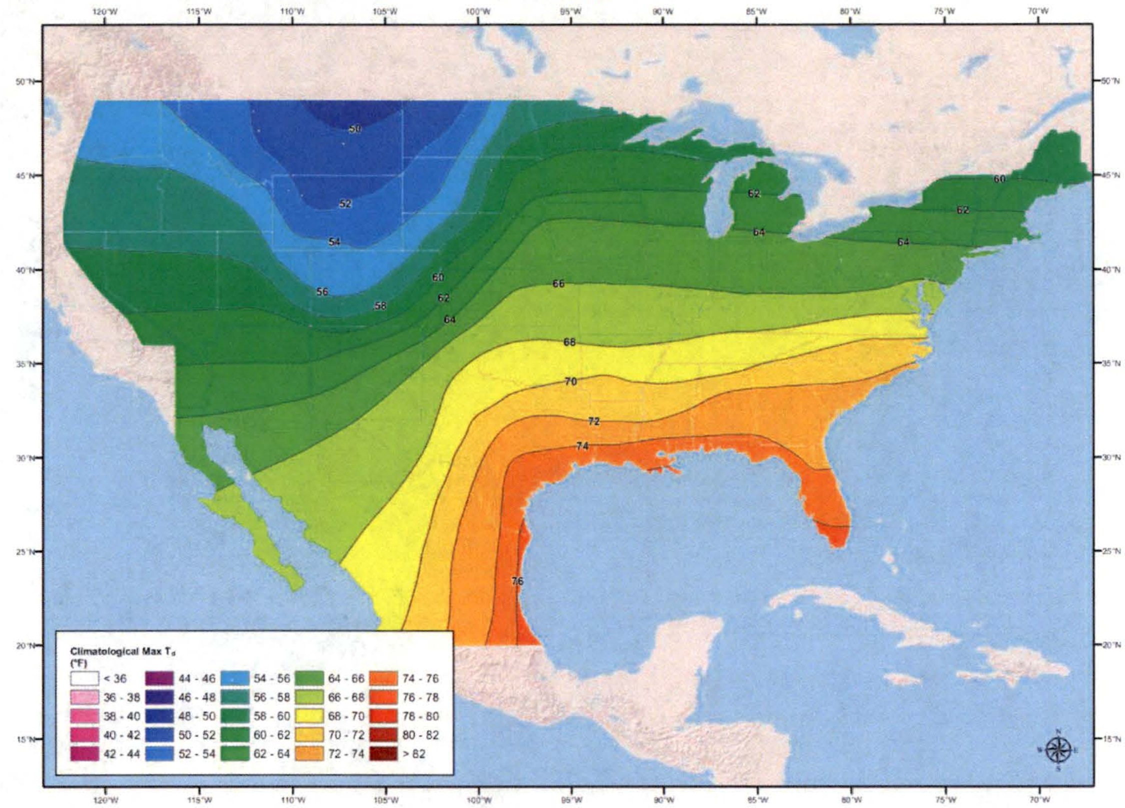


Figure C.35 November 24-hour 100-year maximum dew point climatology

24-hour 100-year Return Frequency Monthly Maximum Dew Point Climatology (°F)
December

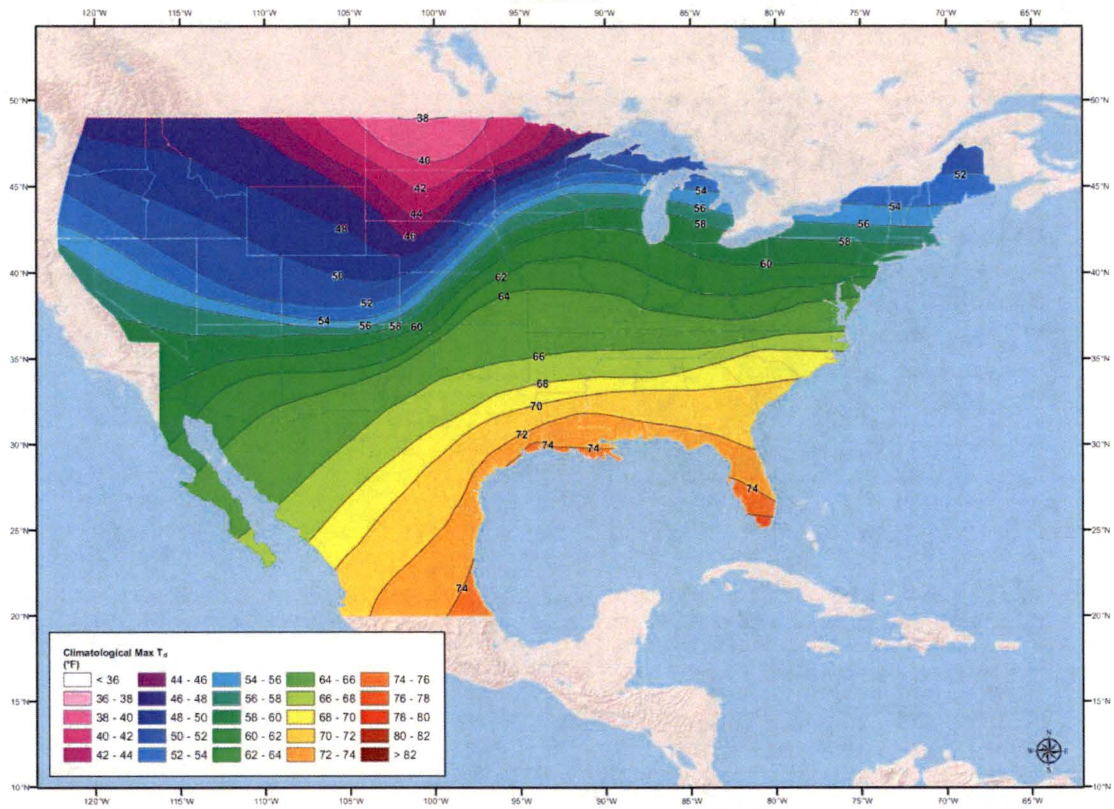


Figure C.36 December 24-hour 100-year maximum dew point climatology

2-Sigma Sea Surface Temperature Maps

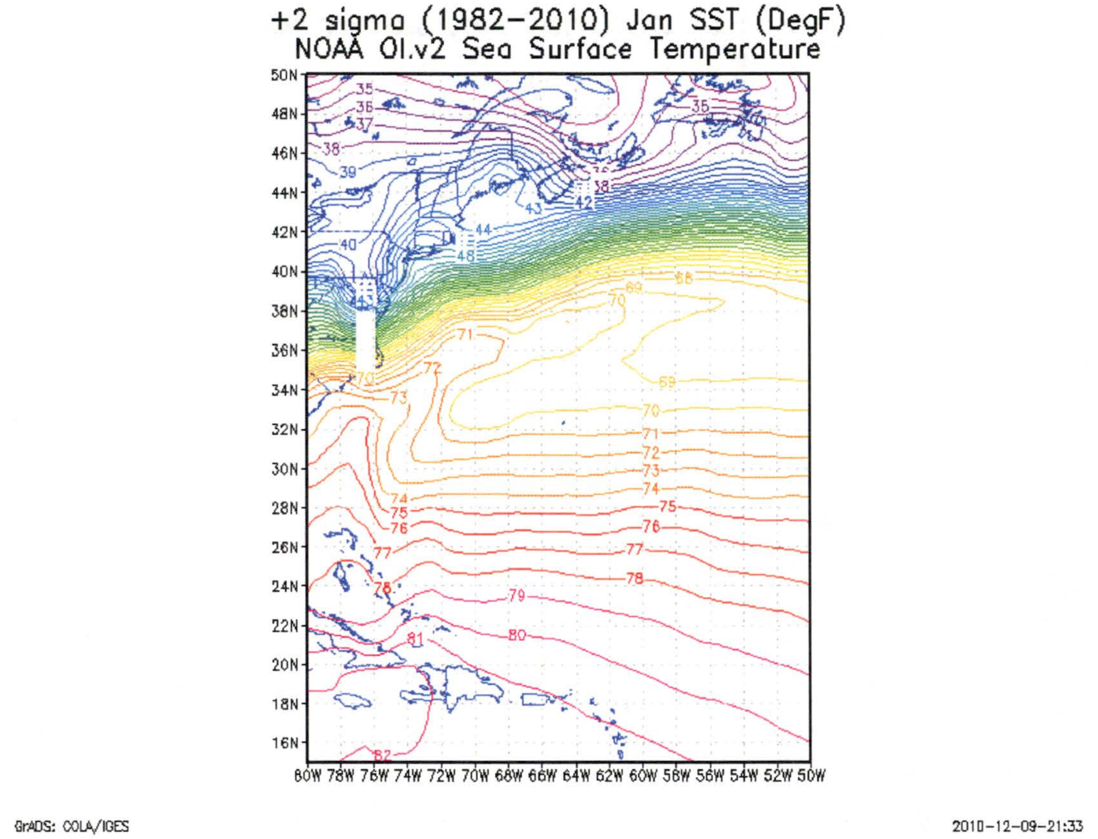


Figure C.37 January +2 sigma SST climatology-western Atlantic Ocean

CALCULATION SHEET			
Calculation Title: Appendix C – Climatological Maximum Dew Point and Sea Surface Temperature Maps	Calculation No.: CDQ000002016000041	Rev. No.: 001	Sheet: C44

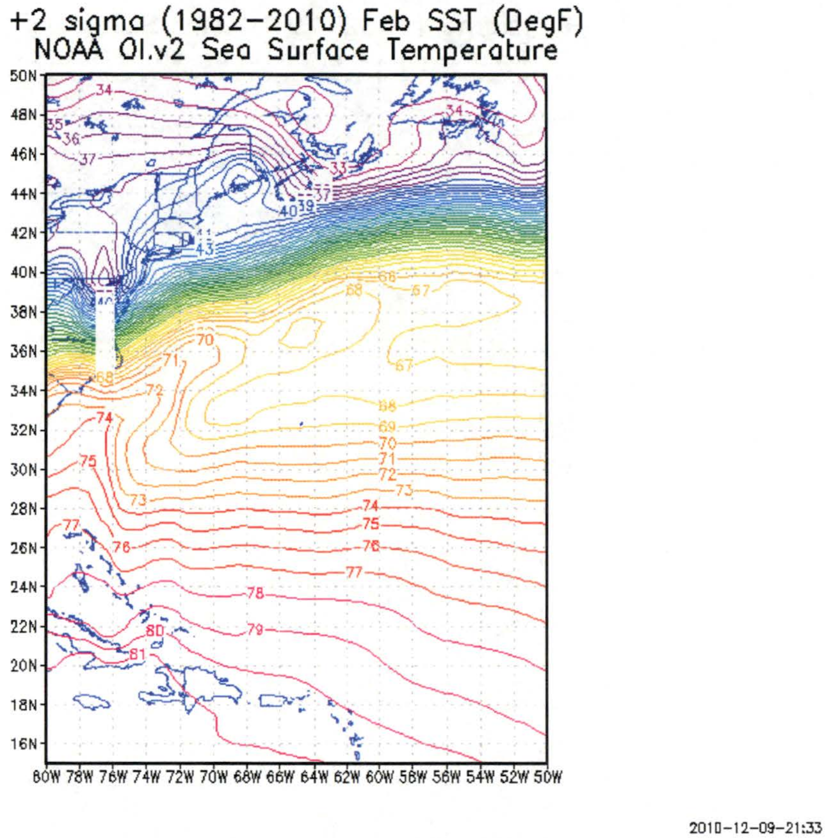


Figure C.38 February +2 sigma SST climatology-western Atlantic Ocean

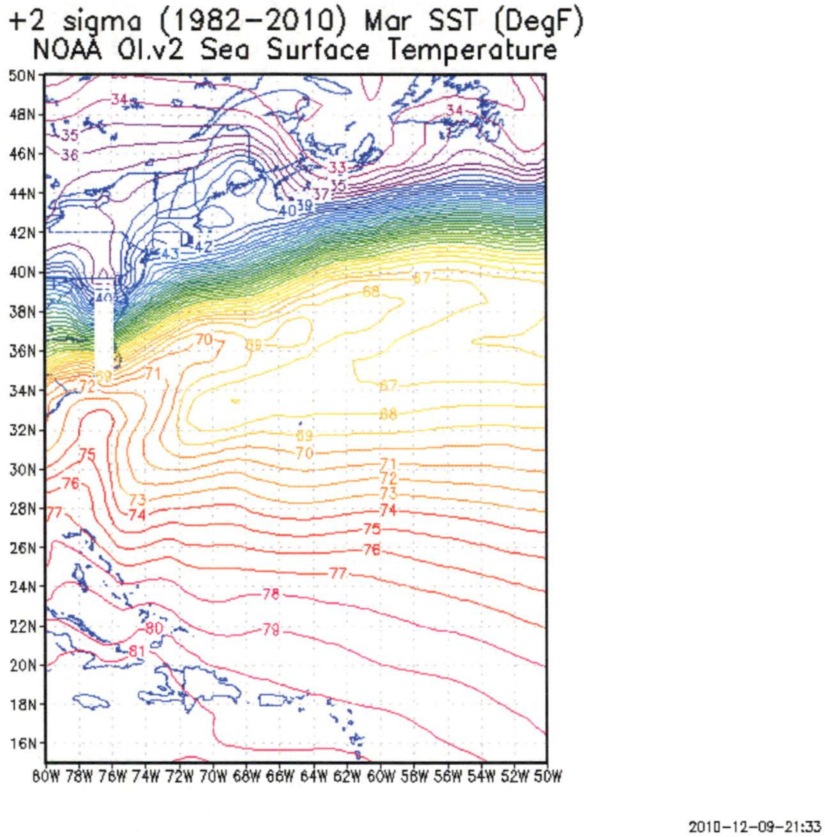


Figure C.39 March +2 sigma SST climatology-western Atlantic Ocean

CALCULATION SHEET

Calculation Title: Appendix C – Climatological Maximum Dew Point and Sea Surface Temperature Maps	Calculation No.: CDQ0000002016000041	Rev. No.: 001	Sheet: C46

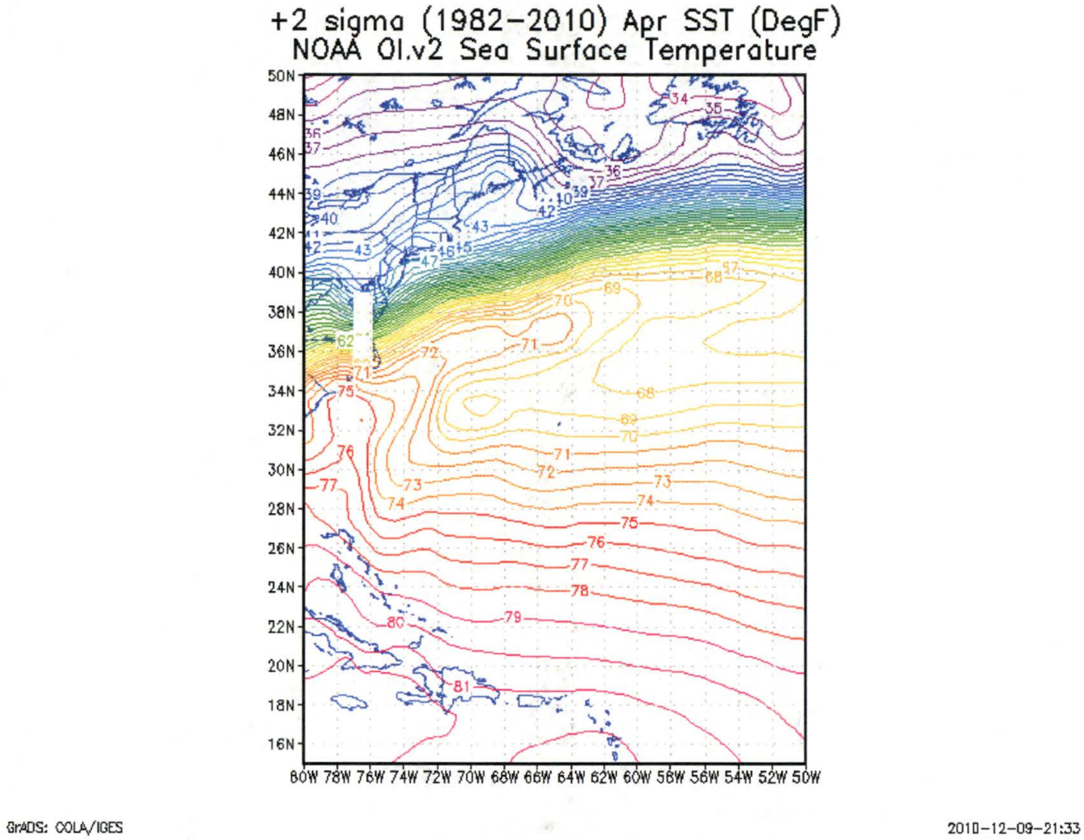


Figure C.40 April +2 sigma SST climatology-western Atlantic Ocean

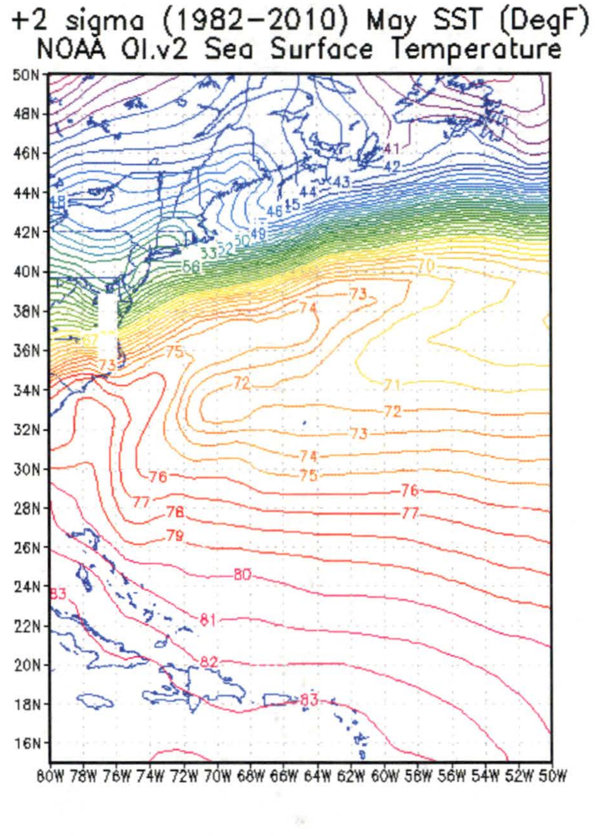


Figure C.41 May +2 sigma SST climatology-western Atlantic Ocean

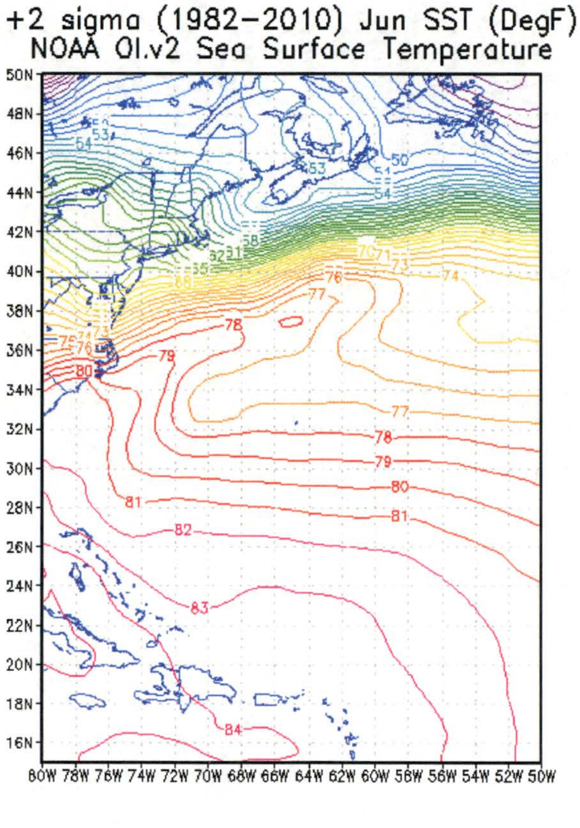


Figure C.42 June +2 sigma SST climatology-western Atlantic Ocean

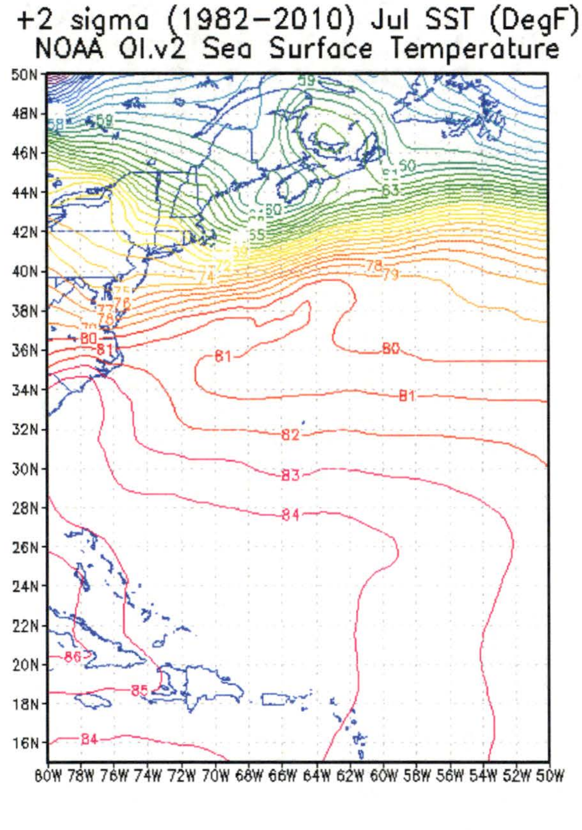


Figure C.43 July +2 sigma SST climatology-western Atlantic Ocean

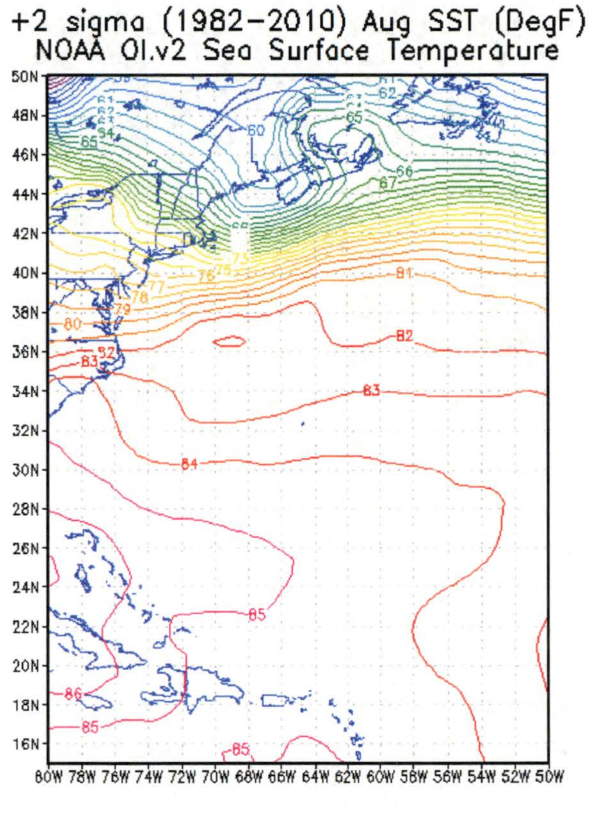


Figure C.44 August +2 sigma SST climatology-western Atlantic Ocean

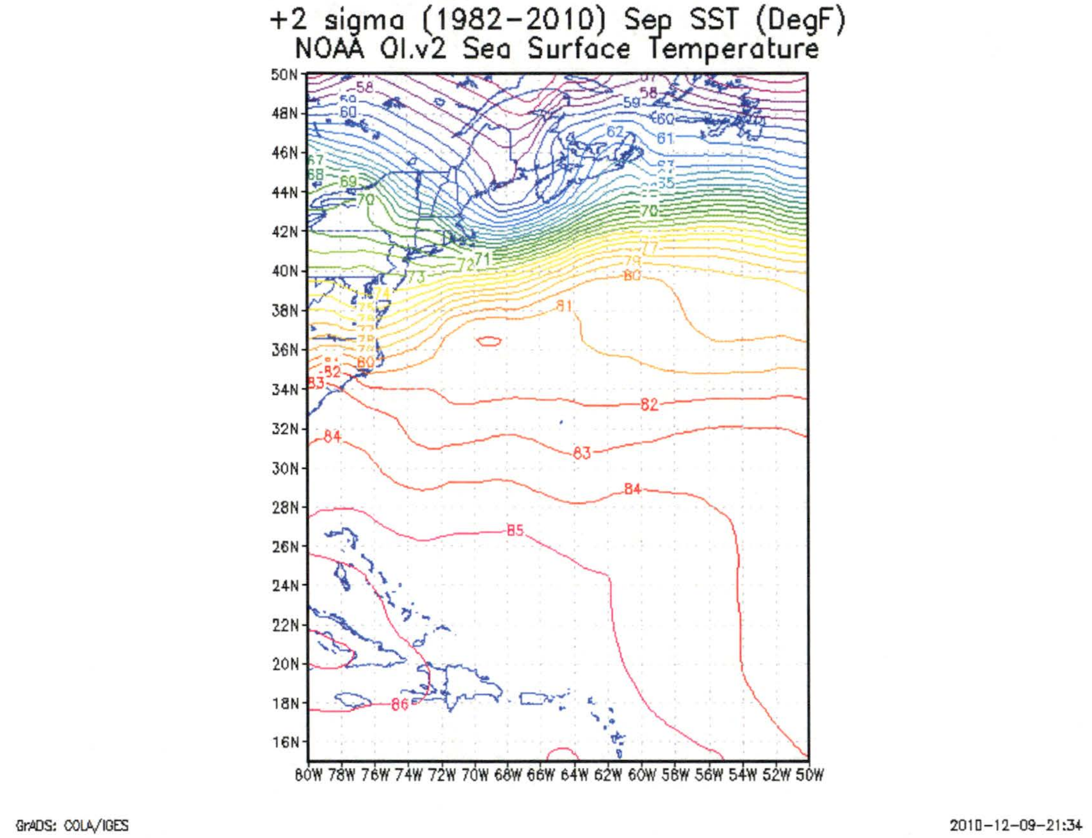


Figure C.45 September +2 sigma SST climatology-western Atlantic Ocean

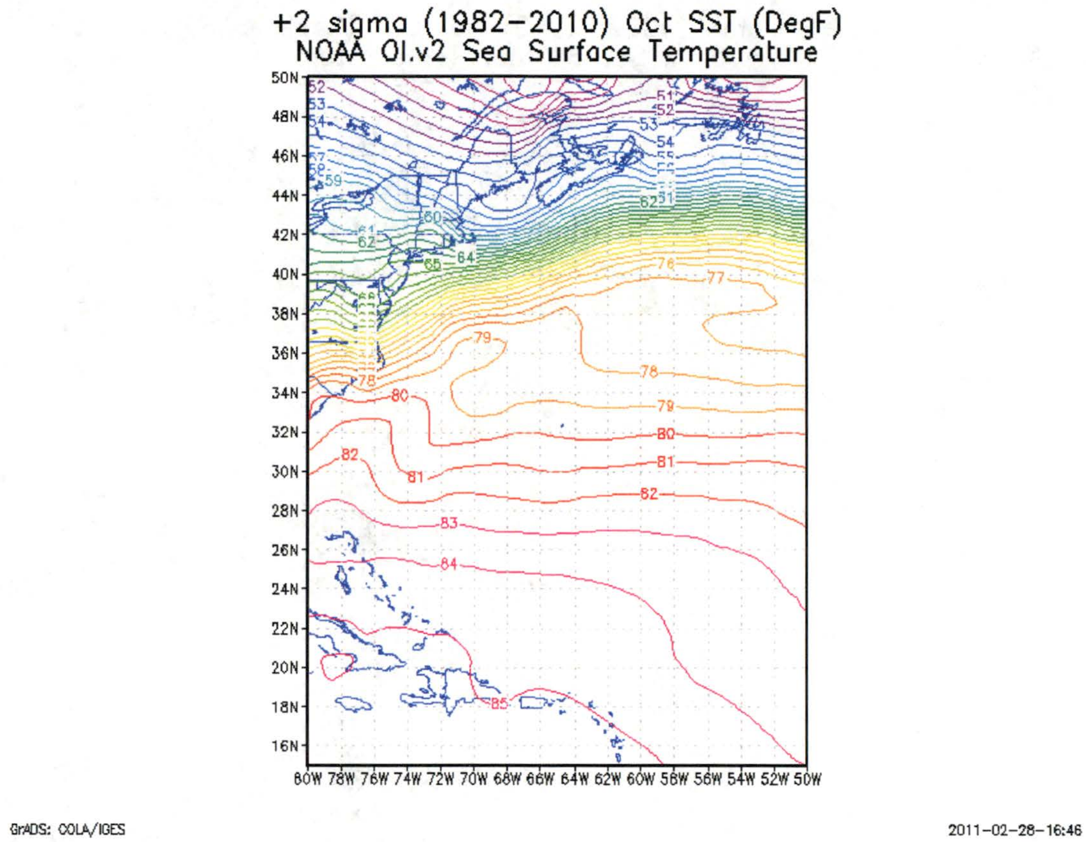


Figure C.46 October +2 sigma SST climatology-western Atlantic Ocean

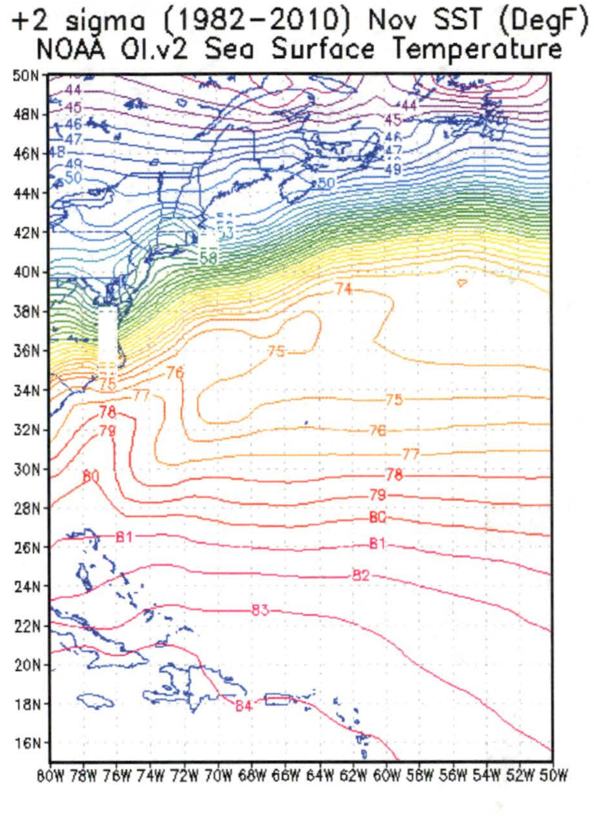


Figure C.47 November +2 sigma SST climatology-western Atlantic Ocean

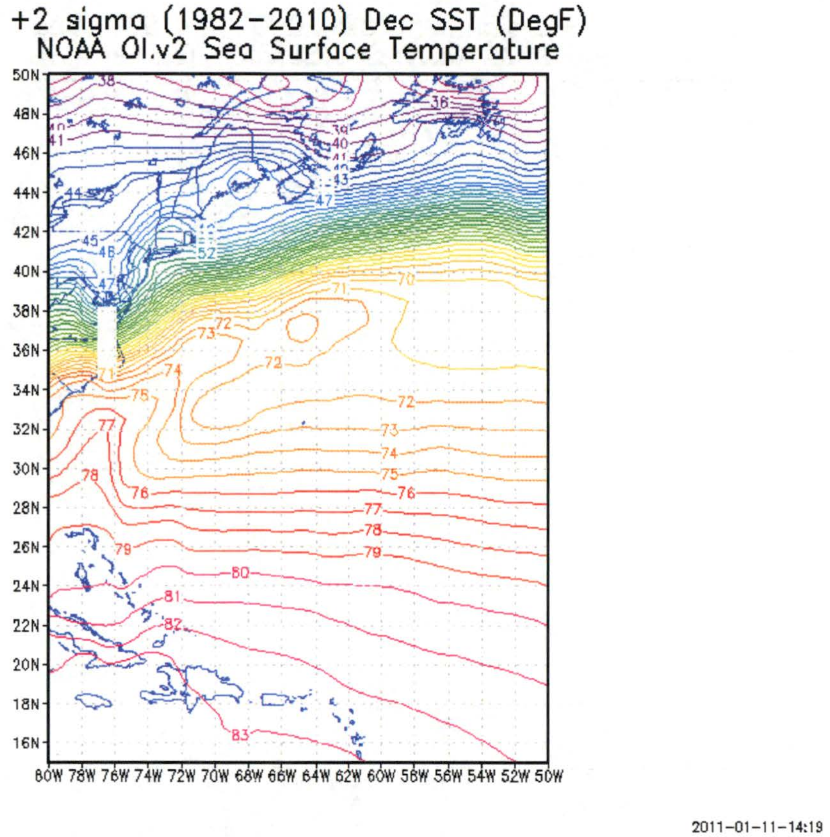


Figure C.48 December +2 sigma SST climatology-western Atlantic Ocean

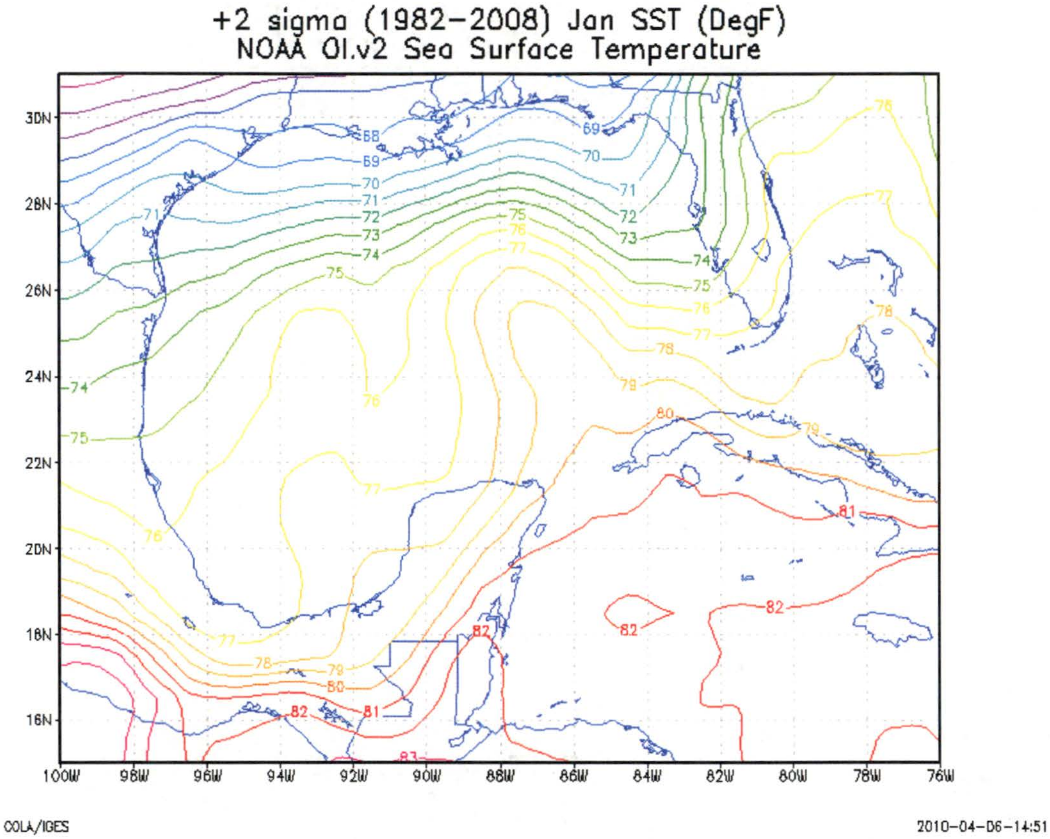


Figure C.49 January +2 sigma SST climatology-Gulf of Mexico

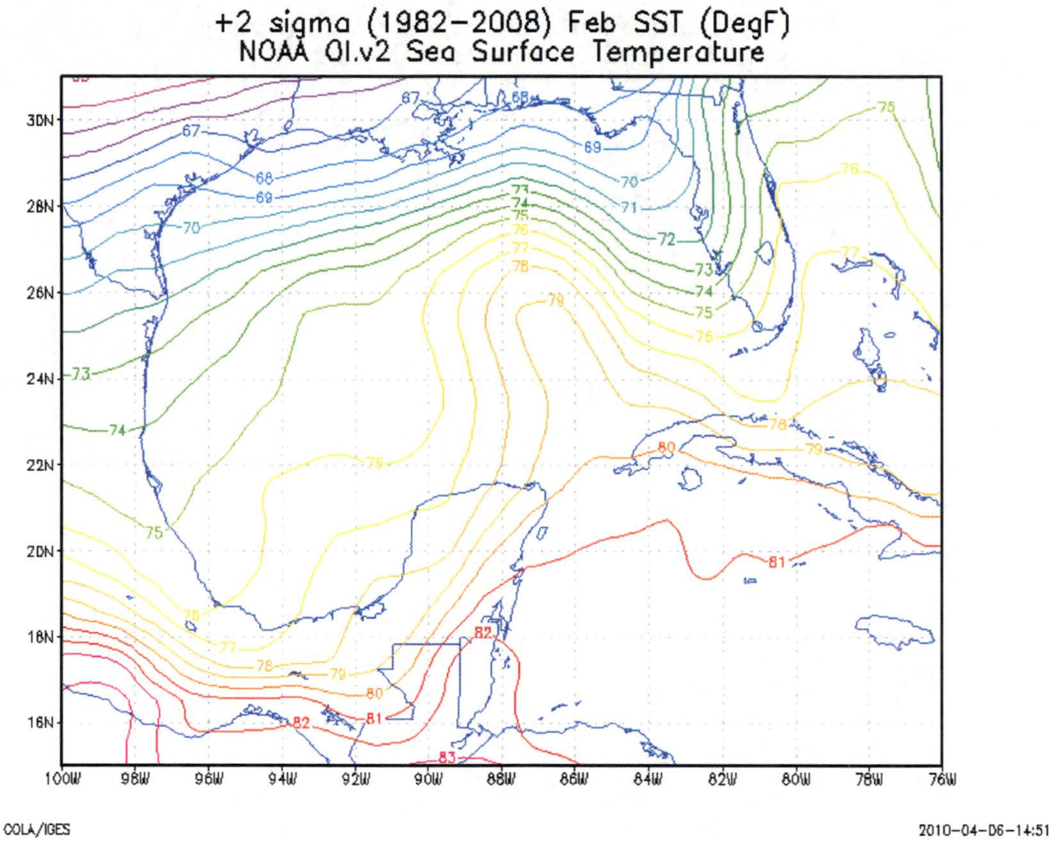


Figure C.50 February +2 sigma SST climatology-Gulf of Mexico

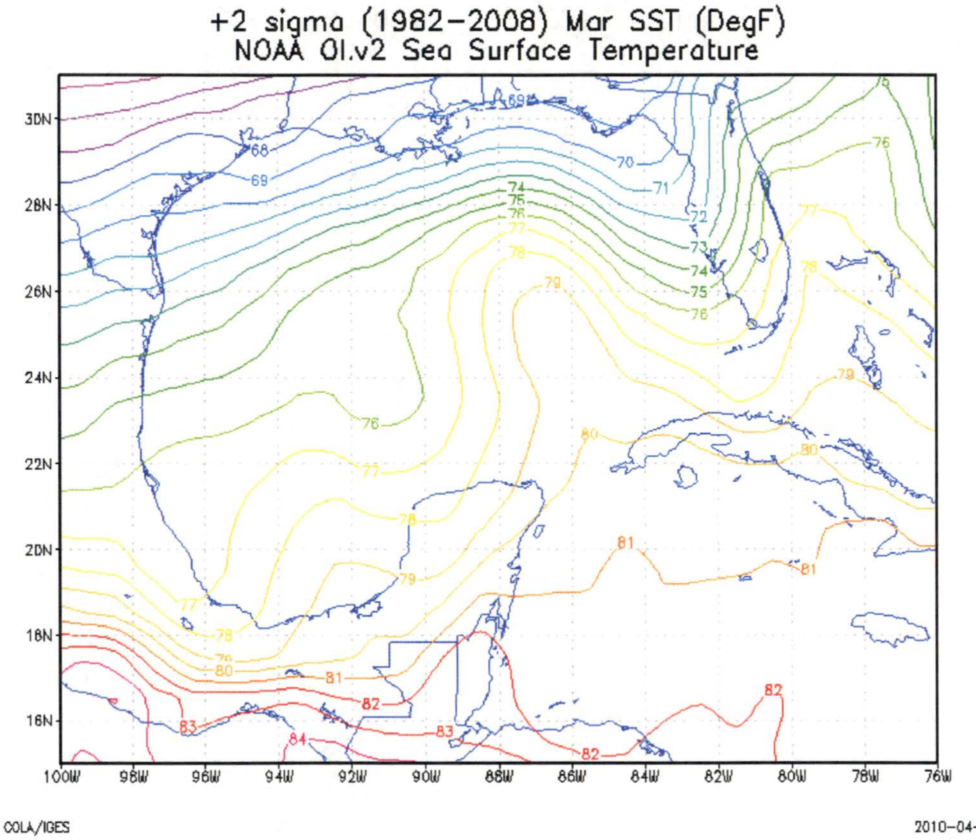


Figure C.51 March +2 sigma SST climatology-Gulf of Mexico

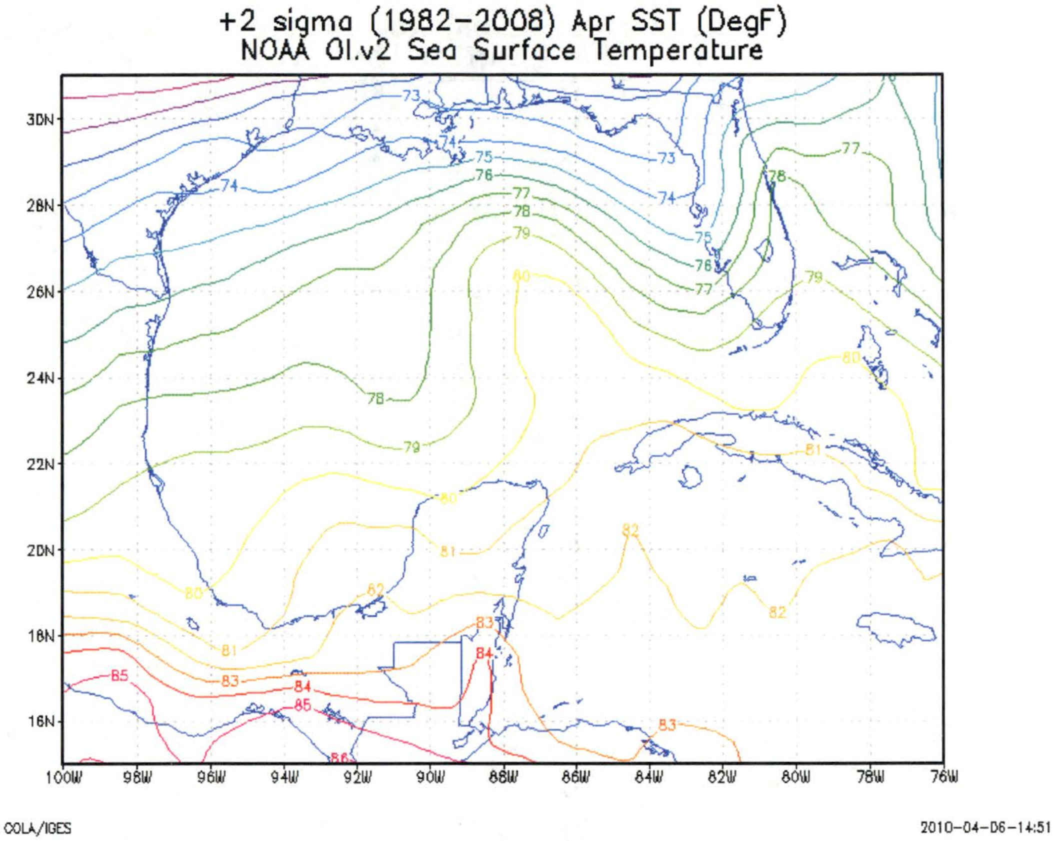


Figure C.52 April +2 sigma SST climatology-Gulf of Mexico

CALCULATION SHEET

Calculation Title: Appendix C – Climatological Maximum Dew Point and Sea Surface Temperature Maps	Calculation No.: CDQ000000201600004	Rev. No.: 001	Sheet: C59

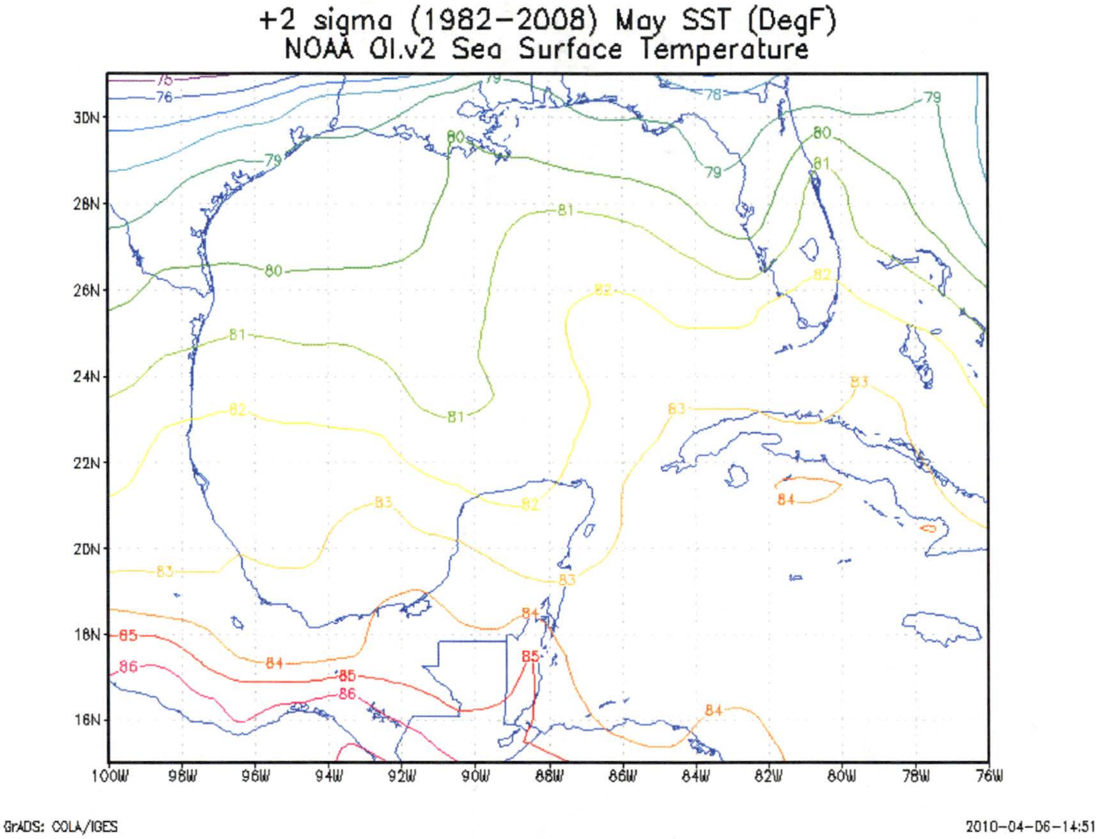


Figure C.53 May +2 sigma SST climatology-Gulf of Mexico

CALCULATION SHEET			
Calculation Title: Appendix C – Climatological Maximum Dew Point and Sea Surface Temperature Maps	Calculation No.: CDQ000002016000041	Rev. No.: 001	Sheet: C60

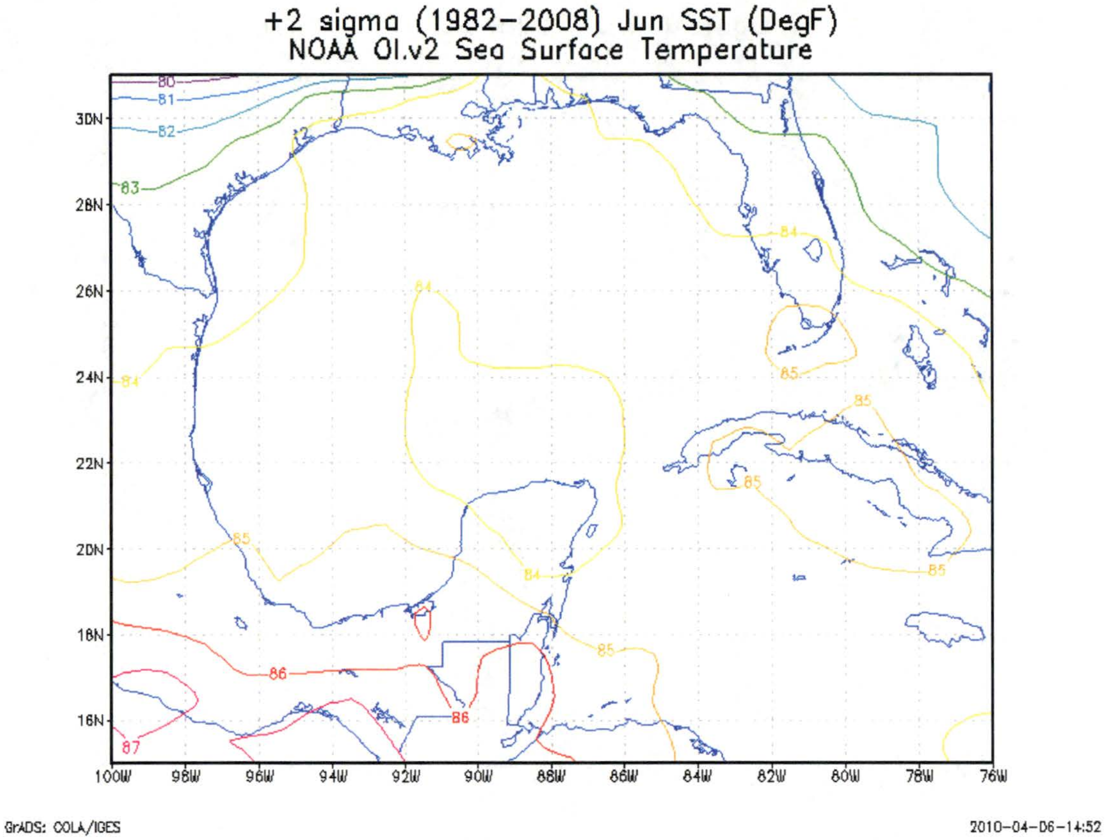


Figure C.54 June +2 sigma SST climatology-Gulf of Mexico

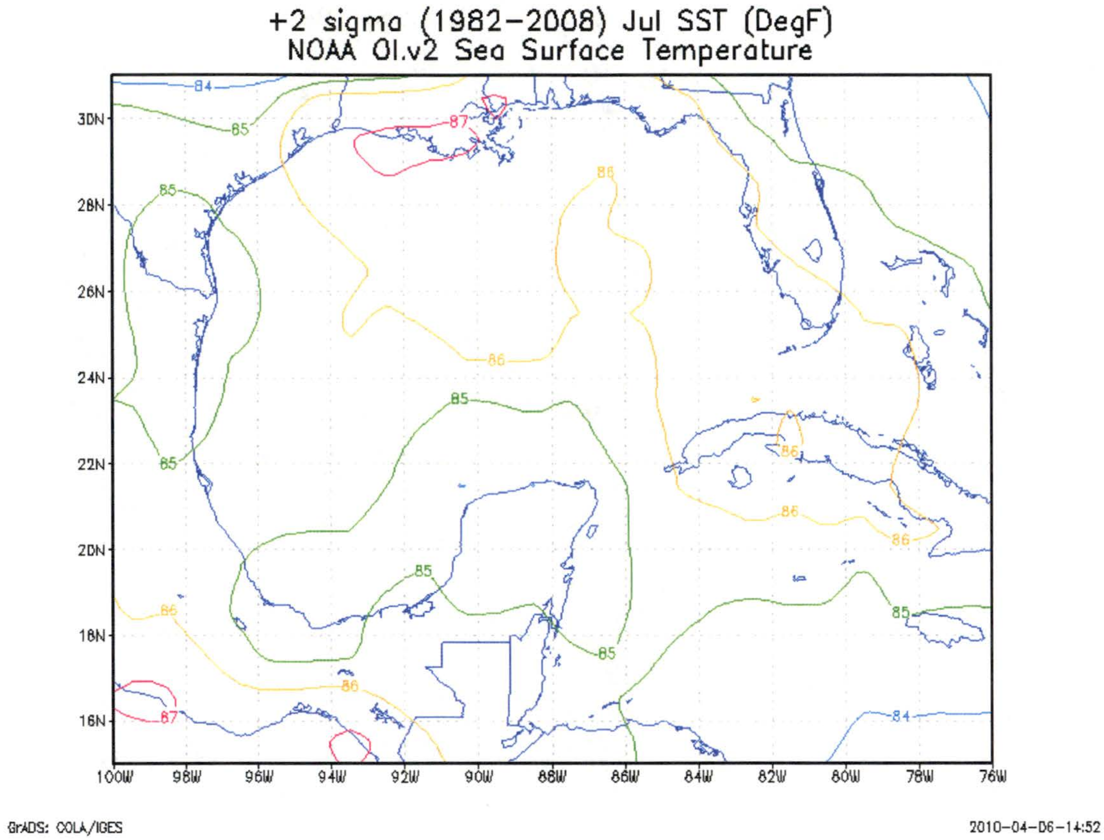


Figure C.55 July +2 sigma SST climatology-Gulf of Mexico

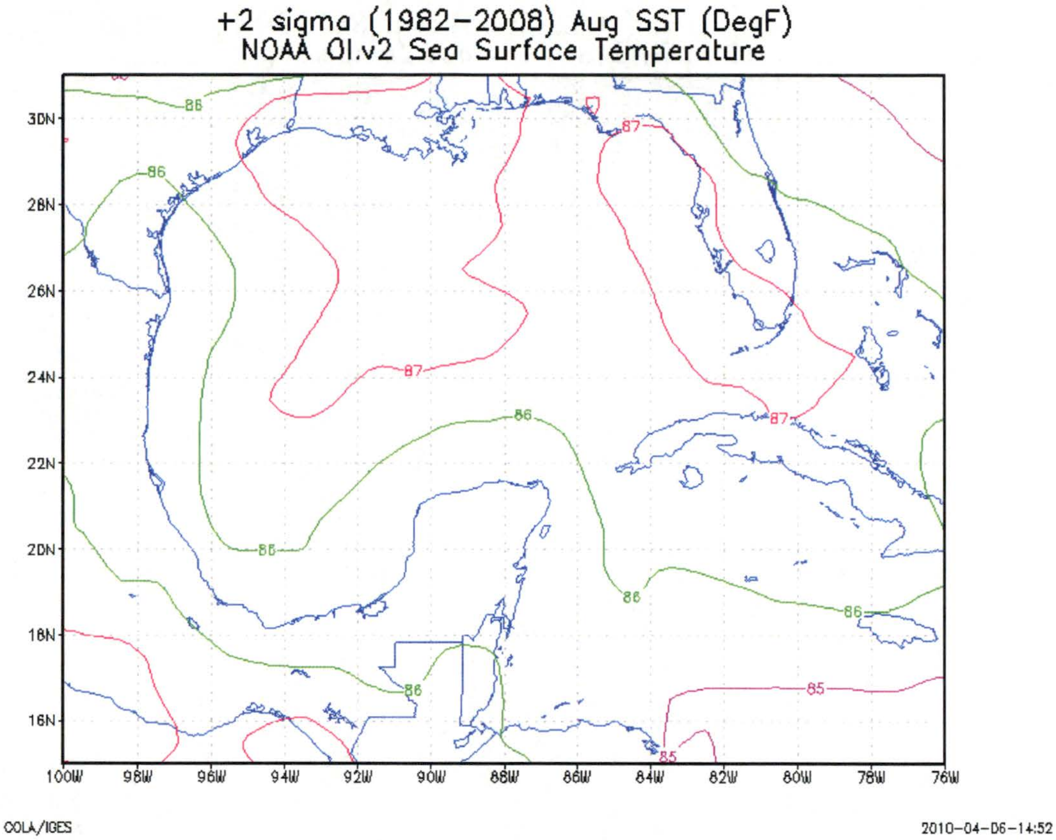


Figure C.56 August +2 sigma SST climatology-Gulf of Mexico

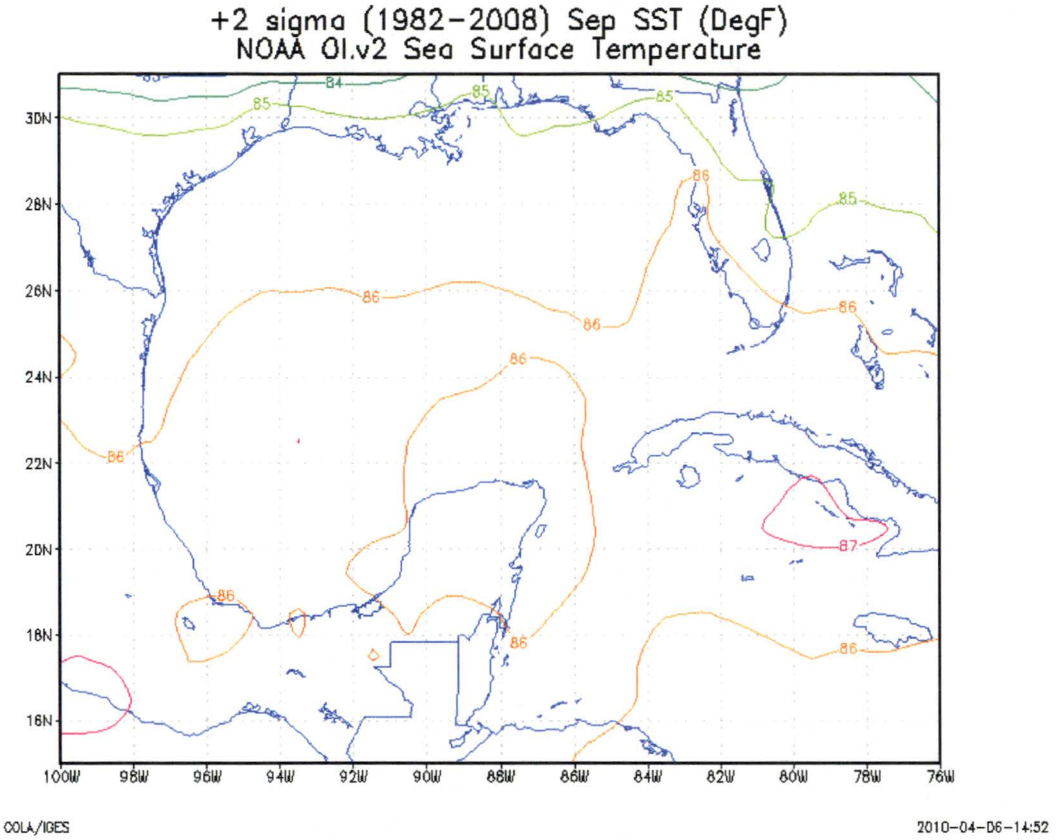


Figure C.57 September +2 sigma SST climatology-Gulf of Mexico

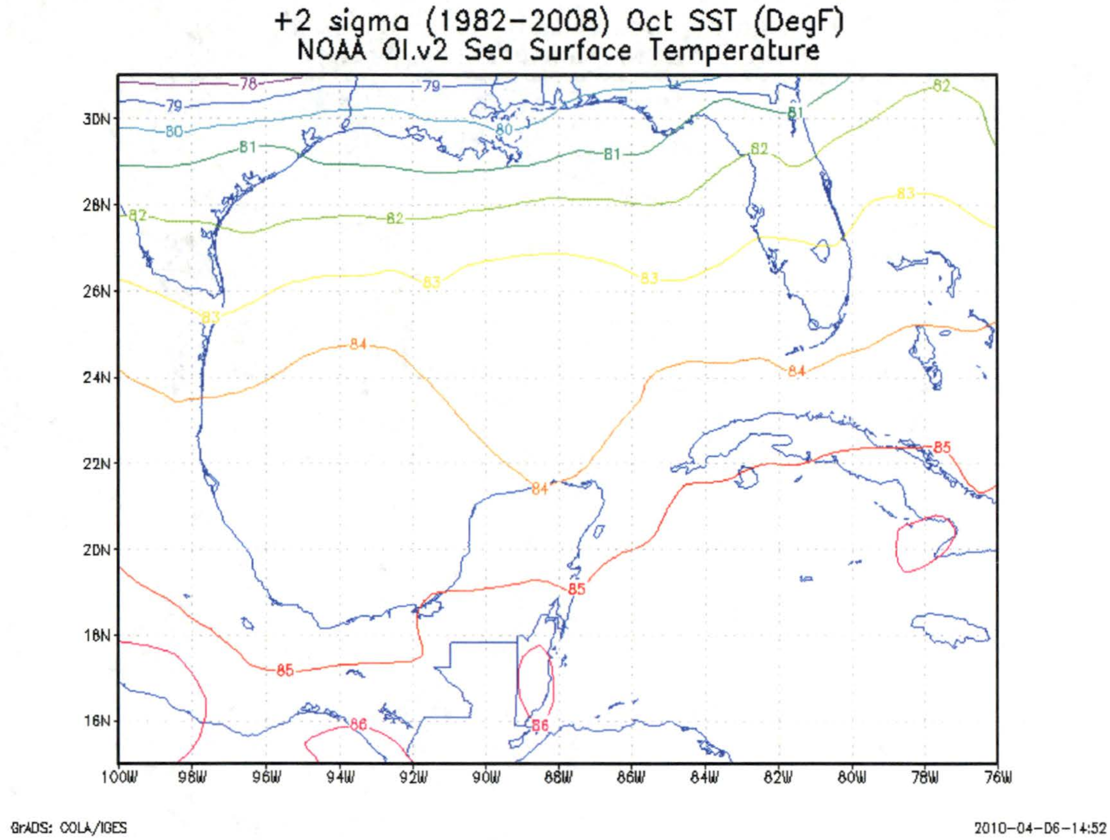


Figure C.58 October +2 sigma SST climatology-Gulf of Mexico

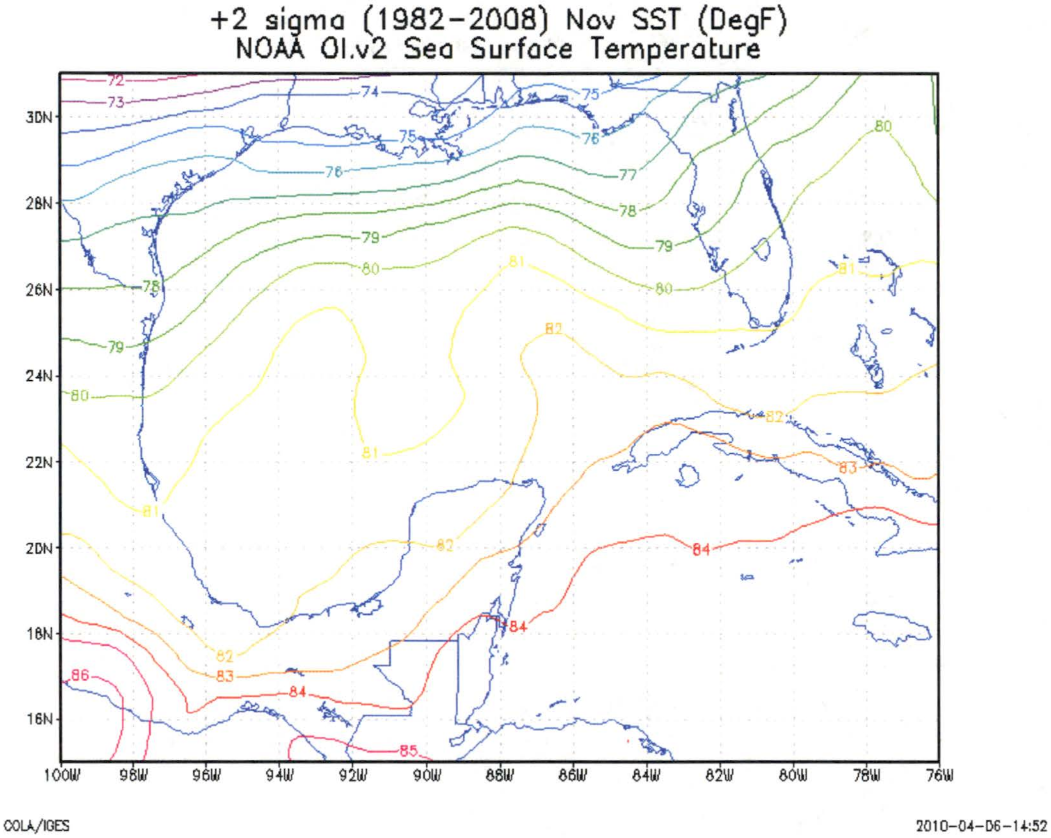


Figure C.59 November +2 sigma SST climatology-Gulf of Mexico

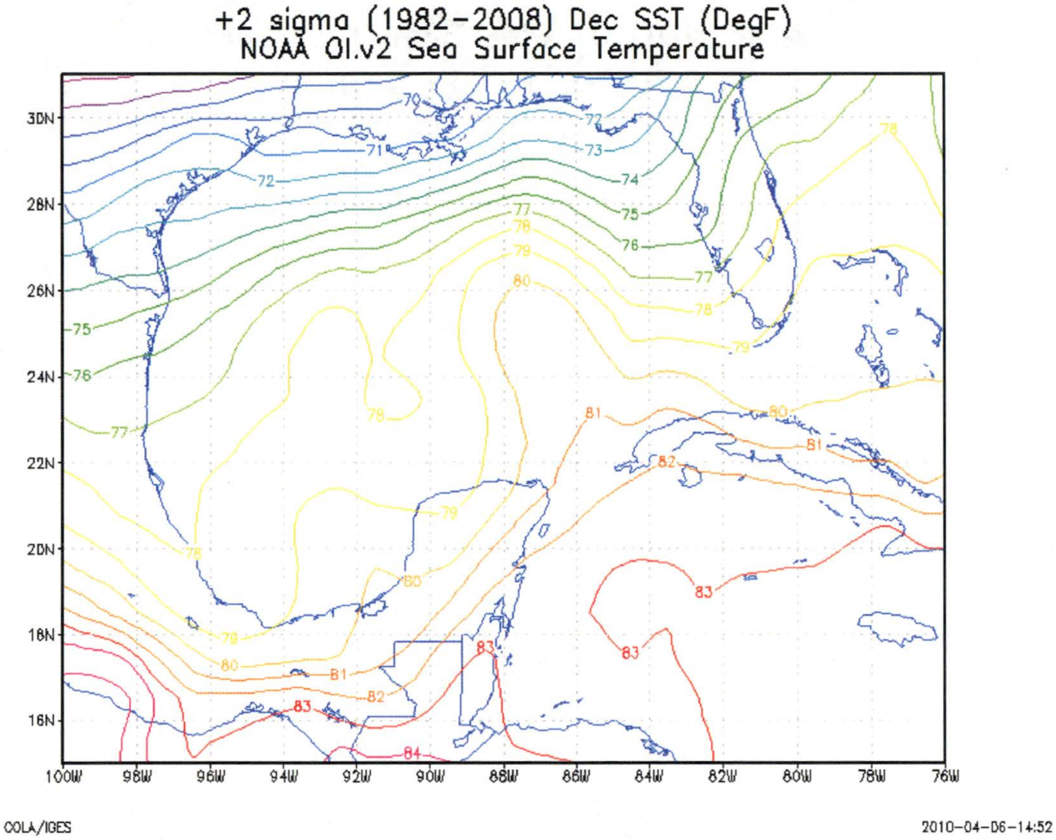


Figure C.60 December +2 sigma SST climatology-Gulf of Mexico

APPENDIX D – PMP Evaluation Tool

```
''' ---------------------------------------------------------------------
Name: PMP_Calc.py
Version: 1.00
ArcGIS Version: ArcGIS Desktop 10.2 SP1 (2014)
Author: Applied Weather Associates
Usage: The tool is designed to be executed within an the ArcMap or ArcCatalog desktop environment.
Required Arguments:
- An AOI polygon shapefile or feature class
Description:
   This tool calculates PMP depths for a given drainage basin for the
specified durations. PMP point values are calculated (in inches) for each
grid point (spaced at 90 arc-second intervals) over the project domain. The
points are converted to gridded PMP datasets for each duration.
---------------------------------------------------------------------'''
###########################################################################################
## import Python modules
import sys
import arcpy
from arcpy import env
import arcpy.management as dm
import arcpy.conversion as con
env.overwriteOutput = True                                   # Set overwrite option
###########################################################################################
## get input parameters
basin = arcpy.GetParameter(0)                                # get AOI Basin Shapefile
home = arcpy.GetParameterAsText(1)                             # get location of 'PMP' Project Folder
outLocation = arcpy.GetParameterAsText(2)
genDurations = arcpy.GetParameter(3)                           # get general storm durations (string)
locDurations = arcpy.GetParameter(4)                           # get local storm durations (string)
tropDurations = arcpy.GetParameter(5)                          # get tropical storm durations (string)
dadGDB = home + "\\Input\\DAD_Tables.gdb"                         # location of DAD tables
adjFactGDB = home + "\\Input\\Storm_Adj_Factors.gdb"                  # location of feature datasets
```

containing total adjustment factors

```
def pmpAnalysis(aoiBasin, stormType, durList):
    ###########################################################################################
    ## Create PMP Point Feature Class from points within AOI basin and add fields
    def createPMPfc():
        arcpy.AddMessage("\nCreating feature class: 'PMP_Points' in Scratch.gdb...")
        dm.MakeFeatureLayer(home + "\\Input\Non_Storm_Data.gdb\\Vector_Grid", "vgLayer")           #
make a feature layer of vector grid cells
        dm.SelectLayerByLocation("vgLayer", "INTERSECT", aoiBasin)                        # select the
vector grid cells that intersect the aoiBasin polygon
        dm.MakeFeatureLayer(home + "\\Input\Non_Storm_Data.gdb\\Grid_Points", "gpLayer")          #
make a feature layer of grid points
        dm.SelectLayerByLocation("gpLayer", "HAVE_THEIR_CENTER_IN", "vgLayer")                    #
select the grid points within the vector grid selection
        con.FeatureClassToFeatureClass("gpLayer", env.scratchGDB, "PMP_Points")                # save
feature layer as "PMP_Points" feature class
        arcpy.AddMessage("(" + str(dm.GetCount("gpLayer")) + " grid points will be analyzed)")
        # Add PMP Fields
        for dur in durList:
            arcpy.AddMessage("\n\t...adding field: PMP_" + str(dur))
            dm.AddField(env.scratchGDB + "\\PMP_Points", "PMP_" + dur, "DOUBLE")
        # Add STORM Fields (this string values identifies the driving storm by SPAS ID number)
        for dur in durList:
            arcpy.AddMessage("\n\t...adding field: STORM_" + str(dur))
            dm.AddField(env.scratchGDB + "\\PMP_Points", "STORM_" + dur, "TEXT", "", "", 16)
        return
    ###########################################################################################
    ## Define getAOIarea() function:
    ## getAOIarea() calculates the area of AOI (basin outline) input shapefile/
    ## featureclass. The basin outline shapefile must be projected. The area
    ## is sqaure miles, converted from the basin layers projected units (feet
    ## or meters). The aoiBasin feature class should only have a single feature
    ## (the basin outline). If there are multiple features, the area will be stored
    ## for the final feature only.
```

```
def getAOIarea():
    sr = arcpy.Describe(aoiBasin).SpatialReference          # Determine aoiBasin spatial reference system
    srname = sr.name
    srtype = sr.type
    srunitname = sr.linearUnitName                    # Units
    arcpy.AddMessage("\nAOI Basin Spatial Reference:  " + srname + "\nUnit Name: " + srunitname +
"\nSpatial Ref. type: " + srtype)
    aoiArea = 0.0
    rows = arcpy.SearchCursor(aoiBasin)
    for row in rows:
      feat = row.getValue("Shape")
      aoiArea += feat.area
    if srtype == 'Geographic':                        # Must have a surface projection
      arcpy.AddMessage("\nThe basin shapefile's spatial reference '" + srtype + "' is not supported.
Please use a 'Projected' shapefile or feature class.\n")
      raise SystemExit
    elif srtype == 'Projected':
      if srunitname == "Meter":
        aoiArea = aoiArea * 0.000000386102            # Converts square meters to square miles
      elif srunitname == "Foot" or "Foot_US":
        aoiArea = aoiArea * 0.00000003587             # Converts square feet to square miles
      else:
        arcpy.AddMessage("\nThe basin shapefile's unit type '" + srunitname + "' is not supported.")
        sys.exit("Invalid linear units")              # Units must be meters or feet
    aoiArea = round(aoiArea, 3)
    arcpy.AddMessage("\nArea of interest: " + str(aoiArea) + " square miles.")
    if arcpy.GetParameter(6) == False:
      aoiArea = arcpy.GetParameter(7)    ## Enable a constant area size
    arcpy.AddMessage("\n***Area used for PMP analysis: " + str(aoiArea) + " sqmi***")
    return aoiArea
##########################################################################################
## Define dadLookup() function:
## The dadLookup() function determines the DAD value for the current storm
```

```
## and duration according to the basin area size.  The DAD depth is interpolated
## linearly between the two nearest areal values within the DAD table.
def dadLookup(stormLayer, duration, area):                # dadLookup() accepts the current storm layer name (string), the current duration (string), and AOI area size (float)
    #arcpy.AddMessage("\t\tfunction dadLookup() called.")
    durField = "H_" + duration                            # defines the name of the duration field (eg., "H_06" for 6-hour)
    dadTable = dadGDB + "\\" + stormLayer
    rows = arcpy.SearchCursor(dadTable)
    try:
        row = rows.next()                                 # Sets DAD area x1 to the value in the first row of the DAD table.
        x1 = row.AREASQMI
        y1 = row.getValue(durField)
        xFlag = "FALSE"                                   # xFlag will remain false for basins that are larger than the largest DAD area.
    except RuntimeError:                                  # return if duration does not exist in DAD table
        return
    row = rows.next()
    i = 0
    while row:                                            # iterates through the DAD table - assiging the bounding values directly above and below the basin area size
        i += 1
        if row.AREASQMI < area:
            x1 = row.AREASQMI
            y1 = row.getValue(durField)
        else:
            xFlag = "TRUE"                                # xFlag is switched to "TRUE" indicating area is within DAD range
            x2 = row.AREASQMI
            y2 = row.getValue(durField)
            break
        row = rows.next()
    del row, rows, i
```

```
if xFlag == "FALSE":
    x2 = area                     # If x2 is equal to the basin area, this means that the largest DAD area is smaller than the basin and the resulting DAD value must be extrapolated.
    arcpy.AddMessage("\t\tThe basin area size: " + str(area) + " sqmi is greater than the largest DAD area: " + str(x1) + " sqmi.\n\t\tDAD value is estimated by extrapolation.")
    y = x1 / x2 * y1              # y (the DAD depth) is estimated by extrapolating the DAD area to the basin area size.
    return y                      # The extrapolated DAD depth (in inches) is returned.
# arcpy.AddMessage("\nArea = " + str(area) + "\nx1 = " + str(x1) + "\nx2 = " + str(x2) + "\ny1 = " + str(y1) + "\ny2 = " + str(y2))
x = area                          # If the basin area size is within the DAD table area range, the DAD depth is interpolated
deltax = x2 - x1                  # to determine the DAD value (y) at area (x) based on next lower (x1) and next higher (x2) areas.
deltay = y2 - y1
diffx = x - x1
y = y1 + diffx * deltay / deltax
if x < x1:
    arcpy.AddMessage("\t\tThe basin area size: " + str(area) + " sqmi is less than the smallest DAD table area: " + str(x1) + " sqmi.\n\t\tDAD value is estimated by extrapolation.")
return y                          # The interpolated DAD depth (in inches) is returned.
###########################################################################################
## Define updatePMP() function:
## This function updates the 'PMP_XX_' and 'STORM_XX' fields of the PMP_Points
## feature class with the largest value from all analyzed storms stored in the
## pmpValues list.
def updatePMP(pmpValues, stormID, duration):          # Accepts four arguments: pmpValues - largest adjusted rainfall for current duration (float list); stormID - driver storm ID for each PMP value (text list); and duration (string)
    pmpfield = "PMP_" + duration
    stormfield = "STORM_" + duration
    gridRows = arcpy.UpdateCursor(env.scratchGDB + "\\PMP_Points")          # iterates through PMP_Points rows
    i = 0
    for row in gridRows:
```

```
        row.setValue(pmpfield, pmpValues[i])                    # Sets the PMP field value
equal to the Max Adj. Rainfall value (if larger than existing value).
        row.setValue(stormfield, stormID[i])                    # Sets the storm ID field to
indicate the driving storm event
        gridRows.updateRow(row)
        i += 1
    del row, gridRows, pmpfield, stormfield
    arcpy.AddMessage("\n\t" + duration + "-hour PMP values update complete. \n")
    return
###########################################################################################
## The outputPMP() function produces raster GRID files for each of the PMP durations.
## Aslo, a space-delimited PMP_Distribition.txt file is created in the 'Text_Output' folder.
def outputPMP(type, area, outPath):
    pmpPoints = env.scratchGDB + "\\PMP_Points"                # Location of 'PMP_Points' feature
class which will provide data for output
    outType = type[:1]
    outArea = str(int(area)).rjust(5, '0')
    outGDB = "PMP_"+ str(int(area)) + ".gdb"                  # Check to see if PMP_XXXXX.gdb already
exists
    if not arcpy.Exists(outPath + "\\" + outGDB):
        arcpy.AddMessage("\nCreating output geodatabase '" + outGDB + "'")
        dm.CreateFileGDB(outPath, outGDB)
    arcpy.AddMessage("\nCopying PMP_Points feature class to " + outGDB + "...")
    con.FeatureClassToFeatureClass(pmpPoints, outPath + "\\" + outGDB, type + "_PMP_Points_" +
str(int(area)))
    arcpy.AddMessage("\nBeginning PMP Raster Creation...")
    for dur in durList:                                # This code creates a raster GRID from the current
PMP point layer
        durField = "PMP_" + dur
        outLoc = outPath + outGDB +"\\" + outType + "_" + dur + "_" + outArea
        arcpy.AddMessage("\n\tInput Path: " + pmpPoints)
        arcpy.AddMessage("\tOutput raster path: " + outPath)
        arcpy.AddMessage("\tField name: " + durField)
        con.FeatureToRaster(pmpPoints, durField, outLoc, "0.025")
```

```
    arcpy.AddMessage("\tOutput raster created...")
  del durField, outLoc, dur
  arcpy.AddMessage("\nPMP Raster Creation complete.")
  ###### This section applies the metadata templates to the output GIS files ######
  pointMetaLoc = home + "\\Input\\Metadata_Templates\\PMP_Points_Metadata_FGDC.xml"   # Location of feature class metadata template
  rasMetaLoc = home + "\\Input\\Metadata_Templates\\PMP_Raster_Metadata_FGDC.xml"   # Location of raster file metadata template
  arcpy.AddMessage("\nAdding metadata to output files...")
##    arcpy.AddMessage("\n\tPMP_Points feature class")
##    con.MetadataImporter(pointMetaLoc, pmpPoints)   # Applies metadata to 'PMP_Points' feature class
  for dur in durList:                        # Applies metadata to PMP Rasters
    outLoc = outPath + outGDB +"\\" + outType + "_" + dur + "_" + outArea
    targetPath = outLoc
    con.MetadataImporter(rasMetaLoc, targetPath)
  del dur, outLoc, targetPath
  arcpy.AddMessage("\nOutput metadata import complete.")
  return
 ###########################################################################################
 ## This portion of the code iterates through each storm feature class in the
 ## 'Storm_Adj_Factors' geodatabase (evaluating the feature class only within
 ## the Local, Tropical, or general feature dataset).  For each duration,
 ## at each grid point within the aoi basin, the transpositionality is
 ## confirmed.  Then the DAD precip depth is retrieved and applied to the
 ## total adjustement factor to yield the total adjusted rainfall.  This
 ## value is then sent to the updatePMP() function to update the 'PMP_Points'
 ## feature class.
##~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
##
 desc = arcpy.Describe(basin)                 # Check to ensure AOI input shape is a Polygon. If not - exit.
 basinShape = desc.shapeType
```

```
    if desc.shapeType == "Polygon":
        arcpy.AddMessage("\nBasin shape type: " + desc.shapeType)
    else:
        arcpy.AddMessage("\nBasin shape type: " + desc.shapeType)
        arcpy.AddMessage("\nError: Input shapefile must be a polygon!\n")
        sys.exit()
    createPMPfc()                                        # Call the createPMPfc() function to create
the PMP_Points feature class.
    env.workspace = adjFactGDB                           # the workspace environment is set
to the 'Storm_Adj_Factors' file geodatabase
    aoiSQMI = round(getAOIarea(),2)                      # Calls the getAOIarea() function to
assign area of AOI shapefile to 'aoiSQMI'
    for dur in durList:
        stormList = arcpy.ListFeatureClasses("", "Point", stormType)        # List all the total adjustment
factor feature classes within the storm type feature dataset.
        arcpy.AddMessage("\n***************************************************************\nEvaluating " + dur + "-
hour duration...")
        pmpList = []
        driverList = []
        gridRows = arcpy.SearchCursor(env.scratchGDB + "\\PMP_Points")
        try:
            for row in gridRows:
                pmpList.append(0.0)                      # creates pmpList of empty float values
for each grid point to store final PMP values
                driverList.append("STORM")               # creates driverList of empty text
values for each grid point to store final Driver Storm IDs
            del row, gridRows
        except UnboundLocalError:
            arcpy.AddMessage("\n***Error: No data present within basin/AOI area.***\n")
            sys.exit()
        for storm in stormList:
            arcpy.AddMessage("\n\tEvaluating storm: " + storm + "...")
            dm.MakeFeatureLayer(storm, "stormLayer")     # creates a feature layer for the
current storm
```

```
        dm.SelectLayerByLocation("stormLayer", "HAVE_THEIR_CENTER_IN", "vgLayer")    # examines
only the grid points that lie within the AOI
        gridRows = arcpy.SearchCursor("stormLayer")
        pmpField = "PMP_" + dur
        i = 0
        try:
          dadPrecip = round(dadLookup(storm, dur, aoiSQMI),3)
          arcpy.AddMessage("\t\t" + dur + "-hour DAD value:  " + str(dadPrecip) + chr(34))
        except TypeError:                                    # In no duration exists in the DAD table -
move to the next storm
          arcpy.AddMessage("\t***Duration '" + str(dur) + "-hour' is not present for " + str(storm) + ".***\n")
          continue
        arcpy.AddMessage("\t\tComparing " + storm + " adjusted rainfall values against current driver
values...\n")
        for row in gridRows:
          if row.TRANS == 1:                                 # Only continue if grid point is transpositionable
('1' is transpostionable, '0' is not).
            try:                                             # get total adj. factor if duration exists
              adjRain = round(dadPrecip * row.TAF,2)
              if adjRain > pmpList[i]:
                pmpList[i] = adjRain
                driverList[i] = storm
            except RuntimeError:
              arcpy.AddMessage("\t\t   *Warning*  Total Adjusted Raifnall value falied to set for row " +
str(row.CNT))
            del adjRain
          i += 1
        del row
      del storm, stormList, gridRows, dadPrecip
      updatePMP(pmpList, driverList, dur)          # calls function to update "PMP Points" feature class
    del dur, pmpList
    arcpy.AddMessage("\n'PMP_Points' Feature Class 'PMP_XX' fields update complete for all '" +
stormType + "' storms.")
    outputPMP(stormType, aoiSQMI, outputPath)           # calls outputPMP() function
```

```
    del aoiSQMI
    return
##~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
##
if genDurations:
    type = "General"
    durations = genDurations
    dm.CreateFolder(outLocation, type)
    outputPath = outLocation + "\\General\\"
    arcpy.AddMessage("\nRunning PMP analysis for storm type: " + type)
    pmpAnalysis(basin, type, durations)          # Calls the pmpAnalysis() function to calculate the general storm PMP
    arcpy.AddMessage("\nGeneral Winter storm analysis complete...\n*******************************************************************************************************")
if locDurations:
    type = "Local"
    durations = locDurations
    dm.CreateFolder(outLocation, type)
    outputPath = outLocation + \\Local\\
    arcpy.AddMessage("\nRunning PMP analysis for storm type: " + type)
    pmpAnalysis(basin, type, durations)    # Calls the pmpAnalysis() function to calculate the local storm PMP
    arcpy.AddMessage("\nLocal storm analysis complete...\n*******************************************************************************************************")
if tropDurations:
    type = "Tropical"
    durations = tropDurations
    dm.CreateFolder(outLocation, type)
    outputPath = outLocation + "\\Tropical\\"
    arcpy.AddMessage("\nRunning PMP analysis for storm type: " + type)
    pmpAnalysis(basin, type, durations)          # Calls the pmpAnalysis() function to calculate the tropical storm PMP
```

```
arcpy.AddMessage("\nTropical storm analysis complete...\n****************************************************************************************************************
")
```