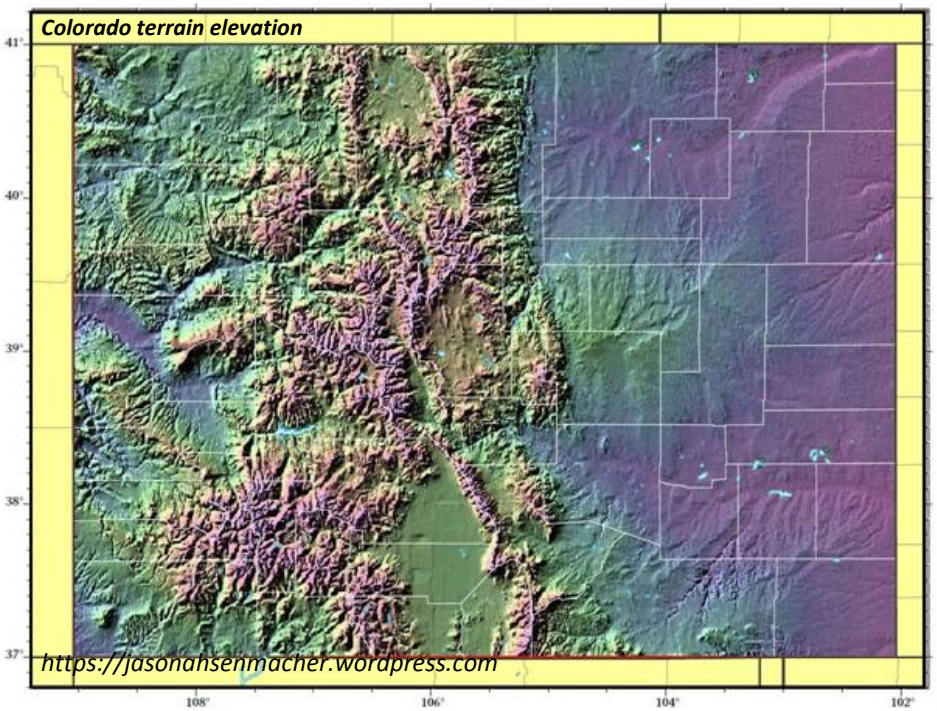
Climatology of Extreme Daily Precipitation in Colorado and Its Diverse Spatial and Seasonal Variability



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CIRES

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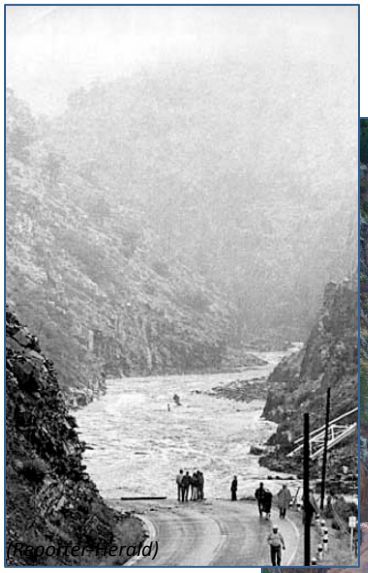
NOAA

Motivation

- Colorado known for dramatic climate and weather extremes (e.g., Hansen et al. 1978)
- Increasing pressure to consider weather and climate change information in many decision-making frameworks
- Water resources management:
  - In observations-sparse regions, regionalize precipitation from "nearby" sites
  - Locations with short/nonexistent records may be represented by nearby locations with very different seasonal and daily precipitation characteristics (consider mountains, valleys, complex terrain)
- Recent events (e.g., 2013 flooding) happening "out of season"; highlight gaps in understanding of regional heavy rainfall

➢ *Renews motivation to study seasonal cycle of heavy precipitation climatology*



1976: Big Thompson Canyon/US 34

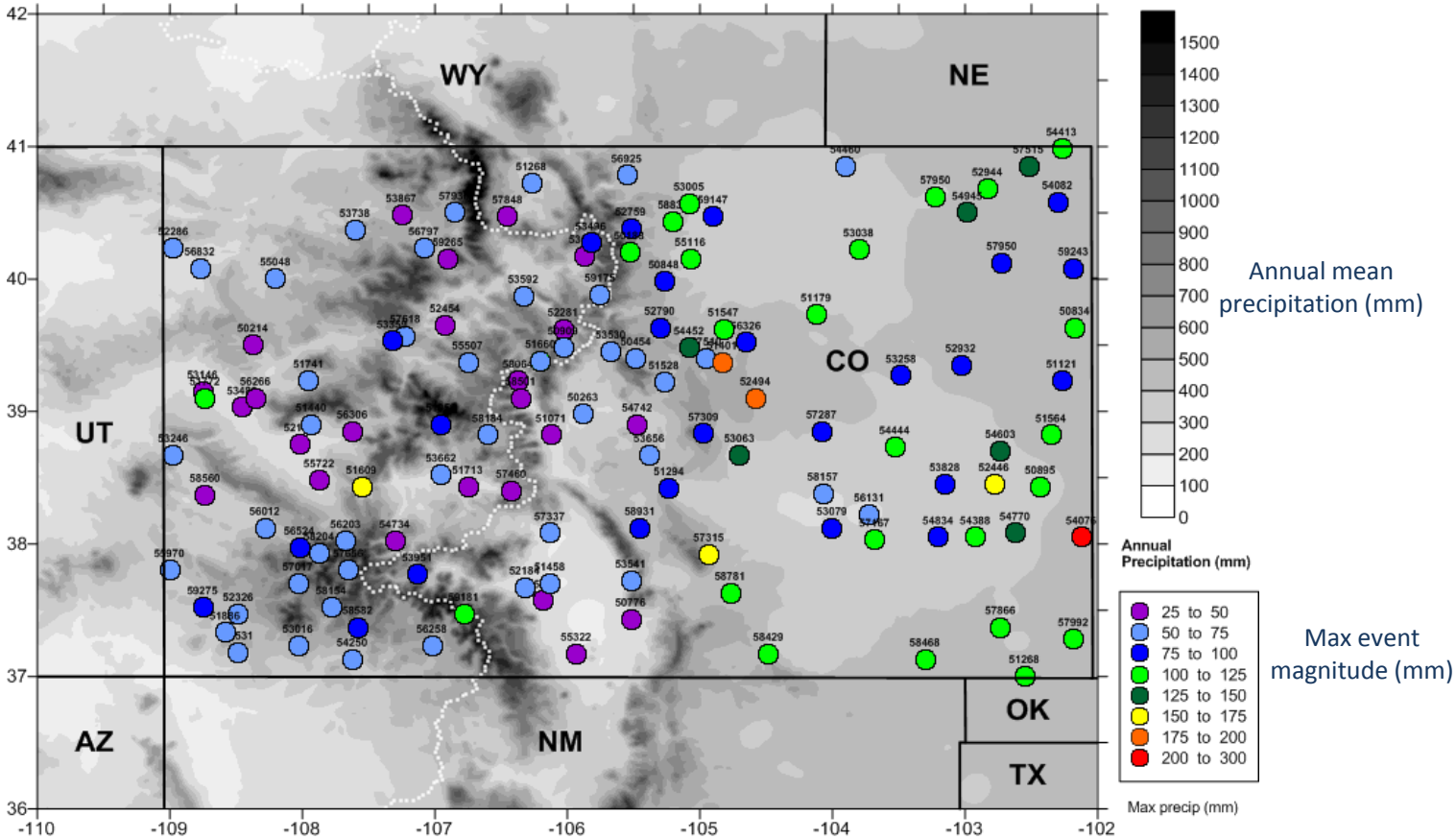
2013: Big Thompson Canyon /US 34

Water resources management/structure design: Remote areas → application of data from neighboring sites with potentially different climatologies

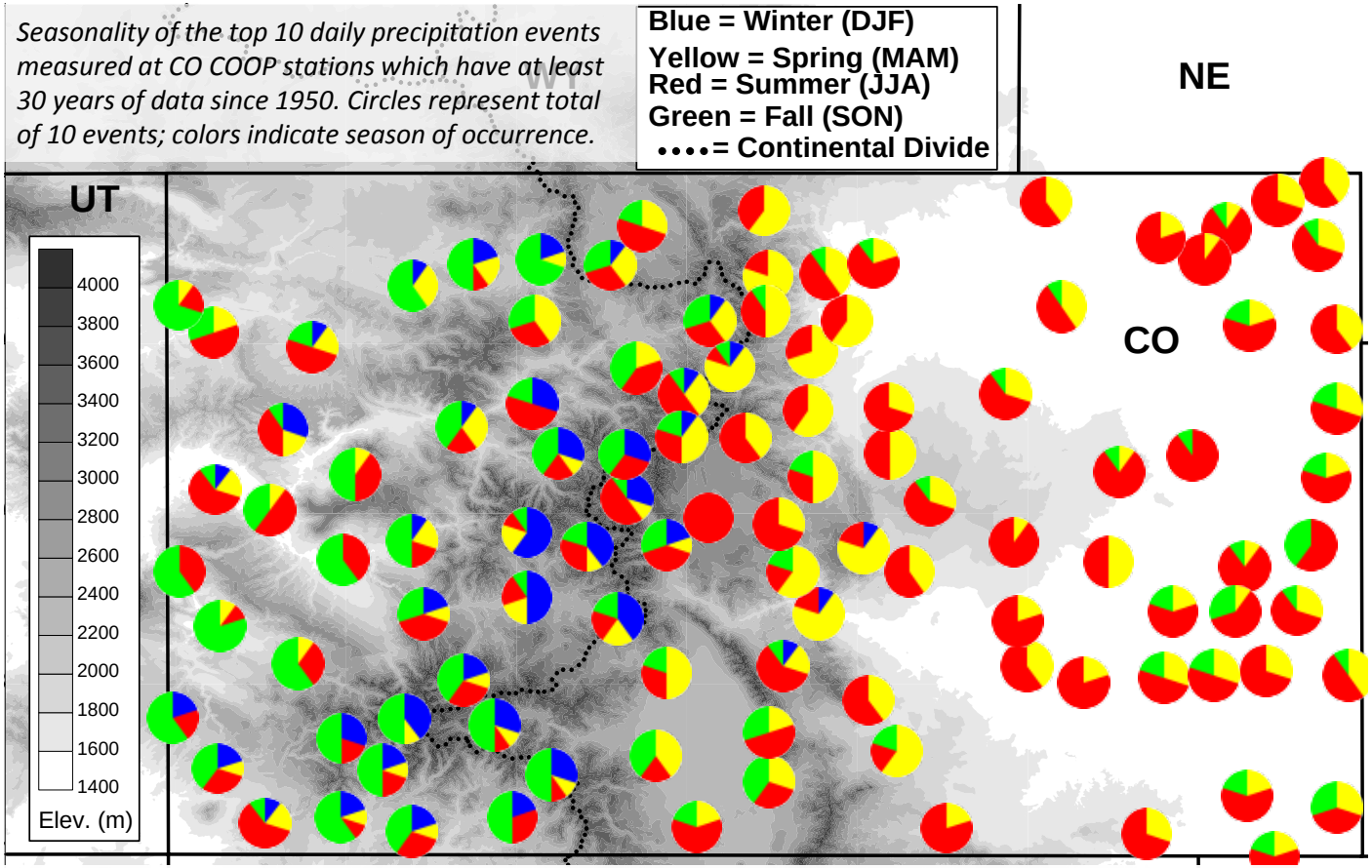
Methods

- Dataset: Cooperative Observer (COOP; NWS 1989) reports
- Daily data; total liquid equivalent (snow/rain not differentiated)
- 130 stations met initial screening criterion: at least 30 years of data 1950 – 2010
- 10 largest daily precipitation totals identified at each station

Maximum event magnitude (mm) by COOP station for 1951 – 2010



Seasonality of Top 10 Daily Precipitation events



- **Significant variation of seasonality across state**

West of Continental Divide:

- Lower elevations: fall dominant (tropical moisture connection)
- Winter events more common than east of Divide -- but still only dominant at one station (Crested Butte, CO, elev 2700 m).

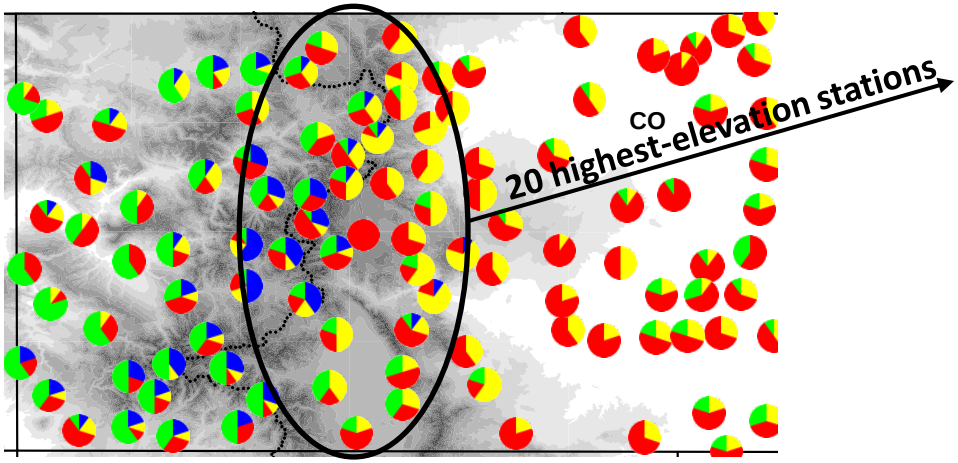
East of Continental Divide:

- Front Range: spring and summer dominant – even at high elevations (e.g. Antero Reservoir, central Colorado, elev 2719 m – all summer)
- Eastern plains: summer dominant; fall events increase toward southern, far-eastern regions of slopes and plains

Central Mountains: A mix!

Seasonality patterns at high-elevation stations

- High-elevation extremes of particular interest:
  - Observations sparse → extrapolation common
  - Complex/steep terrain → enhanced flood risk
  - Paleohydrologic records: rain limited above 7800 ft?
  - Climate change studies: phase (rain/snow) changes at high elevations



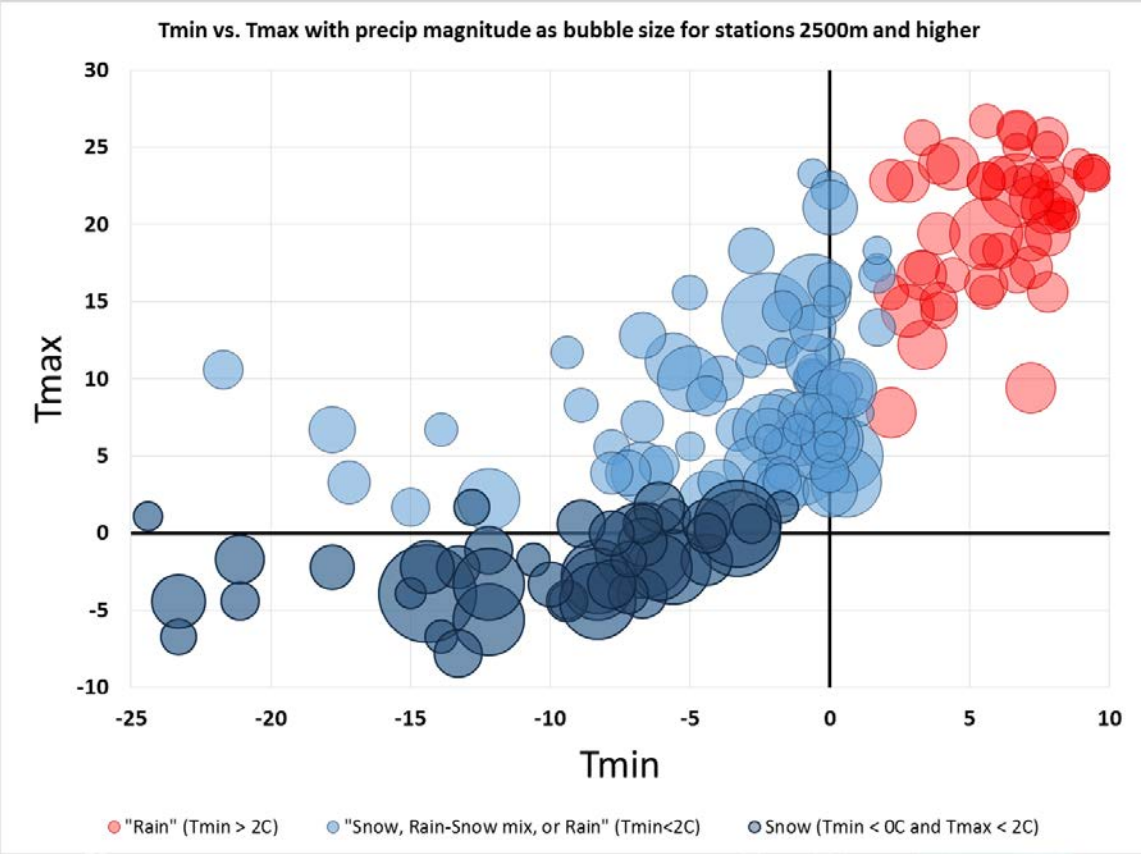
- 20 highest-elevation stations: remarkable mix in seasonality of extremes
  - Winter *not* dominant season near Continental Divide
  - Slightly east: summer more common; slightly west: a mix
- Prevailing notion: winter produces heaviest events at highest elevations?
- Caveats:
  - Severely limited observations at highest elevations.
  - Winter relevance: consider longer (multiple-day) storm periods

➢ Relationship between extreme-precipitation seasonality and elevation is complex; data-borrowing risky

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	

Frozen vs. liquid precipitation

- Distinction between frozen precipitation (snow, hail, graupel) and liquid (rain) difficult from COOP obs (liquid equivalent only)
- Solid vs. liquid: different flood risks
- Assume snow or snow-rain mix if daily surface T_{min} < 2°C

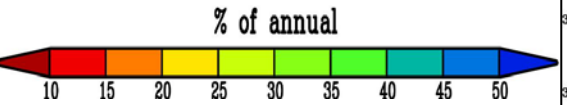


- 21 stations located above 2500m (8200 ft):
  - ~70% top 10 events likely snow-dominated or rain-snow mix
  - 30% likely rain
  - ➢ Flood risk may not be inherently limited to elevations < 2500 m as suggested by past studies (e.g., Jarrett 1993; Cotton et al. 2003)

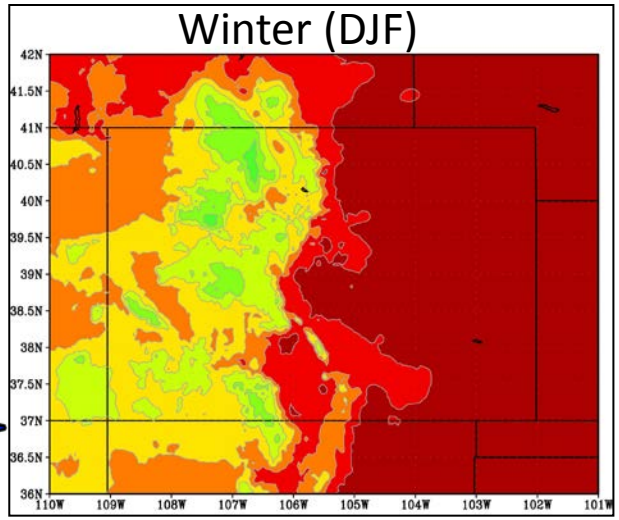
Averages vs. Extremes

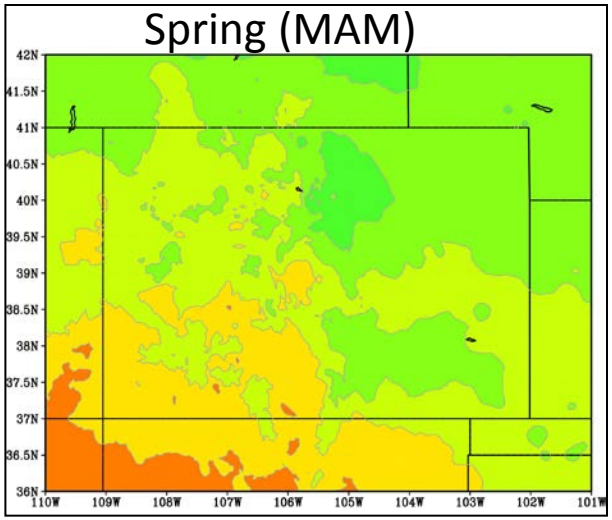
- How often are extreme precipitation events observed outside of the climatologically-favored season?
- Climatological seasonality:

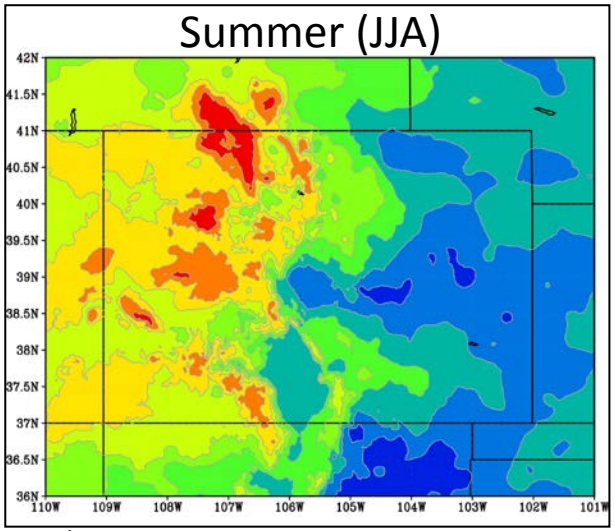
Climatological precipitation based on COOP and SNOTEL data integrated via PRISM[1]

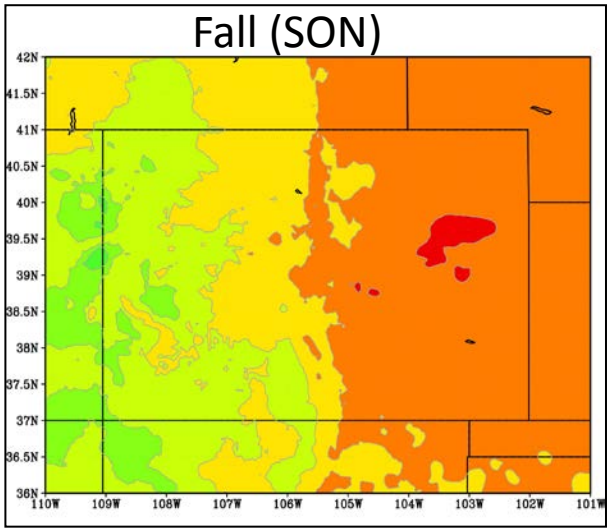


Color: percentage of <u>annual</u> precipitation that occurs during indicated season





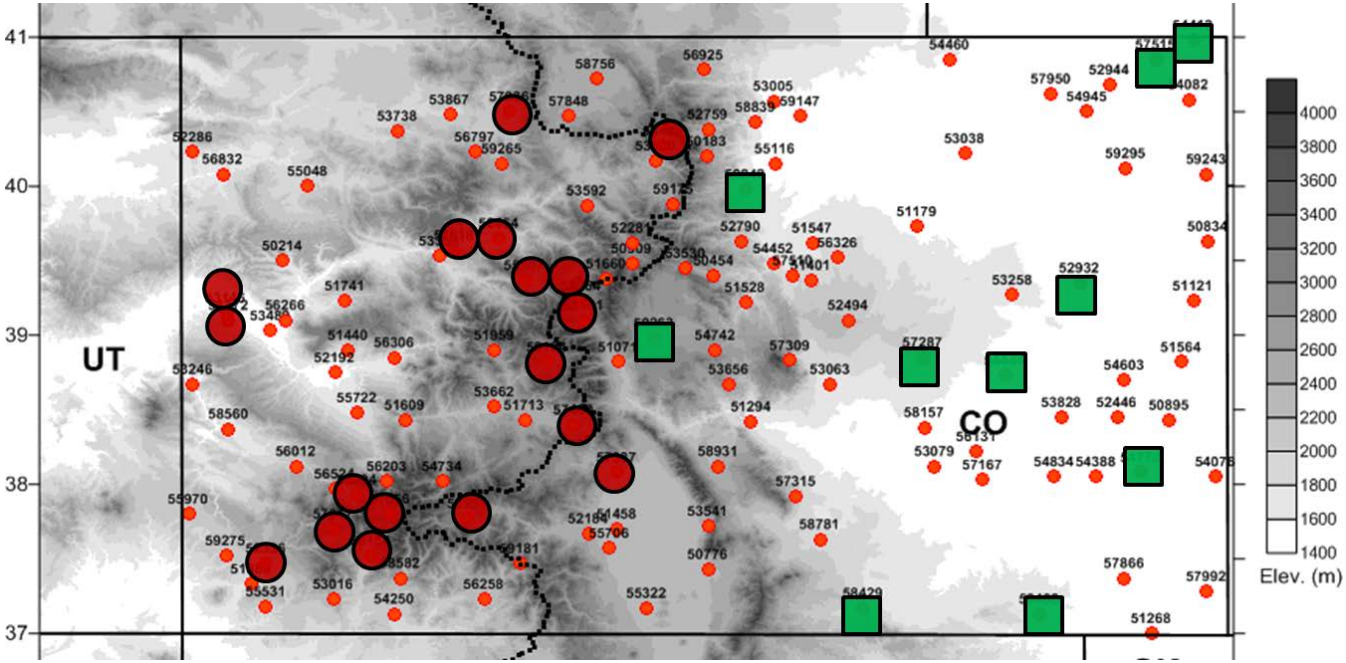




[1]Daly et al. 2002 using 1895 – 2007 period of record

Averages vs. Extremes

- How often are extreme precipitation events observed outside of the climatologically-favored season?



- Red: <4 of top-10 events occurred during station's climatologically three wettest calendar months *and* >4 have occurred during the climatologically driest six months, (i.e., when least expected)
- Green: All top 10 daily events have occurred in the wettest three months of the year (i.e., when more expected)

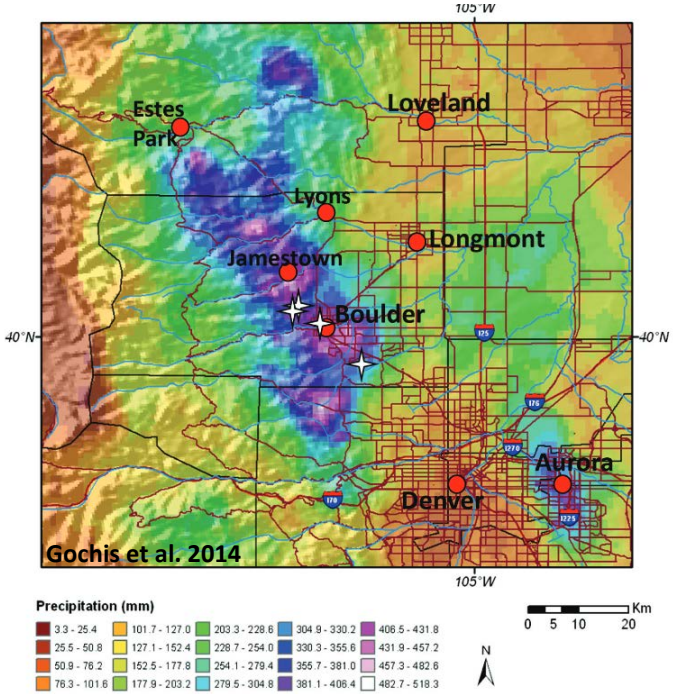
- East of Continental Divide: Extreme events occur during wettest time of year *
- West of Continental Divide: Seasonalities and spatial distributions of extremes diverge notably from seasonal averages

* Front Range fall floods…consider 1951 – 2010 period of analysis…

2013 Front Range Flooding

- Colorado Front Range:
  - Heaviest precipitation events in study period rarely occur in fall
  - Fall typically driest season for average precipitation
- However: Known Front Range historical floods in September September 1938 (Hoerling et al. 2014)
  - 09 – 16 September 2013 (Gochis et al. 2014)

South Boulder Creek - September 1938
(Photo courtesy of Urban Drainage and Flood Control District, UDFCD)

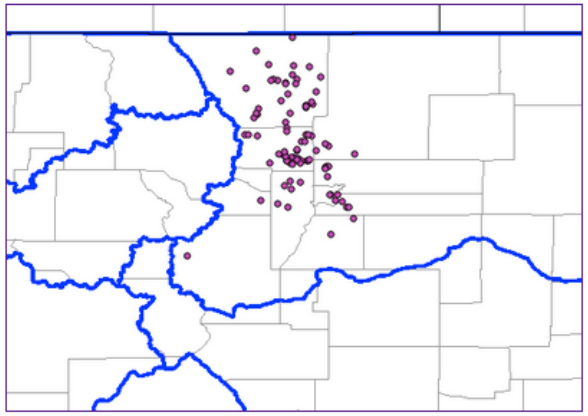


2013 Front Range Flood Accumulated Rainfall
9 – 17 Sept 2013
(Gochis et al. 2014)

2013 Front Range Flooding

- Daily records shattered at six Front Range COOP stations – though not at COOP stations included here
- Including new records would broaden seasonalities of Front Range events to include fall
- Elevation considerations:
  - September storms often snow at higher elevations, but 2013 event unusually warm: liquid form all the way up to the Continental Divide (> 2750m or ~9,000ft)
    - Estes Park, CO: 7820 ft, > 9 inches liquid rainfall (8 – 17 Sept 2013)
    - Deadman Hill, CO: 10,220 ft, ~6 inches liquid rainfall
- Impacts minimized: hydrologic conditions/late water year reservoir draw-downs

Estes Park, CO flooding 13 Sept 2013: Elevation 7820 ft
(Walt Hester)



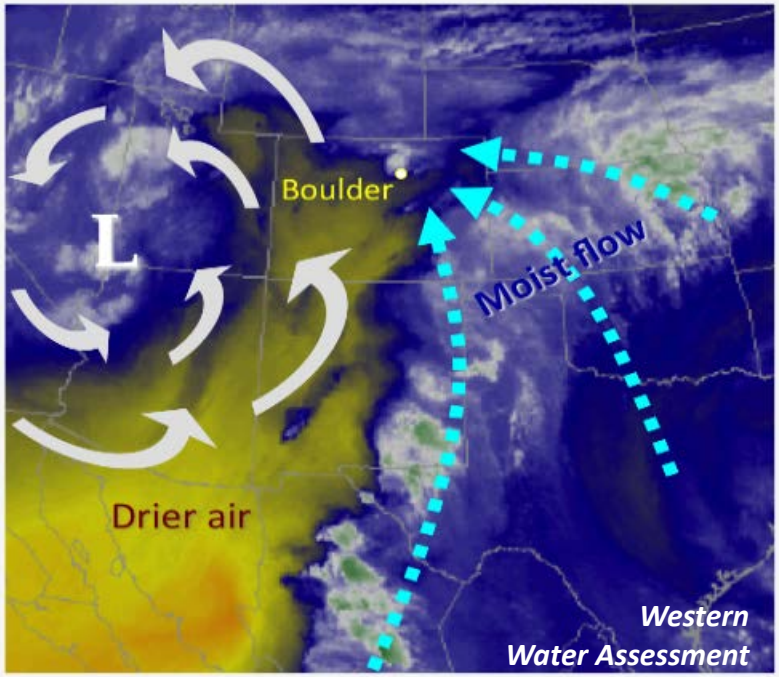
The above stations located in the South Platte Basin recorded all time records for 24-hour precipitation accumulations during this event. Every station shown has at least a 10-year record. See the table below for record values and station names.

1	RALSTON RSVR	COOP	10.5	9/13/13
2	BOULDER	COOP	9.08	9/12/13
3	BOULDER 1.3 NW	CoCoRaHS	8.62	9/12/13
4	BOULDER 1.4 NNW	CoCoRaHS	8.03	9/12/13
5	BOULDER 1.5 NW	CoCoRaHS	8.02	9/12/13
6	BOULDER 3.3 SE	CoCoRaHS	7.31	9/13/13
7	BOULDER 1.6 S	CoCoRaHS	7.3	9/12/13
8	BOULDER 2.9 S	CoCoRaHS	7.2	9/12/13
9	AURORA 2.9 NW	CoCoRaHS	6.78	9/13/13
10	BOULDER 3.0 NNW	CoCoRaHS	6.72	9/12/13
11	FREDERICK 0.5 ENE	CoCoRaHS	6.3	9/12/13
12	GOLDEN 4.8 NW	CoCoRaHS	5.96	9/13/13
13	BOULDER 4.7 E	CoCoRaHS	5.87	9/12/13
14	BOULDER 5 SE	CoCoRaHS	5.61	9/13/13
15	BOULDER 4.6 E	CoCoRaHS	5.17	9/12/13
16	THORNTON 2.3 SSE	CoCoRaHS	5.07	9/12/13
17	VIRGINIA DALE 7 ENE	COOP	4.8	9/13/13
18	LONGMONT 8.2 ESE	CoCoRaHS	4.8	9/12/13
19	THORNTON 2.1 N	CoCoRaHS	4.71	9/12/13
20	DENVER 6.3 SSE	CoCoRaHS	4.42	9/13/13
21	NIWOT 1.8 SSW	CoCoRaHS	4.41	9/12/13
22	BOULDER 1.8 ESE	CoCoRaHS	4.34	9/13/13
23	BOULDER 5.2 NE	CoCoRaHS	4.3	9/12/13
24	NEDERLAND 5.8 E	CoCoRaHS	4.28	9/12/13
25	DRAKE 3.0 NNE	CoCoRaHS	4.23	9/12/13
26	BOULDER 6.8 SE	CoCoRaHS	4.08	9/12/13
27	ESTES PARK 3.3 SSW	CoCoRaHS	4.04	9/13/13
28	THORNTON 5.4 NNE	CoCoRaHS	4.01	9/12/13
29	ESTES PARK 2.2 NE	CoCoRaHS	3.95	9/13/13
30	BELLVUE 5.9 W	CoCoRaHS	3.94	9/12/13
31	ESTES PARK 1 SSE	COOP	3.9	9/12/13
32	BELLVUE 10.3 W	CoCoRaHS	3.85	9/12/13

Colorado Climate Center:
http://coflood2013.colostate.edu/preciptotals.html

2013 Front Range Flooding

- September 2013:
  - Fall: moisture + dynamics → extreme rainfall
  - Late-season shift toward monsoon-like pattern partially responsible
  - May not have been deemed so anomalous (with respect to seasonality) if just weeks earlier
- Changes in seasonality of key environmental features (i.e., monsoon, moisture transport patterns) in future climates?
  - Understand physical rationale for historical, present-day heavy precipitation seasonalities to assess potential shifts seasonal patterns in future
- Prepare for future flood risks: better understand critical ingredients and various ways they can come together -- even in season of "normally" low mean precipitation
- A reminder: Colorado extreme precipitation can occur in any season and at all elevations; flooding a nearly-year-round risk

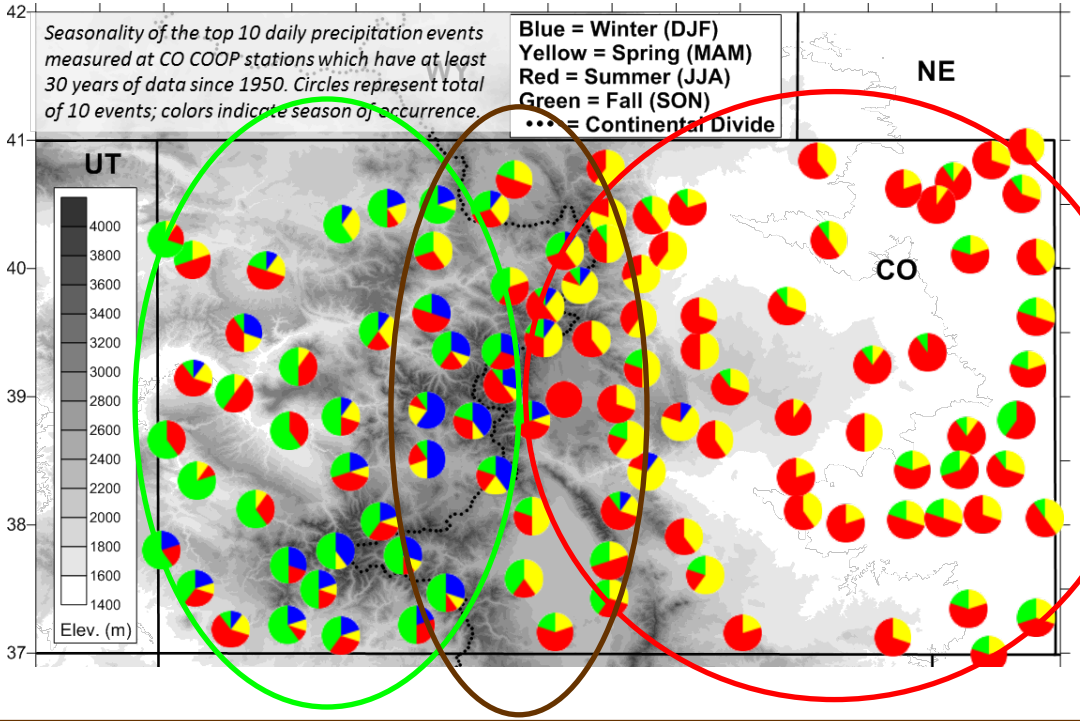


Deep plumes of moisture (blue, white, and green) are drawn towards the Front Range from the Pacific and the Gulf of Mexico by the circulation around an upper-level low (L) over the Great Basin, at 11:15 pm MDT on September 11, 2013, during the peak rainfall intensity in Boulder. Drier air is shown in yellow. (Satellite image: CIMSS, University of Wisconsin)

Summary

- Colorado's historical extreme precipitation remarkably variable: seasonally and geographically
- ~Half a century of COOP daily station data shows:

- West of Continental Divide, Fall dominant
- Winter extremes at higher elevations



- East of Continental Divide, winter extreme events rare
- Summer extremes most common across lower-elevation eastern plains
- Spring dominant in Front Range

- Seasonality of extremes in central, highest mountains particularly complex:
  - Intense precipitation observed in all months
  - Heavy precipitation (> 100 mm/day) even at highest elevations (considered here)
  - Closely-neighboring stations (within 10's of km) very different seasonal distributions
- Sharp gradients of relevance to stakeholders: sometimes forced to extrapolate/translate data from "nearby" sites to fill in observational gaps
- Central mountains data-sparse → misrepresentation of extreme precipitation characteristics?

Future work

- Additional observations and analyses needed to better understand precipitation distributions at highest elevations
  - COOP station record analyzed here includes few locations above 3000 m (~10,000 ft)
- Examine shorter/longer duration periods of analysis:
  - Shorter: Summer/convective events, flash flood risk
  - Longer: extended flooding events, seasonal water supply
- Consider different epoch of analysis: known pre-1950 extreme events of interest
- Investigate relationship between largest precipitation events and largest floods:
  - Fully integrated approach involving hydrometeorology, flood hydrology, and paleoflood hydrology to consider flood potential and flood risk

Acknowledgements

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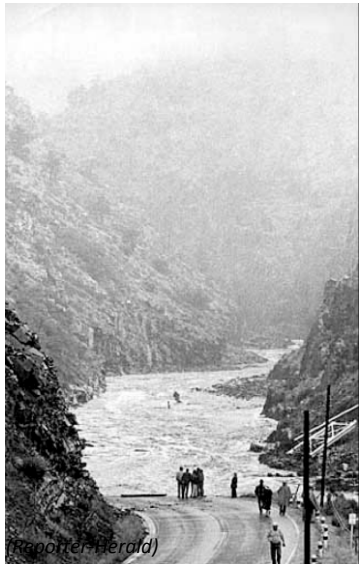
- John England (US Army Corps Engineers)

Boulder, CO
wunderground.com



(Reporter-Herald)

1976: Big Thompson Canyon and washed out US 34

(Capt. D. Overstreet/Air National Guard)

2013: Big Thompson Canyon and washed out US 34

Extra slides

One of the main points of this paper is to indicate the dependence of intense precipitation on elevation and its extremely limited areal extent. Precipitation, streamflow, and geomorphic evidence indicates that there is a distinct decrease in floods above about 7,500 feet (2,300 meters) in the foothills of northern Colorado. In the Arkansas River basin in southern Colorado, this change occurs at an elevation of about 9,500 feet (2,896 meters). In Wyoming, streamflow records indicate that the elevation is about 6,500 feet (1,981 meters). Farther north in South Dakota and Montana, the elevation is less than 6,500 feet (1,981 meters). (Studies need to be done to determine the elevations for decreases in floods.) Therefore, the concept of storm transposition from lower elevations to higher elevations is suspect and is not supported by meteorologic, hydrologic, and paleoflood data.

Known COOP caveats

- 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-hour 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 SNOTEL (SNOw TELemtery) sites; Serrezze et al. 1999].
- 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 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 Ft. Collins flood of 1997 (Petersen et al. 1999)) that occurred at stations not satisfying our 30-years-of-consecutive data requirement.
- 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.

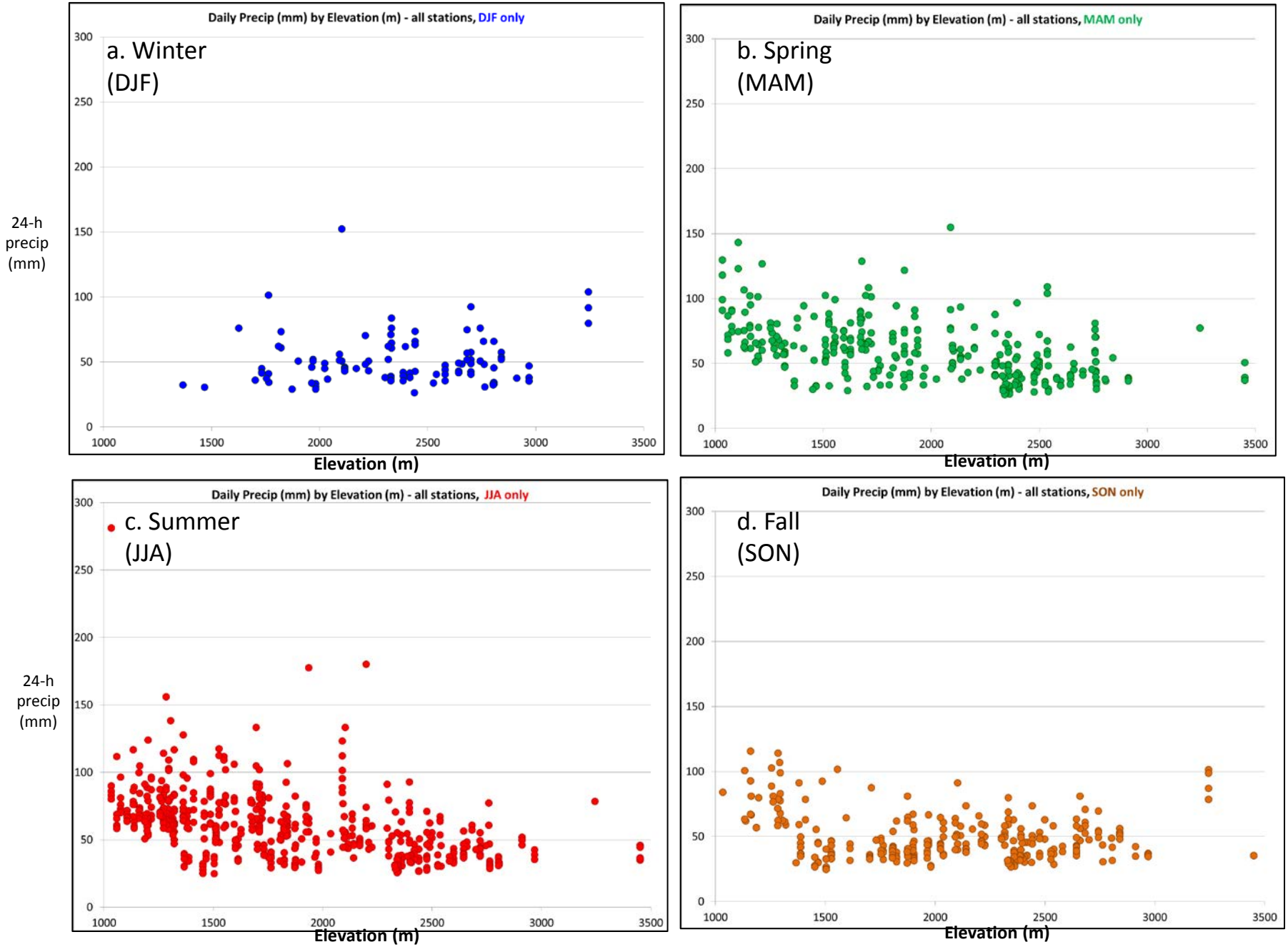
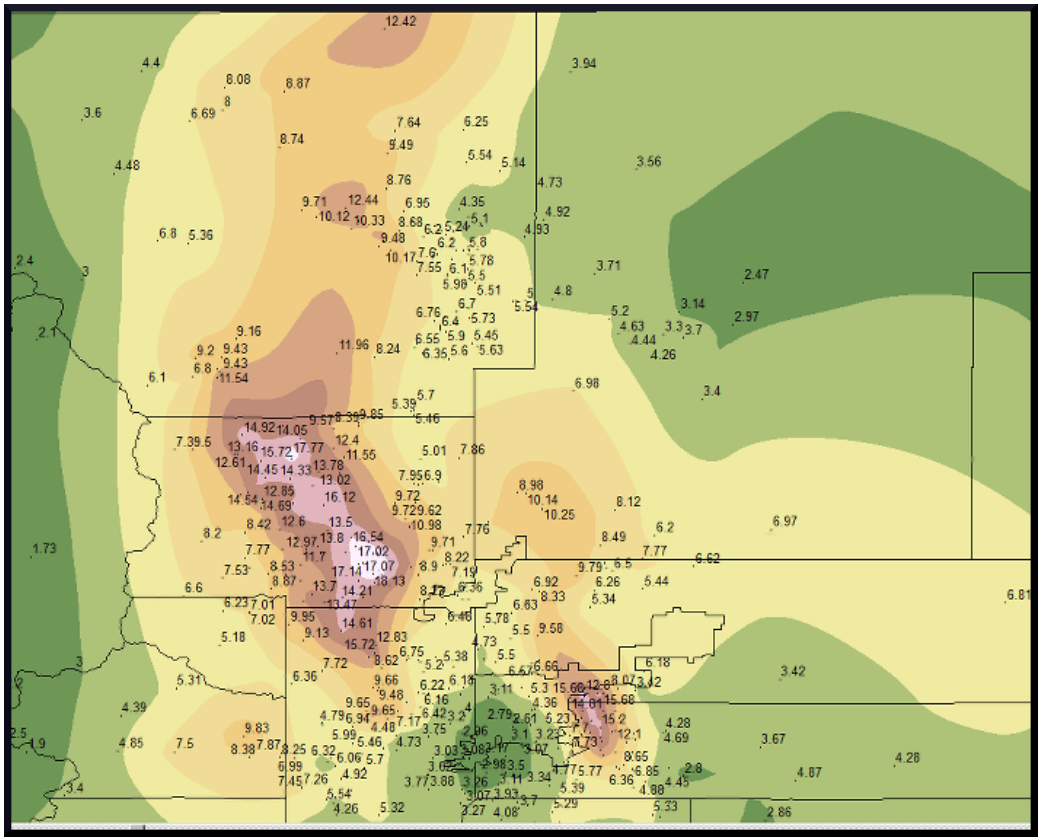
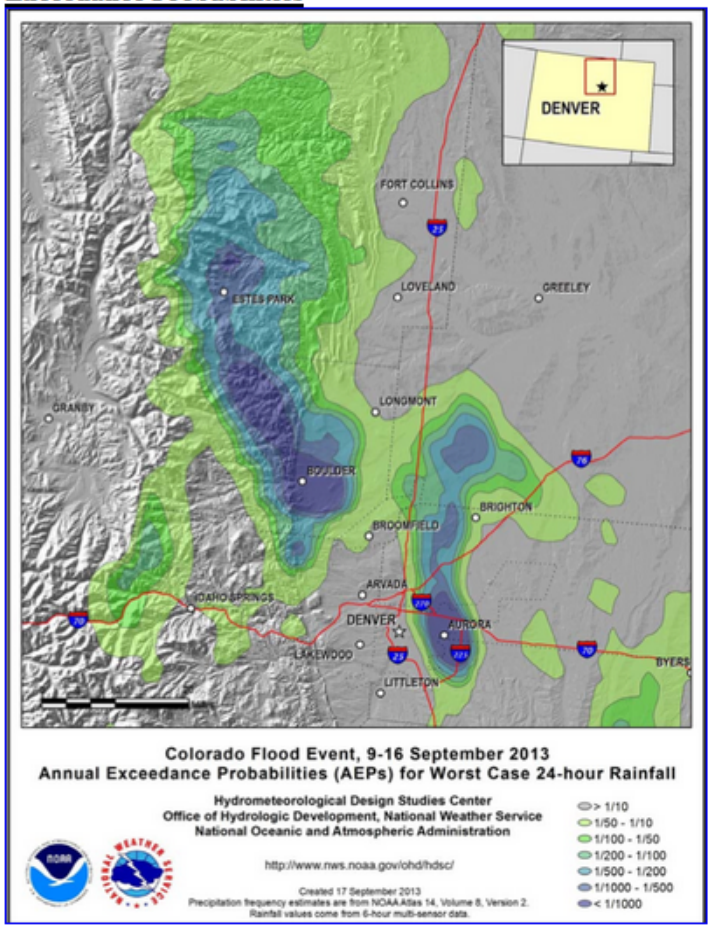


Figure 4. Seasonal event analysis by station elevation. Each dot represents an individual event by season a) DJF, b) MAM, c) JJA, and d) SON. 24-hour precipitation amount on y-axis; elevation (m) on x-axis.

2013 Front Range Flooding



Exceedance Probabilities



The above map shows annual exceedance probabilities (AEP) for 24-hour duration precipitation during the storm event (developed by the Hydrometeorological Design Studies Center at the NWS). Areas in purple (Boulder, Aurora, Estes Park) experienced 24-hour accumulations that are on the order of 1 in 500 year to 1 in 1000 year events.

Read more about Annual Exceedance Probabilities during the storm.

http://coflood2013.colostate.edu/records.html