Climatology of Extreme Daily Precipitation in Colorado and Its Diverse Spatial and Seasonal Variability

KELLY MAHONEY,* F. MARTIN RALPH,+ KLAUS WOLTER,* NOLAN DOESKEN,# MICHAEL DETTINGER,@ DANIEL GOTTAS,& TIMOTHY COLEMAN,* AND ALLEN WHITE&

*Cooperative Institute for Research in Environmental Sciences, Boulder, Colorado
+Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California
#Colorado State University, Fort Collins, Colorado
@U.S. Geological Survey, and Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California
&Physical Sciences Division, NOAA/Earth System Research Laboratory, Boulder, Colorado

(Manuscript received 10 June 2014, in final form 18 November 2014)

ABSTRACT

The climatology of Colorado's historical extreme precipitation events shows a remarkable degree of seasonal and regional variability. Analysis of the largest historical daily precipitation totals at COOP stations across Colorado by season indicates that the largest recorded daily precipitation totals have ranged from less than 60 mm day^{-1} in some areas to more than 250 mm day^{-1} in others. East of the Continental Divide, winter events are rarely among the top 10 events at a given site, but spring events dominate in and near the foothills; summer events are most common across the lower-elevation eastern plains, while fall events are most typical for the lower elevations west of the Divide. The seasonal signal in Colorado's central mountains is complex; high-elevation intense precipitation events have occurred in all months of the year, including summer, when precipitation is more likely to be liquid (as opposed to snow), which poses more of an instantaneous flood risk. Notably, the historic Colorado Front Range daily rainfall totals that contributed to the damaging floods in September 2013 occurred outside of that region's typical season for most extreme precipitation (spring–summer). That event and many others highlight the fact that extreme precipitation in Colorado has occurred historically during all seasons and at all elevations, emphasizing a year-round statewide risk.

1. Motivation

Colorado's vulnerability to extreme precipitation was highlighted in the record-breaking floods of September 2013. Unusually widespread and long-lasting rainfall led to 10 fatalities, ~$3 billion worth of damage, washed-out highways, and isolated communities and triggered 18 federal disaster declarations across the Colorado Front Range (M. Trost, Colorado Department of Public Safety, 2014, personal communication). While the September 2013 floods were extraordinary in terms of societal impacts and precipitation records, the event's occurrence more than one month after the typical monsoonal peak was an additional anomalous aspect of note (Gochis et al. 2015; Hoerling et al. 2014; National Weather Service 2014). Colorado is known for dramatic climate and weather extremes (e.g., Hansen et al. 1978), and this recent 2013 flood event, along with increasing pressure to consider weather and climate change information in many decision-making frameworks (e.g., Lukas et al. 2014), renews motivation to study the seasonal cycle of the state's heavy precipitation climatology.

Realized in both seasonal averages and short-lived events, the interaction of winds, water vapor, and atmospheric forcing with Colorado's extreme topographic complexity produces remarkable precipitation variation over small spatial scales. Heavy or extreme precipitation events in particular are tremendously variable and notoriously hard to analyze because of their infrequent occurrence. Characterization of extreme precipitation is also hampered by observational limitations and difficulties in many of the state's remote areas, and many past studies have grappled with adequate representation of such events and the uncertainties in the reliability of observations (e.g., Hansen et al. 1978; Hansen et al. 1988; McKee and Doesken 1997, hereafter MD97; Cotton et al. 2003).

Corresponding author address: Kelly Mahoney, CIRES, 325 Broadway, R/PSD1, Boulder, CO 80305.
E-mail: kelly.mahoney@noaa.gov

DOI: 10.1175/JHM-D-14-0112.1

From a practical perspective, water resources managers and other stakeholders need information about heavy precipitation for both short- and long-term planning. On seasonal and subseasonal time scales, reservoir operations are modified to accommodate precipitation and runoff forecasts. Longer-term regulations and planning for structural and operational safety of dams and other water management infrastructure are commonly based on theoretical estimates of probable maximum precipitation (PMP) that might fall during each season of the year. While reference documents and procedures have existed for decades to estimate extreme precipitation potentials in this region (e.g., Hansen et al. 1988; Cotton et al. 2003; Perica et al. 2013), recent events (most notably, the extraordinary Front Range flooding of 2013) have highlighted gaps in our understanding of extreme precipitation in Colorado, particularly with respect to the seasonality of extreme precipitation, elevation limits on heavy rainfall, and the types of weather systems that produce such events.

Furthermore, to facilitate analysis where observations are lacking, water resources planners and dam safety engineers regularly regionalize from nearby sites to fill in gaps in networks. Locations with short or nonexistent records may therefore be represented by nearby locations with very different seasonal and daily precipitation characteristics. That is, precipitation maxima estimated from one station or season may be quite inapplicable when applied at other, even nearby, locations in Colorado's complex terrain. Climate change offers additional motivation for understanding heavy precipitation climatologies. To understand how extreme precipitation frequencies and intensities are changing or may change in the future, a robust understanding of historical seasonality and regional variability is a critical starting point (e.g., Kunkel et al. 2012).

This paper documents the seasonality and geographic variability of extreme historical daily precipitation totals across Colorado. Here, extreme refers to the largest daily (24-h total liquid equivalent) precipitation events in the available data, although semantics to describe such events differ in some engineering and stakeholder communities (e.g., Bonnin et al. 2011). A simple analysis method developed in Ralph et al. (2014) to document the general seasonality of precipitation extremes across the western United States is used here. The largest 10 daily precipitation totals during periods of record at each long-term Cooperative Observer (COOP) site are analyzed. In Ralph et al. (2014), these most extreme events were found to have fairly uniform seasonality across large regions of the western United States, but Colorado (and Nevada) showed exceptionally large spatial variability (see their Fig. 3a). This paper examines the geographical variability of extreme precipitation in Colorado in greater detail and compares the historical record with the recent Front Range storms of 2013 (Gochis et al. 2015; Hoerling et al. 2014). The present analysis is purposefully constrained to use a single, reliable data source such that these baseline results encourage subsequent work addressing additional components of generalized flood risk (e.g., snowpack, subdaily precipitation intensity, and surface hydrology). Furthermore, while this study aims to represent the diversity and seasonality of extreme precipitation in Colorado, it is not intended to be an exhaustive catalogue of extreme storm events across the state's observed history. For this type of analysis, the reader is directed to MD97, as well as updated individual extreme storm analyses and reports from the Colorado Climate Center.

2. Data and methods

Extreme precipitation events are characterized here using COOP (National Weather Service 1989) reports from Colorado. These stations record the total liquid equivalent of precipitation every day. Among COOP stations in Colorado, 130 met an initial screening criterion of having at least 30 years of daily data between 1950 and 2010 (Fig. 1). At each such station, the 10 largest daily precipitation totals were identified and the statistics of those 10 events were mapped and analyzed.

The analysis here uses daily accumulated liquid-equivalent precipitation totals reported in the summary of the day observations across Colorado. While the COOP network is quite extensive, the spatial distribution of stations still misses many areas that could be prone to extreme precipitation, including many remote mountain areas. Additional uncertainties may arise because COOP daily rainfall may be recorded in the morning or the evening, depending on the volunteer observer; however, all measurements still represent a 24-h total. Caveats concerning precipitation climatologies in general have been discussed in the literature (e.g., Maddox et al. 1979; Brooks and Stensrud 2000; Schumacher and Johnson 2006; Hitchens et al. 2013). To increase confidence that results here are not too sensitive to this COOP data source, we also compared our findings to previous studies that have included other datasets [e.g., MD97, which uses COOP stations with longer (pre-1950) records and Snowpack Telemetry (SNOTEL) sites; Serreze et al. 1999].

We also note that the choice of a daily (24 h) precipitation period predetermines (to some degree) that a specific class of events constitute this analysis, and that shorter- and longer-duration periods would highlight different types of storms and potential hazards. For example, adopting shorter periods would likely highlight summer/convective events more likely to be associated with flash floods, while analysis of longer-duration accumulations

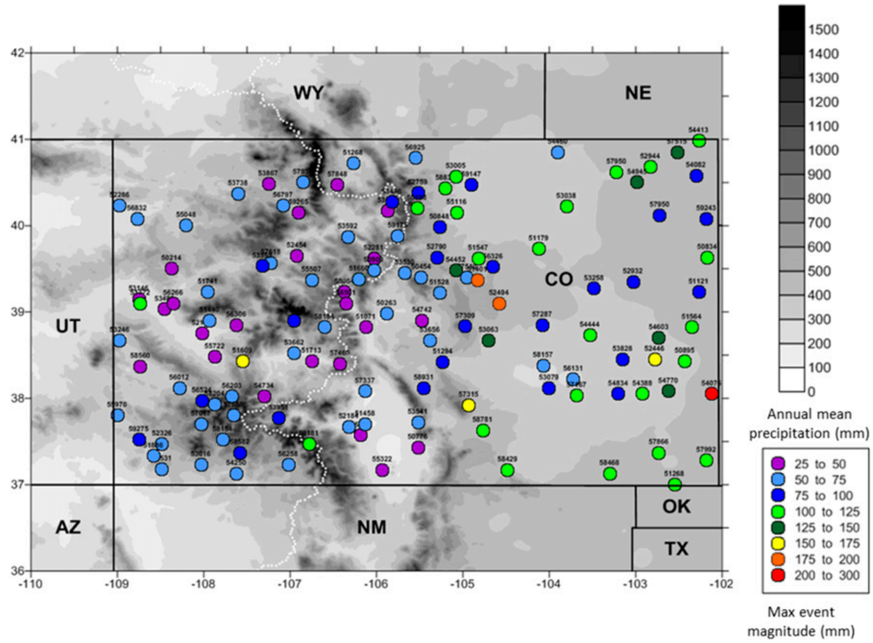

FIG. 1. Max event magnitude (mm) by COOP station for 1951–2010, shaded as in legend at lower right. Annual mean precipitation from PRISM data (http://prism.oregonstate.edu/) based on period of 1981–2010 (mm; gray shading as in legend at upper right). Colorado COOP station ID numbers are listed above circles. Continental Divide is shown by the dashed white line.

would generally illuminate more synoptically driven, persistent cool-season events more likely to be associated with large snowfall in the cool season and/or areal or river flooding in the warm season. Finally, using a different epoch of analysis or a less stringent COOP station selection criteria will also shift results somewhat; there are known pre-1950 extreme events of interest, as well as well-known events [e.g., the Fort Collins flood of 1997 (Petersen et al. 1999)] that occurred at stations not satisfying our requirement of 30 years of consecutive data. Thus, the findings of this study mostly seek to inform questions related to seasonality and spatial diversity. Precipitation totals shown here should not be interpreted to be the absolute maximum amounts observed, as the incorporation of additional datasets and less stringent COOP station selection requirements would certainly reveal higher precipitation event totals in many parts of the state.

3. Results

a. *Seasonality of precipitation extremes*

The historical maximum daily precipitation total at each station is shown in Fig. 1, illustrating the considerable diversity and spread among precipitation extremes in Colorado. Maximum totals (in this purposely constrained selection of sites) range from <60 (mainly at higher elevations) to >250 mm day^{-1} (in the southeast). The largest totals generally occur east of the Continental Divide, likely due to southerly and southeasterly wind regimes that bring moisture into the state along a relatively uninterrupted fetch from the Gulf of Mexico. These general patterns of daily precipitation extremes are consistent with the comprehensive Colorado Extreme Storm Precipitation Data Study prepared by MD97, which included data from both COOP and SNOTEL stations in the mountains, as well as a larger diversity of windows (from >6-h to 3-day totals). The findings of MD97 confirm that in addition to the heaviest events occurring east of the Continental Divide, there is also a tendency for relatively heavy precipitation events in the southwestern part of the state (particularly in the late summer and fall), including at some relatively high-elevation locations (e.g., Wolf Creek Pass and Hermit, Colorado). While MD97 is more comprehensive and considers more events than are analyzed here, the study notes considerable uncertainty regarding the reliability of historic precipitation and flood reports (e.g., 8–9 and appendix B); this corroborates our motivation for electing to constrain the present analysis to the more highly quality-controlled COOP network.

The seasonality of the largest 10 daily precipitation totals for COOP stations in Colorado is illustrated by Fig. 2, indicating significant variation of seasonality

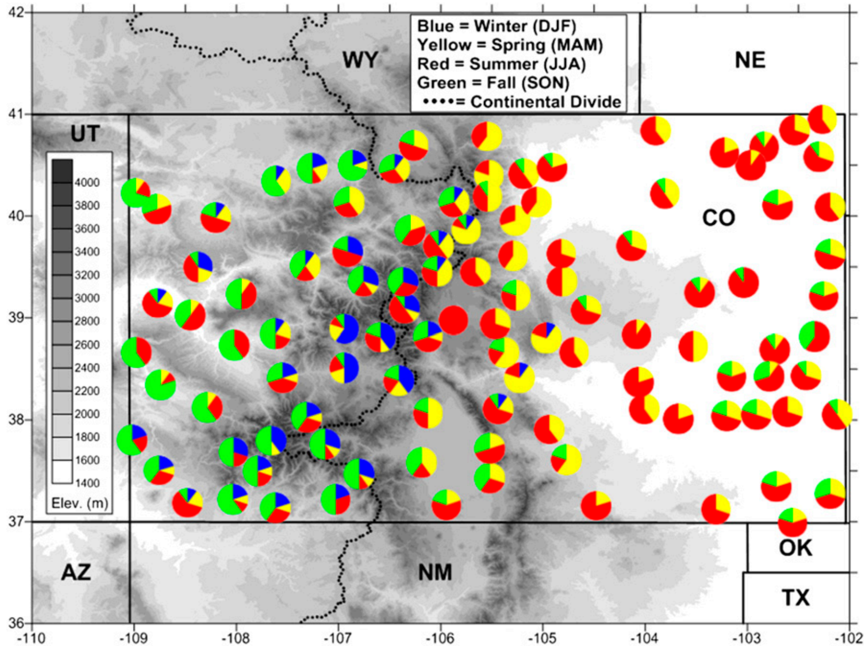

FIG. 2. Seasonality of the top 10 daily precipitation events measured at Colorado COOP stations that have at least 30 years of data since 1950. Circles represent totals of 10 events. Seasons shaded as winter (DJF; blue), spring (MAM; yellow), summer (JJA; red), and fall (SON; green). Terrain elevation (m; gray shading) as in legend at left; Continental Divide shown by dashed black line.

across the state. East of the Continental Divide, winter [December–February (DJF)] events have only yielded the top 10 extremes at a few stations in the Front Range (the region east of the Continental Divide that extends northward from central Colorado and out toward the eastern plains of Colorado). This region gets the plurality of its largest precipitation totals during spring [March–May (MAM)] although some stations even at relatively high elevations east of the Continental Divide (e.g., Antero Reservoir, central Colorado) also have a summer-dominant heavy precipitation seasonality. On the lower-elevation eastern plains (eastward of ~105°W), most of the largest precipitation totals have occurred in summer [June–August (JJA)]. Fall [September–November (SON)] events east of the Continental Divide have been more prevalent toward the southern portion of the eastern slopes and plains.

West of the Continental Divide, a decidedly different seasonality occurs. Given orographic enhancements to precipitation in this high-altitude region from prevailing westerly winds, wintertime precipitation extremes (falling mainly as snow, described more below) have been more common on the western slopes (between ~108° and 106°W longitude), but only dominated at one station (Crested Butte, Colorado, at an elevation of 2700 m). At lower elevations, fall is the dominant season for heavy precipitation west of the Continental Divide, likely stemming from a more active synoptic weather pattern and from larger overall moisture availability (especially when moisture from tropical storm remnants enters Colorado from the southwest) during this season. Southwestern Colorado has experienced more late summer and fall events than northwestern Colorado, and they also have tended to be more intense, with moisture sources generally of tropical origin (e.g., Figs. 1, 2; MD97). Some extreme winter precipitation events in southwestern Colorado have also recently been shown to result from deep-inland penetration of atmospheric rivers from the Pacific coast (Neiman et al. 2013; Rutz et al. 2014; Hughes et al. 2014).

b. Seasonality at highest elevations

High-elevation precipitation extremes are of particular interest from flood risk and climate change perspectives. High-elevation locations are generally characterized by enhanced flood risk due to complex and steep terrain in small, sloped hydrologic catchments. The present analysis shows that close to the Continental Divide, a remarkable mix in the seasonality of extremes emerges. While winters have yielded some top 10 events at stations near the Continental Divide, it has not been the dominant season, and for stations just east of the Divide, summer events have been more common. This is somewhat surprising and challenges the commonly held notion that winter storms produce the heaviest precipitation events at highest elevations. However, severely limited observations at the highest elevations allow that winter precipitation may still be a main contributor in these poorly monitored locations, and also that the winter season may play a larger role in determining the seasonal distribution of precipitation extremes when considering longer (multiple day) storm periods. Additional work and better observations in these areas are needed to more completely resolve these questions. Figure 3 shows the seasonal breakdown of the top 10 precipitation events for the 20 highest-elevation stations in this study, confirming that the relationship between extreme precipitation seasonality and elevation is complex, with all four seasons represented to significantly varying degrees across these highest-elevation stations.

Analyzing the extreme precipitation events by elevation at all stations also shows that heavy precipitation events in excess of 100 mm day^{-1}, while less common, have occurred at even the highest stations included in this study (Fig. 4). Yet, paleohydrologic studies (Jarrett and Costa 1988; Jarrett and Tomlinson 2000) have yielded little evidence of extreme rainfall and flash flooding above 7500 ft (~2300 m) in Colorado. Some of these extreme summer events may have been hailstorms occurring at high elevations (Jarrett and Crow 1988; Cotton et al. 2003), which would lead to less flooding due to a relatively slow melting process and therefore a delayed hydrologic response. In the future, some types of hailstorms may potentially change to rainfall in a warming climate (Mahoney et al. 2012). Discrepancies and open questions such as these prompt additional in-depth studies, particularly subregional and site-specific analyses that can incorporate both hydrologic and precipitation data to more fully characterize flood risk (e.g., England et al. 2014)

While the purpose of this paper is to highlight the seasonality of extreme precipitation in general, the distinction between frozen precipitation (snow, hail, and graupel) and liquid precipitation (rain) implies different associated flood risks. Of the 21 analyzed stations located above 2500 m, ~70% of the top 10 events were likely snow dominated or at least a rain–snow mix, according to a simple surface temperature–based evaluation criteria (e.g., assigning the event to be snow or snow–rain mix if the observed minimum surface temperature was below 2°C; Fig. 5). Thus, the fact that roughly 30% of the events at these high-elevation stations occurred in environments warm enough to have likely been rain stresses that flood risk may not be inherently limited to elevations of 2500 m and lower, as has been suggested by some past studies (e.g., Jarrett 1993; Cotton et al. 2003). Furthermore, many of these locations had some representation of heavy precipitation (both rain and snow) during each season of the year, which corroborates that there is a year-round concern for heavy precipitation impacts in general at high-elevation locations. Clearly, stations with a greater proportion of rain-dominated events face a more probable and direct flood risk from such events, but even locations that receive the majority of their heavy precipitation events as snow also face considerations related to heavy snowfall impacts (risks to safety, life, and property), as well as the hydrologic ramifications of the eventual snowmelt. All of these processes ultimately feed back into water resources decision making and floodplain management.

An important point that bears repeating is that with very few COOP observations even close to treeline (3200–3500 m; Fig. 3) (and even those are often located in protected high interior valleys in relative precipitation shadows; see shading in Fig. 1), this high-elevation-focused aspect of the present climatology requires further investigation. The present analysis also underscores that, in light of the extreme precipitation potential seen in all seasons (Fig. 3) and the fact that historical observations in these high-elevation and often remote locations are sparse (even if the SNOTEL network is considered), improved precipitation monitoring at the highest elevations during all seasons is required to improve the characterization of statewide flood risk (e.g., MD97, 29–32; England et al. 2014). Finally, high-elevation precipitation extremes are of particular interest within the framework of a warming climate because enhanced climate sensitivities have been suggested for higher elevations (e.g., Beniston et al. 1997; Palecki and Groisman 2011); we thus need to better understand present-day elevation-based constraints on heavy rainfall.

c. *Comparison of extreme precipitation seasonalities to seasonal cycles of mean precipitation*

The seasonality of overall precipitation in Colorado is complex. Winter months typically yield the most overall precipitation in the mountains while the eastern plains are at their driest (Fig. 6a). Spring tends to be wettest in the northern Front Range, but driest toward the southwestern corner of the state (Fig. 6b). Moisture transport from the Gulf of Mexico as well as from southerly monsoonal flows contribute most strongly to average rainfall across the eastern plains during summer and least to the precipitation in the northern mountains (Fig. 6c). Fall storms contribute more overall moisture to western valleys (Fig. 6d) while the eastern plains experience marked seasonal drying then (although enhanced variability during the transition months

Station	Location	Elev. (m)	On, E, or W of Cont. Divide	Seasonal pie chart for top 10 precip. events
51660	CLIMAX, CO	3450	On	
59181	WOLF CREEK PASS 1 E, CO	3243	On	
58064	SUGARLOAF RESERVOIR, CO	2968	On	
50909	BRECKENRIDGE, CO	2920	W	
57656	SILVERTON, CO	2840	W	
58184	TAYLOR PARK, CO	2806	W	
58501	TWIN LAKES RES, CO	2803	E	
52281	DILLON 1 E, CO	2763	W	
59175	WINTER PARK, CO	2761	W	
57309	RUXTON PARK, CO	2758	E	
53951	HERMIT 7 ESE, CO	2743	E	
50263	ANTERO RESERVOIR, CO	2719	E	
51959	CRESTED BUTTE, CO	2700	W	
57017	RICO, CO	2682	W	
53496	GRAND LAKE 1 NW, CO	2658	W	
53530	GRANT, CO	2644	E	
58204	TELLURIDE 4 WNW, CO	2643	W	
54734	LAKE CITY, CO	2643	W	
54742	LAKE GEORGE 8 SW, CO	2597	E	
57460	SARGENTS, CO	2579	W	

FIG. 3. Seasonality of the top 10 daily precipitation events measured at Colorado COOP stations that have at least 30 years of data since 1950, ranked by elevation for the highest-elevation 20 stations. Circles represent a total of 10 events at each site, with seasons of events indicated by shading: winter (blue), spring (yellow), summer (red), and fall (green). Location of site relative to the Continental Divide is also indicated.

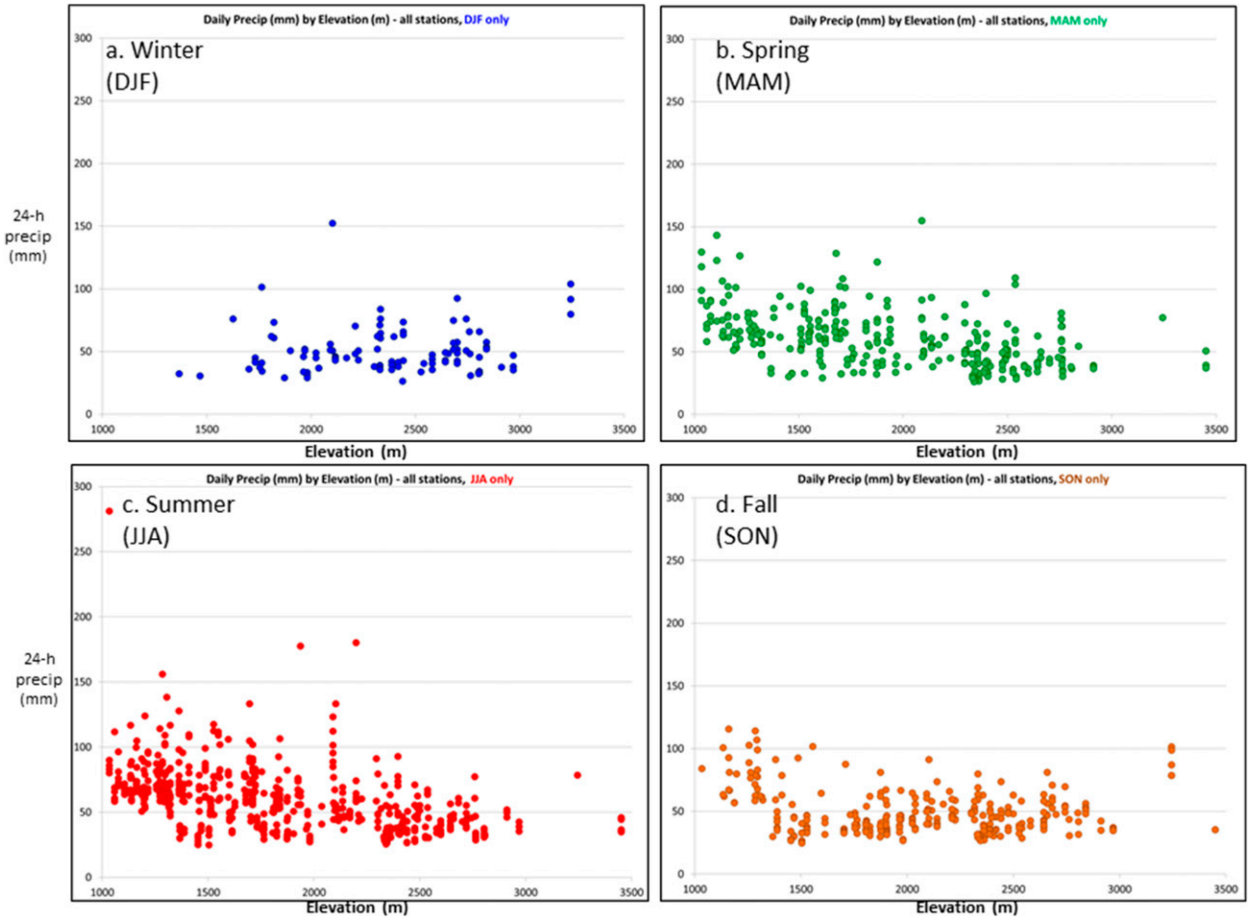

FIG. 4. Seasonal event analysis by station elevation. Each dot represents an individual event by season: (a) winter, (b) spring, (c) summer, and (d) fall. The 24-h precipitation amount is on the y axis (mm) and elevation is on the x axis (m).

of September and October make fall precipitation trends more difficult to generalize).

The seasonalities and spatial distributions of precipitation extremes diverge notably from those of seasonal averages in areas west of the Continental Divide. Red stations in Fig. 7 are where <4 of the top 10 events have occurred during any of the station's climatologically three wettest calendar months and >4 have occurred during the climatologically driest six months, that is, when least expected. Conversely, green stations are where all top 10 daily events have occurred in the wettest three months of the year, thus leaving none during the rest of the year. The stations where extreme events only occur during the wettest time of the year are all east of the Continental Divide.

d. September 2013 Colorado Front Range flooding

In the Colorado Front Range, the heaviest precipitation events have not typically occurred during the fall months of our study period (Fig. 2), which is also not the wettest time of year, on average (Fig. 6d). However, Hansen et al. (1978, their Fig. 8) showed that the Front Range has seen flooding events in September, most famously in September 1938 (Hoerling et al. 2014). Thus not completely unprecedented, from 9 to 16 September 2013, record-breaking precipitation fell in the Front Range (e.g., Colorado Climate Center 2013; Gochis et al. 2015). Daily precipitation records were shattered at six Front Range COOP stations (although no new records were set at COOP stations included in this analysis; Colorado Climate Center 2013). Given the size of this event, inclusion of those record-breaking observations in our seasonality analysis would indeed broaden seasonalities of extreme precipitation events from spring and summer into the fall season in the Front Range area. To highlight some of the noteworthy aspects of this recent event against the longer-term COOP records analyzed here, we elect to compare event details to the 1951–2010 reference period and thus also to maintain study consistency

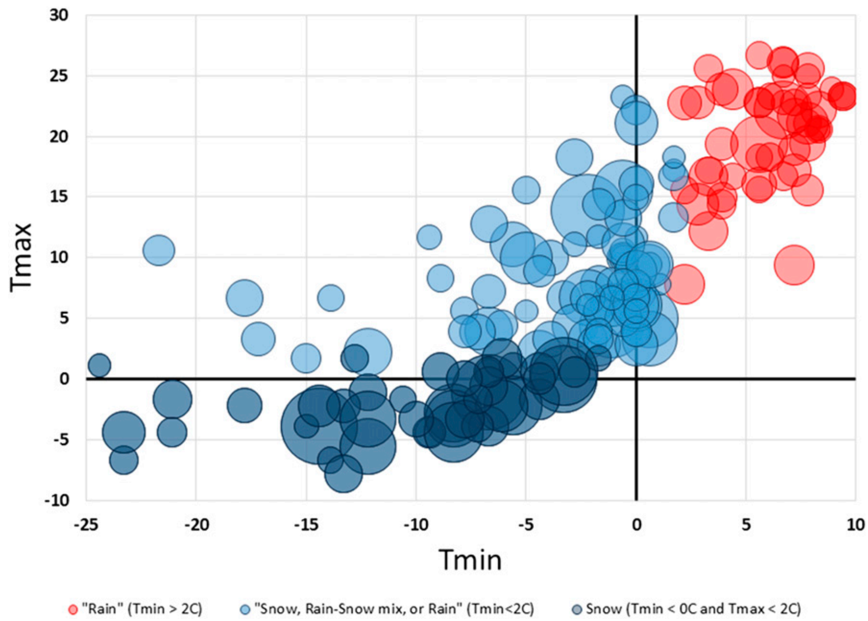

FIG. 5. Min daily temperature (*x* axis; °C) vs max daily temperature (*y* axis; °C) for precipitation events occurring above 2500-m elevation. Circle color indicates likely phase (rain, snow, or mixed) of precipitation shaded according to legend. Circle size indicates relative magnitude of 24-h precipitation total per event.

with the data continuity requirements for the COOP stations detailed in section 2.

In addition to the flooding having occurred during a climatologically drier month in the Front Range, another noteworthy aspect of this event is that September storms often switch to snow at higher elevations in the Front Range, but this event was unusually warm, such that heavy precipitation fell in liquid form all the way up to the Continental Divide (i.e., well above 2750 m or ~9000 ft), thus amplifying resulting floods. For instance, over the approximately week-long period of 8–17 September 2013, Estes Park, Colorado, at ~2300 m (7820 ft), observed more than 9 in. (~230 mm) of liquid rainfall, and Deadman Hill, Colorado, at ~3100 m (10 220 ft), observed nearly 6 in. (~150 mm) of liquid rainfall (Colorado Climate Center 2013). Fortunately, from an impacts perspective, the hydrological conditions were such that most reservoirs had been drawn down to their lowest level during the summer, thus allowing for a significant fraction of the runoff to be captured and mitigate some of the downstream floodwaters. Thus, the late-season occurrence of the 2013 storm had mixed practical consequences.

Despite the fall season being relatively climatologically dry in this region, the September 2013 event, along with other past events occurring in September, does demonstrate the potential for the fall environment to become primed for extreme rainfall. In the September 2013 setup in particular, a late-season shift back toward a monsoon-like pattern was partially responsible for the sustained moisture feed over the region. This timing, in addition to the axis of the moisture plume being shifted east of the Continental Divide as opposed to west of it as in many monsoon flow regimes, allows that the atmospheric pattern in general may not have been all that uncommon, and that the event itself may not have been deemed so anomalous (with respect to its seasonality) had it occurred just a couple of weeks earlier. That the seasonality of these environmental features (i.e., the monsoon and moisture transport patterns) may also change in future climates underscores the need to understand historical and present-day heavy precipitation seasonalities to better assess potential mechanisms for shifting seasonal patterns in the future.

The 2013 Front Range floods will continue to be studied from many perspectives, but the brief discussion here demonstrates very clearly a fundamental point of the present analysis: Colorado extreme precipitation can occur in any season and at all elevations. Thus, flooding can be considered a nearly year-round risk across the state (though winter precipitation, particularly at high elevations, still poses a relatively low risk for now as flood risk associated with extreme snowfall is not as direct as from extreme rainfall). Improved understanding of the critical ingredients that can come together to produce an extreme event—even in a season of ''normally'' low mean precipitation—is key to

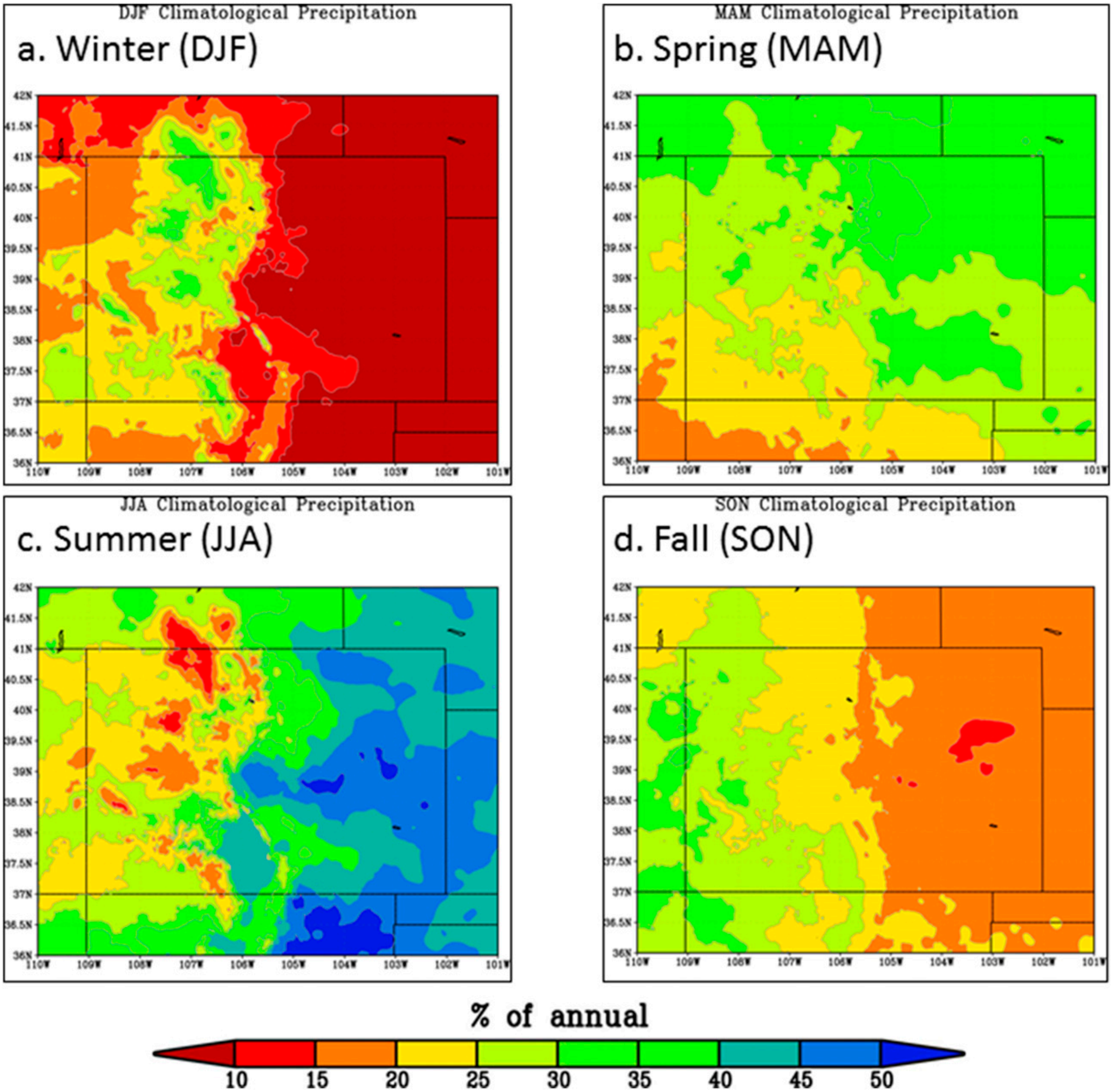

FIG. 6. Seasonal cycle of climatological precipitation based on COOP and SNOTEL data integrated via PRISM [Daly et al. (2002) using 1895–2007 period of record] for (a) winter, (b) spring, (c) summer, and (d) fall. Shading indicates the percentage of the annual precipitation that occurs during the indicated season.

adequately quantifying and preparing for future flood risks.

4. Summary and future work

Colorado's history of extreme precipitation is remarkably variable both seasonally and geographically. This study characterizes the seasonality of extreme precipitation as represented by over half a century of COOP station data and is intended to encourage additional studies of extreme precipitation in Colorado and elsewhere.

Analysis of the 10 largest daily (24 h, liquid equivalent) precipitation events at COOP stations in Colorado shows that extremes have ranged from <60 (mainly at higher elevations) to >250 mm day^{-1} (in the southeastern part of the state). East of the Continental Divide, the most extreme events are rarely seen in winter. Summer

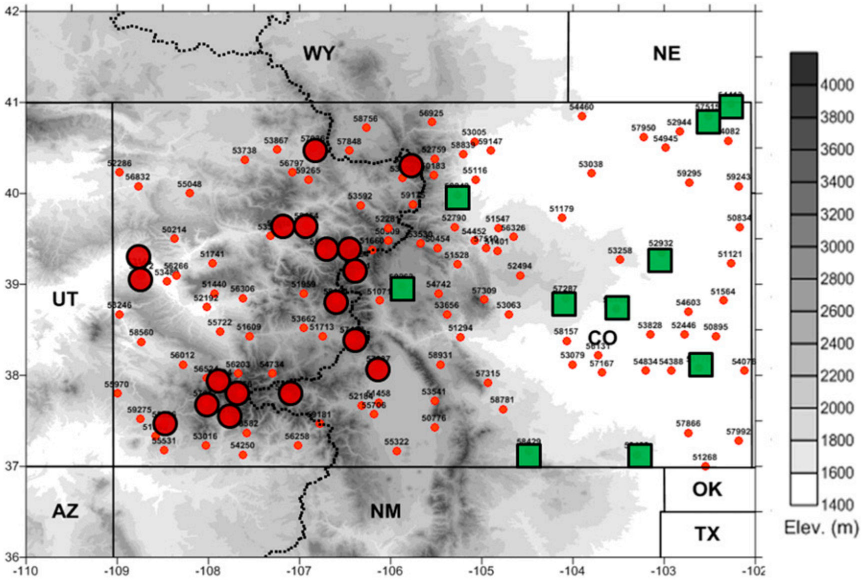

FIG. 7. Comparison of top precipitation events to seasonal climatology. Stations in red circles (green squares) denote those in which <40% (>90%) of the top 10 daily precipitation events fell during any of the climatologically favored three wettest months and >40% (none) of the top 10 daily precipitation events occurred during the climatologically driest six months.

extremes are most common across the lower-elevation eastern plains (east of ~105°W). Spring has produced a large fraction of the extremes in the Front Range. Fall has been the dominant season for extremes west of the Continental Divide, although winter extremes are also occasionally represented at higher-elevation stations there.

The seasonality of precipitation extremes in Colorado's central, highest mountains is particularly complex, with intense precipitation events having occurred in all months, and stations within tens of kilometers of each other showing significantly different seasonal distributions of heavy events. These sharp gradients observed with respect to both extreme precipitation magnitudes and seasonality are of relevance to stakeholders such as water resources planners and dam safety engineers who must sometimes extrapolate or translate data from nearby sites to fill in observational gaps in locations of interest. Our analysis demonstrates that such practices, particularly in the data-sparse Colorado central mountains, may result in the misrepresentation of extreme precipitation characteristics.

We also find that heavy precipitation in excess of 100 mm day^{-1}, while less common, has occurred even at the highest elevations considered here. High-elevation heavy rainfall observed during recent events (along with projections of a warming climate; Lukas et al. 2014) further suggests potentially heightened future flood risk over a larger portion of the year for the mountains. The COOP station record analyzed here includes few locations above 3000 m (~10 000 ft); thus, additional observations and analyses will be needed to more completely understand precipitation distributions at the highest elevations.

Many methods can be used to characterize heavy precipitation events, and in this analysis we have limited our dataset to include only station data with long (30 years) reporting periods. While results may shift somewhat using different precipitation analyses, COOP data are in many ways the best tool for gauging daily precipitation, at least at lower elevations. Note that the choice of a daily (24 h) precipitation focus here also colors our conclusions: adopting shorter-duration periods of analysis would likely favor increased emphasis on summer/convective events that are more important for flash flood risk, while analysis of longer-duration accumulations would generally favor more synoptically driven, persistent cool-season events. Finally, using a different epoch of analysis might also shift results somewhat; there are known pre-1950 extreme events of interest that may be included in future analyses.

We note in conclusion that, with respect to assessing flood risk, this work has been initially limited to addressing the single variable of precipitation. Full consideration of flood potential and flood risk requires the inclusion of additional critical factors that we have not addressed here, and moreover, a fully integrated approach that involves hydrometeorology, flood hydrology, and paleoflood hydrology (e.g., MD97, appendix C;

England et al. 2014). Future work will investigate the relationship between the largest precipitation events and the largest floods to better describe the intricate linkages between the seasonality of heavy precipitation and flood risk.

Acknowledgments. We thank the Bureau of Reclamation for their scientific interest and support for this project. Jon Eischeid created Fig. 6 in this paper, and Zach Schwalbe (Colorado State University/CoCoRaHS) assisted with checking specific event data. We also very much appreciate the comments and suggestions of Dr. John England (Bureau of Reclamation), as well as two anonymous reviewers, which have significantly improved the quality of this manuscript.

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