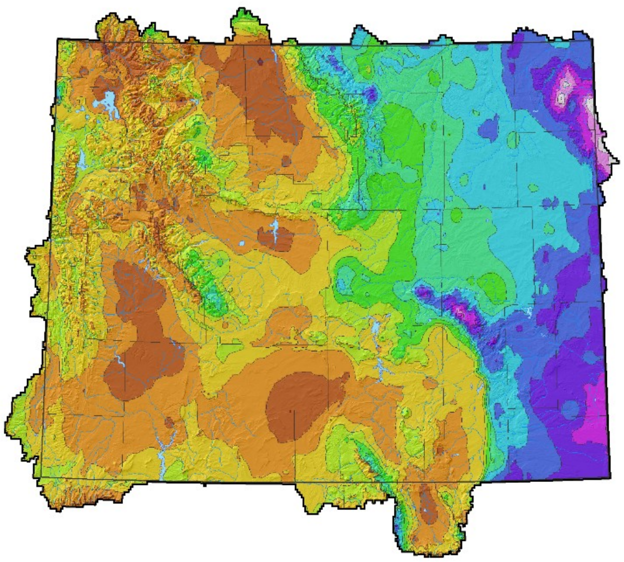
Probable Maximum Precipitation Study for Wyoming



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Notice

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Table of Contents

List of Figures

List of Tables

Executive Summary

Applied Weather Associates (AWA) completed a statewide Probable Maximum Precipitation (PMP) study for Wyoming. This study produced gridded PMP values for the project domain at a spatial resolution of approximately 2.4-square miles. Variations in topography, climate and storm types across the state were explicitly taken into account. A large set of storm data were analyzed for use in developing the PMP values. These values replace those provided in Hydrometeorological Reports (HMRs) 49, 51, 55A, and 57. The PMP values are valid from June 15 through September 15, with a seasonality adjustment to be applied for other dates of interest. Results of this analysis reflect the most current practices used for defining PMP, including comprehensive storm analyses procedures, extensive use of geographical information systems (GIS), explicit quantification of orographic effects, updated maximum dew point climatologies for storm maximization and transposition, and an updated understanding of the weather and climate throughout the state.

The approach used in this study follows the same philosophy used in the numerous site-specific, statewide, and regional PMP studies that AWA has completed in the last fifteen years. This is the storm-based approach and follows the same general procedures used by the National Weather Service (NWS) in the development of the HMRs. The World Meteorological Organization (WMO) Manual for PMP determination WMO Operational Hydrology Report recommends this same approach. The storm based approach identifies extreme rainfall events that have occurred in regions considered transpositionable to locations in Wyoming. These are storms that had meteorological and topographical characteristics similar to extreme rainfall storms that could occur over any location within the project domain. Detailed storm analyses are completed for the largest of these rainfall events.

The data, assumptions, and analysis techniques used in this study have been reviewed and accepted by the Wyoming Water Development Office (WWDO), the Wyoming Sate Engineer's Office (WSEO), the Natural Resources Conservation Service (NRCS), and the Technical Review Board for this study. Although this study produces deterministic values, it must be recognized that there is some subjectivity associated with the PMP development procedures. Examples of decisions where scientific judgment was involved include the determination of storm maximization factors and storm transposition limits. For areas where uncertainties in data analysis results are recognized, conservative assumptions are applied. All data and information supporting decisions in the PMP development process have been documented so that results can be reproduced and verified.

Thirty-four extreme rainfall events were identified as having similar characteristics to extreme storm rainfall centers that could potentially control PMP values at various locations within the state. Several storm events had multiple Depth-Area-Duration (DAD) zones (also referred to as SPAS DAD zones) that were used in the PMP determination process. A total of 42 storm DAD centers were used in the development of PMP for the state. This includes 21 general storm rainfall centers and 21 local storm rainfall centers. In addition, seven of the storm centers exhibit characteristics of both storm types and where therefore used as both general and local storms in the PMP determination process.

Forty-two individual storm center were analyzed using the Storm Precipitation Analysis System (SPAS), which produced several standard products, including DAD values; mass curves; and total storm isohyetal patterns. National Weather Service (NWS) Next Generation Weather Radar

(NEXRAD) data were used in storm analyses when available (generally for storms which occurred after the mid-1990's).

Standard procedures were applied for in-place maximization and moisture transposition adjustments (e.g. HMR 55A Section 5 and Section 8). New techniques and new datasets were used in other procedures to increase accuracy and reliability when justified by utilizing advancements in technology and meteorological understanding, while adhering to the basic approach used in the HMRs and in the WMO Manual. Updated precipitation frequency analyses were completed for this study. These were used with NOAA Atlas 14 precipitation frequency values where available to calculate the Orographic Transposition Factors (OTFs) for each storm. The OTF procedure replaces the storm separation method (SSM) used by the NWS in the most recent HMRs. The OTF procedure, through its correlation process, provides quantifiable and reproducible analyses of the effects of terrain on rainfall. Results of these three factors (maximization, moisture transposition, and orographic transposition) are applied for each storm at each of the grid points for each of the area sizes and durations used in this study to define the PMP values.

Maximization factors were computed for each of the analyzed storm events using an updated dew point climatology representing the maximum moisture that could have been associated with each rainfall event. This climatology includes the maximum average 3-, 6-, 12-, and 24-hour 100-year return frequency values. The most appropriate duration consistent with the duration of the storm rainfall is used. HYSPLIT model trajectories and NWS weather maps were used as guidance in identifying the storm representative moisture source region.

To house, analyze, and produce results from the large datasets developed in the study, the PMP calculation information was stored and analyzed in individual Excel spreadsheets and a GIS database. This combination of Excel and GIS was used to query, calculate, and derive PMP values for each grid point for each duration for each storm type. For local/MCS storms, the durations analyzed were 1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hours. For general storms, the durations analyzed were 1-, 6-, 12-, 24-, 48-, and 72-hours. Area sizes analyzed were 1-, 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-square miles for local storms and 1-, 10-, 50-, 100-, 200-, 500-, 1,000-, 5,000-, and 10,000-square miles for general storms. However, the database allows PMP to be calculated at any area size and/or duration available in the underlying SPAS data.

Glossary

Adiabat: Curve of thermodynamic change taking place without addition or subtraction of heat. On an adiabatic chart or pseudo-adiabatic diagram, a line showing pressure and temperature changes undergone by air rising or condensation of its water vapor; a line, thus, of constant potential temperature.

Adiabatic: Referring to the process described by adiabat.

Advection: The process of transfer (of an air mass property) by virtue of motion. In particular cases, advection may be confined to either the horizontal or vertical components of the motion. However, the term is often used to signify horizontal transfer only.

Air mass: Extensive body of air approximating horizontal homogeneity, identified as to source region and subsequent modifications.

Barrier: A mountain range that partially blocks the flow of warm humid air from a source of moisture to the basin under study.

Basin shape: The physical outline of the basin as determined from topographic maps, field survey, or GIS.

Convective rain: Rainfall caused by the vertical motion of an ascending mass of air that is warmer than the environment and typically forms a cumulonimbus cloud. The horizontal dimension of such a mass of air is generally of the order of 12 miles or less. Convective rain is typically of greater intensity than either of the other two main classes of rainfall (cyclonic and orographic) and is often accompanied by thunder. The term is more particularly used for those cases in which the precipitation covers a large area as a result of the agglomeration of cumulonimbus masses.

Convergence: Horizontal shrinking and vertical stretching of a volume of air, accompanied by net inflow horizontally and internal upward motion.

Cooperative station: A weather observation site where an unpaid observer maintains a climatological station for the National Weather Service.

Correlation Coefficient: The average change in the dependent variable, the orographically transposed rainfall (P_o), for a 1-unit change in the independent variable, the in-place rainfall (P_i).

Cyclone: A distribution of atmospheric pressure in which there is a low central pressure relative to the surroundings. On large-scale weather charts, cyclones are characterized by a system of closed constant pressure lines (isobars), generally approximately circular or oval in form, enclosing a central low-pressure area. Cyclonic circulation is counterclockwise in the northern hemisphere and clockwise in the southern. (That is, the sense of rotation about the local vertical is the same as that of the earth's rotation).

Depth-Area curve: Curve showing, for a given duration, the relation of maximum average depth to size of area within a storm or storms.

Depth-Area-Duration: The precipitation values derived from Depth-Area and Depth-Duration curves at each time and area size increment analyzed for a PMP evaluation.

Depth-Area-Duration Curve: A curve showing the relation between an averaged areal rainfall depth and the area over which it occurs, for a specified time interval, during a specific rainfall event.

Depth-Area-Duration values: The combination of depth-area and duration-depth relations. Also called depth-duration-area.

Depth-Duration curve: Curve showing, for a given area size, the relation of maximum average depth of precipitation to duration periods within a storm or storms.

Dew point: The temperature to which a given parcel of air must be cooled at constant pressure and constant water vapor content for saturation to occur.

Effective barrier height: The height of a barrier determined from elevation analysis that reflects the effect of the barrier on the precipitation process for a storm event. The actual barrier height may be either higher or lower than the effective barrier height.

Endorheic: A closed drainage basin that retains water and allows no outflow to other external bodies of water, such as rivers or oceans, but converges instead into lakes or swamps, permanent or seasonal, that equilibrate through evaporation process.

Envelopment: A process for selecting the largest value from any set of data. In estimating PMP, the maximum and transposed rainfall data are plotted on graph paper, and a smooth curve is drawn through the largest values.

Explicit transposition: The movement of the rainfall amounts associated with a storm within boundaries of a region throughout which a storm may be transposed with only relatively minor modifications of the observed storm rainfall amounts. The area within the transposition limits has similar, but not identical, climatic and topographic characteristics throughout.

Front: The interface or transition zone between two air masses of different parameters. The parameters describing the air masses are temperature and dew point.

General storm: A storm event that produces precipitation over areas in excess of 500-square miles, has a duration longer than 6 hours, and is associated with a major synoptic weather feature.

Hydrologic Unit: A hydrologic unit is a drainage area delineated to nest in a multi-level, hierarchical drainage system. Its boundaries are defined by hydrographic and topographic criteria that delineate an area of land upstream from a specific point on a river, stream or similar surface waters. A hydrologic unit can accept surface water directly from upstream drainage areas, and indirectly from associated surface areas such as remnant, non-contributing, and diversions to form a drainage area with single or multiple outlet points. Hydrologic units are only synonymous with classic watersheds when their boundaries include all the source area contributing surface water to a single defined outlet point.

HYSPLIT: Hybrid Single-Particle Lagrangian Integrated Trajectory. A complete system for computing parcel trajectories to complex dispersion and deposition simulations using either puff or particle approaches. Gridded meteorological data, on one of three conformal (Polar, Lambert, or Mercator latitude-longitude grid) map projections, are required at regular time intervals. Calculations may be performed sequentially or concurrently on multiple meteorological grids, usually specified from fine to coarse resolution.

Implicit transpositioning: The process of applying regional, areal, or durational smoothing to eliminate discontinuities resulting from the application of explicit transposition limits for various storms.

Isohyets: Lines of equal value of precipitation for a given time interval.

Isohyetal pattern: The pattern formed by the isohyets of an individual storm.

Jet Stream: A strong, narrow current concentrated along a quasi-horizontal axis (with respect to the earth's surface) in the upper troposphere or in the lower stratosphere, characterized by strong vertical and lateral wind shears. Along this axis it features at least one velocity maximum (jet streak). Typical jet streams are thousands of kilometers long, hundreds of kilometers wide, and several kilometers deep. Vertical wind shears are on the order of 10 to 20 mph per kilometer of altitude and lateral winds shears are on the order of 10 mph per 100 kilometer of horizontal distance.

Local storm: A storm event that occurs over a small area in a short time period. Precipitation rarely exceeds 6 hours in duration and the area covered by precipitation is less than 500 square miles. Frequently, local storms will last only 1 or 2 hours and precipitation will occur over areas of up to 200 square miles. Precipitation from local storms will be isolated from general-storm rainfall. Often these storms are thunderstorms.

Low Level Jet stream: A band of strong winds at an atmospheric level well below the high troposphere as contrasted with the jet streams of the upper troposphere.

Mass curve: Curve of cumulative values of precipitation through time.

Mesoscale Convective Complex (MCC): For the purposes of this study, a heavy rain-producing storm with horizontal scales of 10 to 1000 kilometers (6 to 625 miles) which includes significant, heavy convective precipitation over short periods of time (hours) during some part of its lifetime.

Mesoscale Convective System (MCS): A complex of thunderstorms which becomes organized on a scale larger than the individual thunderstorms, and normally persists for several hours or more. MCSs may be round or linear in shape, and include systems such as tropical cyclones, squall lines, and MCCs (among others). MCS often is used to describe a cluster of thunderstorms that does not satisfy the size, shape, or duration criteria of an MCC.

Mid-latitude frontal system: An assemblage of fronts as they appear on a synoptic chart north of the tropics and south of the polar latitudes. This term is used for a continuous front and its characteristics along its entire extent, its variations of intensity, and any frontal cyclones along it.

Moisture maximization: The process of adjusting observed precipitation amounts upward based upon the hypothesis of increased moisture inflow to the storm.

Observational day: The 24-hour time period between daily observation times for two consecutive days at cooperative stations, e.g., 6:00PM to 6:00PM.

One-hundred year rainfall event: The point rainfall amount that has a one-percent probability of occurrence in any year. Also referred to as the rainfall amount that has a 1 percent chance of occurring in any single year.

Orographic Transposition Factor (OTF): A factor representing the comparison of precipitation frequency relationships between two locations which is used to quantify how rainfall is affected by topography. It is assumed the precipitation frequency data are a combination of what rainfall would have accumulated with any topographic affect and what accumulated because of the topography at the location and upwind of the location.

Polar front: A semi-permanent, semi-continuous front that separates tropical air masses from polar air masses.

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; commonly expressed in terms of the height to which the liquid water would stand if the vapor were completely condensed and collected in a vessel of the same unit cross-section. The total precipitable water in the atmosphere at a location is that contained in a column or unit cross-section extending from the earth's surface all the way to the "top" of the atmosphere. The 30,000 foot level (approximately 300mb) is considered the top of the atmosphere in this study.

Persisting dew point: The dew point value at a station that has been equaled or exceeded throughout a period. Commonly durations of 12 or 24 hours are used, though other durations may be used at times.

Probable Maximum Flood: The flood that may be expected from the most severe combination of critical meteorological and hydrologic conditions that are reasonably possible in a particular drainage area.

Probable Maximum Precipitation: Theoretically, the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographic location at a certain time of the year.

Pseudo-adiabat: Line on thermodynamic diagram showing the pressure and temperature changes undergone by saturated air rising in the atmosphere, without ice-crystal formation and without exchange of heat with its environment, other than that involved in removal of any liquid water formed by condensation.

Rainshadow: The region, on the lee side of a mountain or mountain range, where the precipitation is noticeably less than on the windward side.

Saturation: Upper limit of water-vapor content in a given space; solely a function of temperature.

Spatial distribution: The geographic distribution of precipitation over a drainage according to an idealized storm pattern of the PMP for the storm area.

Storm transposition: The hypothetical transfer, or relocation of storms, from the location where they occurred to other areas where they could occur. The transfer and the mathematical adjustment of storm rainfall amounts from the storm site to another location is termed "explicit transposition." The areal, durational, and regional smoothing done to obtain comprehensive individual drainage estimates and generalized PMP studies is termed "implicit transposition" (WMO, 1986).

Synoptic: Showing the distribution of meteorological elements over an area at a given time, e.g., a synoptic chart. Use in this report also means a weather system that is large enough to be a major feature on large-scale maps (e.g., of the continental U.S.).

Temperature inversion: An increase in temperature with an increase in height.

Temporal distribution: The time order in which incremental PMP amounts are arranged within a PMP storm.

Tropical Storm: A cyclone of tropical origin that derives its energy from the ocean surface.

Total storm area and total storm duration: The largest area size and longest duration for which depth-area-duration data are available in the records of a major storm rainfall.

Transposition limits: The outer boundaries of the region surrounding an actual storm location that has similar, but not identical, climatic and topographic characteristics throughout. The storm can be transpositioned within the transposition limits with only relatively minor modifications to the observed storm rainfall amounts.

Undercutting: The process of placing an envelopment curve somewhat lower than the highest rainfall amounts on depth-area and depth-duration plots.

Acronyms and Abbreviations used in the report

AMS: Annual maximum series

AWA: Applied Weather Associates

DAD: Depth-Area-Duration

dd: decimal degrees

EPRI: *Electric Power Research Institute*

F: *Fahrenheit*

GCS: Geographical coordinate system

GEV: Generalized extreme value

GIS: Geographic Information System

GRASS: Geographic Resource Analysis Support System

HMR: Hydrometeorological Report

HUC: Hydrologic Unit Code

HYSPLIT: Hybrid Single Particle Lagrangian Integrated Trajectory Model

IPMF: In-place Maximization Factor

mb: millibar

MCS: Mesoscale Convective System

MTF: Moisture Transposition Factor

NCAR: National Center for Atmospheric Research

NCDC: National Climatic Data Center

NCEP: National Centers for Environmental Prediction

NEXRAD: Next Generation Radar

NOAA: National Oceanic and Atmospheric Administration

NWS: National Weather Service

NRCS: Natural Resources Conservation Service

OTF: Orographic Transposition Factor

PMF: Probable Maximum Flood

PMP: Probable Maximum Precipitation

PRISM: Parameter-elevation Relationships on Independent Slopes

PW: Precipitable Water

SPAS: Storm Precipitation and Analysis System

TAF: Total Adjustment Factor

USACE: US Army Corps of Engineers

USBR: Bureau of Reclamation

USGS: United States Geological Survey

WBD: Watershed Boundary Database

WMO: World Meteorological Organization

WRDS: Water Resources Data System (University of Wyoming)

WSEO: Wyoming State Engineer's Office

WWDO: Wyoming Water Development Office

1. Introduction

This study provides Probable Maximum Precipitation (PMP) values for any drainage basin within Wyoming, including regions adjacent to the state that provide runoff into drainage basins within Wyoming. The PMP values are valid for June 15 through September 15, which is the time of the year when the most intense rainfall could occur. A seasonality adjustment is provided to derive PMP values for dates outside of this time period. The PMP values are used in the computation of the Probable Maximum Flood (PMF). PMP values provided in this study supersede PMP values in the four Hydrometeorological Reports (HMRs) for locations in Wyoming. These are HMR 49 (Hansen et al., 1977), HMR 51 (Schreiner and Riedel, 1978), HMR 55A (Hansen et al., 1988), and HMR 57 (Hansen et al., 1994).

1.1 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 US Army Corps of Engineers (USACE), and the US Bureau of Reclamation (USBR) 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 1.1). In addition to these HMRs, numerous Technical Papers and Reports deal with 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) augment generalized PMP reports for specific regions included in the large areas addressed by 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 replace those derived from HMRs 49, 51, 55A, and 57.

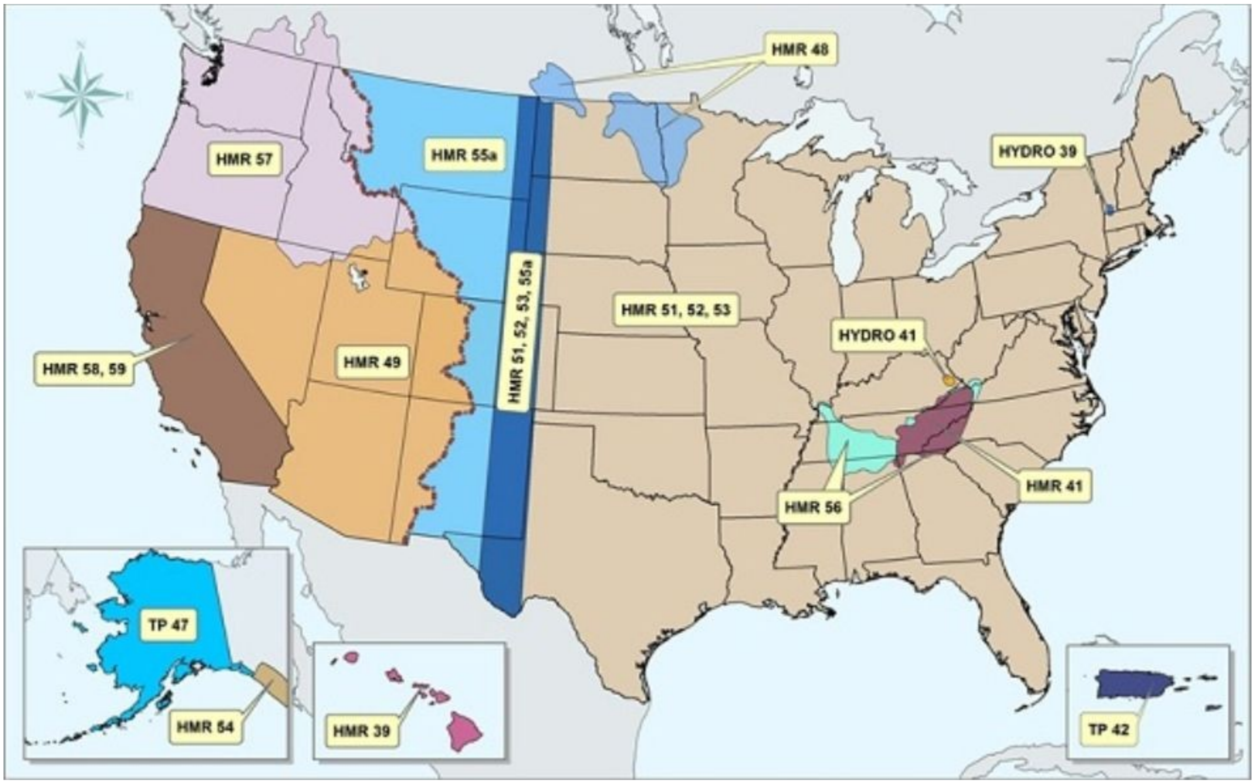


Figure 1.1 Hydrometeorological Report coverages across the United States

Wyoming is included within the domain covered by HMR 49, HMR 51, HMR 55A, and HMR 57. These HMRs cover diverse regions that are not meteorologically and topographically similar. Wyoming contains many diverse regions as well. Wyoming includes the Intermountain West, mountain ranges east and west of the Continental Divide, and High Plains regions (Figure 1.2). In Wyoming, 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 state. 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 1980's, a non-reproducible and subjective process used to address orographic effects, inconsistent data and procedures used among the HMRs, and the outdated procedures used to derive PMP.

National Weather Service HMR Study Domains
Wyoming Statewide PMP Analysis

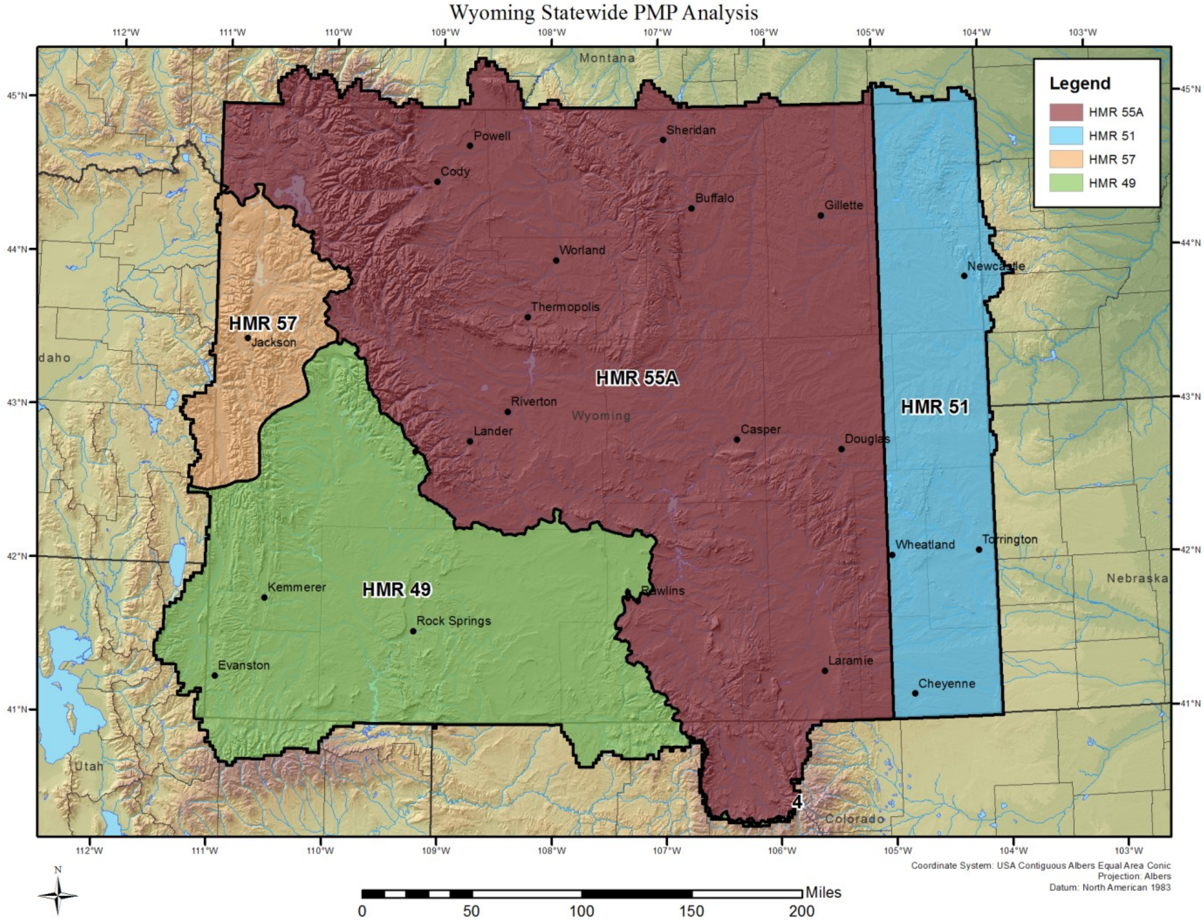


Figure 1.2 Wyoming PMP project domain and HMR coverages. The overall project domain extends beyond the state boundaries in some areas to ensure all drainage areas into Wyoming are included in the analysis.

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.

1.2 Objective

This study determines reliable and reproducible estimates of PMP values for use in computing the PMF for various watersheds in the state and within the overall project domain. The most reliable methods and data available were used and updates to methods and data used in HMRs were applied where appropriate.

1.3 Approach

The approach used in this study followed the 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 Wyoming. The weather and climate of the region are discussed in Section 2. Section 3 discusses the effects of topography on rainfall and PMP within Wyoming. Sections 4 describes the development of the updated dew point climatologies, and Section 5 provides information on the updated precipitation frequency climatologies developed for this study. The initial step of identifying extreme storms and the development of the final list of storms used to derive PMP are in Section 6. Adjustments for storm maximization, storm transposition, and calculation of final PMP values are provided in Sections 7, 8, and 9 respectively. The process for extracting PMP for a drainage basin is discussed in Section 10. Discussions on sensitivities are provided in Section 11 and 12, and recommendations for application are presented in Section 13.

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, and the previous PMP studies completed by AWA. Deviations were incorporated when justified by 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 include local storms and general 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 with similar topography and meteorological conditions. Adjustments were applied to each storm as it was transpositioned to each grid point to represent what the 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). An additional adjustment was applied to regions of the state above 7,500 feet. This was to account for the decrease in rainfall above these elevations which is not captured in the PRISM and precipitation frequency climatologies, and hence not captured properly in the OTF process. Section 9 provides a more detailed discussion on this process and application.

$$\text{Total Adjustment Factor} = IPMF * MTF * OTF \qquad \text{Equation 1.1}$$

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 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 (3-hour persisting dew points were also used in HMR 57). For this project, an updated maximum average dew point climatology developed in previous studies for the 3-, 6-, 12-, and 24-hour duration periods was used to better represent the atmospheric moisture for rainfall durations associated with the different storm types that affect Wyoming. This updated dew point climatology provided 100-year recurrence interval return frequency values for 3-, 6-, 12-, and 24-hour duration periods. 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 3-hour and 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.

Environmental Systems Research Institute's ESRI ArcGIS Desktop GIS software 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 to 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 H for a complete description of SPAS).

1.4 PMP Analysis Domain

The project domain was defined to cover the entire State of Wyoming as well as watersheds that extended beyond state boundaries. This study allows for gridded PMP values to be determined for each grid cell within the project domain. The full PMP analysis domain is shown in Figure 1.3.

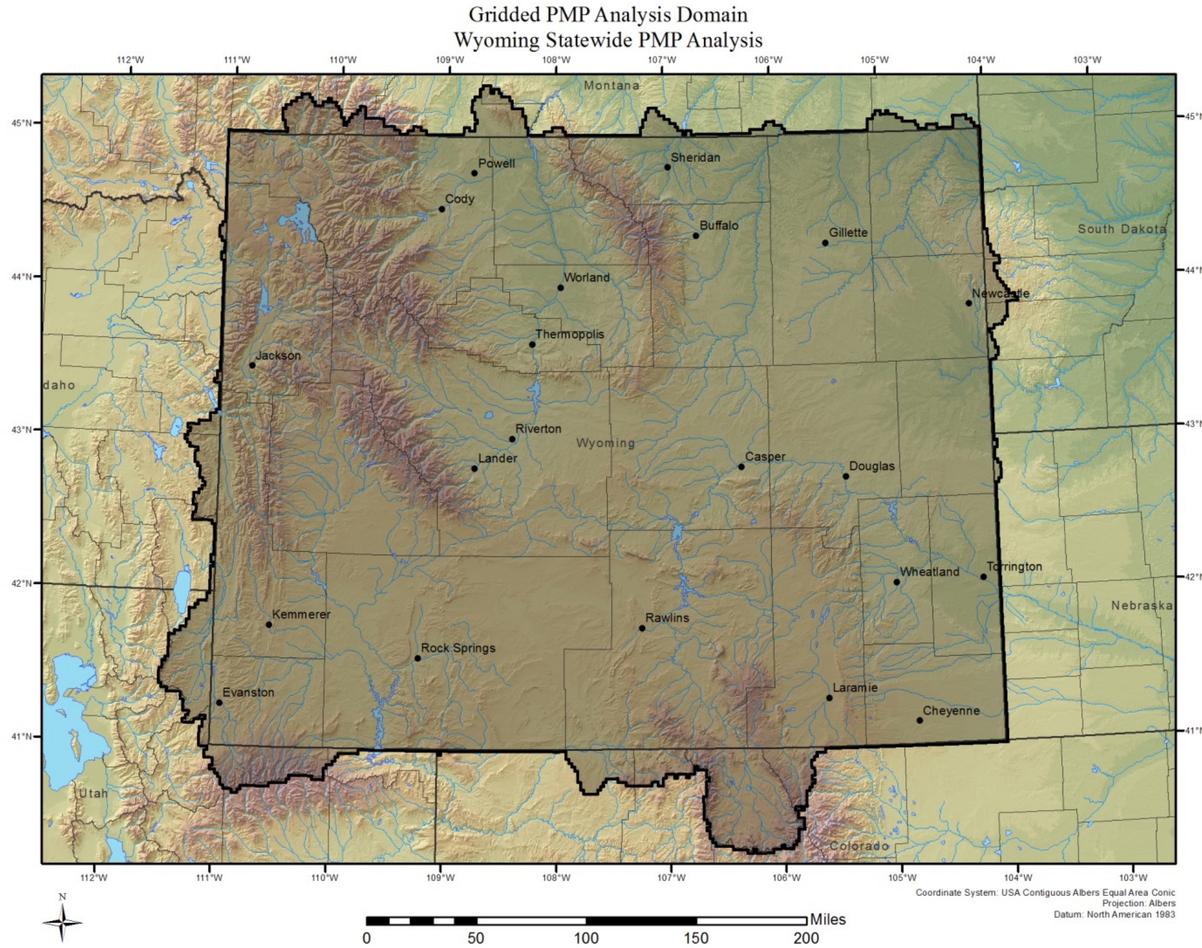


Figure 1.3 PMP analysis project domain

To account for locations that include drainage areas that extend beyond the state boundaries, a detailed interstate stream buffer region was obtained and examined with underlying topography. The United States is divided and sub-divided into successively smaller hydrologic units which are classified into six levels. Each hydrologic unit is identified by a unique hydrologic unit code (HUC) consisting of two to twelve digits based on the six levels of classification in the hydrologic unit system. The hydrologic units are arranged or nested within each other, from the largest geographic area (2-digit regions) to the smallest geographic area (12-digit subwatersheds). The USGS Watershed Boundary Datasets (WBD), at the 4-digit through 12-digit level, were mapped to aid in determining relevant drainage areas (http://datagateway.nrcs.usda.gov, April 2013). In addition, discussions with the Wyoming Water Development Office (WWDO), Wyoming State Engineer's Office (WSEO), Natural Resources Conservation Service (NRCS), and Review Board members were conducted to refine the analysis region beyond state boundaries to fully incorporate all potential sites that may affect Wyoming. Figure 1.4 shows the 8-digit hydrologic unit boundaries for the state's major drainage basins with the 4-digit watersheds labeled in the background.

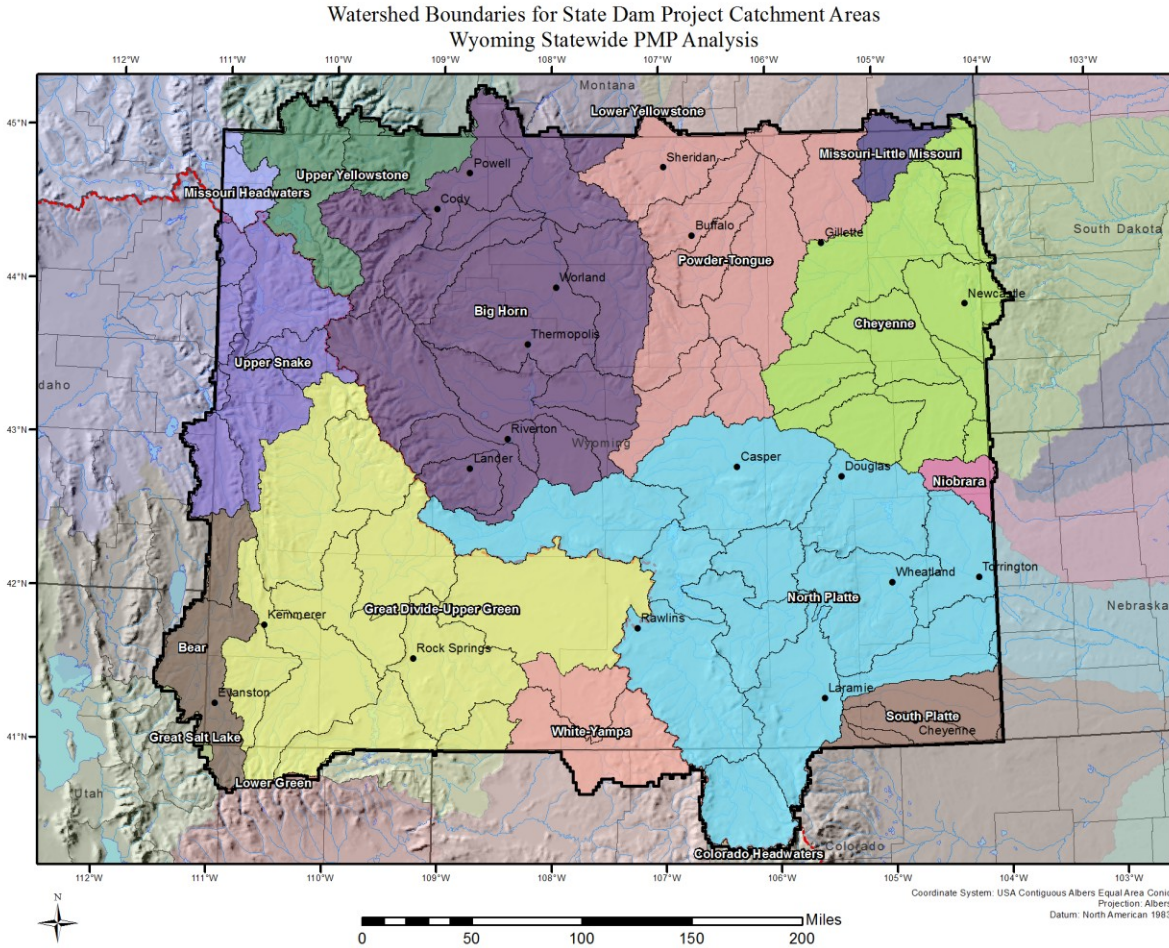


Figure 1.4 Hydrologic watershed boundaries within the analysis domain

1.5 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 (GCS) spatial reference with the World Geodetic System of 1984 (WGS 84) datum. This resulted in 48,343 grid cells with centroids within the domain shown in Figure 1.3. Each grid cell has an approximate area of 2.2-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 41° N and 106° W with the adjacent grid point to the west at 41° N and 106.025° W. As an example, the PMP analysis grid over the Viva Naughton basin is shown in Figure 1.5.

90 Arc-Second PMP Analysis Grid over the Viva Naughton Drainage Basin
Wyoming Statewide PMP Analysis

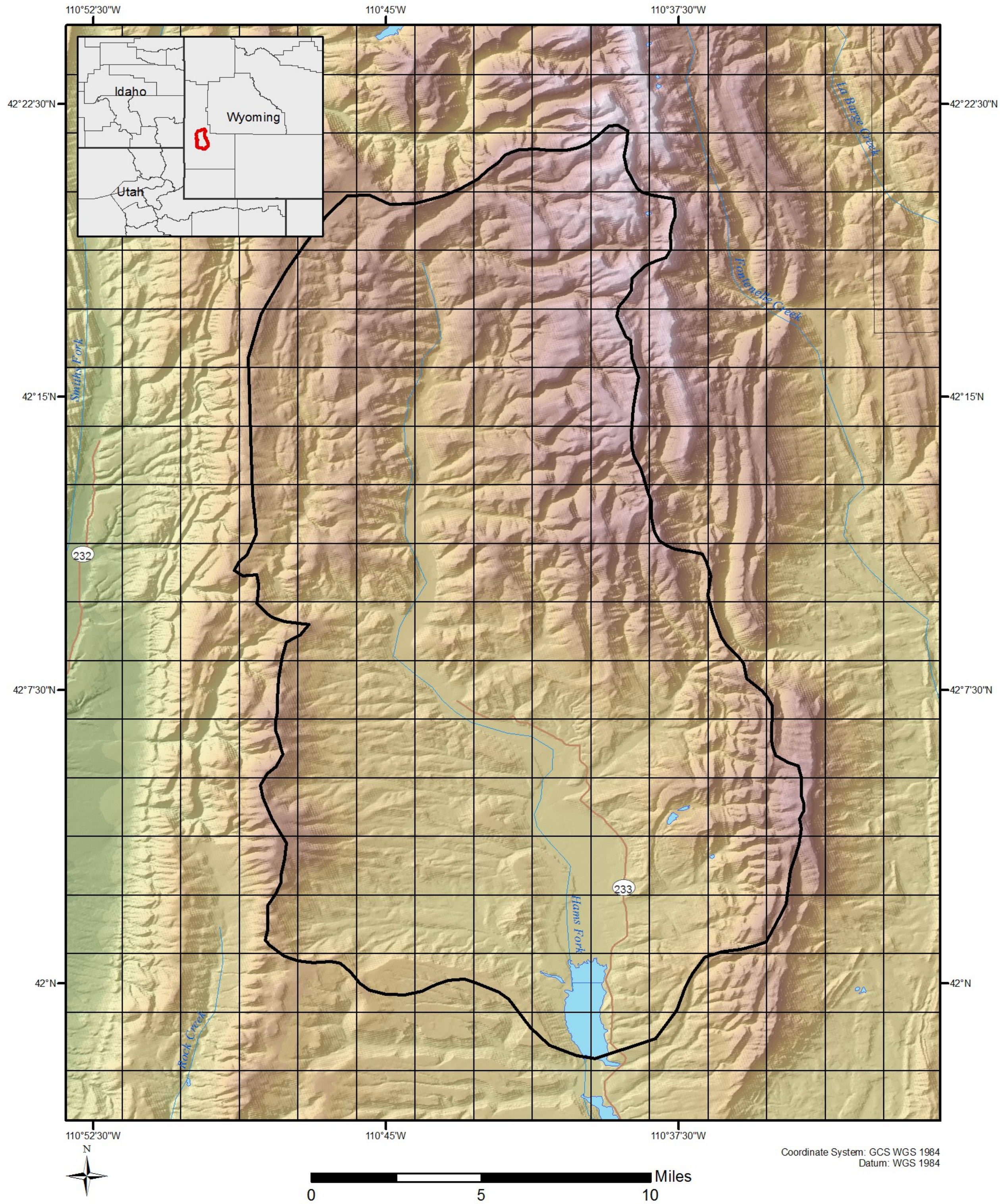


Figure 1.5 PMP analysis grid placement over the Viva Naughton basin

2. Weather and Climate of the Region

This section describes the general weather patterns and climate of Wyoming and how they relate to the development of PMP for this project. More detailed descriptions of the climate of Wyoming and each of the storm types can be found in the following references (e.g. Curtis and Grimes, http://www.wrds.uwyo.edu/sco/climateatlas/title_page.html, or the Western Regional Climate Center, http://www.wrcc.dri.edu/narratives/WYOMING.htm). These references provide additional information and more detailed analysis. Figures 2.1 and 2.2 show the spatial distribution of the PRISM annual maximum and minimum temperatures for the 30-year climatological period of 1981-2010. Figure 2.3 shows the PRISM annual precipitation for the same period.

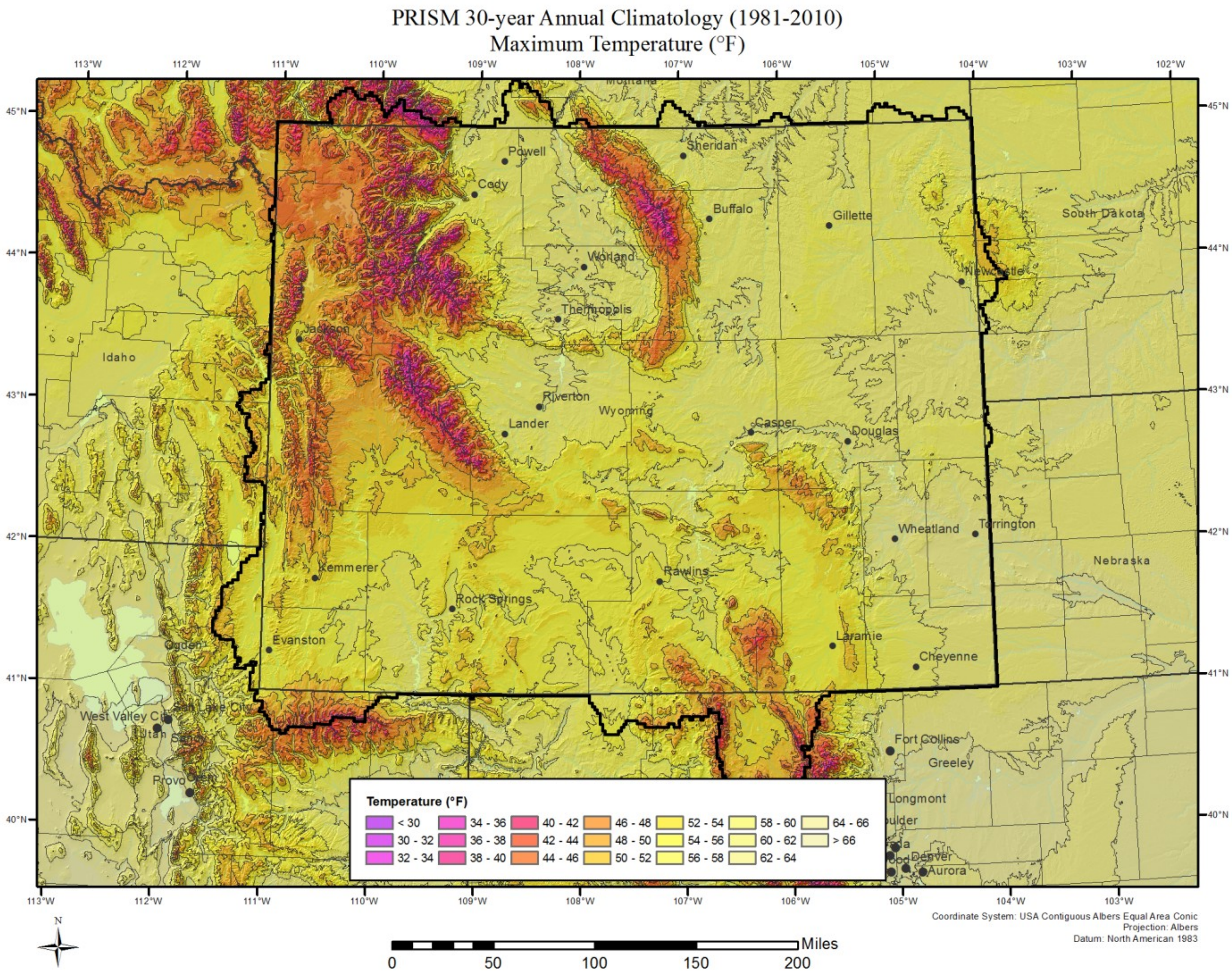


Figure 2.1 PRISM 30-year average annual maximum temperatures

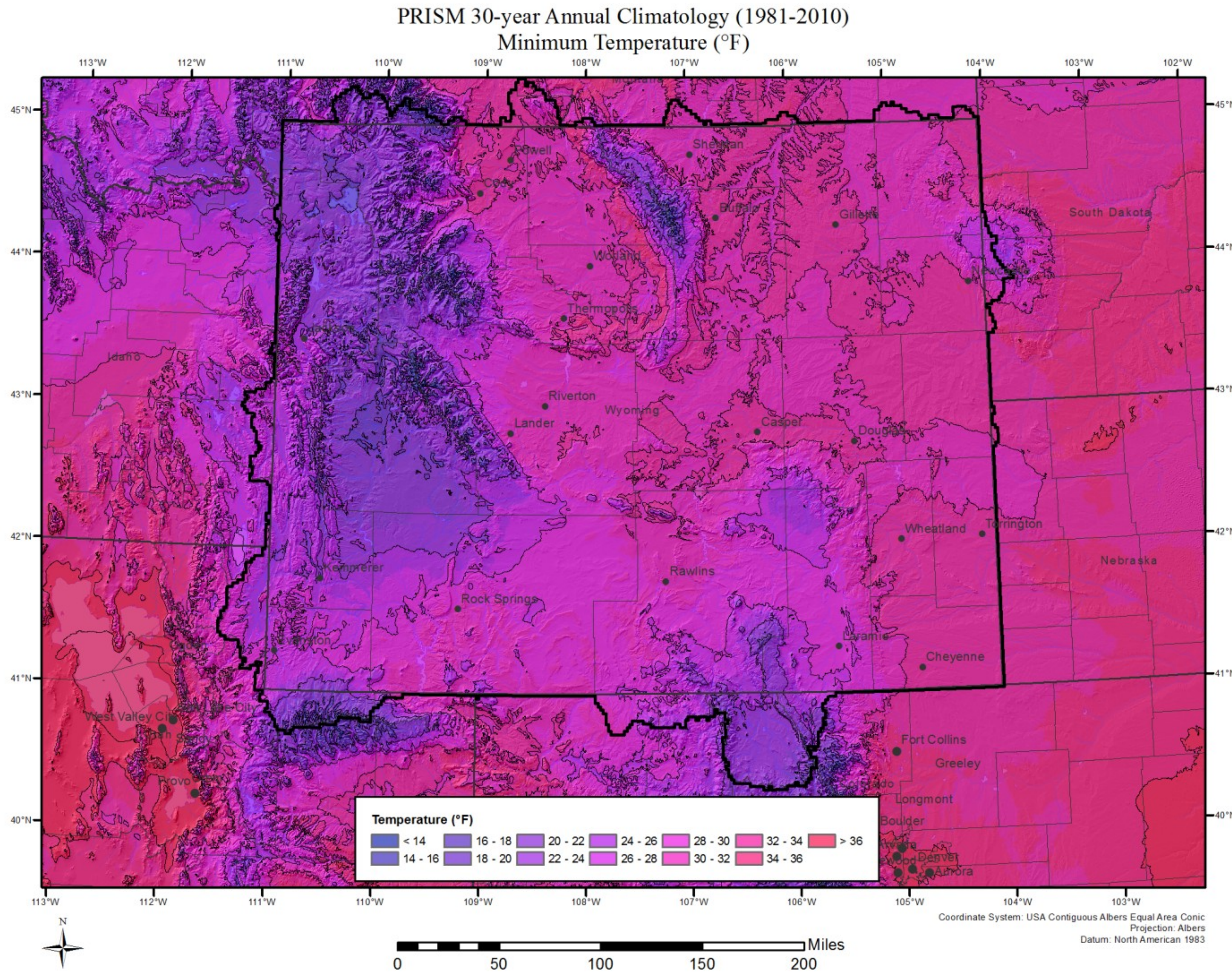


Figure 2.2 PRISM 30-year average annual minimum temperatures

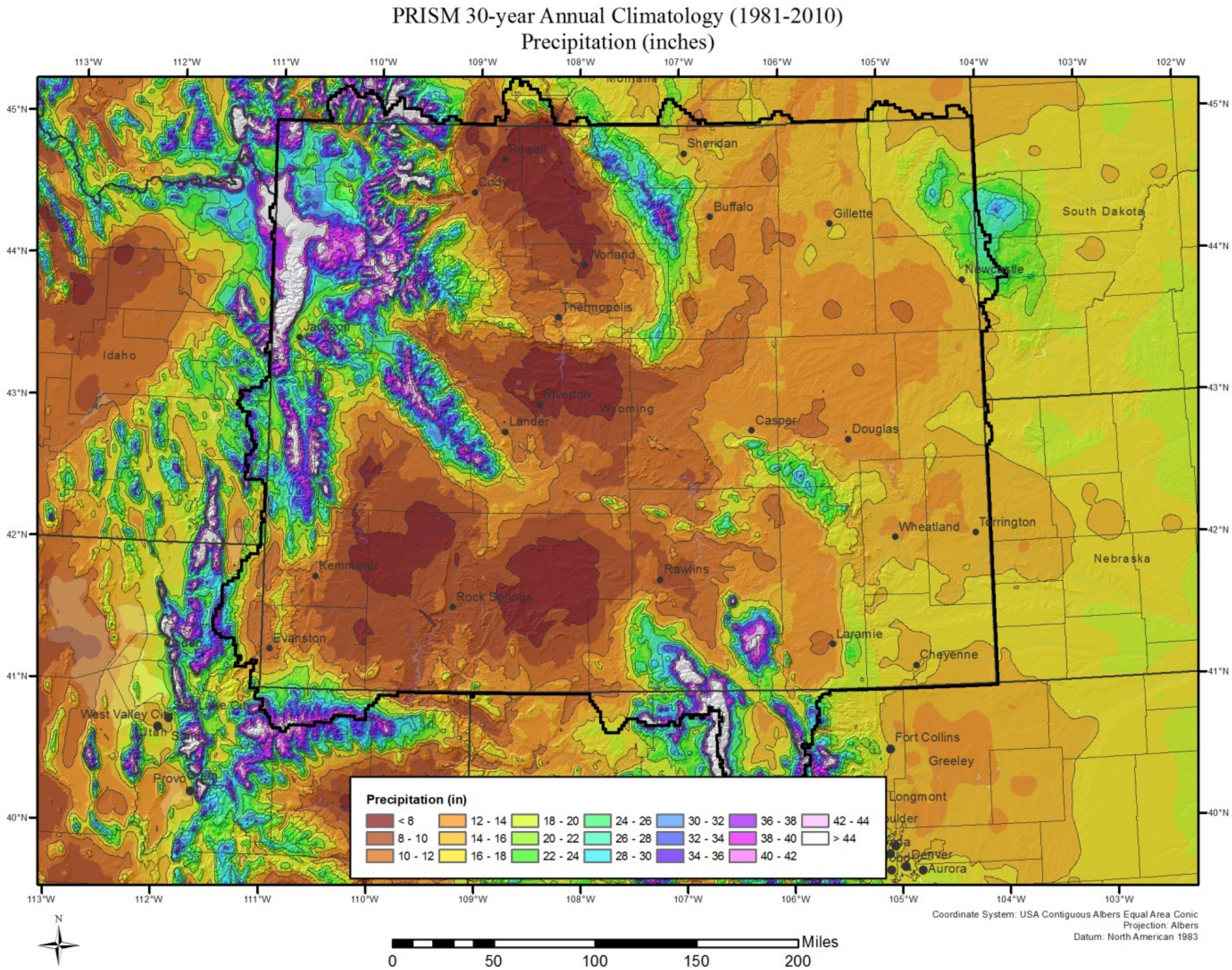


Figure 2.3 PRISM 30-year average annual precipitation (both rain and snow)

2.1 General Climate of Wyoming

Wyoming is affected by weather systems which enter the state from various source regions, including the Pacific Ocean, the Gulf of California, and the Gulf of Mexico. Locations west of the Continental Divide, especially south of the Wind River Range, are exposed to Gulf of California moisture surges during the North American Monsoon (NAM) season. These moisture surges produce localized thunderstorms from early summer through early fall. Mid-latitude storms (also termed synoptic weather systems) which produce mainly rainfall are most common from late summer/early fall and again during late spring. This storm type produces general rainfalls over long durations and large area sizes.

East of the Continental Divide, the predominant low-level moisture source is the Gulf of Mexico. Occasionally, mid latitude storms affect the mountainous regions with moisture in the middle and upper levels of the atmosphere supplied by the Pacific Ocean. Local storms east of the Continental Divide are most common from late spring through early fall. These storms are most effective at producing heavy rainfall when enhanced by low-level moisture and low-level jets transporting moisture from the Gulf of Mexico. This moisture then interacts with the elevated terrain in eastern Wyoming, which produces extra lift. In addition, the high terrain associated with the Rocky Mountains provides an environment where the surface is heated and the air allowed to rise and reach the level of free convection more effectively than surrounding lower elevations. This often leads to the initial development of thunderstorms prior to development over the eastern plains. These storms then generally move from west to east along with the general atmospheric flow. In situations where large amounts of low-level moisture are available, these storms can produce heavy rainfall. When instability and moisture conditions are ideal, these areas of convection can form into Mesoscale Convective Systems (MCSs), moving generally west to east over eastern Wyoming. General storms which affect areas east of the Continental Divide are usually associated with areas of low pressure that develop along the lee slopes of the Rocky Mountains. Winds turn easterly into the terrain, advecting moisture from the Gulf of Mexico into Wyoming. The storm dynamics associated with the area of low pressure combine with the orographic effects of the terrain as the moisture is forced upslope to produce widespread rainfall. If these storms are slow moving, with favorable atmospheric instability and large amounts of atmospheric moisture, widespread flooding rains can be produced. The general storm type that produces rainfall in Wyoming is most common in the late spring and early fall periods.

2.1.1 North American Monsoon Climatology

In June, the 500mb (approximately 18,000 feet) subtropical ridge is located over northwest Mexico (Figure 2.4). As a result, air flow across the region is usually from the southwest. This southwesterly flow during June is a direct result of the position of the 500mb subtropical ridge and produces advection of dry atmospheric conditions and dry weather west of the Continental Divide results. This situation can contribute to enhancement of low pressure east of the Continental Divide which can potentially tap into Gulf of Mexico moisture and produce significant rainfall for locations east of the Continental Divide.

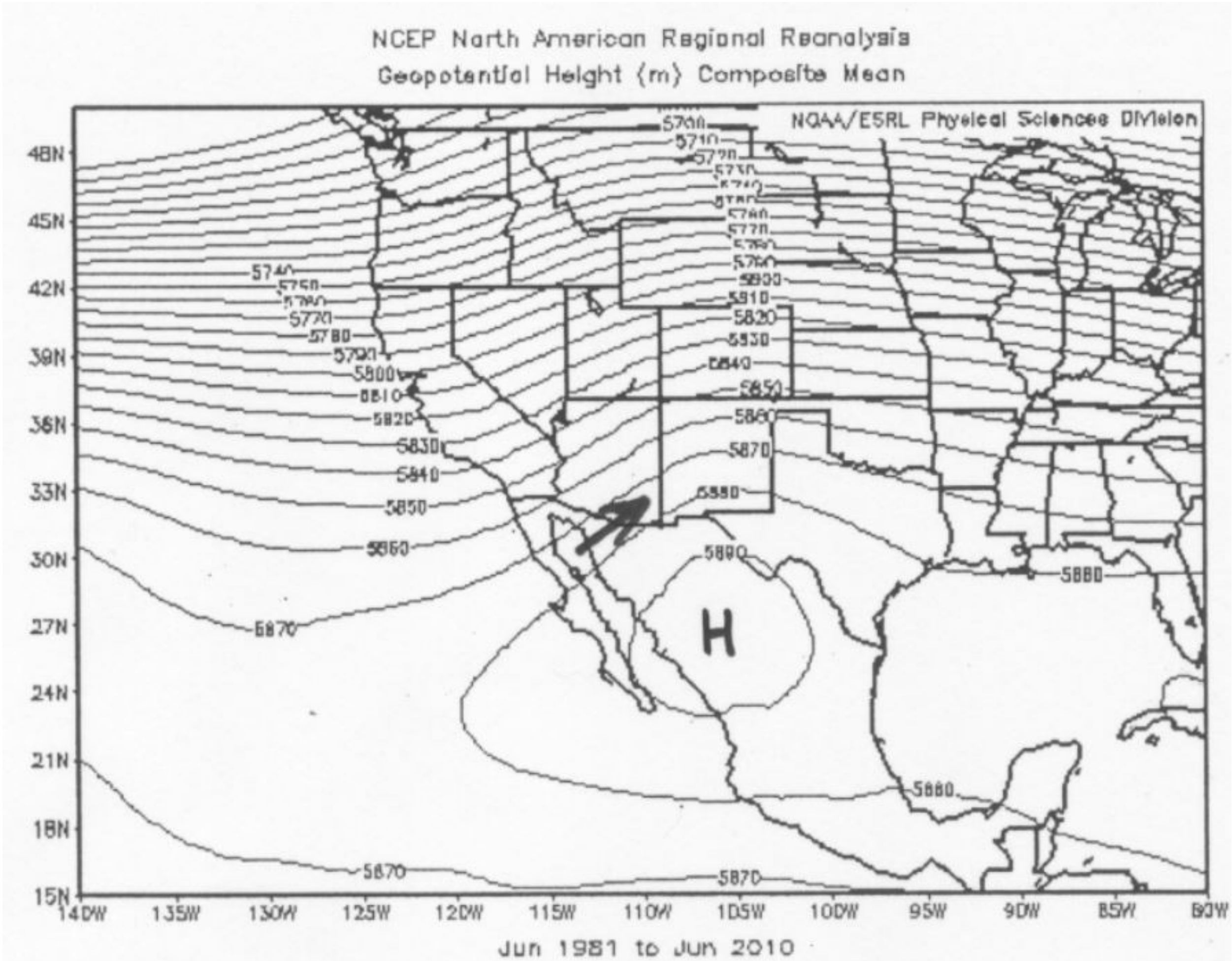


Figure 2.4 June mean flow at 500mb (~18,000 feet) over the western United States

Starting in late June and continuing into July, the 500mb subtropical ridge normally shifts northward and eastward with the center of circulation located over west Texas and New Mexico (Figure 2.5). As a result, easterly flow develops over northwest Mexico in the mid-levels of the atmosphere, while hot temperatures over the continent result in a general onshore (southerly) flow in the low-levels. The shift in the 500mb subtropical ridge is followed by a dramatic increase in thunderstorm activity over northwest Mexico. Wyoming lies on the northern fringes of this area of enhanced thunderstorm activity. It is during this time that western Wyoming experiences periodic increases in moisture originating from the Gulf of California (Gulf Surges) and the eastern tropical Pacific. This enhanced moisture often produces thunderstorms (Douglas 1993, Hales 1972).

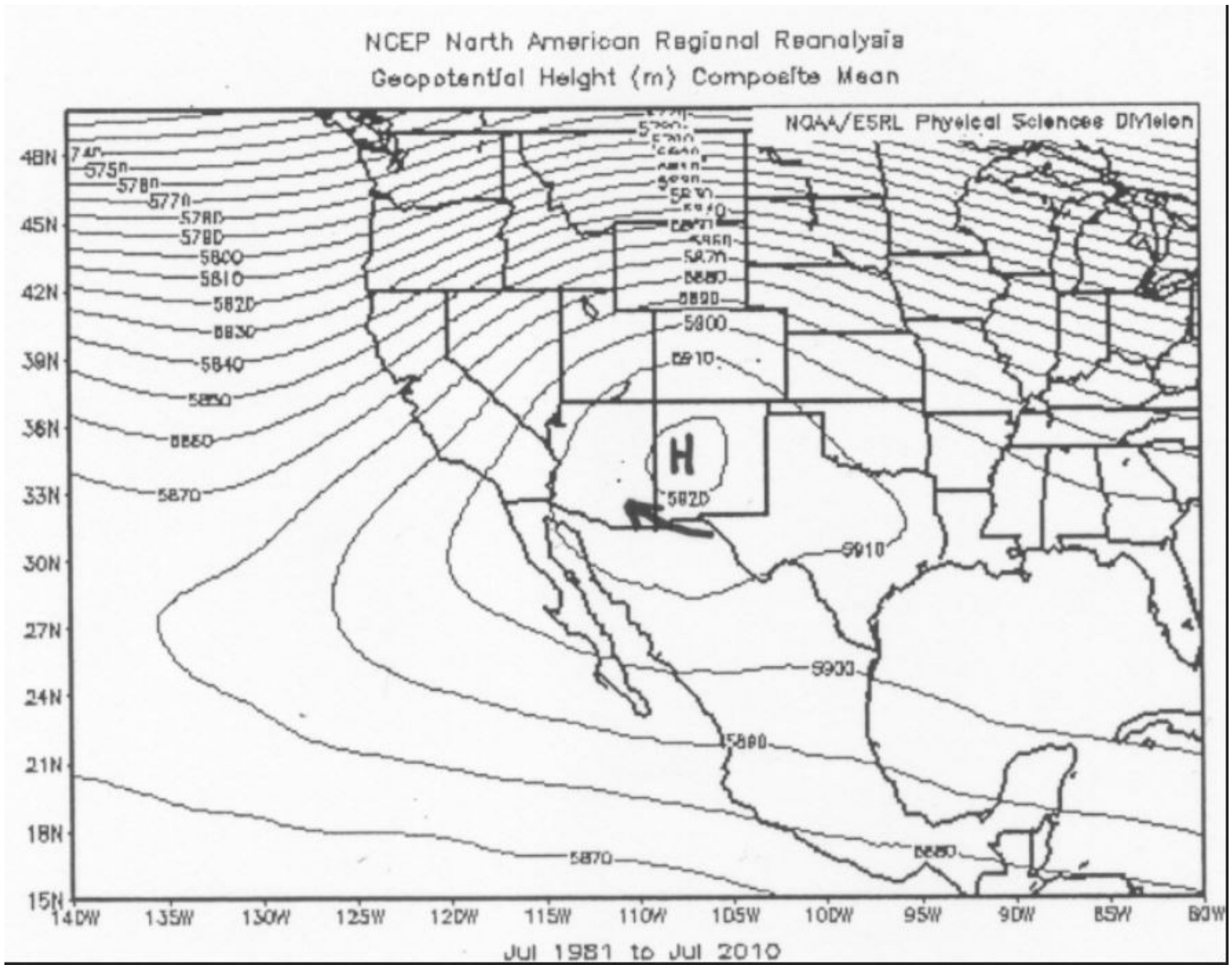


Figure 2.5 July mean flow at 500mb (~18,000 feet) over the western United States

Figure 2.6 shows the generalized surface synoptic conditions and moisture source regions that are found during the NAM season. The positioning of the areas of high and low pressure centers and the resulting circulations around these features produces wind flows from the south/southwest over the southwestern US. This circulation bring atmospheric moisture northward from the Gulf of California into the Desert Southwest and, under unusual scenarios, into western Wyoming, supplying low level moisture that can fuel intense thunderstorm activity. Examples of PMP-type local storms that resulted from this combination of factors include Morgan, UT, August 1958; John Day, OR, June 1969; Elko, NV, August 1970; and Opal, WY, August 1990. For more detailed descriptions of the NAM see Grantz et al., 2007; Higgins et al., 2004; Higgins et al., 1999; Adams and Comrie 1997; Higgins et al., 1997; Douglas 1995; Douglas 1993; Smith 1989; and Hales 1972.

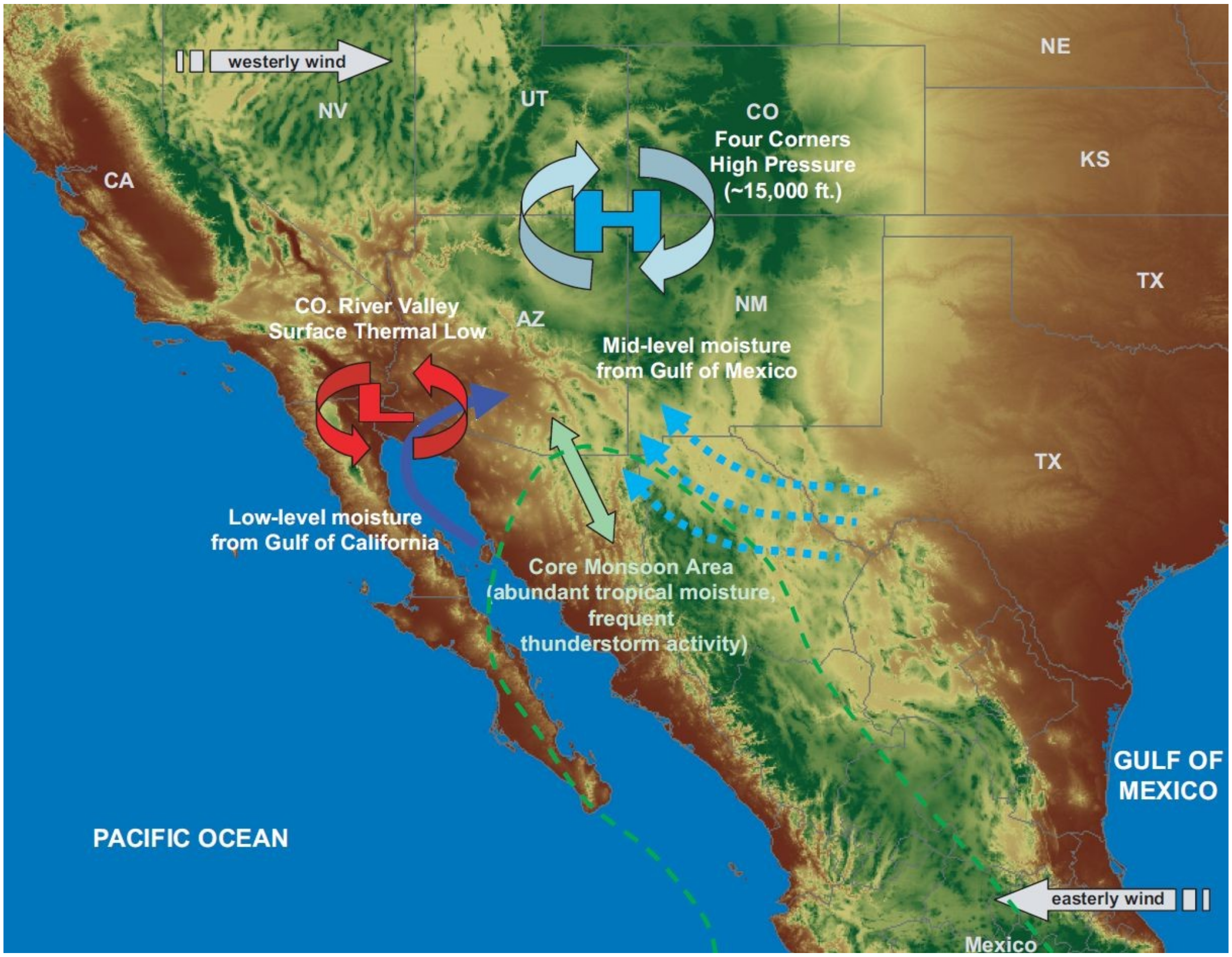


Figure 2.6 Generalized surface synoptic patterns associated with the NAM season (http://www.wrh.noaa.gov/twc/monsoon/monsoon_info.php, October 2014)

2.1.2 Mesoscale Convective Systems

Although the NAM can supply moisture to areas east of the Continental Divide, the dominant atmospheric moisture source, especially in the lower levels of the atmosphere, is the Gulf of Mexico. Thunderstorms which form in this region can last longer and produce greater volumes of rainfall because the moisture source is more sustained than western regions of Wyoming. A common type of storm that occurs in the eastern Wyoming that produces extreme rainfall amounts over relatively small areas is the MCS. These are capable of producing extreme amounts of precipitation for short durations (generally less than 12-hours) and over small area sizes (generally less than 500-square miles). The terrain in eastern Wyoming plays an important role in convective initiation, while the predominantly west/southwest flow helps to move the storms from west to east.

The current name of MCS was applied in the late 1970's to these type of "flood producing" strong thunderstorm systems (Maddox 1980). Mesoscale systems are so named because they are relatively small in areal extent (producing rainfall over tens to hundreds of square miles), whereas synoptic storm events produce rainfall over larger areas of hundreds to thousands of square miles. The MCSs also exhibit a distinctive signature on satellite imagery where they show rapidly growing cirrus shields with very high (cold) cloud tops. The cirrus shields produced by MCSs usually take on a nearly circular spatial pattern, sustained by constantly regenerating thunderstorms fed by moist low-level jet inflow. Climatologically, MCSs primarily form from late May through September, with a maximum occurrence in June.

2.2 General Storm Systems

The polar front and jet stream, which separate cool and dry Canadian air to the north from warm and moist air to the south, sometimes produces heavy rainfall in the region. The frontal systems that develop along this boundary generally move from west to east with the jet stream. These systems are most likely to produce rainfall over the region west of the Continental Divide from September through early November. East of the Continental Divide, these storms most commonly produce rainfall from September through October and May through June. Areas of low pressure which develop along the lee slope of the Rocky Mountains provide favored locations for this storm type to develop and when storm dynamics are enhanced by topography, produce widespread rainfall and flooding. This is in contrast to areas west of the Continental Divide, where the low-level moisture and low pressure areas at the surface are widely distributed by the mountainous topography upstream and within the region. The result is less organized general storms with rainfall anchored to preferred terrain locations.

This type of storm environment (general storm) will not produce high rainfall rates, but can produce flooding as moderate rain continues to fall over the same regions for extended periods of time. The rainfall can fall on significant snowpack in mountainous locations resulting in large runoff volumes. The Gibson Dam, MT, June 1964, and Colorado/Wyoming, September 2013 events are examples of this storm type east of the Continental Divide, with the Rattlesnake, ID, November 1909 event is an example west of the Continental Divide.

2.3 Seasonality of Extreme Storm Events

The seasonality of the local storm and MCS types is clearly shown in Figure 2.7 to occur from late spring through early fall. As described previously, these storms occur when the combination of atmospheric moisture and atmospheric instability are at their greatest. There is less convective storm activity at other times of the year due to decreased solar heating and less moisture in the low levels of the atmosphere to contribute to convective instability.

The seasonality of the general storm type also reflects the strength of the meteorological parameters required for this storm type to produce rainfall (Figure 2.8). These parameters include an active synoptic storm pattern that brings areas of low pressure and associated frontal systems through the region, and temperatures warm enough to produce rainfall at the surface. The lack of storms in July and August reflect the infrequent nature of frontal systems passing through the region as the jet stream is generally displaced to the north, while the ridge of high pressure associated with the NAM controls the general weather pattern. General storms are common occurrence in late fall, winter and early spring months, but produce snowfall instead of rain. Therefore they are not included in PMP development.

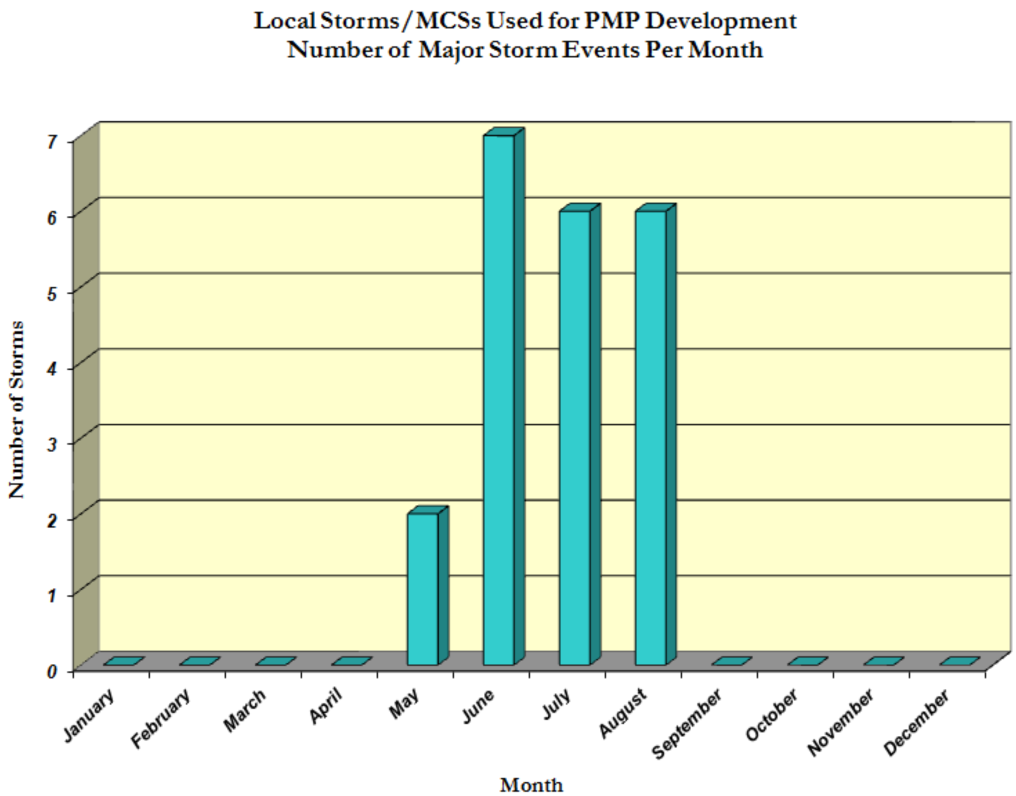


Figure 2.7 Local/MCS storm seasonality of storms used during the Wyoming PMP study

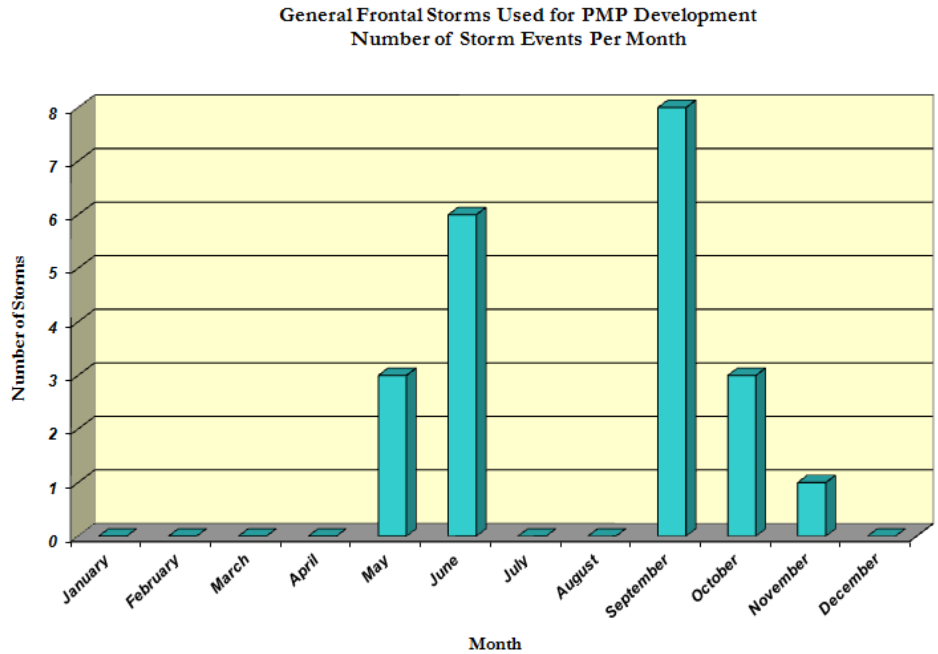


Figure 2.8 General storm seasonality of storms analyzed during the Wyoming PMP study

3. Topographic Effects on PMP Rainfall

The terrain within the state of Wyoming varies significantly, often over relatively short distances (Figure 3.1), particularly in western Wyoming (Figure 3.2). Elevations vary from 3,100 feet at the South Dakota border to 13,800 feet in the Wind River Range. When elevated terrain features are upwind of a drainage basin, depletion of low level atmospheric moisture available to storms over the basin can occur. These must be taken into account in the PMP determination procedure, explicitly in the storm maximization process. Additionally, some drainage basins have terrain features that enhance or decrease lift in the lower atmosphere and thereby increase or decrease precipitation production. 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 1 (Bonnin et al., 2004) and NOAA Atlas 14, Volume 8 (Perica et al., 2013) and Wyoming precipitation and/or rainfall-only precipitation frequency climatologies developed as part of this study (see Section 5 and Appendix E). These climatologies were used to derive the Orographic Transposition Factors (OTFs). This approach is similar to that used in HMRs 55A, 57 and 59 that used the Storm Separation Method (SSM) to quantify orographic effects in topographically significant regions. In contrast to the SSM methodology, the OTF procedure is significantly more objective and reproducible (see Section 9.7.4). In Appendix J, a detailed example of the subjectivity and issues associated with the SSM is provided. In Appendix J, AWA tried to replicate the SSM process and data using information provided in HMRs 55A, 57, and 59. The results of that analysis explicilty showed that the SSM method is not reproducible and highly subjective.

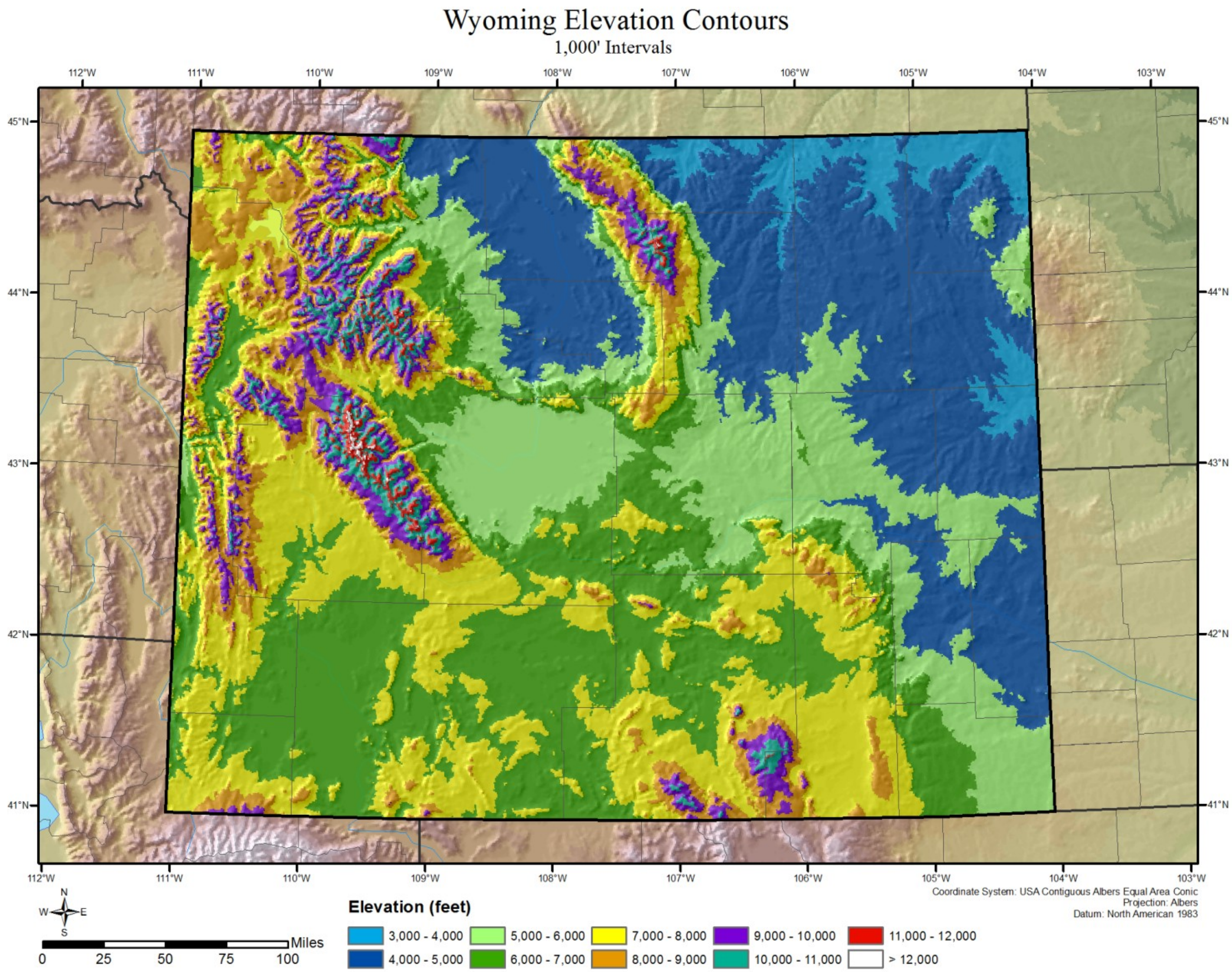


Figure 3.1 Elevation contours at 1,000 foot intervals over Wyoming

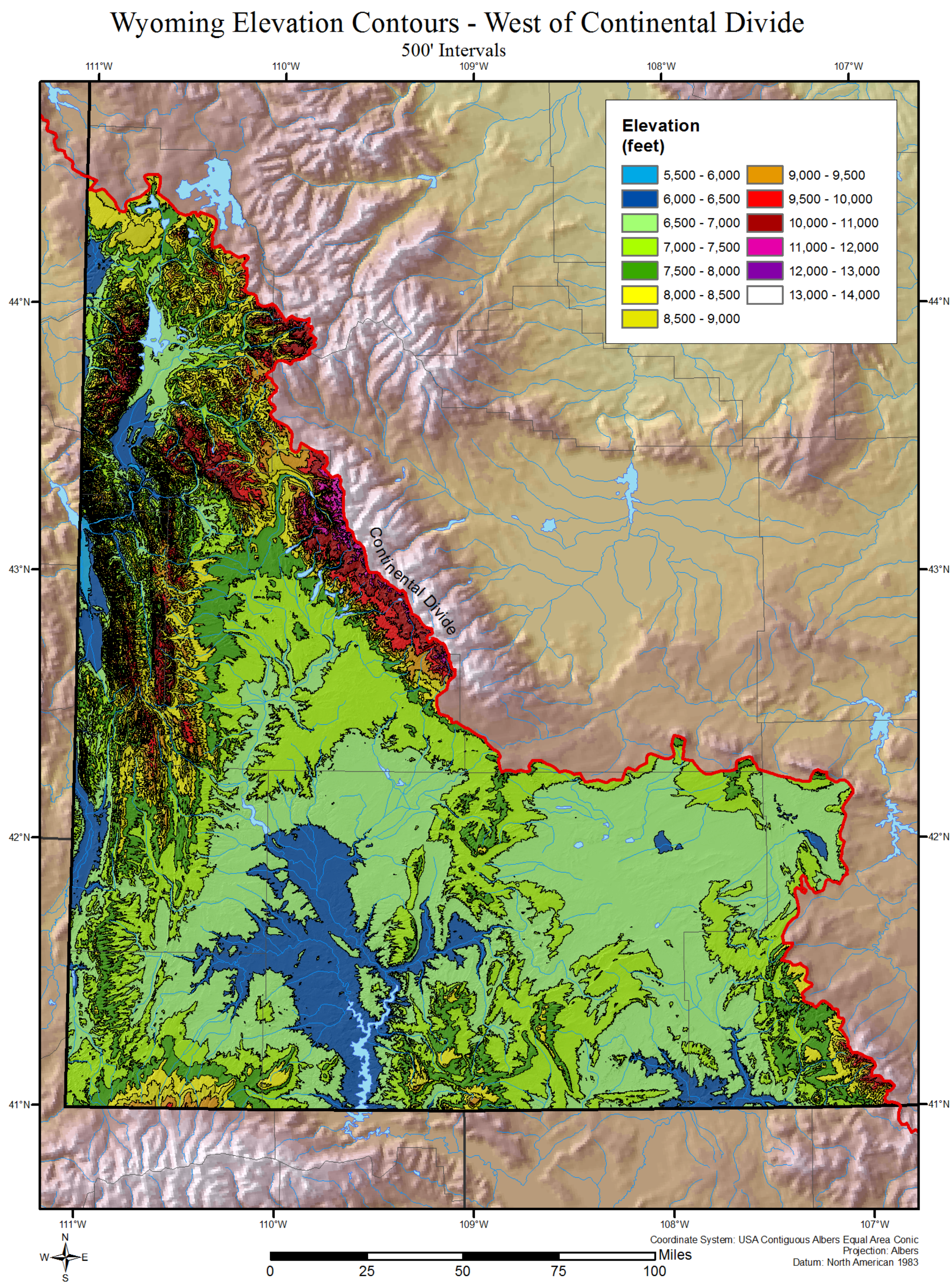


Figure 3.2 Elevation contours at 500 foot intervals over western Wyoming

3.1 Orographic Effects

Orographic effects on rainfall are explicitly captured in climatological analyses that use precipitation data from historical record. These historical rainfall amounts include precipitation that would have accumulated without topography together with the amount of additional precipitation or decreased precipitation that accumulated because of the effects of topography at a surrounding observation site. 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 Wyoming, extreme storm events (PMP-type storms) include local storms (both individual thunderstorms and MCSs) and general storms. Thunderstorms/MCSs are the primary controlling storm type of the precipitation frequency climatology at durations of 6 hours or less, while the general storms are responsible for the precipitation frequency climatology values for durations of 12 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.

The procedure used in this study to account for orographic effects determines the differences between the climatological information at the in-place storm location and the individual grid point. This is a departure from the SSM used in HMRs 55A, 57, and 59. The SSM used in the HMRs is highly subjective and is not reproducible. This results from the fact that there are unknown variables involved in the computation, specifically what amount of rainfall would have accumulated without the topography (convergence only or free atmospheric forces precipitation, e.g. HMR 55A Section 7.1). A detailed description of the HMR SSM process and an attempt to replicate/validate the process is provided in Appendix J.

The OTF process used in this study (as well as all AWA PMP studies where topography plays a major role in rainfall spatial distribution and magnitude) reduces the amount of subjectivity involved and provides a dataset which is reproducible. By evaluating the rainfall values for a range of return frequencies at both locations, a relationship between the two locations was established. For this study, gridded precipitation and rainfall-only frequency climatologies developed for the Wyoming project domain and NOAA Atlas 14, Volume 1 (Bonnin et al., 2004) and NOAA Atlas 14, Volume 8 (Perica et al., 2013) were used to develop the rainfall frequency relationships and quantify orographic effects.

The rainfall-only and 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 the difference in orographic effect between the two locations being compared. It is also assumed that the influence of terrain is the primary contributing factor to the variability in the relationship between precipitation climatology values at two distinct point locations of interest.

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 3.1.

$$P_o = mP_i + b$$ Equation 3.1

where,

P_o	=	target orographically adjusted rainfall (inches)
P_i	=	in-place rainfall (inches)
m	=	correlation coefficient
b	=	origin offset (inches)

Equation 3.1 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 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). 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 storms, is applied for all other analyzed durations for the given storm type. For general storms, the 24-hour rainfall-only precipitation frequency climatology was used at the storm center locations.

The orographic relationship can be visualized by plotting the average precipitation frequency depths 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 return frequencies, the coefficient of determination (*R-squared*) for the best-fit trendline is consistently very close to 1.00 indicating the goodness-of-fit of the statistical model (see Figure 9.5). As an alternative to producing the best-fit linear trendline graphically, linear regression can be used to determine the relationship mathematically. An example of the determination of the orographic relationship and development of the OTF is given in Section 9.7.4.

4. Dew Point Climatology Development

This study incorporated updated procedures and data analysis methods used in other PMP studies completed by AWA but were not in the development of the HMRs. This section describes the development of the updated dew point climatologies. The maximum average dew point climatology was developed and used in the storm maximization process.

4.1 6- 12- and 24-hour Maximum Average Dew Point Climatology Methodology

These updated dew point climatologies replace those provided in the HMRs. The initial task in the development of the updated climatology was a search of the National Climatic Data Center (NCDC) hourly stations that record hourly dew point temperature data within a defined search domain surrounding Wyoming (Figure 4.1).

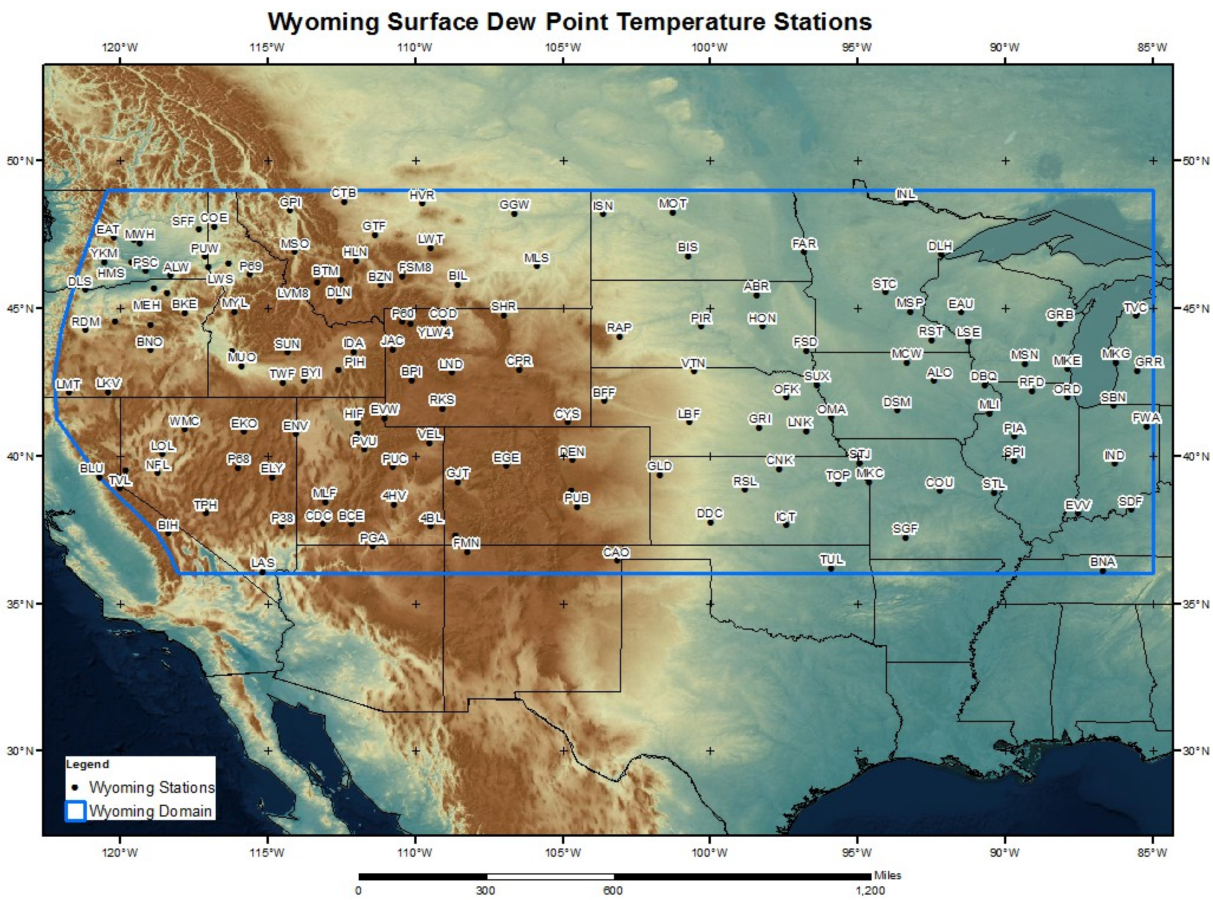


Figure 4.1 Hourly dew point station locations used for the updated maximum dew point climatology development

Once stations were identified, AWA extracted the archived NCDC hourly datasets for the maximum average 6-hour, 12-hour, and 24-hour dew point temperatures for each reporting station. A total of 157 hourly stations were within the search domain. These stations are listed in Table 4.1. Initial quality control (QC) limited stations to 30-years or greater period-of-record. After this initial QC, 152 hourly stations were selected for the dew point temperature analysis. A script was written to extract each station's monthly maximum dew point temperatures for 6-, 12- and 24-hour durations for each year, providing annual maximum series (AMS) for that station. The AMS for each month for each station served as input to an R-statistical script that calculated L-moment statistics. Using the generalized-extreme-value (GEV) distribution, the 20-year, 50-year, and 100-year return frequency dew point temperature values were calculated for each month for each station. The extracted dew point data were adjusted to the 15th of each month and adjusted to 1000mb dew point values.

The updated dew point climatologies replace the 12-hour maximum persisting dew point climatologies published by the US Department of Commerce Environmental Data Service in the Climatic Atlas of the United States (EDS, 1968). The 12-hour maximum persisting dew point climatologies were used to represent the maximum dew points for storm maximization procedures in the HMRs. The 12-hour maximum persisting dew point climatologies used in the HMRs were outdated but more importantly did not adequately represent the atmospheric moisture available in the PMP storm environment. The 12-hour persisting dew point values often missed or underestimated the atmospheric moisture available and led to overly conservative maximization calculations (see Section 7.1.2).

The updated climatology more accurately represents the atmospheric moisture fueling storms by using average maximum dew point values observed over durations specific to each storm's rainfall duration. The average maximum dew point values for various durations replace the maximum 12-hour persisting dew point values.

Table 4.1 Stations used to derive the maximum dew point climatology

ID	Name	State	Latitude	Longitude	Elevation	POR
BIH	BISHOP	CA	37.3667	-118.3670	4145	62
BIL	BILLINGS	MT	45.8000	-108.5330	3570	62
BNO	BURNS	OR	43.5833	-118.9500	4170	48
BOI	BOISE	ID	43.5667	-116.2170	2868	62
BTM	BUTTE	MT	45.9647	-112.5010	5539	62
CTB	CUTBANK	MT	48.6167	-112.3830	3837	62
EKO	ELKO	NV	40.8264	-115.7870	5049	62
ELY	ELY	NV	39.2833	-114.8500	6262	57
GJT	GRAND JUNCTION	CO	39.1167	-108.5330	4839	62
GPI	KALISPELL	MT	48.3114	-114.2550	2973	32
GTF	GREAT FALLS	MT	47.4833	-111.3670	3657	62
HLN	HELENA	MT	46.6000	-112.0000	3898	62
HVR	HAVRE	MT	48.5500	-109.7670	2599	49
LND	LANDER	WY	42.8167	-108.7330	5558	62
LOL	LOVELOCK	NV	40.0681	-118.5690	3899	62
LWS	LEWISTON	ID	46.3833	-117.0170	1437	62
LWT	LEWISTOWN	MT	47.0500	-109.4670	4144	62
MSO	MISSOULA	MT	46.9167	-114.0830	3189	62
PDT	PENDLETON	OR	45.6833	-118.8500	1495	72
PIH	POCATELLO	ID	42.9167	-112.6000	4478	62
RDM	REDMOND	OR	44.2667	-121.1500	3084	62
RKS	ROCK SPRINGS	WY	41.6000	-109.0670	6739	62
RNO	RENO	NV	39.5000	-119.7830	4400	61
SFF	SPOKANE	WA	47.6667	-117.3330	1952	62
SLC	SALT LAKE CITY	UT	40.7667	-111.9670	4227	62
TPH	TONOPAH	NV	38.0511	-117.0900	5429	59
WMC	WINNEMUCA	NV	40.9000	-117.8000	4314	61
YKM	YAKIMA	WA	46.5667	-120.5330	1066	62
BPI	BIG PINEY	WY	42.5667	-110.1000	6969	33
BYI	BURLEY	ID	42.5417	-113.7660	4156	33
IDA	IDAHO FALLS	ID	43.5167	-112.0670	4744	33
COD	CODY	WY	44.5167	-109.0170	5095	33
BZN	BOZEMAN	MT	45.7833	-111.1500	4462	33
BKE	BAKER	OR	44.8428	-117.8090	3367	33
MEH	MEACHAM	OR	45.5000	-118.4000	3726	33
ALW	WALLA WALLA	WA	46.1000	-118.2830	1207	33
EAT	WENATCHEE	WA	47.3978	-120.2010	1229	33
LMT	KLAMATH FALLS	OR	42.1500	-121.7330	4091	33
LKV	LAKEVIEW	OR	42.1667	-120.4000	4728	18
TRK	TRUCKEE	CA	39.3167	-120.1330	5899	33

Table 4.1 Stations used to derive the maximum dew point climatology (continued)

ID	Name	State	Latitude	Longitude	Elevation	POR
TVL	SOUTH LAKE TAHOE	CA	38.8983	-119.9950	6252	33
NFL	FALLON	NV	39.4166	-118.7010	3934	33
P68	EUREKA	NV	39.6014	-116.0060	5945	30
PUC	PRICE	UT	39.6167	-110.7500	5903	33
PVU	PROVO	UT	40.2167	-111.7170	4492	30
HIF	HILL AFB	UT	41.1167	-111.9670	4787	33
EVW	EVANSTON	WY	41.2750	-111.0320	6601	33
JAC	JACKSON	WY	43.6000	-110.7330	6444	33
MYL	MCCALL	ID	44.8833	-116.1000	5025	28
P69	LOWELL	ID	46.1442	-115.5960	1480	29
COE	COEUR DALENE	ID	47.7667	-116.8170	2158	29
LVM8	CALVERT CREEK	MT	45.8833	-113.3330	6430	33
DLN	DILLON	MT	45.2500	-112.5500	5240	33
SUN	HAILEY	ID	43.5000	-114.3000	5315	33
TWF	TWIN FALLS	ID	42.4833	-114.4830	4150	33
MUO	MOUNTAIN HOME	ID	43.0500	-115.8670	2995	33
DRO3	JOHN DAY	OR	44.4233	-118.9590	3063	33
P60	YELLOWSTONE	WY	44.5500	-110.4170	8002	30
ENV	WENDOVER	UT	40.7333	-114.0330	4239	33
VEL	VERNAL	UT	40.4500	-109.5170	5259	33
DLS	THE DALLES	OR	45.6194	-121.1710	235	33
HMS	HANFORD	WA	46.5667	-119.6000	733	25
PSC	PASCO	WA	46.2667	-119.1170	404	33
EPH	EPHRATA	WA	47.3081	-119.5150	1259	33
MWH	MOSES LAKE	WA	47.2000	-119.3170	1188	33
PUW	PULLMAN-MOSCOW	WA	46.7439	-117.1140	2551	33
ABR	ABERDEEN	SD	45.4500	-98.4333	1300	62
ALO	WATERLOO	IA	42.5500	-92.4000	878	61
BFF	SCOTTSBLUFF	NE	41.8667	-103.6000	3958	62
BIS	BISMARCK	ND	46.7667	-100.7500	1660	62
BNA	NASHVILLE	TN	36.1167	-86.6833	605	62
CAO	CLAYTON	NM	36.4500	-103.1500	4972	62
CNK	CONCORDIA	KS	39.5500	-97.6500	1484	62
COS	COLO. SPRNGS	CO	38.8167	-104.7170	6170	62
COU	COLUMBIA	MO	38.8167	-92.2167	898	41
CPR	CASPER	WY	42.9167	-106.4670	5290	60
CYS	CHEYENNE	WY	41.1500	-104.8170	6141	62
DBQ	DUBUQUE	IA	42.4000	-90.7000	1080	59
DDC	DODGE CITY	KS	37.7667	-99.9667	2592	62
DEN	DENVER INTL	CO	39.8667	-104.6670	5382	62

Table 4.1 Stations used to derive the maximum dew point climatology (continued)

ID	Name	State	Latitude	Longitude	Elevation	POR
DLH	DULUTH	MN	46.8333	-92.1833	1417	62
DSM	DES MOINES	IA	41.5333	-93.6500	963	65
EAU	EAU CLAIRE	WI	44.8667	-91.4833	888	61
EGE	EAGLE	CO	39.6500	-106.9170	6513	62
EVV	EVANSVILLE	IN	38.0500	-87.5333	388	62
FAR	FARGO	ND	46.9000	-96.8000	899	62
FSD	SIOUX FALLS	SD	43.5667	-96.7333	1427	62
FWA	FORT WAYNE	IN	41.0000	-85.2000	828	62
GGW	GLASGOW	MT	48.2167	-106.6170	2298	55
GLD	GOODLAND	KS	39.3667	-101.7000	3688	62
GRB	GREEN BAY	WI	44.4833	-88.1333	702	61
GRI	GRAND ISLAND	NE	40.9667	-98.3167	1856	62
GRR	GRAND RAPIDS	MI	42.8833	-85.5167	803	46
HON	HURON	SD	44.3833	-98.2167	1289	70
ICT	WICHITA	KS	37.6500	-97.4167	1340	56
IND	INDIANAPOLIS	IN	39.7333	-86.2833	808	62
INL	INTERNATIONAL FALLS	MN	48.5667	-93.3833	1183	62
ISN	WILLISTON	ND	48.1833	-103.6330	1905	48
LBF	NORTH PLATTE	NE	41.1333	-100.6830	2787	62
LNK	LINCOLN	NE	40.8500	-96.7500	1189	62
LSE	LA CROSSE	WI	43.8789	-91.2528	651	62
MCI	KANSAS CITY	MO	39.3167	-94.7167	1025	38
MCW	MASON CITY	IA	43.1544	-93.3269	1194	62
MKC	KANSAS CITY	MO	39.1167	-94.6000	758	62
MKE	MILWAUKEE	WI	42.9500	-87.9000	693	62
MKG	MUSKEGON	MI	43.1667	-86.2333	633	62
MLI	MOLINE	IL	41.4500	-90.5167	594	62
MLS	MILES CITY	MT	46.4267	-105.8820	2627	62
MOT	MINOT	ND	48.2553	-101.2730	1665	62
MSN	MADISON	WI	43.1333	-89.3333	866	62
MSP	MINNEAPOLIS	MN	44.8833	-93.2167	838	65
OFK	NORFOLK	NE	41.9833	-97.4333	1551	62
OMA	OMAHA	NE	41.3000	-95.9000	982	62
ORD	CHICAGO-OHARE	IL	41.9833	-87.9000	674	52
PIA	PEORIA	IL	40.6667	-89.6833	662	62
PIR	PIERRE	SD	44.3814	-100.2860	1734	62
PUB	PUEBLO	CO	38.2833	-104.5170	4720	56
RAP	RAPID CITY	SD	44.0500	-103.0670	3168	60
RFD	ROCKFORD	IL	42.2000	-89.1000	734	59
RSL	RUSSELL	KS	38.8667	-98.8167	1869	60

Table 4.1 Stations used to derive the maximum dew point climatology (continued)

ID	Name	State	Latitude	Longitude	Elevation	POR
RST	ROCHESTER	MN	43.9167	-92.5000	1320	62
SBN	SOUTH BEND	IN	41.7000	-86.3167	773	62
SDF	LOUISVILLE	KY	38.1833	-85.7333	488	62
SGF	SPRINGFIELD	MO	37.2333	-93.3833	1270	62
SHR	SHERIDAN	WY	44.7667	-106.9670	3968	62
SPI	SPRINGFIELD	IL	39.8333	-89.6667	613	62
STC	ST CLOUD	MN	45.5500	-94.0667	1024	62
STL	ST. LOUIS	MO	38.7500	-90.3833	564	65
SUX	SIOUX CITY	IA	42.4000	-96.3833	1103	62
TOP	TOPEKA	KS	39.0667	-95.6333	885	62
TUL	TULSA	OK	36.2000	-95.9000	676	62
TVC	TRAVERSE CITY	MI	44.7366	-85.5700	630	62
STJ	ST. JOSEPH	MO	39.7667	-94.9167	818	62
VTN	VALENTINE	NE	42.8667	-100.5500	2598	34
MLF	MILFORD	UT	38.4333	-113.0170	5033	60
LAS	LAS VEGAS	NV	36.0833	-115.1670	2180	60
P38	CALIENTE	NV	37.6167	-114.5170	4380	25
CDC	CEDAR CITY	UT	37.7000	-113.1000	5618	60
BCE	BRYCE CANYON	UT	37.7022	-112.1540	7584	60
PGA	PAGE	AZ	36.9333	-111.4500	4278	31
CEZ	CORTEZ	CO	37.3000	-108.6330	5916	31
FMN	FARMINGTON	NM	36.7500	-108.2330	5502	59
RWL	RAWLINS	WY	41.8000	-107.2000	6734	33
LAR	LARAMIE	WY	41.3164	-105.6720	7264	33
HDN	HAYDEN	CO	40.5000	-107.2500	6604	33
CAG	CRAIG	CO	40.5000	-107.5330	6191	31
ASE	ASPEN	CO	39.2167	-106.8670	8416	33
LXV	LEADVILLE	CO	39.2500	-106.3000	10158	33
GUC	GUNNISON	CO	38.5500	-106.9170	7668	33
DRO	DURANGO	CO	37.1500	-107.7500	6683	33
MTJ	MONTROSE	CO	38.5000	-107.8830	5758	33
ALS	ALAMOSA	CO	37.4500	-105.8670	7541	33

4.1.1 Procedure for Adjusting to the 15th of the Month

The station data were corrected to the 15th of each month using a linear relationship between the previous month, current month, and the next month. The 15th adjustment was performed using a series of Excel macros. The steps are listed below:

1) Calculate the difference in days between the observed average date of the annual maximum series occurrence of the month being analyzed and the 15th.
2) Depending whether the difference in step 1 is positive or negative (direction of adjustment) calculate the ratio/difference between the non-adjusted dew point temperature (for the months of interest) and the number of days between the dates.
3) Apply the ratio calculated in step 2 to the difference calculated in step 1.
4) Check the adjusted dew point value with the previous and next month values, and the other two durations.
5) Calculate the difference between the original dew point value and the adjusted dew point value.
6) Create station plots of the duration and frequency for additional QC measure.
7) Create a list of the adjusted dew point values for each station in a GIS format.

4.1.2 1000mb Adjustment Procedures

A moist lapse rate (2.7°F/1,000 feet, see http://www.weather.bm/glossary/Glossary.asp for a description of this standard moist lapse rate) was used to adjust the 15th of the month dew point temperature, at the station elevation, to 1000mb (assumed to be at elevation zero, i.e. sea level). A linear relationship between elevation and lapse rate was created and applied to each station. The June 24-hour maximum average dew point data for Lander, WY are shown in Table 4.2. The table shows the original station data, the data adjusted to the 15th, and the data adjusted to 1000mb.

Table 4.2 Original 24-hour average dew point data, adjusted dew point data (to the 15th), and the 1000mb dew point data for 20-year, 50-year, and 100-year frequencies at Lander, WY

Lander, WY	20-year	50-year	100-year
Station Data	55.4°F	56.5°F	57.0°F
15th Data	53.3°F	53.7°F	53.9°F
1000mb Data	68.3°F	68.7°F	68.9°F

4.1.3 Spatial Interpolation of Data

Maximum and minimum monthly dew point temperature PRISM grids were downloaded for the continental United States for the time period of 1971-2000. For this time period, PRISM grids were used to calculate the mean monthly dew point temperature $\overline{td}_m$:

$$\overline{td}_m = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \text{Equation 4.1}$$

where *m* is the month of interest, *n* is the number of months and x_i are the monthly dew temperature values. The PRISM data were converted from degrees Celsius to degrees Fahrenheit. The mean monthly PRISM dew point data were extracted for each of the 152 dew point stations.

Linear relationships between PRISM data (described above) and the station dew point temperature data (1000mb) for each duration (6-, 12-, and 24-hour) and frequency (20-, 50-, and 100-year) were calculated, where *y* equals the stations dew point temperature (°F) value, and *x* equals the stations mean monthly PRISM dew point temperature (°F) value. Examples of the linear relationships between mean monthly PRISM dew point data and the 100-year 24-hour dew point data for May, June, July, and August are shown in Figure 4.2a-d.

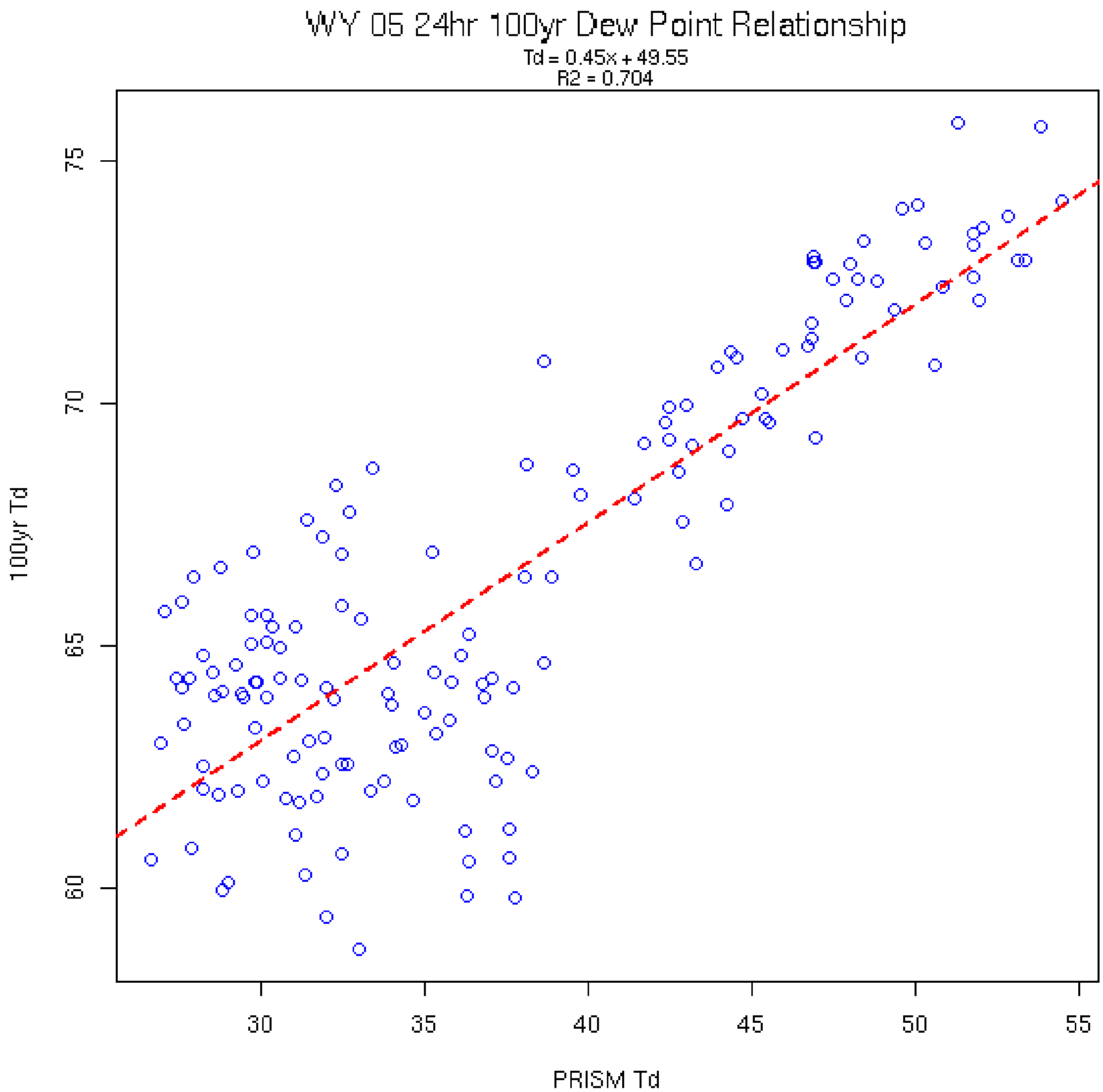


Figure 4.2a Linear relationships between mean monthly PRISM dew point values and the 100-year 24-hour maximum average dew point values for May

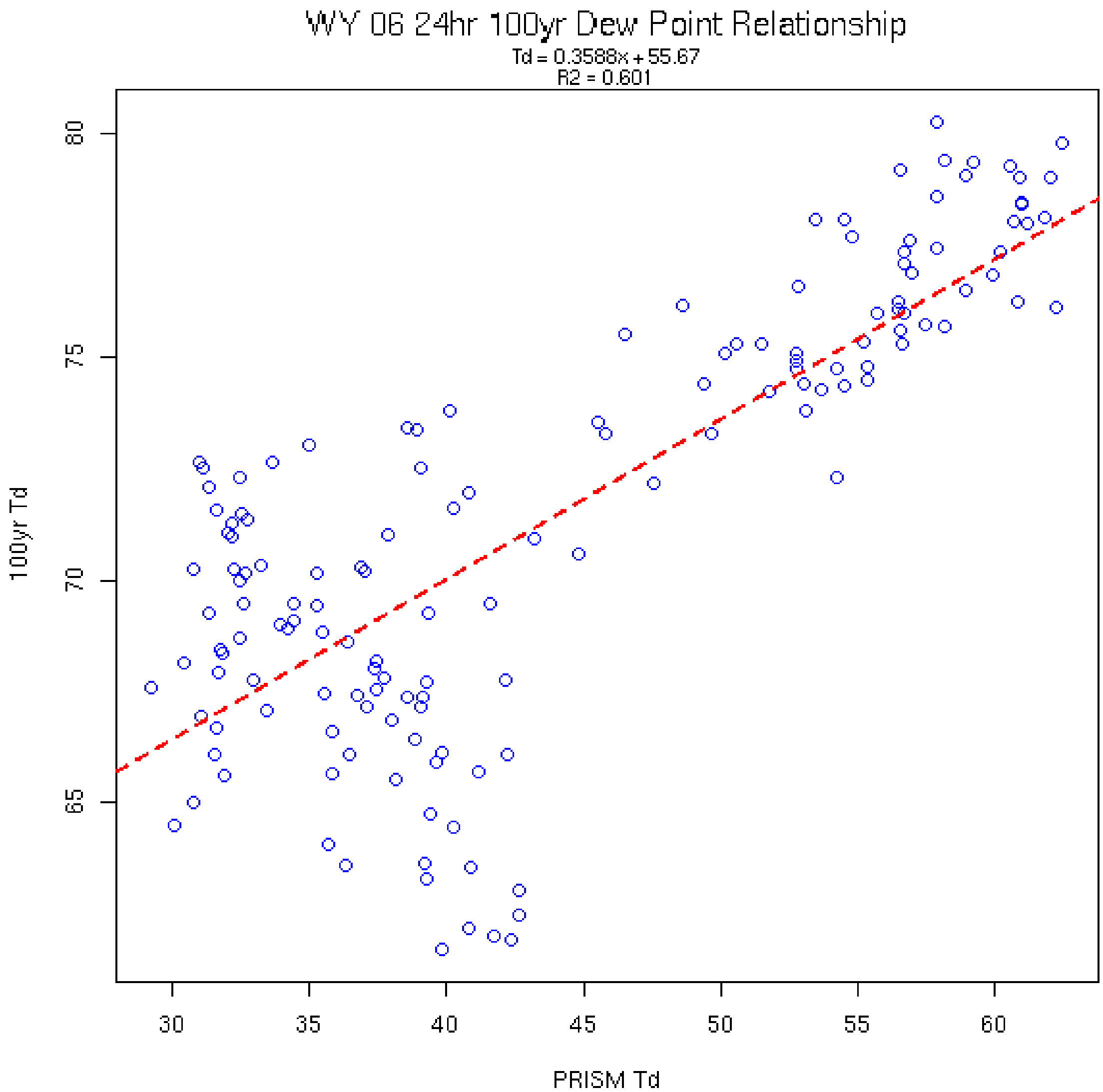


Figure 4.2b Linear relationships between mean monthly PRISM dew point values and the 100-year 24-hour maximum average dew point values for June

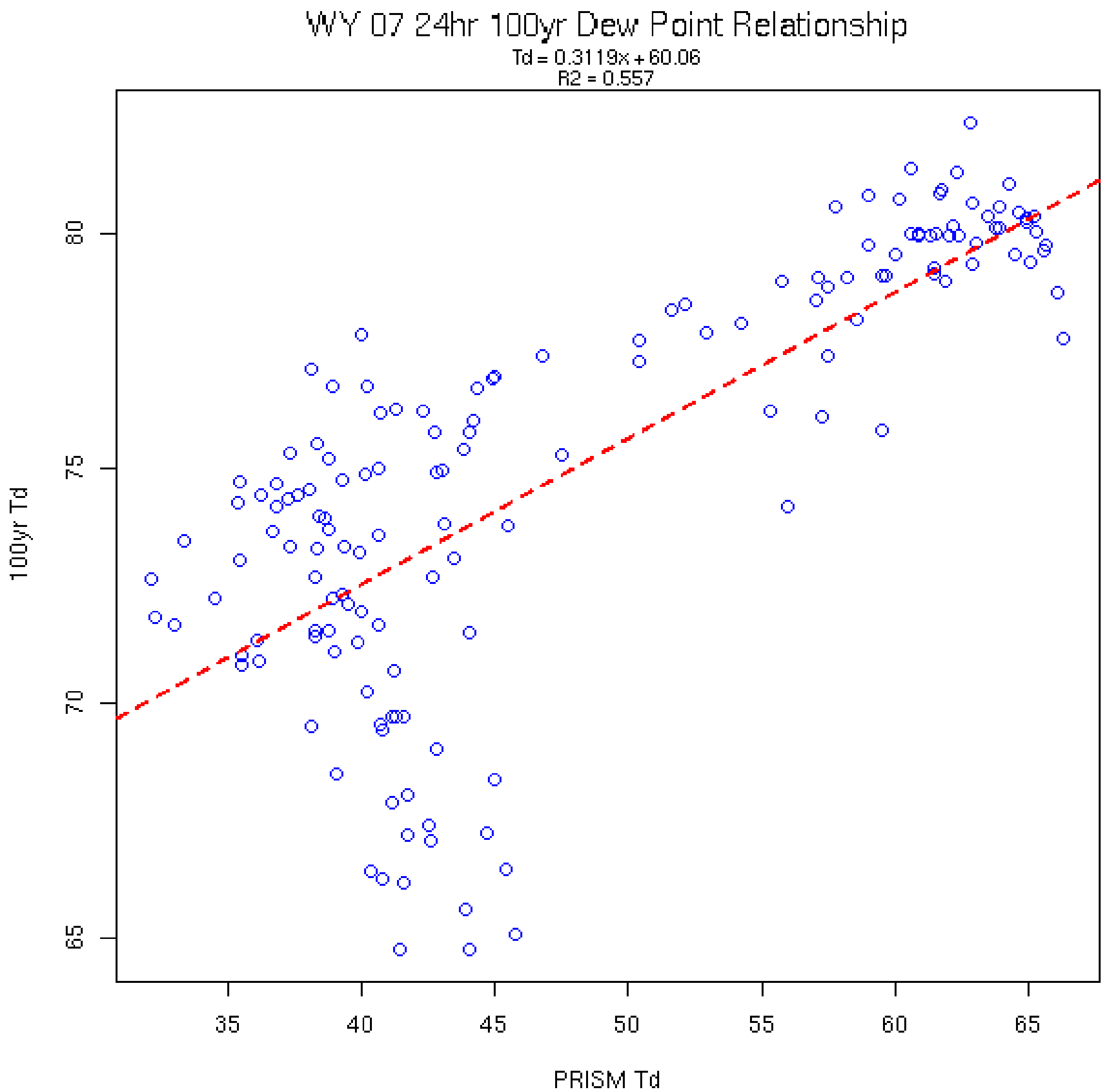


Figure 4.2c Linear relationships between mean monthly PRISM dew point values and the 100-year 24-hour maximum average dew point values for July

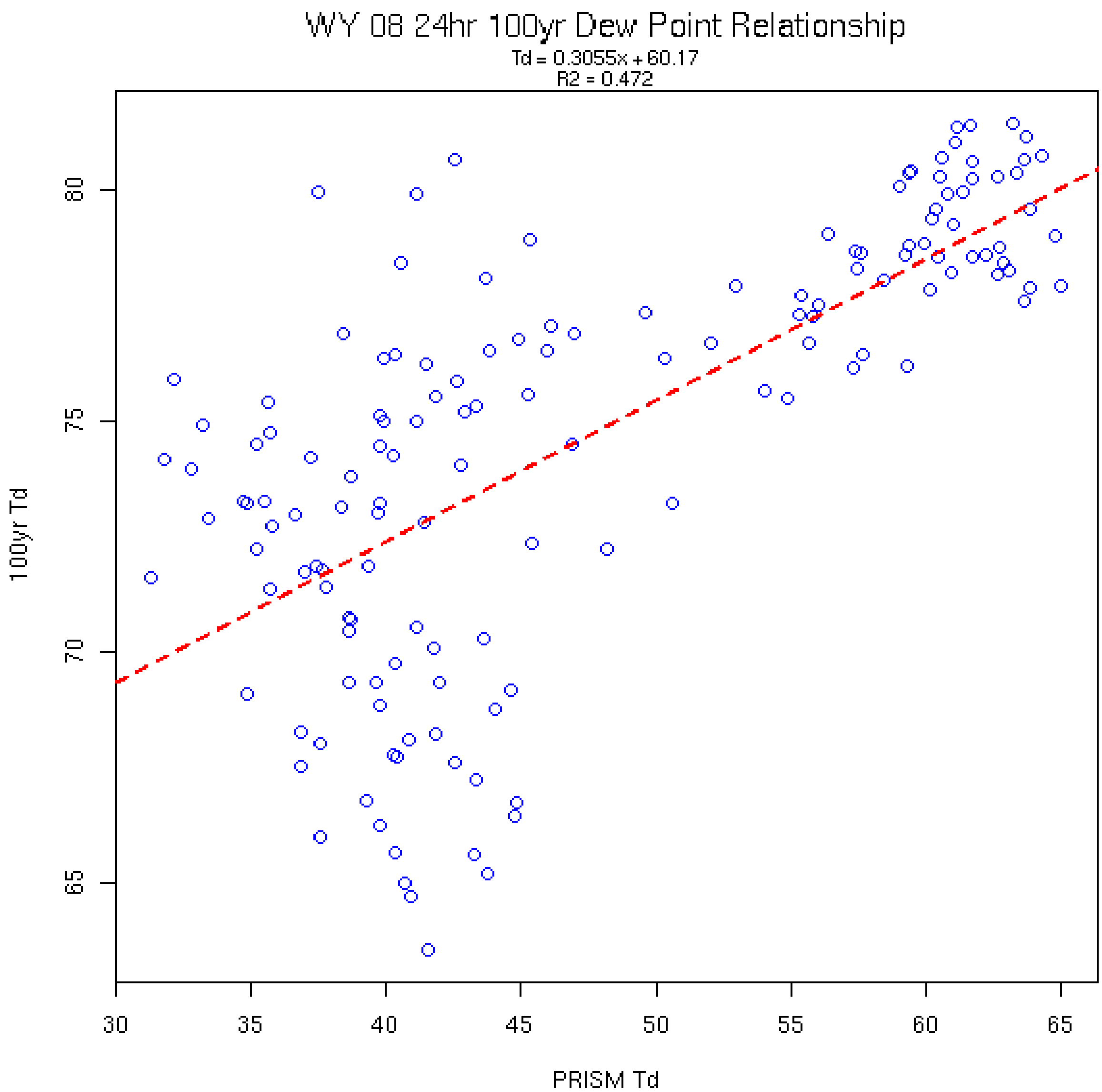


Figure 4.2d Linear relationships between mean monthly PRISM dew point values and the 100-year 24-hour maximum average dew point values for August

The derived linear relationships were applied to the mean monthly dew point PRISM grids, which provided a first estimate of the dew point temperature spatial distribution. Residuals (actual – predicted) between the station and the first estimate were calculated at each station.

The residuals were spatially distributed across the search domain using an inverse-distance algorithm. The spatially distributed residual grids were smoothed to reduce bulls-eye effects. The smoothed residual grid was added to the first estimate grid to create the second estimate grid. The second estimate grids were smoothed to further reduce bulls-eye effects. The smoothed second estimate grids represent the final maximum average dew point temperature distribution.

The spatial interpolation method was tested and applied for the Nebraska statewide study (Tomlinson et al., 2008) the Tarrant Regional Water District studies (Tomlinson et al., 2011; Kappel et al., 2012), Brassua Maine study (Tomlinson et al., 2011), the Ohio statewide study (Tomlinson et al., 2013) and the Arizona statewide study (Tomlinson et al., 2013). Perl and R-statistical programs were used to automate the process within GRASS GIS environment. The GRASS GIS script also created 1°F dew point contours from the final interpolated dew point grids. The GRASS GIS dew point analysis and 0.5°F contours for the June, July, August, and September 100-year 24-hour are shown in Figure 4.3 a-d. The GRASS GIS dew point rasters and contour shapefiles were exported from the GRASS GIS environment to an ArcGIS environment for creation of the final dew point map layouts.

Creation of the final dew point maps used in this project was completed after manual interpretation of the automated contours and meteorological analysis by AWA. During this manual analysis, inconsistencies were removed and smoothing was applied where meteorological, climatological, and topographical factors warranted such actions. Further, expertise was used to compensate for the lack of spatial coverage in some sections of Wyoming domain and to ensure continuity between months and durations.

The Wyoming dew point climatology domain was blended together with existing dew point climatologies created using the same procedures but as part of different PMP projects. The blended dew point climatologies created a seamless 6-, 12-, and 24-hour 100-year climatology for the continental United States east of the Cascade and Sierra Nevada mountain ranges. Figures 4.4-4.6 display examples of the final blended dew point maps and Appendix B contains all the maps used as part of this PMP analysis.

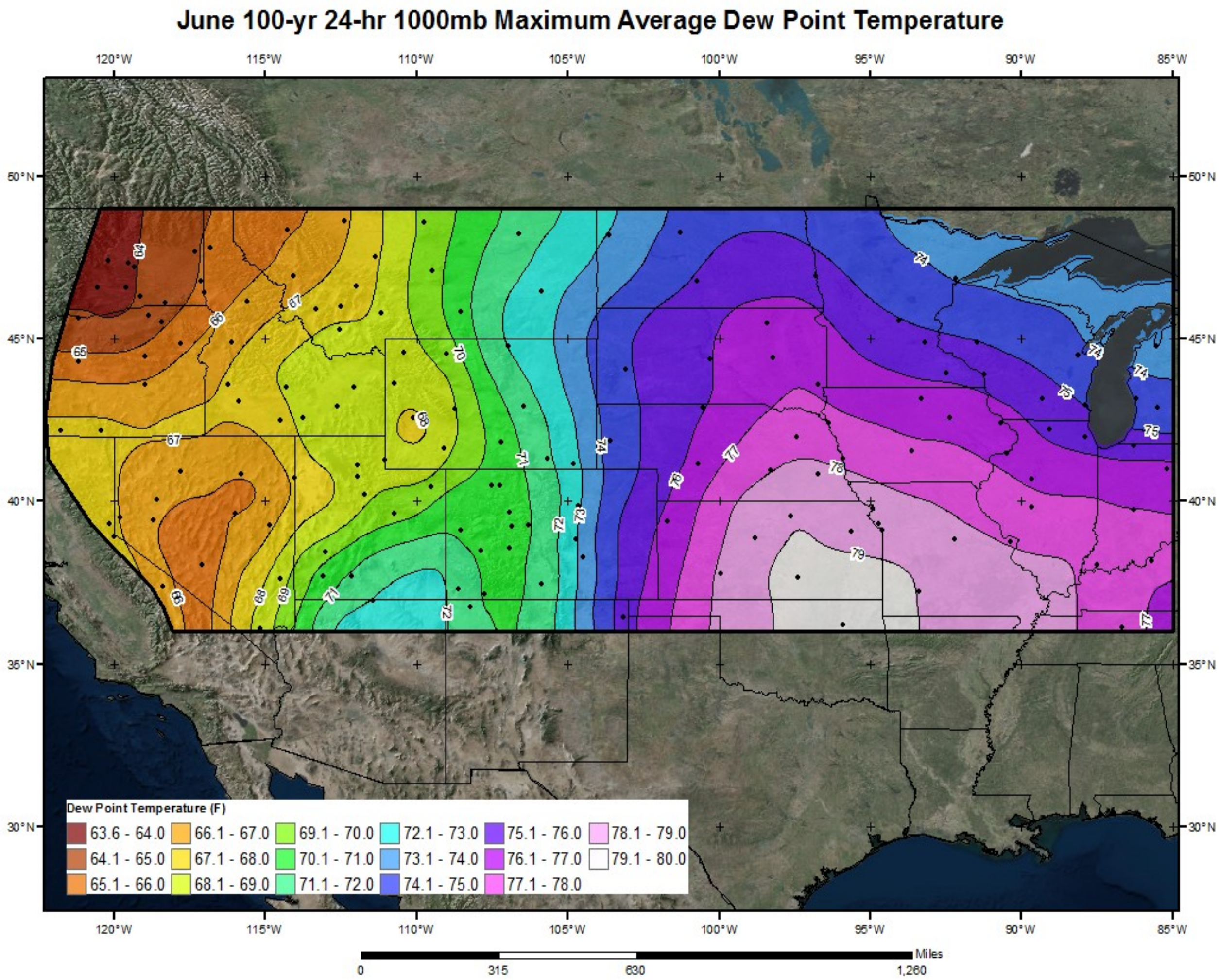


Figure 4.3a June 100-year return frequency maximum average 24-hour dew point map

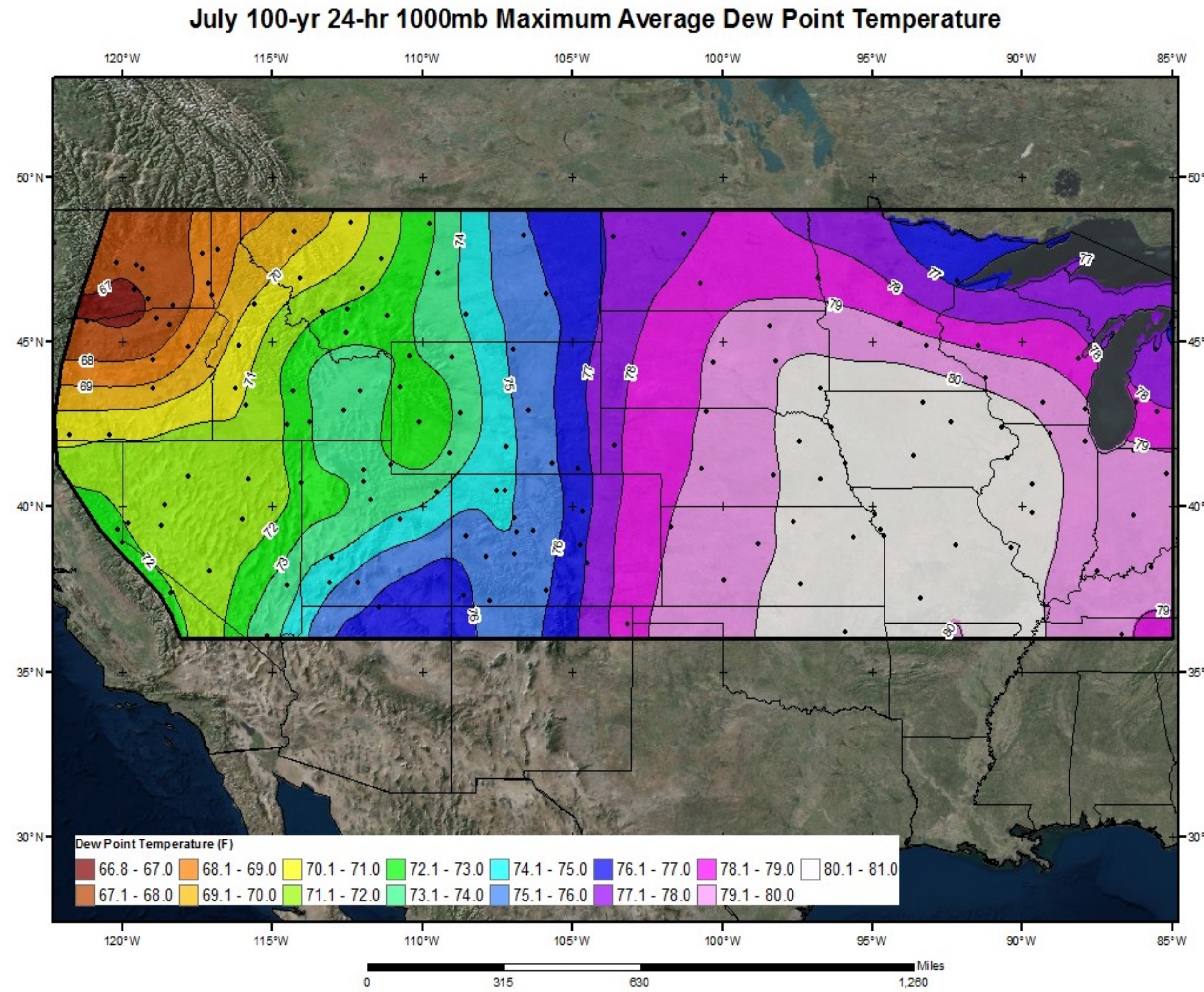


Figure 4.3b July 100-year return frequency maximum average 24-hour dew point map

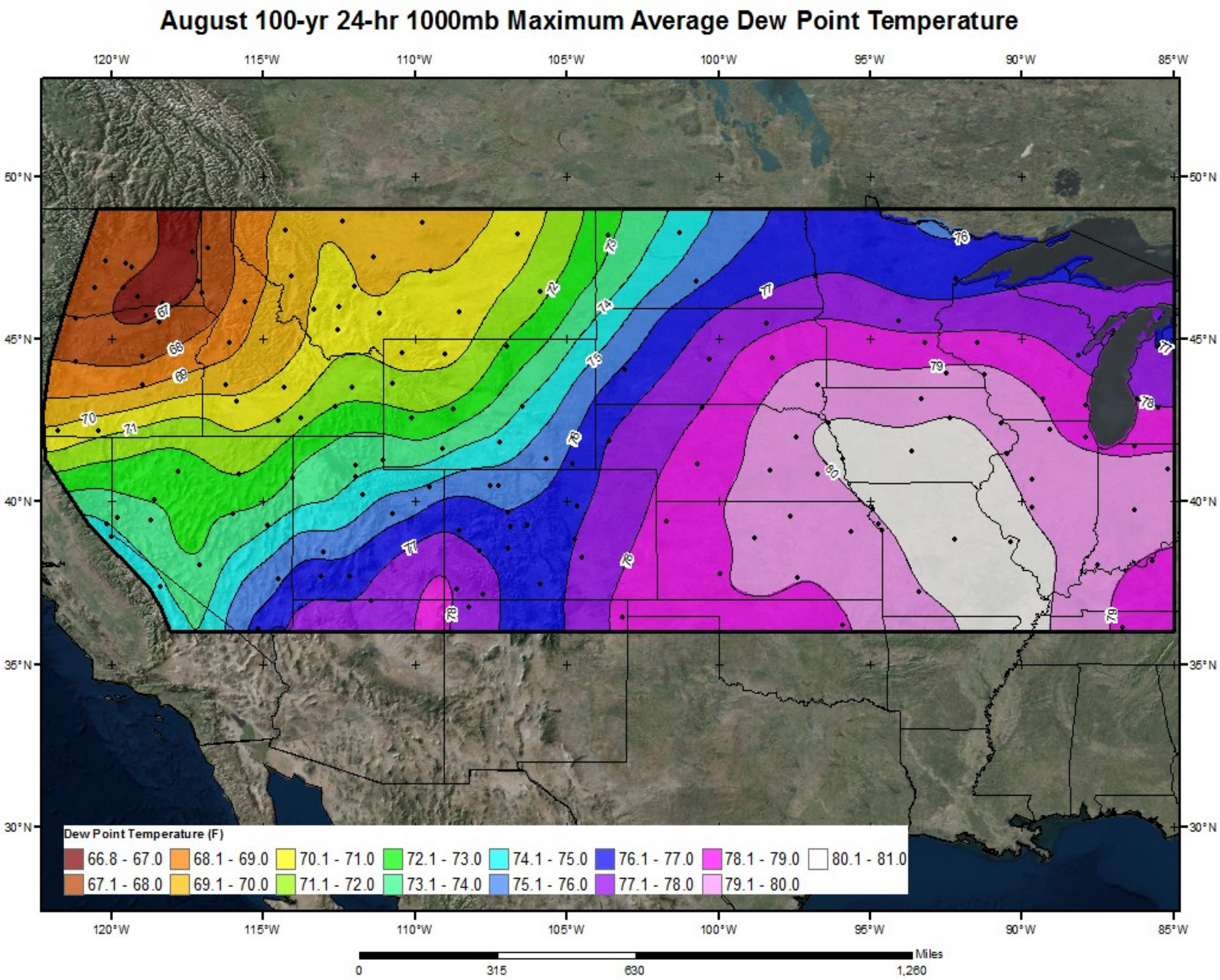


Figure 4.3c August 100-year return frequency maximum average 24-hour dew point map

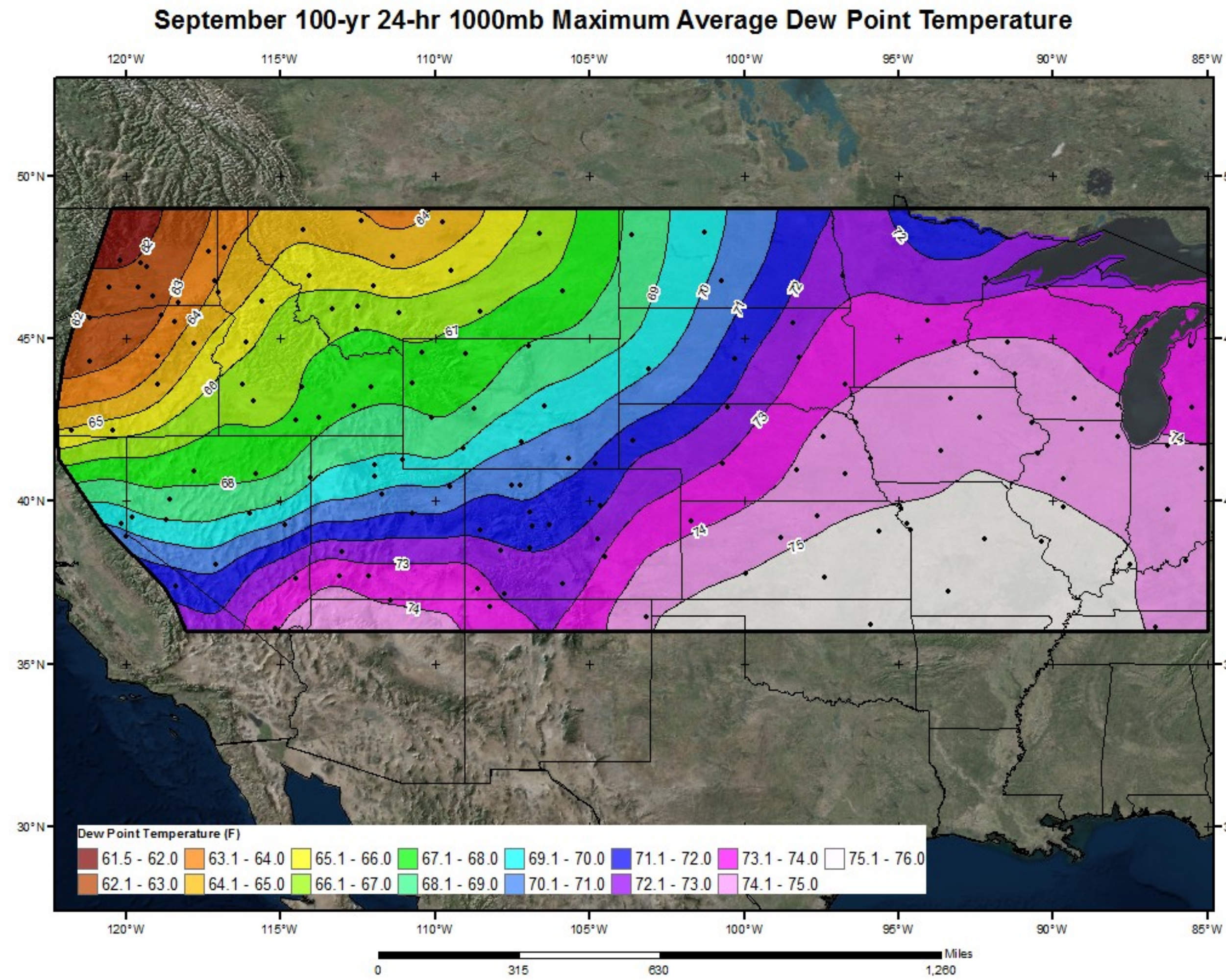


Figure 4.3d September 100-year return frequency maximum average 24-hour dew point map

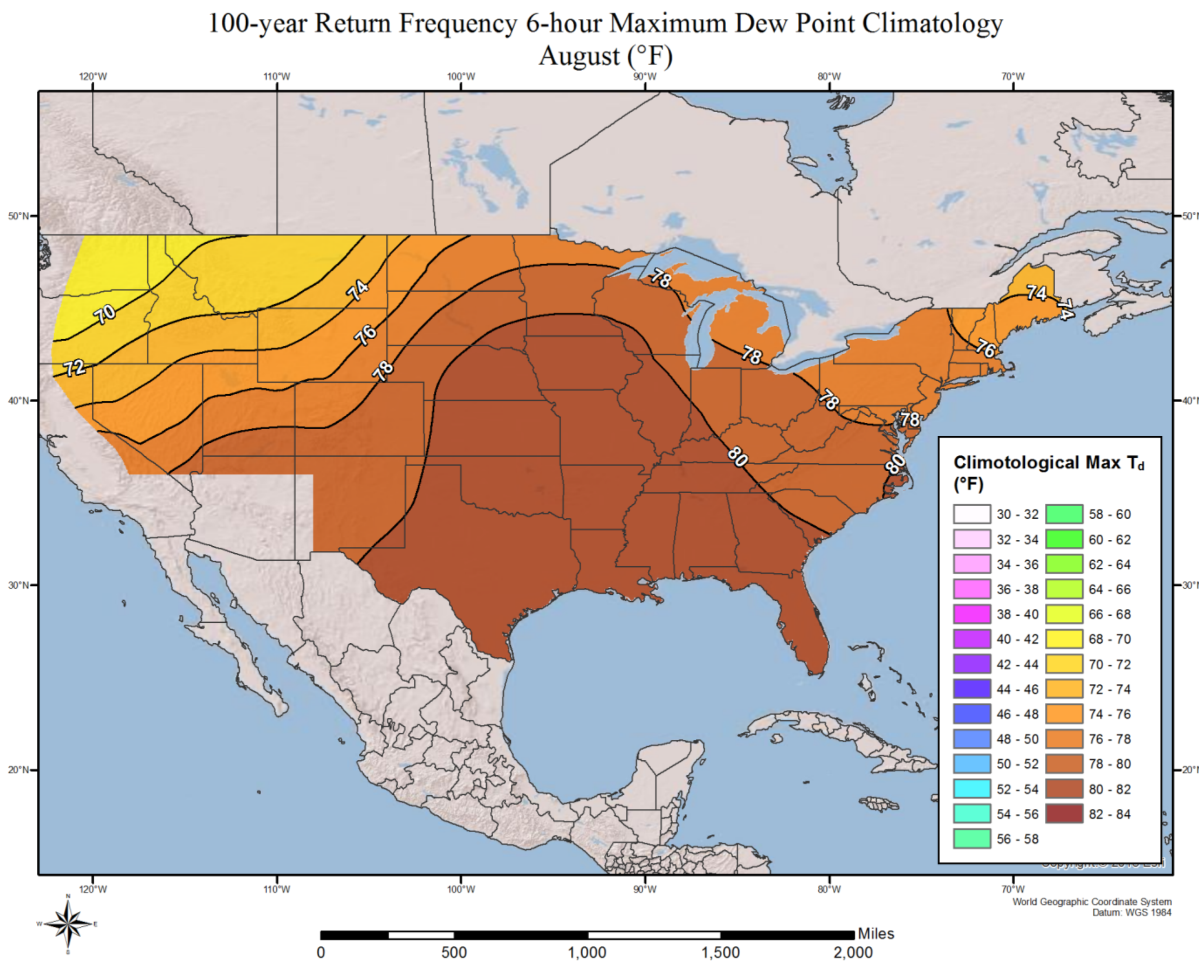


Figure 4.4 August 100-year return frequency maximum average 6-hour dew point map

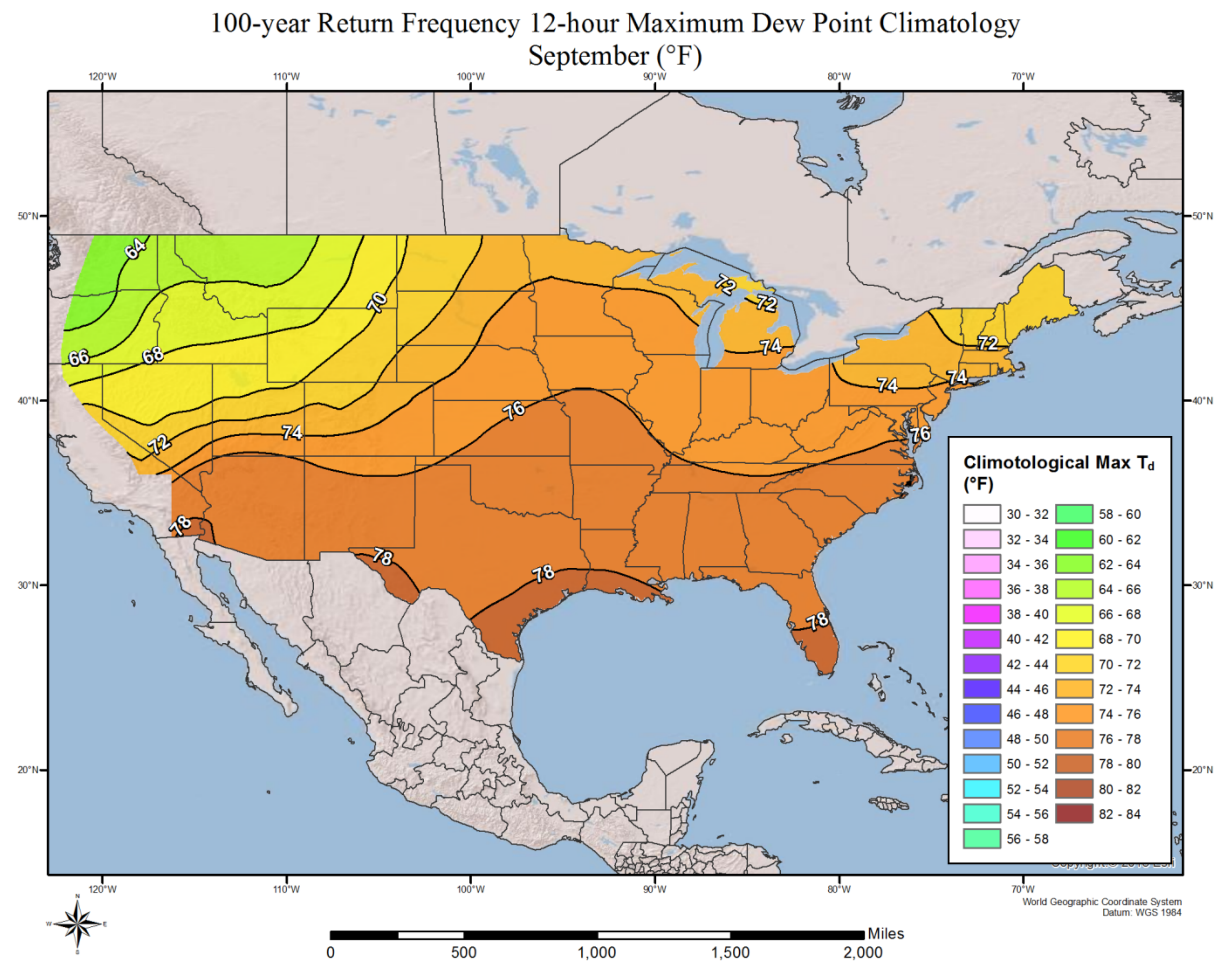


Figure 4.5 September 100-year return frequency maximum average 12-hour dew point map

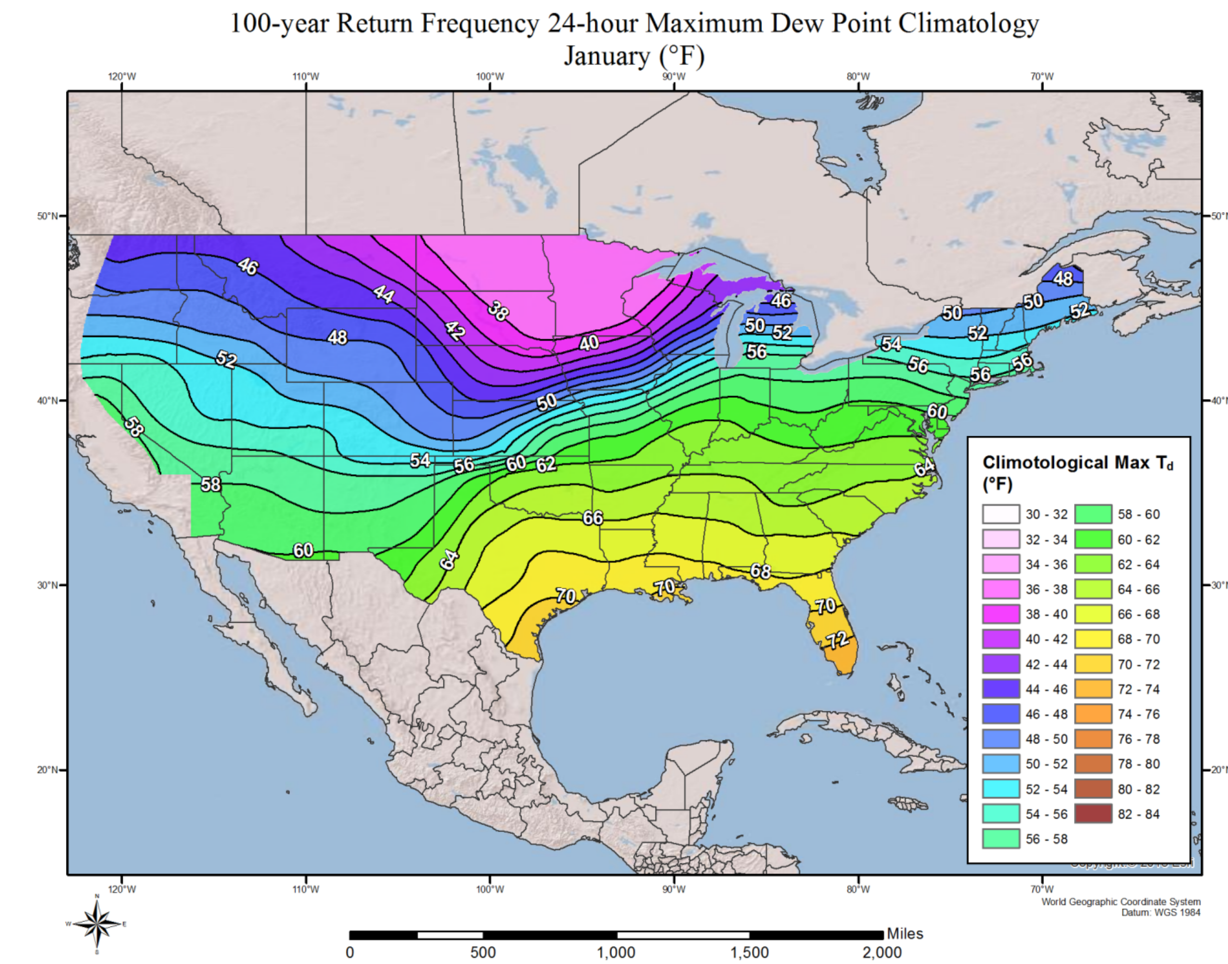


Figure 4.6 January 100-year return frequency maximum average 24-hour dew point map

4.2 3-hour Maximum Average Dew Point Climatology Methodology

A 3-hour dew point climatology was determined to be needed to properly represent the moisture responsible for the shorter duration local storm events west of the Contented Divide. In these situations, the storm rainfall and moisture supplying the storms generally occur in 3-hours or less. Therefore, the 6-hour climatology does not represent the moisture source for these storms as well as the 3-hour climatology does. Based on a comparison of 3-hour vs. 6-hour 100-year dew point values at subset of four locations (Lander, WY; Cheyenne, WY; Flagstaff, AZ; and Phoenix, AZ) 3-hour 100-year values tended to be 1.5 to 3.0-degrees warmer than the 6-hour 100-year values. These values replace those provided in HMR 50 and HMR 57. Note that most of the information describing the 3-hour dew point climatology development in this section is the same as the Section 4.1 descriptions.

The initial task in the development of the 3-hour dew point climatology was a search of the National Climatic Data Center (NCDC) hourly stations that record hourly dew point temperature data within a defined search domain surrounding Wyoming (Figure 4.7). The 3-hour dew point climatology was developed to quantify local storm events west of the Continental Divide which exhibit high intensity, short duration (less than 3 hours) rainfall accumulation patterns. Therefore, the 3-hour climatology built on the same analysis done for the Arizona statewide PMP study and was only developed for locations west of the Continental Divide.

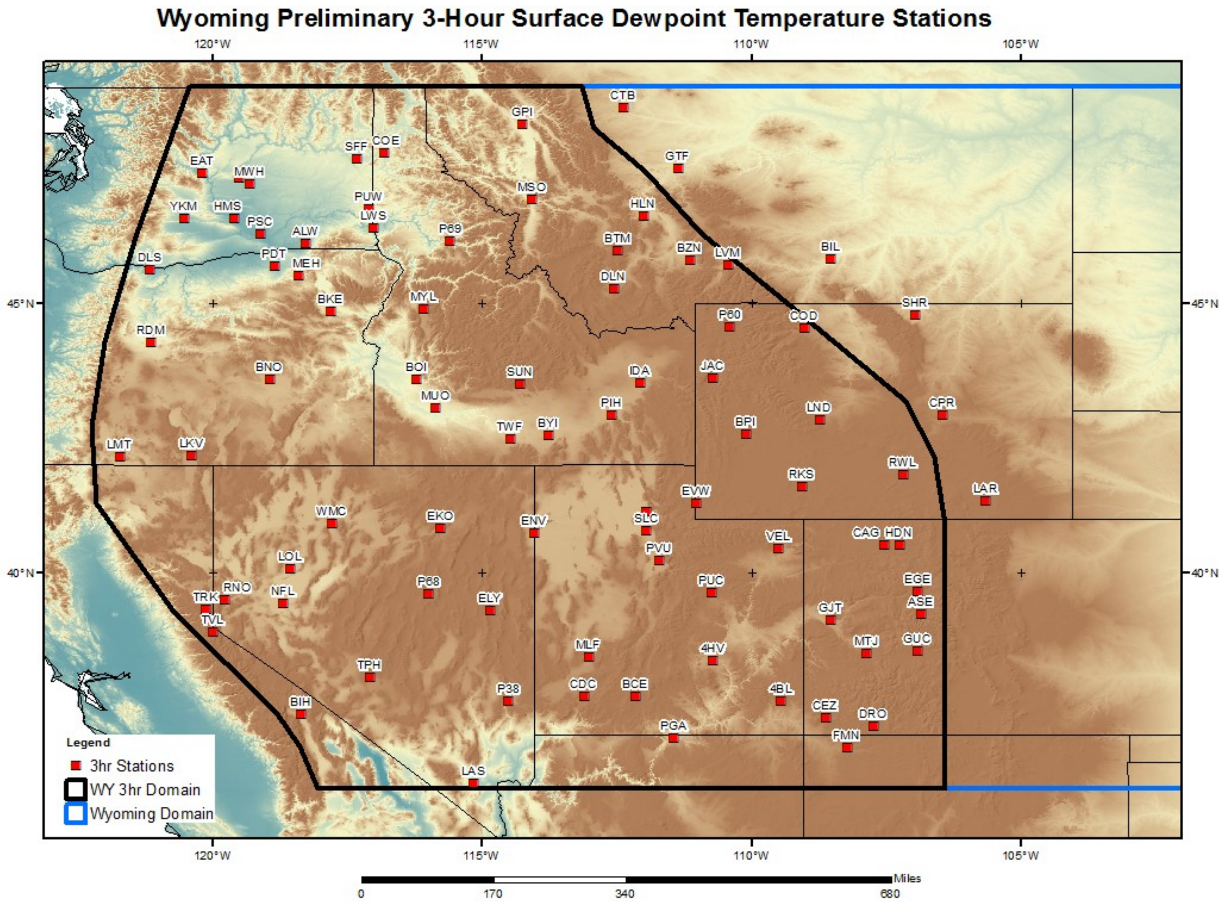


Figure 4.7 Hourly dew point station locations used for the updated maximum dew point climatology

Once these stations were identified, AWA extracted the archived NCDC hourly datasets for the maximum average 3-hour dew point temperatures for each reporting station. The stations selected are listed in Table 4.3. Initial quality control (QC) limited stations to 30-years or greater period-of-record. After this initial QC, 84 hourly stations were selected for the dew point temperature analysis. A script was written to extract each station's monthly maximum dew point temperatures for 3-hour durations for each year, providing annual maximum series (AMS) for that station. The AMS for each month for each station served as input to an R-statistical script that calculated L-moment statistics. Using the generalized-extreme-value (GEV) distribution, the 20-year, 50-year, and 100-year return frequency dew point temperature values were calculated for each month for each station. The extracted dew point data were adjusted to the 15th of each month and adjusted to 1000mb dew point values.

Table 4.3 Stations used to derive the maximum 3-hour dew point climatology

ID	Name	State	Latitude	Longitude	Elevation
ALW	WALLA WALLA	WA	46.1	-118.283	1207
ASE	ASPEN	CO	39.2167	-106.867	8416
BIH	BISHOP	CA	37.3667	-118.367	4145
BKE	BAKER	OR	44.8428	-117.809	3367
BNO	BURNS	OR	43.5833	-118.95	4170
BOI	BOISE	ID	43.5667	-116.217	2868
BPI	BIG PINEY	WY	42.5667	-110.1	6969
BTM	BUTTE	MT	45.9647	-112.501	5539
BYI	BURLEY	ID	42.5417	-113.766	4156
BZN	BOZEMAN	MT	45.7833	-111.15	4462
CAG	CRAIG	CO	40.5	-107.533	6191
COD	CODY	WY	44.5167	-109.017	5095
COE	COEUR DALENE	ID	47.7667	-116.817	2158
DLN	DILLON	MT	45.25	-112.55	5240
DLS	THE DALLES	OR	45.6194	-121.171	235
DRO	DURANGO	CO	37.15	-107.75	6683
EAT	WENATCHEE	WA	47.3978	-120.201	1229
EGE	EAGLE	CO	39.65	-106.917	6513
EKO	ELKO	NV	40.8264	-115.787	5049
ELY	ELY	NV	39.2833	-114.85	6262
ENV	WENDOVER	UT	40.7333	-114.033	4239
EPH	EPHRATA	WA	47.3081	-119.515	1259
EVW	EVANSTON	WY	41.275	-111.032	6601
GJT	GRAND JUNCTION	CO	39.1167	-108.533	4839
GPI	KALISPELL	MT	48.3114	-114.255	2973
GUC	GUNNISON	CO	38.55	-106.917	7668
HDN	HAYDEN	CO	40.5	-107.25	6604
HIF	HILL AFB	UT	41.1167	-111.967	4787
HLN	HELENA	MT	46.6	-112	3898
HMS	HANFORD	WA	46.5667	-119.6	733
IDA	IDAHO FALLS	ID	43.5167	-112.067	4744
JAC	JACKSON	WY	43.6	-110.733	6444
LKV	LAKEVIEW	OR	42.1667	-120.4	4728
LMT	KLAMATH FALLS	OR	42.15	-121.733	4091
LND	LANDER	WY	42.8167	-108.733	5558
LOL	LOVELOCK	NV	40.0681	-118.569	3899
LVM	LIVINGSTON	MT	45.6983	-110.441	4652
LWS	LEWISTON	ID	46.3833	-117.017	1437
MEH	MEACHAM	OR	45.5	-118.4	3726
MSO	MISSOULA	MT	46.9167	-114.083	3189

Table 4.3 Stations used to derive the maximum 3-hour dew point climatology (continued)

ID	Name	State	Latitude	Longitude	Elevation
MTJ	MONTROSE	CO	38.5	-107.883	5758
MUO	MOUNTAIN HOME	ID	43.05	-115.867	2995
MWH	MOSES LAKE	WA	47.2	-119.317	1188
MYL	MCCALL	ID	44.8833	-116.1	5025
NFL	FALLON	NV	39.4166	-118.701	3934
P60	YELLOWSTONE	WY	44.55	-110.417	8002
P68	EUREKA	NV	39.6014	-116.006	5945
P69	LOWELL	ID	46.1442	-115.596	1480
PDT	PENDLETON	OR	45.6833	-118.85	1495
PIH	POCATELLO	ID	42.9167	-112.6	4478
PSC	PASCO	WA	46.2667	-119.117	404
PUC	PRICE	UT	39.6167	-110.75	5903
PUW	PULLMAN-MOSCOW	WA	46.7439	-117.114	2551
PVU	PROVO	UT	40.2167	-111.717	4492
RDM	REDMOND	OR	44.2667	-121.15	3084
RKS	ROCK SPRINGS	WY	41.6	-109.067	6739
RNO	RENO	NV	39.5	-119.783	4400
RWL	RAWLINS	WY	41.8	-107.2	6734
SFF	SPOKANE	WA	47.6667	-117.333	1952
SLC	SALT LAKE CITY	UT	40.7667	-111.967	4227
SUN	HAILEY	ID	43.5	-114.3	5315
TPH	TONOPAH	NV	38.0511	-117.09	5429
TRK	TRUCKEE	CA	39.3167	-120.133	5899
TVL	SOUTH LAKE TAHOE	CA	38.8983	-119.995	6252
TWF	TWIN FALLS	ID	42.4833	-114.483	4150
VEL	VERNAL	UT	40.45	-109.517	5259
WMC	WINNEMUCA	NV	40.9	-117.8	4314
YKM	YAKIMA	WA	46.5667	-120.533	1066
LAR	LARAMIE	WY	41.3164	-105.672	7264
CPR	CASPER	WY	42.9167	-106.467	5290
SHR	SHERIDAN	WY	44.7667	-106.967	3968
BIL	BILLINGS	MT	45.8	-108.533	3570
GTF	GREAT FALLS	MT	47.4833	-111.367	3657
CTB	CUTBANK	MT	48.6167	-112.383	3837
4BL	BLANDING	UT	37.6167	-109.467	6132
4HV	HANKSVILLE	UT	38.3667	-110.717	4311
BCE	BRYCE CANYON	UT	37.7022	-112.154	7584
CDC	CEDAR CITY	UT	37.7	-113.1	5618
CEZ	CORTEZ	CO	37.3	-108.633	5916
FMN	FARMINGTON	NM	36.75	-108.233	5502

Table 4.3 Stations used to derive the maximum 3-hour dew point climatology (continued)

ID	Name	State	Latitude	Longitude	Elevation
LAS	LAS VEGAS	NV	36.0833	-115.167	2180
MLF	MILFORD	UT	38.4333	-113.017	5033
P38	CALIENTE	NV	37.6167	-114.517	4380
PGA	PAGE	AZ	36.9333	-111.45	4278

4.2.1 Procedure for Adjusting to the 15th of the Month

The station data were corrected to the 15th of each month using a linear relationship between the previous month, current month, and the next month. The 15th adjustment was performed using a series of Excel macros. The steps are listed below:

1) Calculate the difference in days between the observed average date of the annual maximum series occurrence and the 15th.
2) Depending whether the difference in step 1 is positive or negative (direction of adjustment) calculate the ratio/difference between the non-adjusted dew point temperature (for the months of interest) and the number of days between the dates.
3) Apply the ratio calculated in step 2 to the difference calculated in step 1.
4) Check the adjusted dew point value with the previous and next month values, and the other two durations.
5) Calculate the difference between the original dew point value and the adjusted dew point value.
6) Create station plots of the duration and frequency for additional QC measure.
7) Create a list of the adjusted dew point values for each station in a GIS format.

4.2.2 1000mb Adjustment Procedures

A moist lapse rate (2.7°F/1000 feet) was used to adjust the 15th of the month dew point temperature, at the station elevation, to 1000mb (assumed to be at elevation zero, i.e. sea level). A linear relationship between elevation and lapse rate was created and applied to each station. The June 3-hour maximum average dew point data for Lander, WY are shown in Table 4.4. The table shows the original station data, the data adjusted to the 15th, and the data adjusted to 1000mb.

Table 4.4 Original 3-hour average dew point data, adjusted dew point data (to the 15th), and the 1000mb dew point data for 20-year, 50-year, and 100-year frequencies at Lander, WY

Lander, WY	20-year	50-year	100-year
Station Data	58.8°F	60.1°F	60.8°F
15th Data	58.5°F	59.8°F	60.6°F
1000mb Data	73.5°F	74.8°F	75.6°F

4.2.3 Spatial Interpolation of Data

Maximum and minimum monthly dew point temperature PRISM grids were downloaded for the continental United States for the time period of 1971-2000. PRISM grids were used to calculate the mean monthly dew point temperature $\overline{td}_m$ for this time period:

$$\overline{td}_m = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \text{Equation 4.2}$$

where *m* is the month of interest, *n* is the number of months and x_i are the monthly dew temperature values. The PRISM data were converted from degrees Celsius to degrees Fahrenheit. The mean monthly PRISM dew point data were extracted for each of the 152 dew point stations.

Linear relationships between PRISM data (described above) and the station dew point temperature data (1000mb) for each duration (3-hour) and frequency (20-, 50-, and 100-year) were calculated, where *y* equals the stations dew point temperature (°F) value, and *x* equals the stations mean monthly PRISM dew point temperature (°F) value. An example of the linear relationships between mean monthly PRISM dew point data and the 100-year 3-hour dew point data for May, June, July, and August are shown in Figures 4.8a-d.

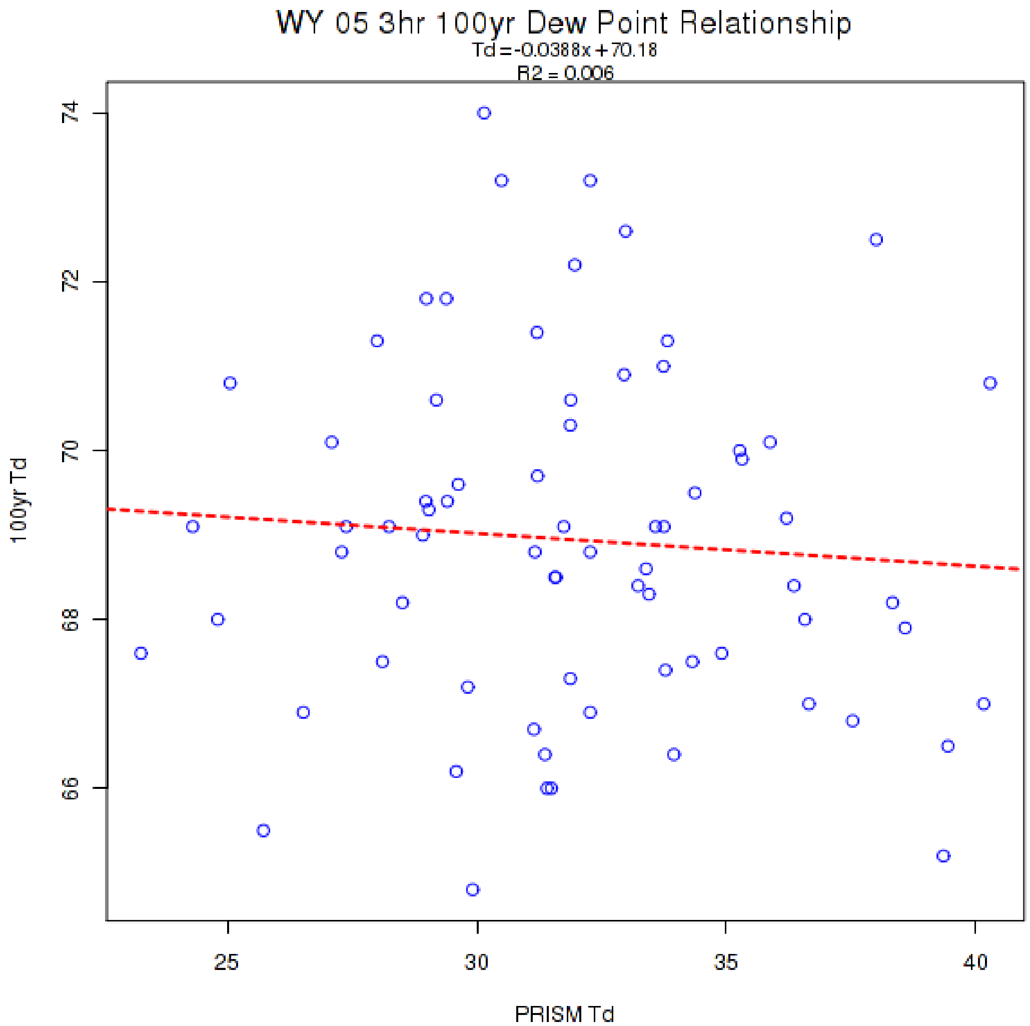


Figure 4.8a Linear relationships for the 3-hour duration between mean monthly PRISM dew point values and the 100-year 3-hour maximum average dew point values for May

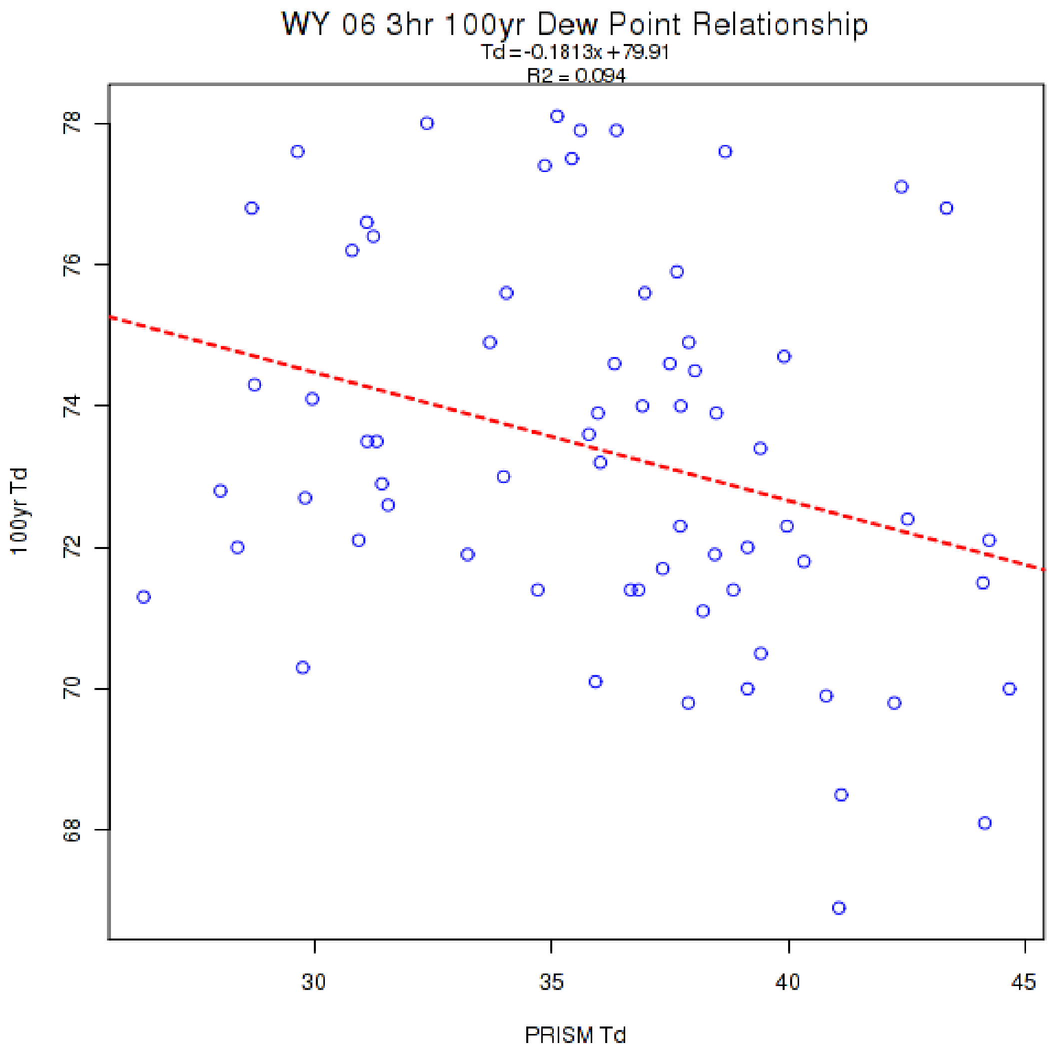


Figure 4.8b Linear relationships for the 3-hour duration between mean monthly PRISM dew point values and the 100-year 3-hour maximum average dew point values for June

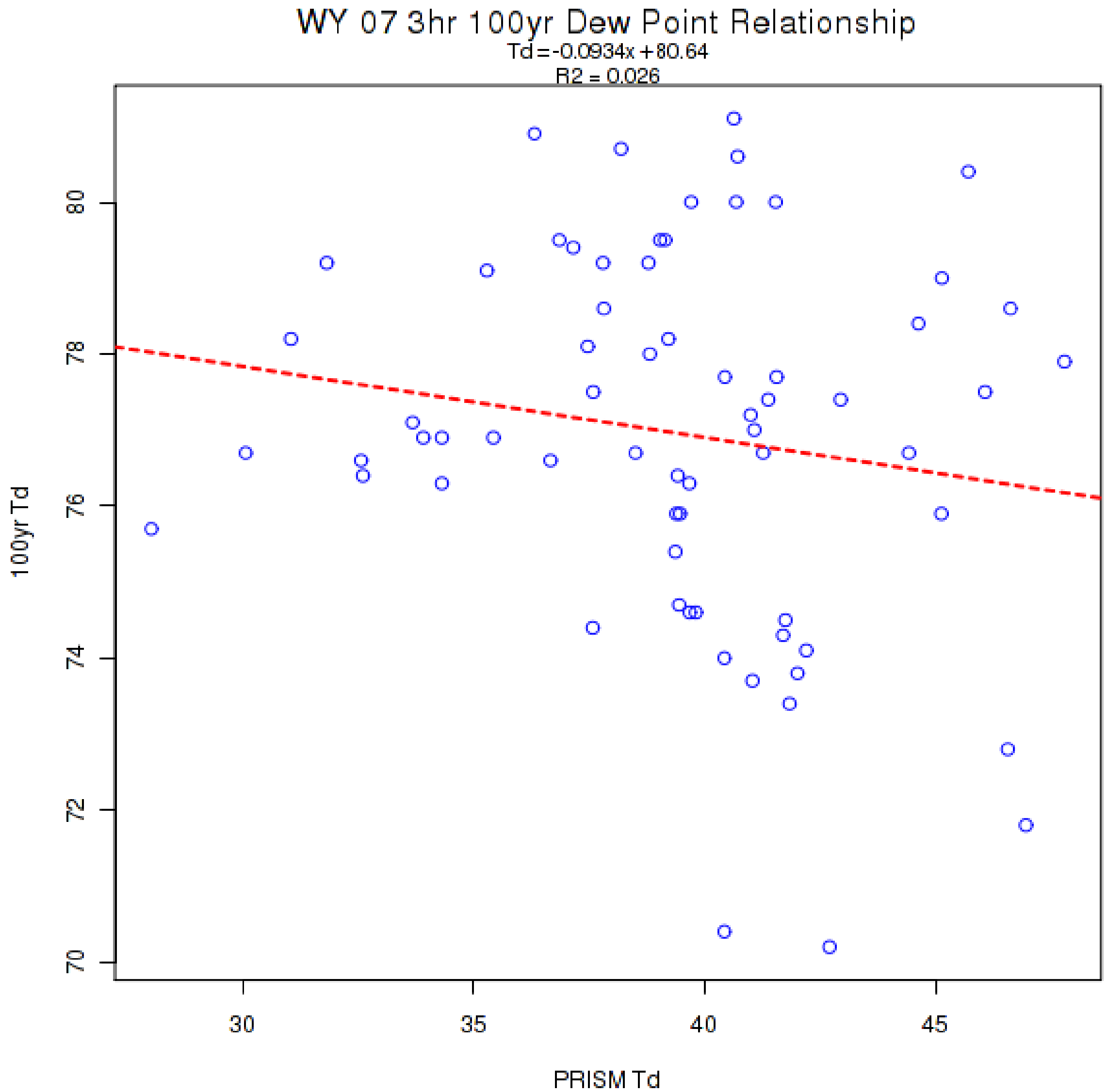


Figure 4.8c Linear relationships for the 3-hour duration between mean monthly PRISM dew point values and the 100-year 3-hour maximum average dew point values for July

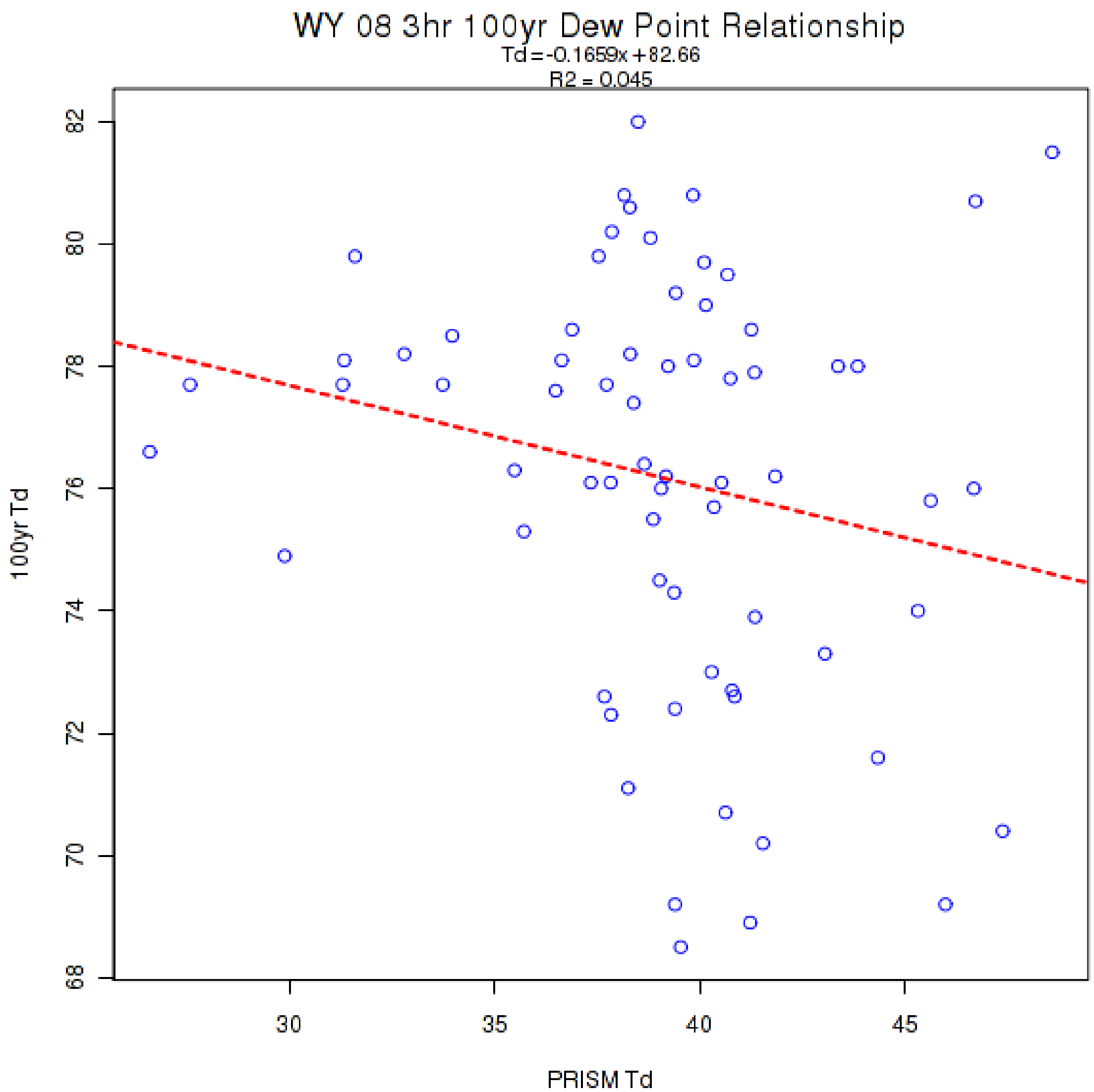


Figure 4.8d Linear relationships for the 3-hour duration between mean monthly PRISM dew point values and the 100-year 3-hour maximum average dew point values for August

The derived linear relationships were applied to the mean monthly dew point PRISM grids, which provided a first estimate of the dew point temperature spatial distribution. Residuals (actual – predicted) between the station and the first estimate were calculated at each station.

The residuals were spatially distributed across the search domain using an inverse-distance algorithm. The spatially distributed residual grids were smoothed to reduce bulls-eye effects. The smoothed residual grid was added to the first estimate grid to create the second estimate grid. The second estimate grids were smoothed in order to further reduce bulls-eye effects. The smoothed second estimate grids represent the final dew point temperature distribution.

The spatial interpolation method was tested and applied for the Nebraska statewide study (Tomlinson et al., 2008) the Tarrant Regional Water District studies (Tomlinson et al., 2011; Kappel et al., 2012), Brassua Maine study (Tomlinson et al., 2011), the Ohio statewide study (Tomlinson et al., 2013) and the Arizona statewide study (Tomlinson et al., 2013). Perl and R-statistical programs were used to automate the process within GRASS GIS environment. The GRASS GIS script also created 1°F dew point contours from the final interpolated dew point grids. The GRASS GIS dew point rasters and contour shapefiles were exported from the GRASS GIS environment to an ArcGIS environment for creation of the final dew point map layouts.

Creation of the final dew point maps used in this project was completed after manual interpretation of the automated contours and meteorological analysis by AWA. During this manual analysis, inconsistencies were removed and smoothing was applied where meteorological, climatological, and topographical factors warranted such actions. Further, expertise was used to compensate for the lack of spatial coverage in some sections of Wyoming domain and to ensure continuity between months and durations. Figures 4.9-4.12 display examples of the final 3-hour dew point maps and Appendix B contains all the maps used as part of this PMP analysis.

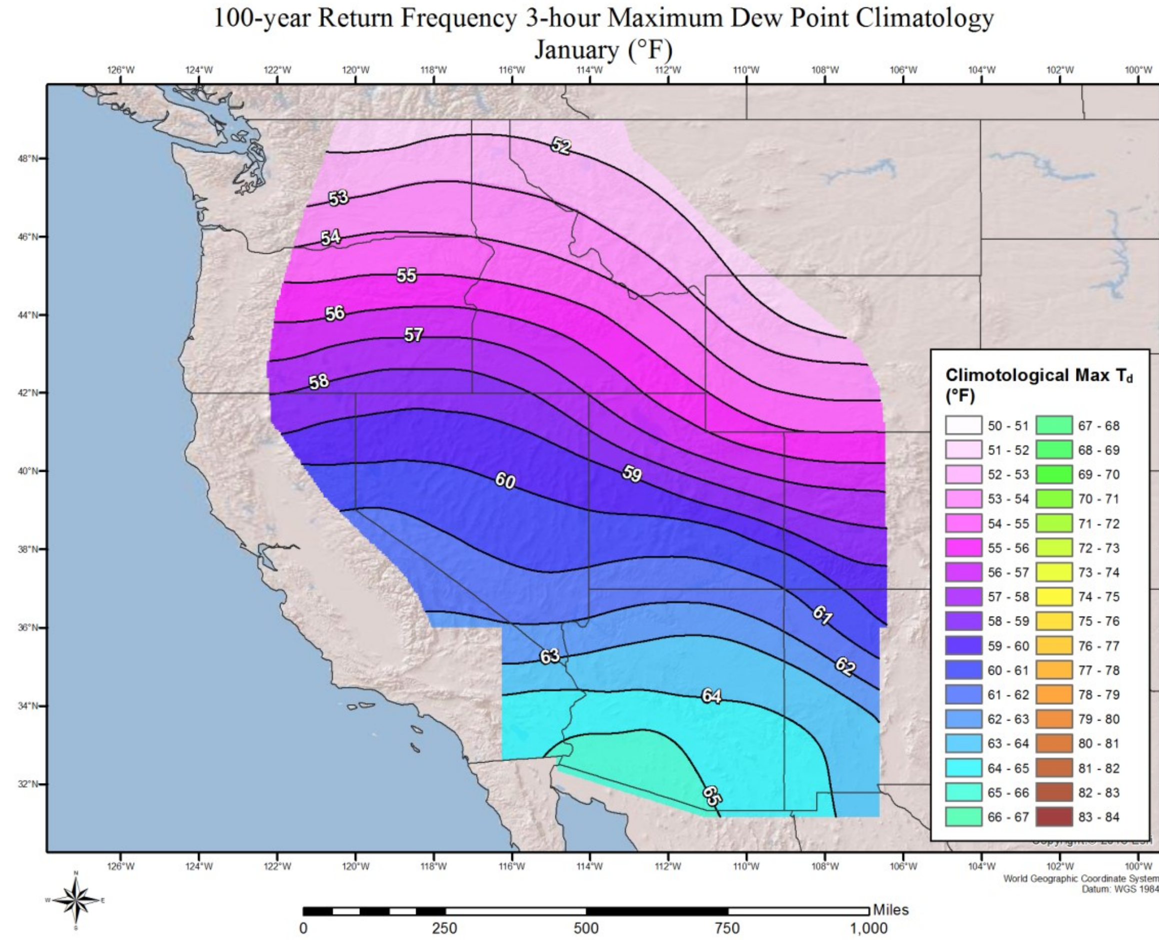


Figure 4.9 January 100-year return frequency maximum average 3-hour dew point map

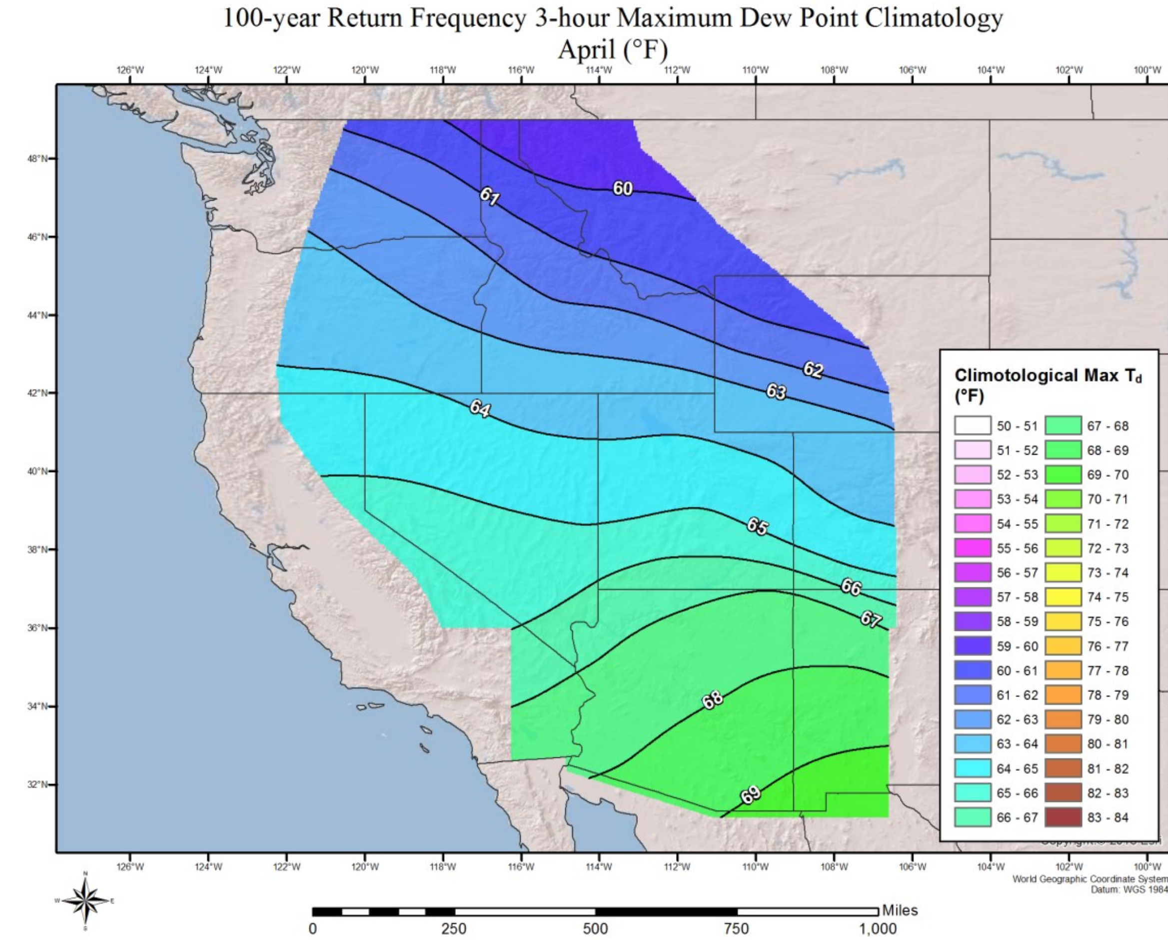


Figure 4.10 April 100-year return frequency maximum average 3-hour dew point map

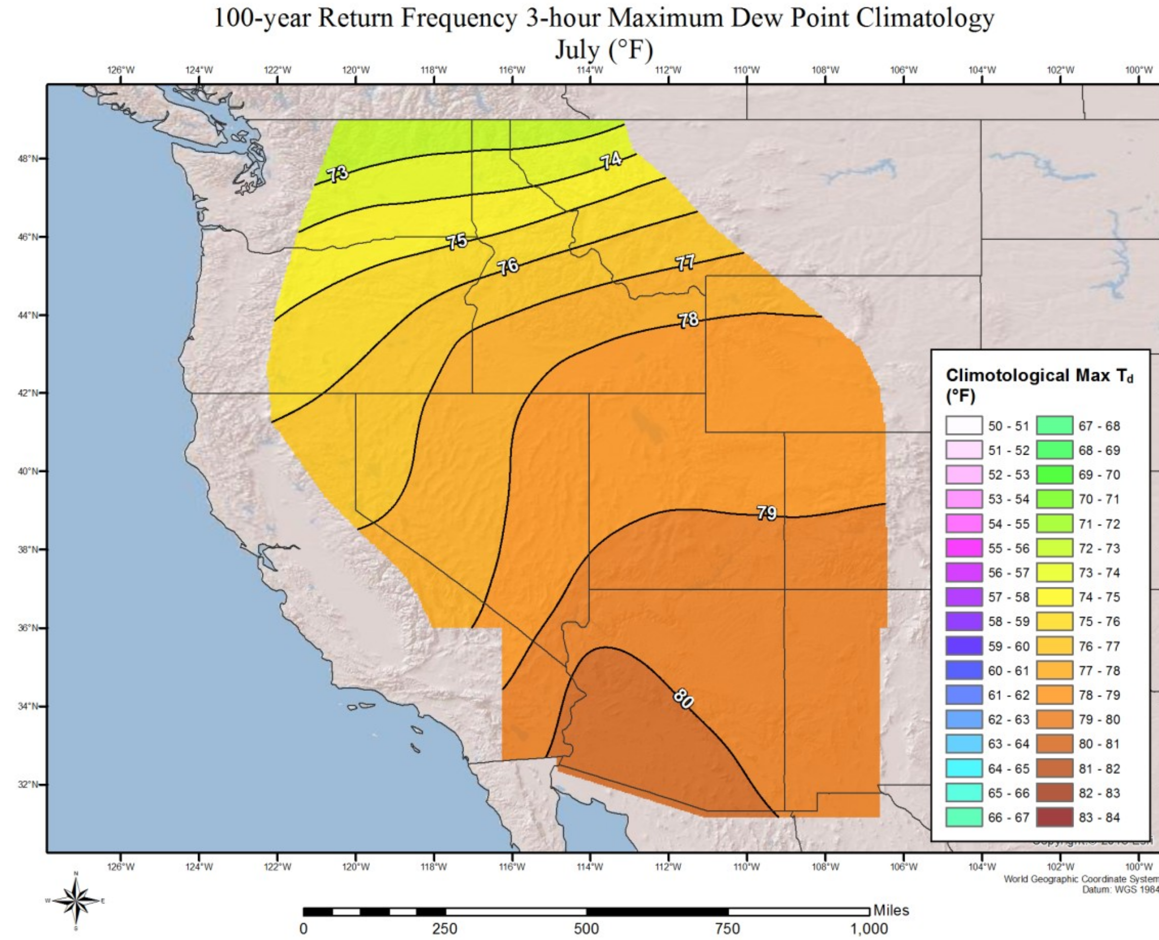


Figure 4.11 July 100-year return frequency maximum average 3-hour dew point map

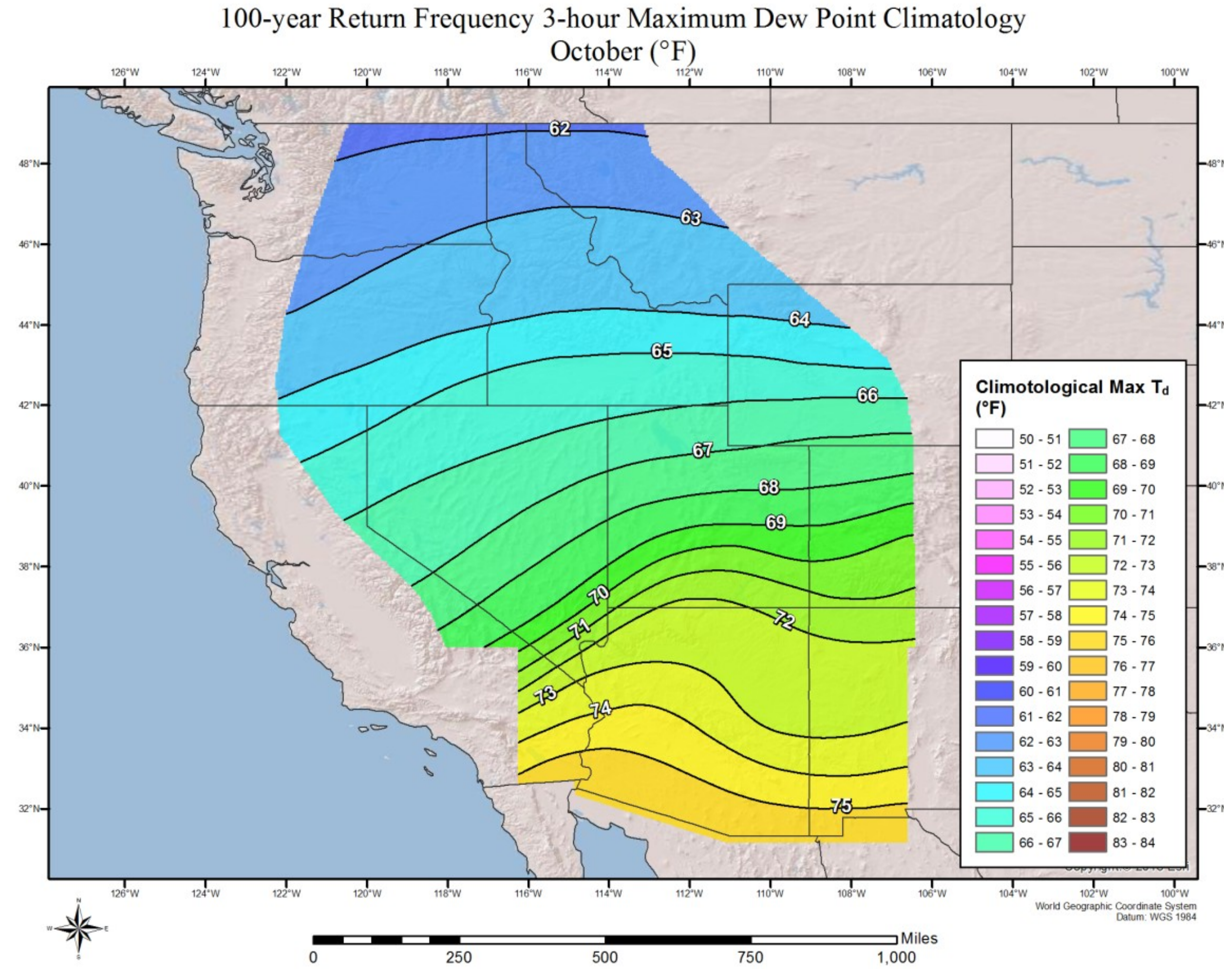


Figure 4.12 October 100-year return frequency maximum average 3-hour dew point map

5. Precipitation and Rainfall Frequency Analyses

Precipitation frequency estimates are a necessary component of the OTF procedure in determining PMP values. Although precipitation frequency estimates are available in NOAA Atlas 2 Volume II (Miller, 1973), they are outdated, lack accuracy across higher terrain and do not distinguish between rainfall-only and total precipitation (rainfall and snow) estimates. Updated return frequencies are available for some states in NOAA Atlas 14 (Bonnin et al., 2004, 2006) but not for the state of Wyoming. For these reasons, a regional precipitation and rainfall frequency analysis was conducted for this study for the 6- and 24-hour durations for average recurrence intervals (ARIs) of the 2-year through 1,000-year durations. Additionally, "local" regional rainfall frequency analyses were conducted for areas outside of Wyoming where extreme storms had occurred but corresponding updated rainfall frequency estimates were not available from NOAA Atlas 14 (Bonnin et al., 2004, 2006).

5.1 Regional 6- and 24-hour Precipitation Frequency Analysis

A 6- and 24-hour regional precipitation frequency analysis was conducted for Wyoming to provide an update of NOAA Atlas 2 Volume II, published in 1973. NOAA Atlas 2 used precipitation data collected through 1966, while this project included precipitation data collected through 2010. This provides 44 years of additional data. Hourly and daily station data from the National Climatic Data Center and the NRCS (SNOTEL) were the primary sources of data, but 19th century Forts data from the Midwestern Regional Climate Center was also used to extend the period of record back to the late 1800s at several locations. General climatic regions were created based on similar topographic, climatic and meteorological characteristics, and then subdivided into homogenous regions of stations that shared the same probability distribution of extreme events. Utilizing LRAP (L-moment Regional Analysis Program) together with quality-controlled annual maximum precipitation values extracted for stations within each of the homogeneous regions, regional L-moment statistics were computed and applied to derive precipitation frequency estimates. Consistent with methodologies used in NOAA Atlas 14, the station precipitation frequency estimates were spatially interpolated utilizing a climatologically-aided interpolation approach. The final product consisted of GIS grids (1-km^2 resolution) of precipitation frequency estimates and color cartographic maps for 6- and 24-hour durations. Figure 5.1 24-hour precipitation frequency estimates with an average recurrence interval of 100 shows the 100-year 24-hour precipitation frequency estimates for Wyoming. Appendices D and E provide additional information on the development of the precipitation frequency analysis.

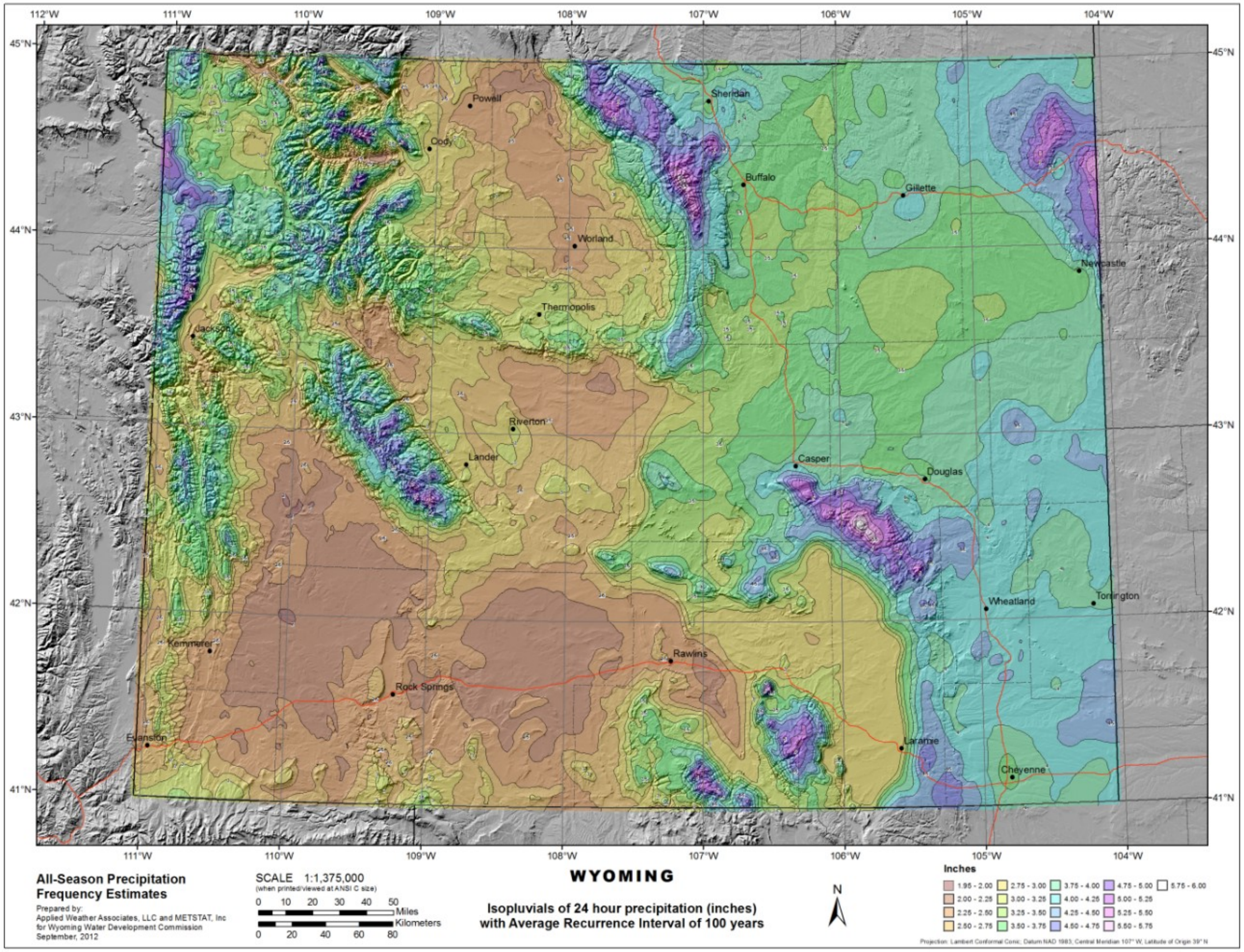


Figure 5.1 24-hour precipitation frequency estimates with an average recurrence interval of 100 years

5.2 Regional 6- and 24-hour Rainfall-only Frequency Analysis

It became apparent during the precipitation frequency analysis that a large proportion of the extreme 24-hour precipitation events across the higher terrain of Wyoming were associated with heavy snowstorms and snow water equivalent (SWE) data. Figure 5.2 shows a map of the percentage of annual maximum precipitation values occurring during the cool season (November through April) when snowfall largely dominates. Figure 5.3 shows differences between 24-hour precipitation and rainfall-only frequency estimates at selected stations. (A description of the rainfall-only frequency analysis follows.) Given the large differences between precipitation versus rainfall-only frequency estimates and the high percentage (>90%) of cool season events driving the frequency estimates, it was clear that snowfall dominated extreme precipitation events across large portions of Wyoming. The same analysis using 6-hour precipitation showed a predominance of warm-season storms, making the rainfall-only and precipitation frequency estimates equal.

Since snow does not contribute to PMP (melting snow contributes to a PMF), rainfall-only frequency estimates were needed. The same methodology was used in the precipitation frequency analysis, except the annual maximums were constrained to rainfall-only and/or rainfall-dominated amounts. Rainfall amounts were initially isolated by extracting the highest measured values of precipitation from the warm season at varying elevation bands. Many storms during the transition season (spring and fall) were identified as a mixture of rain and snow. Any rain/snow amounts where the snowfall contributed 50% or less of the total 1-day precipitation were accepted as rainfall values. Given wet snows usually accompanied transitional season storms, a 10" of snow to 1" of water ratio was assumed for converting the reported snow depth into a snow-water equivalent (SWE). The final product consisted of GIS grids (1 km^2 resolution) of rainfall-only frequency estimates and color cartographic maps for the 24-hour duration. Figure 5.4 shows the 100-year 24-hour rainfall-only map of Wyoming. Appendix E provides additional information.

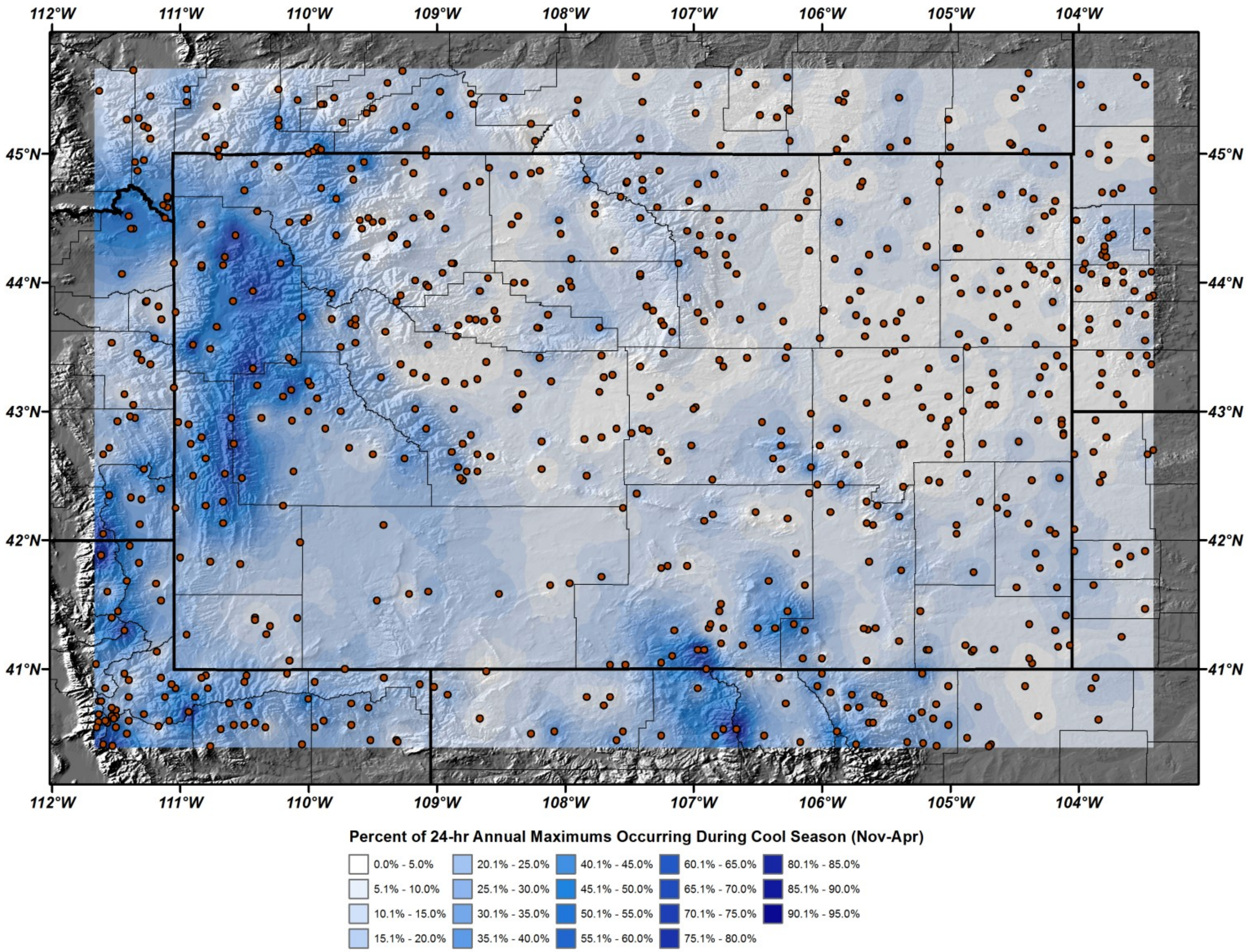


Figure 5.2 Percentages of annual maximum precipitation values that occurred during the cool season (November through April)

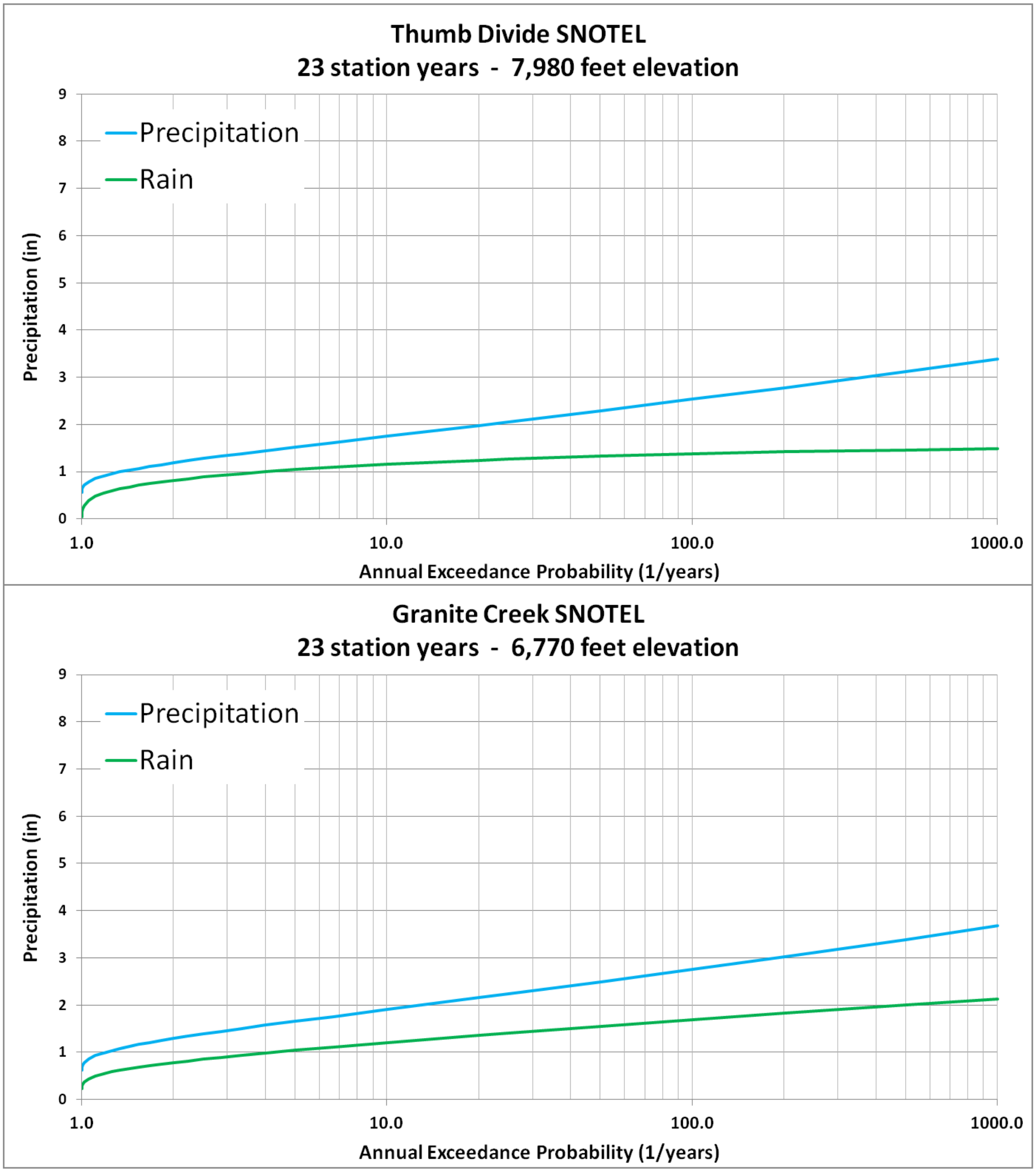


Figure 5.3 Graphs show 24-hour precipitation (blue lines) and rainfall-only (green lines) frequency estimates at selected stations.

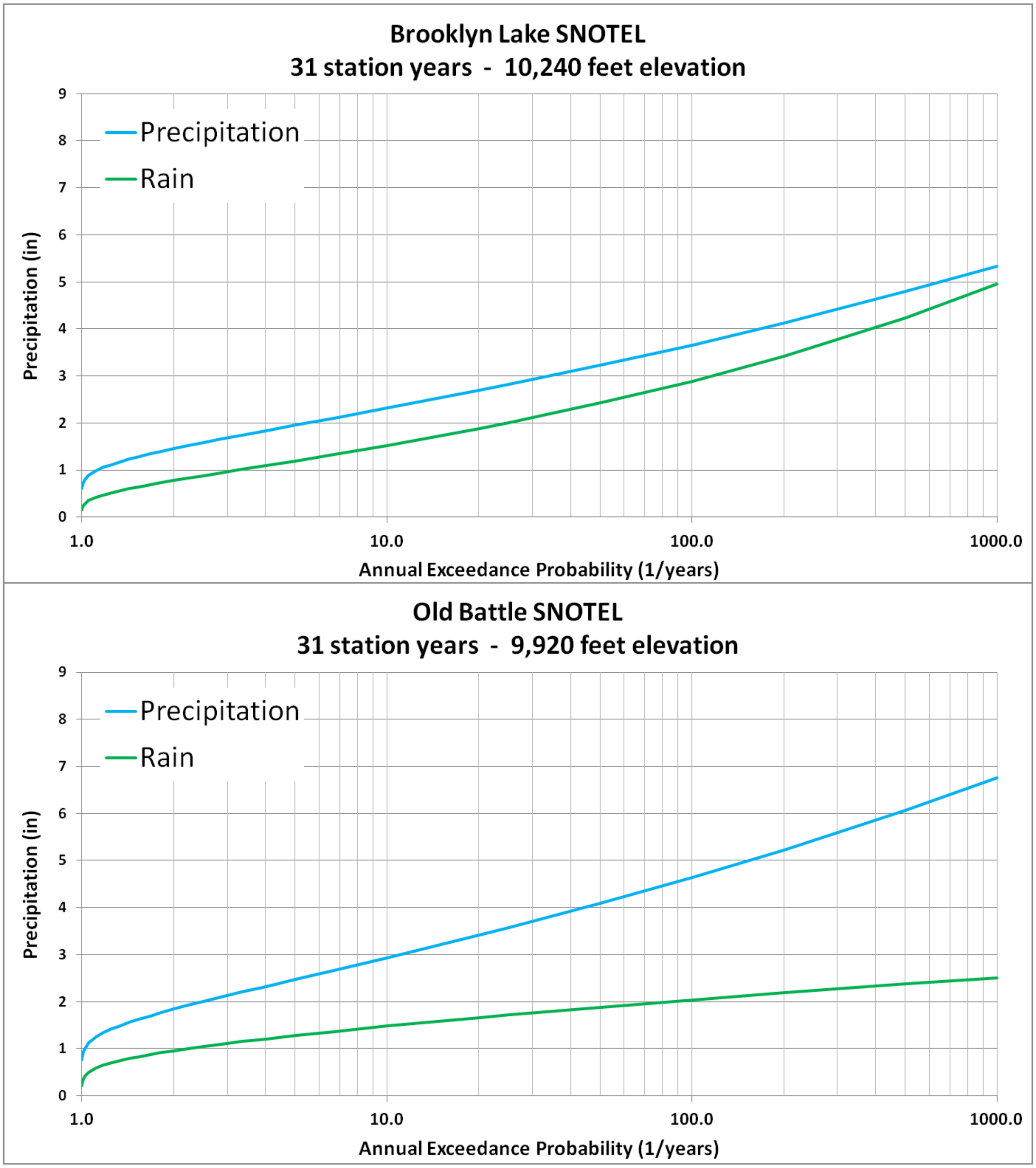


Figure 5.3 Graphs show 24-hour precipitation (blue lines) and rainfall-only (green lines) frequency estimates at selected stations. (Continued)

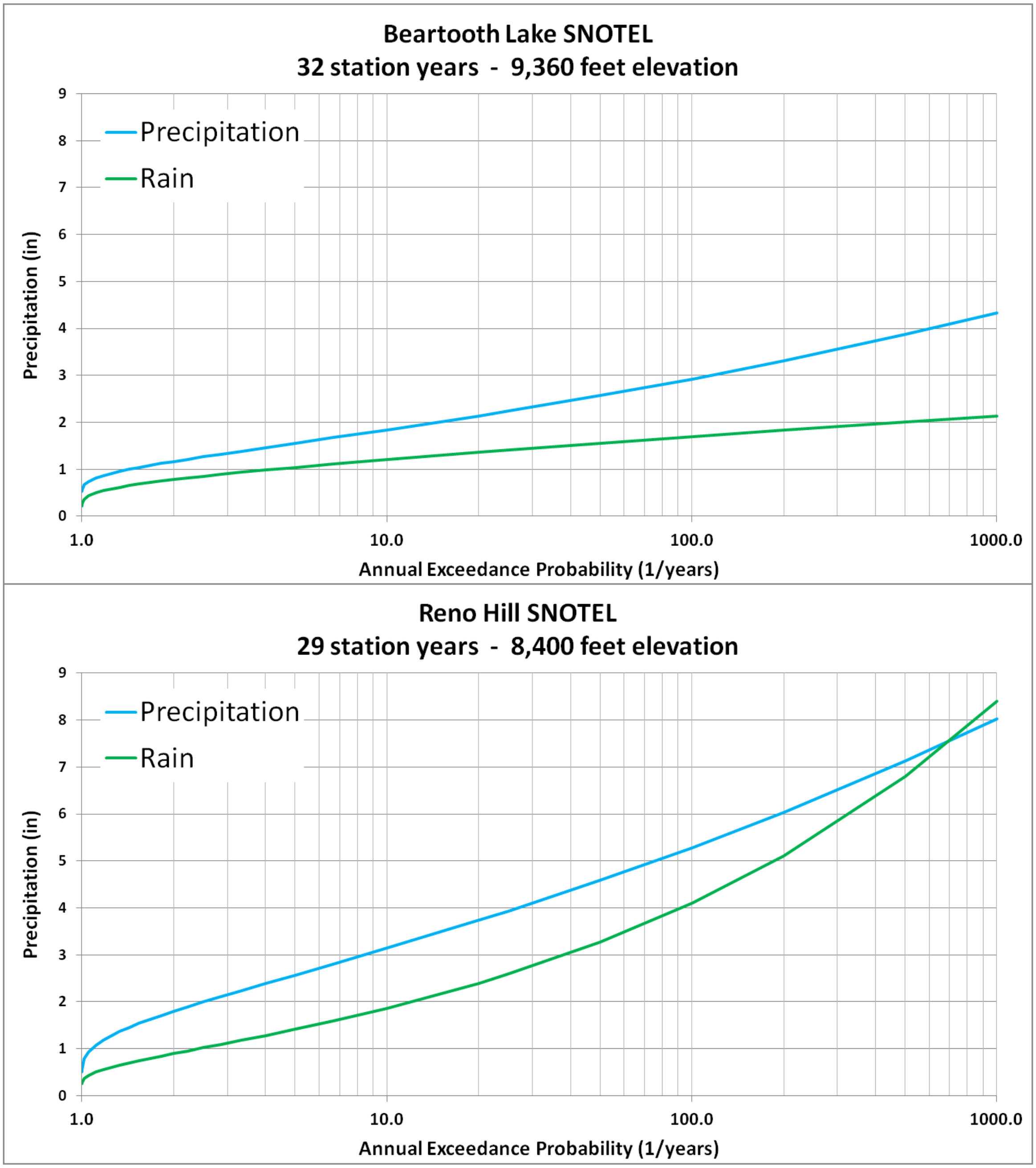
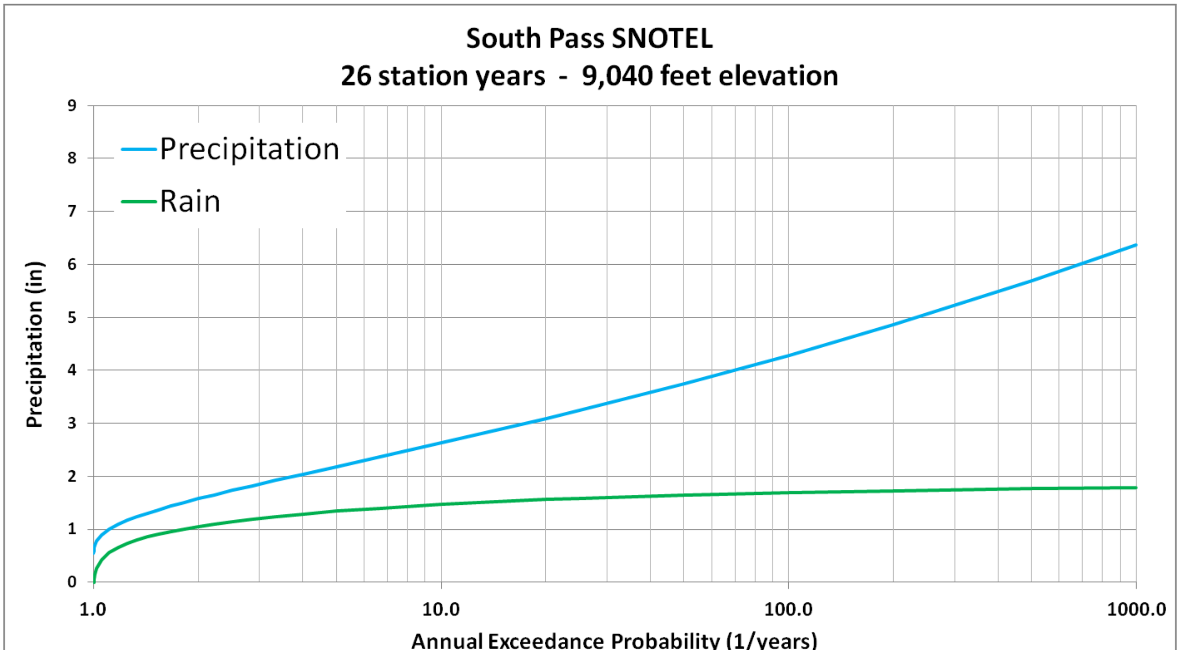


Figure 5.3 Graphs show 24-hour precipitation (blue lines) and rainfall-only (green lines) frequency estimates at selected stations. (Continued)



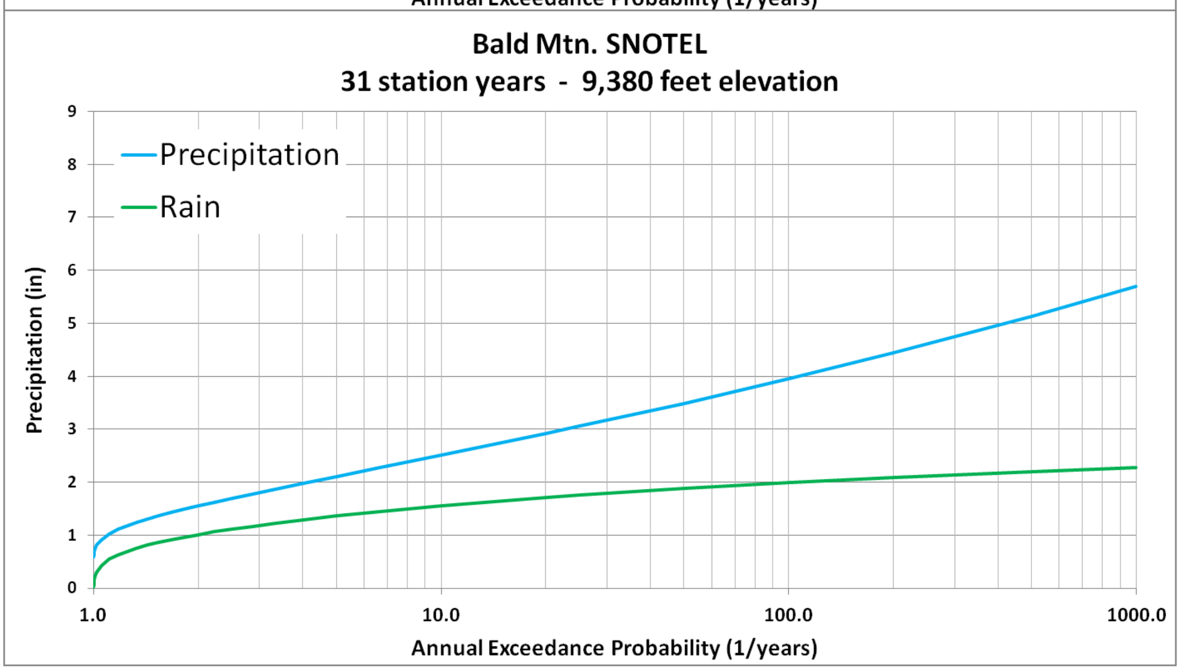


Figure 5.3 Graphs show 24-hour precipitation (blue lines) and rainfall-only (green lines) frequency estimates at selected stations. (Continued)

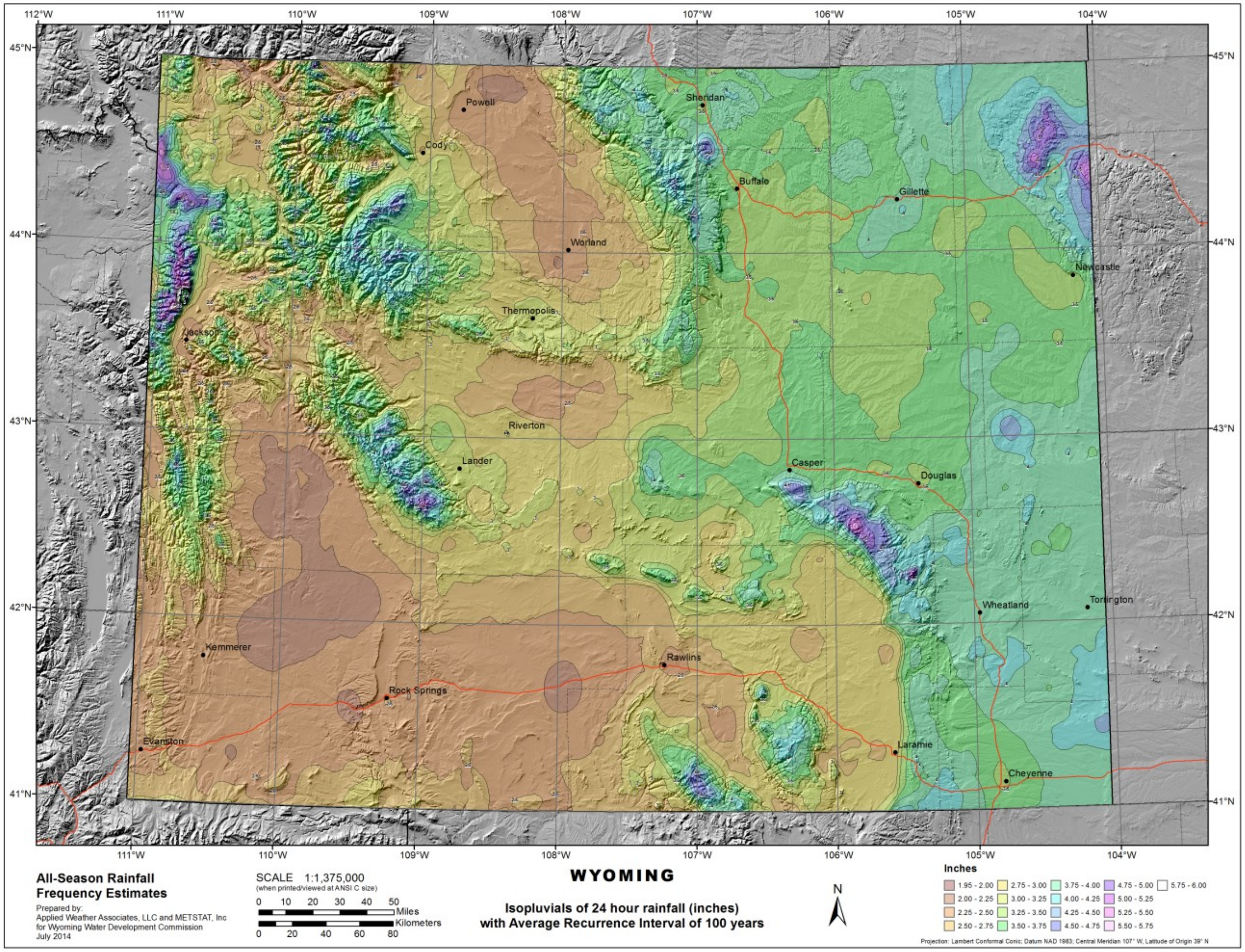


Figure 5.4 24-hour rainfall-only frequency estimates with an average recurrence interval of 100 years

5.3 Local Rainfall-only Frequency Analysis

The OTF methodology requires rainfall frequency estimates for (1) the location of the storm center associated with SPAS storm analyses and (2) all points within the Wyoming PMP analysis domain. The state-wide frequency analysis addressed (2) for storms in Wyoming, but a number of storms that are transposed occurred outside of the state. For storm centers occurring in states to the south and east of Wyoming, NOAA Atlas 14 precipitation/rainfall frequency estimates were used. For storm centers in Oregon, Idaho, Montana and Canada, "local" regional rainfall frequency analyses were required (Figure 5.5). To maintain consistency among the rainfall frequency estimates, an approach consistent to that used in this studies precipitation frequency analysis and in NOAA Atlas 14 was implemented, but on a smaller (i.e. "local") scale. Please refer to Appendix E for more information.

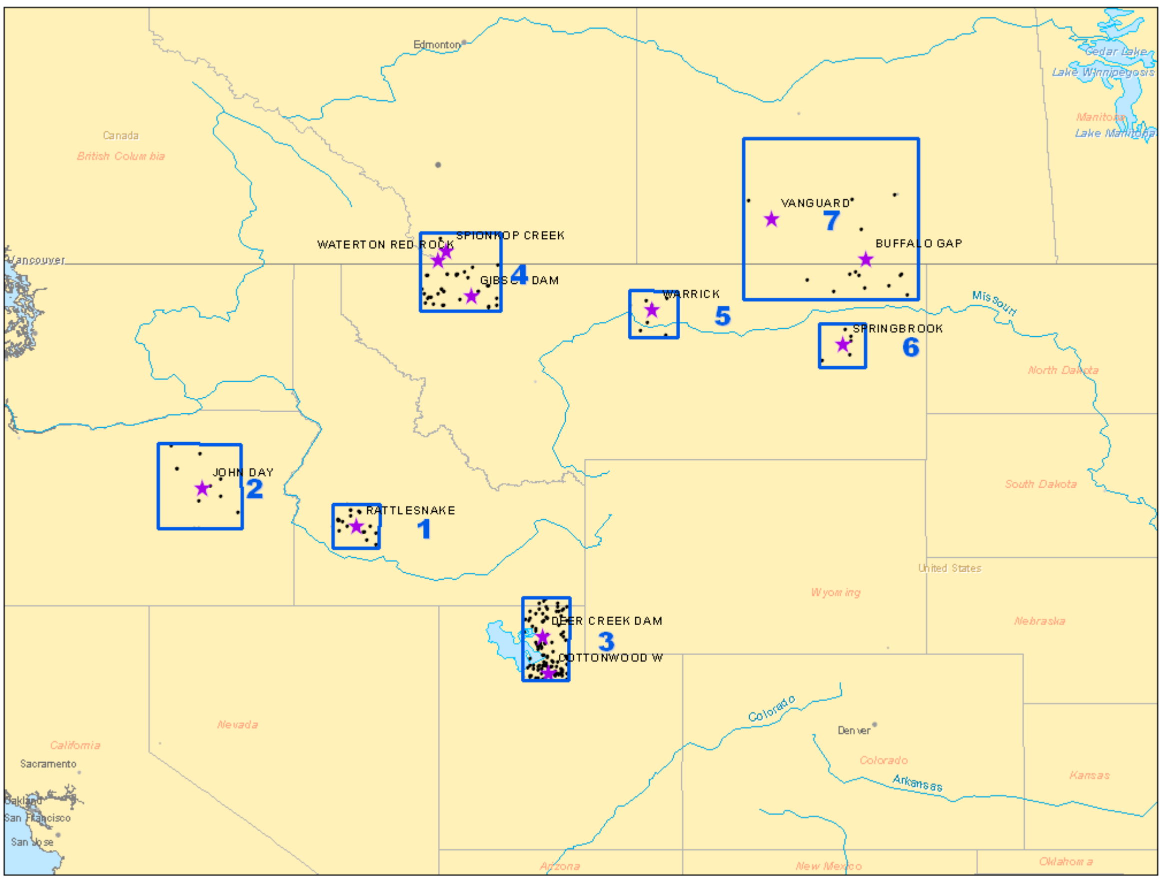


Figure 5.5 Regions for "local" rainfall frequency analysis showing the stations (black dots) and storm centers (blue star with location label).

6. Extreme Storm Identification

6.1 Storm Search Area

A storm search was conducted using previous storm search results from several AWA site-specific PMP studies. Previously used storm search domains were expanded to identify all storms that could potentially affect PMP values in the project domain used for the Wyoming PMP analysis. The list included all storms identified in HMR 49, HMR 51, HMR 55A, and HMR 57, which occurred in meteorological and topographical regions similar to Wyoming. Previous storm searches used in AWA PMP studies, such as the Arizona statewide PMP study and Nebraska statewide PMP study, were used and the storm lists from those studies updated through October of 2014. The search area covered an extensive region both west and east of the Continental Divide. The region extended from the crest of the Cascades and Sierra Nevada mountains to the west, south to 34°N, east to 92°W, and north to 52°N (Figure 6.1). This region included areas that were later determined to not be transpositionable to any point within with Wyoming PMP domain. This large domain was needed to ensure all storms which could potentially influence PMP values at any location within the project domain were included. Those storms and their limits of transpositionability were not known explicitly until extensive analysis were completed. Therefore a large region of potential storms was used in the storm search.

6.2 Data Sources

The storm search was conducted using a database containing rainfall data from several sources. The primary data sources are listed below:

1) Cooperative Summary of the Day / TD3200 through 2012. These data were published by the National Climatic Data Center (NCDC).
2) Hourly Weather Observations published by NCDC, U.S. Environmental Protection Agency, and Forecast Systems Laboratory (now National Severe Storms Laboratory).
3) NCDC Recovery Disk
4) Hydrometeorological Reports
5) US Corps of Engineers Storm Studies
6) Bureau of Reclamation storm data
7) Environment Canada storm studies
8) Other data published by state climate offices
9) Previous PMP and storm analysis work
10) Concurrent PMP studies
11) Discussions with various parties involved in the Wyoming PMP project
12) American Meteorological Society journals

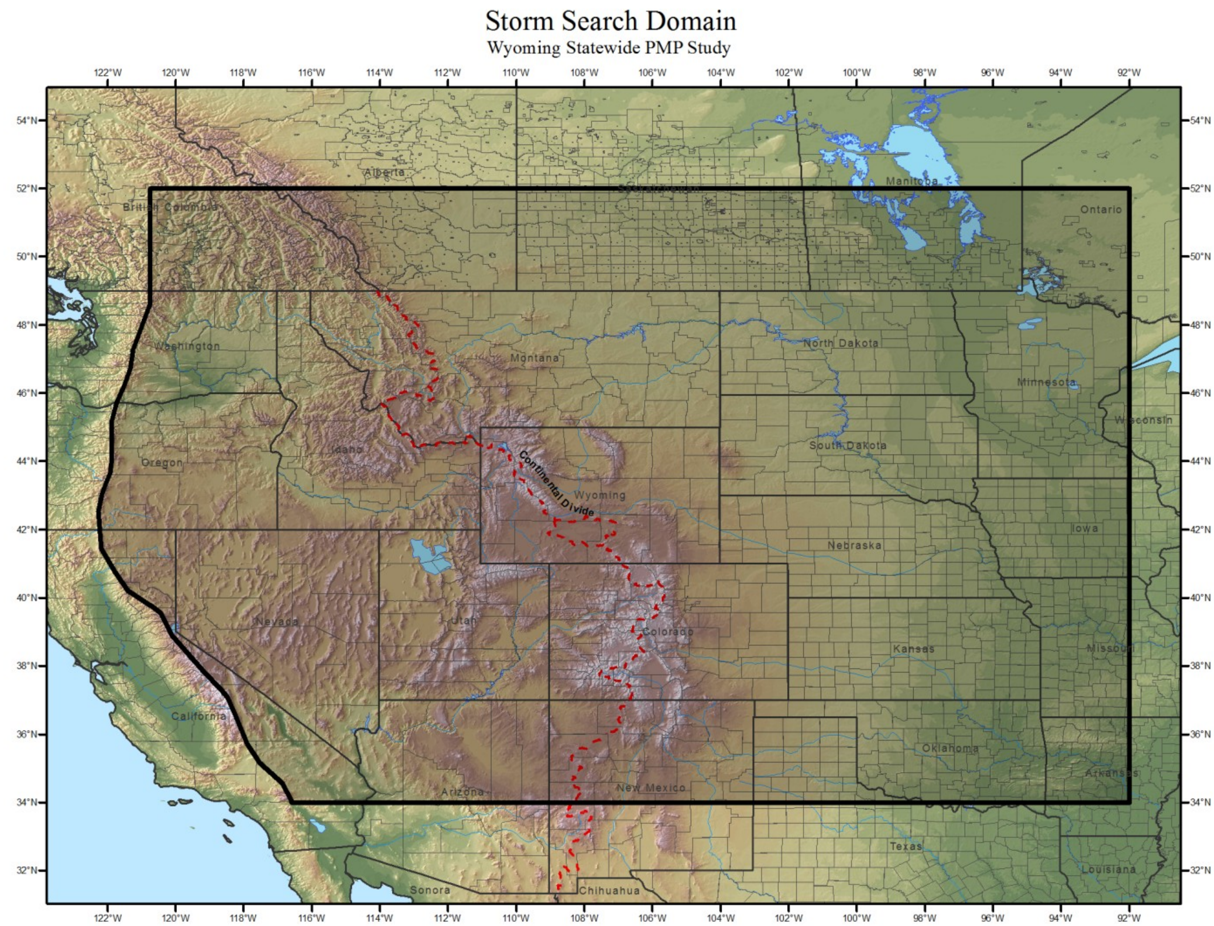


Figure 6.1 Storm search domain

6.3 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 the two storm types; local storms and general 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 return frequency 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.

These storms were plotted in a GIS 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 discussion and review with the Review Board, representatives from WWDO, WSEO, WRDS, NRCS, as well as other stakeholders involved in the project. 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 Wyoming and surrounding regions.

6.4 Developing the Short List of Extreme Storms

The long list of potential storms included 580 unique storm events. 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.

The next step was to determine which of these storms would ultimately need to be fully analyzed using SPAS. Several steps were taken to compare the magnitude of each of the events with the magnitude of other events on the potential storms to analyze list. Storms were sorted by storm type and location for initial comparison. This helped eliminate several storms which occurred in the same climate region but were of significantly less 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. The storms which made it through these final evaluations were placed on the short storm list (Table 6.1 and Figure 6.2). Each of these storms was analyzed 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 42 individual SPAS 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 6.2 through 6.4 display the locations of all the storms used for PMP development. Figure 6.2 shows the location of all the storms on the short storm list, while Figure 6.3 shows the locations of all the local/MCS storms and Figure 6.4 shows the locations of all the general and hybrid storms.

Table 6.1 Short storm list used to derive PMP values (all storms were analyzed with SPAS)

Storm Name	State	Lat	Lon	Elevation	Year	Month	Day	Maximum Point Rainfall	Precipitation Source	Storm Rep Analysis Duration	Storm Type
BAYFIELD	CO	37.5620	-106.8791	12437	1970	9	3	5.95	1075_4	24	General
WAGON WHEEL	CO	37.6625	-106.9375	12500	1911	10	3	7.88	1107_1	24	General
GIBSON DAM	MT	48.3542	-113.3708	8000	1964	6	6	19.16	1211_1	24	General
DEER CREEK DAM	UT	41.6300	-111.9700	5741	2010	10	23	5.09	1241_2	24	General
LAKE MALOYA	NM	37.0090	-104.3410	7944	1955	5	17	14.82	1251_1	24	General
WATERTON RED ROCK	AB	49.0875	-114.0458	7845	1975	6	14	14.46	1252_1	24	General
BIG ELK MEADOW	CO	40.2667	-105.4167	7667	1969	5	3	20.01	1253_1	24	General
MT TIMPANOGOS	UT	40.4042	-111.6375	10200	1982	9	24	10.13	1265_1	24	General
FLAT TOP MOUNTAIN	UT	40.3792	-112.2041	9062	1982	9	24	10.02	1265_2	24	General
COTTONWOOD	UT	41.6042	-112.0125	7007	1982	9	24	9.71	1265_3	24	General
CONRAD RANCH	UT	40.5854	-111.5896	9712	1979	10	18	5.78	1266_1	24	General
RATTLESNAKE	ID	43.6475	-115.7441	3236	1909	11	18	16.21	1274_1	24	General
BOULDER	CO	40.0150	-105.2650	5308	2013	9	8	20.41	1302_1	24	General
CHEYENNE MOUNTAIN	CO	38.7450	-104.8650	9323	2013	9	8	18.92	1302_2	24	General
AURORA	CO	39.7050	-104.8350	5573	2013	9	8	15.45	1302_3	24	General
DUBOIS	ID	44.2500	-112.1925	5550	1944	6	25	4.32	1323_1	12	General
SAVAGETON	WY	43.8458	-105.8042	4774	1923	9	27	17.56	1325_1	24	General
WARRICK	MT	48.0791	-109.7041	4123	1906	6	5	13.69	1335_1	24	General
SPRINGBROOK	MT	47.3642	-105.7778	2687	1921	6	17	15.20	1336_1	24	General
SPIONKOP CREEK	AB	49.1708	-114.1625	5350	1995	6	4	14.48	1338_1	24	General
CRYSTAL LAKE	MT	45.3150	-107.1750	5000	2011	5	19	9.15	1404_1	24	General
OGALLALA	NE	41.0300	-101.7800	3215	2002	7	6	14.92	1033_1	6	Local
PAWNEE CREEK	CO	40.7752	-103.6253	4500	1997	7	29	13.58	1036_1	6	Local
CEDAR CITY	UT	37.3750	-113.0750	7887	2006	7	31	5.69	1120_2	3	Local
BLUFF	UT	37.2550	-109.5750	4900	2001	8	14	6.29	1131_1	3	Local
RAPID CITY	SD	43.8875	-103.4042	4721	1972	6	8	15.80	1212_1	6	Local/General
CHEYENNE	WY	41.1354	-104.8188	6236	1985	8	1	7.15	1213_1	6	Local
FORT COLLINS	CO	40.5475	-105.1325	5135	1997	7	27	14.48	1230_1	12	Local/General
BIG THOMPSON CANYON	CO	40.4792	-105.4292	8133	1976	7	31	12.52	1231_1	6	Local
FRIJOLE CREEK	CO	37.0960	-104.3790	5728	1981	7	2	16.33	1247_1	6	Local
MORGAN	UT	41.0790	-111.6540	7311	1958	8	15	7.10	1248_1	3	Local
BLANDING	UT	37.8258	-109.5425	10367	1968	7	31	6.67	1249_1	12	Local
ELKO RAILROAD	NV	40.7760	-115.7590	5886	1970	8	26	4.68	1250_1	3	Local
OPAL	WY	41.7375	-110.2458	6924	1990	8	15	7.16	1264_1	3	Local
HOLLY	CO	37.7125	-102.4042	4100	1965	6	14	19.18	1293_1	6	Local
RATON	NM	36.7542	-104.5375	6427	1965	6	14	11.04	1293_2	6	Local/General
ELBERT	CO	39.1875	-104.2958	6207	1965	6	14	16.28	1293_3	6	Local/General
PLUM CREEK	CO	39.2208	-104.8958	7067	1965	6	14	14.25	1293_4	6	Local/General
PENROSE	CO	38.4638	-105.0705	5400	1921	6	3	12.20	1294_1	6	Local/General
ELBERT-CHERRY CREEK	CO	39.2375	-104.4875	6800	1935	5	29	24.00	1295_1	6	Local/General
HALE	CO	39.6125	-102.2625	3700	1935	5	29	18.00	1295_3	6	Local
JOHN DAY	OR	44.4458	-118.8792	3614	1969	6	9	7.09	1321_1	3	Local

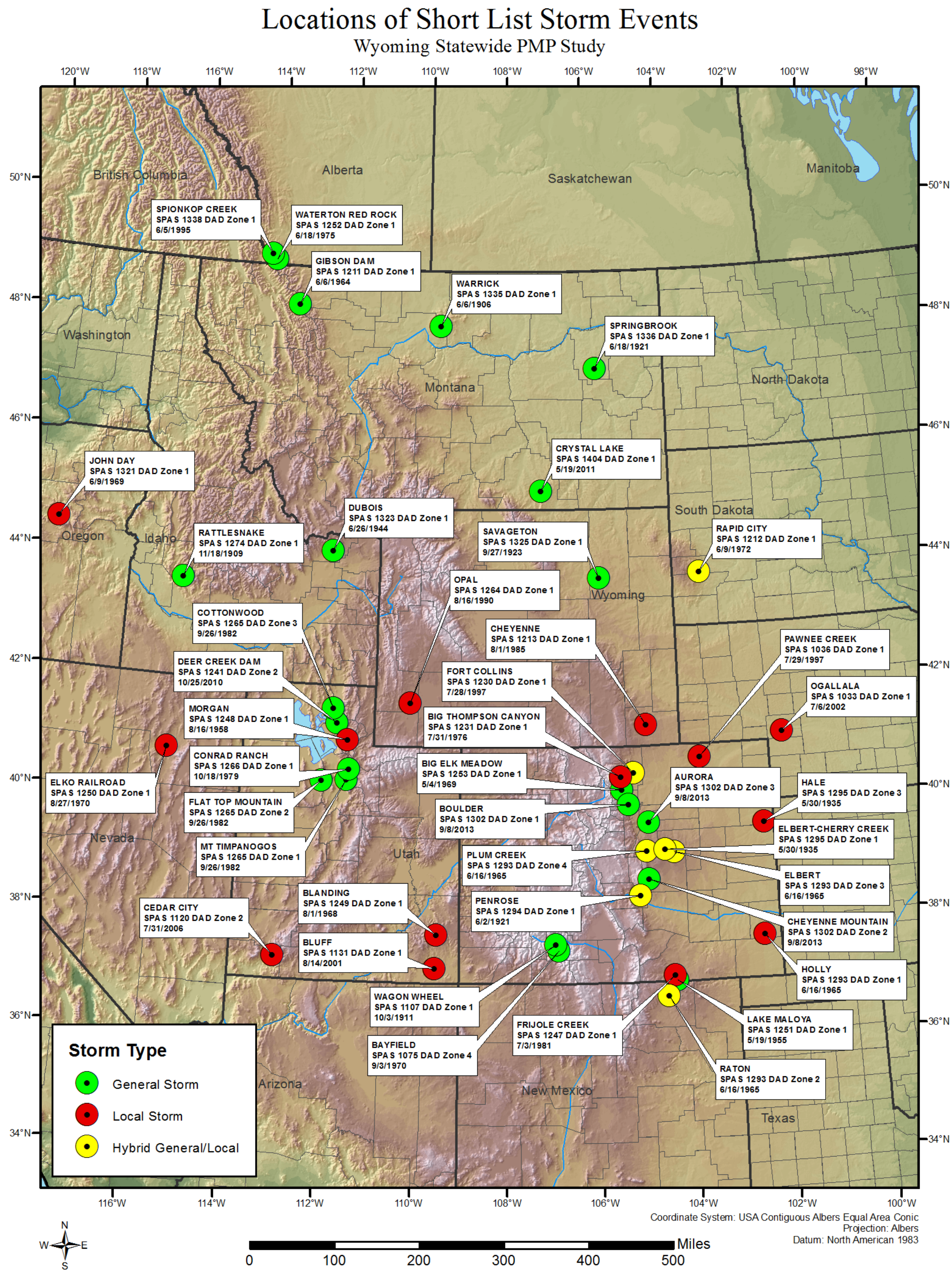


Figure 6.2 Storm locations for storms on the short storm list with SPAS DAD zones identified

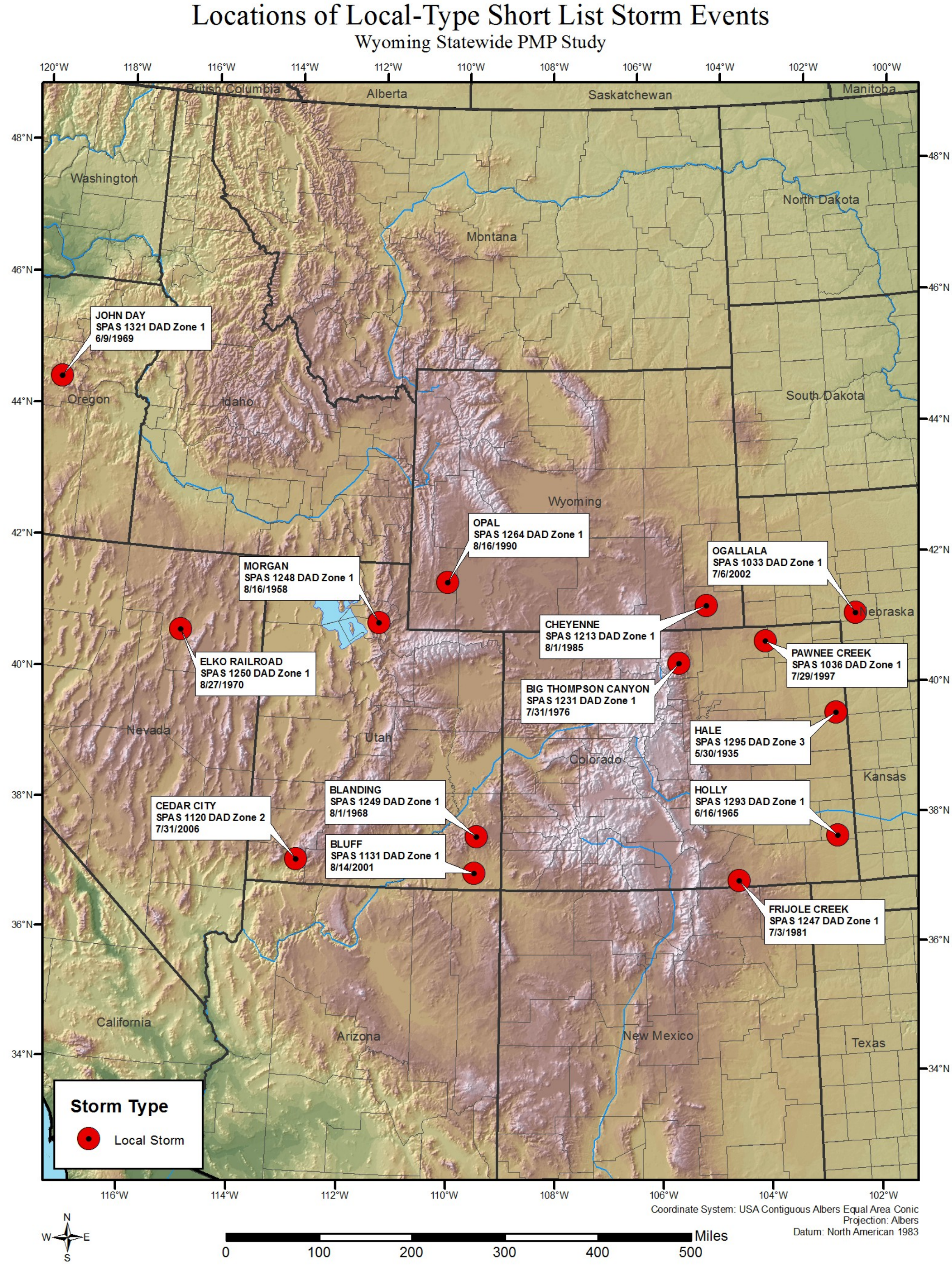


Figure 6.3 Storm locations for local/MCS storms on the short storm list

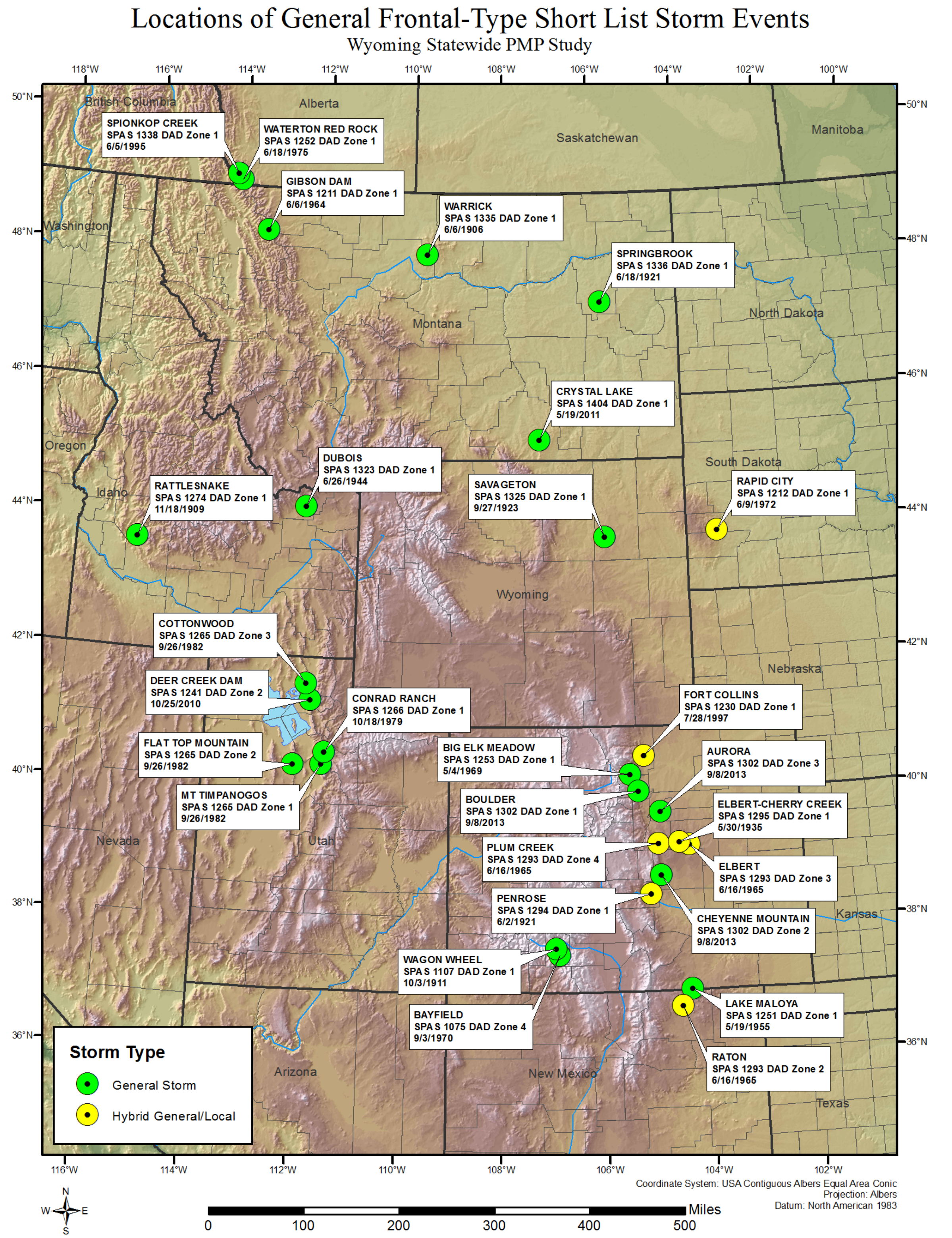


Figure 6.4 Storm locations for general storms on the short storm list (includes the hybrid storms which were used in both the local and general storm PMP development)

7. 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 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. The maximum dew point values provided in the maximum average dew point climatologies are for the 1000mb 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 1000mb 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 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 manual (1986) 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. An example is the May 1935 (SPAS 1295) event in Colorado that was not moved 15 days towards the warm season following HMR 51 and HMR 55A guidance. A more detailed discussion of this procedure and example calculations are provided in Appendix C.

7.1 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. 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 return frequency maps representing the 50-year recurrence interval using the L-moments method. The Review Committee for that study included representatives from NWS, FERC, Bureau of

Reclamation, and others. They agreed that the 50-year return frequency values were appropriate for use in PMP calculations. For the Nebraska statewide study, the Review Committee and FERC Board of Consultants agreed that the 100-year return frequency dew point climatology maps were appropriate because their use added a layer of conservatism over the 50-year return period. This has subsequently been employed in all PMP studies. This study is again using the 100-year return frequency climatology constructed using data updated through 2013 (Figure 7.1).

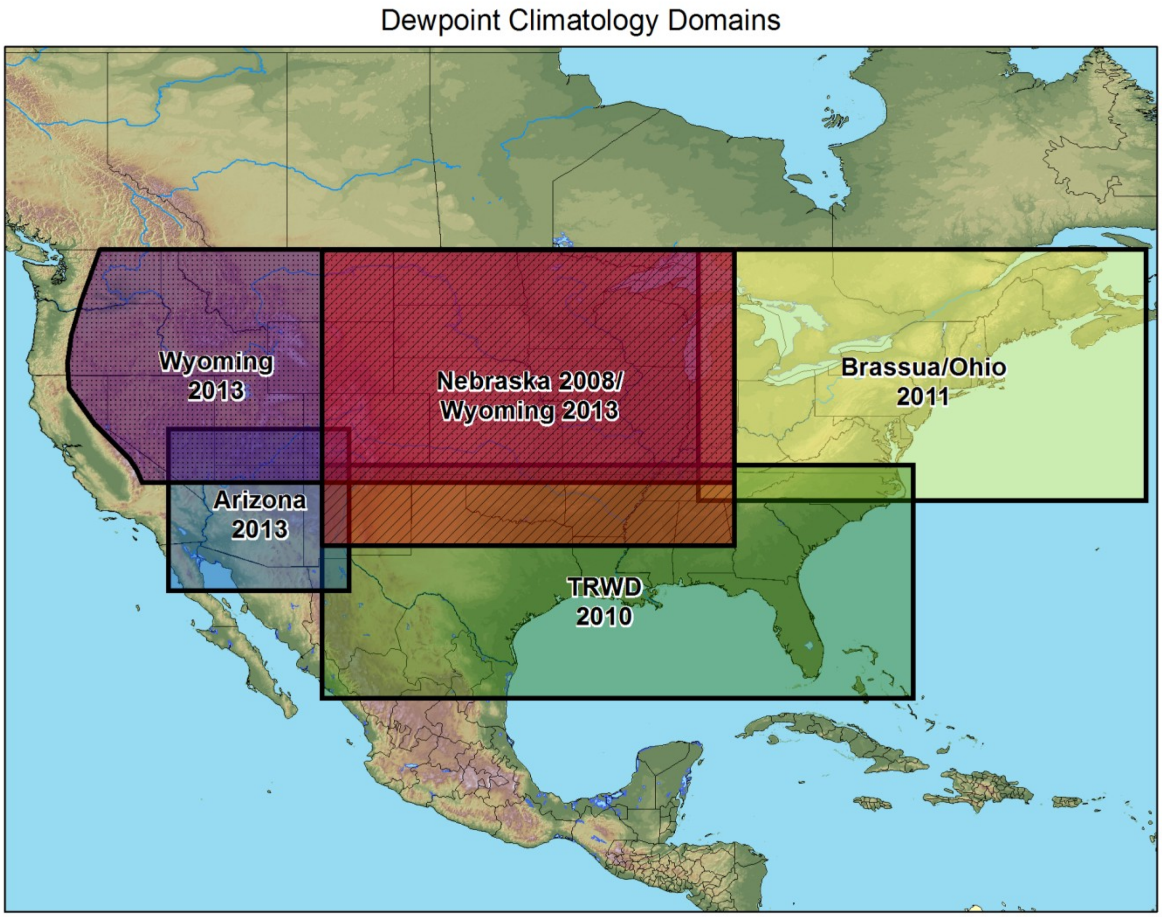


Figure 7.1 Maximum dew point climatology development regions and dates

Observed storm rainfall amounts are maximized using the ratio of precipitable water for the maximum dew point to precipitable water for the storm representative dew point, assuming a vertically saturated atmosphere. The difference between the *maximum* precipitable water and *actual* precipitable water associated with a storm event is converted into a percent and the storm rainfall totals as they occurred are enhanced (maximized) by this factor, called the in-place maximization factor (IPMF). By definition, maximization factors are always greater than or equal to 1. Following HMR (e.g. HMR 51 Section 3.2.2 and HMR 55A Section 8.4.1.1) and previous AWA PMP in-place storm maximization guidance, the in-place maximization value is capped at 1.50. This 1.50 limitation is based on the consideration that if the moisture is increased beyond 50% (an IPMF of 1.50), the assumption that the moisture can be increased without altering the storm's dynamics is no longer valid (HMR 55A, Section 8.4.1.1). The assumption is that properly analyzed and maximized storms should be some percent larger than the actual storm, but increases beyond certain limits (e.g. 50%) would change the characteristics of the storm. In some cases when the IPMF is greater than 1.5, the storm representative dew point did not adequately represent the true moisture source, either because of a lack of dew point data or misidentification of the moisture source region location. In this study, ten general storms were affected by this 1.50 cap on the IPMF (see Figure 6.4 for location of each of the storms listed):

- October 1911, SPAS 1107
- June 1964, SPAS 1211
- May 1955, SPAS 1251
- June 1975, SPAS 1252
- May 1969, SPAS 1253
- October 1979, SPAS 1266
- November 1909, SPAS 1274
- June 1944, SPAS 1323
- June 1906, SPAS 1335
- May 2011, SPAS 1404

The IMPF calculation procedure in this study used the updated maximum dew point climatology described in Section 4. An interesting result of this analysis showed that in several cases, surface dew point and the standard IPMF factor process did not properly identify the primary moisture source associated with rainfall events, resulting in relatively high IPMFs. Several factors combine to produce these general storm rainfall events along the Front Range of the Rockies. Although not all of the processes leading to these consistently high IPMFs are understood, some likely causes include the effects of topography (upslope), the interactions of lift by convergence associated with the low pressure system, and frontal dynamics. Examination of the synoptic pattern associated with several of these events (e.g. HMR 55A Section 2.4.1.6) shows that there is an influx of moisture at the mid-levels of the atmosphere (~5,000 to 20,000 feet) from the west (Pacific) that is not reflected at the surface. Because of this, the storm maximization calculation representing the moisture supplying the storms is often not well defined by surface based dew point observations. Several factors affect the standard process of using surface based dew points to represent the moisture source for these storm events. In most cases, the moisture source for the storms is a combination of the Pacific Ocean, which has been disrupted by the interaction of the mountain ranges upstream of the region, and the Gulf of Mexico. In addition, there are generally fewer dew point observation stations in the relatively less populated regions to represent the moisture content of the atmosphere. Finally, the surface flow into these storms transitions from a preferred southeasterly component in southern Front Range to a northeasterly component in northern Front Range (e.g. HMR 55A Figure 3.3). Therefore, the Gulf of Mexico low-level moisture source is more intermittent and not reflected in storm patterns producing extreme rainfall in the northern Front Range.

For two of these general storm events, Gibson Dam, MT, June 1964 (SPAS 1211) and Rattlesnake, ID, November 1909 (SPAS 1274), there was insufficient data to accurately determine the storm representative dew point. Further, because each of these storms was the controlling storm in regions where they were transpositioned, a more accurate representation of the IMPF was required. Discussions with the Review Board, WWDO, NRCS, FERC, and others involved in this project determined that it was more appropriate to look at the average IPMF for all storms of the same type in the same region and utilize those data to justify a more appropriate IPMF. This analysis produced an average IPMF of 1.30 for general storms east of the Continental Divide and 1.40 for general storms west of the Continental Divide. Therefore, the IPMF for the Gibson Dam, MT, June 1964 (SPAS 1211) event was at 1.30 and the IPMF for the Rattlesnake, ID, November 1909 (SPAS 1274) event was set to 1.40. The rationale for this decision was based on the extraordinary magnitude of these two storms, which are highly unlikely to have maximization factors greater than the overall average of many storm, most of which are much smaller in magnitude.

7.2 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. 3-, 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 (3-hour, 6-hour, 12-hour, or 24-hour depending on storm's rainfall accumulation). These values were then normalized to 1000mb (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 trajectory 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 the 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.

The process involves deriving the average dew point values at all stations with dew point data in a large region along the HYSPLIT inflow vectors. Values representing the average 3-, 6-, 12-, and 24-hour dew points are analyzed in Excel spreadsheets, and with the appropriate duration representing the storm being analyzed, plotted for evaluation of the storm representative dew point. This evaluation includes an analysis of the timing of the observed dew point 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 stations 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 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 climatologies. Appendix F of this report contains each of the HYSPLIT trajectories analyzed as part of this study for each storm (when used).

7.2.1 Storm Representative Dew Point Determination Example

As an example, Figure 7.2 shows the HYSPLIT trajectory model results used to analyze the inflow vector for the Holly, CO June 1965 (SPAS 1293) storm. Note, in this HYSPLIT analysis, both the surface and 850mb inflow vectors (red and blue lines) are very similar in direction and distance, while the 700mb inflow vector (green line) is similar initially, then changes direction after the first 12 hours. In this case, surface dew point values were analyzed for a region starting at the storm center and extending southeastward into northern Texas and western Oklahoma. All the HYSPLIT inflow vectors showed a south to southeast inflow direction (the most common for Front Range storms). The air mass source region supplying the atmospheric moisture for this storm was located over northern Texas and western Oklahoma 12-36 hours prior to the rainfall occurring at Holly, Colorado and was advected into the rainfall region. 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 7.3 displays the stations analyzed and their representative 6-hour average dew point values. The region encircled in red is considered the moisture source region for this storm.

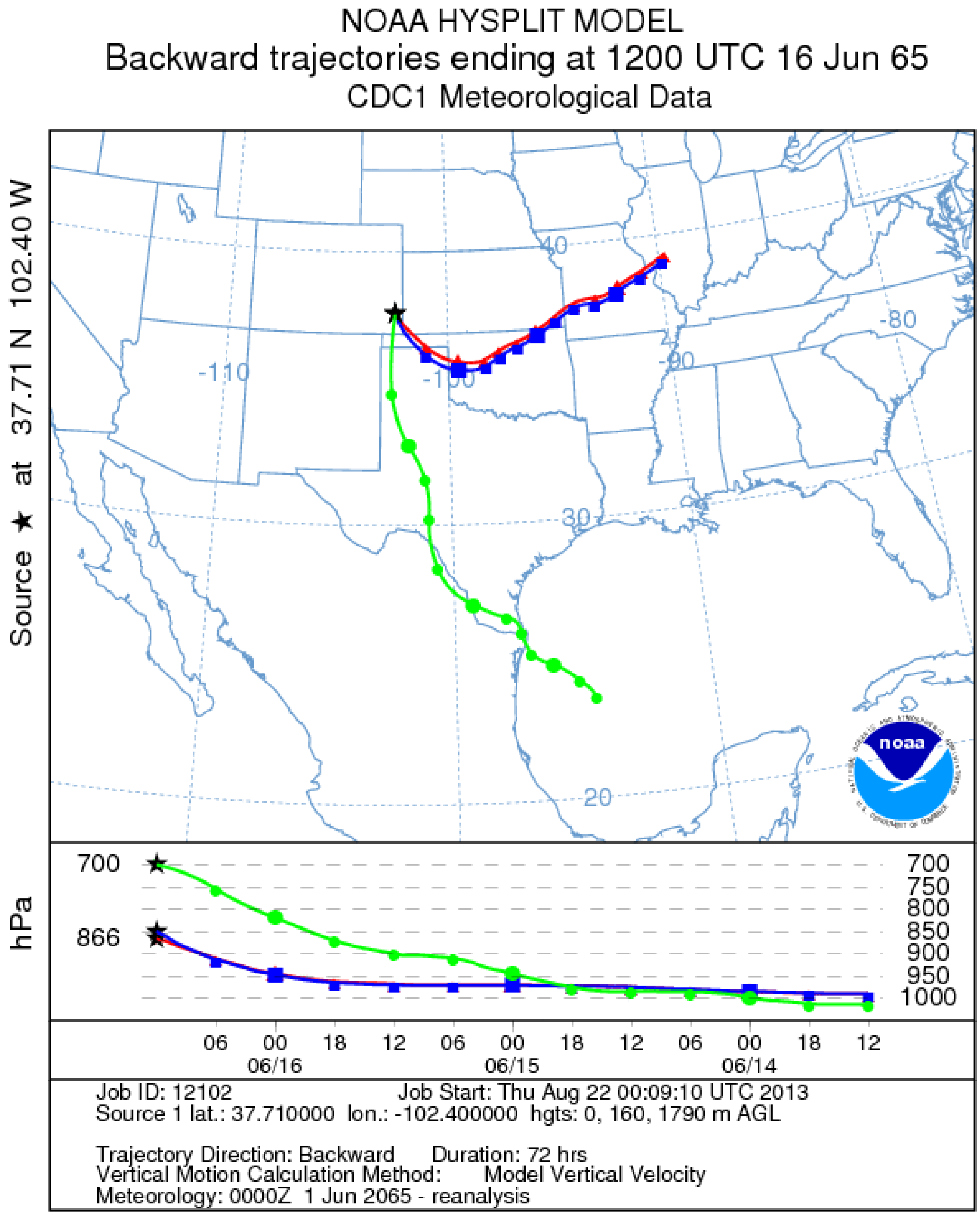


Figure 7.2 HYSPLIT trajectory model results for the Holly, CO June 1965 storm

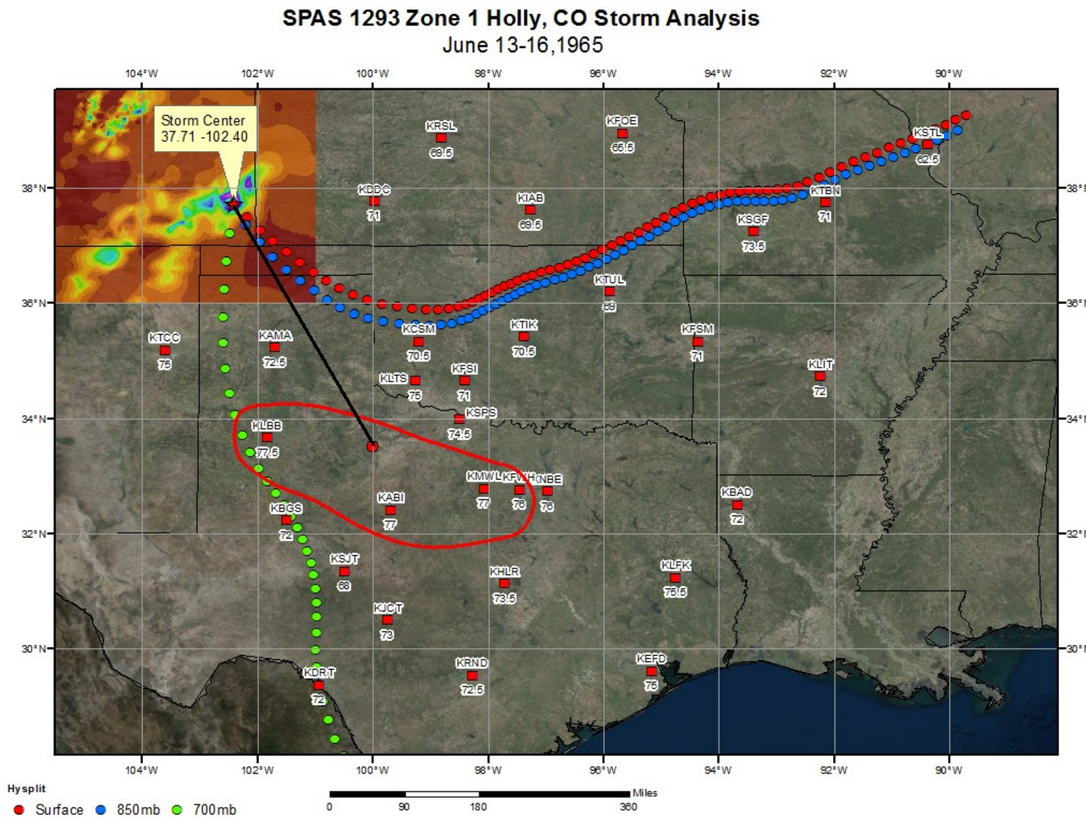


Figure 7.3 Surface stations, 6-hour average dew points, and moisture source region, along with HYSPLIT trajectory model results for the Holly, CO June 1965 storm

7.2.2 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 eastern Wyoming) 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 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 1000mb 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 1000mb) at Kansas City, MO and 66°F (68°F at 1000mb) at Topeka, KS for an average 12-hour persisting 1000mb adjusted value of 66.5°F (Table 7.1).

Table 7.1 Comparison of 6-hour average storm representative dew point vs. 12-hour persisting storm representative dew point for the David City, NE, 1963 storm

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.

7.2.3 Rationale for Adjusting HMR 51 Persisting Dew Point Values

In some cases, (e.g., storms on the short storm list previously analyzed in the USACE Storm Studies and used in NWS HMRs), 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 consistent results for Local/MCS and General type 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 in the Nebraska and Ohio statewide PMP studies and in this study. These analyses investigated additional modern storms specifically relevant for Wyoming. 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 was 2°F for General storms (Table 7.2). 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.

Table 7.2 Storms used to evaluate average vs. persisting dew point values specific to Wyoming. The table is categorized by local/MCS storms and synoptic storm types.

	Local Storms				
Storm Event	**Date**	**Avg. 12-hr Persisting Td**	**Avg. Td**	**Avg. Delta**	**Duration Analzyed**
Big Thompson Canyon, CO	July 31, 1976	59.0	78.5	19.5	6hr
Bluff, UT	August 14, 2001	58.0	76.5	18.5	6hr
Cedar City, UT	July 31, 2006	69.0	74.0	5.0	6hr
Morgan, UT	August 18, 1958	66.0	72.5	6.5	6hr
Ogallala, NE	July 6-7, 2002	74.5	76.5	2.0	6hr
Ft Collins, CO	July 28-29, 1997	74.0	77.5	3.5	6hr
Cheyenne, WY	August 1-2, 1985	71.0	77.0	6.0	6hr
Frijole Creek, CO	July 3, 1981	75.0	77.0	2.0	6hr
Rapid City, SD	July 8-10, 1972	71.5	78.5	7.0	6hr
			Average	**7.8**	
	General Storms				
Storm Event	**Date**	**Avg. 12-hr Persisting Td**	**Avg. Td**	**Avg. Delta**	**Duration Analzyed**
Big Elk Meadows, CO	May 3-8, 1969	63.5	65.0	1.5	24hr
Gibson Dam, MT	June 6-9, 1964	61.0	66.0	5.0	24hr
Waterton Dam, AB	June 18-20, 1975	68.0	71.0	3.0	24hr
Lake Maloya, NM	May 18-20, 1955	69.0	70.5	1.5	24hr
Deer Creek, UT	October 23-25, 2010	59.0	59.0	0.0	24hr
			Average	**2.2**	

8. 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 9.

The search for extreme rainfall events identified storms that occurred throughout the Intermountain West and the Great Plains (see Figure 6.1). This region was considered meteorologically and geographically similar to one or more locations within Wyoming.

The storms on the eastern side of the Continental Divide are supplied with low-level atmospheric moisture primarily from the Gulf of Mexico; conversely storms on the western side receive their moisture from the Gulf of California and Pacific Ocean. These air masses cannot cross the Continental Divide without significant loss of moisture content. Therefore, storm transposition was limited to the side of the Continental Divide on which the storm occurred. Transposition limits were defined by dividing the state into eight transposition zones. Each transposition zone was delineated after careful consideration of a combination of criteria including; physiographic provinces (defined by both the Wyoming State Geological Survey and the USGS), climatological zones defined by NCDC and the Köppen classification, variations in topography, and ecological regions. The 6-hour and 24-hour L-moment statistical station regions defined in the precipitation frequency analysis (Section 5) were also evaluated as delineation criteria.

These criteria helped identify regions of similar meteorology and topography. Eight transposition zones were defined as follows (Figure 8.1):

1) Black Hills
2) Great Plains
3) Eastern Rocky Mountains (east of the Continental Divide)
4) Eastern Rocky Mountains (west of the Continental Divide)
5) Wyoming Basin (east of the Continental Divide)
6) Wyoming Basin (west of the Continental Divide)
7) Western Rocky Mountains (east of the Continental Divide)
8) Western Rocky Mountains (west of the Continental Divide)

The Continental Divide bisects the Wyoming in two places resulting in the endorheic Great Divide Basin. This region was assigned to zone 6 on the western side of the Continental Divide. This is because it is more climatologically and topographically similar to zone 6 than to zone 5 on the eastern side of the Divide and is largely protected from moisture approaching from the east. 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.

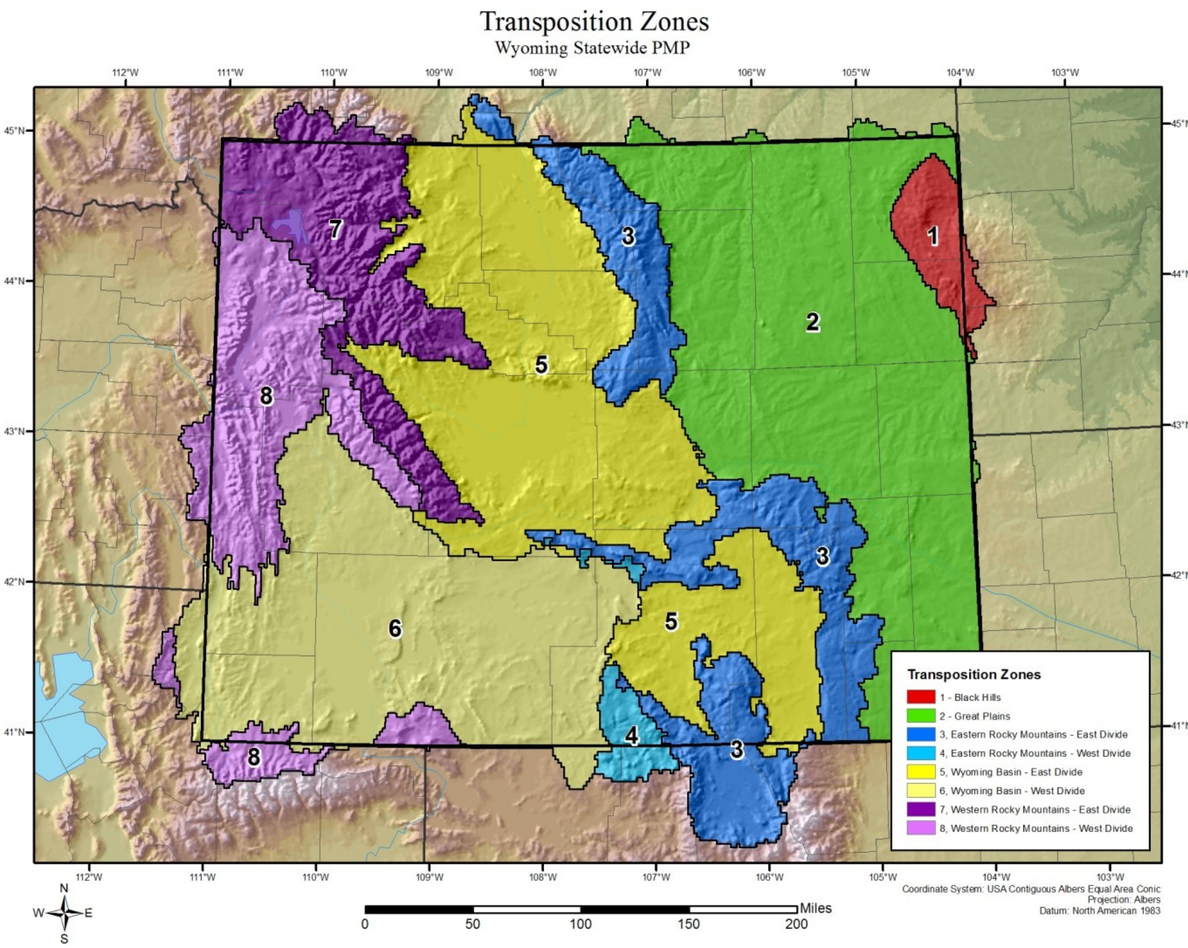


Figure 8.1 Transposition zones used to define transposition limits for individual storms

The 42 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 5th Review Board meeting and the limits were refined during and between subsequent meetings. During the meetings, extensive discussions with all members present took place to explicitly define transposition limits for each of the 42 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 eight 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 either too high or too low. 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 L provides a description of the iterations and adjustments that were applied during each PMP version to arrive of 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. This is to be expected, as the topography across Wyoming varies significantly in elevation, aspect and slope, often over very short distances.

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 they were larger than expected, suggesting 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 this 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 conservative approach of including the MTF should remain.

The spatial variations in the OTF were useful in making decisions on transposition limits for a storm. As described in Section 7, 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 transposition limits have most likely been exceeded. Mapping the OTF and MTF values across the state provided visual guidance to aid with defining transposition zones allowing areas of excessively large transposition factors to be defined as non-transposable. Therefore, storms were reevaluated for transpositionability in regions which results 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, a cap of 1.50 was applied to be consistent with the IPMF cap.

From these analyses, refinements such as limiting a storm's transposition location using an elevation constraint or by an OTF amount were applied. An example of the August 2001 event at Bluff, UT (SPAS 1131) is provided. This storm occurred on the Colorado Plateau at an elevation of 5,000 feet. Broadly, the storm is only considered to be transposable to the western side of the Continental Divide, the side on which it occurred, meaning zones 4, 6, and 8. Elevation, terrain, moisture source, storm type, and distance are examined to further refine the transposition limits. Figure 8.2 shows the OTF values for the storm across the statewide domain. While Zone 6 and most of zone 4 present moderate OTF values (less than 1.50), the mountain ranges of Zone 8 result in OTF values well above 1.50. Zone 8 is mostly above 7,500 feet and mountainous. It is apparent that this storm could not be moved to Zone 8 without significantly altering its storm dynamics and violating the definition of transpositionability. Therefore, the storm's transposition limits were defined as Zones 4 and 6.

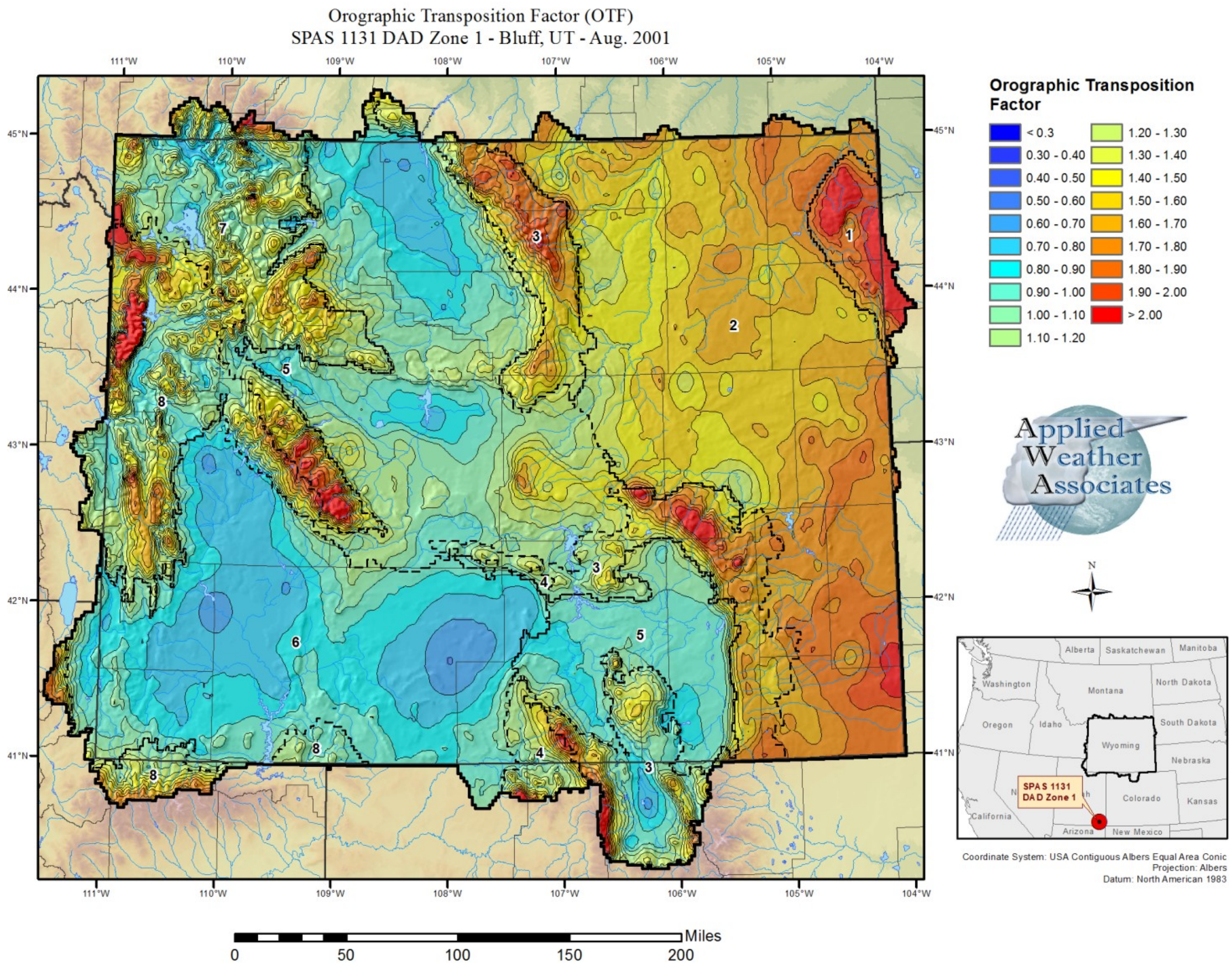


Figure 8.2 Orographic Transposition Factors for Bluff, UT August 2001, SPAS 1131

9. 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 transposable 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 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. In-place maximization and moisture transposition are described in Sections 7 and 8. Orographic transposition is described in Section 3. These calculations were completed for all storms for every grid point analyzed over the entire domain. Several storms have multiple centers analyzed. Each SPAS DAD zone was considered as independent events for the purpose of PMP calculation. In addition, seven of the storm events were considered hybrid-type storms exhibiting characteristics of both local and general storms. In these situations, these storms were analyzed as both local and general storm type events with separate PMP values developed for each scenario. In total there were 42 separate events analyzed; 14 local storms, 21 general storms, and 7 hybrid type storms.

An Excel storm adjustment spreadsheet 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 predetermined criteria (see Section 8). 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 (see Section 9.8.1). At any point in the future, new storm feature classes could be added, removed, or edited.

The PMP Evaluation Tool receives 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 storms PMP are 1-, 6-, 12-, 24-, 48-, and 72-hours. The durations calculated for local/MCS storms PMP were 1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hours. The PMP area sizes calculated for general storm PMP were 1-, 10-, 50-, 100-, 200-, 500-, 1,000-, 5,000-, and 10,000-square miles. The PMP area sizes calculated for local/MCS storm PMP were 1-, 10-, 25-, 50-, 100-, 200-, 500-, and 1,000-square miles.

The following sections describe the procedure for calculating the IPMF, the MTF, the OTF, and the TAF for the creation of the storm adjustment feature classes. Examples of each of these calculations are presented followed by discussion of the implementation and application of the PMP Evaluation Tool to calculate PMP.

9.1 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 7.2. 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 48,343 point features across the statewide domain. Before the dew point extraction, each of these point features was 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 Section 7, 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 9.1.

$$W_p = W_{p,30,000'} - W_{p,elev} \qquad \text{Equation 9.1}$$

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.)

9.2 In-Place Maximization Factor

In-place storm maximization is applied for each storm event using the methodology described in Section 7. Storm maximization is quantified by the IPMF using Equation 9.2.

$$IPMF = \frac{W_{p,max}}{W_{p,rep}} \qquad \text{Equation 9.2}$$

where,

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

9.3 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 9.3.

$$MTF = \frac{W_{p,trans}}{W_{p,max}}$$ Equation 9.3

where,

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

9.4 Orographic Transposition Factor

Section 3.1 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.

$$OTF = \frac{P_o}{P_i}$$ Equation 9.4

where,

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

The orographically adjusted rainfall is determined by applying the function in Equation 3.1 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 9.5 (from Equation 3.1)

where,

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

9.5 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 9.1. 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.

Contents | Preview | Description

OBJECTID *	Shape *	CNT	STORM	LON	LAT	ZONE_	ELEV	IPMF	MTF	OTF	TAF	TRANS
1	Point	1	1211_1	-106.325	40.325	3	10731.62764	1.3	1.359649	0.454047	0.802548	0
2	Point	2	1211_1	-106.3	40.325	3	10669.29168	1.3	1.359649	0.45575	0.805558	0
3	Point	3	1211_1	-106.25	40.325	3	10718.50428	1.3	1.359649	0.451202	0.79752	0
4	Point	4	1211_1	-106.225	40.325	3	10416.667	1.3	1.359649	0.446863	0.78985	0
5	Point	5	1211_1	-106.2	40.325	3	10629.9216	1.3	1.359649	0.446376	0.788989	0
6	Point	6	1211_1	-106.175	40.325	3	9924.541	1.3	1.359649	0.454005	0.802474	0
7	Point	7	1211_1	-106.15	40.325	3	11200.78776	1.3	1.359649	0.489492	0.865199	0
8	Point	8	1211_1	-106.125	40.325	3	11046.58828	1.3	1.359649	0.518222	0.91598	0
9	Point	9	1211_1	-106.45	40.35	3	9589.89532	1.3	1.359649	0.559971	0.989772	0
10	Point	10	1211_1	-106.425	40.35	3	9655.51212	1.3	1.359649	0.546669	0.966262	0
11	Point	11	1211_1	-106.4	40.35	3	10305.11844	1.3	1.359649	0.561633	0.99271	0
12	Point	12	1211_1	-106.375	40.35	3	10698.81924	1.3	1.359649	0.577728	1.02116	0
13	Point	13	1211_1	-106.35	40.35	3	10859.5804	1.3	1.359649	0.586313	1.036334	0
14	Point	14	1211_1	-106.325	40.35	3	10725.06596	1.3	1.359649	0.597527	1.056155	0
15	Point	15	1211_1	-106.3	40.35	3	11174.54104	1.3	1.359649	0.605827	1.070825	0
16	Point	16	1211_1	-106.275	40.35	3	10725.06596	1.3	1.359649	0.601789	1.063688	0
17	Point	17	1211_1	-106.25	40.35	3	10528.21556	1.3	1.359649	0.59197	1.046334	0
18	Point	18	1211_1	-106.225	40.35	3	9927.82184	1.3	1.359649	0.572856	1.012548	0
19	Point	19	1211_1	-106.2	40.35	3	9652.23128	1.3	1.359649	0.567762	1.003544	0
20	Point	20	1211_1	-106.175	40.35	3	10882.54628	1.3	1.359649	0.584418	1.032985	0
21	Point	21	1211_1	-106.15	40.35	3	10364.17356	1.3	1.359649	0.595843	1.053179	0
22	Point	22	1211_1	-106.125	40.35	3	10419.94784	1.3	1.359649	0.595564	1.052685	0
23	Point	23	1211_1	-106.1	40.35	3	9803.14992	1.3	1.359649	0.575382	1.017014	0
24	Point	24	1211_1	-106.075	40.35	3	9996.71948	1.3	1.359649	0.559648	0.989202	0
25	Point	25	1211_1	-106.05	40.35	3	9885.17092	1.3	1.359649	0.557122	0.984738	0
26	Point	26	1211_1	-106	40.35	3	9763.77984	1.3	1.394737	0.571341	1.035932	0
27	Point	27	1211_1	-105.975	40.35	3	11286.0896	1.3	1.394737	0.638412	1.157541	0
28	Point	28	1211_1	-105.95	40.35	3	11466.5358	1.3	1.394737	0.665938	1.207451	0
29	Point	29	1211_1	-106.6	40.375	3	9596.457	1.3	1.359649	0.672087	1.187942	0
30	Point	30	1211_1	-106.575	40.375	3	8671.26012	1.3	1.359649	0.662267	1.170585	0
31	Point	31	1211_1	-106.55	40.375	3	8897.63808	1.3	1.359649	0.659118	1.165019	0

1 (of 48343)

Figure 9.1 Example of a storm adjustment factor feature class table

For a grid point, the total adjusted rainfall depths for all storms transposable 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.

9.6 Elevation Adjustment

While the OTF method provides an effective approach for quantifying the effect of terrain and elevation, it has limitations for representing the orographic effect on PMP-type rainfall at very high elevations. These limitations are related to lack of representation of extreme rainfall events at very high elevations for use in developing the precipitation frequency climatology. This is due in part to the sparseness of rainfall-only station data over the Wyoming high-elevation mountain ranges and that high elevation rainfall events do not occur or very rarely occur. The potential for very high elevation rainfall in this region is not well understood and is difficult to quantify due to lack of data. However, there is paleohydrology-based research suggesting that the mechanisms for producing PMP-type rainfall are not present in the Rocky Mountain region above 7,000 feet in Wyoming (Jarrett and Costa 1982, Jarrett 1993). In addition, from a meteorological perspective, the lack of depth of moisture through the atmospheric column limits the amount of rainfall that can occur at the high elevations and is another reason high volume rainfall events do not occur in the mountainous regions of Wyoming. This is different than mean annual precipitation, which is influenced greatly by snowfall. Because snowfall is not relevant for PMP derivation, this factor must be accounted for.

HMRs in mountainous regions (49, 55A, 57, and 59) apply a varying set of reductions to account for the effect of high-elevations on PMP: -5% per 1,000 feet above 5,000 feet elevation in the Semiarid Southwest (HMR 49); -5 to -10% per 1,000 feet dependent on maximum-persisting dew point above 5,000 feet elevation in the eastern Rocky Mountains (HMR 55A); -9% per 1,000 feet above 6,000 feet elevation in the Pacific Northwest and California (HMRs 57 and 59).

Previous research and methodologies were considered for the application of an adjustment factor to account for the overestimation of PMP at high altitudes. Discussions with the Review Board, WWDO, NRCS, FERC, and others involved in this study concluded that using the HMR guidance of a 9%/1,000 feet reduction was appropriate given the lack of other quantifiable information. This is approximately the pseudo-adiabatic lapse rate for a saturated atmosphere, and therefore has a meteorological foundation considering how important the quantification of atmospheric moisture availability is in defining PMP values. In addition, the geography and elevations specific to the study were considered with the help of a GIS. During this analysis, AWA investigated the regions where this factor was to be applied. Several iterations were completed to ensure the locations where this adjustment was applied were mountainous (i.e. highly orographic) regions. In addition, AWA rounded the starting elevation to 7,500 feet although research by Jarrett and Costa showed the rainfall versus snowmelt controlled flood elevation was around 7,200 feet in Wyoming, This was done to allow for the uncertainty involved in the process. Therefore, a threshold elevation of 7,500 feet was determined to be appropriate for Wyoming while adapting the reduction from HMRs 57 and 59 of -9% per 1,000 feet. Figure 9.2 shows the areas within the project domain above 7,500 feet affected by the reduction. The adjustment was applied to the PMP for both storm types at grid points above 7,500 feet.

The elevation adjustment was applied by creating a gridded elevation adjustment factor dataset within ArcMap based on a converting the 9%/1,000 feet value to a 0.9% reduction per 100 feet according to the elevation at each grid point. The gridded reduction factors are shown in Figure 9.3. The calculated PMP at each grid point was then multiplied by this adjustment factor to provide the final elevation-adjusted PMP.

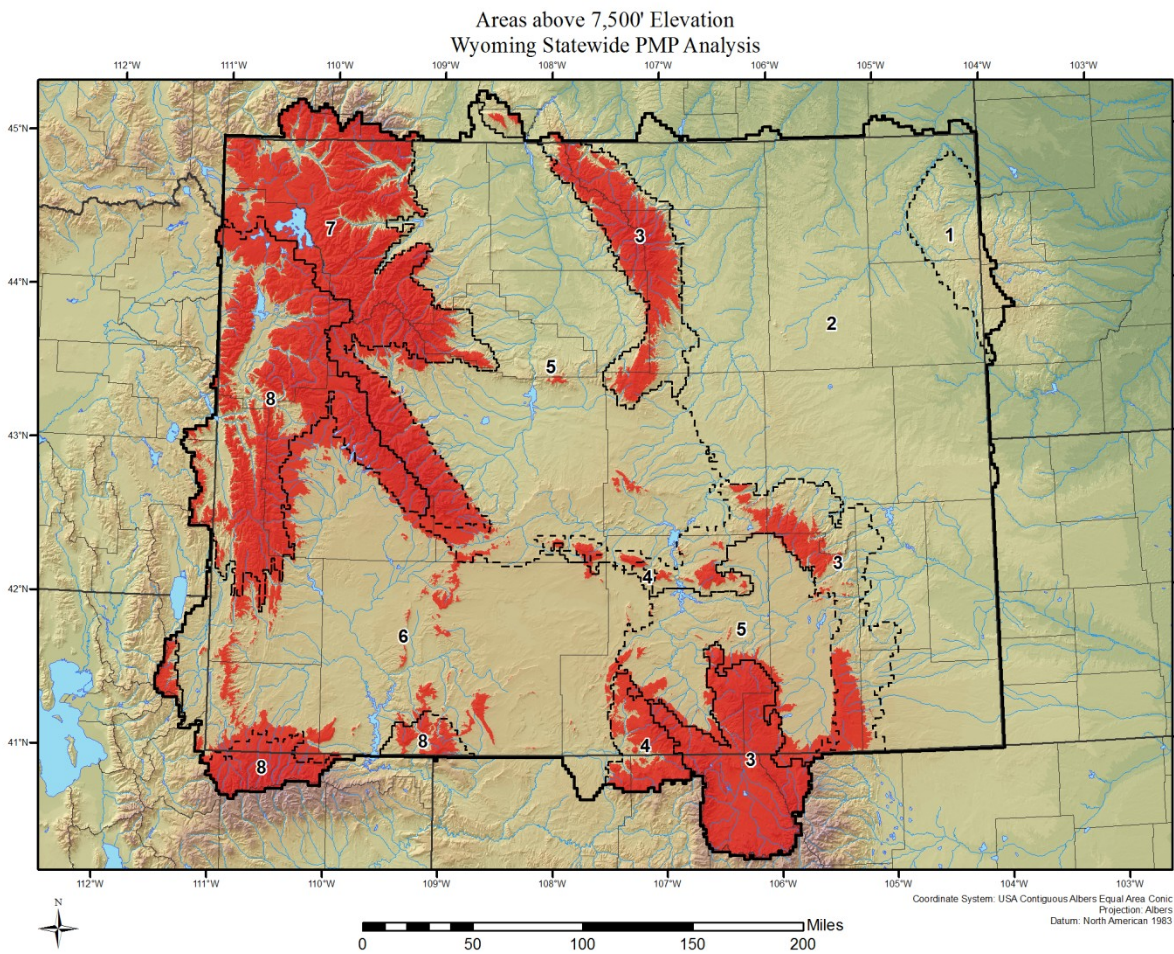


Figure 9.2 Areas with elevations above 7,500 feet within the project domain.

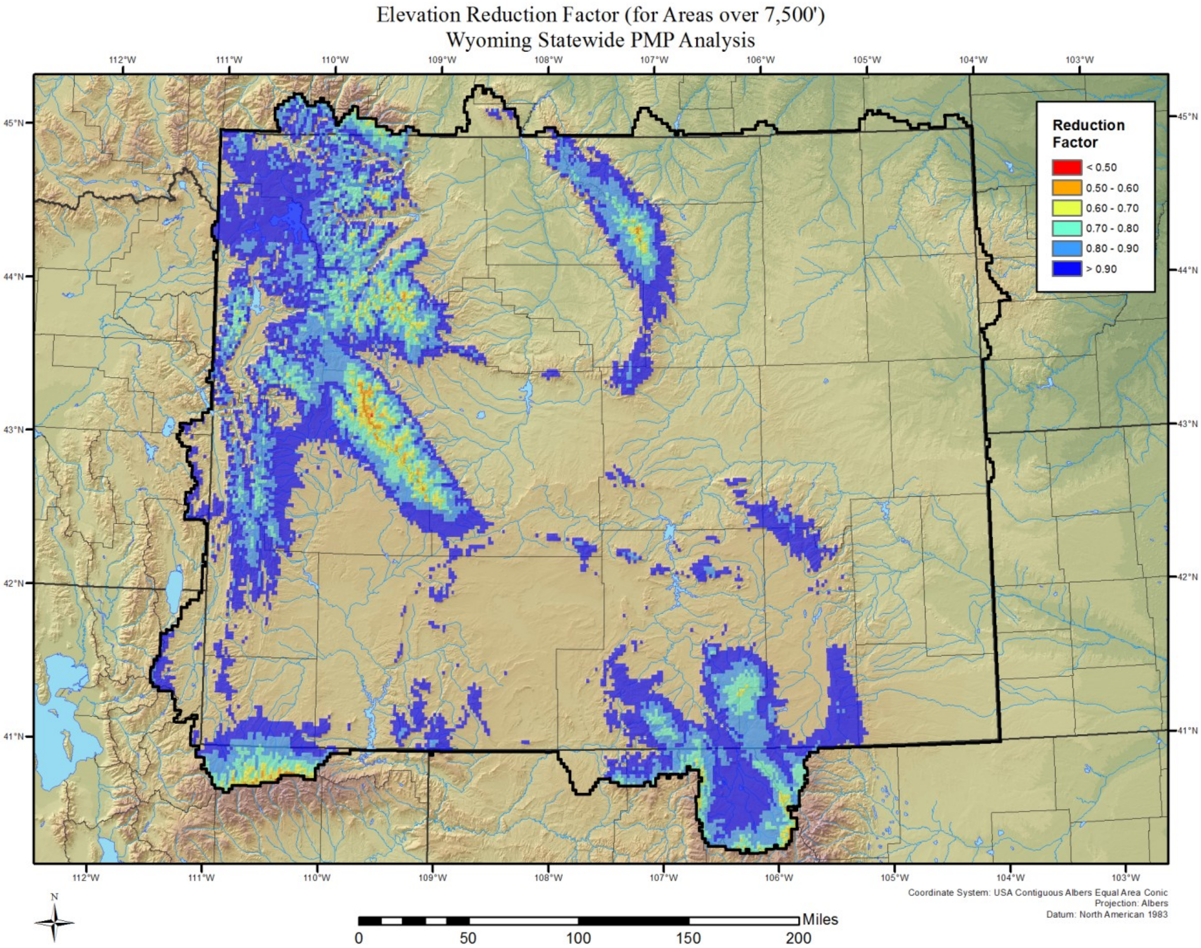


Figure 9.3 Elevation reduction factors for areas above 7,500 feet in elevation within the project domain

9.7 Sample Calculations

The following sections provide sample calculations for the storm adjustment factors for the Savageton, WY September, 1923 (SPAS 1325) general storm event when transposed to 44.5° N, 107.0° W (grid point #41,953). The target location is about 70 miles northwest of the storm location at an elevation of 8,500 feet along the eastern slope of the Big Horn Mountain Range (Figure 9.4). The eastern slope of the Rocky Mountains, including the Big Horn Range, are particularly vulnerable to extreme rainfall as they provide a significant barrier and mechanism for uplift and convergence of moisture-laden air masses crossing the Great Plains. This event was among the largest on record for this region, producing over 17 inches of rainfall in 72 hours.

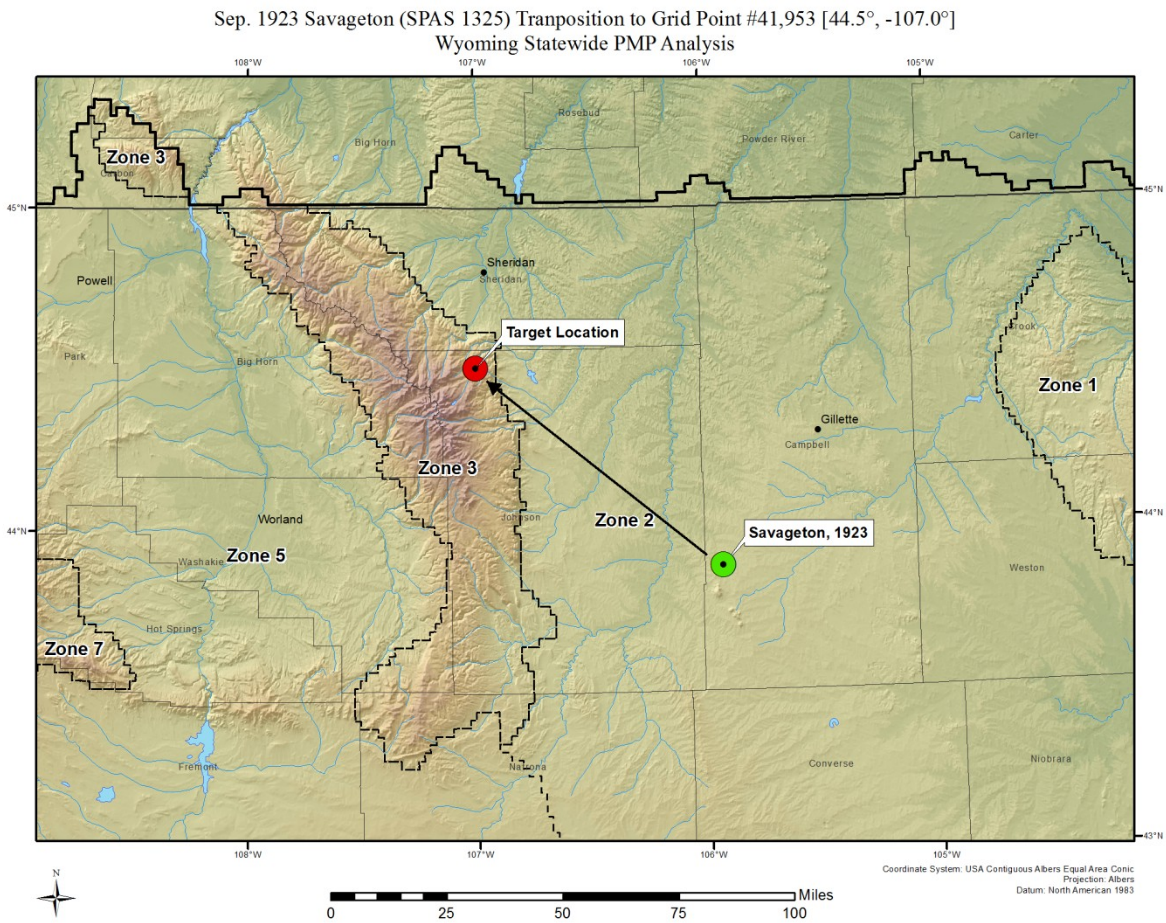


Figure 9.4 Location of Savageton, WY, September 1923 (SPAS 1325) transposition to grid point #41,953

9.7.1 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 9.1. The storm representative dew point temperature is 71.5 °F at the storm representative dew point location 450 southeast of the storm center (see Appendix F for the detailed storm maximization and analysis information). The storm center elevation is approximated at 4,800 feet at the storm center location of 43.88° N, 105.93° W. The storm representative available moisture ($W_{p,\ rep}$) is calculated using Equation 9.1:

$$W_{p,rep} = W(@71.5°)_{p,30,000'} - W(@71.5°)_{p,4,800'}$$

or,

$$W_{p,rep} = 2.42" - 0.935"$$

$$\boldsymbol{W_{p,rep} = 1.485"}$$

The storm occurred at the end of September and was adjusted 15 days toward the warm season to a temporal transposition date of September 15th. The September climatological 100-year maximum 24-hour average dew point at the storm representative dew point location is 74.5°F at the in-place elevation of 4,800 feet. The in-place climatological maximum available moisture ($W_{p,\,max}$) is calculated.

$$W_{p,max} = W(@74.5°)_{p,30{,}000'} - W(@74.5°)_{p,4{,}800'}$$

$$W_{p,max} = 2.79'' - 1.04$$

$$\boldsymbol{W_{p,max} = 1.75''}$$

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 450 miles southeast offset is 74.0 °F at the elevation of 4,800 feet[1]. The horizontally transpositioned climatological maximum available moisture ($W_{p,\,trans}$) is calculated.

$$W_{p,trans} = W(@74.0°)_{p,30{,}000'} - W(@74.0°)_{p,4{,}800'}$$

$$W_{p,trans} = 2.73'' - 1.02''$$

$$\boldsymbol{W_{p,trans} = 1.71''}$$

9.7.2 In-place Maximization Factor

Using Equation 9.2:

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

$$IPMF = \frac{1.75''}{1.485''}$$

$$\boldsymbol{IPMF = 1.178}$$

9.7.3 Moisture Transposition Factor

Using Equation 9.3:

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

[1] Note: Although the elevation at grid cell #41,953 is at 8,500 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.

$$MTF = \frac{1.71"}{1.75"}$$

$$\boldsymbol{MTF = 0.977}$$

9.7.4 Orographic Transposition Factor

Table 9.1 gives an example of 24-hour rainfall frequency values at both the Savageton, WY, September 1923 storm center location (source) grid point and the target grid point location used to determine the orographic relationship.

Table 9.1 10-year through 1,000-year rainfall frequency depths from the precipitation frequency climatology developed during this study 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)	2.31	2.62	3.09	3.48	3.90	4.50	5.00
TARGET (Y-axis)	2.61	2.96	3.51	3.96	4.45	5.16	5.74

When the rainfall frequency values are plotted (Figure 9.5), a best fit trendline 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 Savageton, WY, September 1923 storm center are plotted on the *x*-axis while the target values for the target grid point are plotted on the *y*-axis.

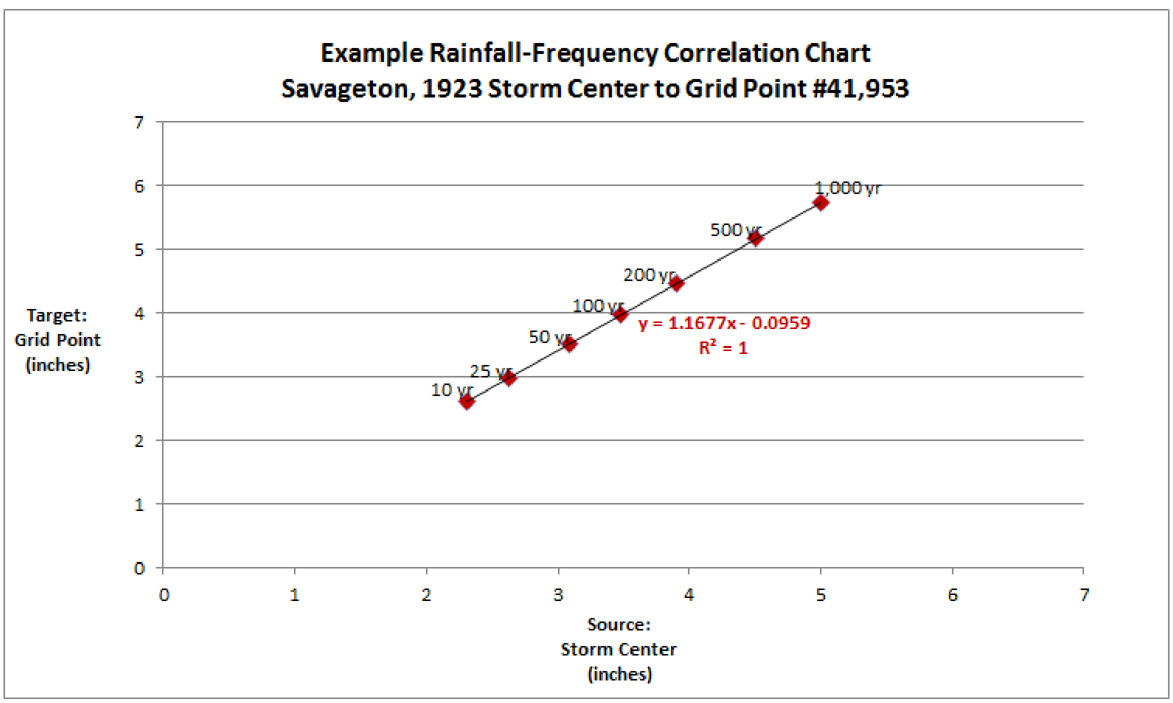


Figure 9.5 Example of rainfall frequency values linear correlation between the storm center and target locations.

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

$$y = mx + b \qquad \text{Equation 9.6}$$

The slope, *m* is the correlation coefficient, representing 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 Savageton, WY, September 1923 (SPAS 1325) 24-hour orographically adjusted rainfall transpositioned to the target grid point, using the linear trendline in Figure 9.5 is:

$$y = 1.17x - 0.10$$

The maximum SPAS analyzed 24-hour point rainfall value of 10.32" is entered as the *x* value to compute the target *y*-value, or orographically adjusted rainfall (P_o) of 11.97".

$$P_o = 1.17(10.32) - 0.10$$

$$\boldsymbol{P_o = 11.97''}$$

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 9.4:

$$OTF = \frac{11.97''}{10.32''}$$

$$\boldsymbol{OTF = 1.16}$$

The OTF at grid #41,953 is 1.16, or a 16% rainfall increase 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.

9.7.5 Total Adjustment Factor

$$TAF = IPMF * MTF * OTF$$

$$TAF = 1.18 * 0.98 * 1.16$$

$$\boldsymbol{TAF = 1.34}$$

The total adjustment factor for Savageton, 1923 (SPAS 1325) when moved to the grid point at 44.5° N, 107° W, representing storm maximization and transposition, is 1.34. This is an overall increase of 34% 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 transposable storms, it becomes the PMP depth at that grid point for that duration.

9.7.6 Elevation Adjustment

For this example calculation, the Savageton, WY, September 1923 event produces the largest total adjusted rainfall and controls PMP at the target grid point. Therefore, a further elevation adjustment was applied since the target location is above 7,500 feet elevation. At 8,500 feet, the total adjusted rainfall is reduced by 9% based on the 9% per 1,000 foot reduction rate above 7,500 feet elevation.

9.8 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 transposable to the target grid point. This process must be repeated for each of the 48,343 grid points within the statewide domain and for each duration for each storm type.

9.8.1 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 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 for a specific area size. PMP values are calculated for local/MCS storm types at the 1-, 2-, 3-, 4-, 5-, 6-, 12-, and 24-hour durations and for general storm types at the 1-, 6-, 12-, 24-, 48-, and 72-hour durations. These gridded PMP values are used to calculate a basin average PMP depth for any of these durations using the process described in Section 10.

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. The final PMP datasets are stored in ESRI GRID raster format and have been provided to the state of Wyoming (All data are included as part of the digital Appendix M). The GRID files are stored within a file geodatabase specific to the PMP area-size analyzed. The geodatabase follows a naming convention of PMP_X.gdb, where X is the area size of the analysis. Within each geodatabase there is a separate GRID file for each duration. 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 "L_06_00025" would be the 25-square mile 6-hour local storm PMP. The following PMP maps are provided in Appendix A:

Local Storm PMP

- 1-hour 1-square mile
- 1-hour 10-square mile
- 1-hour 100-square mile
- 6-hour 1-square mile
- 6-hour 10-square mile
- 6-hour 100-square mile
- 24-hour 1-square mile
- 24-hour 10-square mile
- 24-hour 100-square mile

General Frontal Storm PMP

- 24-hour 10-square mile
- 24-hour 100-square mile
- 24-hour 1,000-square mile
- 72-hour 10-square mile
- 72-hour 100-square mile
- 72-hour 1,000-square mile

High-resolution PDF files for each of these maps are provided in the Digital Appendix M and are available from the WWDO website, http://wwdc.state.wy.us/.

9.9 Temporal Distribution of PMP Values

This study does not include guidance for applying temporal distributions to PMP values. The authors recognize that temporal distributions should vary with storm type and potentially basin size and location. For this study, over forty storms were analyzed with SPAS at 1-hour or higher temporal resolutions and mass curves were produced for each analyzed DAD zone. These individual temporal storm distributions could be applied in hydrologic models and greatly aid in the development of storm type specific and/or region specific temporal distribution patterns. The mass curves showing the accumulation of rainfall through time for each event are included in Appendix F or this report.

10. Procedure for Calculating Basin-Specific PMP

The gridded PMP datasets provided with this study are designed to allow for the calculation of basin-average PMP depths for drainage basins within the project domain. Although not required, it is recommended that ESRI's ArcGIS 10.x (or later) software be used to aid in the extraction of the gridded data for a given drainage basin. It is also recommended that the user have a basic familiarity with the operation of this software.

Since PMP is calculated at specific standard area sizes, the user may need to interpolate depths for their basin size using the available bounding area size PMP depths. For example, consider a 125-square mile drainage basin. PMP for 100- and 200-square miles are provided, but not specifically for 125-square miles. The 125-square mile PMP can be interpolated from the bounding 100- and 200-square mile values. In this example the user would take 75% of the 100-square mile PMP and 25% of the 200-square mile PMP and derive the 125-square mile value. In addition, PMP values on a Depth-Area graph are not always linear. Therefore, it may be useful to do a non-linear curve fit to the surrounding PMP values for four or more area sizes. This would be most useful when there is a large difference in area size between the two bounding area sizes available. These data are readily available from the PMP data base.

The following steps are followed to obtain basin average PMP:

1) Create or obtain a polygon shapefile of the drainage basin outline and calculate the basin area. The calculated PMP is the average depth for the area of the basin. The areal reduction is inherent within the PMP development process and *no further areal reduction should be applied*. This is described in Section 9.5.
2) Using ArcMap, for a given duration import the two PMP GRID datasets for standard area sizes that bound the basin area size from step 1.
3) Extract the PMP GRID data to the basin shapefile for both of the bounding area sizes. There are numerous methods for extracting data using ArcGIS and the best approach depends on the experience level and needs of the user and the basin itself. For example, the Extract by Mask tool will effectively clip the GRID to the basin shapefile but will not include any grid cells with their centroids outside the basin boundary. If the basin is very small, the user may want to extract all cells touching the boundary and include part or all of them in the PMP average. The PMP GRIDs can be resampled to a higher spatial resolution before extraction to obtain an extracted dataset that adheres more closely to the basin outline. It is recommended that the user gain a sufficient understanding of the extraction method used.
4) Obtain the mean raster value for the extracted area from the GRID layers at both of the bounding area sizes. These values are the basin-average PMP depth for each of the bounding standard area sizes.
5) Interpolate the basin-size PMP depth from the basin average values obtained in Step 4 for both bounding area sizes. The user can apply a linear interpolation or plot four or

more data points and apply a non-linear curve fit using a Depth-Area analysis. The linear interpolation can be done using equation 10.1:

$$P = \frac{(A-A_1)(P_2-P_1)}{(A_2-A_1)} + P_1 \qquad \text{Equation 10.1}$$

Where,
A_1= smaller-bounding area size (sq. mi.)
P_1 = basin-average PMP for smaller-bounding area size (in.)
A_2 = larger-bounding area size (sq. mi.)
P_2 = basin-average PMP for larger-bounding area size (in.)
A = target basin area size (sq. mi.)
P = interpolated basin-average PMP (in.)

6) (Optional) The PMP GRID datasets provide all-season PMP depths valid for June 15th through September 15th[2]. To apply a cool-season adjustment, multiply the basin average PMP by the seasonal adjustment factor for the appropriate time of year. The monthly seasonal adjustment factors can be obtained from the maps in Appendix G or the Seasonal Adjustment Factor gridded datasets. For large basins, a gridded basin average may be taken by extracting the values with the same process used for PMP extraction. To adjust PMP for a specific date, the adjustment factor can be interpolated between the two bounding months. Snow water equivalent (SWE) depths can then be applied to seasonally adjusted PMP according to hydrologic guidance.

In the event that GIS software cannot be used, basin average PMP depth can be obtained from hard-copy maps by tracing the basin outline and manually estimating an average over the basin domain for the bounding area sizes then following the interpolation process in step 5. Interpolation may not be as accurate as what can be obtained from the GIS datasets, due to the fewer number of standard area sized hard copy maps available.

10.1 Basin Average PMP Calculation

The following steps provide a sample application of the above steps for the calculation of basin average local convective PMP depths at the 1-hour duration for a sample drainage basin.

1) A basin outline shapefile is obtained for the Willow Park Dam drainage basin. The basin area is calculated to be 32-square miles (Figure 10.1).

[2] Note to designers and regulators: The application of seasonal adjustment factors to the selected PMP quantities should be considered if a rain-on-snow event is a possibility in a particular basin or study area as the PMP values derived in this study represent the period June 15 through September 15.

Figure 10.1 Willow Park Dam drainage basin (32-square miles)

2) The 1-hour PMP GRID layers for the bounding standard area sizes of 25-square miles and 50-square miles are added to ArcMap; “L_01_00025” and “L_01_00050”.
3) The Spatial Analyst *Extract by Mask* tool is run for both the 25- and 50-square mile bounding GRID layers using each PMP GRID as the input raster and the basin shapefile as the feature mask (Figure 10.2). The output rasters are ‘snapped’ to original rasters to maintain spatial alignment (Figure 10.3).

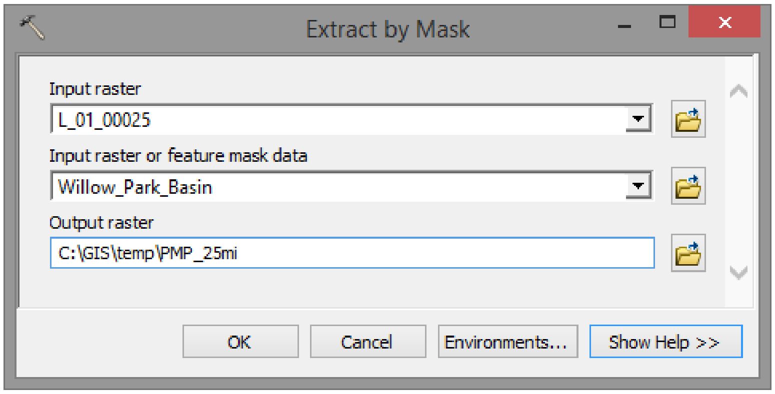


Figure 10.2 *Extract by Mask tool* dialogue

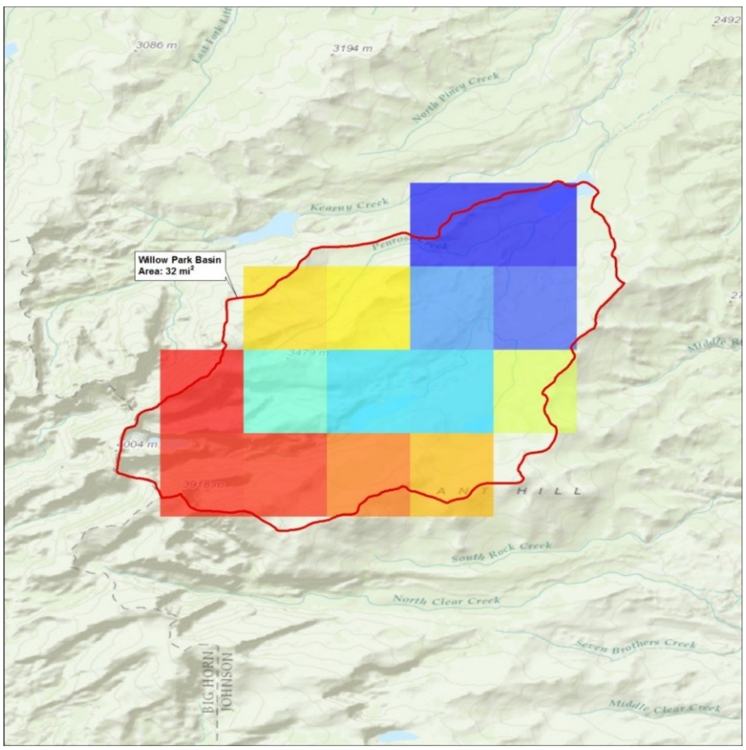


Figure 10.3 Gridded data extracted to basin.

4) The gridded mean value is taken from the layer properties for both of the extracted bounding layers. The 25-square mile basin average PMP is 4.45" and the 50-square mile basin average PMP is 3.76".
5) Equation 10.1 is used to interpolate to the 32-square mile area size:

$$P = \frac{(32mi^2 - 25mi^2)(3.76" - 4.45")}{(50mi^2 - 25mi^2)} + 4.45"$$

$$P = 4.26"$$

The Willow Park Dam 1-hour local storm basin average PMP is 4.26".

11. PMP Sensitivity and Comparisons

The PMP and intermediate data produced for this study was 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. 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 11.1 and 11.2 display sample statewide PMP maps used in this evaluation for 6-hour local storm at the 10-square mile area size and 72-hour general storm at the 100-square mile area size, respectively. Figures 11.3 and 11.4 display the controlling storms by storm type across the entire domain. Often a transposition zone is entirely controlled by a single storm. However, in Figure 11.3 Zones 5 and 6, there are more than one storm controlling these storms in a striped pattern. This is caused when two storms produce total adjusted rainfall values that are very close and the controlling storm can alternate based on small fluctuations in the orographic or moisture adjustment factors (OTF and MTF). In the case of Figure 11.3, the striped pattern is a reflection of the maximum average dew point climatology isotherm pattern. 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.

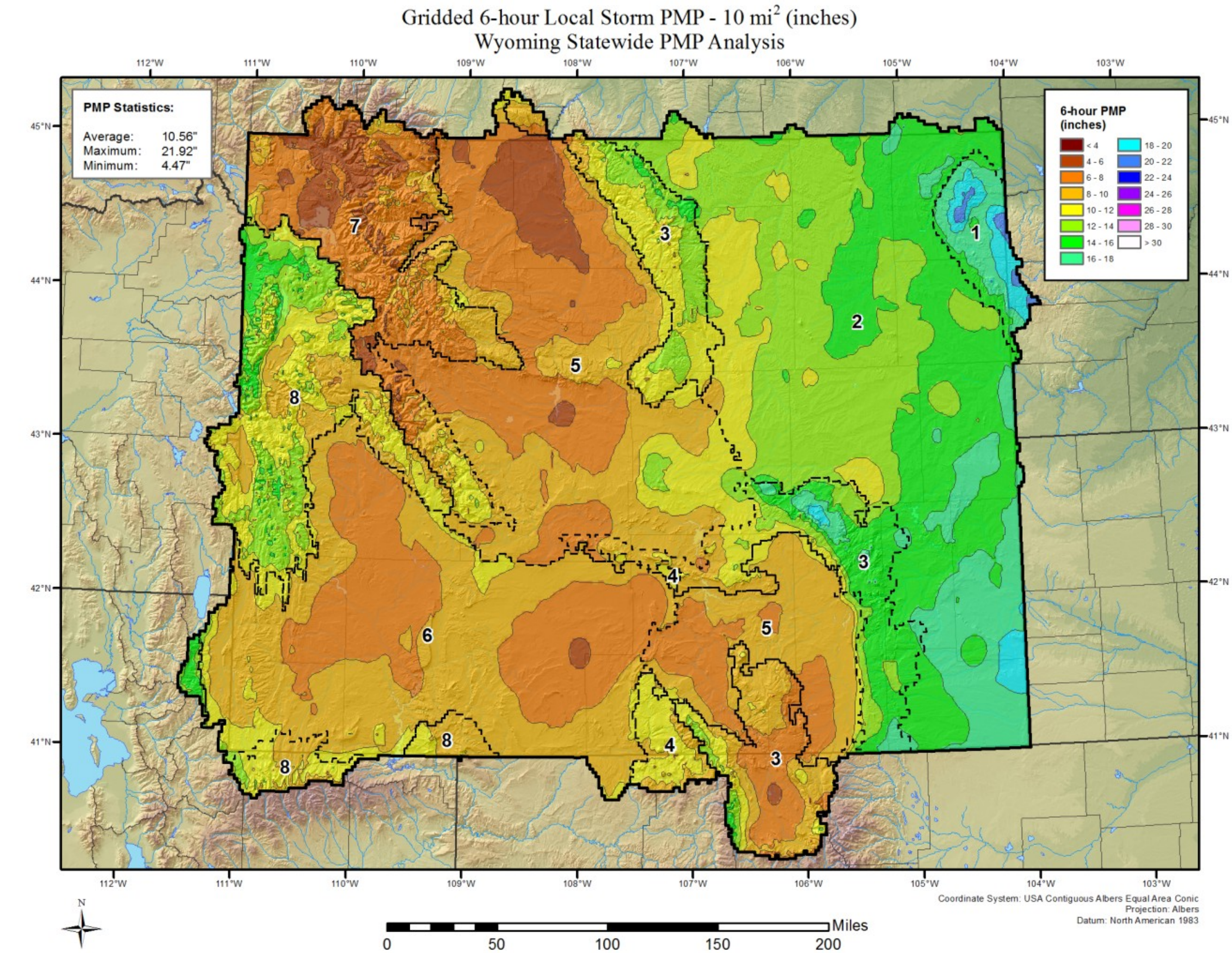


Figure 11.1 Statewide map of the 6-hour, 10-square mile PMP values derived from local/MCS storms

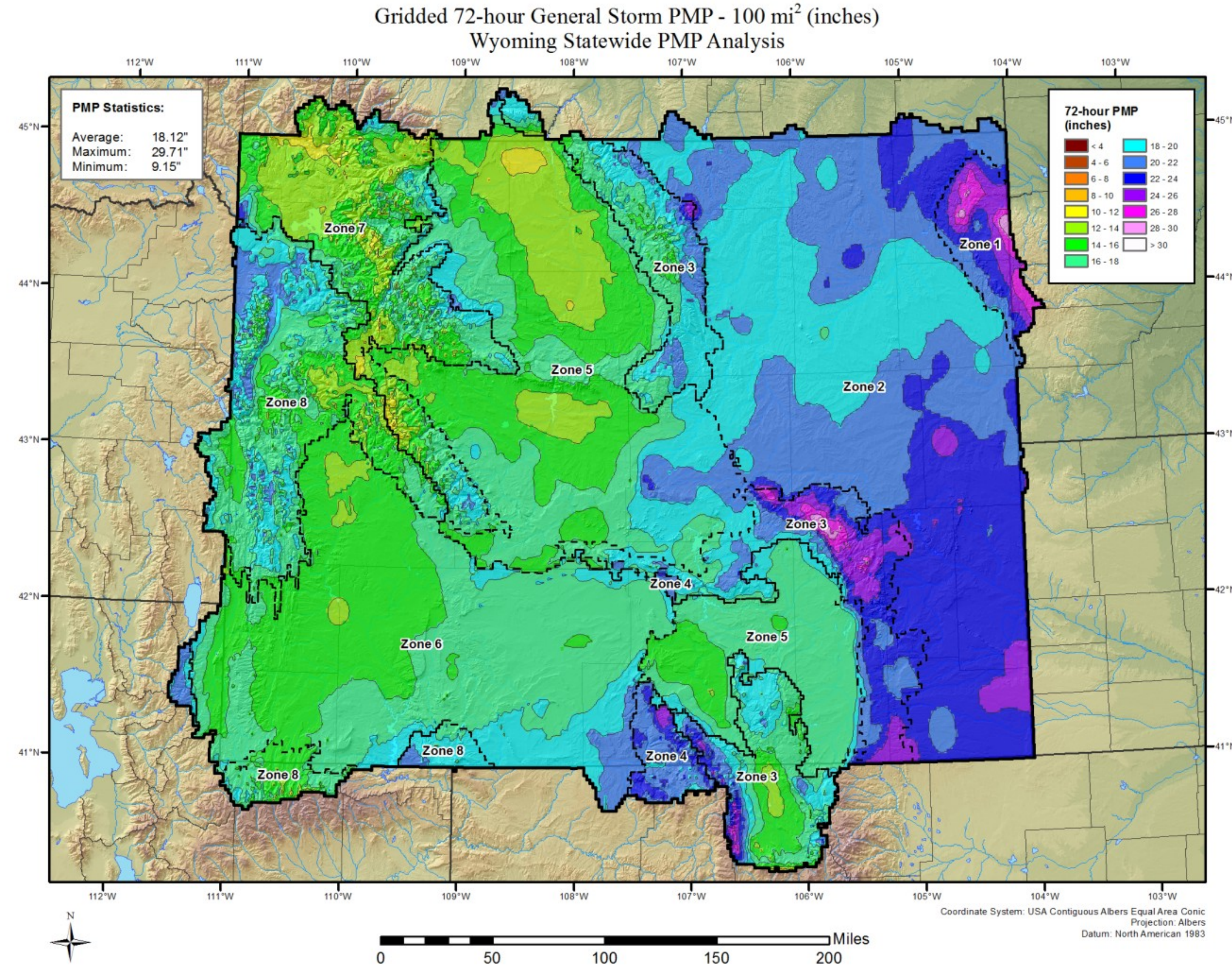


Figure 11.2 Statewide map of the 72-hour, 100-square mile PMP values derived from general storms

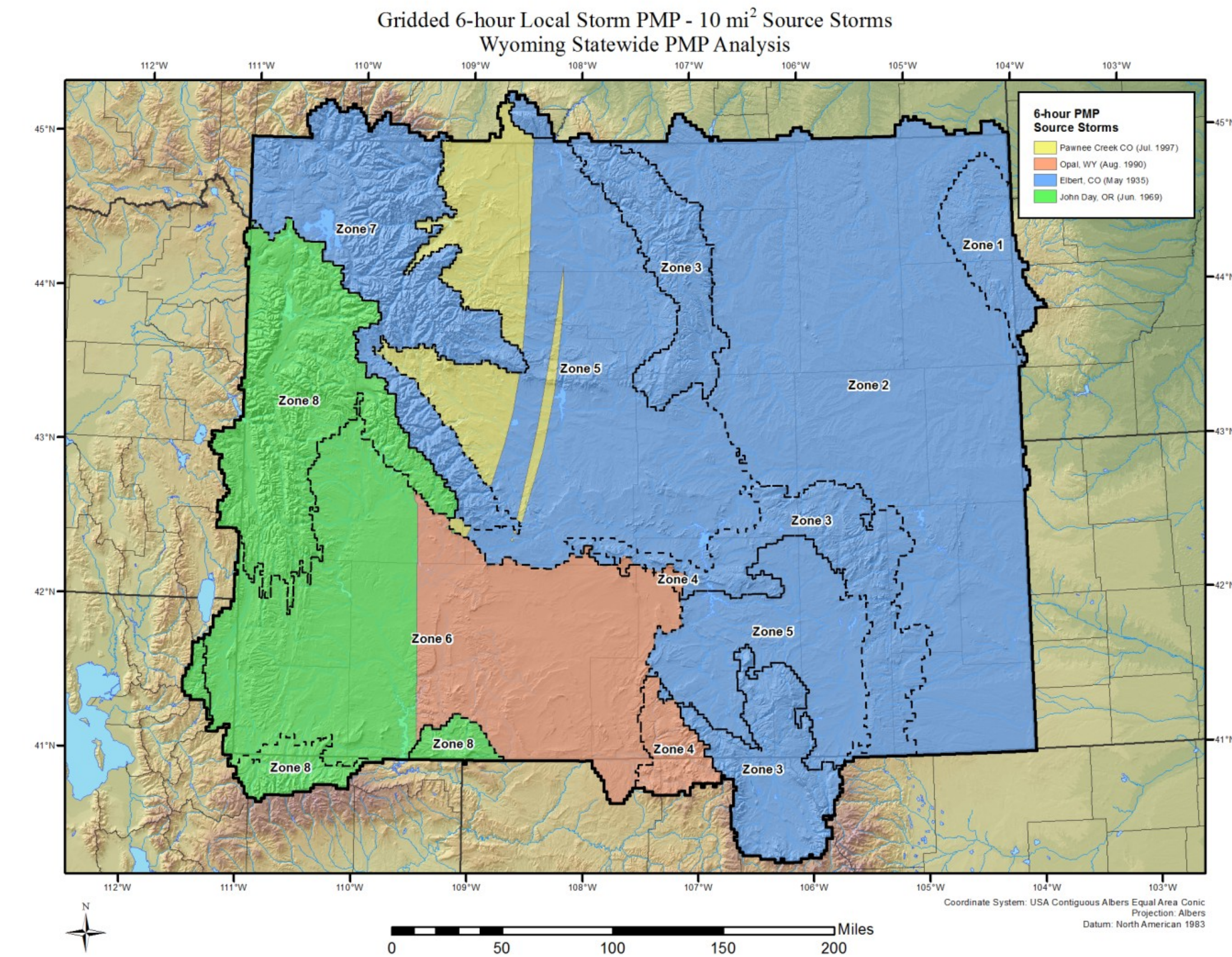


Figure 11.3 Statewide map of the controlling storms of the local/MCS storm type for the 6-hour 10-square mile PMP

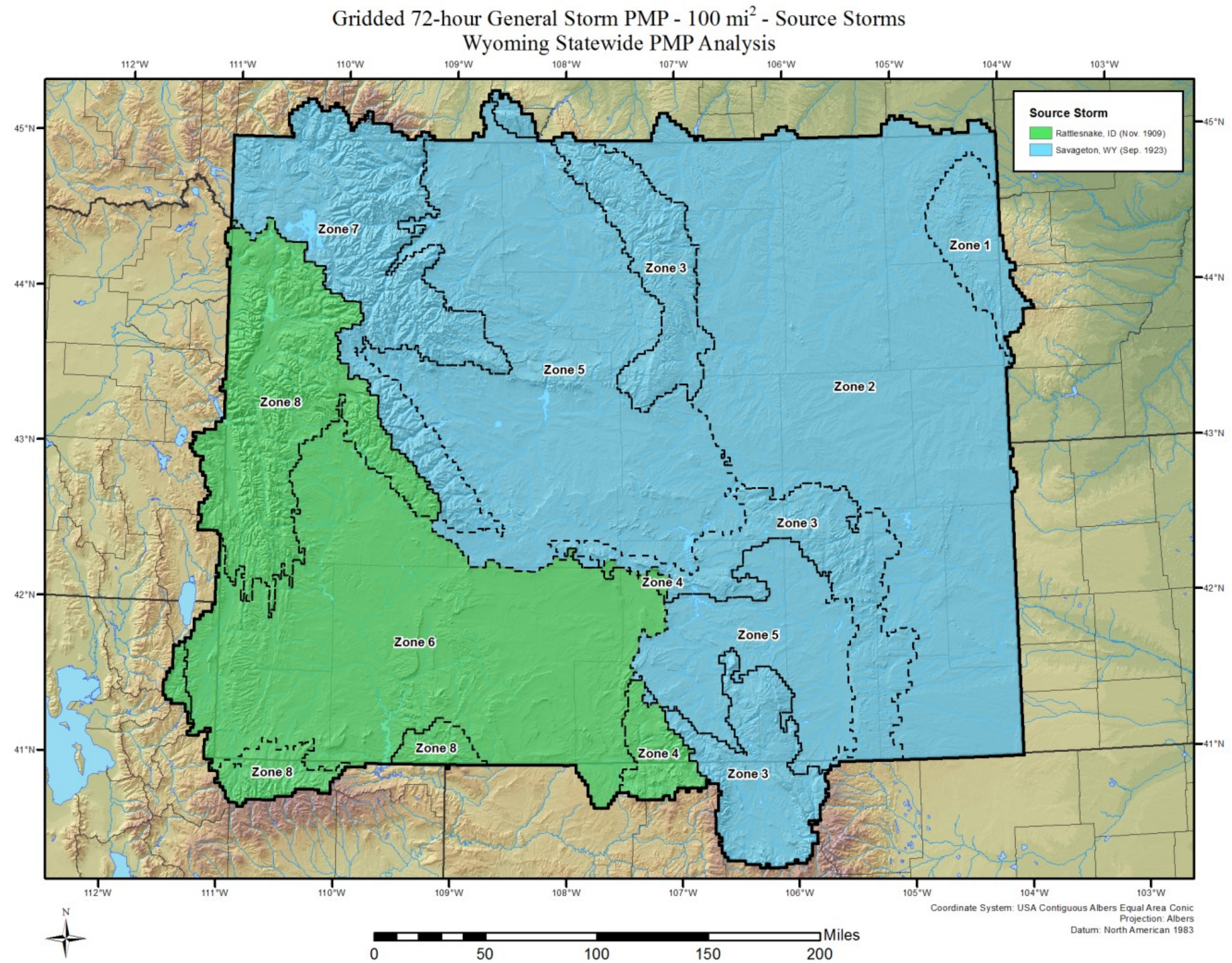


Figure 11.4 Statewide map of the controlling storms of the general storm type 72-hour 100-square mile PMP

11.1 Evaluation of Basin-Specific PMP

PMP was calculated for two sample drainage basins: the Dull Knife basin in the Big Horn Range in north central Wyoming, and the Viva Naughton basin on the southern slopes of the Wyoming Range in western Wyoming. Dull Knife basin has an approximate area of 25-square miles and an average elevation of 9,000 feet. The Dull Knife basin lies entirely within the highly orographic transposition Zone 3. Viva Naughton has an area of 232-square miles and an average elevation of 8,250 feet. This basin is bisected by the highly orographic Zone 8 and the sheltered Zone 6. The basin locations are shown in Figure 11.5.

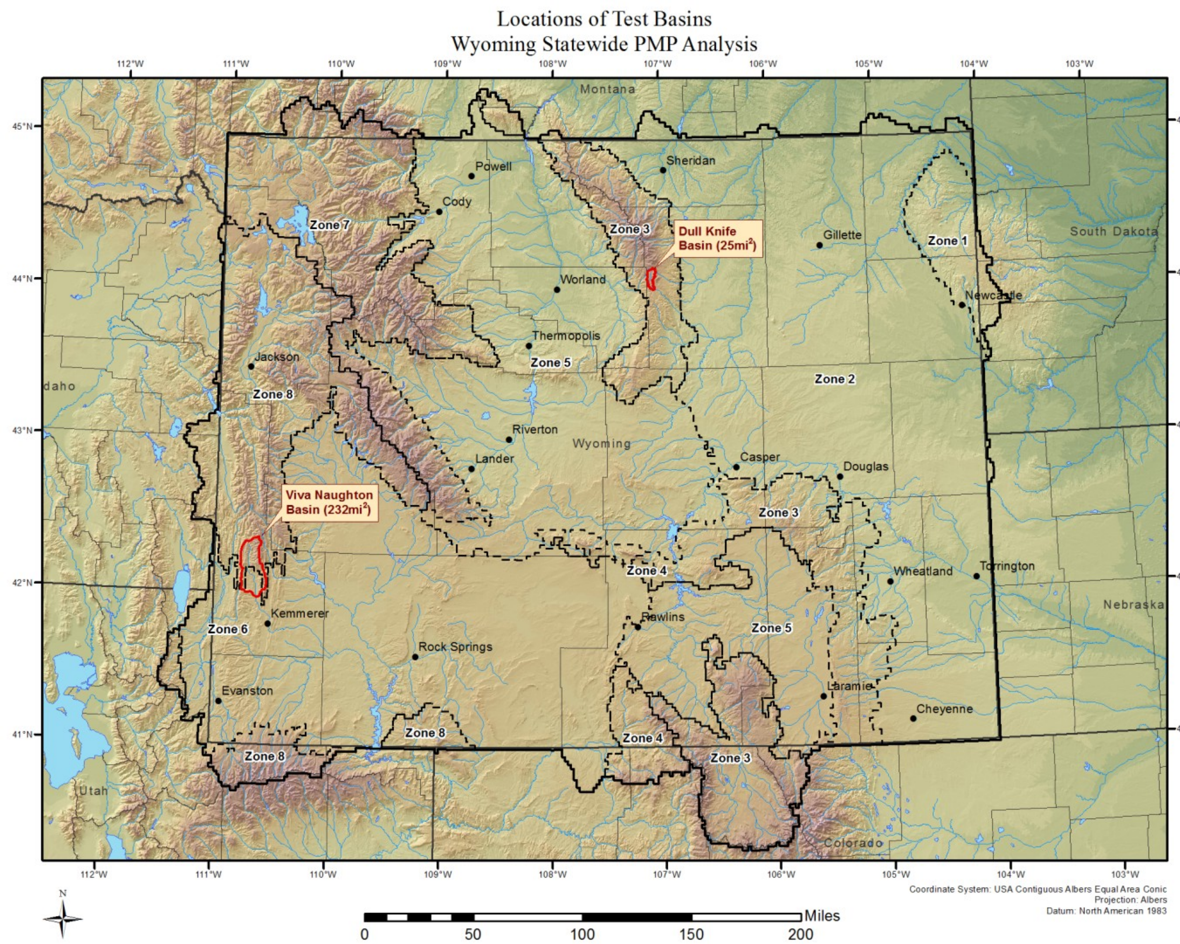


Figure 11.5 Sample basin locations

Gridded PMP values were determined for each basin at their precise area sizes following the methods described in Section 10.1 and tabulated for Dull Knife local storm PMP (Table 11.1), Dull Knife general storm PMP (Table 11.2), Viva Naughton local storm PMP (Table 11.3), and Viva Naughton general storm PMP (Table 11.4). The basin area size PMP depths were calculated using the methods described in the beginning of this section. For durations shorter than 24-hours, local storm PMP provides the largest values, which is to be expected for basins at these locations and at these area sizes. The PMP magnitudes at all durations are within the reasonable range for each storm type.

Table 11.1 Local storm 25-square mile basin average PMP depths and the controlling storms for the Dull Knife basin

	1-hour	2-hour	3-hour	4-hour	5-hour	6-hour	12-hour	24-hour
Basin Average PMP (25 mi^2)	4.21"	5.83"	7.40"	8.01"	8.13"	9.90"	12.91"	13.08"
Source Storm	SPAS 1231 DAD Zone 1 (July 1976 - Big Thompson Canyon, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)

Table 11.2 General storm 25-square mile basin average PMP depths and the controlling storms for the Dull Knife basin

	1-hour	6-hour	12-hour	24-hour	48-hour	72-hour
Basin Average PMP (25 mi^2)	2.85"	8.14"	10.61"	13.76"	17.12"	17.25"
Source Storm	SPAS 1293 DAD Zone 4 (June 1965 - Plum Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1295 DAD Zone 1 (May 1935 - Cherry Creek, CO)	SPAS 1211 (June 1964 - Gibson Dam, MT)	SPAS 1325 (Sep. 1923 - Savageton, WY)	SPAS 1325 (Sep. 1923 - Savageton, WY)

Table 11.3 Local storm 232-square mile basin average PMP depths and controlling storms for the Viva Naughton basin

	1-hour	2-hour	3-hour	4-hour	5-hour	6-hour	12-hour	24-hour
Basin Average PMP (232 mi^2)	6.57"	8.53"	8.53"	8.53"	8.53"	8.53"	8.53"	8.53"
Source Storm	**SPAS 1264** (Aug. 1990 - Opal, WY)	**SPAS 1264** (Aug. 1990 - Opal, WY)	**SPAS 1264** (Aug. 1990 - Opal, WY)	**SPAS 1264** (Aug. 1990 - Opal, WY)	**SPAS 1264** (Aug. 1990 - Opal, WY)	**SPAS 1264** (Aug. 1990 - Opal, WY)	**SPAS 1264** (Aug. 1990 - Opal, WY)	**SPAS 1264** (Aug. 1990 - Opal, WY)

Table 11.4 General storm 232-square mile basin average PMP depths and controlling storms for the Viva Naughton basin

	1-hour	6-hour	12-hour	24-hour	48-hour	72-hour
Basin Average PMP (232 mi^2)	1.01"	4.34"	7.00"	8.14"	13.03"	13.82"
Source Storm	SPAS 1274 (Nov. 1909 - Rattlesnake, ID)	SPAS 1274 (Nov. 1909 - Rattlesnake, ID)	SPAS 1274 (Nov. 1909 - Rattlesnake, ID)	SPAS 1274 (Nov. 1909 - Rattlesnake, ID)	SPAS 1274 (Nov. 1909 - Rattlesnake, ID)	SPAS 1274 (Nov. 1909 - Rattlesnake, ID)

The local storm gridded PMP was mapped over each basin at the 1-hour duration to evaluate the spatial distribution. The gridded PMP values were resampled to a higher spatial resolution to aid with the visualization of the spatial distribution. The spatial distribution is consistent for all durations within a given storm type and is representative of the precipitation or rainfall-only frequency climatology. Figure 11.6 illustrates the 1-hour PMP distributed over the Dull Knife basin. The spatial distribution of PMP values reflects the effect of terrain from the Big Horn Mountains with the majority of the rainfall anchored to the peaks on the northeast side of the basin. These peaks focus the majority of rainfall from the atmosphere and act as a barrier to the remainder of the basin. Previous studies such as HMR 55A were unable to capture the effect of terrain on PMP for a small basin like the one shown in the example. Figure 11.7 illustrates the 1-hour PMP distributed over the Viva Naughton basin. Again, the rainfall is anchored to the terrain as would be expected with the majority of the rainfall over the western ridges which are the first terrain features encountered by moisture as it moves southwest to northeast over the basin. The lowest rainfall occurs over the low-elevation protected areas of the reservoir and the peaks on the northeast side of the basin which are partially protected by the ridges to the west and are at elevations above 9,000 feet.

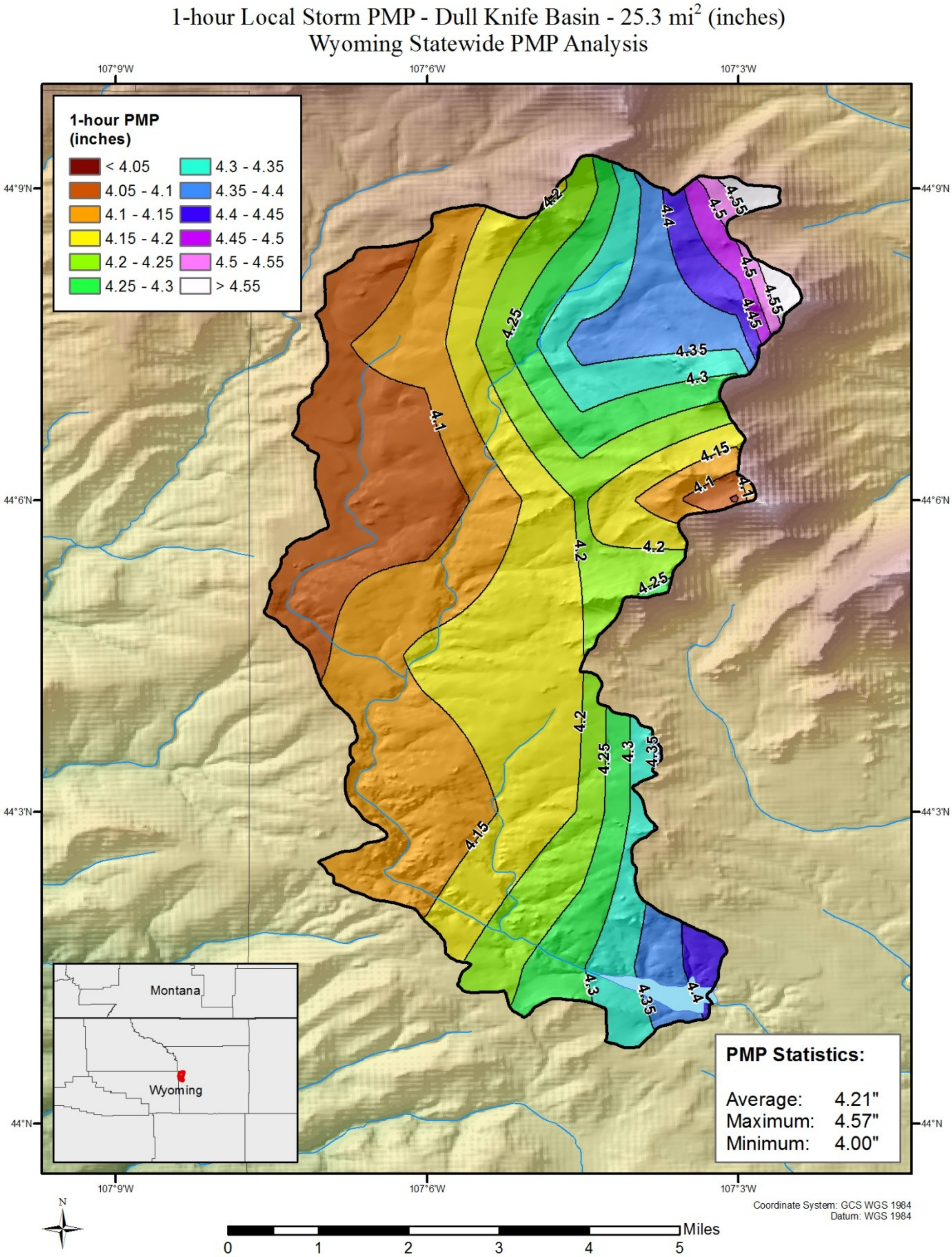


Figure 11.6 Spatial distribution of the 1-hour local storm PMP over the Dull Knife basin

1-hour Local Storm PMP - Viva Naughton Basin - 232 mi^2 (inches)
Wyoming Statewide PMP Analysis

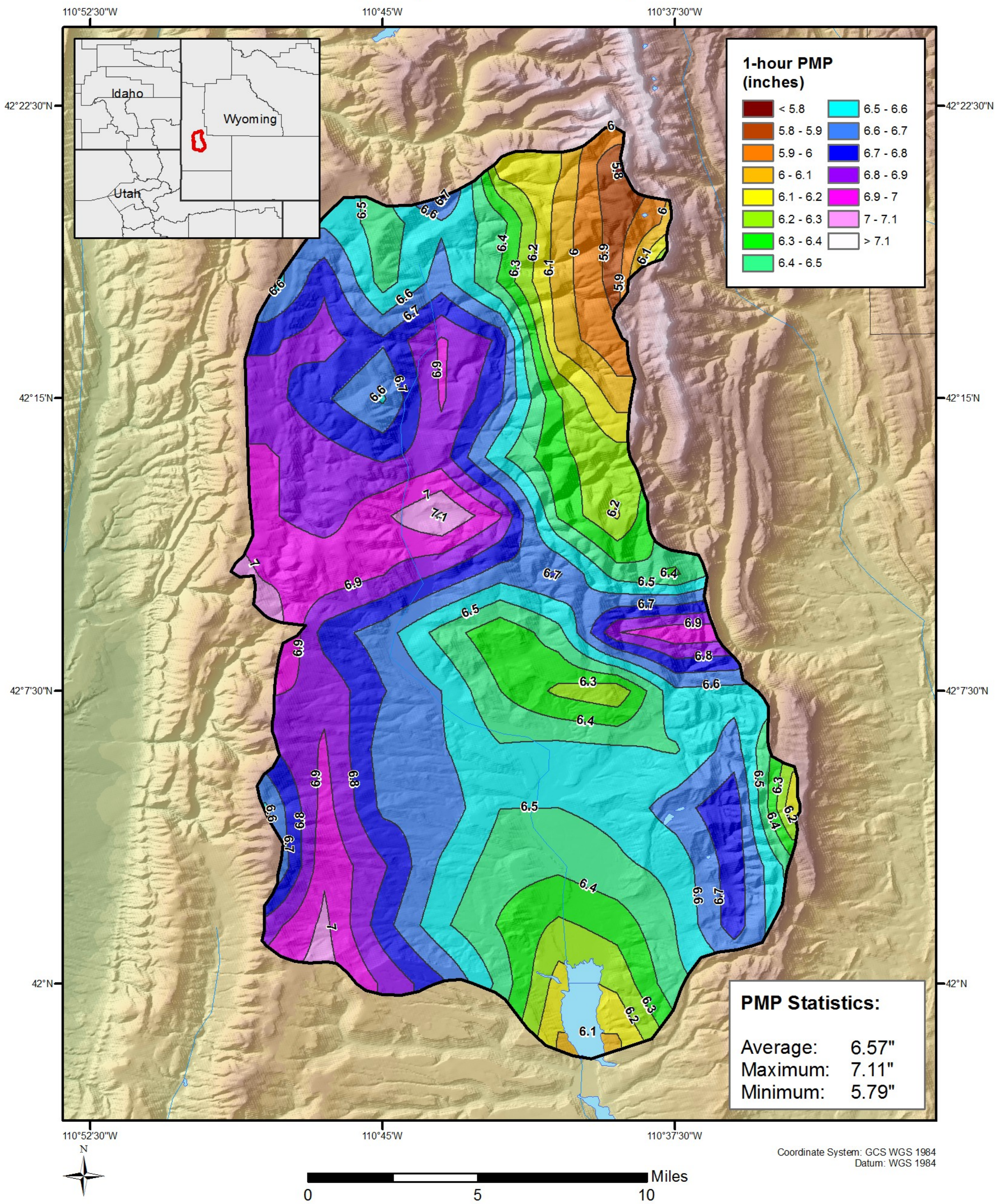


Figure 11.7 Spatial distribution of the 1-hour local storm PMP over the Viva Naughton basin

11.2 Comparison of the PMP Values with Precipitation and Rainfall-Only 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, with values as low as 1.7 and as high as 5.5 for regions east of 117° W 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). HMR 55A presents 100-year 24-hour NOAA Atlas 2 precipitation frequency ratios to 24-hour 10-square mile PMP for Wyoming ranging from 5.0 to 9.8 (HMR55A, p. 210).

For this study the general storm 24-hour 10-square mile PMP was compared directly to the 100-year 24-hour precipitation frequency and rainfall-only 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 11.5 provides the statistics for the comparison with 100-year 24-hour precipitation and Table 11.6 provides the statistics for the rainfall-only depths. The PMP to 100-year return period precipitation ratios vary from 3.4 to 5.1 and the rainfall-only ratios vary from 4.0 to 5.3 and are in reasonable proportion expected for the study area.

Table 11.5 Comparison of general frontal storm 24-hour 10-square mile PMP with 100-year 24-hour precipitation values

Gridded Average by Transposition Zone					
ZONE	NAME	24hr 10mi^2 General PMP (inches)	100yr 24hr Precip (inches)	100yr 24hr Precip Percent of PMP	Ratio of PMP to 100yr 24hr Precip
1	Black Hills	18.59	4.48	24%	4.1
2	Great Plains	15.75	3.89	25%	4.1
3	Eastern Rocky Mountains - East Divide	14.77	3.78	26%	3.9
4	Eastern Rocky Mountains - West Divide	16.21	3.32	20%	4.9
5	Wyoming Basin - East Divide	10.80	3.04	28%	3.6
6	Wyoming Basin - West Divide	12.42	2.55	21%	4.9
7	Western Rocky Mountains - East Divide	12.39	3.52	28%	3.5
8	Western Rocky Mountains - West Divide	12.91	3.33	26%	3.9

Table 11.6 Comparison of general storm 24-hour 10-square mile PMP with 100-year 24-hour rainfall-only values

Gridded Average by Transposition Zone					
ZONE	NAME	24hr 10mi^2 General PMP (inches)	100yr 24hr Rainfall (inches)	100yr 24hr Rainfall Percent of PMP	Ratio of PMP to 100yr 24hr Rainfall
1	Black Hills	18.59	4.26	23%	4.4
2	Great Plains	15.75	3.69	23%	4.3
3	Eastern Rocky Mountains - East Divide	14.77	3.59	24%	4.1
4	Eastern Rocky Mountains - West Divide	16.21	3.15	19%	5.1
5	Wyoming Basin - East Divide	10.80	2.89	27%	3.7
6	Wyoming Basin - West Divide	12.42	2.42	20%	5.1
7	Western Rocky Mountains - East Divide	12.39	3.35	27%	3.7
8	Western Rocky Mountains - West Divide	12.91	3.16	24%	4.1

11.3 Comparison of the PMP Values with HMR PMP Values

Previous PMP values from HMR 49, HMR 51, HMR 55A, and HMR 57 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. The PMP values in this study resulted in a wide range of both reductions and increases as compared to the HMRs.

Figure 11.8 displays the locations where comparisons were made for local/MCS and general storms across the project domain against the appropriate HMR. Table 11.7 provides the results of those comparisons for the local/MCS using the 1-square mile 1-hour PMP values. Table 11.8 provides the results of those comparisons for the general storm using the 10-square mile 24-hour PMP values.

For the local/MCS storms, notice that the HMR 55A values appear to be far too high compared to maximized storm data in the regions where topography creates a rainshadow effect, (i.e. protected interior valleys). This similar pattern occurs with the general storms. The OTF process accurately accounts for these regions and the lack of moisture available to storms. In these situations, the HMR SSM methodology does not allow for values less than 1 and therefore does not properly represent a physically possible storm in these regions where orographic affects would decrease rainfall. The inaccurate HMR 55A PMP values are also reflected internally by a sharp contrast between HMR 55A and HMR 57 where a greater than 50% difference exists between adjacent points between the two HMR's. In contrast, the gradient between AWA PMP values is much less extreme, better reflecting the meteorological gradients expected, and is a function of one process for deriving PMP having been applied consistently across the entire domain.

The large increase in the updated PMP values versus HMR 49 for the general storm type was noted. This is the same result that was found during the Arizona statewide PMP study. This reflects the lack of general storm data that was used in HMR 49, where a total of 5 general storms were used to define PMP across the entire HMR 49 domain. This, in addition to not having an accurate way to quantify the effects of topography, resulted in severe miscalculation of the general storm PMP in HMR 49.

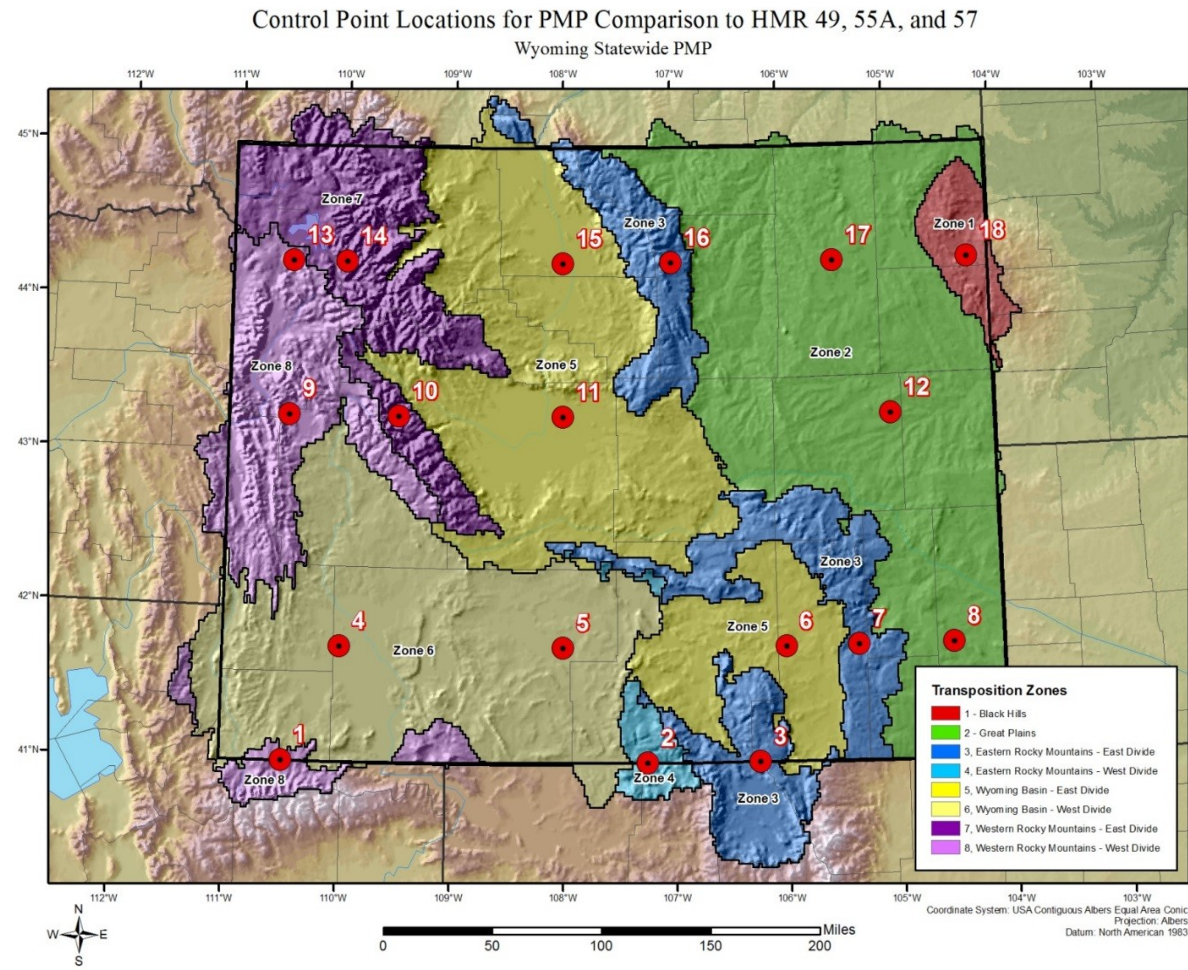


Figure 11.8 Locations used to compare the updated local/MCS storm 1-square mile 1-hour and general storm 10-square mile 24-hour PMP to the appropriate HMR PMP

Table 11.7 Comparisons of Wyoming local storm/MCS PMP values versus the appropriate HMR PMP for 1-square mile 1-hour

Comparison of HMR 49, 55A, 57 local storm PMP to AWA Wyoming local storm PMP over various control points: 1mi² 1-hour								
Control Point	Longitude	Latitude	Trans Zone	Elev_Ft	HMR Source	HMR Local PMP 1mi² 1-hr*	AWA Local PMP 1mi² 1-hr	Percent Change (HMR to AWA)
1	-110.5°	41°	8	9,032	HMR 49	7.2"	7.3"	2%
2	-107.25°	41°	4	6,709	HMR 49	7.8"	7.2"	-8%
3	-106.25°	41°	3	8,921	HMR 55a	7.4"	3.4"	-54%
4	-110°	41.75°	6	6,522	HMR 49	7.9"	5.5"	-30%
5	-108°	41.75°	6	6,785	HMR 55a	8.8"	4.6"	-47%
6	-106°	41.75°	5	6,982	HMR 55a	9.8"	3.5"	-64%
7	-105.35°	41.75°	3	6,450	HMR 55a	10.4"	6.5"	-37%
8	-104.5°	41.75°	2	5,331	HMR 55a	11.1"	7.4"	-33%
9	-110.5°	43.25°	8	6,545	HMR 57	8.4"	6.9"	-17%
10	-109.5°	43.25°	7	9,865	HMR 55a	7.3"	4.1"	-44%
11	-108°	43.25°	5	5,249	HMR 55a	9.6"	2.9"	-70%
12	-105°	43.25°	2	4,613	HMR 55a	10.6"	6.1"	-42%
13	-110.5°	44.25°	8	7,543	HMR 57	7.4"	9.6"	29%
14	-110°	44.25°	7	8,789	HMR 55a	7.4"	3.7"	-50%
15	-108°	44.25°	5	4,055	HMR 55a	9.4"	2.7"	-71%
16	-107°	44.25°	3	8,750	HMR 55a	8.4"	6.2"	-26%
17	-105.5°	44.25°	2	4,603	HMR 55a	10.2"	6.7"	-35%
18	-104.25°	44.25°	1	5,469	HMR 55a	10.6"	8.2"	-23%
*HMR depths adjusted for elevation				Average:		8.9"	5.7"	-35%

Table 11.8 Comparisons of Wyoming general storm PMP values versus the appropriate HMR PMP for 10-square mile 24-hour

Comparison of HMR 49, 55A, and 57 general storm PMP to AWA Wyoming general storm PMP over various control points: 10mi² 24-hour								
Control Point	Longitude	Latitude	Trans Zone	Elev_Ft	HMR Source	HMR General PMP 10mi² 24-hr	AWA General PMP 10mi² 24-hr	Percent Change (HMR to AWA)
1	-110.5°	41°	8	9,032	HMR 49	8.7"	11.7"	34%
2	-107.25°	41°	4	6,709	HMR 49	12.5"	14.7"	17%
3	-106.25°	41°	3	8,921	HMR 55a	19.5"	10.6"	-46%
4	-110°	41.75°	6	6,522	HMR 49	7.5"	11.3"	50%
5	-108°	41.75°	6	6,785	HMR 55a	16.5"	12.2"	-26%
6	-106°	41.75°	5	6,982	HMR 55a	21.0"	12.1"	-43%
7	-105.35°	41.75°	3	6,450	HMR 55a	27.5"	16.1"	-41%
8	-104.5°	41.75°	2	5,331	HMR 55a	30.0"	17.0"	-43%
9	-110.5°	43.25°	8	6,545	HMR 57	9.0"	11.4"	27%
10	-109.5°	43.25°	7	9,865	HMR 55a	26.5"	8.9"	-66%
11	-108°	43.25°	5	5,249	HMR 55a	19.5"	8.6"	-56%
12	-105°	43.25°	2	4,613	HMR 55a	29.0"	16.8"	-42%
13	-110.5°	44.25°	8	7,543	HMR 57	14.5"	15.2"	5%
14	-110°	44.25°	7	8,789	HMR 55a	21.8"	12.3"	-44%
15	-108°	44.25°	5	4,055	HMR 55a	16.9"	8.8"	-48%
16	-107°	44.25°	3	8,750	HMR 55a	26.2"	17.5"	-33%
17	-105.5°	44.25°	2	4,603	HMR 55a	28.1"	17.3"	-38%
18	-104.25°	44.25°	1	5,469	HMR 55a	29.0"	18.2"	-37%
				Average:		20.2"	13.4"	-24%

11.4 Comparison of the PMP Values with Nebraska PMP Values

In addition to the comparison with the HMR PMP values, a comparison was made against the PMP values computed during the Nebraska statewide PMP study complete by AWA in 2008 (Tomlinson et al., 2008). Comparisons were made at the two grid point locations located within the state of Wyoming (Figure 11.9) for areas sizes up to 1000-square miles at the 6-, 12-, 24-, 48-, and 72-hour durations (Table 11.9 and Table 11.10) . Unfortunately, several factors made direct comparisons less meaningful. Reasons for this include the fact that manual smoothing was applied to the Nebraska PMP development with an emphasis applied to resolving PMP values within the state of Nebraska only. Therefore, storms more relevant for eastern Wyoming such as Cherry Creek, CO, May 1935 and Penrose, CO, June 1921 were not included, while storms specific to Nebraska influenced values in eastern Wyoming. This resulted in the Nebraska PMP values being larger for than the Wyoming PMP values at 24-hours and less. In contrast, the addition of the updated SPAS analysis of the Savageton, WY, September 1923 and Crystal Lake, MT, May 2011 storms results in Wyoming PMP values being larger than the Nebraska values at the 72-hour duration. Finally, because orographic effects were not relevant for Nebraska, no attempt was made to utilize the OTF. In contrast, the OTF calculation was completed for all locations within the Wyoming project domain. Therefore, differences are to be expected where the two studies overlap in the Wyoming project domain. The average difference of all area sizes and durations compared for grid point 12 was an 11% increase and for grid point 18, a 6% decrease. These results are within the expected range given the differences in emphasis on storm types between the two studies and the way PMP values were developed.

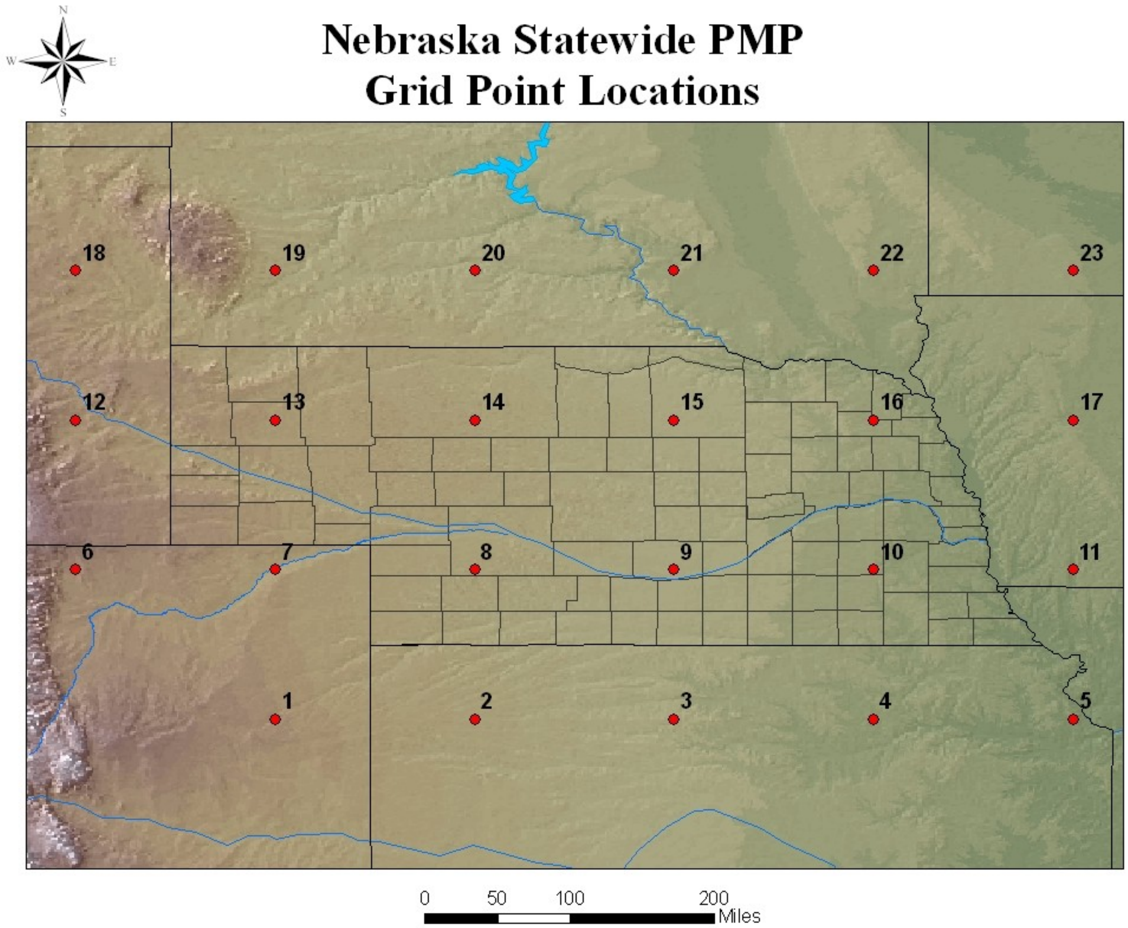


Figure 11.9 Grid points used for PMP development in the Nebraska PMP study. Grid points 12 and 18 in eastern Wyoming were used for comparisons against the Wyoming PMP values.

Table 11.9 Comparison of PMP values at grid point 12 and the Nebraska PMP study

Nebraska PMP: Grid Point #12 [42.25°, -105.00°]					
	6-hour	12-hour	24-hour	48-hour	72-hour
10 SQMI	16.2	17.5	17.5	18.8	18.8
100 SQMI	12.6	14.6	15.0	17.7	17.7
200 SQMI	10.6	12.8	13.5	16.9	17.1
500 SQMI	8.0	10.0	10.9	15.1	15.6
1K SQMI	6.2	8.1	9.2	13.2	13.8
Wyoming PMP: Grid Point #12 [42.25°, -105.00°]					
	6-hour	12-hour	24-hour	48-hour	72-hour
10 SQMI	13.2	17.2	17.2	24.5	24.7
100 SQMI	9.8	12.0	13.7	22.8	23.2
200 SQMI	9.5	10.9	13.1	22.0	22.2
500 SQMI	9.1	10.0	11.5	19.6	20.1
1K SQMI	8.6	9.4	9.9	16.9	17.3
Percent Difference					
	6-hour	12-hour	24-hour	48-hour	72-hour
10 SQMI	-18.3%	-1.7%	-1.7%	30.3%	31.2%
100 SQMI	-22.4%	-17.9%	-8.5%	28.9%	31.2%
200 SQMI	-10.6%	-15.1%	-3.0%	30.0%	30.1%
500 SQMI	13.5%	0.1%	5.5%	29.8%	28.9%
1K SQMI	39.2%	16.3%	7.6%	28.2%	25.4%

Table 11.10 Comparison of PMP values at grid point 18 and the Nebraska PMP study

Nebraska PMP: Grid Point #18 [43.75°, -105.00°]					
	6-hour	12-hour	24-hour	48-hour	72-hour
10 SQMI	17.0	18.3	18.3	18.3	18.3
100 SQMI	13.2	15.3	15.5	17.1	17.4
200 SQMI	11.5	13.4	13.7	16.2	16.8
500 SQMI	8.9	10.4	10.9	14.4	15.2
1K SQMI	7.0	8.5	9.1	12.8	13.5
Wyoming PMP: Grid Point #18 [43.75°, -105.00°]					
	6-hour	12-hour	24-hour	48-hour	72-hour
10 SQMI	11.4	14.8	14.8	20.6	20.8
100 SQMI	8.7	10.3	11.6	19.2	19.5
200 SQMI	8.4	9.2	11.0	18.5	18.7
500 SQMI	8.1	8.9	9.7	16.5	16.9
1K SQMI	7.7	8.4	8.8	14.2	14.6
Percent Difference					
	6-hour	12-hour	24-hour	48-hour	72-hour
10 SQMI	-33.2%	-19.3%	-19.3%	12.6%	13.4%
100 SQMI	-34.1%	-32.8%	-25.5%	12.2%	12.3%
200 SQMI	-26.6%	-31.7%	-19.6%	14.1%	11.4%
500 SQMI	-9.2%	-14.4%	-11.2%	14.5%	11.3%
1K SQMI	9.7%	-1.4%	-3.2%	11.3%	7.9%

12. Sensitivity Discussions Related to PMP Derivations

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 are 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.

12.1 Assumptions

12.1.1 Saturated Storm Atmosphere

The atmospheric air masses that provide available moisture to both the historic storm 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 storm and the PMP storm. Limited evaluation of this assumption in the EPRI Michigan/Wisconsin PMP study (Tomlinson 1993) and the Blenheim Gilboa study (Tomlinson et al., 2008) indicated that historic storm atmospheric profiles are generally not entirely saturated and contain somewhat less precipitable water than is assumed in the PMP procedure. It follows that the PMP storm (if it were to occur) would also have somewhat less precipitable water available than the assumed saturated PMP atmosphere would contain. The *ratio* of precipitable water associated with each storm is used in the PMP calculation procedure. If the precipitable water values for each storm are both slightly overestimated, the ratio of these values will be essentially unchanged. For example, consider the case where instead of a historic storm with a storm representative dew point of 70°F having 2.25 inches of precipitable water assuming a saturated atmosphere, it actually had 90% of that value or about 2.02 inches. The PMP procedure assumes the same type of storm with similar atmospheric characteristics for the maximized storm but with a higher dew point, say 76°F. The maximized storm, having similar atmospheric conditions, would have about 2.69 inches of precipitable water instead of the 2.99 inches associated with a saturated atmosphere with a dew point of 76°F. The maximization factor computed, using the assumed saturated atmospheric values, would be 2.99/2.25 = 1.33. If both storms were about 90% saturated, the maximization factor would be 2.69/2.02 = 1.33. Therefore, potential inaccuracy of assuming saturated atmospheres (whereas the atmospheres may be somewhat less than saturated) should have a minimal impact on storm maximization and subsequent PMP calculations.

12.1.2 Maximum Storm Efficiency

The assumption is made that if a sufficient period of record is available for rainfall observations, at least a few storms would have been observed that attained or came close to attaining the maximum efficiency possible in nature for converting atmospheric moisture to rainfall for regions with similar climates and topography. The further 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 in the atmosphere associated with each storm.

There are two issues to be considered. First is the assumption that a storm has occurred that has a rainfall efficiency close to the maximum possible. Unfortunately, state-of-the-science in meteorology does not support a theoretical evaluation of storm efficiency. However, if the period of record is considered (generally over 100 years), along with the extended geographic region with transpositionable storms, it is accepted that there should have been at least one storm with dynamics that approached the maximum efficiency for rainfall production.

The other issue is the assumption that storm efficiency does not change if additional atmospheric moisture is available. Storm dynamics could potentially become more efficient or possibly less efficient depending on the interaction of cloud microphysical processes with the storm dynamics. Offsetting effects could indeed lead to the storm efficiency remaining essentially unchanged. For the present, the assumption of no change in storm efficiency is accepted.

12.2 Parameters

12.2.1 Storm Representative Dew Point and Maximum Dew Point

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^{o}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^{o}F change in either the in-place maximum dew point or the transposition maximum dew point.

For example, consider the following case:

Storm representative dew point:	75^{o}F	Precipitable water:	2.85 "
Maximum dew point:	79^{o}F	Precipitable water:	3.44"

Maximization factor = 3.44"/2.85" = 1.21

If the storm's representative dew point were 74^{o}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^{o}F with precipitable water of 3.29",
Maximization factor = 3.29"/2.85" = 1.15 (a decrease of approximately 5%)

12.2.2 Sensitivity of the Elevation Adjustment Factor to Changes in Storm Elevation

Elevated topographic features remove atmospheric moisture from an air mass as it moves over the terrain. When storms are transpositioned, the elevation of the original storm is used in this study to compute the amount of atmospheric moisture depleted from or added to the storm atmosphere. The absolute amount of moisture depletion or addition is somewhat dependent on the dew point values, but is primarily dependent on the elevation at the original storm location and the elevation of the study basin. The elevation adjustment is slightly less than 1% for every 100 feet of elevation change between the original storm location and the study basin elevation.

For example, consider the following case:

Maximum dew point:	79^{o}F
Study basin elevation:	100 feet
Historic storm location elevation:	500 feet
Precipitable water between 1000mb and the top of the atmosphere:	3.44 inches
Precipitable water between 1000mb and 100':	0.03 inches
Precipitable water between 1000mb and 500':	0.15 inches

Elevation Adjustment Factor = (3.44"-0.03")/(3.44"-0.15") = 1.04 (about 1% per 100 feet)

If the historic storm location elevation were 1,000', the precipitable water between 1000mb and 1,000' is 0.28"
Elevation Adjustment Factor = (3.44"-0.03")/(3.44"-0.28") = 1.08 (about 1% per 100 feet)

13. Recommendations for Application

13.1 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 state of Wyoming. 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 together 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.

13.2 Climate Change Assumptions

The effect of climate change on the number and intensity of extreme rainfall events in the state of Wyoming 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 using values from this project. Based on these discussions, it is apparent that the current practice of PMP determination should *not* be modified in an attempt to address potential changes associated with climate change. 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).

13.3 Future Work Requirements

Although this study was comprehensive in its development and calculation of PMP values, there remain several related areas which could use further analysis and study.

Temporal distributions can be thought of as the time order in which incremental PMP amounts are arranged within a PMP storm. Initial analysis of the temporal accumulations of the PMP rainfall began during this work. This is an important aspect for properly determining the PMF where PMP values are distributed over time and the total analysis duration in question. Analysis should continue using the storm data derived in this study to determine whether any adjustments to current guidelines are warranted. This could potentially be by storm type and storm location and vary east and west of the Continental Divide. The underlying principal would be that the guidelines would be storm-based using the storms in this study and therefore most accurately represent temporal distributions expected to occur with Wyoming PMP-type storms.

At present, Wyoming does not possess any rules or regulations that specify such criteria to designers. In the past, Wyoming has been deferring to the NRCS and its guidelines. The NRCS design manual, TR-60, Earth Dams and Reservoirs, provides a cumulative temporal distribution curve that has been used by Wyoming in the past (NRCS, 2005). Given these updated PMP values, it is questionable whether this curve is still appropriate for use in Wyoming as design criteria.

Further study is required to fully analyze temporal distributions and determine applicability for use in Wyoming as design criteria. Storms that are found to be controlling PMP values must be analyzed in terms of their original temporal distributions and potential applicability for use in Wyoming as specified design criteria. Previously used curves must also be reexamined in terms of continual use and updated as needed. The project team should consist of a broad oversight committee including AWA, WWDO, NRCS, SEO, safety of dams officials, climatologists and meteorologists, and design engineers each having experience and expertise in performing hydrologic studies in Wyoming. The goal of the project would be to appropriately capture reasonable temporal distributions based on controlling PMP storms, storm types, and storm durations that could be used by Wyoming as design criteria

Initial analysis of the temporal accumulations of the PMP rainfall began during this work and is ongoing. This is an important aspect to properly determine the PMF. Analysis should continue using the storm data derived in this study to determine whether any adjustments to the current guidelines are warranted. This could potentially be by storm type and storm location and vary east and west of the Continental Divide. The underlying principal would be that the guidelines would be storm-based using the storms in this study and therefore most accurately represent temporal distributions expected to occur with Wyoming PMP-type storms.

Another area of future study that would improve the usefulness of this work would be to develop explicit cool-season PMP values. These would replace the seasonality adjustments that were developed in this study. The cool-season PMP would be developed using explicit cool-season rainfall events in the same way the all-season (June 15-September 15) PMP values were developed. Along with the cool-season PMP, two components could be developed which would help determine the amount of snow available coincident, expressed as snow water equivalent (SWE) with the cool-season PMP rainfall and how much of that snow melts during the cool-season PMP rainfall. Explicit values of SWE by location and season could be derived based on data from various locations within Wyoming. Additionally, investigations of the hourly temperature, dew point, and wind speed which occur prior to, during, and immediately following the cool-season PMP rainfall could be derived from the meteorological environment associated with the storms used to develop the cool-season PMP values.

The field of paleohydrology can provide a valuable dataset of past flood peak and information on flood hydrology at high elevations. Investigations should be undertaken to derive paleoflood data in as many regions of Wyoming as possible. This data would help support and put in context the PMP values derived in this study and supply an independent dataset which could be used in assessing the PMP values and expanding the historical storm record especially in high elevation and data sparse regions.

Finally, increasing the number of meteorological and hydrological observation locations across the state is critical to capturing the rainfall and flood events that will occur in the future. These data are the foundation for being able to assess storms and floods in relation to PMP and to update and add to the database developed during this work.

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