The Paroxysmal Precipitation of the Desert: Flash Floods in the Southwestern US

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Key Points:

- The 14 September 2015 Hildale Storm was a hailstorm that produced catastrophic flooding in southern Utah.
- The climatology of monsoon thunderstorms that produce flash floods in the Southwestern US exhibits large spatial heterogeneity.
- Record flood peaks in many Colorado Plateau watersheds over a wide range of basin scales are produced by "small", monsoon thunderstorms that pass close to the basin outlet.

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Abstract

The 14 September 2015 Hildale, Utah storm resulted in 20 flash flood fatalities, making it the most deadly natural disaster in Utah history; it is the quintessential example of the "paroxysmal precipitation of the desert". The measured peak discharge from Maxwell Canyon at a drainage area of 5.3 km^2 was 266 $m^3\ s^{-1}$, a value that exceeds envelope curve peaks for Utah. The 14 September 2015 flash flood reflects features common to other major flash flood events in the region, as well as unique features. The flood was produced by a hailstorm that was moving rapidly from southwest to northeast and intensified as it interacted with complex terrain. Polarimetric radar observations show that the storm exhibited striking temporal variability, with the Maxwell Canyon tributary of Short Creek and a small portion of the East Fork Virgin River basin experiencing extreme precipitation. Periods of extreme rainfall rates for the 14 September 2015 storm are characterized by K_{DP} signatures of extreme rainfall in polarimetric radar measurements. Similar K_{DP} signatures characterized multiple storms that have produced record and near-record flood peaks in Colorado Plateau watersheds. The climatology of monsoon thunderstorms that produce flash floods exhibits striking spatial heterogeneities in storm occurrence and motion. The hydroclimatology of flash flooding in arid/semi-arid watersheds of the southwestern US exhibits relatively weak dependence on drainage basin area. Large flood peaks over a broad range of basin scales can be produced by small thunderstorms like the 14 September 2015 Hildale Storm, which pass close to the basin outlet.

1 Introduction

"Sooner or later the cloudburst visits every tract, and when it comes the local drainage-way discharges in a few hours more water than is yielded to it by the ordinary precipitation of many years... So far as may be judged from the size of the channels draining small catchment basins, the rare, brief, paroxysmal precipitation of the desert is at least equal while it lasts to the rainfall of the fertile plain." G. K. Gilbert [1890]

Gilbert used the term paroxysmal in its dictionary formulation, "marked by bursts of destructive force or intense activity" (Merriam-Webster), to describe the storms that shape the channels of southwestern US rivers. Gilbert's insights were grounded in observations made during field investigations with the Surveys of the southwestern US (Powell (1895)), especially those leading to his landmark studies of the Henry Mountains (Gilbert (1877)) and Lake Bonneville (Gilbert (1890)). The broad objective of this study is motivated by Gilbert's apt description of southwestern US storms: we look to characterize the paroxysmal nature of precipitation for extreme flash-flood producing storms in the southwestern US.

The 14 September 2015 cloudburst in southern Utah resulted in 20 flash flood fatalities, making it the most deadly natural disaster in Utah history (Deseret News, 15 September 2015). It is the quintessential example of the storms Gilbert described. Of the 20 fatalities, 13 occurred in Hildale, Utah and resulted from flooding in Short Creek. The remaining 7 fatalities occurred 20 km to the north when hikers were trapped by floodwaters in a slot canyon in Zion National Park. The 20 fatalities were the product of a single hailstorm. Polarimetric radar observations show that the storm exhibited striking temporal variability, with the Maxwell Canyon tributary of Short Creek and a small portion of the East Fork Virgin River basin experiencing extreme precipitation. Close analyses of the 14 September 2015 storm are at the center of this study (Section 4); we will compare structure, motion and evolution of the storm that produced catastrophic flooding in Maxwell Canyon with properties of a large sample of flash flood producing storms in southern Utah and northern Arizona (Section 3) and a smaller population of storms producing record and near-record floods in Colorado Plateau drainage basins (Figure 1).

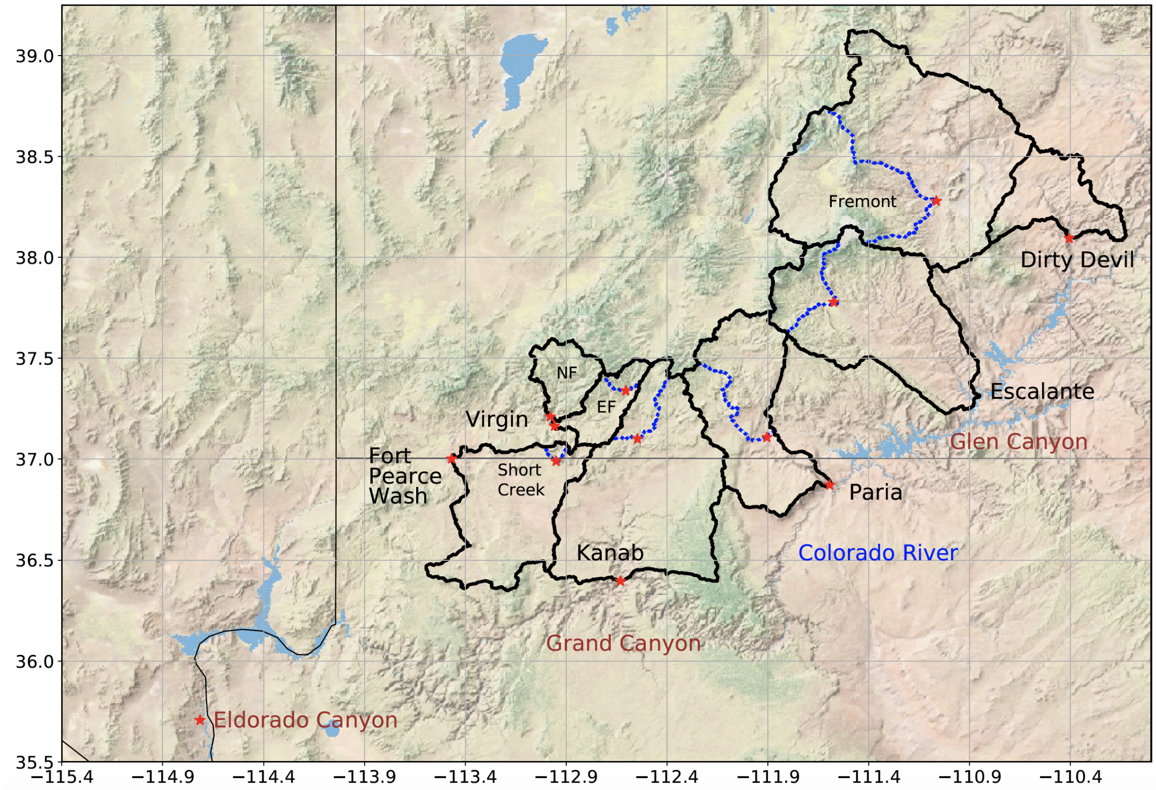

Figure 1. Basin boundaries for the Kanab Creek, Paria River, Escalante River, Dirty Devil River and Virgin Rivers basins (EF denotes the East Fork of the Virgin and NF denotes North Fork of the Virgin). Outer basins are outlined in black; blue Boundaries are for gaged sub-basins. Short Creek, the setting of the 14 September 2015 flood, is a sub-basin of Fort Pearce Wash and is marked with a star. Location of the September 1974 Eldorado Canyon flood is also marked by a star. Locations of stream gaging stations are denoted by stars.

Peak discharge measurements made by the U. S. Geological Survey (USGS) for the 14 September 2015 flood in Short Creek at a drainage area of 58 km^2 and for the Maxwell Canyon tributary at a drainage area of 5.3 km^2 are both 266 $m^3\ s^{-1}$ (personal communication from Cory Angeroth on 27 June 2016). The 266 $m^3\ s^{-1}$ flood peak for Maxwell Canyon is on the envelope curve of flood peaks for the Colorado Plateau (Figure 2; see Enzel et al. (1993); see also Crippen and Bue (1977), Thomas et al. (1994), Berwick (1962), Thomas and Lindskov (1983) and Webb et al. (1988)). The dependence of flood peak magnitudes on drainage area is relatively weak in southwestern US rivers, compared to other regions of the US (Thomas and Lindskov (1983) and Thomas et al. (1994); see also Etheredge et al. (2004)). Flood peak magnitudes are closely linked to storm scale; cloudbursts, like the Hildale Storm, can produce record flood peaks over a wide range of drainage areas, as will be shown in Sections 4 and 5.

The Short Creek flood occurred 41 years to the day after the event that produced, by far, the most extreme flood peak measurement in the region (Figure 2) - the Eldorado Canyon flood of 14 September 1974 produced a peak discharge of 2150 $m^3\ s^{-1}$ at a drainage area of 50 km^2. Maximum flood peak measurements for basin scales up to 10,000 km^2 do not exceed the Eldorado Canyon peak. “Intense rainfall, thunder and hail” accompanied the Eldorado Canyon flood (Glancy and Harmsen (1975)). The 14 Septem-

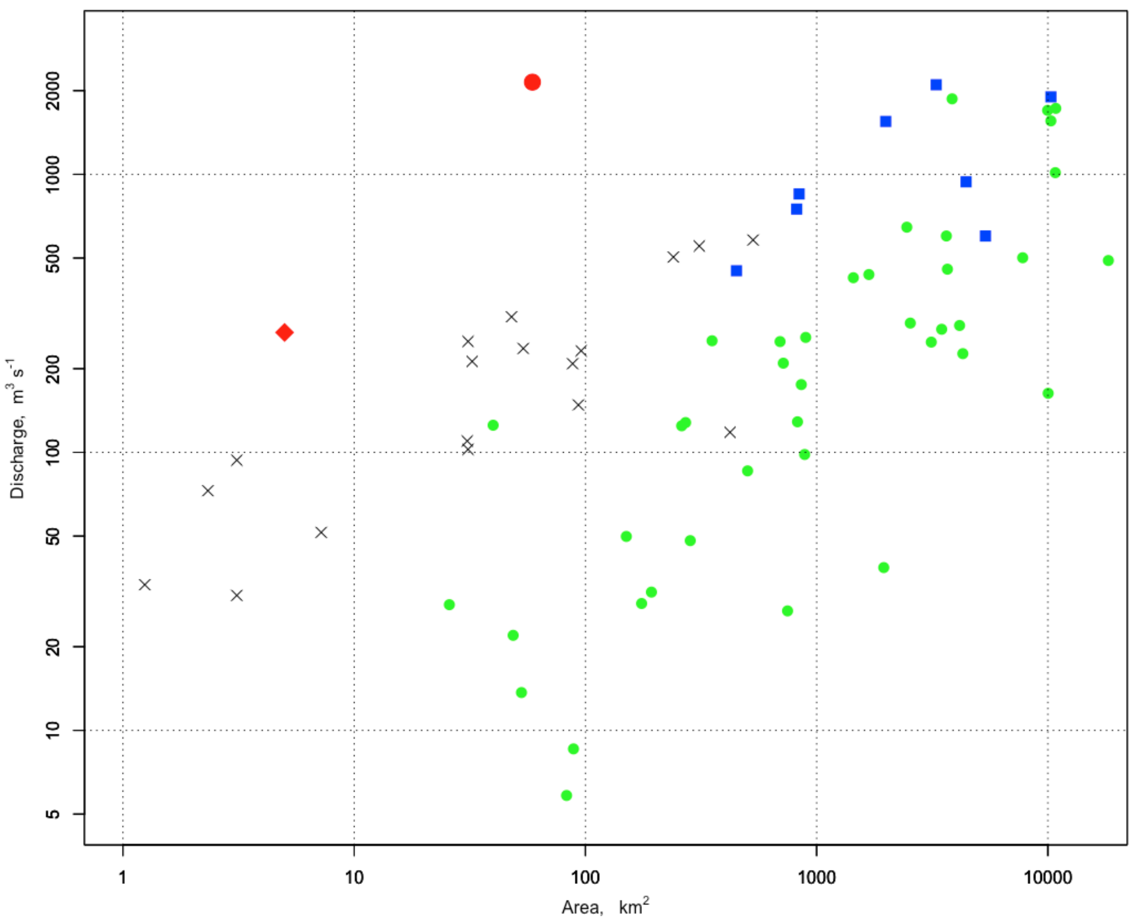

Figure 2. Record flood peaks in the southwestern US study region, with the 14 September 2015 peak from Maxwell Canyon shown as a red diamond. The green circles are record flood peaks from USGS stream gaging stations. Flood peaks denoted by black “x” are are from the “miscellaneous” record in Utah (Crippen and Bue (1977)). The flood peaks in blue are paleoflood peaks from Enzel et al. (1993). The 14 September 1974 Eldorado Canyon flood peak is shown as a red circle.

ber 1974 Eldorado Canyon flood and the 14 September 2015 Maxwell Canyon flood control the envelope curve of Utah; both were produced by hailstorms in complex terrain.

The storms that Gilbert referred to as cloudbursts typically occur during the North American Monsoon (NAM) season, which peaks during July and August and extends into September (Adams and Comrie (1997), Maddox et al. (1980), Higgins et al. (1997), Watson, Holle, and Lopez (1994), Osterkamp and Friedman (2000),Vivoni et al. (2006), Luong et al. (2017), Mazon et al. (2016), Maddox et al. (1995), Hu and Dominguez (2015), Corbosiero et al. (2009), Goodrich et al. (1997), K. M. Wood and Ritchie (2013), Pascale et al. (2017) and Bieda et al. (2009)). There is no formal meteorological definition of cloudburst - in usage dating back at least to the early 19th century, the key ingredients are extreme rainfall rates over short durations, typically with severe flooding as a consequence. Woolley (1946) summarizes the legacy of cloudburst storms as agents of flash flooding in Utah (see also Leopold (1942), Leopold (1946), Hales (1975), Webb et al. (1988) and Hjalimarsom and Thomas (1992) for broader examination of cloudburst flooding in the southwestern US).

In the southwestern US it is difficult to know when and where cloudbursts occur, even with modern observing capabilities. The study region includes some of the most remote areas of the conterminous US and the density of rain gages and stream gages is low. We rely heavily on polarimetric radar observations (see, for example, Kumjian and Ryzhkov (2008), Romine et al. (2008), Kumjian (2013), Ryzhkov et al. (2013) and Cunha et al. (2013)) to examine rainfall and storm properties. Specific differential phase shift (K_{DP}) measurements (Kumjian (2013)) play an especially important role in detection of exceptional rainfall rates. In many regions of the southwestern US, it is difficult to obtain useful radar measurements due to blockage problems associated with mountainous terrain (Maddox et al. (2003)). In southern Utah, the National Weather Service (NWS) avoided this problem by deployment of the Cedar City, Utah WSR-88D on the top of Blow Hard Mountain at an elevation of 3.2 km MSL (V. T. Wood et al. (2003)). This is fortuitous in allowing us to examine storm properties without the problems of terrain blockage. The elevation of the radar, however, means that we can not see what is of most interest, rainfall near the ground surface. The lowest beam of the Cedar City radar samples the atmosphere above Short Creek at an elevation of approximately 3 km above ground level.

Gilbert's observations on the "size of channels" in small southwestern US watersheds presaged the "arroyo problem", which centers on observations that channels in Colorado Plateau rivers incised and widened dramatically in the second half of the 19th century (see, for example, Graf (1983), Webb and Hereford (2001) and Harvey and Pederson (2011)). Most arroyos began to fill by the middle of the 20th century (Leopold (1976)). Explanations for the sequence of alterations to Colorado Plateau river channels center on the climatology of extreme rainfall (Leopold (1976), Graf (1983) and Webb et al. (1988)). Gilbert's observations point to a broader issue - channels in small southwestern US watersheds can be larger and deeper than their counterparts in the "fertile plain". Both the arroyo problem and the larger problems of drainage evolution in southwestern US rivers require advances in understanding the nature of extreme rainfall from thunderstorm systems during the North American Monsoon (Adams and Comrie (1997), Higgins et al. (1997), Morin et al. (2005), Watson, Holle, and Lopez (1994), Goodrich et al. (1997) and Vivoni et al. (2006)).

The September 2015 Hildale, Utah storm was a severe thunderstorm which produced hail and copious lightning. The most intense hailstorms have been discounted as important flood agents. Cotton et al. (2010) note that "storms producing the largest hailstones occur in strongly sheared environments; thus, in general, we should not expect that the storm systems producing the largest hailstones are also heavy rain producing storms." Doswell et al. (1996), Smith et al. (2001) and Rogash and Racy (2002) provided a different perspective, noting that the most intense hailstorms, supercell thunderstorms, are important flood hazards in the US (see also Hitchens and Brooks (2013), Nielsen et al. (2015), Smith et al. (2018) and Nielsen and Schumacher (2018)). Extensive research on hailstorms has provided a broad characterization of their structure and evolution (see, for example, Kumjian et al. (2015) and Hubbert et al. (1998)). An issue that has not been resolved is how heavy rainfall is distributed within a hailstorm and how the structure and evolution of extreme rainfall within a hailstorm is linked to storm dynamics and microphysics (see, for example, Romine et al. (2008) and Kumjian et al. (2015)). The occurrence of hail and extreme rainfall rates in close proximity is an important feature of some of the most extreme floods in the US (Smith et al. (2018)).

We compare structure and evolution of the 14 September 2015 storm with the larger population of thunderstorms that produce flash floods in the region. Climatological analyses of storm properties are based on a catalog of flash flood days during the period from

1998 - 2016 in southern Utah and northern Arizona. Flash flood reports in the National Center for Environmental Information (NCEI) Storm Events data set are used to select the flash flood days. We examine storm structure and evolution through Lagrangian analyses of storm motion, size and convective intensity, based on storm tracking of 3-D reflectivity fields using the TITAN algorithms (Dixon and Wiener (1993)). We use measures of convective intensity derived from storm tracking algorithms, including maximum reflectivity and echo top height in the tracked storm cell (Dixon and Wiener (1993), Tapia et al. (1998) and Javier et al. (2007)).

The climatologies of flash floods and thunderstorms in the southwestern US are linked. Thunderstorm climatology for the region is examined through analyses of Cloud-to-Ground (CG) lightning data from the National Lightning Detection Network (NLDN; see Reap and MacGorman (1989), Watson, Holle, and López (1994), Petersen and Rutledge (1998), Lang and Rutledge (2002) and Villarini and Smith (2013)). Lightning climatology provides only a rough depiction of flash flood climatology in the southwestern US - virtually all of the flash floods during the NAM season are from thunderstorms, but only a small fraction of thunderstorms produce major flash floods.

The 14 September 2015 Hildale storm intensified rapidly as it approached the Short Creek watershed and the Vermillion Cliffs, which form the southwestern boundary of the watershed. Complex terrain plays a central role in determining the spatial and temporal structure of rainfall in the study region. The links between mountainous terrain and Lagrangian storm properties - including storm initiation, size, motion and convective intensity - are important elements of the climatology of thunderstorms and flash floods in the Colorado Plateau. The interplay of spatial heterogeneity of storm evolution and drainage network structure (Morin et al. (2006)) suggests that mountainous watersheds should exhibit distinctive patterns of flood response that will be unique to the specific settings in the landscape. “Hotspots” of extreme flood occurrence are one pattern that may emerge for the Colorado Plateau; flood hotspots have been described in numerous settings with complex terrain, including the Balcones Escarpment of Texas (Baker (1975) and Costa (1987)), the Front Range of the Rocky Mountains (Jarrett and Costa (1988)), the Black Hills of South Dakota (Harden et al. (2011)) and the Blue Mountains of eastern Oregon (Smith et al. (2018)).

Questions that motivate the study include the following: 1) What are the characteristic patterns of storm structure and evolution for extreme flood producing storms in arid/semi-arid regions? 2) How does extreme flood response in arid/semi-arid watersheds depend on temporal and spatial variability of rainfall rate? 3) What are the storm and terrain features that control spatial heterogeneity of flood peaks? 4) What are the precipitation mechanisms associated with extreme rainfall rates? 5) Are all basins in the Colorado Plateau “unique” in their flood hazards? These questions are tied to an overarching hypothesis that “small” intense thunderstorms, like the September 1974 Eldorado Canyon storm and the September 2015 Maxwell Canyon storm, are principal agents of extreme flooding over a broad range of basin scales in the southwestern US.

2 Data and Methods

The climatology of thunderstorms in the southern Utah - northern Arizona study region is examined through analyses of cloud-to-ground (CG) lightning observations from the NLDN (see Orville (2008) and Cummins and Murphy (2009)). Our analyses are based on observations during the period 1991 - 2016 and we restrict consideration to negative strikes with intensities less than -10 kA (see Cummins et al. (1998) and Villarini and Smith (2013)).

We use polarimetric radar fields from the Cedar City WSR-88D radar to examine storm structure and motion and to assess spatial and temporal variability of rainfall rate;

the polarimetric upgrade of the Cedar City radar occurred in 2012. We primarily examine two polarimetric radar fields: horizontal reflectivity (Z_H) and specific differential phase shift (K_{DP}); an introduction to radar polarimetric measurements can be found in Kumjian (2013). Horizontal reflectivity Z_H provides an aggregate characterization of number and sizes of hydrometeors. Differential reflectivity Z_{DR} is the ratio between the horizontal and vertical reflectivity and provides information on characteristic sizes of raindrops and hydrometeor type. Differential phase shift Φ_{DP} (in degrees) is the difference in phase shift between the horizontal and vertically polarized waves. Specific differential phase K_{DP} (degrees km^{-1}) is the range derivative of the differential phase shift along a radial radar beam. K_{DP} is dependent on the size as well as number concentration of rain drops, and provides a useful tool for detecting heavy rainfall (see Kumjian (2013) for discussion of microphysical processes affecting K_{DP} measurements).

We converted WSR-88D Archive Level-II fields from radial coordinates into 3-D Cartesian grids using the RADX tools developed at the NCAR Research Applications Lab. Specific differential phase (K_{DP}) is computed in polar space. All the fields (including horizontal reflectivity Z_H and differential reflectivity Z_{DR}) are gridded using a three dimensional linear interpolation scheme. Reflectivity and differential reflectivity are converted from dB to linear, gridded and then back to dB. The spatial resolution of the gridded radar fields is 1 km. The time required for the radar to complete a full volume scan of the atmosphere is typically 5-6 minutes. Volume scan observations for the 14 September 2015 storm include multiple base scans providing a time resolution of 2-3 minutes for low elevation measurements of polarimetric variables.

To examine storm structure, motion and size for flash flood producing storms we performed storm tracking analyses of 3-D reflectivity fields derived from KICX volume scan reflectivity data. Flash flood reports from the NCEI Storm Events data base provided the sample of storm events. Storm days consisted of all days (1200 UTC - 1200 UTC) with flash flood reports in the northern Arizona - southern Utah study region during the NAM period (July - September) for the years from 1998 - 2015. The NCEI flash flood events data are based on observer reports; they are unlikely to capture all days with flash flooding - especially minor flash flooding - but they provide an extensive sample of flash flood events. We omitted days for which WSR-88D reflectivity observations were not available, resulting in a total of 360 days.

Lagrangian analyses were based on the TITAN storm tracking algorithms (Dixon and Wiener (1993); see also Tapia et al. (1998), Javier et al. (2007) and Yang et al. (2017) for related analyses). A reflectivity threshold of 45 dBZ and volume threshold of 5 km^3 were used to identify convective storm elements (see Dixon and Wiener (1993)). Variables computed from tracking analyses include location of the storm centroid, echo top height (45 dBZ), maximum reflectivity in the storm (dBZ), storm speed, storm direction and storm area. Analyses focus on intense storm elements, which we take to be tracked storm elements with echo tops greater than 8.5 km (above radar elevation); elevation of the KICX radar is approximately 3 km MSL. We also restricted analyses to elevations above 3 km MSL to account for radar elevation.

We use operational polarimetric rainfall fields developed by the NWS from the KICX radar to examine rainfall rate variability over large watersheds. The digital polarimetric rainfall (DPR) fields are converted from polar coordinates to a regular 1 km grid using the NOAA Weather and Climate Toolkit. The DPR algorithm uses specific differential phase shift to estimate rainfall rate in hail and it uses reflectivity and differential reflectivity to estimate rainfall rate when the hydrometeor classification is rain. Using gridded DPR rainfall rate fields, we examine rainfall relative to the drainage network using the rainfall-weighted flow distance to the basin outlet (see Smith et al. (2002) and Smith et al. (2005)). Elevation of the radar beam limits the accuracy of rainfall rate fields, but they provide useful tools for examining the effects of rainfall location, relative to the basin outlet, on flood response.

We use USGS stream gaging records to examine flood peak distributions (see Ryberg et al. (2017)). Measurements of many extreme floods are made by indirect discharge methods, involving field measurements of peak water surface profiles and channel cross-sections, combined with hydraulic computations (Costa and Jarrett (2008) and Koenig et al. (2016)). Indirect measurements are made for floods at stream gaging sites when the gage is destroyed or fails to operate properly. They are also made at miscellaneous sites, i.e. sites that do not have stream gaging stations, typically for the most extreme floods. The 14 September 2015 peak discharge measurements in Short Creek are in the miscellaneous site category. Peak discharge from indirect measurements have significant errors, especially for the most extreme flood peaks (see Costa and Jarrett (2008) and House and Pearthree (1995) for analyses of extreme flood measurements in the southwestern US).

Paleohydrologic reconstructions of flood peaks also play an important role in examining the upper tail of flood peaks in the southwestern US (as in Figure 2; see Webb et al. (1988), Enzel et al. (1993), Ely (1997) and Baker (2008)). They are an especially important resource for examining spatial heterogeneities of extreme floods over regions of complex terrain (see, for example, Martinez-Goytre et al. (1994), House and Baker (2001) and Harden et al. (2011)).

KINEROS2 is a physically based rainfall runoff model developed for watersheds in semi-arid environments (Morin et al. (2006), Goodrich et al. (2011) and Schaffner et al. (2016)). The model represents the watershed as a cascade of overland flow elements (planes or curvilinear) and channels. In our KINEROS2 model formulation for Maxwell Canyon at a drainage area of 5.3 km^2, we have 120 overland flow planes and 50 channel segments. The structure of the overland flow planes and channels conforms with field inspection by the authors in November 2016. We used the Automated Geospatial Assessment (AGWA) routines, developed by the USDA-ARS (Miller et al. (2007) and Goodrich et al. (2012)) for implementing KINEROS2. Schaffner et al. (2016) demonstrated the utility of KINEROS2 for categorical flash flood forecasting in Short Creek using real-time radar data.

3 Study Region and Thunderstorm Climatology

Thunderstorms are the dominant agent of flash flooding in much of the Colorado Plateau and the climatology of thunderstorms provides insights to the climatology of flash flooding. In this section we examine the thunderstorm climatology in the southwestern US study region through analyses of cloud-to-ground (CG) lightning observations from the NLDN (see Orville (2008) and Cummins and Murphy (2009)). We use storm tracking analyses of 3-D reflectivity fields for 360 flash flood days to examine the climatology of storm structure, motion and convective instensity.

There are striking spatial heterogeneities in thunderstorm frequency over the study region and these features are strongly linked to terrain (Figure 3). The largest lightning flash densities are located in high elevation plateau regions of the Colorado Plateau and the mountains to the west in the Basin and Range province. The boundary between the Colorado Plateau and Basin and Range provinces is roughly the low elevation region extending northeast to southwest from the Escalante Desert through the Virgin River Valley to Lake Mead (Figure 3). The Basin and Range includes the northeast portion of the Mojave Desert. Mean annual CG flash densities vary by more than a factor of 5 from the high elevation regions of the Shivwits Plateau, Kaibab Plateau, Aquarius Plateau, Kaiparowits Plateau, Paunsaugunt Plateau, Markagunt Plateau and Pine Valley Mountains to low elevation regions including Lake Mead, the Virgin River Valley, the Escalante Desert and Glen Canyon (see Figure 3 for locations). Peak CG flash densities exceed 3 strikes km^{-2} over Boulder Mountain in the Aquarius Plateau (3450 meters MSL) and over Mount Dellenbaugh at the southwest end of the Shivwits Plateau (2130 meters MSL). Flash densities are less than 1.2 strikes km^{-2} in the Grand Canyon, just south of the

Shivwits Plateau. Mean annual CG flash densities are less than 0.6 CG strikes km^{-2} over portions of Lake Mead, Glen Canyon and the Escalante Desert.

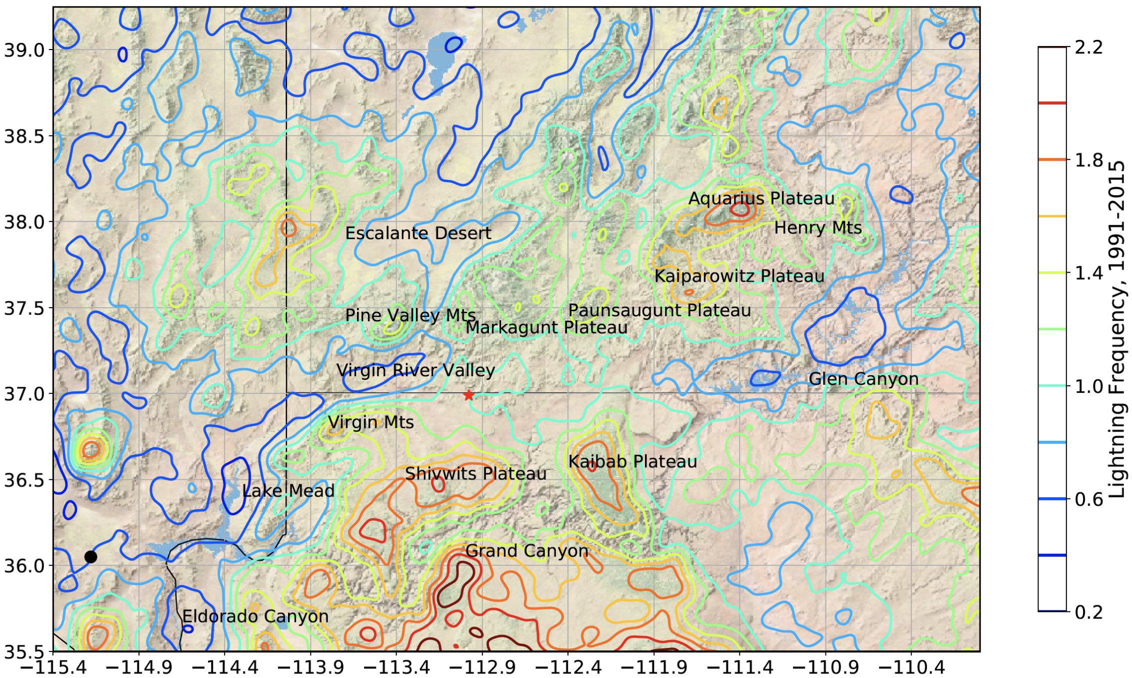

Figure 3. Mean CG flash density (strikes km^{-2}) for southern Utah, northern Arizona and eastern Nevada. Geographic features are labeled. The red star shows the location of the Short Creek stream gaging station. The Las Vegas radiosonde location is denoted by a black circle.

The changes in elevation moving south to north from the Grand Canyon into the Markagunt, Paunsaugunt and Kaiparowitz Plateaus are conceptualized in terms of a sequence of discrete jumps in elevation, termed the Grand Staircase. The second step is the Vermillion Cliffs and it marks the boundary of the Short Creek drainage basin (Figure 1); terrain boundaries are locations of large gradients in rainfall and lightning for the 14 September 2015 storm.

Virtually all of the thunderstorms in the study region occur during the July - September period that defines the North American Monsoon season (Figure 4). In the figure we show boxplots of the area with daily CG flash density exceeding 1 CG strike km^{-2} (top) and 2 CG strikes km^{-2} (bottom) for the period 1991 - 2006. The transition into the monsoon season is abrupt (Figure 4); the median area with flash density greater than 1 CG strike km^{-2} is close to 0 for June. The frequency of major thunderstorm outbreaks peaks during August, with a significant decline into September. Thunderstorm frequency in October is also small, but October thunderstorm systems are linked to extreme flood peaks in the study region, as will be shown in Section 5.

Individual thunderstorms that occur in the study region during the NAM season have spatial scales that are typically smaller than 50 km^2, as detailed below. During thunderstorm days, the total area affected by these storms is often several orders of magnitude larger than the scale of the individual storms. The median area with flash density exceeding 1 CG strike km^{-2} is 1600 km^2 in July, 2100 km^2 in August and less than 200

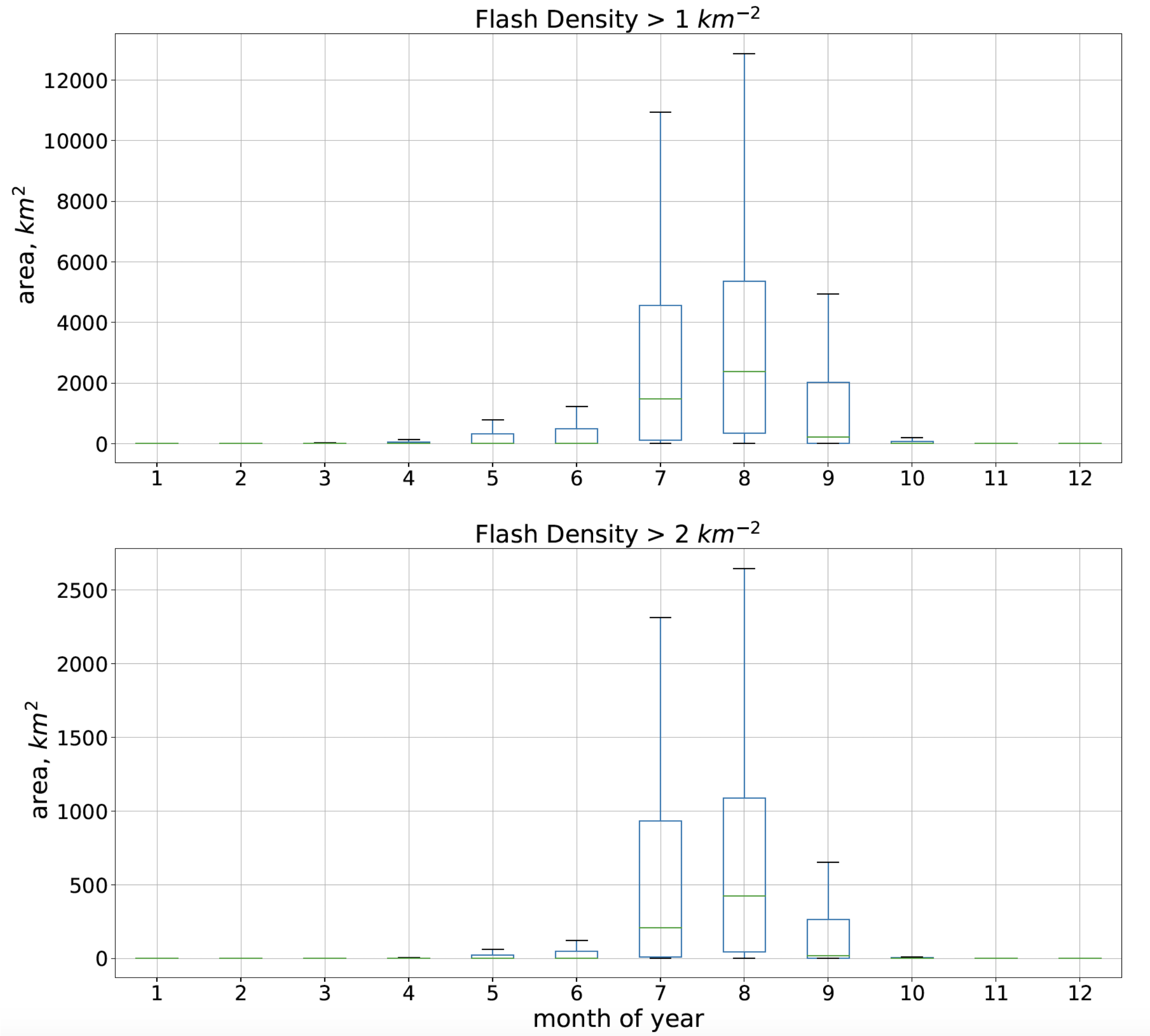

Figure 4. Monthly boxplots of daily area with CG flash density exceeding 1 km^{-2} (top) and 2 km^{-2} (bottom). Month 1 is January.

km^2 in September (Figure 4). The median area with CG flash density exceeding 2 CG strikes km^{-2} peaks at 480 km^2 in August.

The climatology of thunderstorms in the study region is coupled to the seasonality of water vapor (Figure 5). Boxplots of CG flash density, stratified by values of precipitable water at Page, Arizona (near Glen Canyon Dam), highlight the dependence of thunderstorm occurrence on water vapor. The increase in thunderstorm frequency during the North American Monsoon season (Figure 4) is directly tied to the abrupt increase in water vapor transport from the Pacific Ocean by way of the Gulf of California (Adams and Comrie (1997)). Within the NAM season, the occurrence of thunderstorms is closely linked to monsoon surge events that produce periods of peak precipitable water (see, for example, Watson, Holle, and López (1994) and Higgins et al. (2004)). Strong synoptic forcing is an important element of water vapor flux for numerous monsoon storms that produce extreme rainfall and flooding (Yang et al. (2017)).

To examine storm structure, motion and size for flash flood producing storms we carried out storm tracking analyses of 3-D reflectivity fields derived from KICX volume

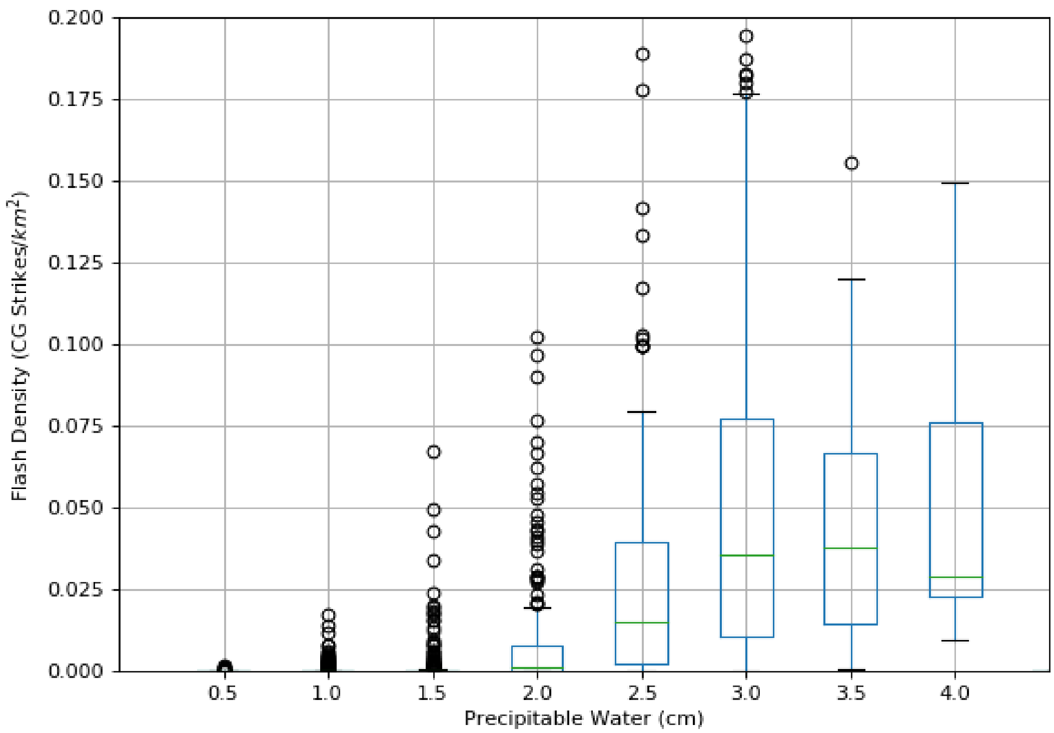

Figure 5. Daily flash density boxplots conditioned on precipitable water (in cm). Precipitable water bins cover 0.5 cm (the 3.0 cm bin, for example, includes days with precipitable water between 2.75 and 3.25 cm) Precipitable water measurements are from the Page, Arizona GPS (Global Positioning System) precipitable water station.

scan reflectivity data for 360 storm days. Lagrangian analyses are based on the TITAN storm tracking algorithms (Section 2). A reflectivity threshold of 45 dBZ and volume threshold of 5 km^3 were used to identify storm elements.

Storm motion on flash flood days is predominantly from southwest to northeast (Figure 6) for the three months of the North American Monsoon season. The wind roses in Figure 6 reflect motion for storm elements with echo top height greater than 8.5 km.

Storm motion from southwest to northeast is most tightly concentrated for storms with the largest speeds (Figure 6). The median storm speed for the NAM season is 12 $km\ h^{-1}$ and the 0.9 quantile storm speed is 32 $km\ h^{-1}$ (Figure 7).

There are rare storm elements, like those on 14 September 2015, with storm speeds greater than 50 $km\ h^{-1}$. The 14 September 2015 Hildale storm was similar to flash flood producing storms in the region in terms of storm direction, but on the upper bound of storm speed. Storm motion from southwest to northeast reflects steering winds that are associated with transport from the source of moisture - the Pacific Ocean to the southwest of the region.

The climatology of storm motion shows a pronounced seasonal transition from July through September. The predominant direction of motion in July is from the southwest,

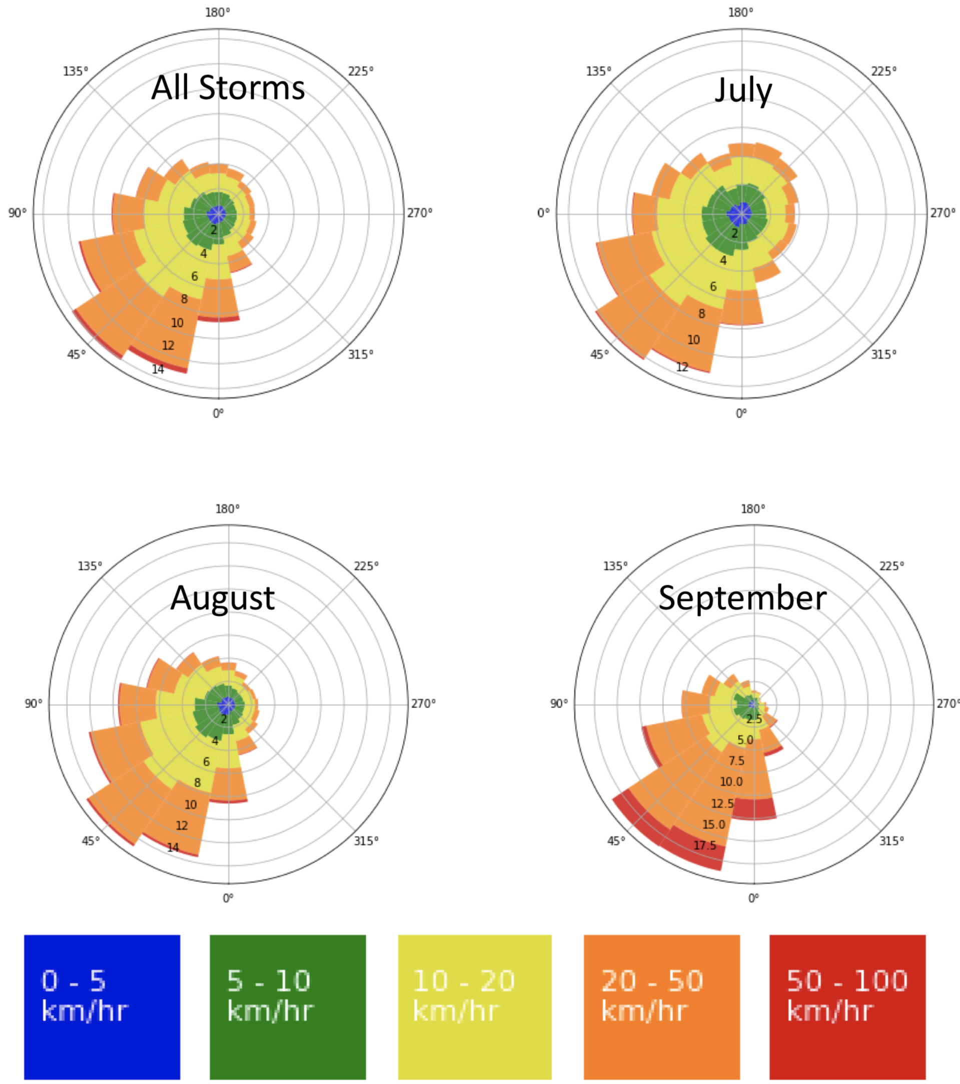

Figure 6. Windrose of storm motion and speed for flash-flood producing storms, 1998 - 2015 (tracked storm elements with 45 dBZ tops greater than 8.5 km); all storms (upper left), July (upper right), August (lower left) and September (lower right)

but there is a population of storms that depart from the norm, including storms with relatively small speeds covering all directions of motion. August is a transition month, including storms deviating from southwest flow (like July) and a population of high storm speed events (like September). During September, when short-wave troughs moving from the northwest extend into the southwestern US, the distribution of storm motion is more tightly concentrated in the southwest to northeast sector.

Superimposed on the general southwest to northeast motion of storms for the region is geographic variability in mean storm motion for flash flood days (Figures 8 and 9). Mean motion vectors were computed from tracked storm elements with echo top height greater than 8.5 km. There are minima in storm speed over mountainous terrain and maxima over low elevation regions. Average storm speeds have a local maximum upwind of Short Creek and local minima in the headwater high-elevation regions of the North Fork and East Fork Virgin Rivers. The Glen Canyon region has an elongated zone of mean storm speeds greater than 27 $km\ h^{-1}$ (Figure 9). There are large contrasts in mean storm speed for the headwater portions of the Escalante and Paria River basins, relative to downstream portions of the drainage basins (Figure 9); these storm properties are linked to scale-dependent flood response and spatial heterogeneities of extreme floods (as detailed in Section 5).

The median value of storm area for storm elements with echo top height greater than 8.5 km is 18 km^2 (Figure 7). The 0.9 quantile of storm area is 50 km^2. There is only modest variation in storm area distribution over the NAM season, in contrast to storm motion. Storm scale is one of the principal determinants of scale-dependent flood response in the study region, as discussed in detail below. Upscale growth of storms as they move away from peak elevations is modest compared with major flood-producing storms along the Front Range of the Rockies (see Javier et al. (2007) for additional discussion). Organization of convection into long lines is rare, but can play a role in extreme flooding (as discussed in Section 5).

Like storm size, the distribution of maximum reflectivity values shows relatively little seasonal and geographic contrast. The median value of maximum reflectivity for storm elements with echo top height of 8.5 km is 55 dBZ (Figure 7), a value that typically indicates the presence of some hail. The 0.9 quantile of maximum reflectivity for flash flood days is 62 dBZ. Fewer than 1 in 100 storm elements on flash flood days have maximum reflectivity values that reach 70 dBZ - the 14 September 2015 Hildale storm is one.

4 The 14 September 2015 Storms and Floods

The Short Creek watershed (Figure 10) is located in one of the most remote areas in the conterminous US. The lower watershed of Short Creek includes the paired communities of Hildale, Utah and Colorado City, Arizona, which are divided by the Utah - Arizona boundary. Two thunderstorms passed over Short Creek on 14 September 2015 (Figure 11). For the first storm, which took a more easterly path, rainfall in Short Creek began around 2005 UTC (2:05 PM, Mountain Daily Time [MDT]) and ended by 2030 UTC. Rainfall in Maxwell Canyon for the second storm began at approximately 2215 UTC - the duration of rainfall over Maxwell Canyon was likely more than 10 minutes but less than 20. This second storm was the principal agent of catastrophic flooding in Maxwell Canyon and downstream in Short Creek. We will refer to this storm as the Hildale Storm, covering its entire life cycle from approximately 2130 UTC to 2345 UTC. The chronology of catastrophic flooding in Short Creek is closely tied to the structure and evolution of the Hildale Storm during the 20-minute time window from 2210 - 2230 UTC (Figure 12).

The first storm produced a significant flash flood in Short Creek and multiple cars waited at a low-water crossing of Short Creek until the peak receded (the storm track is denoted “Storm 1” in Figure 11). The second peak came down the Maxwell Canyon tributary and washed the waiting cars into Short Creek, resulting in 13 of the fatalities from the storm. Shortly after the second peak in Short Creek swept through Hildale and Colorado City, 7 hikers were killed in Keyhole Canyon (see Figures 10 and 11), a popular canyoneering site in Zion National Park, 20 km north of Hildale. The upstream drainage area of Keyhole Canyon is approximately 1 km^2. The Hildale storm was responsible for the Short Creek and Zion fatalities, along with a record flood peak in the East Fork Virgin River at a drainage area of 890 km^2.

Stage measurements on Short Creek made by the Mojave County Flood Control District in Colorado City, Arizona exhibited a sharp rise beginning at 2100 UTC in response to the first storm, with a peak stage of 1.11 m (3.64 feet) at 2134 UTC (see Figure 10 for location). Stage decreased below 0.3 m (1 foot) at 2245 UTC, which marks the beginning of contributions from the second storm. Over the next 15 minutes, stage increased rapidly to the flood peak of 2.03 m (6.67 feet) at 2300 UTC. The stream gage was disabled at 2317 UTC, with stage having decreased to 1.24 m (4.08 feet). A rain gage, which is colocated with the Short Creek stream gaging station, reported the first measured rainfall for the second storm at 2218 UTC. For the 7-minute period from 2218 UTC until 2225 UTC, 12 mm were recorded for a 7-minute rainfall rate exceeding 100 $mm\ h^{-1}$. An additional 2 mm of rain were recorded over the next 4 minutes. The Short Creek station is at relatively low elevation, 1492 meters MSL, compared to the headwaters of Maxwell Canyon, which have peak elevations exceeding 2000 meters MSL. Much more intense rainfall occurred to the north and west of the Short Creek stream gaging station over the Maxwell Canyon tributary.

The Hildale Storm was a monsoon thunderstorm in an environment with strong synoptic forcing. An upper level trough off the coast of California promoted exceptionally strong water vapor transport into the southwestern US, with rapid increase in precipitable water preceding initiation of the Hildalle Storm. For the Page, Arizona GPS station, observed precipitable water increased from 8 mm at 0000 UTC on September 13 to 20 mm at 0000 UTC on September 14, followed by a sharp increase to 30 mm by 0600 UTC. Precipitable water from the Las Vegas, Nevada sounding at 1200 UTC on September 14 was 31.8 mm, an increase of 5.8 mm from the 0000 UTC sounding (see Figure 3 for location of the Las Vegas sounding). The Las Vegas precipitable water peak of 31.8 mm has been exceeded on fewer than 20 days in September since 1948.

Extreme rainfall over Maxwell Canyon was associated with a storm that exhibited peaks in convective intensity for the storm, for the day and generally for the collection of flash flood producing storms in the region (Figure 13; compare with results in the previous section). The Hildale Storm initiated southwest of Maxwell Canyon at approximately 2130 UTC (Figure 11) and intensified rapidly after 2145 UTC, with maximum reflectivity values reaching 65 dBZ by 2152 UTC (Figure 13 top). Convective intensity of the storm increased during the 10 minutes leading up to initiation of heavy rainfall over Maxwell Canyon at approximately 2215 UTC. Maximum reflectivity of the storm remained above 65 dBZ from 2217 UTC until 2310 UTC, with peak values exceeding 70 dBZ. The peak echo top height, i.e. the highest elevation with a reflectivity greater than 45 dBZ, of 11.5 km occurred around 2225 UTC. The rapid increase in convective intensity around 2217 UTC occurred as the storm approached Maxwell Canyon.

The area of peak lightning flash density was associated with passage of storms over the Vermiliion Cliffs, which mark the western boundary of Maxwell Canyon (Figure 14). The lightning map shows that the sharp terrain gradient at the Vermillion Cliffs was an area of peak convective intensity for the Hildale storm. The storm total lightning field reflects the contributions from the two storms described above (tracks are shown in Figure 11). The lightning flash density for the day over Maxwell Canyon was more that twice the mean annual value (Figure 3).

The Hildale Storm was exceptional for its rapid motion, in contrast to many flash-flood producing storms (Doswell et al. (1996) and Schumacher (2009)). During the 20 minute period centered on heavy rainfall over Maxwell Canyon, storm speed exceeded 50 $km\ h^{-1}$, with a peak speed of of 62 $km\ h^{-1}$ at 2243 UTC (Figure 13 bottom). Storm speed for the Hildale Storm was large in comparison with other tracked storm elements on 14 September 2015; the median storm speed for tracked storm elements with echo top height exceeding 8.5 km was 30 $km\ h^{-1}$ with only 10% of storm elements having storm speeds exceeding 45 $km\ h^{-1}$. Like convective intensity, storm speed for the Hildale storm was also extreme relative to the sample of flash flood producing storms in the region during the period from 1998 - 2016 (as detailed in Section 3).

During the critical period of extreme rainfall from 2210 to 2230 UTC, storm area ranged from 50 to 60 km^2 (Figure 13 middle). Storm area was anomalously large for the storm, for the day and for the population of flash flood producing storm elements (Figure 7). Flood peak measurements for Maxwell Canyon and Short Creek suggest that the most extreme rainfall was concentrated in Maxwell Canyon, which has a drainage area that is smaller than the storm size. Characterizing the extreme nature of rainfall from the Hildale storm centers on determining where and when extreme rainfall occurred within the Hildale Storm, as depicted in Figure 12.

The Hildale storm exhibited cyclonic rotation in radar polarimetric fields and in Doppler velocity fields. Dynamical processes associated with rotational motion in mesovortices and supercells can contribute to extreme rainfall rates, as detailed in (Nielsen & Schumacher, 2018) and (Weijenborg et al., 2017). During the period of heavy rainfall over Maxwell Canyon (Figure 12) the hail core was located in the northwest portion of the storm, with a line of elevated reflectivity extending to the east of the hail core and a line of elevated reflectivity extending south of the hail core. The line extending south of the hail core moved cyclonically from southwest of the hail core to southeast of the hail core over the 15 minute period. The cyclonically rotating storm structure around the hail core is also illustrated in the the Doppler velocity fields from 2214 to 2227 UTC (Figure 12; middle column). Doppler velocity observations show that the hail core was located at the nose of a low-level inflow jet, i.e. a low level maximum in wind speed.

Motion of the Hildale storm was slightly to the left of the steering level winds from 2100 to 2230. In Figure 15, we show vertical wind profiles derived from Cedar City WSR-88D Doppler Velocity measurements using the Velocity Azimuth Display (VAD) algorithm. Wind speed ranged from 35 to 50 $km\ h^{-1}$ (10 - 14 $m\ s^{-1}$) and wind direction was near constant at 225 degrees (south - southwesterly wind). Motion for the Hildale storm was more northerly than the larger population of storms on 14 September (Figure 15). Dynamical effects associated with storm rotation and flow channeling in the Short Creek canyon may have contributed to storm motion. There was little change in steering winds from the time of the first storm to the second - contrast in motion was principally tied to dynamical controls of storm evolution.

The evolution of extreme rainfall from the Hildale Storm is best reflected in K_{DP} fields (Figure 12; right column), which suggest that the line of elevated reflectivity extending north to south of the hail core and along the western margin of the storm was the "source" of extreme rainfall over Maxwell Canyon. Elevated K_{DP} values at approximately 3 km AGL increased rapidly from 2206 to 2214 UTC, with a north-to-south oriented arc of values reaching 3 degrees km^{-1}. The line of elevated K_{DP} was located upwind of Maxwell Canyon, with the timing and orientation of the line consistent with extreme rainfall rates over the watershed during the period from 2015 to 2030 UTC (based on storm speed and elevation of the radar beam). Melting hail and liquid water shed from hail are likely sources of extreme rainfall over Maxwell Canyon (Romine et al. (2008)). Strong downdrafts associated with negative buoyancy from precipitation drag and evaporation of rain and melting of hail likely contributed to extreme rainfall rates over Maxwell Canyon.

The period of extreme rainfall indicated by elevated K_{DP} values was short-lived, forming shortly after 2200 UTC and diminishing after 2218 UTC (Figure 12). Although the K_{DP} signature of extreme rainfall decayed rapidly after the storm passed Maxwell Canyon, it redeveloped as the storm approached the East Fork Virgin River and Keyhole Canyon (Figure 16). Like flash flooding in Maxwell Canyon, extreme rainfall over Keyhole Canyon and the East Fork Virgin River was linked to a small region of elevated K_{DP} in close proximity to the hail core of the Hildale Storm. K_{DP} fields point to the paroxysmal nature of the Hildale Storm. Multiple pulses of extreme rainfall rates evolved over a period less than 60 minutes in duration; pulses of extreme rainfall rates had life cycles of 10 - 20 minutes and exhibited rapidly varying spatial distributions of extreme rainfall rates.

The 266 $m^3\ s^{-1}$ peak discharge measurement in the 5.3 km^2 Maxwell Canyon watershed provides evidence of the extreme rainfall rates from the Hildale Storm; a rough comparison with rainfall rate is through the 181 $mm\ h^{-1}$ representation of peak discharge that is obtained by dividing 266 $m^3\ s^{-1}$ by 5.3 km^2 and converting units to $mm\ h^{-1}$. The 181 $mm\ h^{-1}$ peak discharge reflects an idealized steady state flow through the watershed.

What are the rainfall rates over a 10 - 20 minute period that are required to produce a peak discharge of 266 $m^3\ s^{-1}$ over the 5.3 km^2 watershed? We examine this question using simulations of flood response with the KINEROS2 hydrologic model. We implemented the model for Maxwell Canyon with parameters derived from GIS data layers using the AGWA algorithms (see Morin et al. (2006) and Goodrich et al. (2011) and Section 2 for additional details). We use a digital elevation model with 10-m resolution, land use map from National Land Cover Dataset with a spatial resolution of 30 m and soil attributes from the SSURGO dataset. The Manning roughness coefficient for channels is 0.035. Field inspection of the watershed in November 2016 indicated that virtually the entire upper watershed of Maxwell Canyon had erosive runoff from the storm. We do not attempt to distinguish spatially varying rainfall over the watershed (given the elevation of the beam and rapid storm motion, polarimetric radar measurements provide little guidance on the spatial distribution of rain over the 5 km^2 watershed). Field observations were also used to partition the watershed into channel and plane overland flow elements. We assumed that the channel of Maxwell Canyon was fully wetted (by the first storm) when rainfall initiated around 2215 UTC.

Assuming a wet watershed and channel, the constant rainfall rate over a 15 minute period needed to produce a peak discharge of 266 $m^3\ s^{-1}$ in Maxwell Canyon is 215 $mm\ h^{-1}$, a rainfall rate larger than the 1000-year, 15 minute rainfall rate for Short Creek (203 $mm\ h^{-1}$; NOAA Atlas 14, Volume 1, Version 5). For 10 minute time interval, the constant rainfall rate increases to 280 $mm\ h^{-1}$. For 20 minute time interval, the rainfall rate decreases to 190 $mm\ h^{-1}$.

Rainfall rates inferred from hydrologic model analyses are larger than the 100 $mm\ h^{-1}$ rain rates at 7-minute time scale measured at the downstream Short Creek stream gaging station (a rain gage is colocated at the station). As noted above, radar, lightning and peak discharge measurements all point to rainfall rates in Maxwell Canyon that were markedly larger than those at the low-elevation gaging station. The peak discharge measurement of 266 $m^3\ s^{-1}$, combined with hydrologic modeling analyses points to rainfall rates over Maxwell Canyon exceeding 200 $mm\ h^{-1}$ at time scales less than 15 minutes. A key assumption in assessing rainfall rates through these analyses is the accuracy of indirect discharge measurements of flood peak magnitudes; as noted in the introduction measurement error is a major issue for the most extreme floods (see House and Pearthree (1995) for a particularly insightful examination of extreme flood peak measurements in the southwestern US).

Hydrologic modeling analyses for Maxwell Canyon provide general guidance on rainfall rates associated with peak discharge values around 270 $m^3\ s^{-1}$ for 5 km^2 watersheds. Flood peaks from small drainage areas can result in record flood peaks over much larger downstream watersheds. The Hildale storm was the principal agent for the flood of record in the East Fork of the Virgin River at a drainage area of 890 km^2 (Figure 17) from a 26-year record. The rainfall-weighted flow distance (Smith et al. (2002)) to the basin outlet for the East Fork Virgin River decreased to a value close to 8 km at 2240 UTC as the Hildale storm passed through the lower portion of the drainage basin, consistent with the rapid rise to the peak discharge of 98 $m^3\ s^{-1}$ at 0015 UTC on September 15 (Figure 17).

The rainfall rate field at 2245 UTC (Figure 17) shows a storm with large rainfall rates close to the basin outlet. Elevation of the radar beam and storm speed dictate that the rainfall distribution at 2245 UTC was shifted somewhat from the location shown in Figure 17, but the conclusion that extreme rainfall was concentrated close to the outlet clearly holds. The record flood in the East Fork Virgin River at a drainage area of 890 km^2 was largely the product of a storm that was smaller than 60 km^2 and passed through the watershed in less than 20 minutes.

5 Extreme Floods in the Colorado Plateau

In this section we examine the hydroclimatology of extreme floods in the Colorado Plateau through analyses of extreme rainfall and flooding in Fort Pearce Wash, Kanab Creek, the Virgin River, the Paria River, the Dirty Devil River and the Escalante River (Figure 1). Our focus is on the upper tail of flood peaks, including floods ranging from 10-year return interval to record floods. We examine scale-dependent flood response from the perspective of both basin size and storm size; motion of storms relative to the basin outlet is a key element of flood analyses. We also assess how geographic variability in storm occurrence, motion and intensity contribute to spatial heterogeneity of flood peaks. The seasonally varying structure of extreme rainfall and flooding is a third central topic of this section; we will focus on a spectrum of storm types stratified by convective intensity and synoptic forcing.

Peak magnitudes for the 14 September 2015 flood decreased rapidly downstream of Short Creek, as is common for influent ephemeral watersheds (Goodrich et al. (1997) and Goodrich et al. (2004)); the peak in Fort Pearce Wash of 40 $m^3\ s^{-1}$ (black line in Figure 18) at a drainage area of 3400 km^2 was 15% of the the upstream peaks in Maxwell Canyon at 5 km^2 and Short Creek at 50 km^2 scale (see Figure 1 for watershed location). The decrease in discharge from Short Creek to the Fort Pearce Wash gaging station resulted from flood peak attenuation and channel infiltration losses; the time of travel for the flood wave from Short Creek to the Fort Pearce Wash gaging station, approximately 11 hours, provides ample time for both.

The largest flood peaks in the 22-year record of Fort Pearce Wash occurred on 15 August 2003 and 16 July 2012 (Figure 18). Both had magnitudes that were close to the 266 $m^3\ s^{-1}$ maximum discharge values from the 14 September 2015 storm in Maxwell Canyon and Short Creek from the Hildale Storm. Response times in Fort Pearce Wash for the August 2003 and July 2012 storms were comparable to the September 2015 flood response in Short Creek, despite the fact that the watershed is almost 2 orders of magnitude larger. The hydrograph for the July 2012 flood illustrates the common usage of "flash" as a verb for Colorado Plateau rivers. From a dry channel, discharge increased to the 270 $m^3\ s^{-1}$ peak in 40 minutes, with a similarly rapid falling limb of the hydrograph (Figure 18). The peak discharge and time to peak are similar for the August 2003 flood.

Fort Pearce Wash flashed on 16 July 2012 in response to extreme rainfall rates from a severe thunderstorm that tracked through the region from 2200 to 2400 UTC (Figures 18 and 19). The rainfall-weighted flow distance to the basin outlet of Fort Pearce Wash was approximately 12 km at 2245 UTC (the time for which the rainfall rate field is shown in Figure 18). Like the record flood for the East Fork Virgin River on 14 September 2015, the rapid rise and fall of the Fort Pearce Wash hydrograph for the 16 July 2012 storm was produced by extreme rainfall rates during a short period from a storm near the basin outlet (Figure 18). For record floods in Fort Pearce Wash, the size of storms producing extreme rainfall rates is the important spatial scale, not the drainage area of the watershed. Extreme flood magnitudes of southwestern US watersheds over a wide range of basin scales is dependent on hydrologic response to small areas of intense rainfall and channel infiltration losses in downstream channel segments.

Storm properties for the July 2012 flood in Fort Pearce Wash reprise themes that emerge from analyses of the 14 September 2015 flood in its headwaters. Like the Hildale storm, the 16 July 2012 storm was large relative to flash flood producing storms in the study region, with 45 dBZ storm area exceeding 60 km^2. Also like the Hildale storm, the storm was rapidly moving, with storm speeds between 30 and 40 $km\ h^{-1}$, and motion was from southwest to northeast (Figure 18; compare also with the climatological analyses in Figures 7 and 8). K_{DP} signatures of extreme rainfall rates for the September 2015 Hildale Storm were also prominent features of the 16 July 2012 Fort Peace Wash storm (Figure 19); they were concentrated during a period of 15-20 minutes beginning at approximately 2240 UTC (Figure 19). The storm exhibited rotational signatures of a supercell thunderstorm, based on Doppler velocity observations and the NWS mesocyclone detection algorithm. Dynamical processes associated with storm rotation likely contributed to the extreme rainfall rates during the period from 2240 - 2300 UTC (see Nielsen and Schumacher (2018)). Like the Hildale Storm, the 16 July 2012 storm was an end-member on the convective intensity spectrum of flash flood producing storms and exhibited rapidly varying pulses of extreme rainfall rates.

The geography of extreme flooding in Colorado Plateau watersheds is tied to spatially varying properties of storm occurrence and motion; analyses of flash flood producing storms in Section 3 provide a climatological setting for interpreting spatial heterogeneity of extreme floods. Terrain features make some watersheds, including Short Creek and the larger Fort Pearce Wash watershed, prone to extreme flooding from storms that exhibit the dominant southwest to northeast motion. Mean storm motion for flash flood producing storms in high elevation regions of the Colorado Plateau differ markedly from storms in low elevation regions (Figures 6, 8 and 9). Record and near-record floods in the Escalante River on 24 August 1998 (Figures 20), the upper Paria River on 19 August 2012 (Figures 21 and 22) and North Fork Virgin River on 12 July 2018 (Figure 23) were produced by thunderstorms that initiated along high elevation, headwater portions of the watershed and exhibited storm motion that differed markedly from the southwest-to-northeast pattern of the 14 September 2015 Hildale storm and 16 July 2012 Fort Pearce Wash storm.

The largest flood peak in the 62-year USGS stream gaging record of the Escalante River at 823 km^2 scale is the 130 $m^3\ s^{-1}$ peak from the 24 August 1998 storm (Figure 20). The storm producing the 1998 peak was a severe thunderstorm that formed along the drainage divide between the Escalante and Paria River basins. Over its life cycle the storm moved slowly to the east, away from the drainage divide. Small net storm motion resulted in heavy rainfall, intense lightning, flooding and landslides in the upper Escalante River basin (Figure 20 and NCEI Storm Events database). The most intense rainfall was concentrated in a small portion of the watershed and it was not close to the basin outlet; if the storm centroid had been 20 km further east, the flood peak at the USGS stream gaging station would likely have been much larger than 130 $m^3\ s^{-1}$. Or viewed from the perspective of the storm, peak discharge values in the drainage network close to the most extreme rainfall were likely much larger than 130 $m^3\ s^{-1}$.

Thunderstorms on 19 August 2012 (Figure 21) produced a flood peak of 214 $m^3 s^{-1}$ at the upper Paria River stream gage near Kanab, Utah at a drainage area of 1680 km^2. The August 2012 storm formed at high elevation close to the drainage divide and moved from northwest to southeast. There are large spatial gradients in mean motion of flash flood producing storms over the Paria watershed; motion of the 19 August 2012 storm was in line with mean motion in the headwaters of the Paria (Figure 9). The upper Paria flashed in response to the 19 August 2012 storm with discharge increasing from near 0 to 214 $m^3 s^{-1}$ in 45 minutes. The August 2012 storm was a multicell storm, with an elongated region of elevated K_{DP} at 2046 UTC (Figure 21). Storm motion down the watershed contributed to the extreme nature of the flood peak (see Morin et al. (2006)).

The downstream peak for the lower Paria River at Lees Ferry, Arizona for the 19 August 2012 flood (see Figure 21 for location) was less than a third of the upstream peak near Kanab, again reflecting the prominent role of channel losses and flood peak attenuation in Colorado Plateau rivers and southwest ephemeral streams in general (see Hereford (1986) and Goodrich et al. (2018)). The distributions of flood peaks at the two Paria gaging stations for the period of overlapping records (1959 - 1973 and 2003 - 2015) are strikingly similar (Figure 22), despite the large difference in drainage area, 1680 km^2 versus 3680 km^2, highlighting the weak dependence of flood peak magnitudes on drainage area. Spatial heterogeneity of extreme flooding in the Paria watershed is linked to the climatology of storm size and motion. Average storm speeds are small in the upper Paria watershed; in the lower watershed mean storm speeds are large with a pronounced southwest to northeast orientation. The spatial contrasts in structure and motion of monsoon thunderstorms combine with open channel flow processes to determine flood peak properties over the Paria River basin, and more generally, over the Colorado Plateau.

Major flooding in the North Fork Virgin River on 12 July 2018 resulted from a thunderstorm that initiated over high elevations and moved slowly to the south (Figure 23). Discharge at the USGS stream gaging station, which has a drainage area of 891 km^2, rose from near 0 to the peak discharge of 153 m^3 s^{-1} in 30 minutes (Figure 24). The most extreme flooding, as reflected in locations of landslides, was concentrated in a small portion of the North Fork Virgin drainage basin and is contained within the area of maximum K_{DP} at 0200 UTC in Figure 23. Like the 14 September 2015 storm, the July 2018 storm exhibited rapidly varying K_{DP} signatures of extreme rainfall rates, with locations of peaks in K_{DP} paired with locations of hillslope damage and flooding. A 2-hour accumulation of 62 mm from a rain gage located west of the storm track at 0215 UTC (denoted by a red star in Figure 23) has a return interval that is longer than 200 years; more extreme rainfall accumulations likely occurred along the track of the storm.

The record flood peak for the 92 years of observations from the North Fork Virgin River is 259 m^3 s^{-1} and occurred on 7 December 1966 (Butler and Munforff (1970)). The peak discharge of 646 m^3 s^{-1} at the downstream Virgin River station, which has a drainage area of 2480 km^2, is 70% larger than the second largest flood peak in a stream gaging record of more than 100 years. It is one of the largest flood peaks in the systematic USGS stream gaging record from the Colorado Plateau (Figure 2). Rainfall totals for the December 1966 storm were unprecedented. The 24-hour accumulation of 112 mm at Orderville, Utah on December 6 (Butler and Munforff (1970)) has a return interval of approximately 500 years (NOAA Atlas 14, Volume 1, Version 5). The 3-day total rainfall at Orderville was 184 mm. Not surprisingly, there are sharp contrasts in the timing of flood response between the December 1996 flood and the July 2018 flood (Figure 24).

Winter storms are important flood agents for large watersheds in the Colorado Plateau, both in the current climate and during the past several millennia (House and Hirschboeck (1993), Ely et al. (1994) and Ely (1997)). The December 1966 flood peaks were produced by a powerful extratropical cyclone affecting the region from 5 - 7 December 1966 (Butler and Munforff (1970)). A major difference between the December 1966 storm and the July 2018 storm is the spatial extent of extreme rainfall; the December 1966 storm produced heavy rainfall over the entire Virgin River basin; the July 2018 storm produced extreme rainfall over a small portion of the North Fork Virgin River basin.

The differences between fall/winter storms and monsoon thunderstorms are not, however, as sharp as they may seem. Radar observations (see Plate 2 of Butler and Munforff (1970)) suggest that embedded convection may have contributed peak rainfall rates over the Virgin River basin for the December 1966 storm. The flood peak of 259 m^3 s^{-1} on the North Fork Virgin River followed a rapid rise produced by an organized region of heavy rainfall (Figure 24 and Plate 2 of Butler and Munforff (1970)). The downstream rise to the 646 m^3 s^{-1} peak in the Virgin River was even sharper. The seasonally varying properties of monsoon thunderstorms from July through September are tied to the increasing frequency of synoptic scale disturbances in September. Extreme rainfall from synoptic disturbances that produce floods through the fall and winter seasons can exhibit convective features that are important elements of extreme rainfall from monsoon thunderstorms. Extreme flooding in the Colorado Plateau arises from a spectrum of storms from the perspective of synoptic forcing and convective intensity.

The largest flood peak among the Colorado Plateau USGS stream gaging stations is the 1014 $m^3\ s^{-1}$ peak which occurred on 7 October 2006 in the Dirty Devil River at a drainage area of 10,800 km^2 (Figure 2; see Figure 1 for basin location). Although the storm lies outside of the monsoon season, it produced severe thunderstorms with extensive lightning, large hail and tornadoes (NCEI Storm Events database). Thunderstorm frequency during October, as shown in Figure 4, is quite low. The October 2006 flood was the product of an extratropical system with a cutoff low west of the study region. Synoptic scale forcing for the October 2006 storm resulted in organization of rainfall into broken lines of convection with associated regions of stratiform rain. Lines of convection generally moved eastward and embedded storm elements tracked from south to north, resulting in heavy rainfall over the region for a period of more than 24 hours (Figure 25).

A similar storm on 27 September 2014 produced the second largest flood peak, 84 $m^3\ s^{-1}$, in the 50 year record of Kanab Creek. The largest peak in Kanab Creek, which has a drainage area of 502 km^2, was 86 $m^3\ s^{-1}$ and occurred on 8 September 1961. Heavy rainfall on 27 September 2014 was organized by a cutoff low centered in California; flooding and flash flooding extended from southern Arizona through Utah into the northern Rocky Mountains of Wyoming, Idaho and Montana. Synoptic forcing on 27 September 2014 resulted in organization of rainfall into broken lines of convection (Figure 26). The storms produced near-record daily lightning counts for the study region, with peak flash densities exceeding 5 CG strikes km^{-2}. As the cutoff low moved slowly to the east, lines of convection shifted eastward, with heaviest rainfall over the North Fork Virgin River between 1530 and 1630 UTC and heaviest rainfall over Kanab Creek from 1630. - 1830 UTC (Figure 26).

Organization of rainfall into broken lines of convection resulted in multiple storm elements producing rainfall in both Kanab Creek and the North Fork Virgin River (the location of a flash flood fatality during the event: see NCEI Storm Events Database). Persistence of heavy rainfall over multiple hours contributed to flooding in Kanab Creek. The most intense storm elements that passed through Kanab Creek (Figure 26) did not, however, track close to the outlet of Kanab Creek, resulting in a flood peak that was less than 1/3 the magnitude of the September 2015 Maxwell Canyon peak.

The recent history of flooding in Kanab Creek has been relatively quiet by historical standards. Woolley notes that "on August 30, 1882, a terrific flood swept down Kanab Creek Canyon and literally swamped the town. This was followed by similar cloudburst floods each summer until 1886. In that period of 5 years the channel was changed almost beyond the comprehension of even those who saw it. Its depth increased by 50 feet or more and its width by about 200 feet in places" (Woolley (1946)). Kanab Creek provides one of the most striking examples of arroyo formation during the late 19th century.

Analyses of the arroyo problem have pointed to extended periods - multi-year to multi-decadal - with elevated frequency of extreme floods throughout the Colorado Plateau (Graf (1983), Webb and Hereford (2001), Antevs (1952), Hereford and Webb (1992), Balling Jr. and Wells (1990), Higgins and Shi (2000) and Harvey and Pederson (2011)). Paleoflood studies point to clustering of extreme floods over millennial time scales. The Colorado Plateau has experienced multiple periods of elevated flood frequency during the past 1000 years (Webb and Baker (1988), Webb et al. (1988), Ely et al. (1993) and Harden et al. (2010)).

Paleohydrologic reconstructions in the Escalante River (Webb et al. (1988)) include a 600 m^3 s^{-1} peak close to the current stream gaging location from a "cloudburst" storm on 27 August 1932 (Woolley (1946) and Webb et al. (1988)). Paleoflood peaks approaching 2000 m^3 s^{-1} (Figure 2) have been reported for the lower Escalante River at drainage areas between 3000 and 4000 km^2 (Webb et al. (1988) and Enzel et al. (1993)). These are the largest flood peaks for basins with drainage area greater than 100 km^2, but not for smaller basins - the 14 September 1974 Eldorado Canyon hailstorm produced a peak larger than 2000 m^3 s^{-1} at 50 km^2 (Figure 2).

There is a large gap between the 130 m^3 s^{-1} peak in the Escalante River on 24 August 1998 and the 600 m^3 s^{-1} peak in August 1932 and an even larger distance to the 2,000 m^3 s^{-1} paleoflood peaks in the lower Escalante. "Organization" of rainfall in space and time, as illustrated by the December 1966, October 2006 and September 2014 storms provides one avenue for bridging the gap. The paroxysmal precipitation of the desert, as illustrated by the 14 September 2015 Hildale Storm and the 14 September 1974 Eldorado Canyon Storm provides another. The combination of extremes in convective intensity and synoptic forcing - an organized system of Eldorado Canyon-like storms - provides scenarios for extremes in flooding over a wide range of basin scales.

6 Summary and Conclusions

The major findings of this paper are the following:

- The 14 September 2015 Hildale Storm in southern Utah, which resulted in 20 flash flood fatalities, provides the quintessential example of the paroxysmal precipitation of the desert. Polarimetric radar measurements suggest that two 10-20 minute periods of extreme rainfall rates during the 2 hour life cycle of the hailstorm resulted in catastrophic flash flooding. Both periods are characterized by K_{DP} signatures of extreme rainfall. Similar K_{DP} signatures characterized multiple storms that have produced record and near-record flood peaks in Colorado Plateau watersheds.
- The Hildale Storm developed a cyclonic structure with a line extending east of the hail core and a cyclonically rotating line that initially extended south from the hail core. The southward-oriented line developed the elevated K_{DP} signature that was the precursor to extreme rainfall rates over Maxwell Canyon. Melting hail and liquid water shed from hail are likely sources of extreme rainfall rates over Maxwell Canyon and Keyhole Canyon. Negative buoyancy associated with precipitation drag and evaporation of rain and melting of hail may have contributed to downdraft enhancement of extreme rainfall rates. Hydrologic modeling analyses indicate that 15-minute rainfall rates in excess of 200 mm h^{-1} are needed to produce a flood peak of 266 m^3 s^{-1} in Maxwell Canyon at a drainage area of 5.3 km^2.
- For the sample of flash flood producing storms during the period from 1998 - 2016, the 14 September 2015 hailstorm was among the most extreme in terms of convective intensity. The Hildale storm was also exceptional for its storm speed, which exceeded 50 km h^{-1}, placing it in the extreme upper tail of storm speeds for flash flood events in the region. Slow storm speed or small net storm motion are among the most common attributes of extreme flash flood events (Doswell et al. (1996)). Extreme storm speed for the Hildale storm sharpens the focus on extreme short-term rainfall rates as the key element of catastrophic flooding.
- Synoptic scale forcing was an important element of water vapor flux into Arizona and southern Utah, preceding initiation of the Hildale Storm. Precipitable water increased steadily from less than 10 mm to 30 mm in the 24 hours preceding storm initiation. A rear inflow jet created by the Hildale storm combined with the strong southwest to northeast water vapor flux over the region to create an environment with exceptionally strong water vapor flux to the storm.

- There is a pronounced seasonal cycle in NAM thunderstorm characteristics, including an evolving climatology of storm motion. The NAM season is dominated by storms that move from southwest to northeast, but July includes a significant population of storms with motion deviating from the norm. The seasonal cycle is also characterized by an increasing frequency of baroclinic disturbances in September, when southwest to northeast storm motion is most prominent.
- "Sooner or later the cloudburst visits every tract", as Gilbert noted, but every tract is unique in the paroxysmal nature of rainfall. The climatology of thunderstorms in the southwestern US study region exhibits spatial heterogeneities that are tied to terrain and large-scale features of storm environment. Superimposed on terrain controls of storm initiation are the seasonal and spatial variations in storm size, motion and convective intensity. Analyses of record and near-record floods in Kanab Creek, Virgin River, Paria River and Escalante River illustrate the controls of storm occurrence, motion and size on flood peak magnitudes.
- The distribution of flood peak magnitudes in Colorado Plateau watersheds is weakly dependent on basin scale, relative to other regions of the US. Flood response is closely linked to the spatial scale of thunderstorms, which have typical sizes ranging from 10 to 50 km^2. Large floods peaks in many watersheds are produced by "small", monsoon thunderstorms that pass close to the basin outlet. Flood peak attenuation and channel infiltration losses also contribute to an environment in which small storms play a major role in flood frequency for much larger watersheds.
- Organization of rainfall in time and space contributes to extreme flood peaks from Fall - Winter storms. The December 1966, October 2006 and September 2014 flood episodes illustrate settings in which multiple storm elements and sub-watersheds contributed synchronously to produce extreme flooding. The boundary between monsoon thunderstorms and Fall - Winter storms is not absolute. The September 2014 and October 2006 storms included copious lightning, hail and tornadoes; radar observations from December 1966 storm suggest that embedded convection contributed to extreme rainfall rates and record flooding.

Our analyses provide insights to the "nature" of extreme floods in arid/semi-arid watersheds of the southwestern US, but also point to questions for future research. Are extreme floods fundamentally different from more common floods? Is the upper tail of flood peaks controlled by extremes of common flood agents or by unusual combinations of flood agents (organized systems of severe thunderstorms producing rainfall rates comparable to the September 2015 Hildale storm, for example)? How do storm climatology and drainage basin structure combine to determine scale-dependent flood response and spatially varying flood hazards? Are there prominent "hotspots" of extreme floods in the Colorado Plateau? Do the Eldorado Canyon (14 September 1974) and Hildale (14 September 2015) Storms provide examples of physical mechanisms controlling the most extreme rainfall rates for monsoon thunderstorms? How hard can it rain? Conventional flood records cover too little time to provide compelling evidence on the spatial heterogeneities of flood peaks in the southwestern US. Paleoflood measurements provide a critical avenue for effectively increasing the time window available for examining extreme floods. Polarimetric radar measurements, especially K_{DP}, provide promising avenues for assessing storm processes that control the paroxysmal precipitation of the desert.

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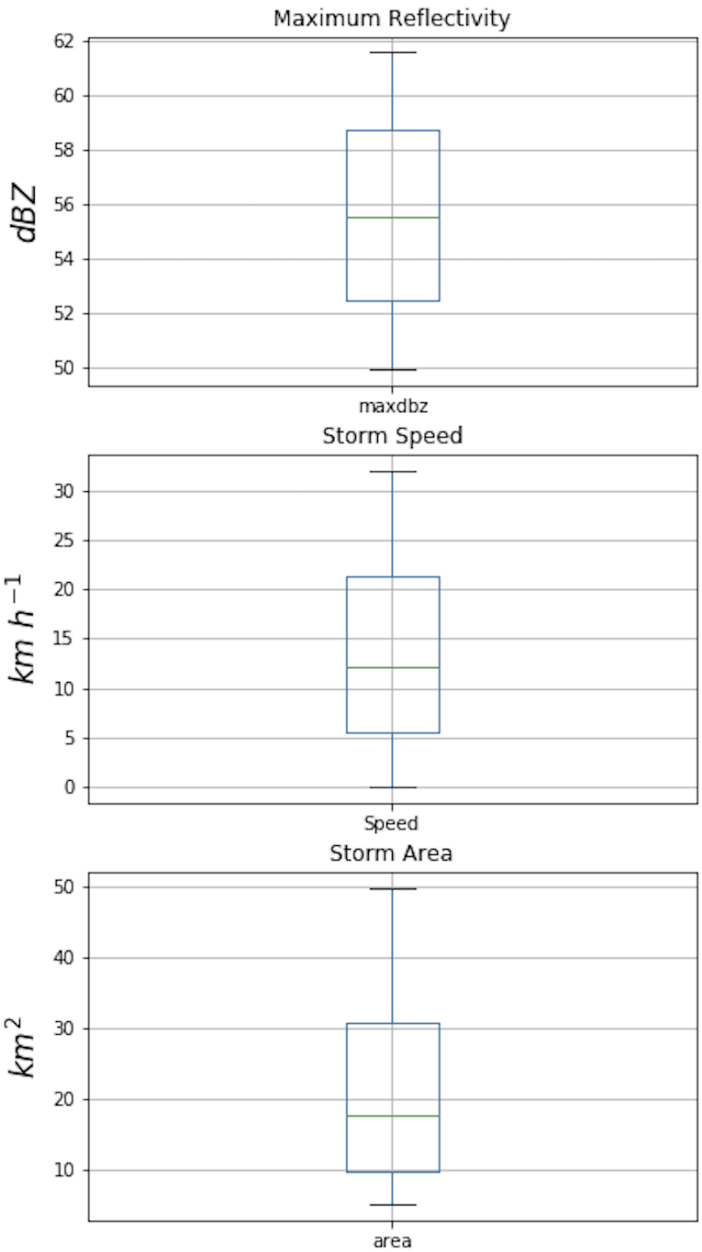

Figure 7. Box plots of maximum reflectivity (top), storm speed (middle) and storm area (bottom) for flash-flood producing storms, 1998 - 2015 (tracked storm elements with 45 dBZ tops greater than 8.5 km). Whiskers are for 0.1 and 0.9 quantiles.

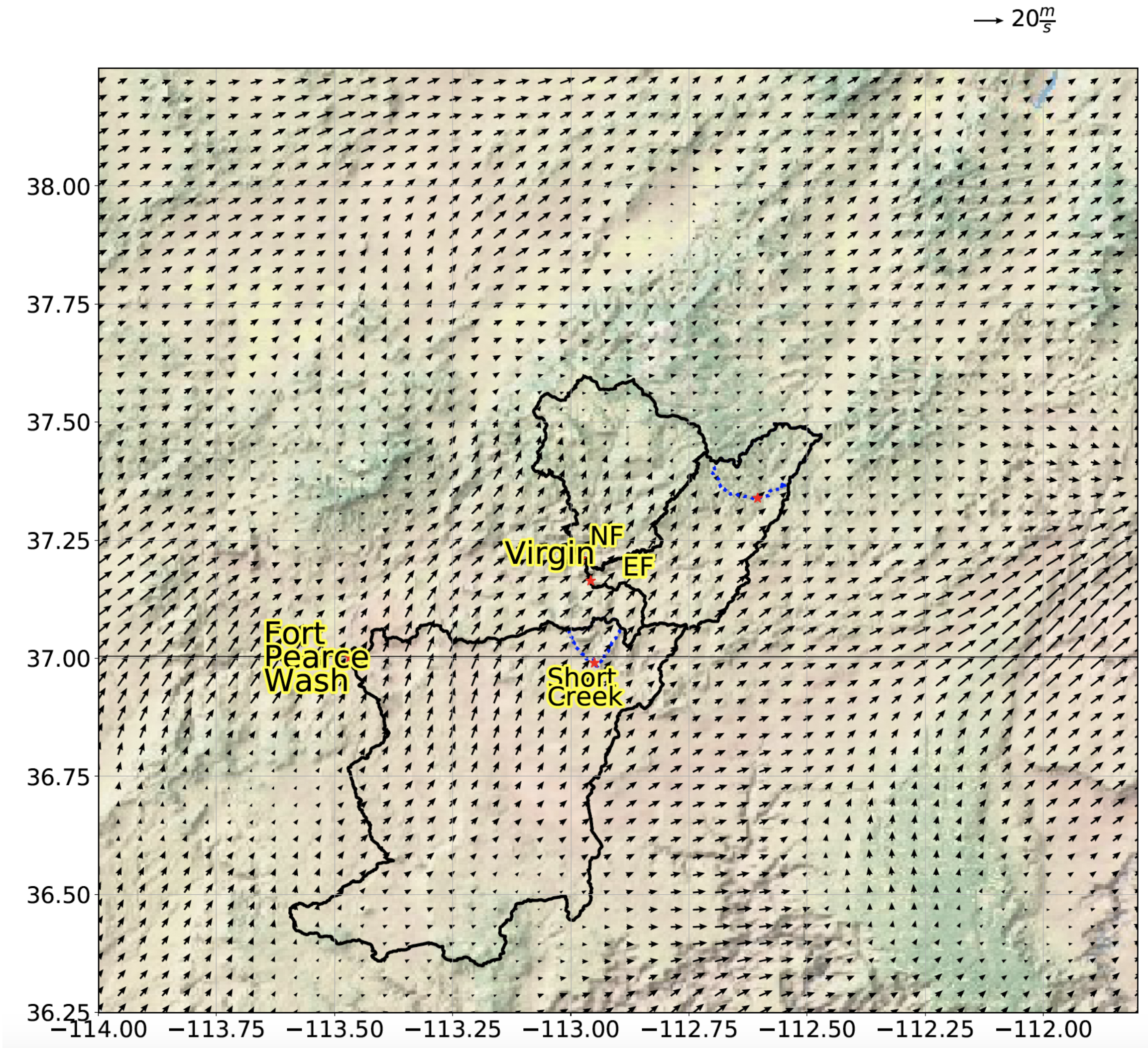

Figure 8. Mean storm motion vectors for flash-flood producing storms, 1998 - 2015 (tracked storm elements with 45 dBZ tops greater than 8 km); western region with Fort Pearce Wash (and Short Creek), East Fork Virgin (EF) and North Fork Virgin (NF) river basin boundaries.

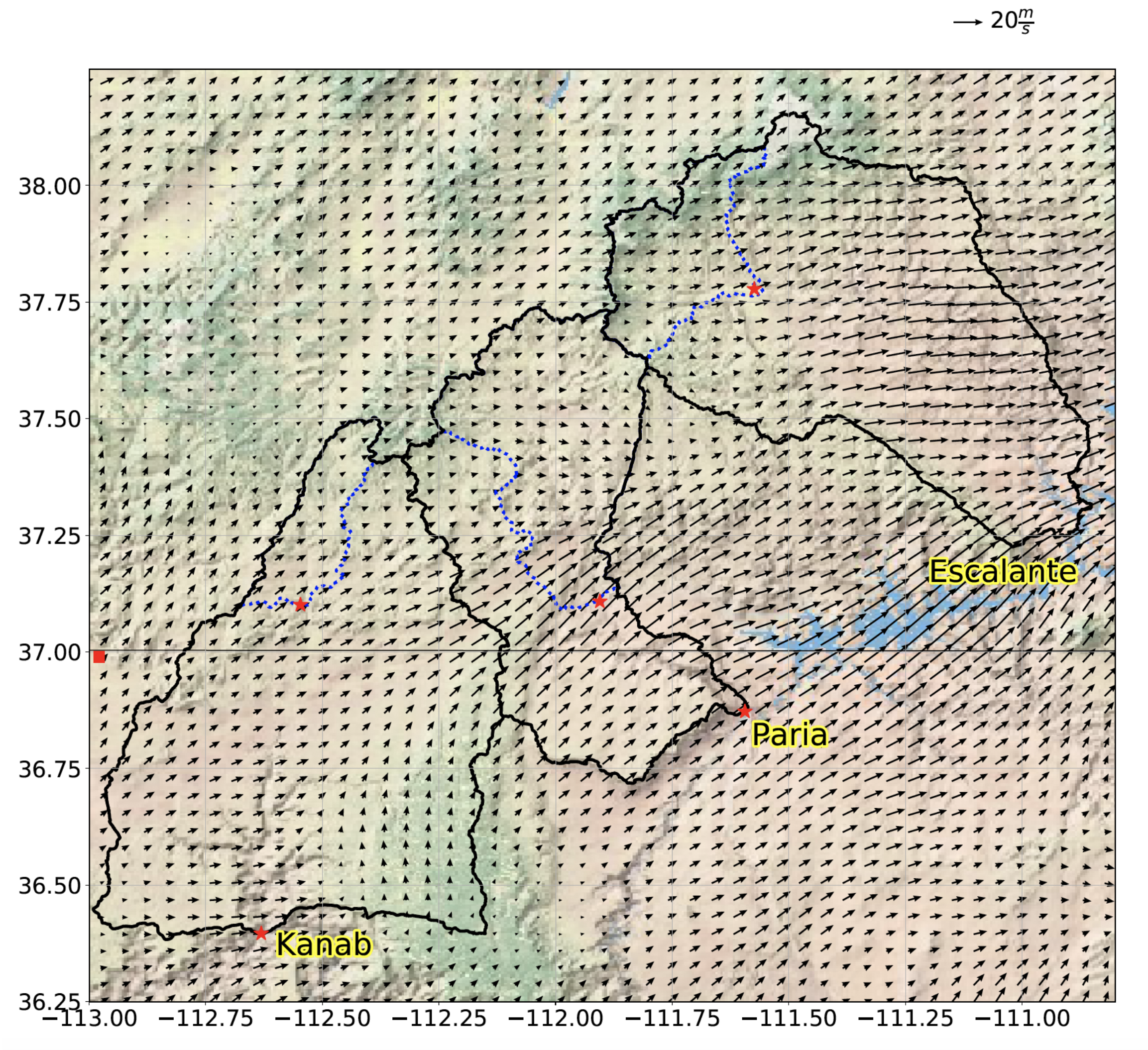

Figure 9. Mean storm motion vectors for flash-flood producing storms, 1998 - 2015 (tracked storm elements with 45 dBZ tops greater than 8 km); eastern region, with basin boundaries for Kanab Creek, the Escalante and the Paria River. Lake Powell (shown in blue) inundates Glen Canyon.

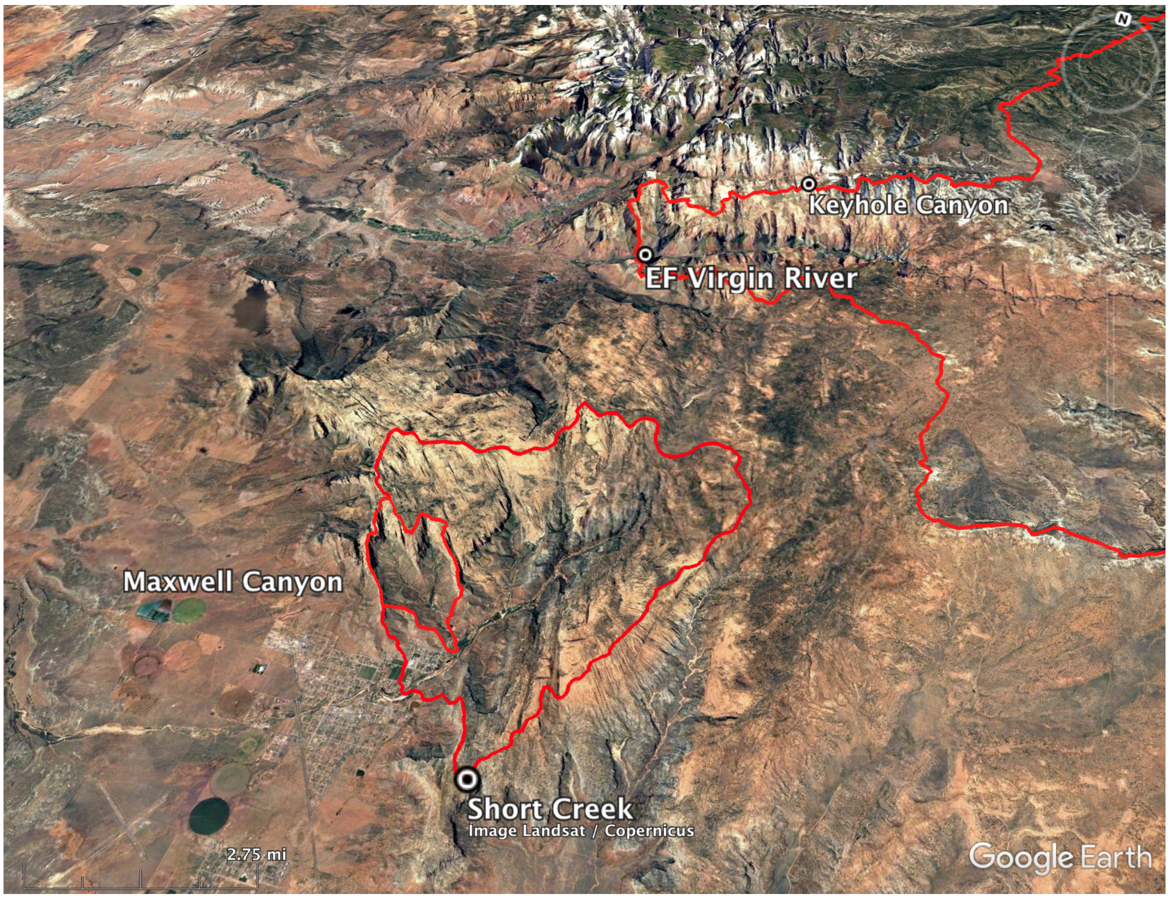

Figure 10. Short Creek, Maxwell Canyon and Virgin River study region. Basin boundaries of Maxwell Canyon and Short Creek are shown, along with a partial basin boundary for the East Fork Virgin River (location of the USGS stream gaging station is marked by black circle). Keyhole Canyon is also marked by a black circle.

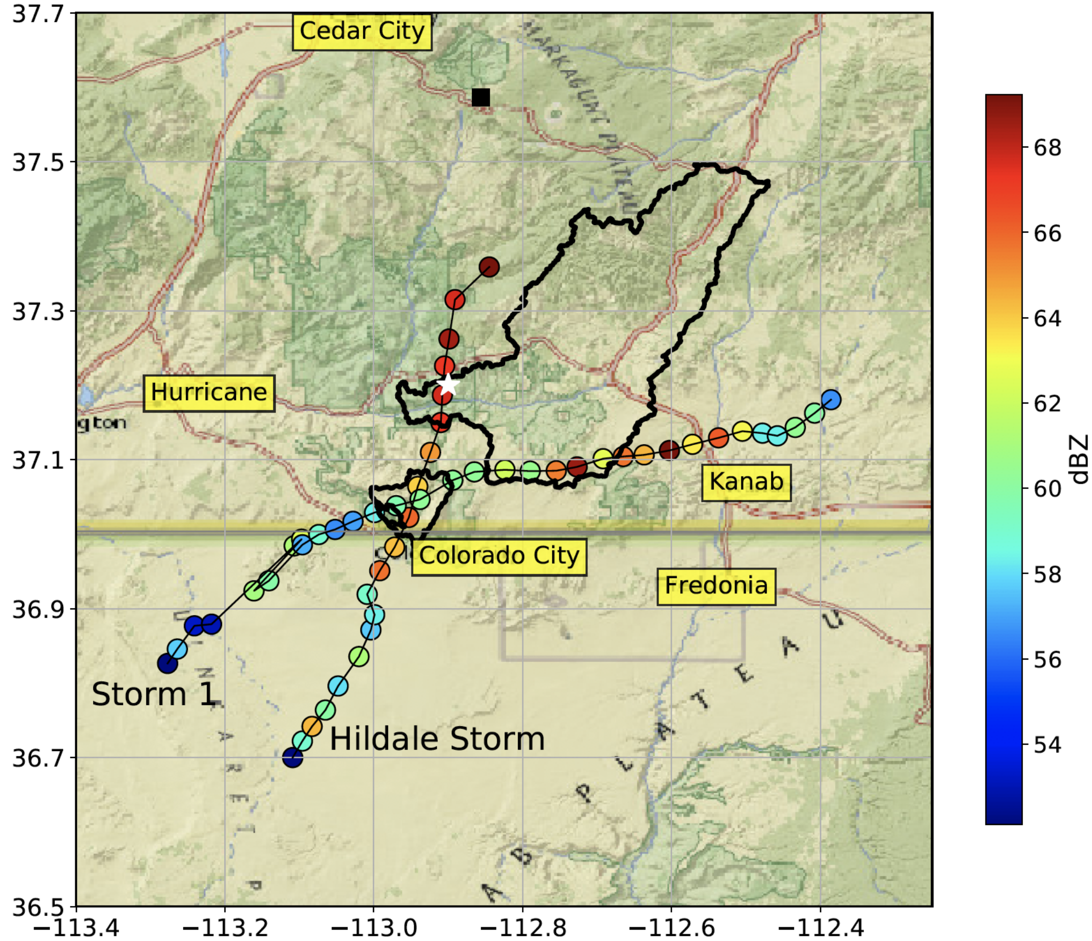

Figure 11. Tracks for the two storms that passed through Short Creek on 14 September 2015; the Hildale Storm is the second to pass through Short Creek. The first storm is denoted "Storm 1". Points are color coded by maximum reflectivity (dBZ). The Short Creek and E. Fork Virgin River basin boundaries are outlined (see also Figure 10). Keyhole Canyon is marked by a white star and the KICX radar location is denoted by a black square.

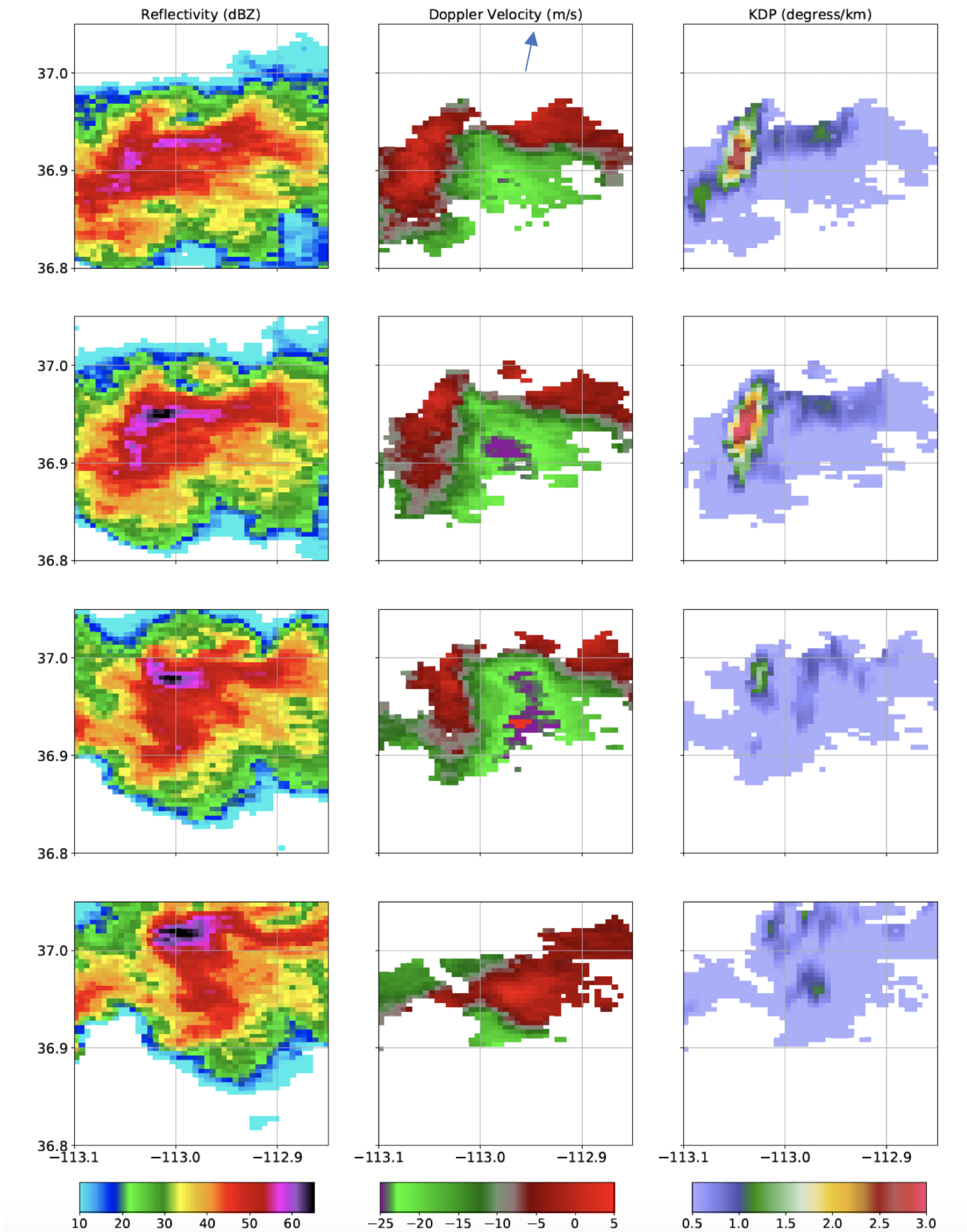

Figure 12. Reflectivity (left), Doppler velocity (middle) and specific differential phase shift (K_{DP}; right) at 2214, 2218, 2222 and 2227 UTC (from top to bottom) on 14 September 2015 from the Cedar City WSR-88D. Blue arrow in top Doppler velocity image shows direction of the Cedar City radar.

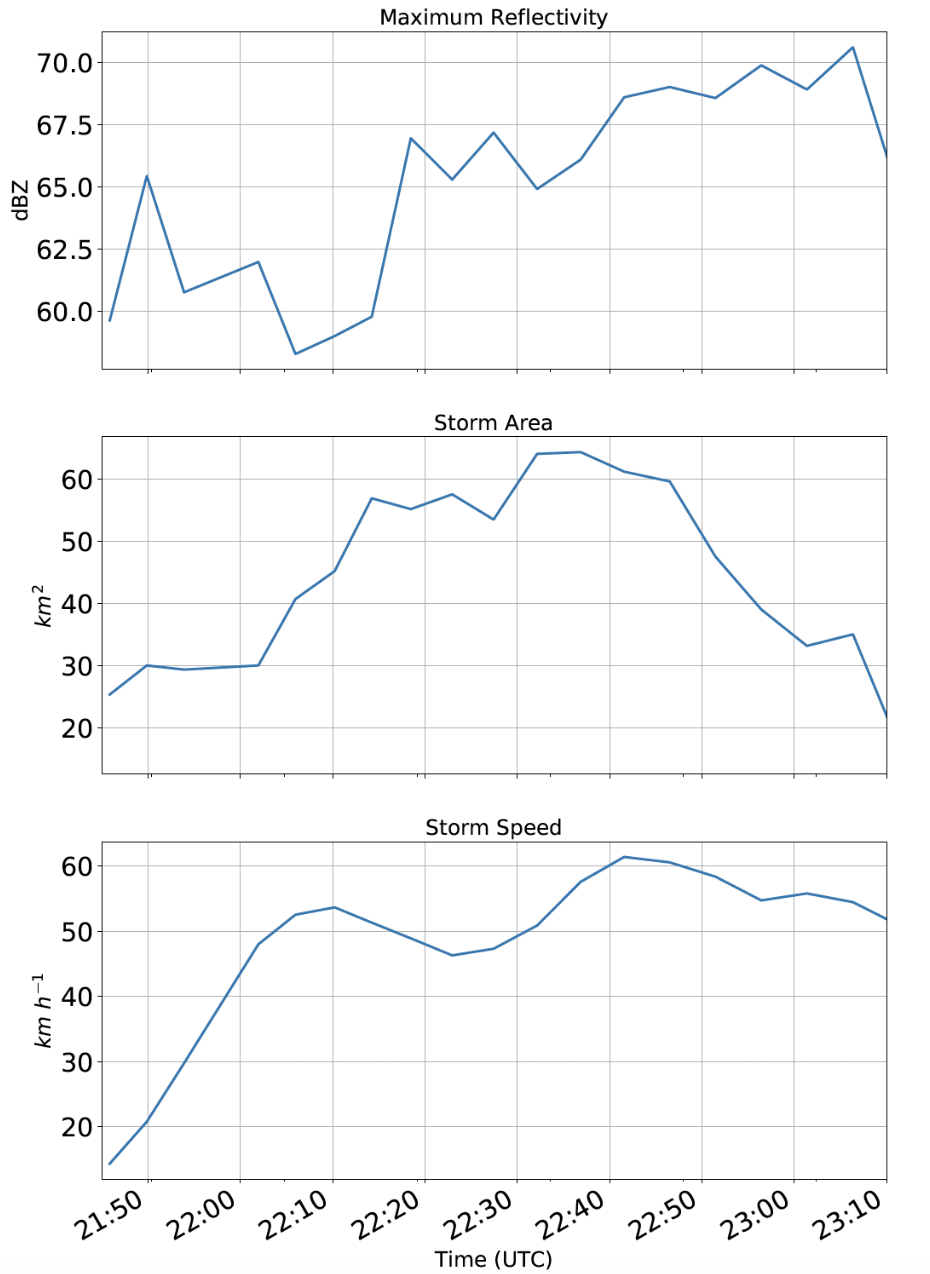

Figure 13. Time series of maximum reflectivity (dBZ; top), storm area (km^2; middle) and storm speed ($km\ h^{-1}$; bottom) for the 14 September 2015 Hildale Storm, based on TITAN storm tracking analyses (see also Figure 11).

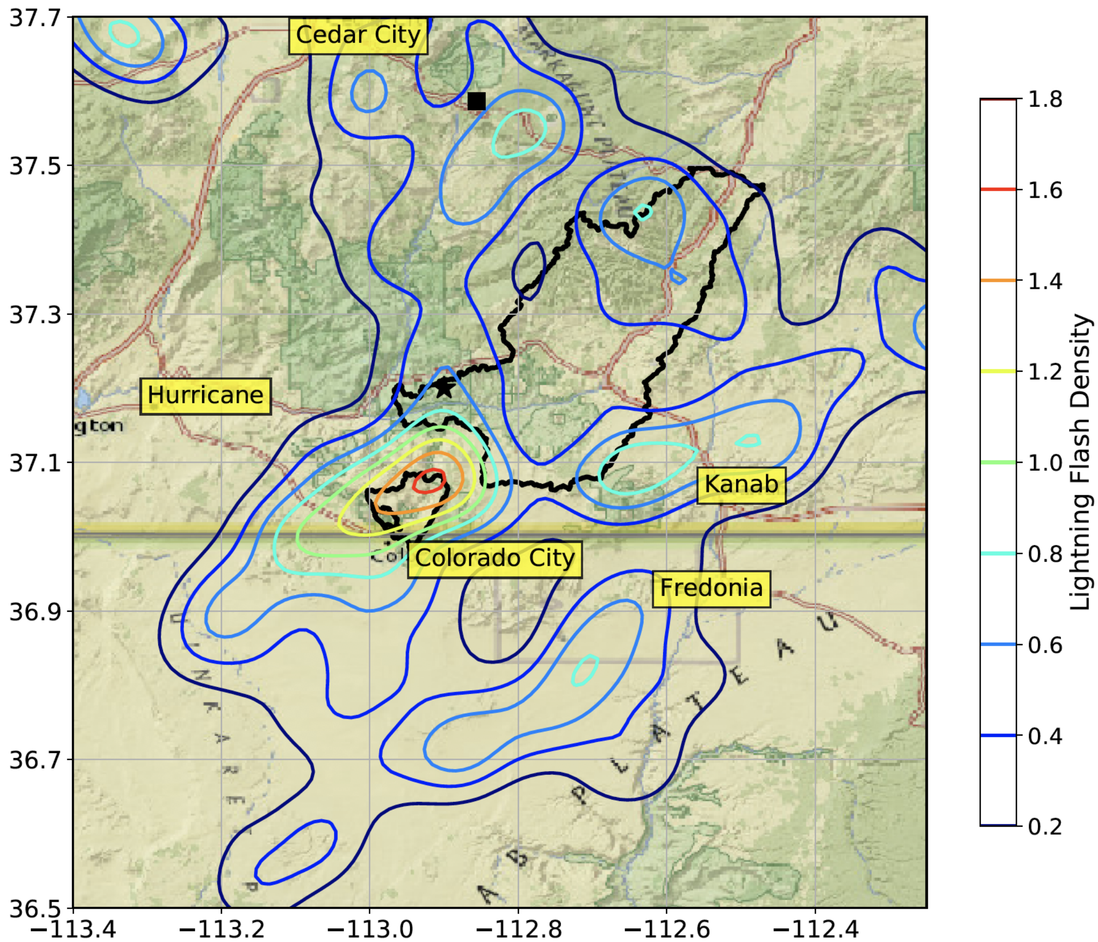

Figure 14. CG lightning flash density contours (CG strikes km^{-2}) for the 14 September 2015 storm. The Maxwell Canyon, Short Creek and E. Fork Virgin River basin boundaries are outlined. Keyhole Canyon is marked by a black star. The KICX radar location is denoted by a black square.

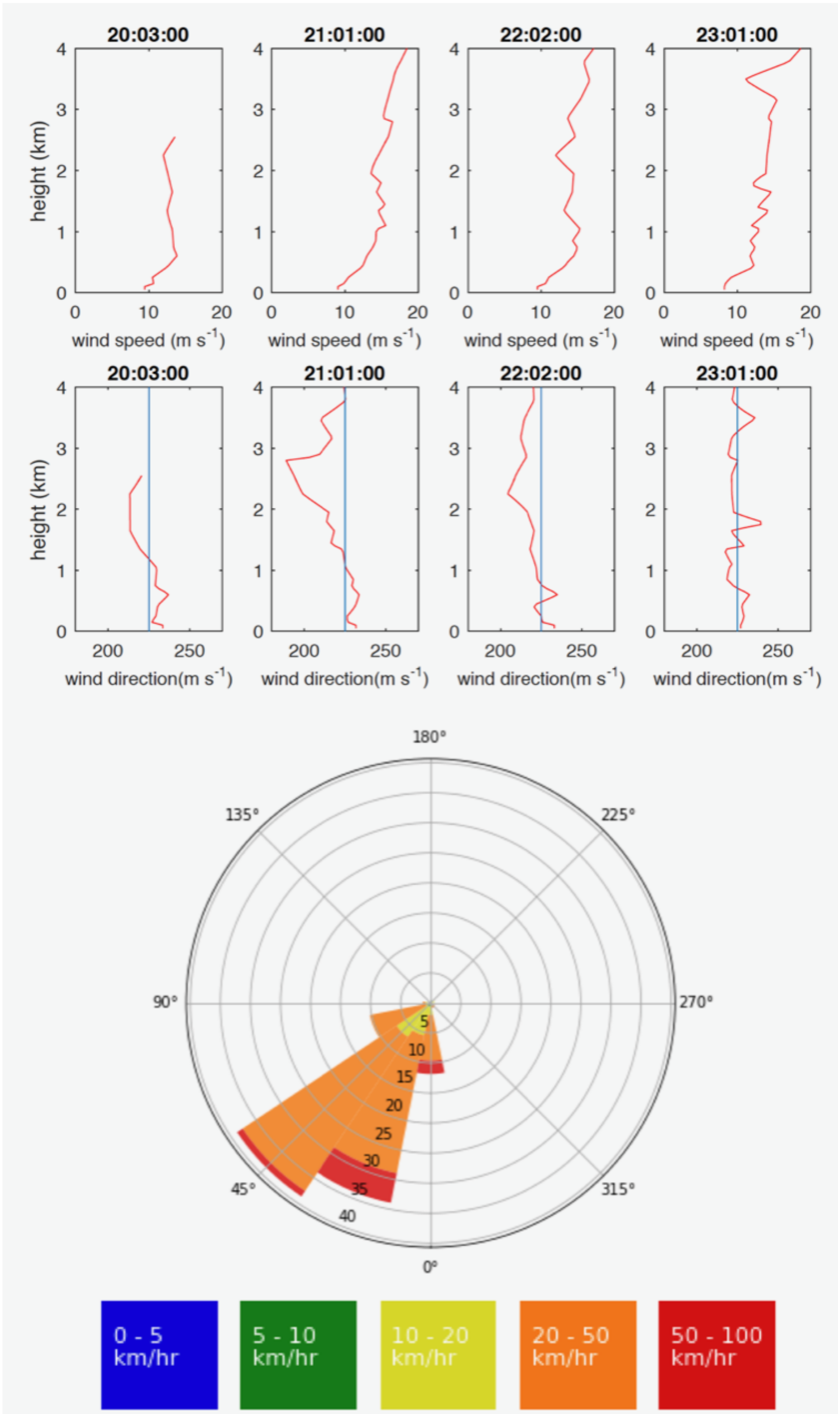

Figure 15. Wind profiles from KICX Velocity Azimuth Display (VAD) analyses from 2000 - 2300 UTC (top). Elevation is given in height above the radar; elevation of the radar is 3200 meters MSL. The vertical blue line for wind direction is 225 degrees (wind direction from south-west). Wind rose of storm direction and storm speed for all tracked storms on 14 September 2015 with tops greater than 8.5 km (bottom).

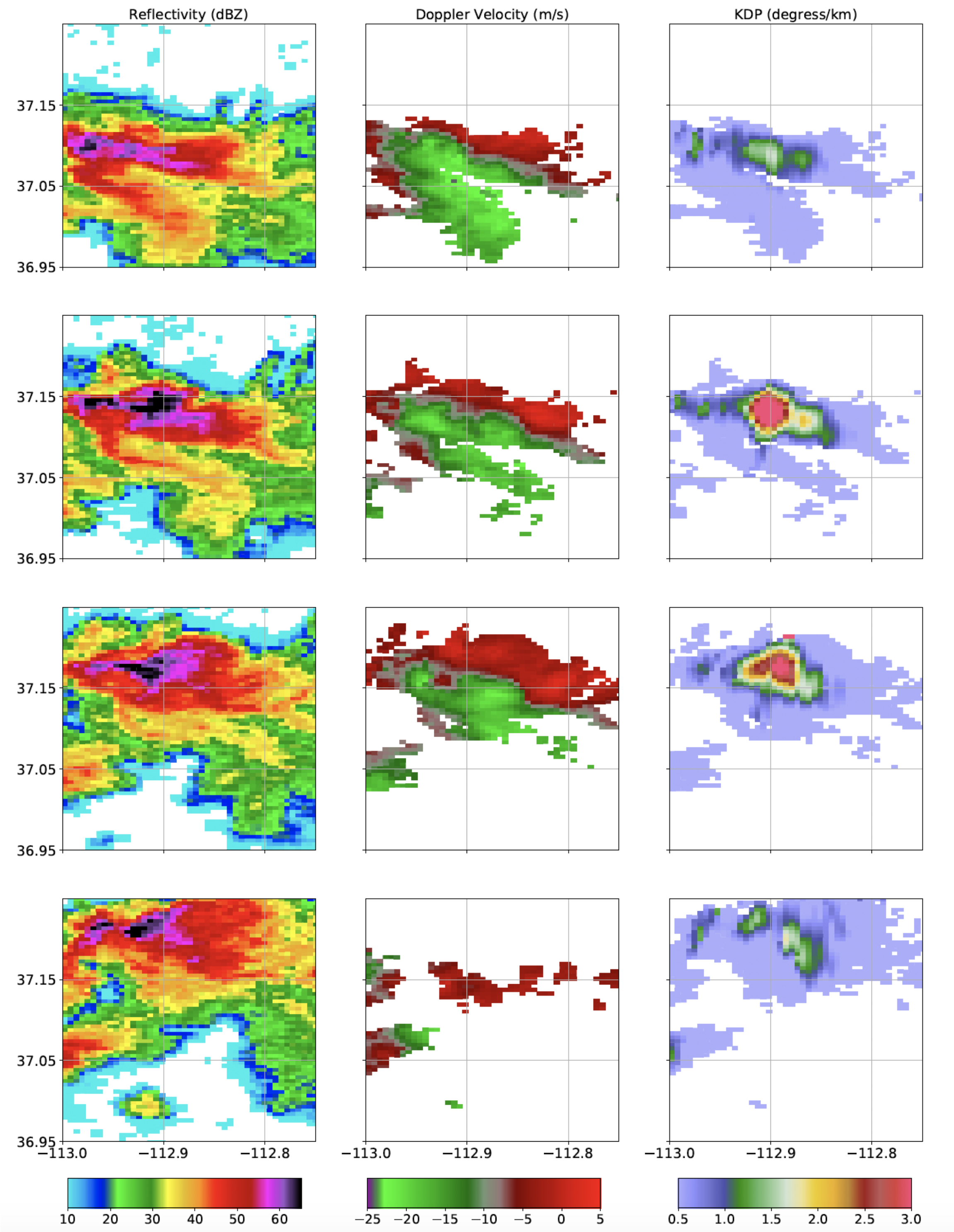

Figure 16. Reflectivity (left), Doppler velocity (middle) and specific differential phase shift (K_{DP}; right) at 2236, 2241, 2246 and 2251 UTC (top to bottom) on 14 September 2015 from the Cedar City WSR-88D.

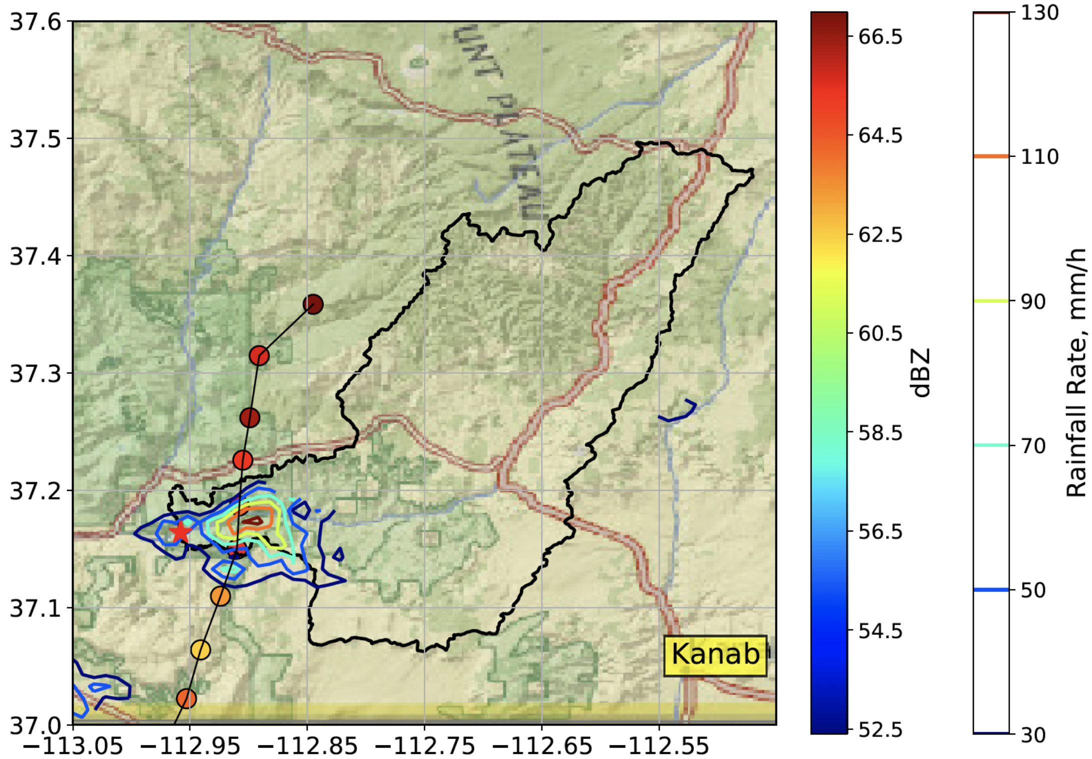

Figure 17. Rainfall rate field at 2245 UTC on 14 September 2015 with basin boundary for East Fork Virgin River and storm tracks of the Hildale storm from 2232 UTC to 2306 UTC. Outlet of the basin is denoted by a red star.

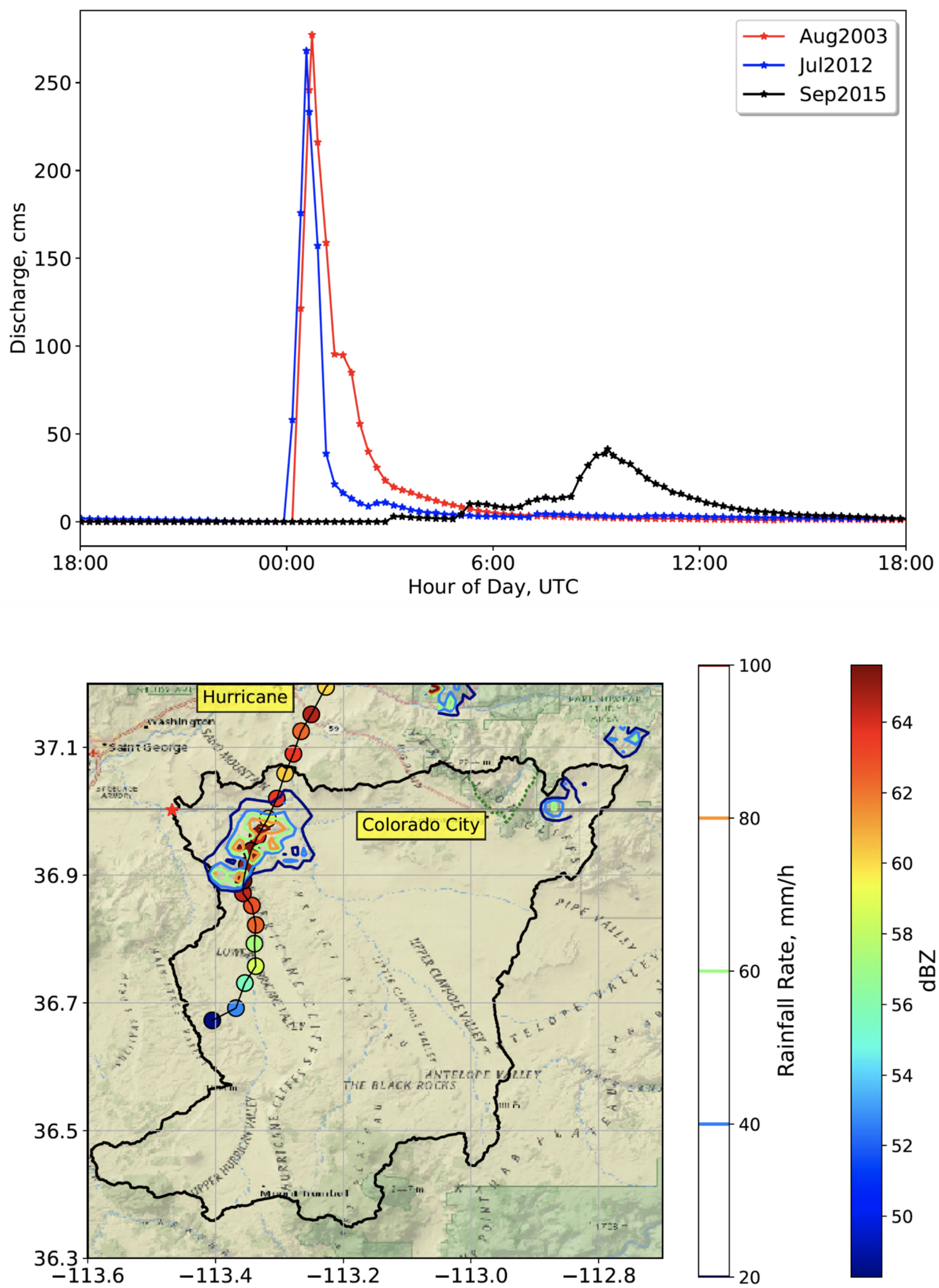

Figure 18. Discharge hydrographs (top) for Fort Pearce Wash on 15 August 2003 (red), 16-17 July 2012 (blue) and 14-15 September 2015 (black). Rainfall rate field at 2245 UTC on 16 July 2012 (bottom), with the Fort Pearce Wash basin boundary outlined in black; the outlet is denoted by a red star (in the northwest corner of the watershed). The Short Creek boundary is outlined in green.

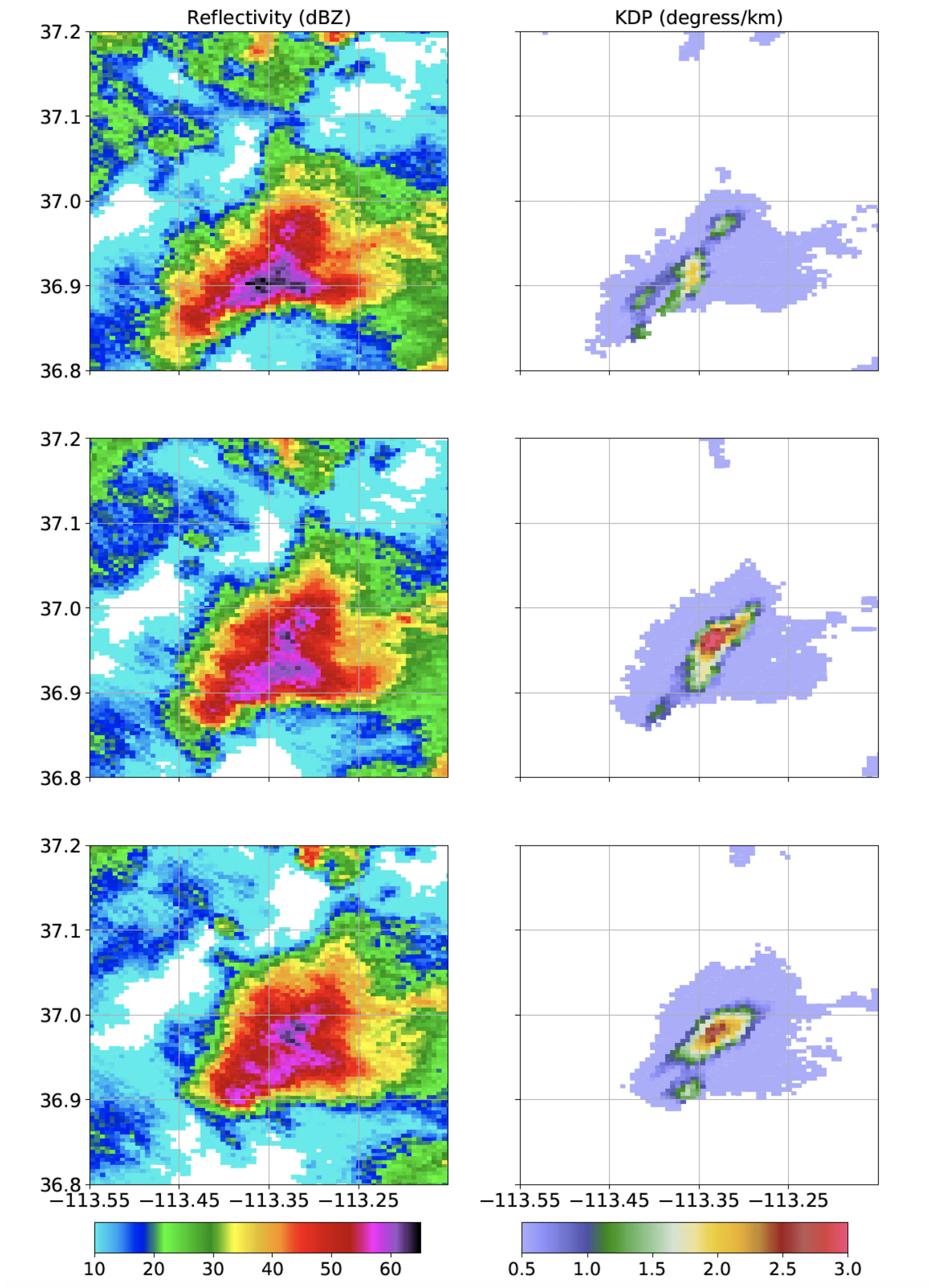

Figure 19. Reflectivity (left) and KDP (right) fields for 2242 UTC (top), 2247 UTC (middle) and 2251 UTC (bottom) on 18 July 2012.

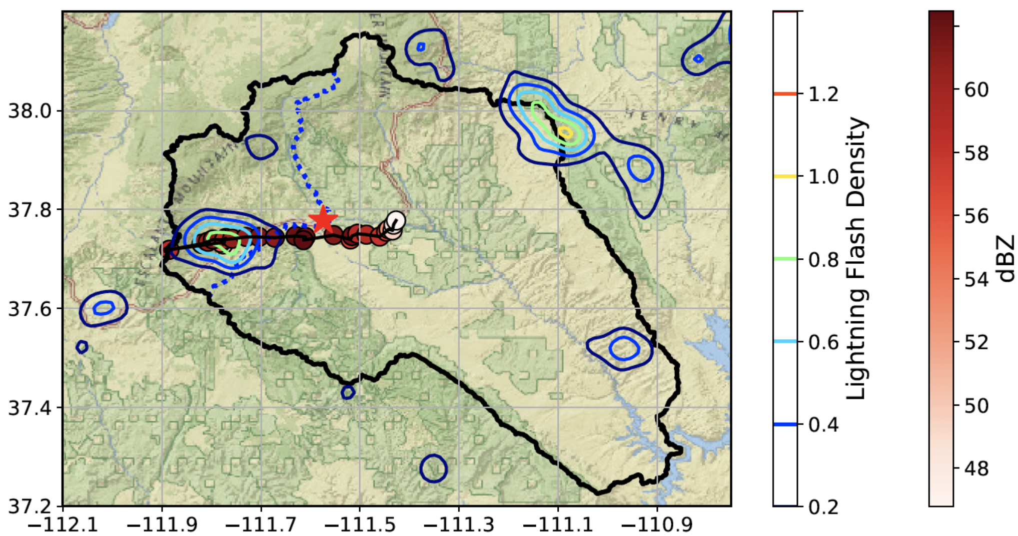

Figure 20. Storm total lightning flash density for the 24 August 1998 storm that produced record flood peak in the upper Escalante River. Storm tracks from 1847 to 1957 UTC illustrate west to east storm motion. The USGS stream gage location is denoted by a red star; the dashed blue line marks the boundary of the 823 km^2 watershed.

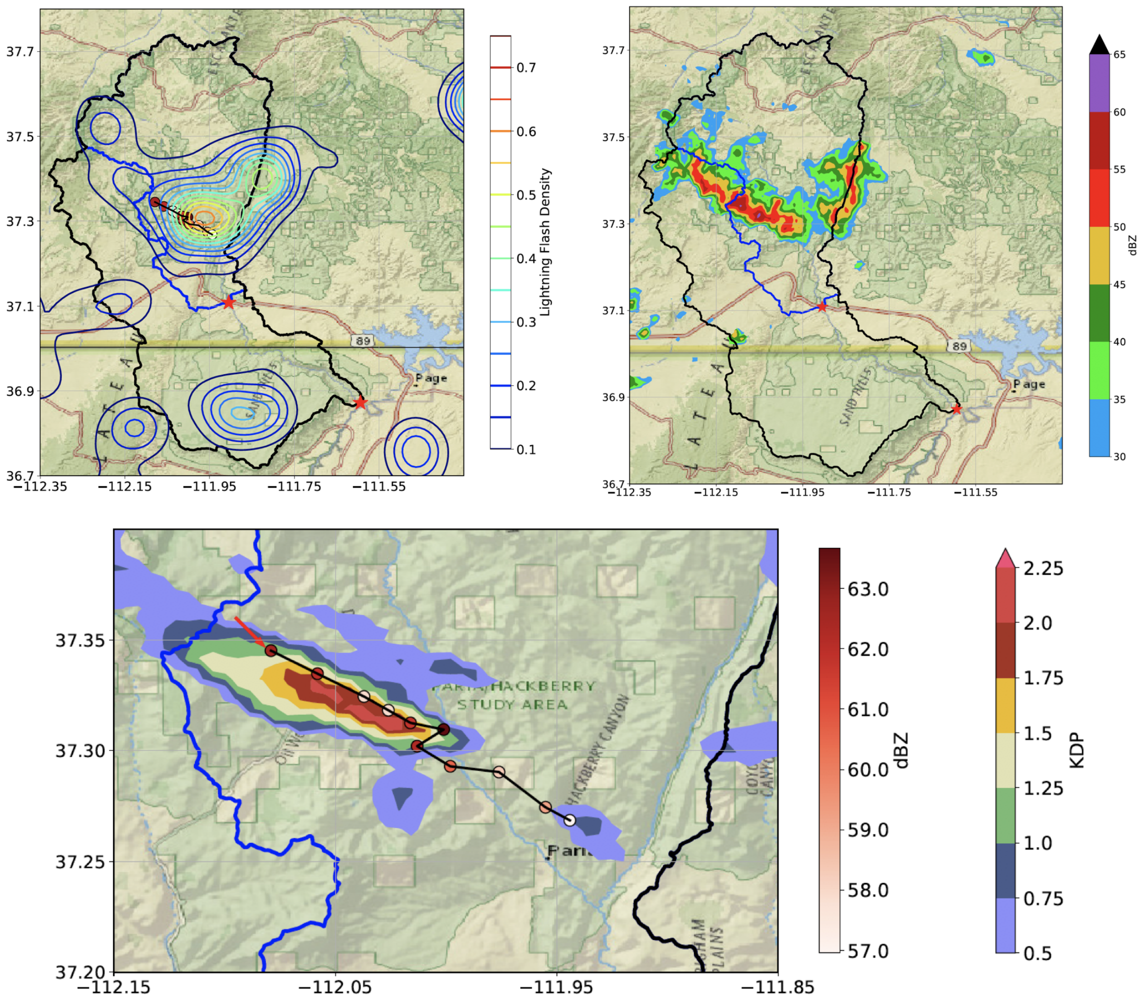

Figure 21. Storm total lightning flash density contours (CG strikes km^{-2}) with storm tracks for the 19 August 2012 Paria storm (upper left). Reflectivity field (dBZ) at 2046 UTC (upper right); closeup of K_{DP} field (degrees km^{-1}) at 2046 UTC with storm tracks (bottom). The red arrow in the bottom figure shows the location of the first tracked storm element. Stream gaging locations (red stars) and basin boundaries for the upper and lower Paria River are shown in the upper plots.

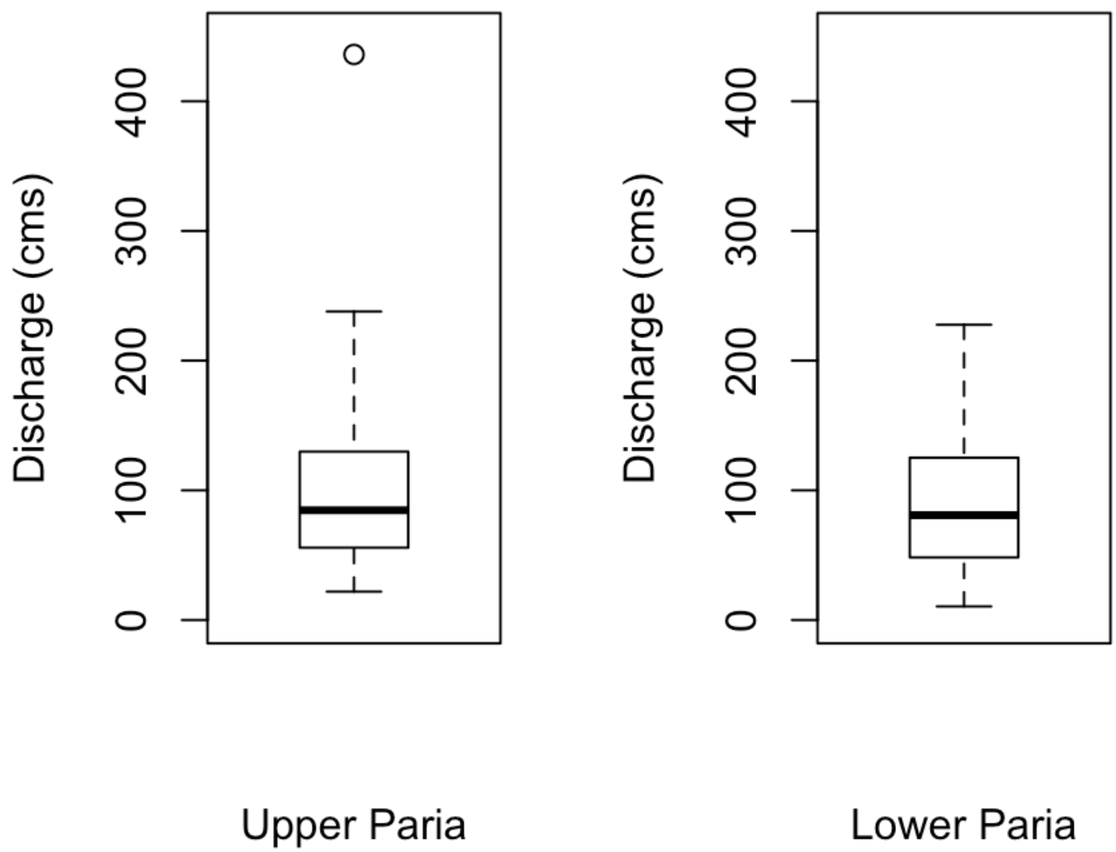

Figure 22. Boxplots of annual peak discharge for the upper Paria (left; drainage area of 1680 km^2) and lower Paria (right; drainage area of 3680 km^2) during the period of overlapping record.

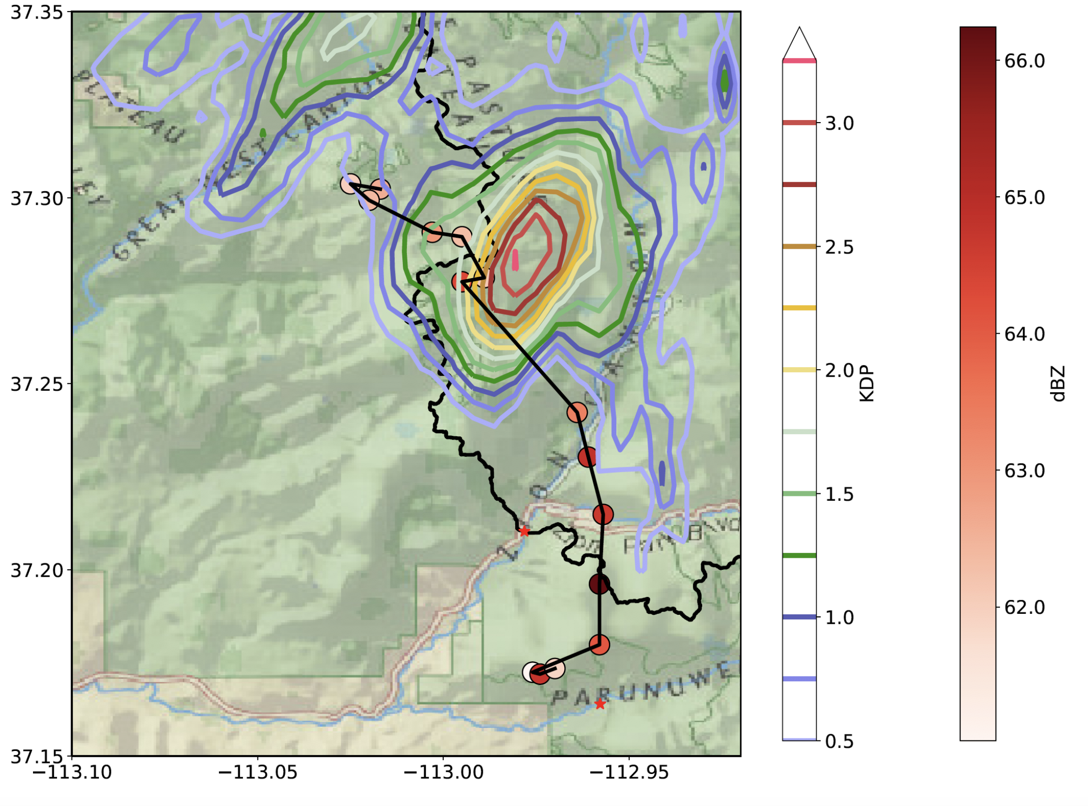

Figure 23. K_{DP} contours (degrees km^{-1}) at 0200 UTC on 12 July 2018 with storm tracks from 0130 UTC (top) to 0248 UTC (bottom).

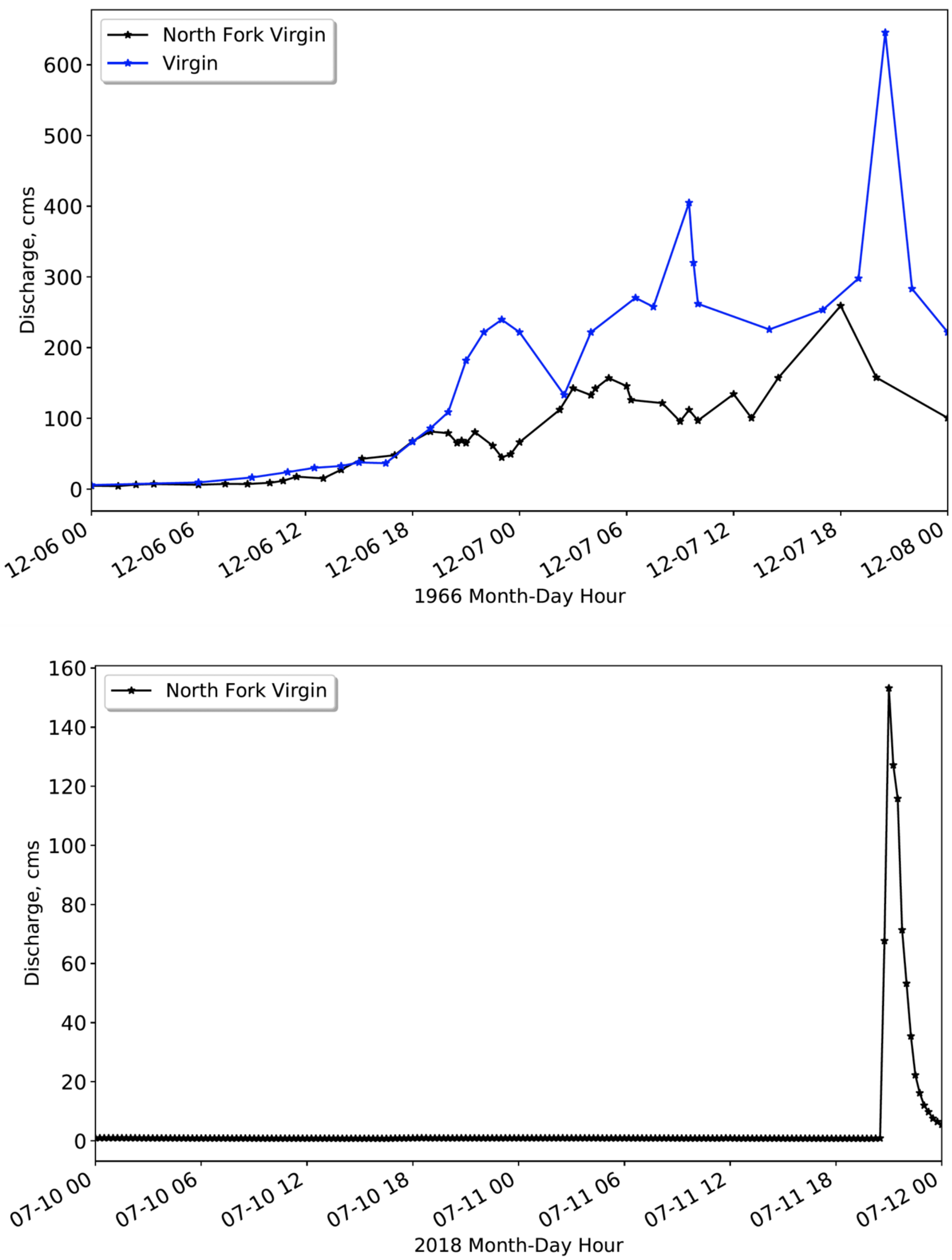

Figure 24. Discharge hydrographs for North Fork Virgin River (black) and Virgin River (blue) from 6 - 7 December 1966 (top); discharge hydrograph for North Fork Virgin River from 10 - 11 July 2018 (bottom).

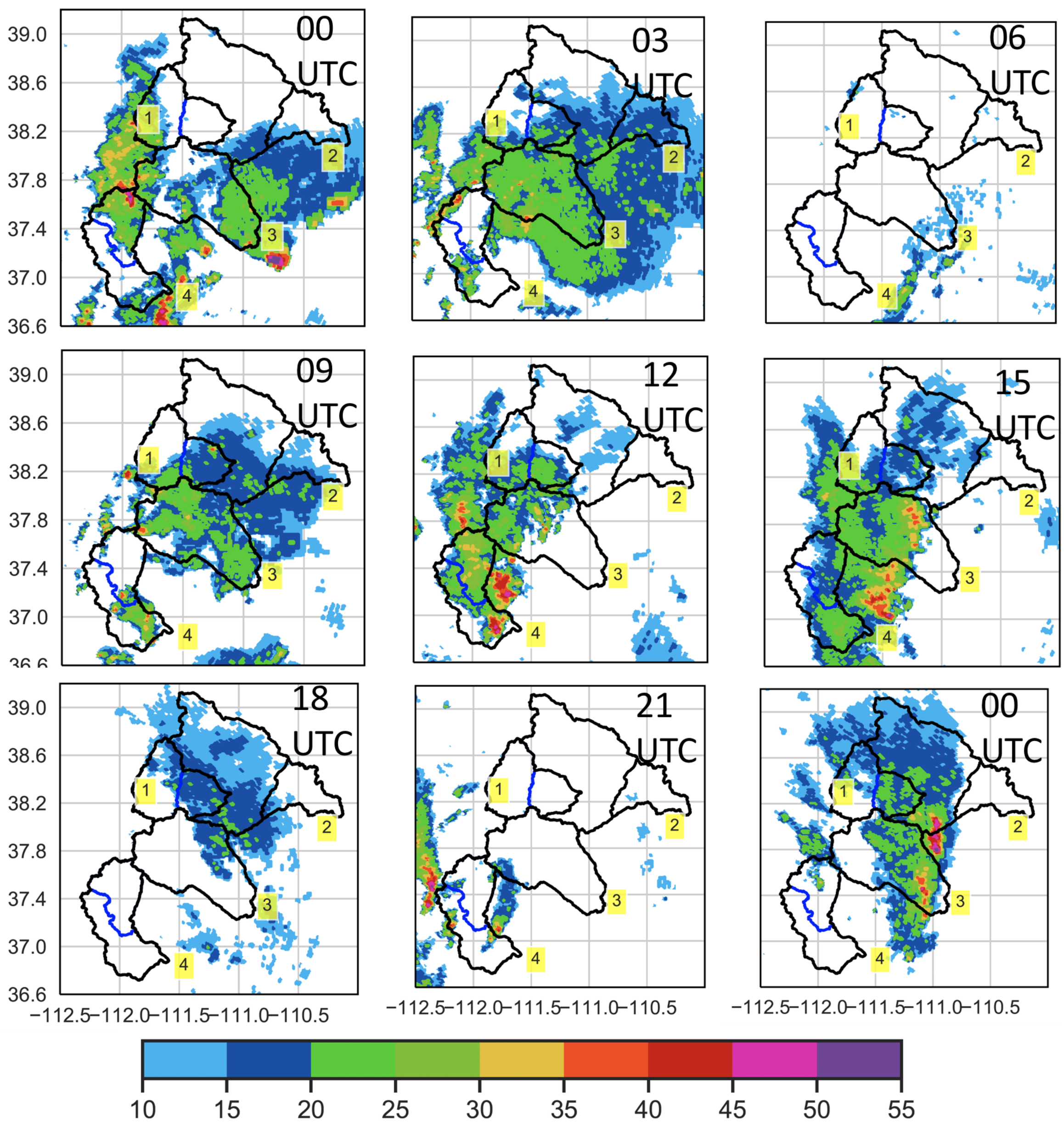

Figure 25. Reflectivity fields (dBZ) from 0000 UTC on 6 October 2006 to 0000 UTC on 7 October 2006 from the Cedar City WSR-88D. Basin boundaries are Upper Freemont (1), Dirty Devil (2), Escalante (3) and Lower Paria (4).

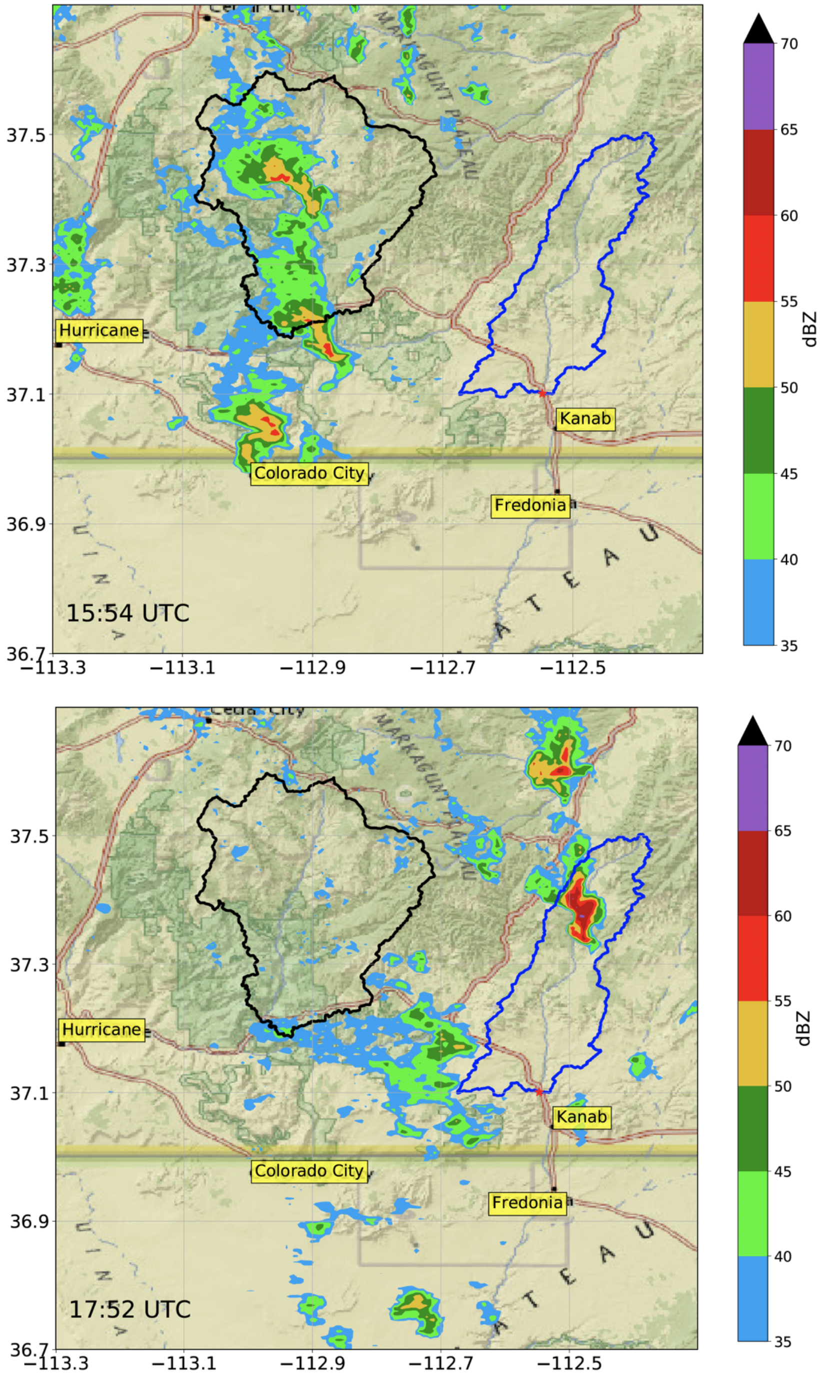

Figure 26. Reflectivity fields (dBZ) at 1544 UTC (top) and 1752 UTC (bottom) on 27 September 2014. Basin boundaries for the North Fork Virgin River (black) and Kanab Creek (blue) are shown.