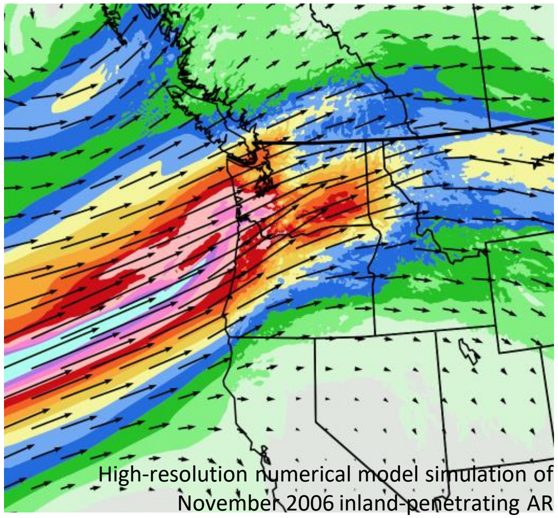
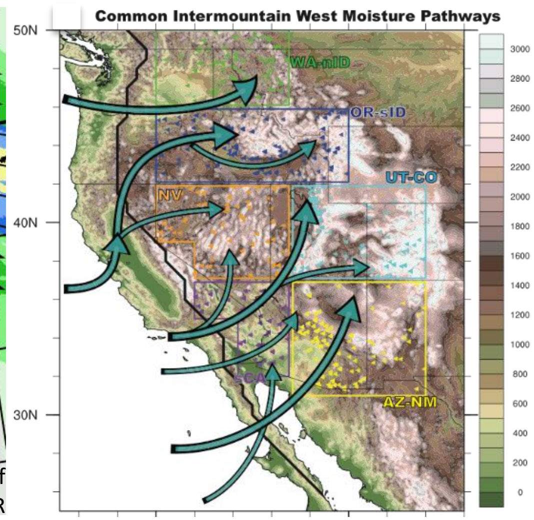
Moisture Sources for Heavy Precipitation in the Intermountain West



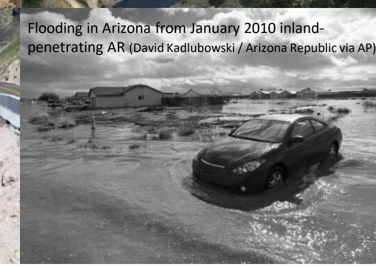
High-resolution numerical model simulation of November 2006 inland-penetrating AR



Flooding at Montana's Glacier National Park produced by inland-penetrating atmospheric river in November 2006 (National Park Service)

Anderson Ranch Dam, Southwest Idaho

Road repairs in Glacier National Park due to Nov 2006 flooding caused by inland-penetrating atmospheric river (National Park Service)



Flooding in Arizona from January 2010 inland-penetrating AR (David Kadlubowski / Arizona Republic via AP)

Kelly Mahoney

Michael Alexander, Jamie Scott, Dustin Swales, Mimi Hughes, Michael Mueller
NOAA ESRL Physical Sciences Division

Western States Water Council Meeting
16 May 2018

Final Report: Water and Climate Change Research

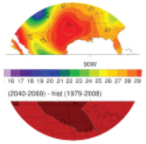
The Water and Climate Change Research Project (2011–2017) was a joint effort between the Bureau of Reclamation and the Cooperative Institute for Research in Environmental Sciences (CIRES). The effort was comprised of several separate research projects intended to advance the scientific capabilities that support effective water management. This is the final report for BOR R11AC81334.

RECLAMATION Managing Water in the West · NOAA · University of Colorado Boulder · CIRES

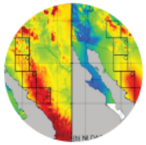
Projects

Improving Extreme Precipitation Estimation Using Regional, High-resolution Model-based Methods (Task 1 & Task 5)
Technical Lead: Kelly Mahoney (formerly CIRES)
Collaborators: Michael Mueller (CIRES), Michael Alexander (NOAA), James Scott (CIRES), Mimi Hughes (CIRES), Dustin Swales (CIRES), Joe Barsugli (CIRES)

Diagnosing the Moisture Sources for Extreme Precipitation Events in the Intermountain West (Task 2 and Task 6)
Technical Lead: Kelly Mahoney (NOAA, formerly CIRES)
Collaborator: Michael Alexander (NOAA)



Evaluating the Relevance, Trustworthiness, and Applicability of CMIP5 Climate Projections for Water Resources and Environmental Planning (Task 3)
Technical Lead: James Scott (CIRES)
Collaborators: Michael Alexander (NOAA), Levi Brekke (Bureau of Reclamation)



High-resolution Meteorological and Hydrologic Data Extension to Transboundary Basins in Southern Canada and Northern Mexico (Task 7)
Technical Lead: Ben Livneh (CIRES)

Enhancing Winter Orographic Snowfall in the West Through Cloud Seeding (Task 8)
Technical Lead: David Reynolds (CIRES)

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Diagnosing the Moisture Sources for Extreme Precipitation Events in the Western US

Technical Lead: Kelly Mahoney (NOAA, formerly CIRES)
Collaborator: Michael Alexander (NOAA)

Publications:

High-resolution Model-based Investigation of Moisture Transport into the Pacific Northwest During a Strong Atmospheric River Event (Accepted)
Authors: Michael Mueller, Kelly Mahoney, Mimi R. Hughes

Changes in Atmospheric Rivers and moisture Transport over the NOrtheast Pacific and western North America in Response to ENSO Diversity (In Press)
Authors: Hye-Mi Kim, Y. Zhou, Michael A. Alexander

Examining Moisture Pathways and Extreme Precipitation in the U.S. Intermountain West using Self Organizing Maps (2016) Authors: Dustin Swales, Michael A. Alexander, and Mimi Hughes

Publications continued on reverse side

It is important to both scientists and water managers to better understand the synoptic (weather-related) and climatic processes that influence heavy precipitation events in the US intermountain west in addition to the windward side of the Sierra and Cascade Mountains. This research has the potential to better inform decisions about dam safety and flood hydrology, for example by helping to guide storm transposition for estimating maximum precipitation. In addition, there is the potential to improve longer-term outlooks through a better understanding of how these extreme events are related to climate variability and change.

Long narrow bands of enhanced water vapor transport generally located ahead of cold fronts, termed atmospheric rivers (ARs), are associated with heavy rain and snow events along the US west coast. Recent studies suggest that ARs could move inland and contribute a significant fraction (10%-50%) of wintertime precipitation in the intermountain west. Since flow over mountain causes air to cool and thus hold less moisture; How does the moisture penetrate the high terrain and complex topography near the US west coast in sufficient amounts to produce extreme precipitation events in the intermountain west (IMW, from the Cascade/Sierras – continental divide)? Here we investigate the following questions associated with extreme precipitation events in the US IMW during the cold season (October-March):

- Are there dominant moisture pathways?
- Do they differ for different regions in the IMW?
- Is the moisture transport influenced by mountain gaps?
- What synoptic features are associated with the moisture transport?

Findings & Outcomes:

Two methods were used to identify the paths of moisture transport that reach the US intermountain west (IMW) during heavy precipitation events in winter: 1) Backward in time trajectories and 2) Empirical Orthogonal Functions (EOFs, patterns) of IVT.

Both methods indicate that moisture originating from the Pacific that produces extreme precipitation in the IMW US during winter take dominant pathways that are influenced by gaps in the Cascade (Oregon-Washington), Sierra-Nevada (California) and Peninsula Mountains (southern California through Baja California).

Publications:

Spatial variability of seasonal extreme precipitation in the western United States (2015)
Authors: Cameron Bracken, Balaji Rajagopalan, Michael A. Alexander, and Subhrendu Gangopadhyay

ENSO's Modulation of Water Vapor Transport over the Pacific–North American Region (2015)
Authors: Hye-Mi Kim and Michael Alexander

Moisture Pathways into the U.S. Intermountain West Associated with Heavy Winter Precipitation Events (2014)
Authors: Michael A. Alexander, James D. Scott, Dustin Swales, Mimi Hughes, Kelly Mahoney, and Catherine A. Smith

Video:
Tracking Pathways of Atmospheric Rivers

This video, produced by the Bureau of Reclamation in collaboration with researchers from CIRES and NOAA, explains the importance of atmospheric rivers to the natural and managed water systems across the Western U.S.

The following paths for different regions were identified: 1) the Columbia River basin is a conduit for moisture to reach eastern Washington, northern Idaho and western Montana; 2) a surprising path from central and northern California, north of the high Sierras (~41°N), then north into eastern Oregon and Idaho, into the mountains of central Idaho and along the Snake River Plain (see Fig. 1 for paths 1 & 2); 3) to the north and south (~35°N) of the high Sierras to reach Nevada; 4) just south of the Sierras into portions of Utah, Colorado and Arizona; and 5) flow centered over gaps in the Peninsula Mountains near the US-Mexico border, at ~29°N and over the southern portion of the peninsula that has relatively low topography, bringing moisture to Arizona and western New Mexico.

The general synoptic conditions associated with heavy precipitation events in the IMW include a trough ridge couplet at 500 h Pa, with the trough located northwest of the ridge and a tight gradient between them over and upstream of where the heavy precipitation occurs. The accompanying circulation results in strong moisture transport from the southwest, consistent with studies of ARs that impact the Pacific coast, but that reach a maximum near the topographic gaps. Smaller-scale cutoff lows, which move on shore at ~30°N, transport tropical moisture across southern Baja and the Gulf of California resulting in heavy precipitation over central Arizona.

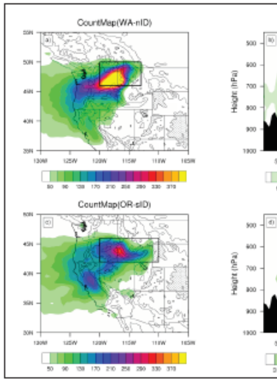

Figure (above). Count maps (left) and cross section (right) indicating the number of back trajectories that pass through a cfsr grid column originating in the a) wa-nid and b) or-sid. The trajectories are initiated at 00, 6, 12 and 18z on days when one of the top 150 (independent) precipitation events occurred. The trajectories are initiated at the four cfsr grid point around the station that recorded the event at a single pressure level located between 50 and 100 hpa above the surface). A total of 2400 trajectories were initiated in each region. The position of a trajectory is estimated at one-hour intervals over the five previous days using the six-hourly three-dimensional cfsr wind fields. Topography is depicted via a 5-point smoother applied to the 30 arc-second (~1 km) terrain height, with contours at 1000 m (3281 ft), 1500 m (4921 ft) and 2300 m (7546 ft) and stippling above 2300m. Vertical cross section of the back trajectory counts along the crest of the cascade, sierra and peninsular mountains for the a) wa-nid, and b) or-sid. The terrain is shown in black.

Topic breakdown

- Inland-penetrating ARs:
  - Initial Reclamation-funded moisture pathway work
  - How is/was it used?
- Process-based understanding through case studies
- Future work, discussion on potential opportunities

Topic breakdown

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Based on the collective work of:
Michael Alexander, Jamie Scott, Dustin Swales, Mimi Hughes, Kelly Mahoney, Michael Mueller, Joseph Barsugli, Cathy Smith

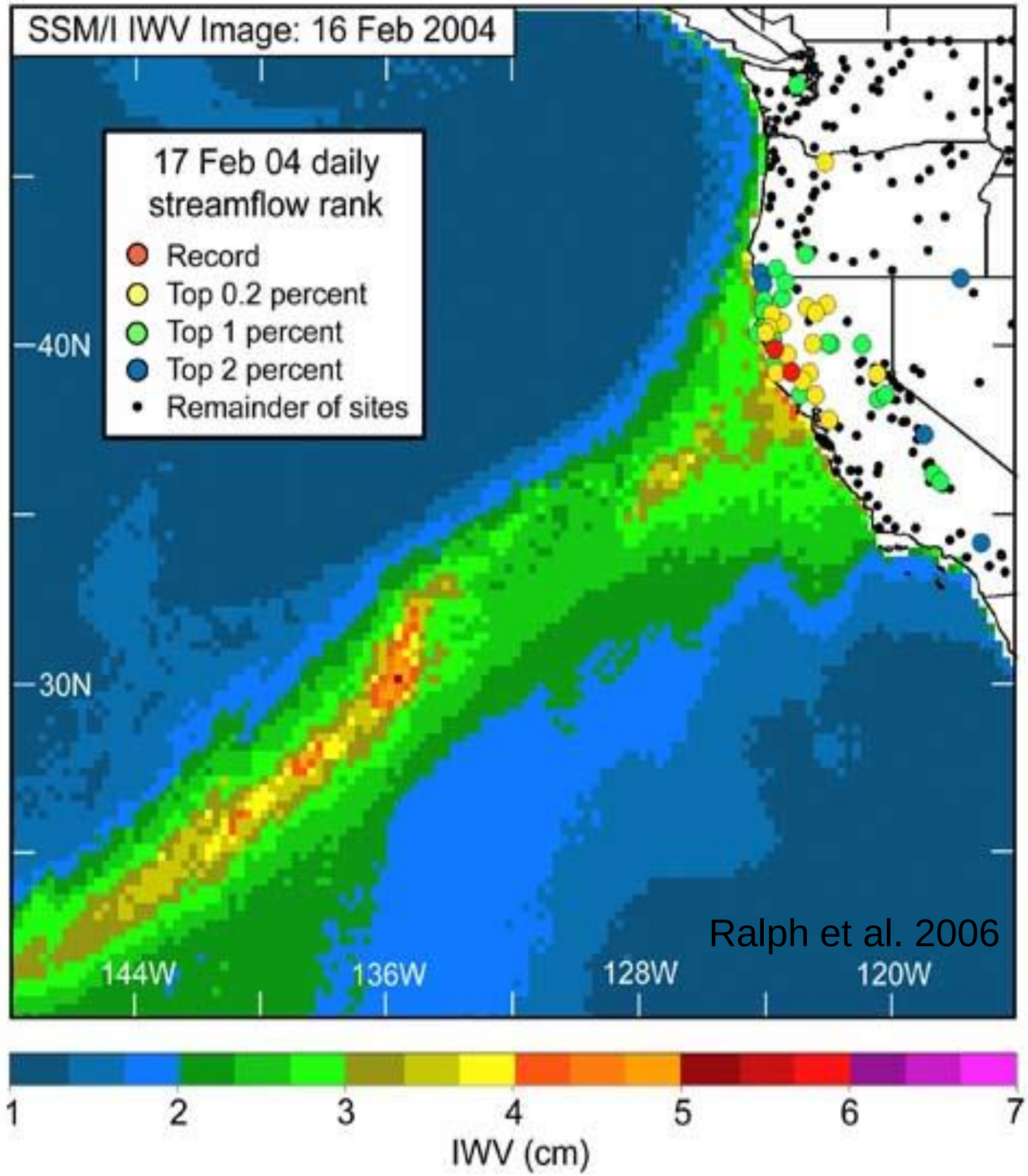
Funding, stakeholder engagement from:

Bureau of Reclamation (defining project, funding)

Partners: Levi Brekke, John England, Katie Holman, David Keeney, Jason Caldwell, Victoria Sankovich

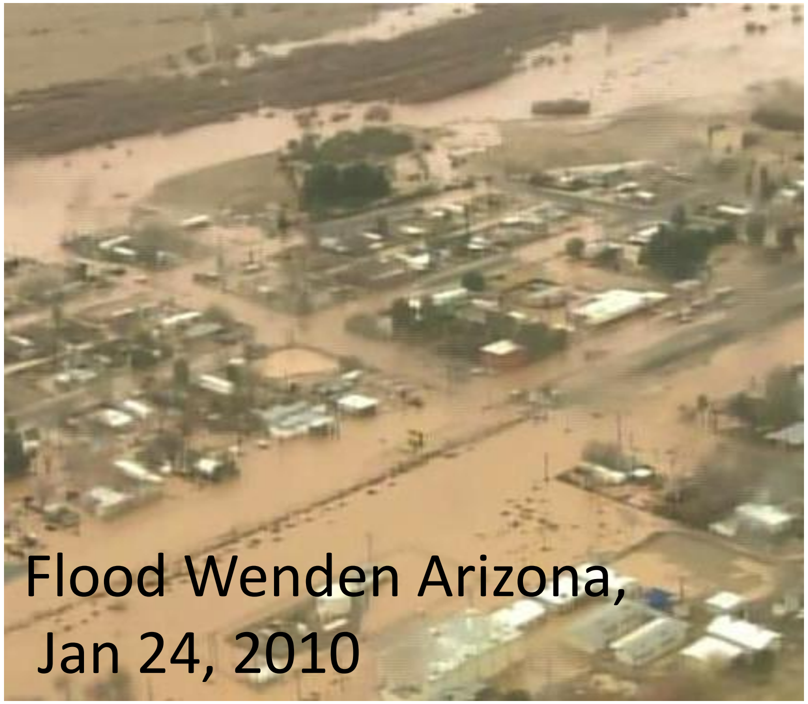
Heavy Winter Precipitation West Coast, Cascades, Sierras

Atmospheric Rivers (Pineapple Express)



IWV –Integrated Water Vapor through the atmosphere

Inland-penetrating ARs: Initial motivation



- What is the moisture source for intense winter precipitation events in the US inter-mountain west (IMW)?
- Do air parcels take specific pathways to reach key regions in states such as Arizona, Idaho and Colorado?

M. Alexander (NOAA)

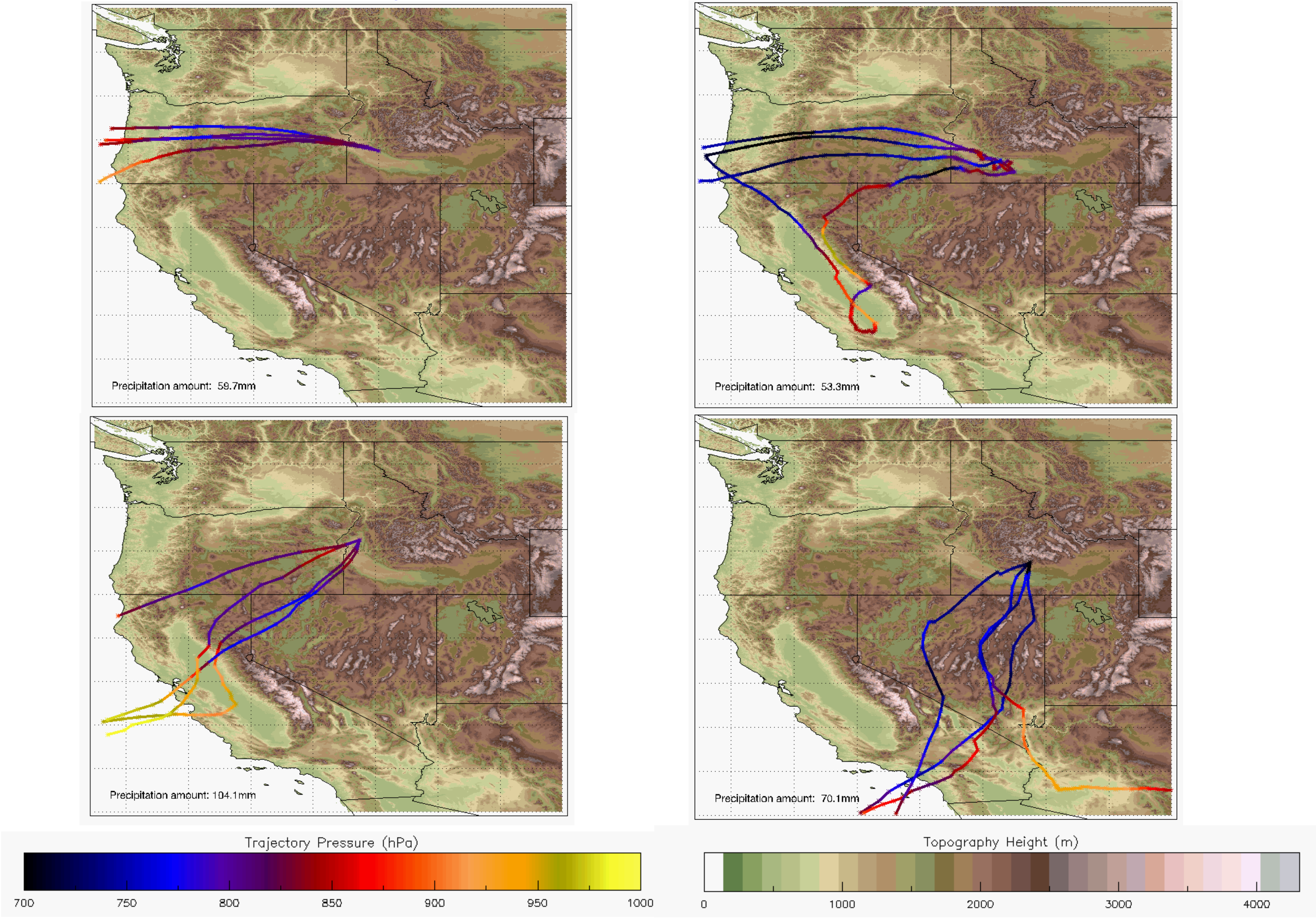
Methods for identifying moisture pathways during heavy precipitation events

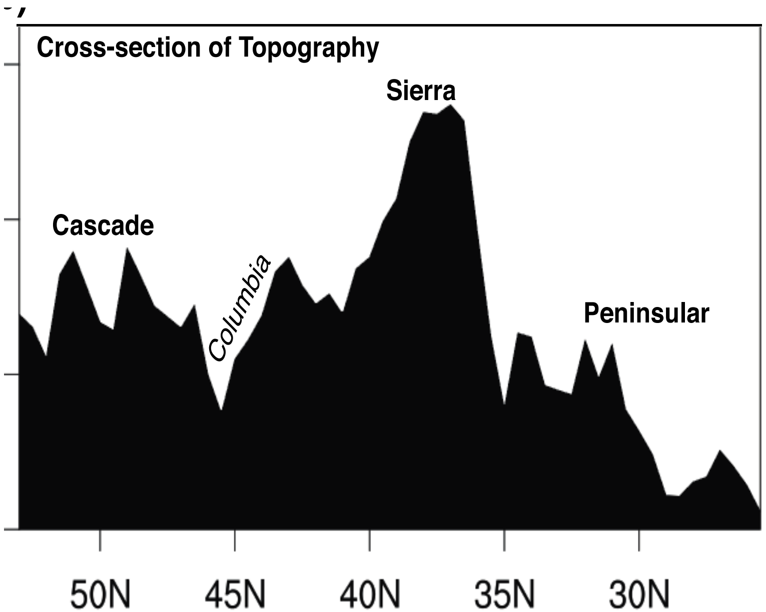
Three semi-independent methods:

1. Backward trajectories
   - Initiating with daily observations of heavy 24-h precipitation events
2. EOFs of vertically-integrated water vapor transport (IVT) from Climate forecast System Reanalysis (CFSR)
   - Reanalysis combination of observations & model (40-km resolution)
3. Self-organizing maps
   - CFSR + extreme precipitation climatology (Livneh 2013)

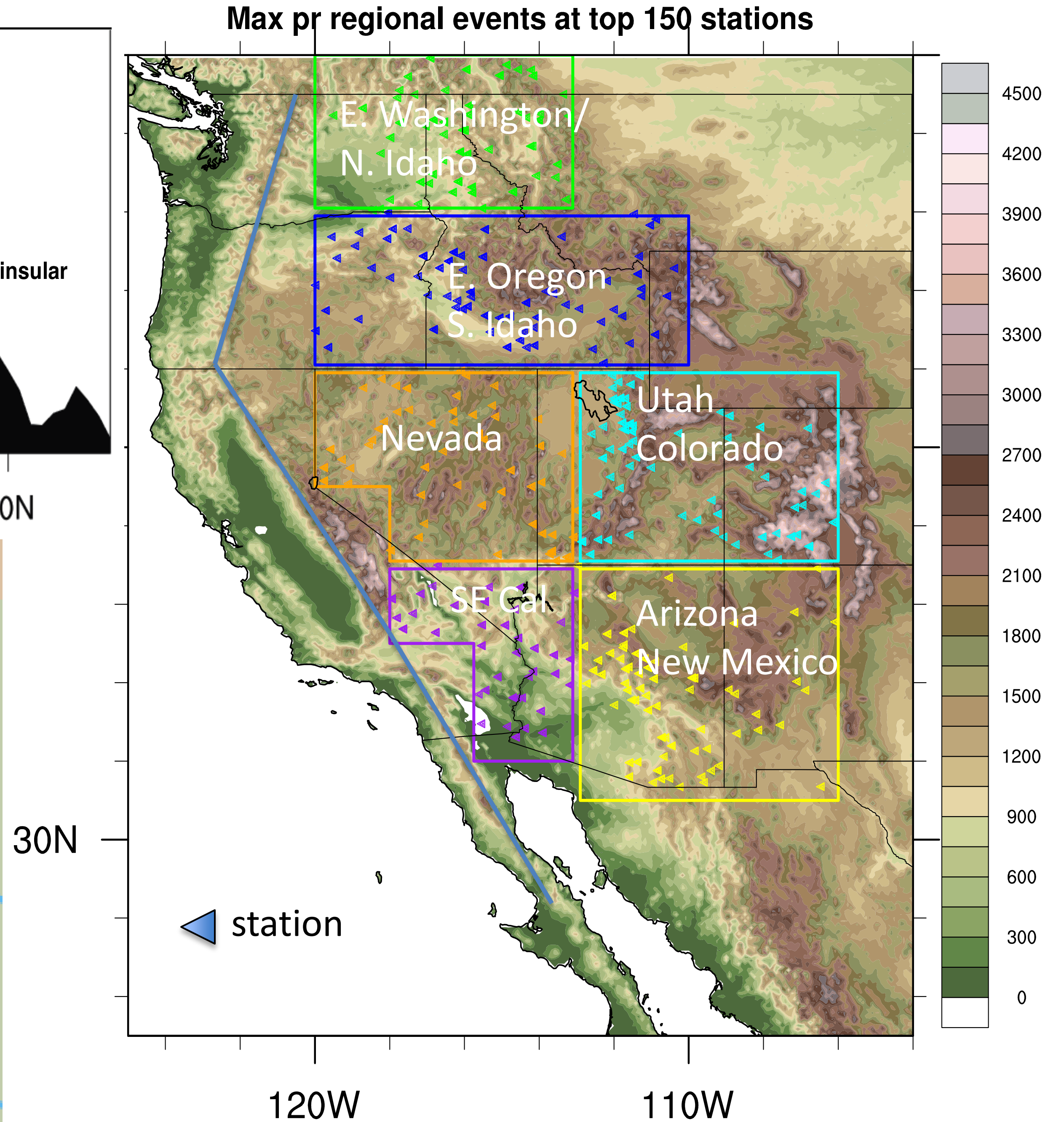
- All results are for 1979-2010 (When CFSR is available)
- Cool season (Oct-Mar)

Back-trajectory approach:
Example of 4 different events in S. Idaho



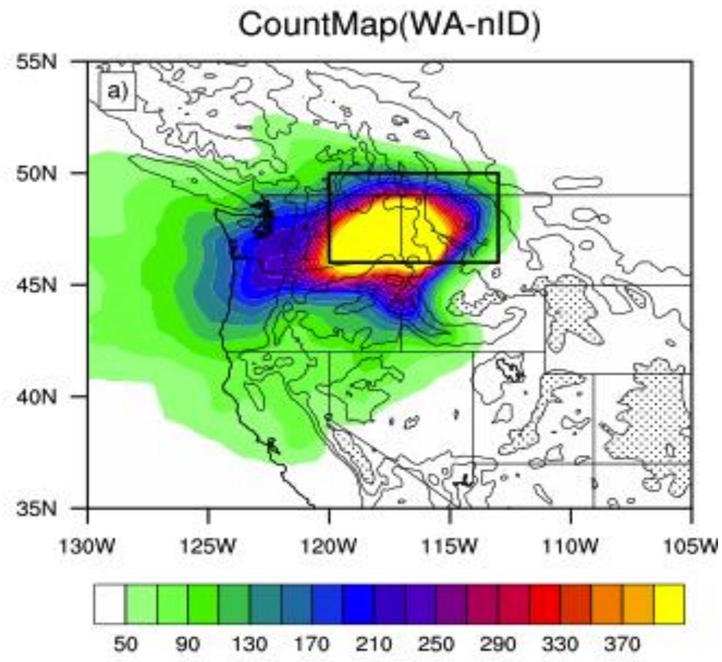

Cross-section of Topography
Sierra
Cascade
Columbia
Peninsular
50N
45N
40N
35N
30N

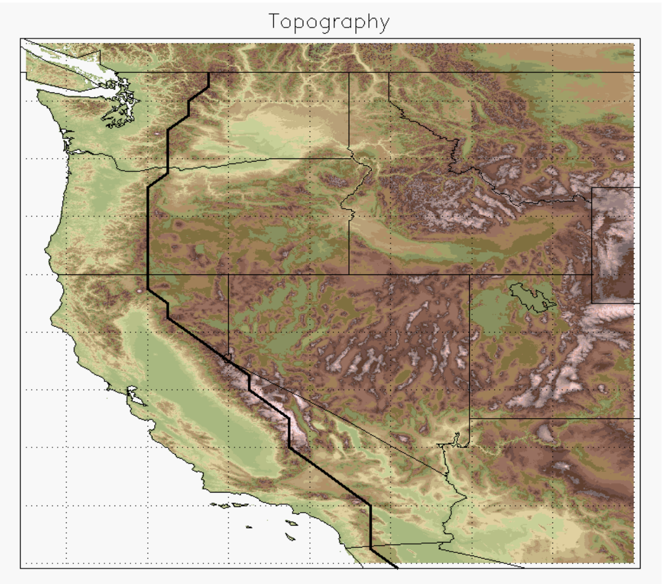

CANADA
Montana
Idaho
Wyoming
U.S.A.
CONTINENTAL DIVIDE
Colorado
New Mexico
Pacific Ocean


Max pr regional events at top 150 stations
E. Washington/ N. Idaho
E. Oregon S. Idaho
Nevada
Utah Colorado
SE Cal
Arizona New Mexico
station
30N
120W
110W
4500
4200
3900
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0

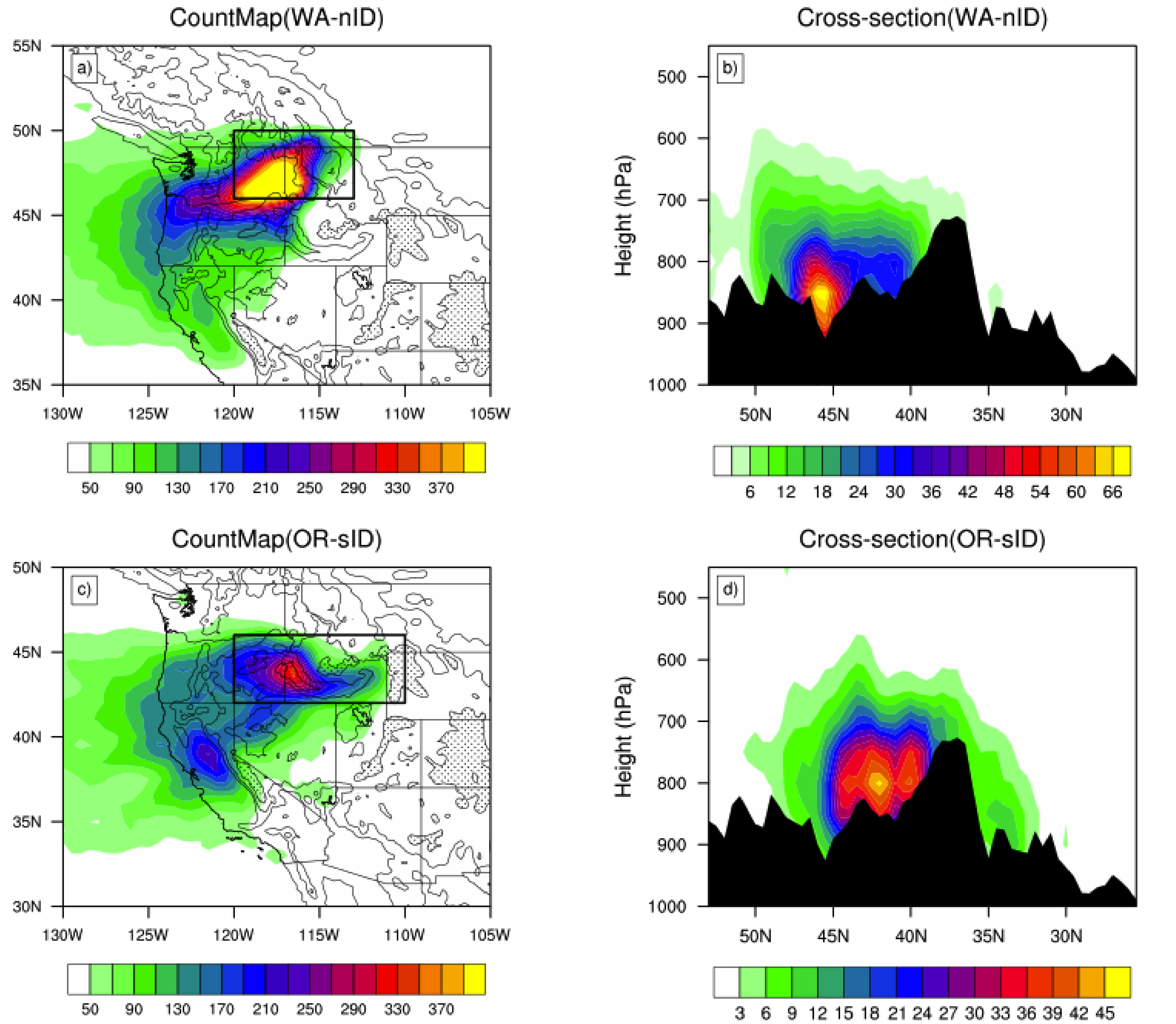
Trajectory analysis: Counts maps & cross sections

- Count maps - # of trajectories passing through a CFSR grid column
  - Topography contoured (1000, 1500 m); hatching > 2300 m
- Cross sections: Illustrate trajectory counts along Cascades, Sierras, and Peninsula Mountains (Southern & Baja California)

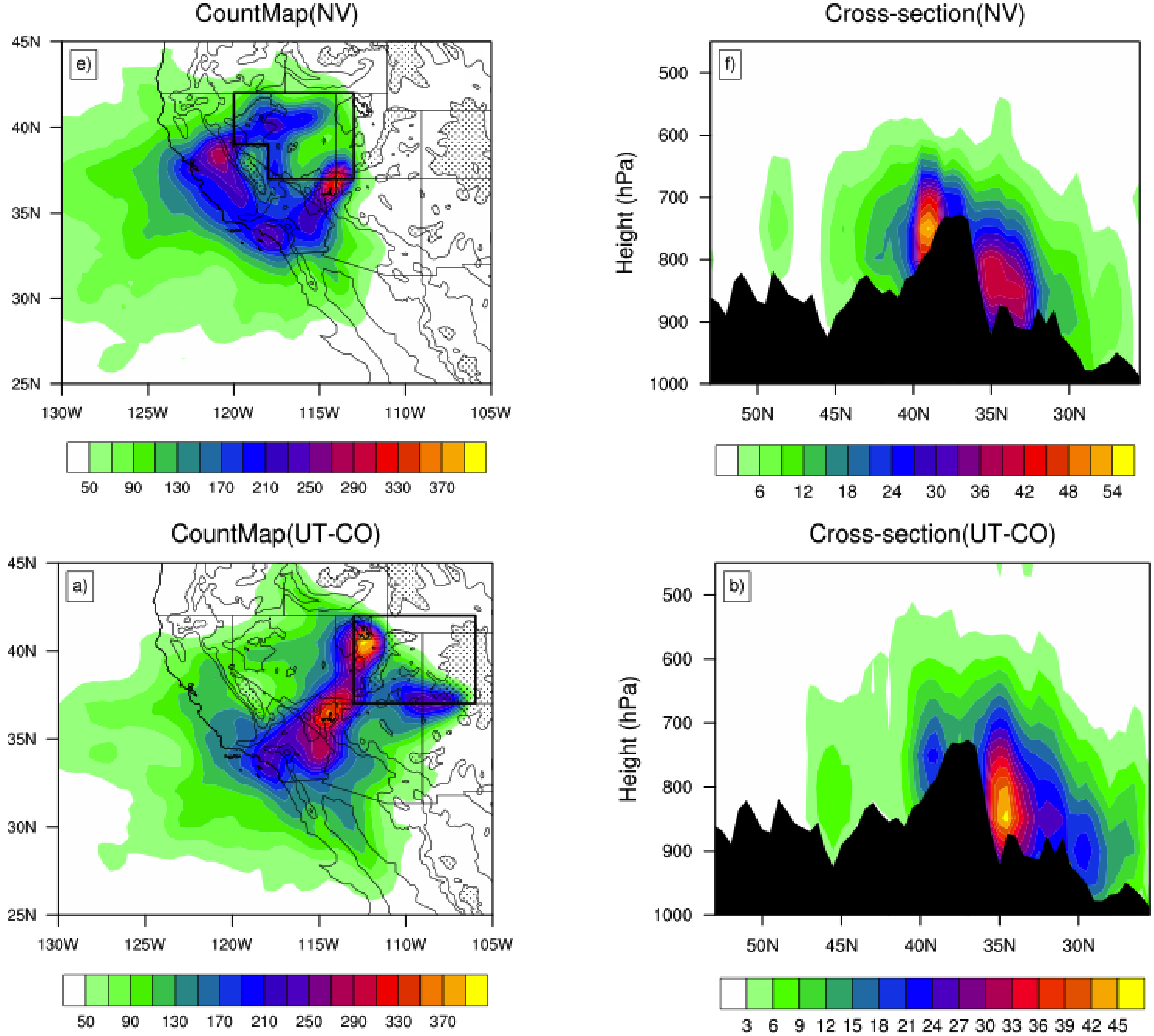




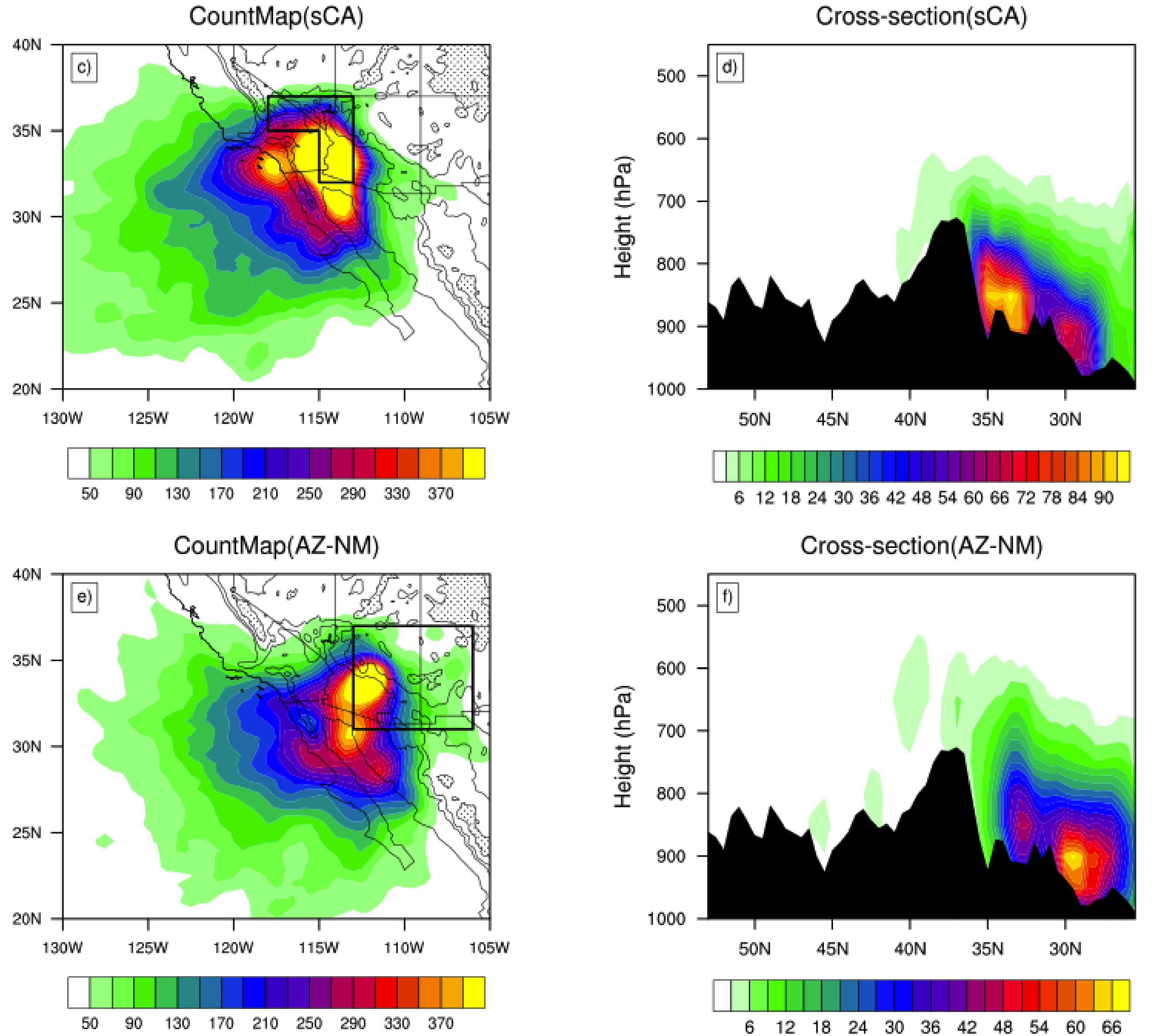
Trajectory approach: Counts maps, cross sections by region



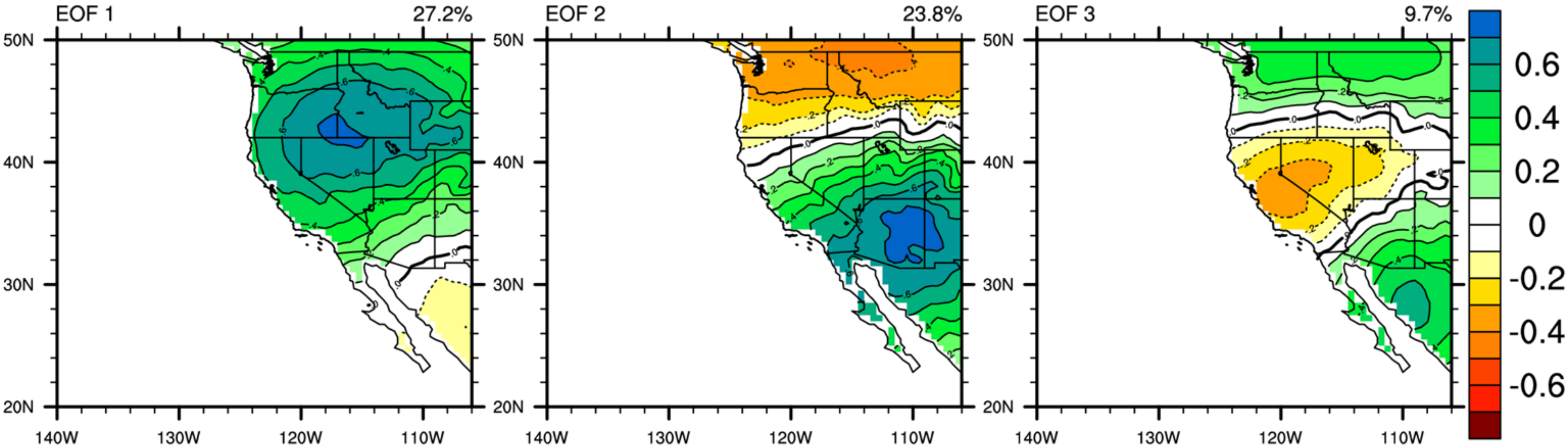
Trajectory approach: Counts maps, cross sections by region



Trajectory approach: Counts maps, cross sections by region



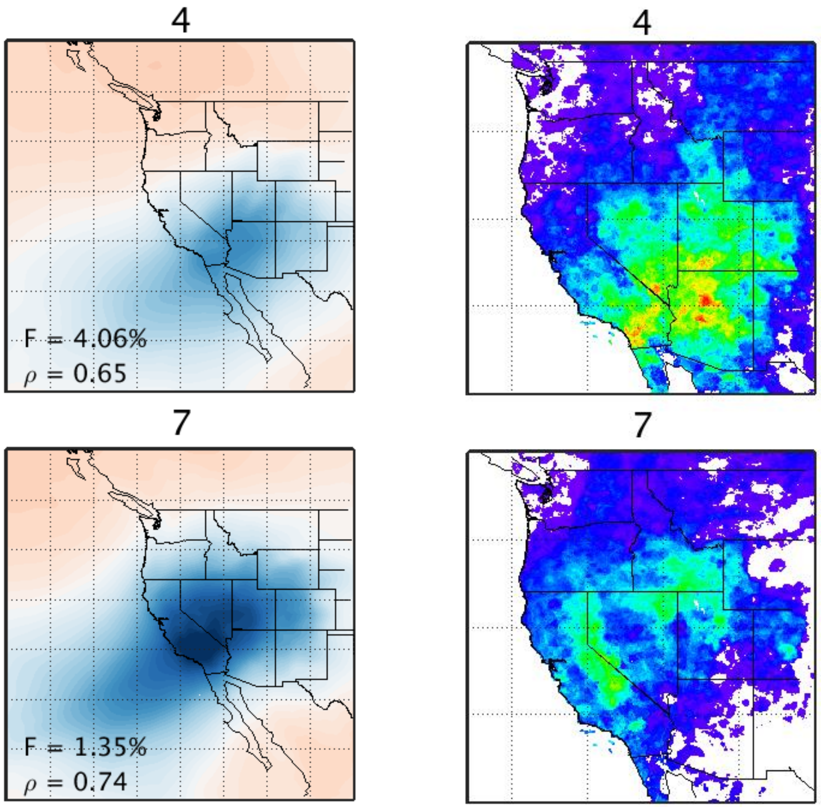
EOF approach example:
Identify synoptic patterns associated with IVT anomalies



- EOFs illustrate general synoptic conditions associated with heavy precipitation events in the IMW
- Common features include 500 hPa trough located northwest of ridge, tight gradient just upstream of heavy precipitation → strong moisture transport from southwest that reaches a maximum near topographic gaps.
- EOFs based on land only and normalized Precipitation
  - By normalizing and using land only emphasizes variability in the interior.
  - Can use composites to show the full fields (including over the ocean) based on the value of the principal component (PC, time series):

Self-organizing maps: Moisture sources for extreme precipitation events in the Intermountain West

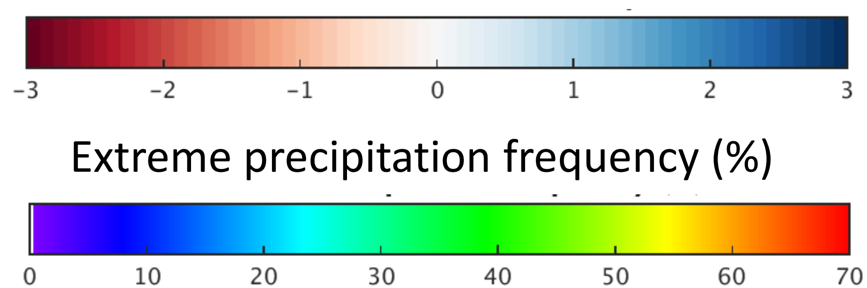
Self-organized map nodes 4 and 7



Standardized IVT Extreme precip %

- Iterative grouping of similar maps
- A substantial number of extreme precipitation events associated with infrequently occurring synoptic patterns
- Confirms moisture pathways in Alexander et al. (2015)

Standardized IVT Anomaly



Extreme precipitation frequency (%)

Figures from Swales et al. 2016

Summary

- Trajectory, EOF, self-organized maps analyses:
  - Pacific moisture producing extreme precipitation in interior west takes clear pathways through terrain gaps (Alexander et al. 2015)
  - Topography clearly influences moisture transport and precipitation, but large-scale atmospheric circulation and synoptic conditions shape conditions necessary for heavy precipitation to occur
  - Depth, intensity of moisture tied to controlling synoptic and mesoscale processes
- There can be two (or more) pathways to a given region; a single pathway can transverse more than one region
- Pathways identified not limited to moist air: air also flows through these gaps from the west during dry conditions (often more from north and at higher elevations)
- Limited observations in certain locations (e.g., northern Colorado, high elevation locations in general) limit trajectory results
- Better methods for identifying regions, including precipitation estimates from higher elevations and finer resolution data may lead to a more precise depiction of moisture pathways in the intermountain west.

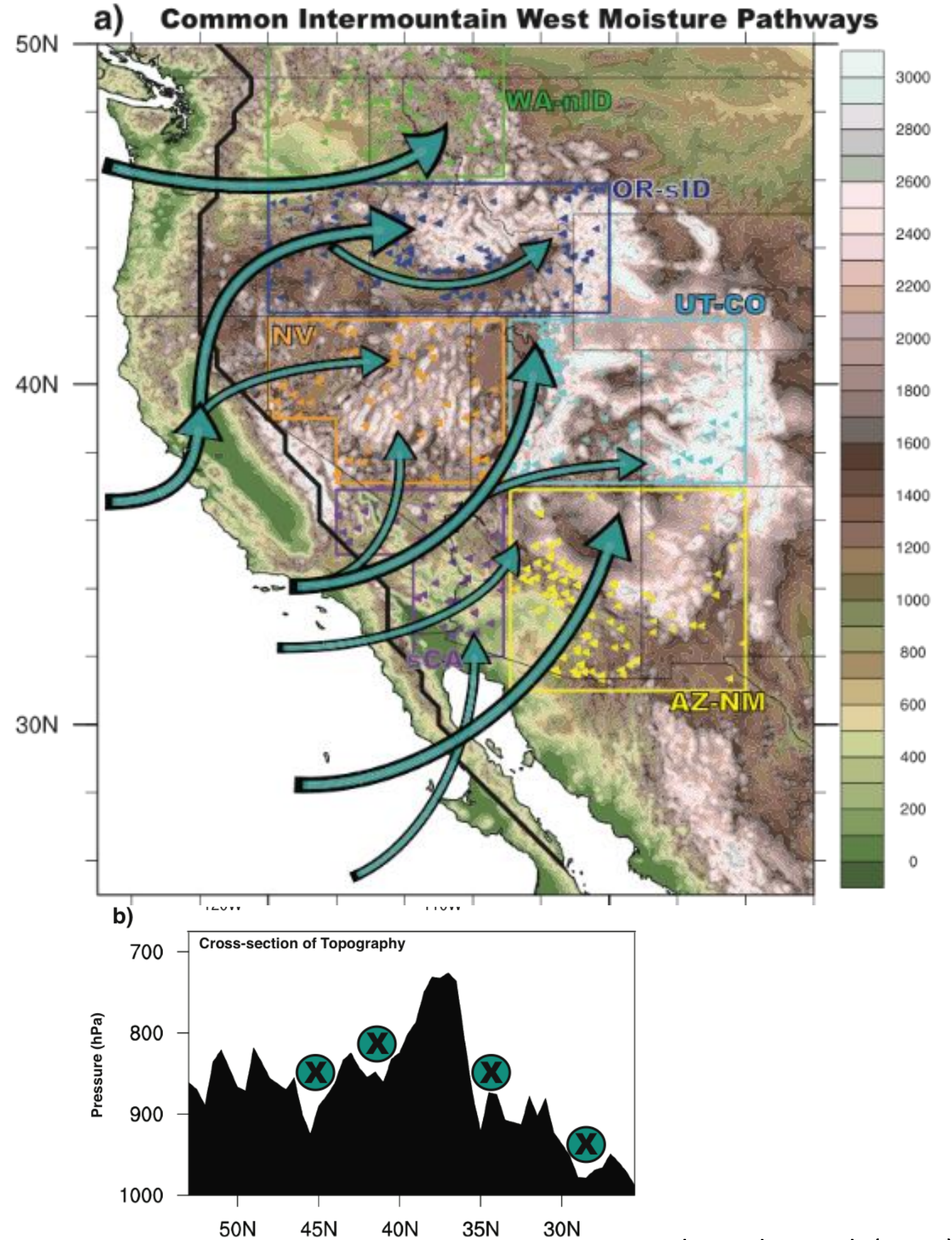
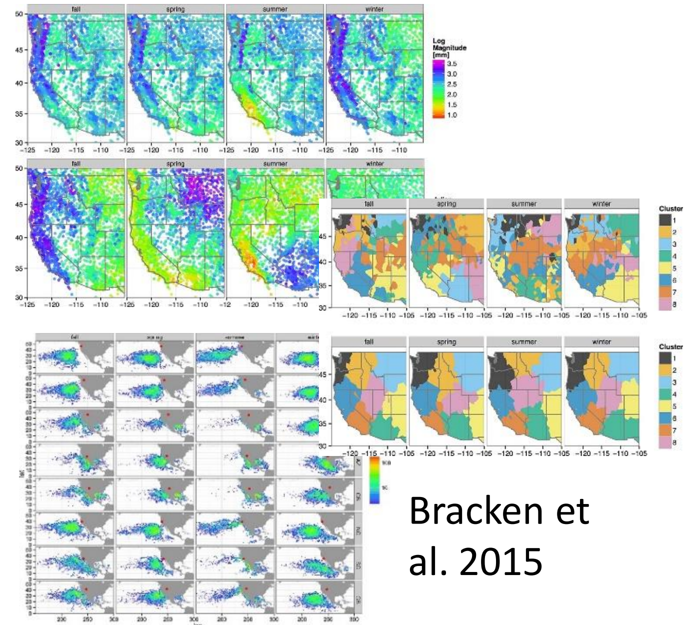


Fig. 13

Alexander et al. (2015)

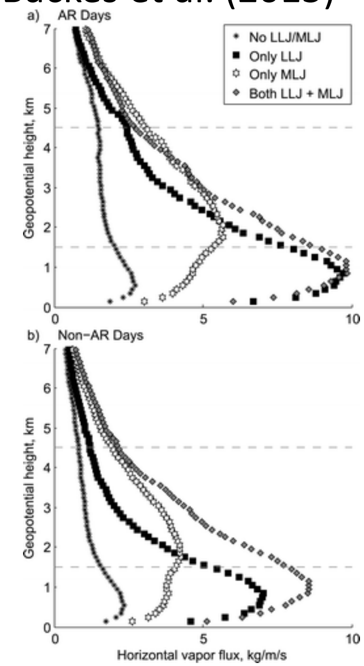
Related work occurring among other groups

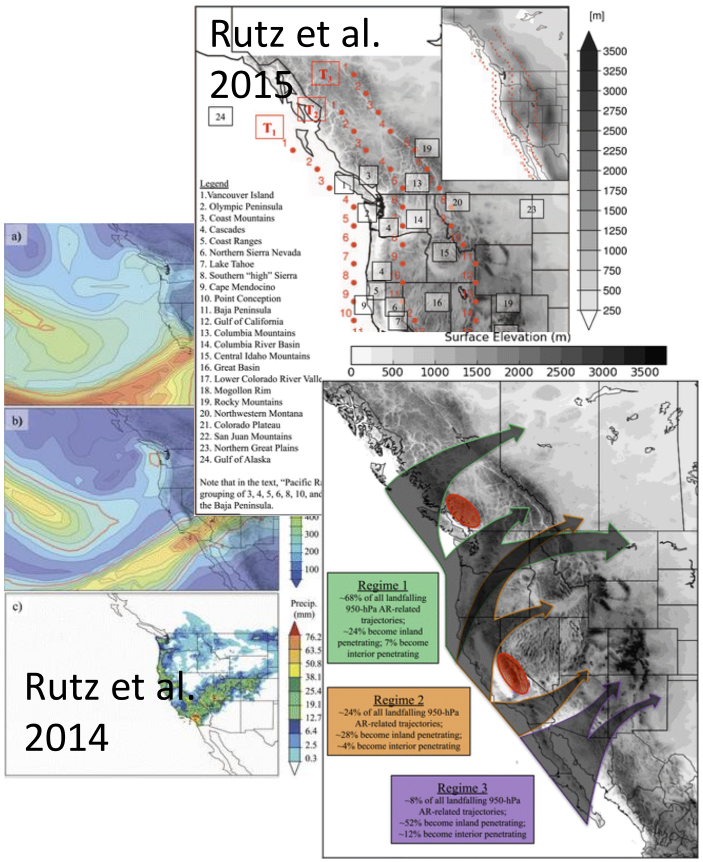
- Rutz et al. (2012), (2014), (2015)
- Bracken et al. (2015)
- Backes et al. (2015)
- Hatchett et al. (2017)

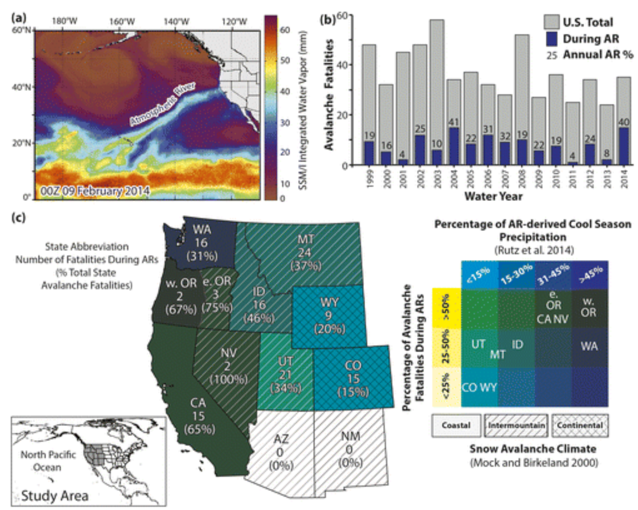


Bracken et al. 2015

Backes et al. (2015)







Hatchett et al. 2017

Diagnosing the Moisture Sources for Extreme Precipitation Events in the Intermountain West

Summary

There are preferred pathways through mountain gaps for moisture to reach the interior west:

Through Columbia River valley => across Washington => N. Idaho => W. Montana

Northern California => north of the high Sierras => Northern Nevada => Southern Idaho

Across Baja California (2-3 gaps) => North into Arizona* => Utah and Colorado

* case study/WRF simulation

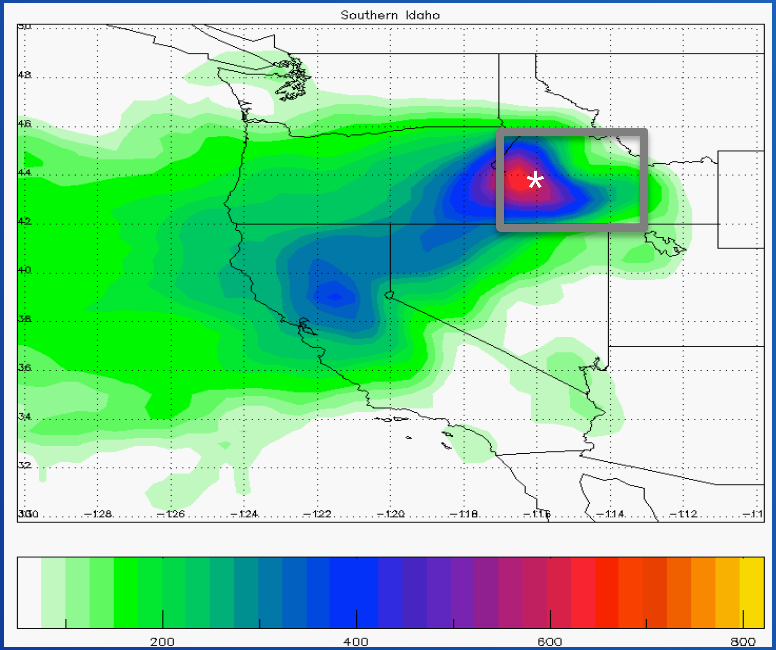
Key Lessons Learned

- Results may dependent on methods:
  - e.g. subjective regions, EOF limitations
  - resolution dependence?

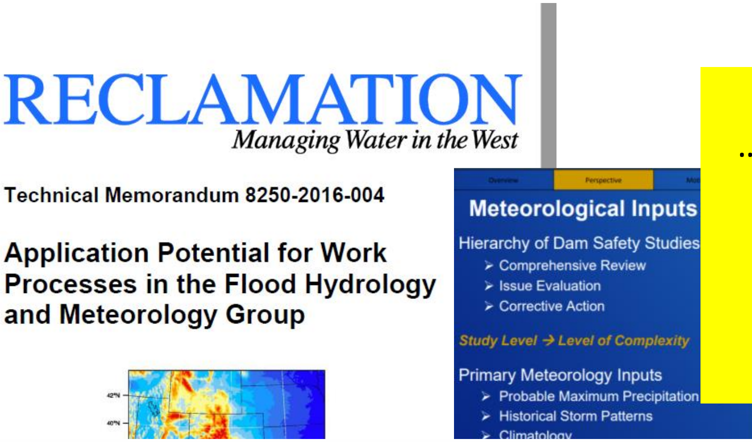
Next Steps/Future Work (next talk)

- Transfer to data & methods to Reclamation
- Additional methods for grouping storms
- Generate/ana… resolution si… s
- Examine Impact of climate change on ARs

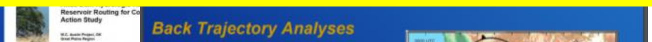
(How) Was this research used by Reclamation?

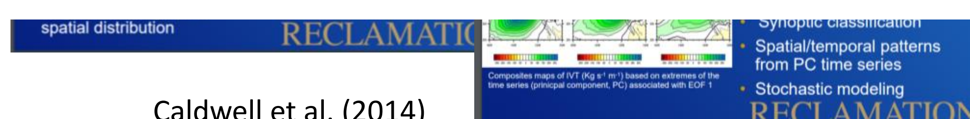


Reclamation application of NOAA/CIRES research



Post-project, from Reclamation (Technical Service Center) partners: …we share information about moisture pathways with other people in the agency who know little about weather and climate…we use this information in reports (like background info) to discuss how/where moisture travels across the West to remote, high-elevation watersheds. We have not used the trajectory code in any official capacity (unlike the WRF simulations)…





Caldwell et al. (2014)

Topic breakdown

- Inland-penetrating ARs:
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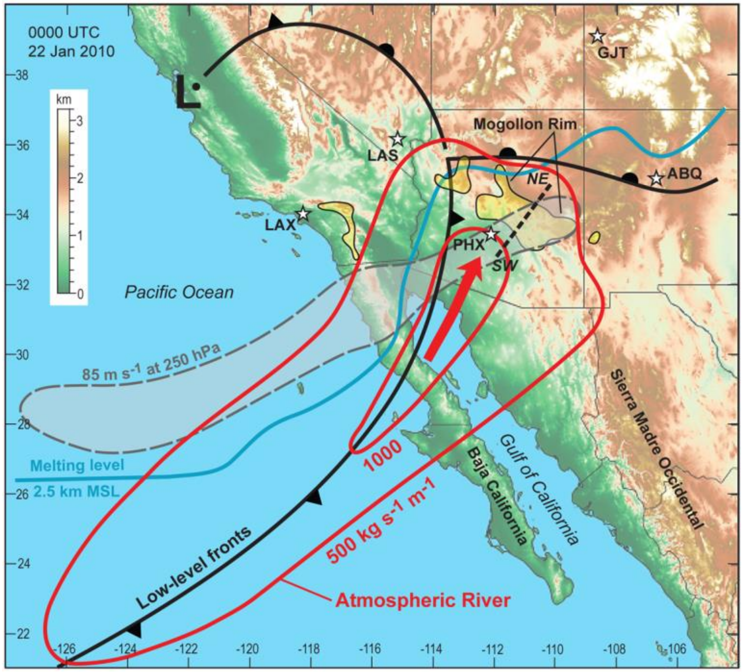
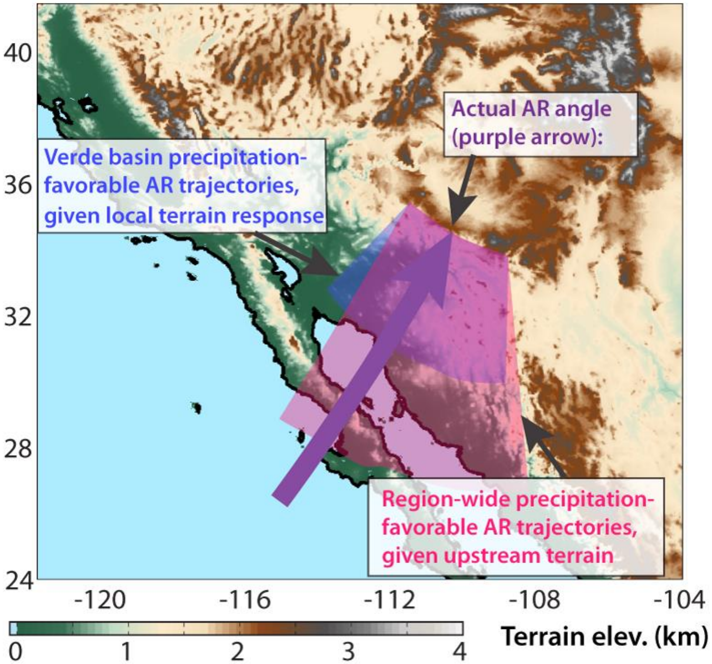
Process-based understanding: Extreme precipitation events in multiple interior mountain ranges: January 2010 flooding

- In-depth observational and high-resolution numerical model study of AR-driven flood in Arizona's Mogollon Rim and points further inland
- Sequential moisture removal by multiple mountain ranges
- Removal proportional to terrain height
- Landfall angle key to basin-wide precipitation impact.
- Simplified linear model of orographic precipitation: R2O potential



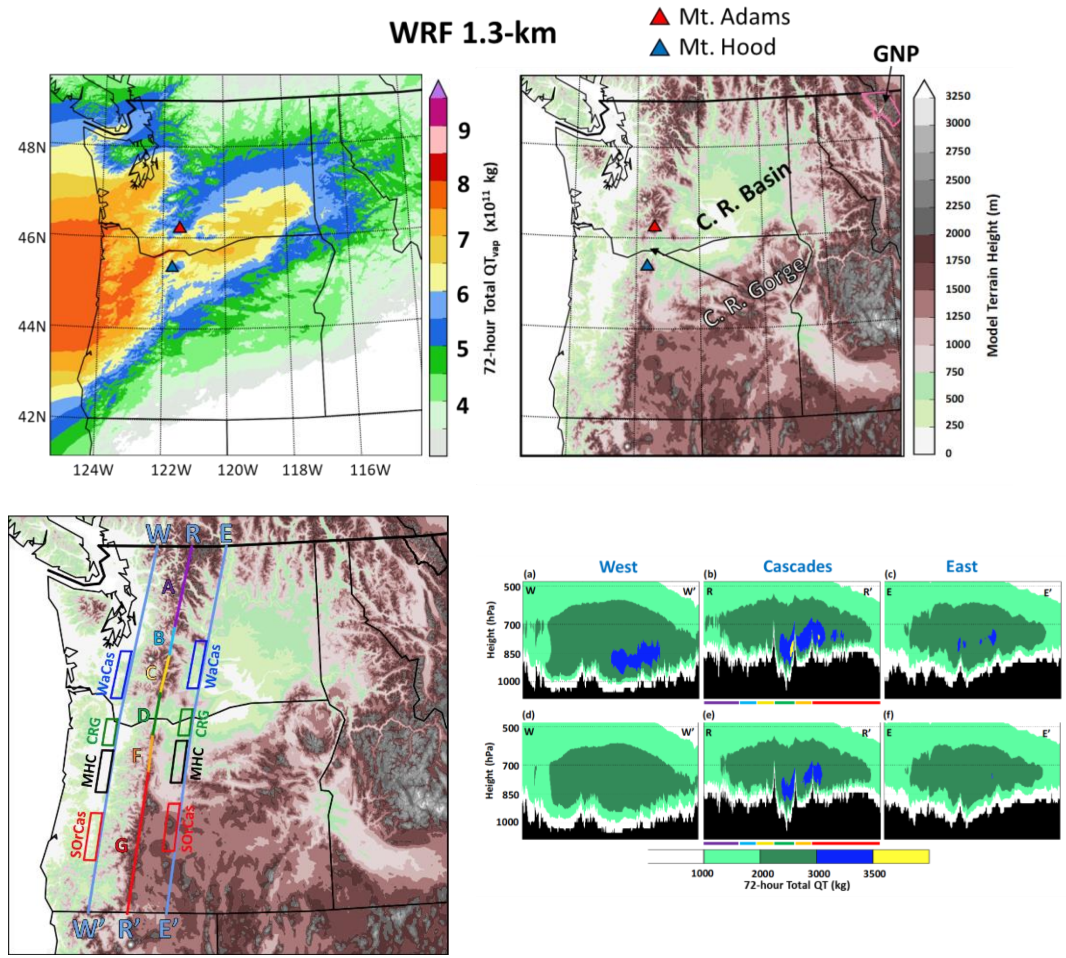


Figures from Neiman et al. 2013 (left) and Hughes et al. 2014 (right)

Process based understanding:

High-resolution modeling to understand inland moisture transport during November 2006 Glacier National Park flooding

- 5-7 November 2006: Record-breaking rainfall in Cascades and interior mountains
- Extreme rainfall and snowmelt → destructive flooding at Montana's Glacier National Park (800-km inland)
- High-resolution modeling: insight to micro-, meso-, synoptic-scale processes:
  - No single dominant pathway through Pacific Northwest during this event
  - Path of least resistance through Columbia River Gorge
  - Inland moisture transport most effective during strong, *vertically deep* AR conditions
  - Compare vertical depth of moisture transport to downstream terrain barriers

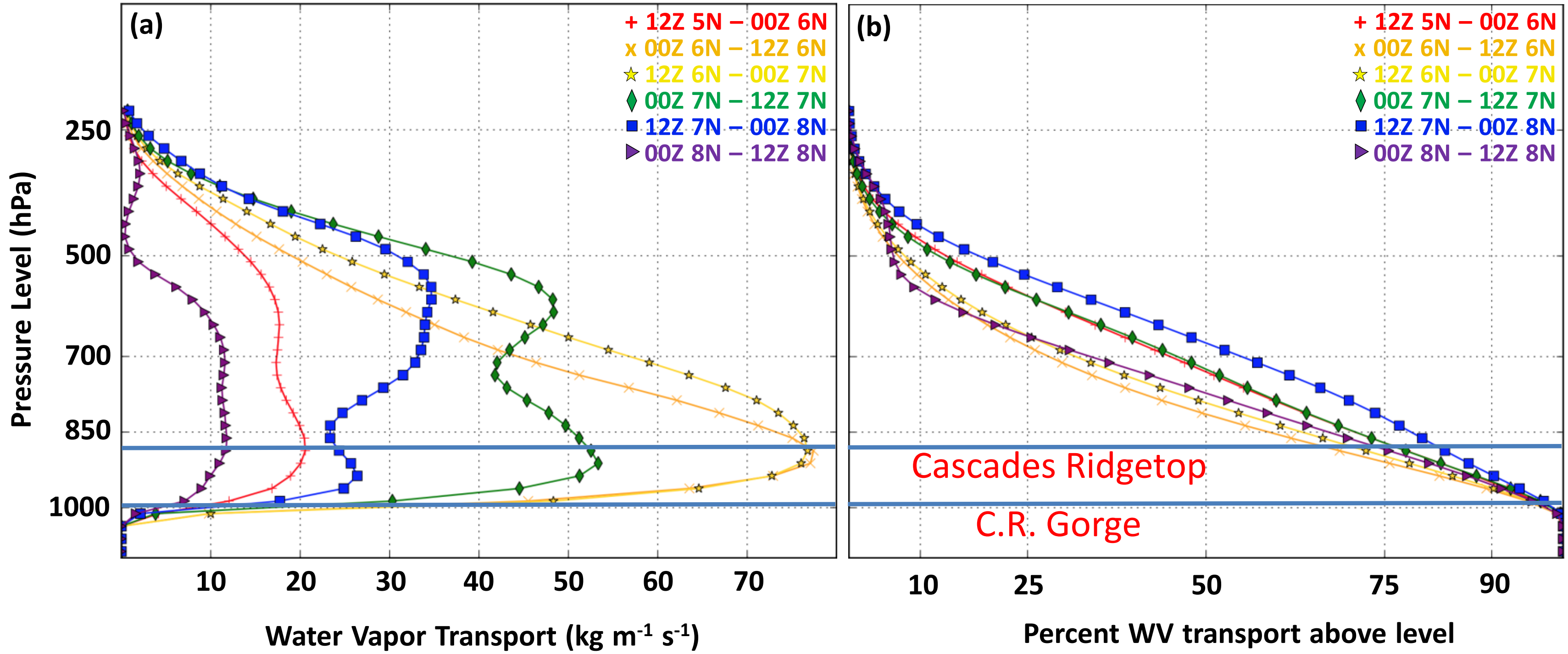


Mueller, M.J., K.M. Mahoney, and M. Hughes, 2017: High-Resolution Model-Based Investigation of Moisture Transport into the Pacific Northwest during a Strong Atmospheric River Event. *Mon. Wea. Rev.*

Where were the primary corridors for inland moisture penetration?

Vertical Vapor Transport Profile

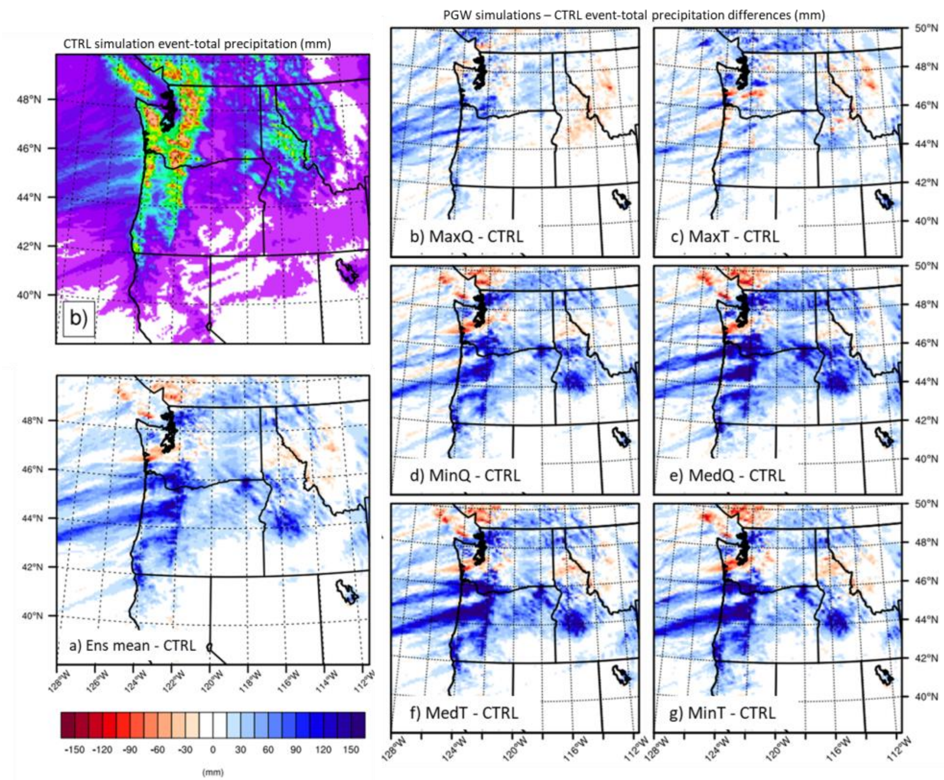
Vertical profiles near Portland, OR (western end of C.R. Gorge)



- Vertical evolution of water vapor transport in 12-hr averages
- At onset, transport maximum below 850 hPa
- As event matured, secondary maximum 700-500 hPa layer
- All transport above C.R. Gorge, 65-85% above Cascades ridgetop

Process-based understanding: Inland-Penetrating Atmospheric River Flood Event under Potential Future Thermodynamic Conditions

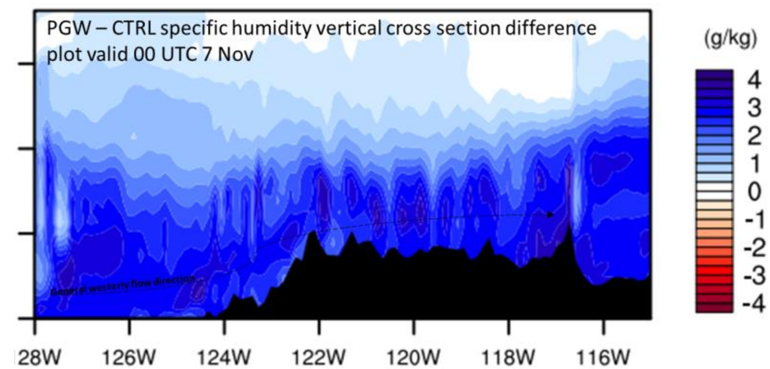
- How are inland moisture pathways impacted by large-scale thermodynamic changes?

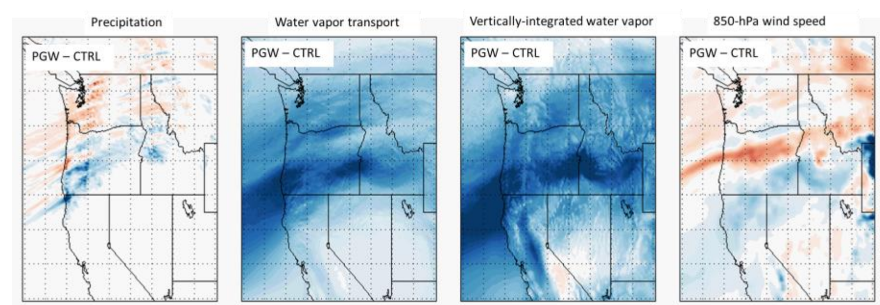


➢ Precipitation (Future – Past): Precipitation increases in **all** future simulations: notable changes across specific inland locations, especially Idaho's Sawtooth Mountain Range.

➢ Precipitation that fell as snow in 2006 becomes rain in future simulations for mid- and high-elevations. Potential enhanced flood risk?

- Pseudo-global warming (PGW) simulations: "future" inland precipitation increases occur via stronger, deeper moisture transport more effectively crossing Oregon's Coastal and Cascade mountain ranges.





➢ Inland moisture transport increases from both thermodynamics and dynamics: enhanced absolute environmental moisture + localized strengthened lower- and mid-level dynamics

Mahoney et al. (2018) J. Clim.

Gauging flood potential by improving probable maximum precipitation

Everyone at the Table: Colorado and New Mexico's Comprehensive Approach to Modernizing Extreme Precipitation Estimation for Dam Safety Decision-Making

Kelly Mahoney[1], Bill McCormick[2], Trevor Alcott[3], Rob Cifelli[1], Eric James[4], Robert S. Webb[1]
[1]NOAA Earth Systems Research Laboratory, Physical Sciences Division, [2]Colorado Division of Water Resources,
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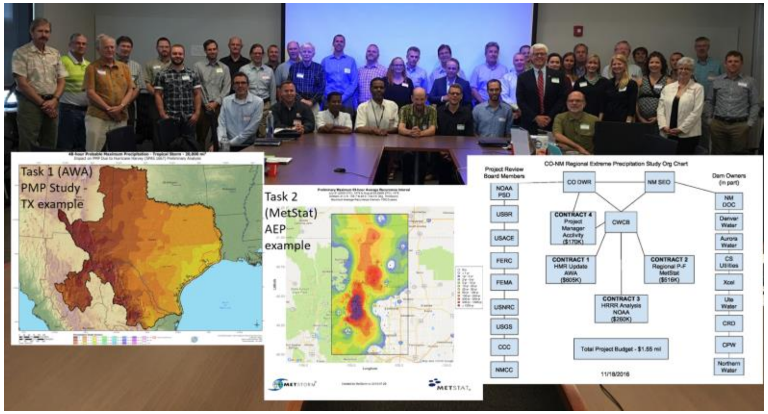
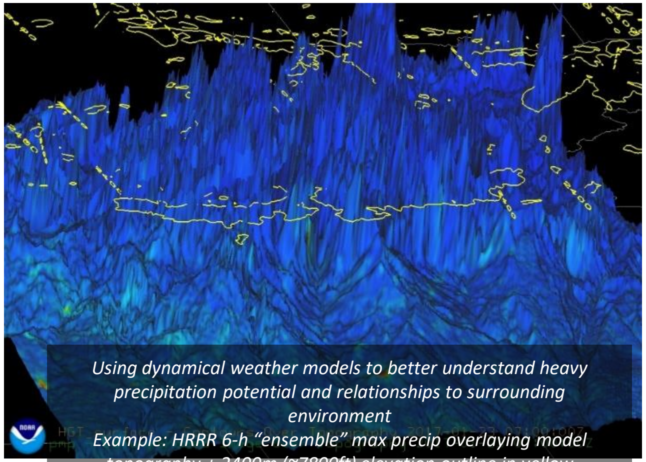
The challenge

- Are our high-hazard dam spillways currently safe?
- Dam spillways must be able to safely route flows from extreme precipitation to avoid loss of life and downstream property damage.
- Estimating potential extreme rainfall amounts (through probable maximum precipitation; "PMP") is a critical component of dam spillway design.
- PMP estimation methods are outdated; can new approaches improve estimates?
- Impact of climate change not currently represented in PMP; (how) should it be?





Using dynamical weather models to better understand heavy precipitation potential and relationships to surrounding environment
Example: HRRR 6-h "ensemble" max precip overlaying model topography + 2400m (~7800ft) elevation outline in yellow

Science to Action

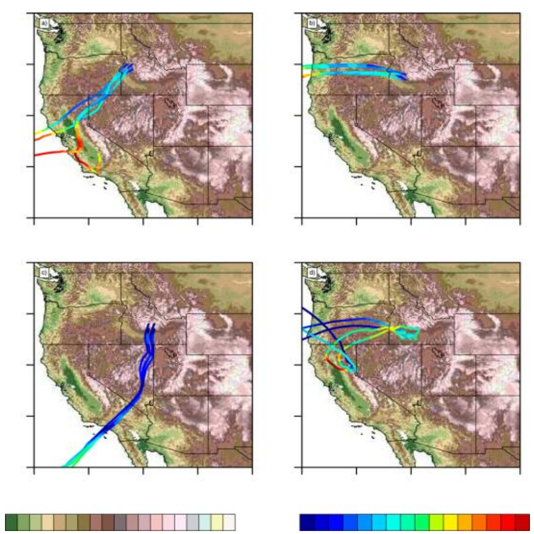
Colorado Division of Water Resources & New Mexico Office of the State Engineer updating extreme precipitation estimates for dam spillway adequacy evaluations, **prioritizing best available methods and scientific understanding available.**

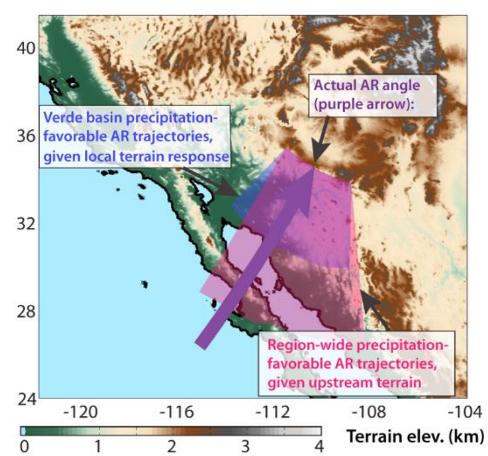
- Ensemble of methods being used to update extreme precipitation estimates
- Three technical tasks: pursuing different methods, conducted concurrently and in collaboration with each other
- **NOAA contributions include:**

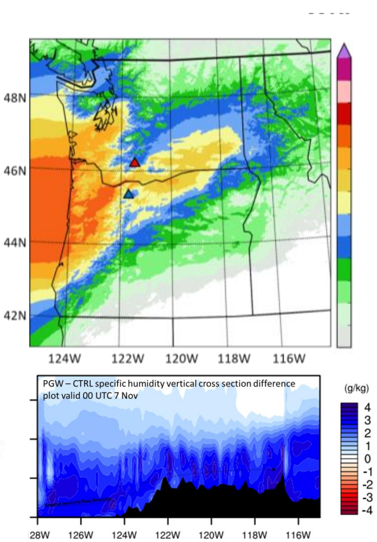
1) A "super-ensemble" of hourly High-Resolution Rapid Refresh (HRRR) model forecasts: Use all forecast cycles and forecast hours from 2012 – present to create novel high-resolution "dataset of opportunity"
2) Use high-resolution model data to improve max, mean, mean-annual-maximum fields to inform PMP/AEP products;
3) Storm seasonality, storm patterns, precipitation-elevation relationships, rain-vs.-snow
4) Simulation of specific historic flood events
5) Recommendations based on improved physical process simulation, understanding

Summary

- NOAA ESRL Physical Sciences Division/CIRES well-versed in physical processes affecting inland-penetrating AR precipitation
- Work to-date has greater focus on climatology, process understanding relative to predictability at any scale
- Upcoming work with Reclamation Mid-Pacific Region to better understand western US precipitation processes, impacts in NA-CORDEX dataset

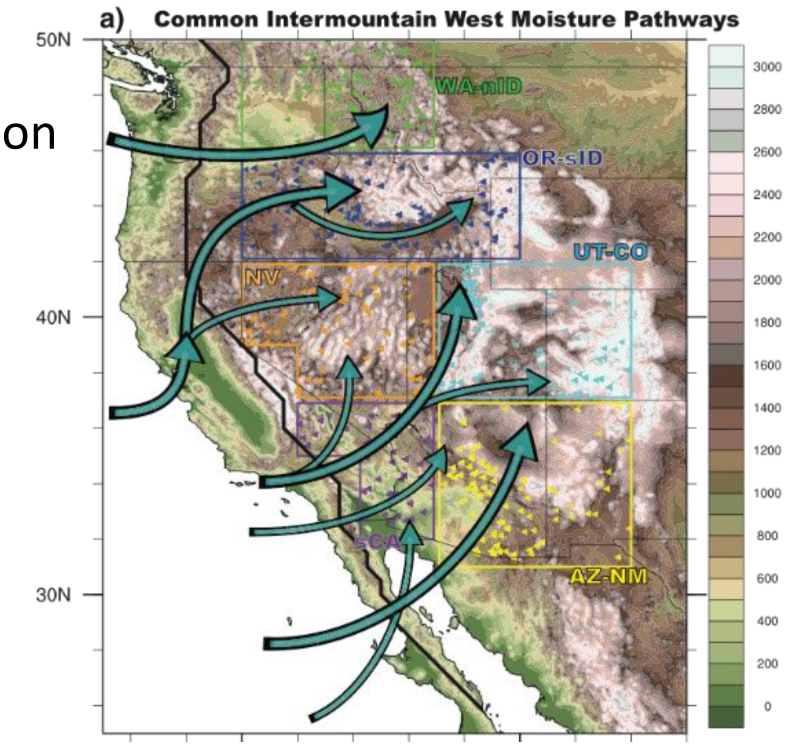






Summary

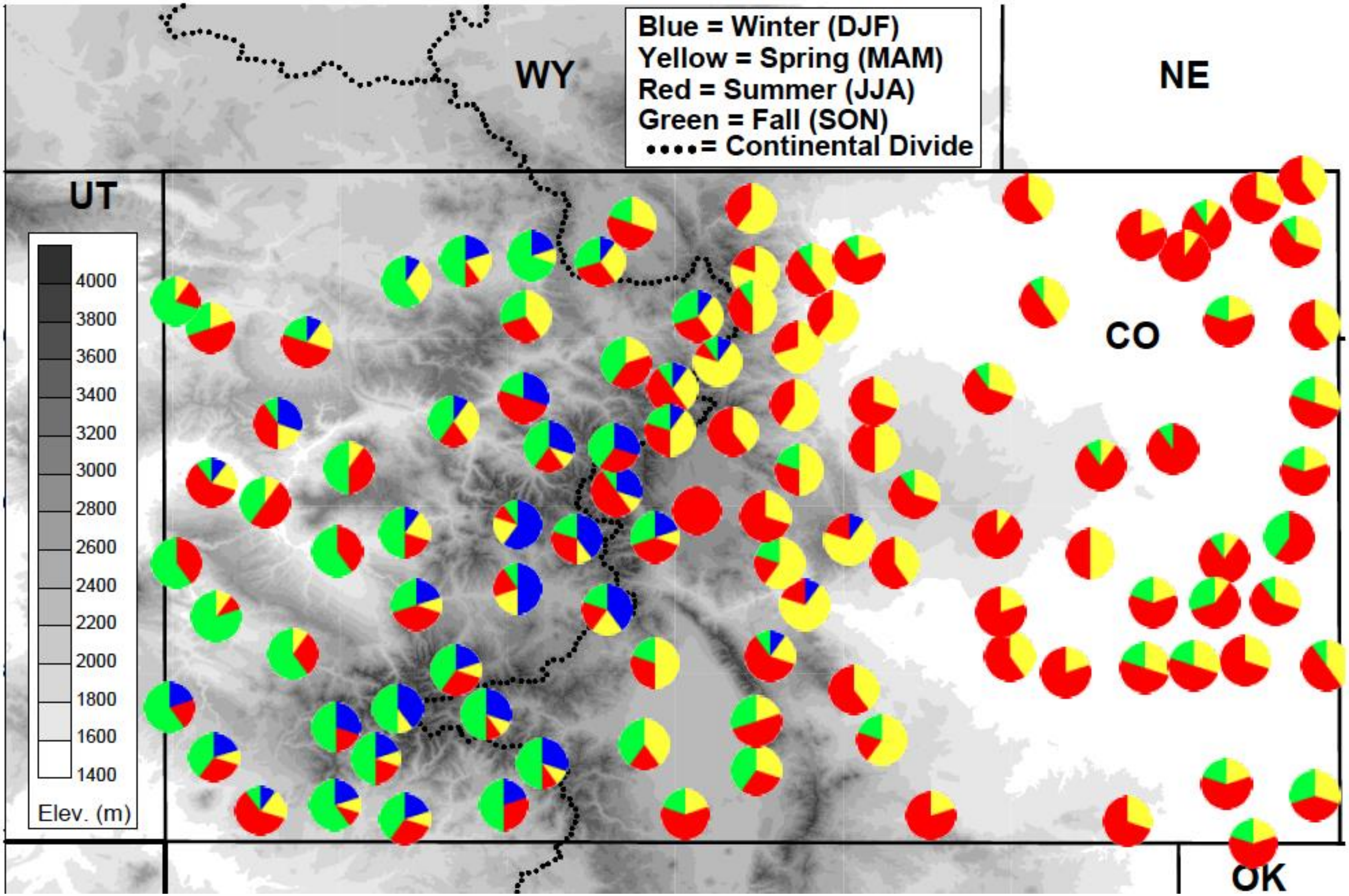
- Opportunities to extend and apply this work to S2S challenges?



- ARs quite predictable on weather time scales
- AR events, specific weather, impacts: little skill on S2S scales
- Will improvements in global model resolution, physics, initialization…
  - improve ENSO, MJO, QBO, etc., →
  - improve jet stream representation, parent midlatitude synoptic cyclone patterns →
  - improve/enable probabilistic S2S inland AR precipitation forecasts??

- While we await improvements (or if they don't materialize as desired), can we better sync up user needs with burgeoning inland pathway scientific understanding to refine/reframe questions for inland impacts and planning?

Additional Slides

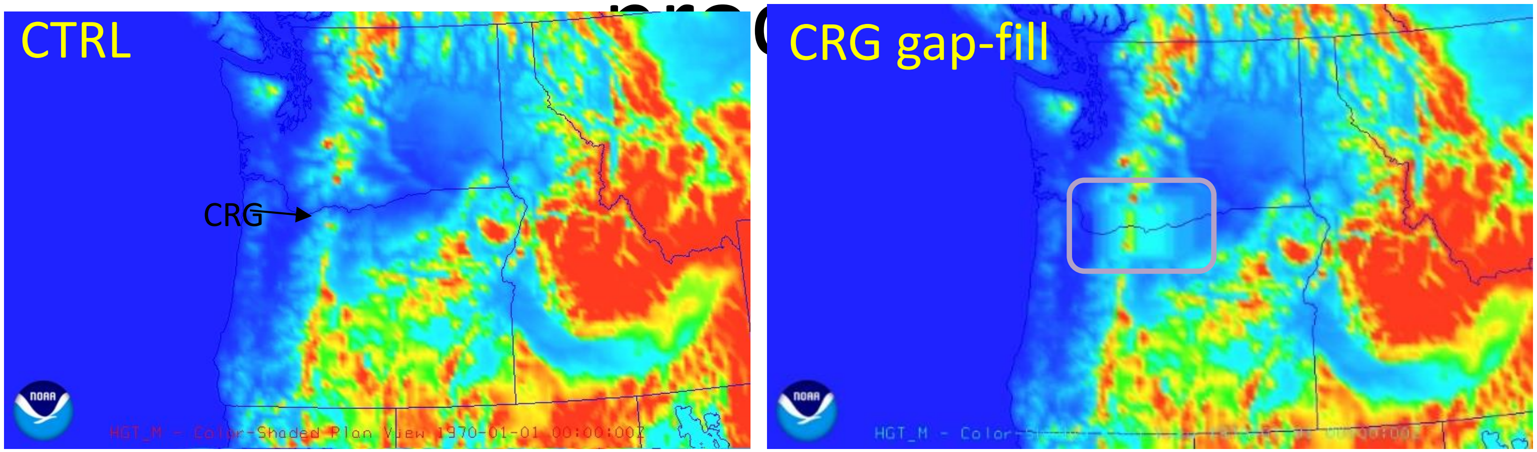


Mahoney et al. 2015

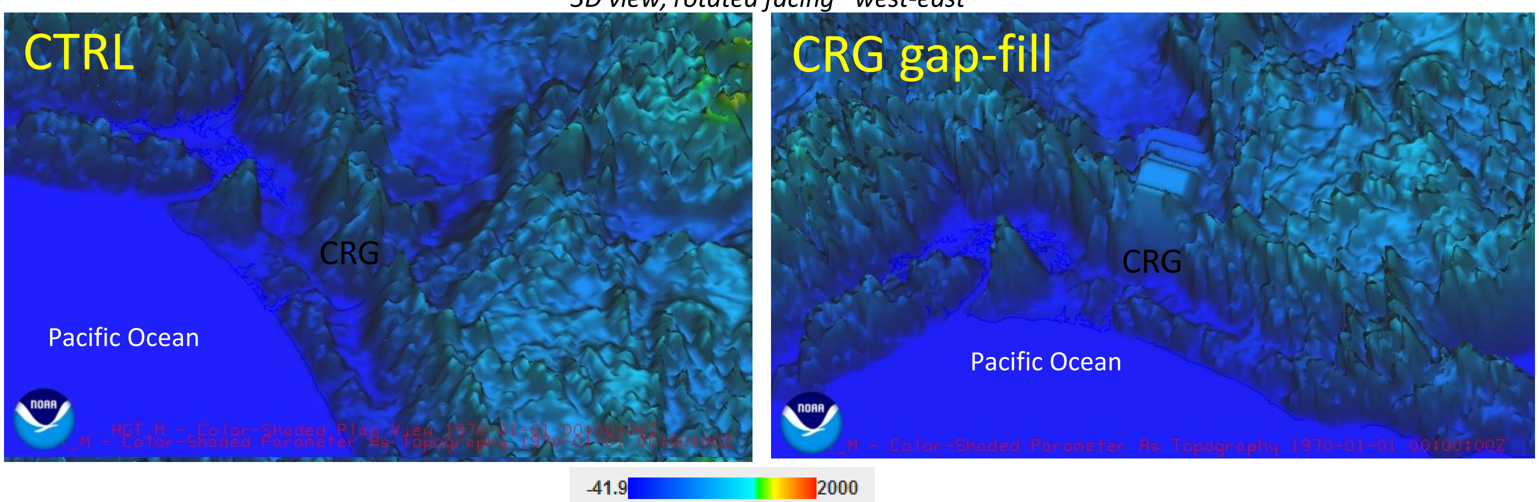
WRF model Columbia River Gorge terrain experiments

- How does “filling in” the Columbia River Gorge affect inland moisture transport and precipitation amount, distribution?
  - For an extreme precipitation event (Nov 2006 flooding)
  - For a recent high-impact event (Oct 2016 wind/rain event) – not shown yet

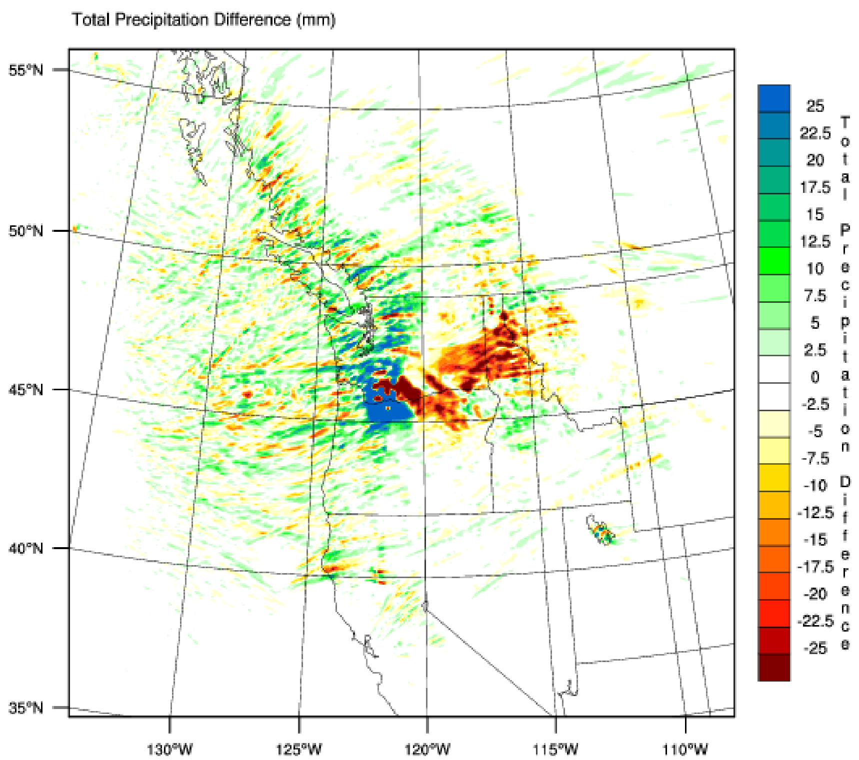
Fill in the CRG using WRF's pre-

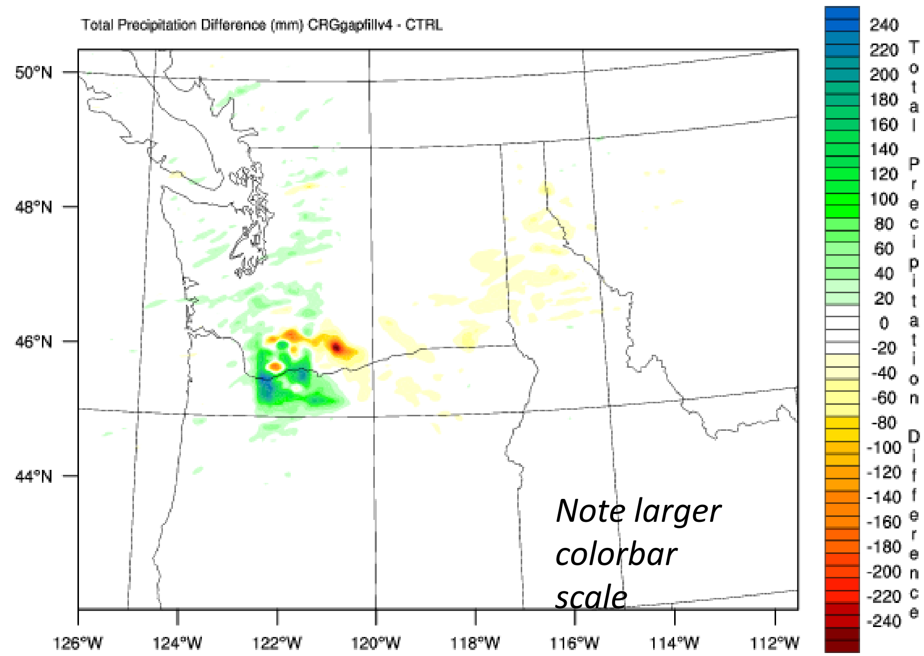


3D view, rotated facing ~west-east



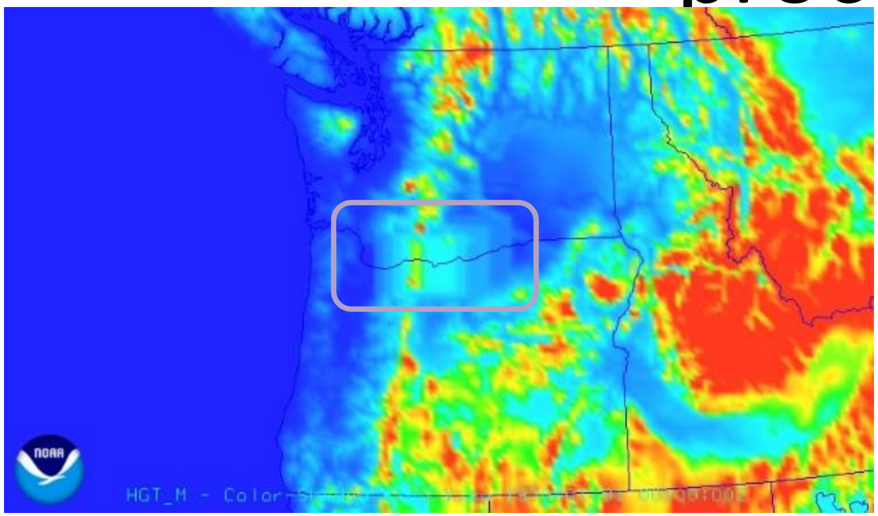
Precipitation differences CRG gap fill – Control

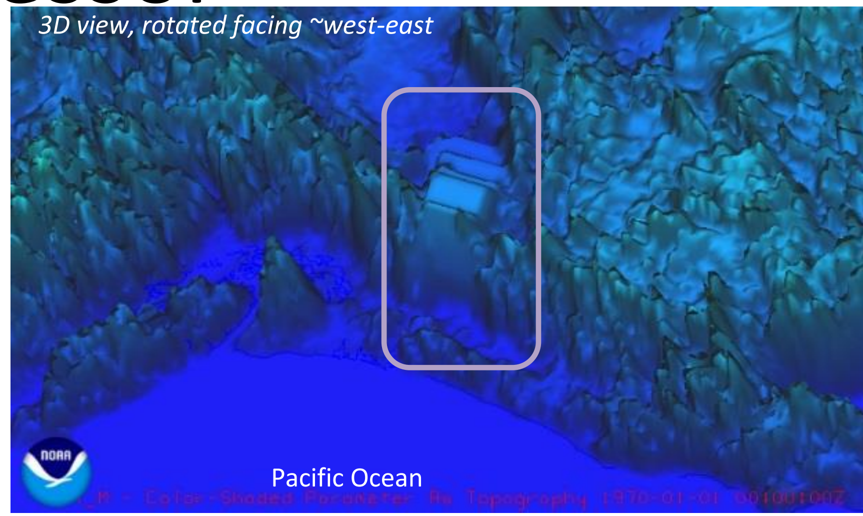




Both maps: Nov 2006 Glacier Flood case
Zoom in on right

Fill in the CRG using WRF's pre-processor



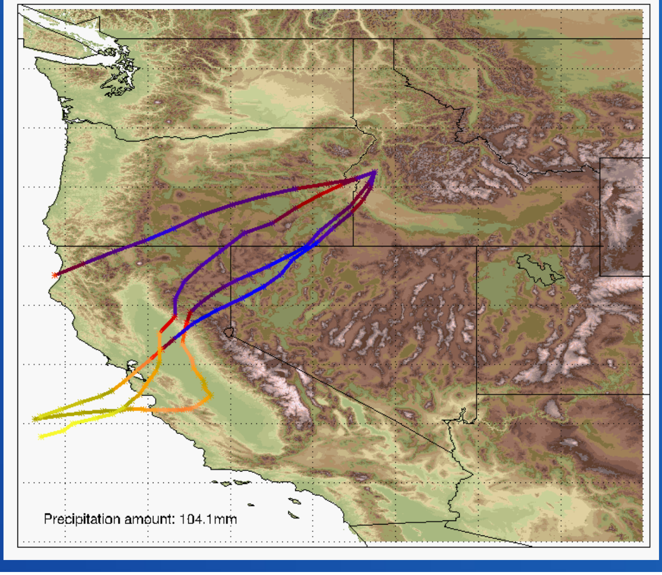


- A little rough for now, but doesn't seem to introduce any instabilities

Diagnosing the Moisture Sources for Extreme Precipitation Events in the Intermountain West

Gap(s) Addressed

- Improved use of existing-quality weather, climate and/or hydrologic predictions in the development of operations outlooks
- Development of improved weather and climate predictions
- Improved precipitation forecasts for landfalling storms in coastal areas



Research Question(s)

How does the large volume of water necessary to sustain intense precipitation events during winter in the intermountain west reach its destination given the distance from the moisture source in the Pacific and the complex regional topography?

Collaborators/Schedule/Source of Support

- U. Colorado/CIRES
- Reclamation Research & Development Office
- Reclamation
- Flood Hydrology & Consequence Group (FHCG)
- Majority complete in FY12-13, potential for continued support FY14-15 focus on research-to-operations with FHGC

M. Alexander (NOAA)

RECLAMATION

Backward Trajectory Analysis

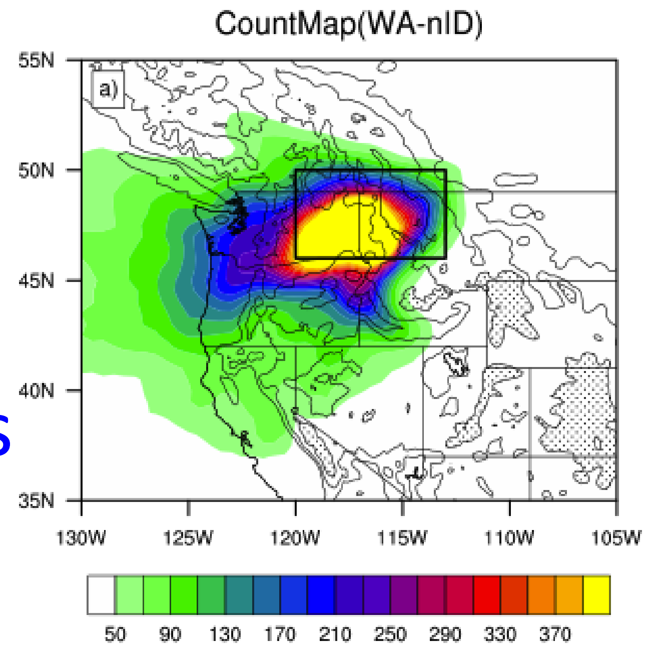
- Six regions selected chosen subjectively based on:
  - Adequate number of stations
  - Topographic features (e.g. not dividing mountain gaps)
  - Grouping stations that exhibit similar precipitation maxima
  - Contain heavy precipitation events
  - Reclamation Interest
  - Guided by IVT EOF Analysis
- Trajectories computed for the top 150 24-hour precipitation events for the 4 CFSR grid points surrounding a station
- Trajectories start at a level 50-100 hPa above the surface Generally in the upper boundary layer/lower free atmosphere (often where the moisture maximum is located)
- 2400 trajectories = 150 unique events (only 1 station) X 4 grid points x 4 times per day x 1 level

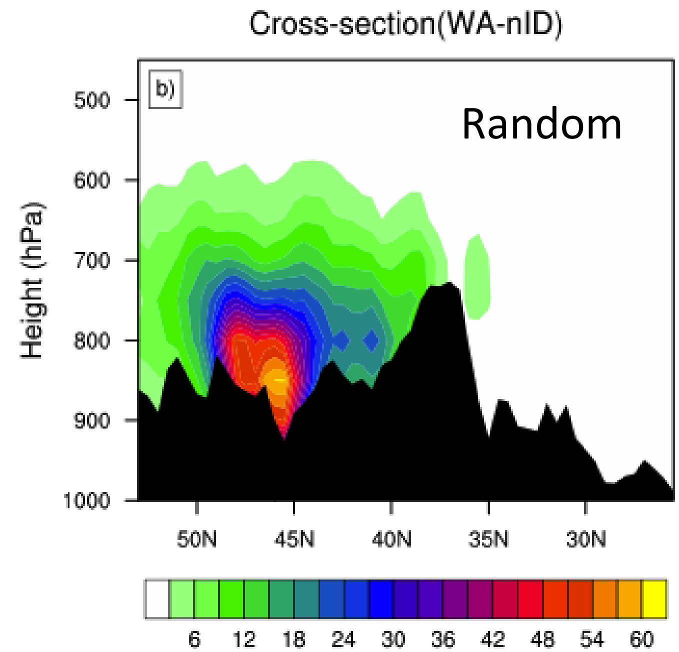
Are these pathways unique to extreme precipitation events?

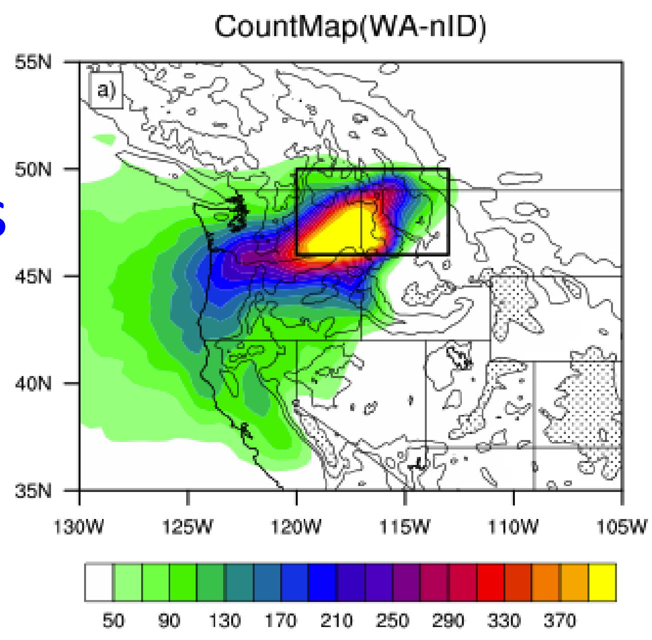
Examine back trajectories initiated at random stations (at which a top event occurred) on random winter days

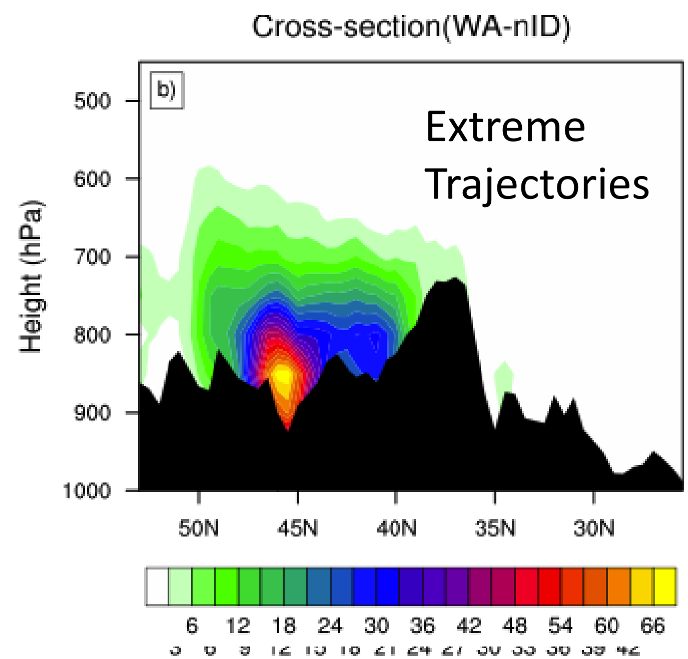
Counts
&
X-sections

for the
Random
Generated
trajectories

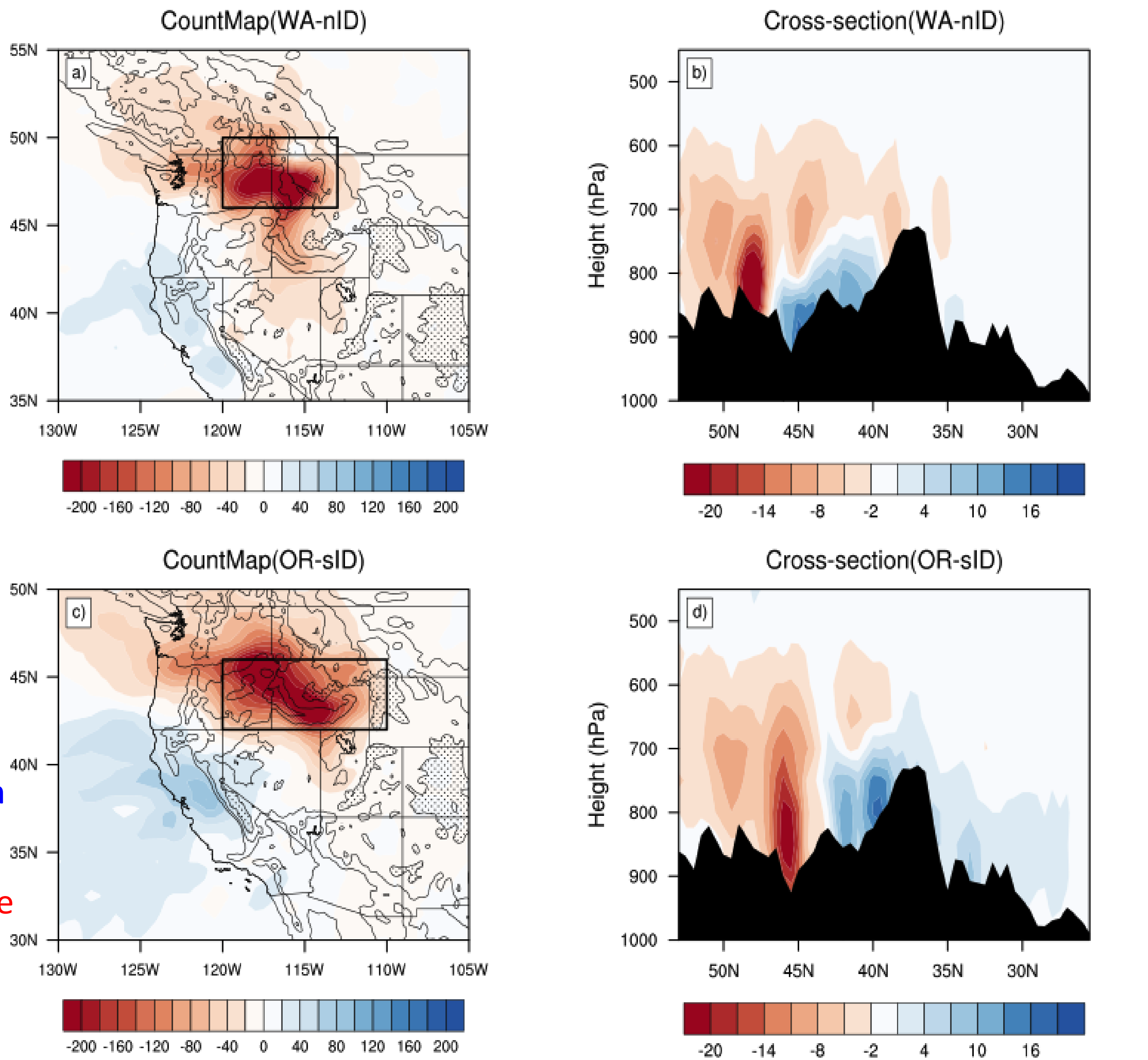








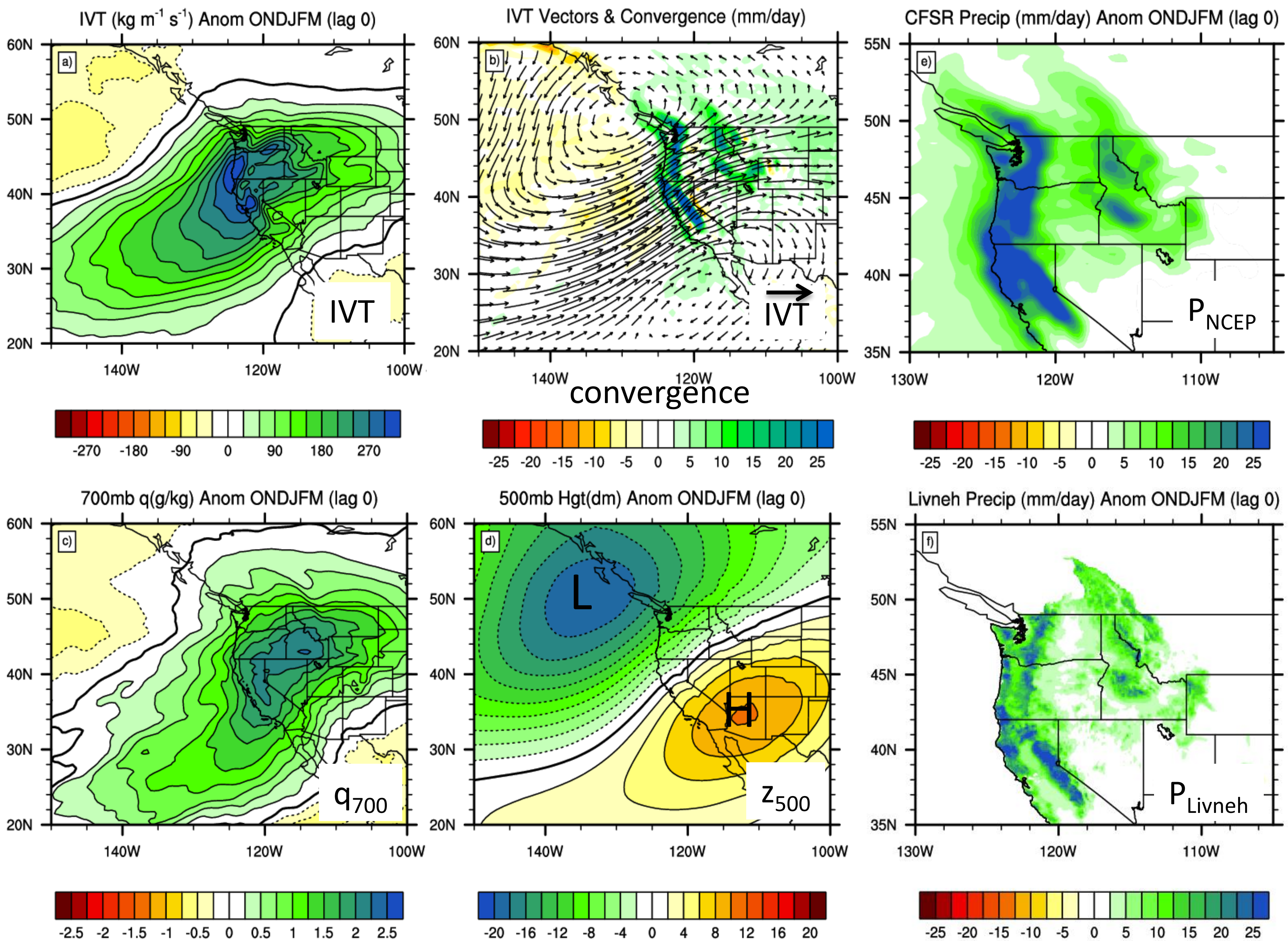
Extreme minus Random



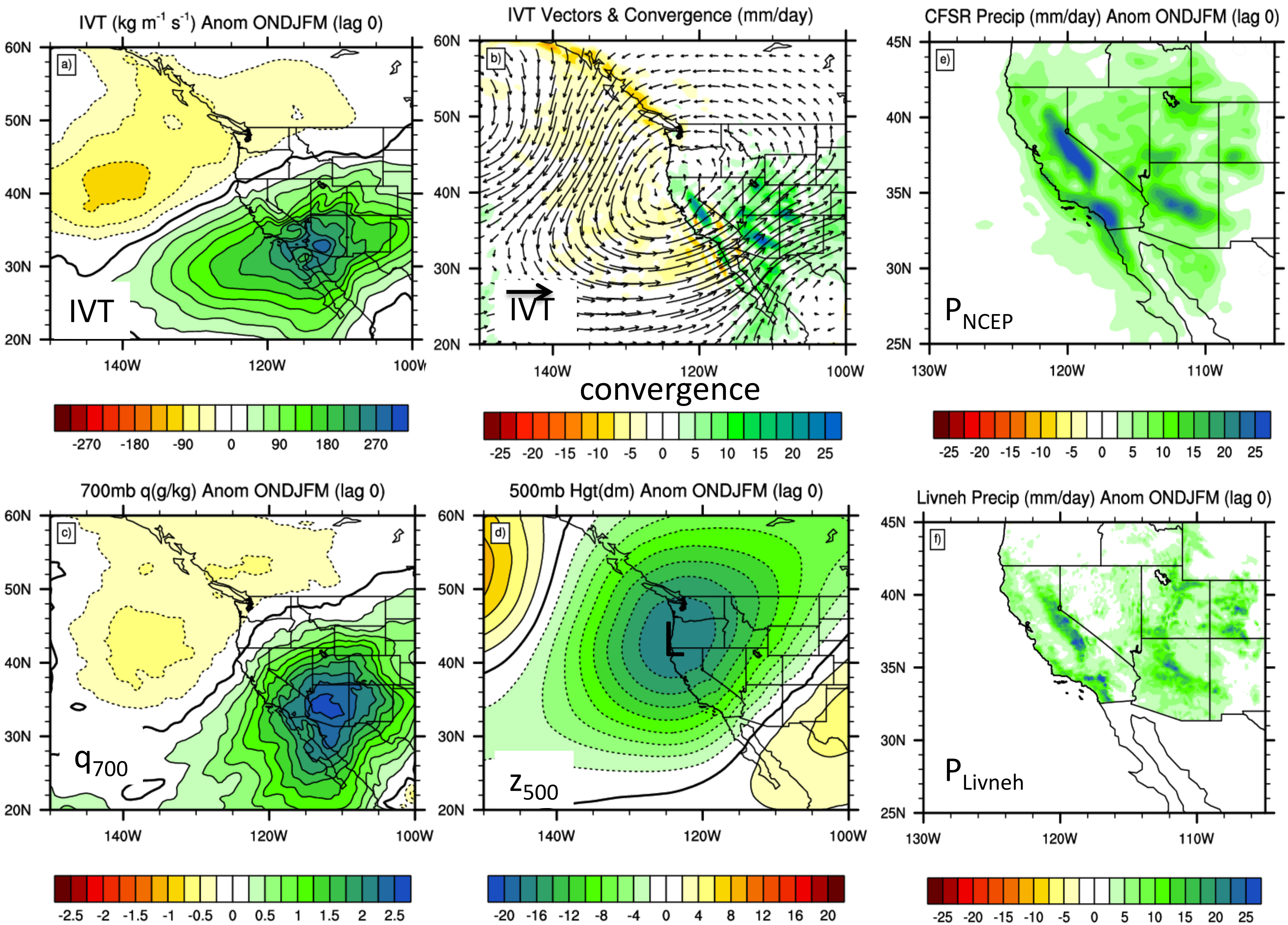
Blue:
Extreme > Random

Red:
Random > Extreme

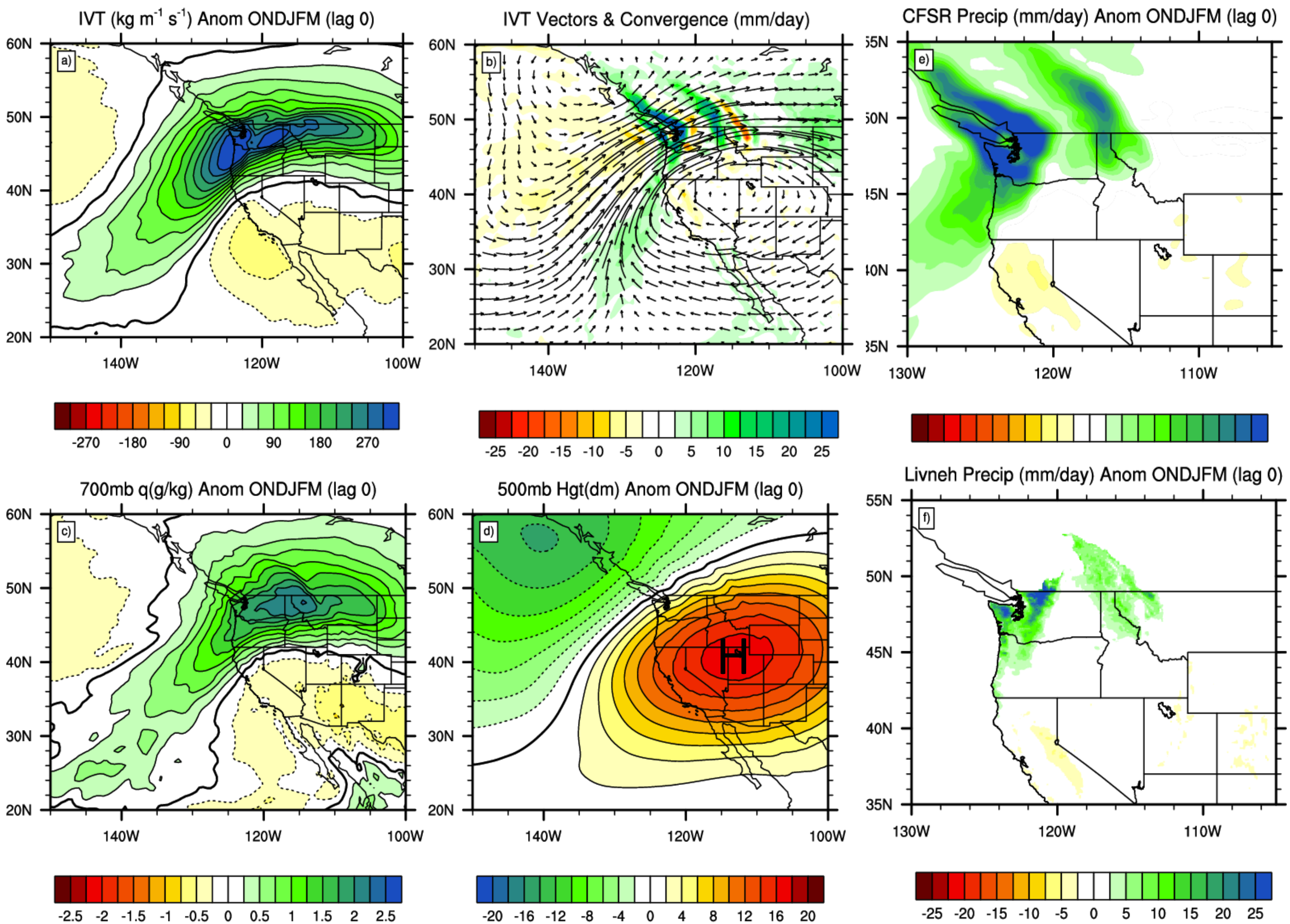
Composite based on top 1% of EOF/PC 1 IVT values



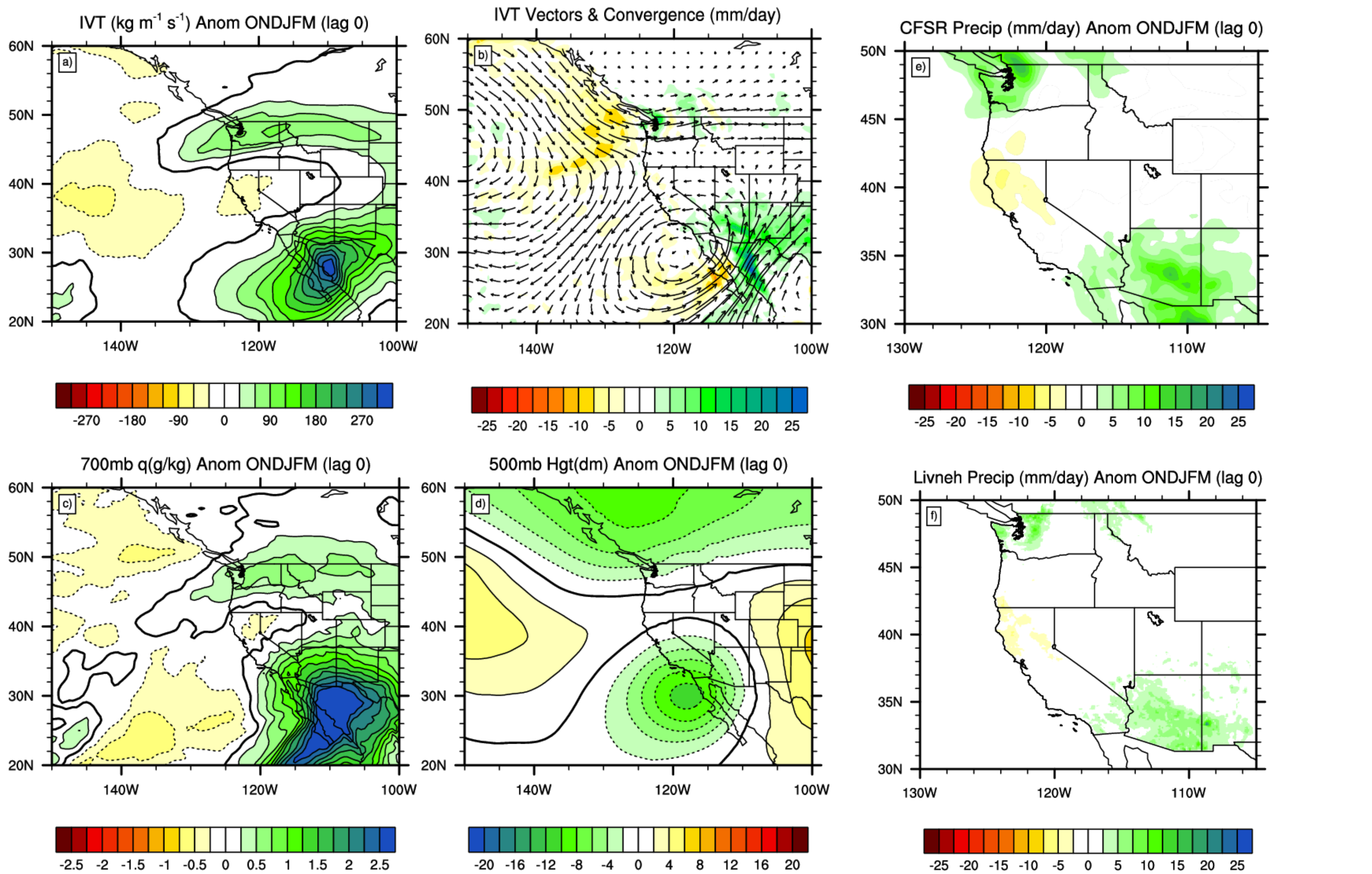
Composite based on top 1% of EOF/PC 2



Composite based on Bottom 1% of EOF/PC 2



Composite based on top 1% of EOF/PC 3 - modified



Regional Station Precipitation: Top 150