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

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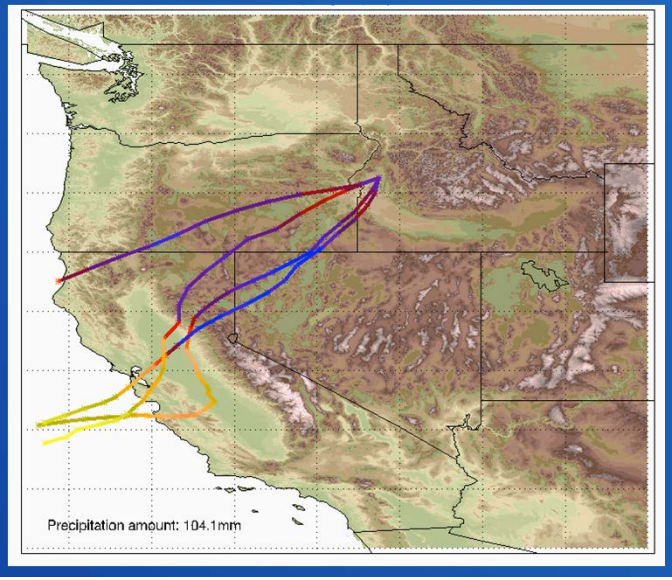
RECLAMATION

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?

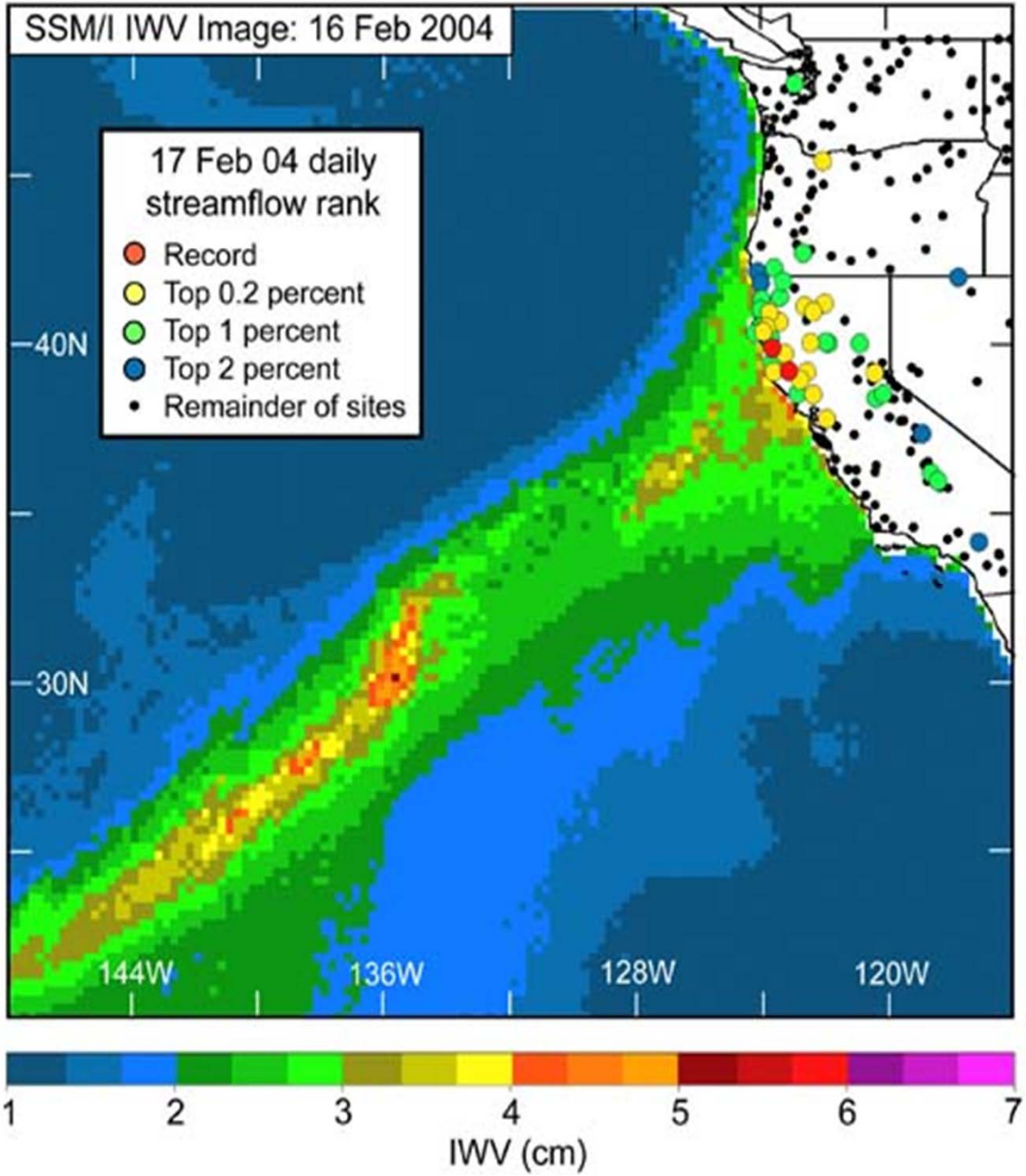
Collaborators/Schedule/Source of Support

- 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

RECLAMATION

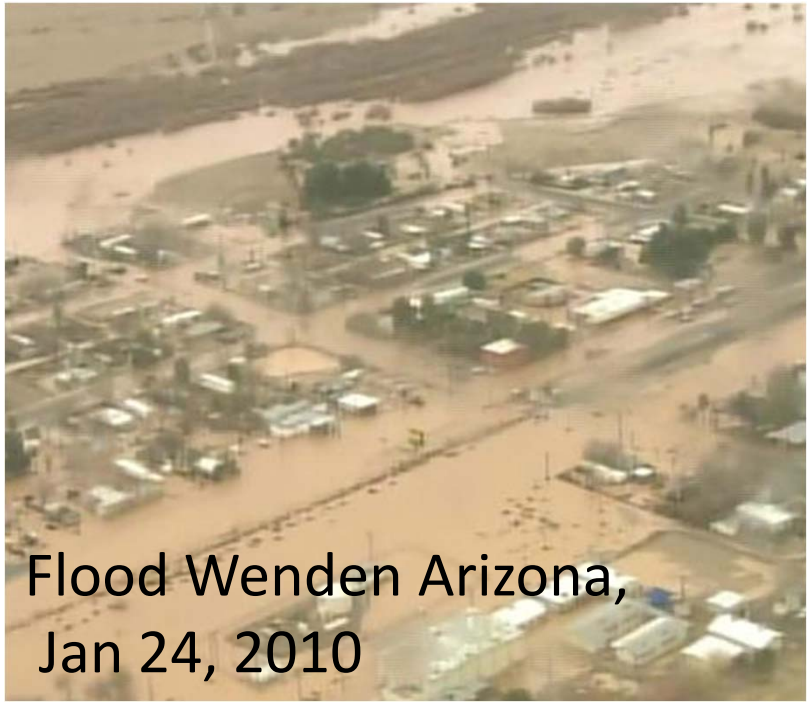
Heavy Winter Precipitation West Coast, Cascades, Sierras

Atmospheric Rivers (Pineapple Express)



IWV –Integrated Water Vapor through the atmosphere

Hypothesis

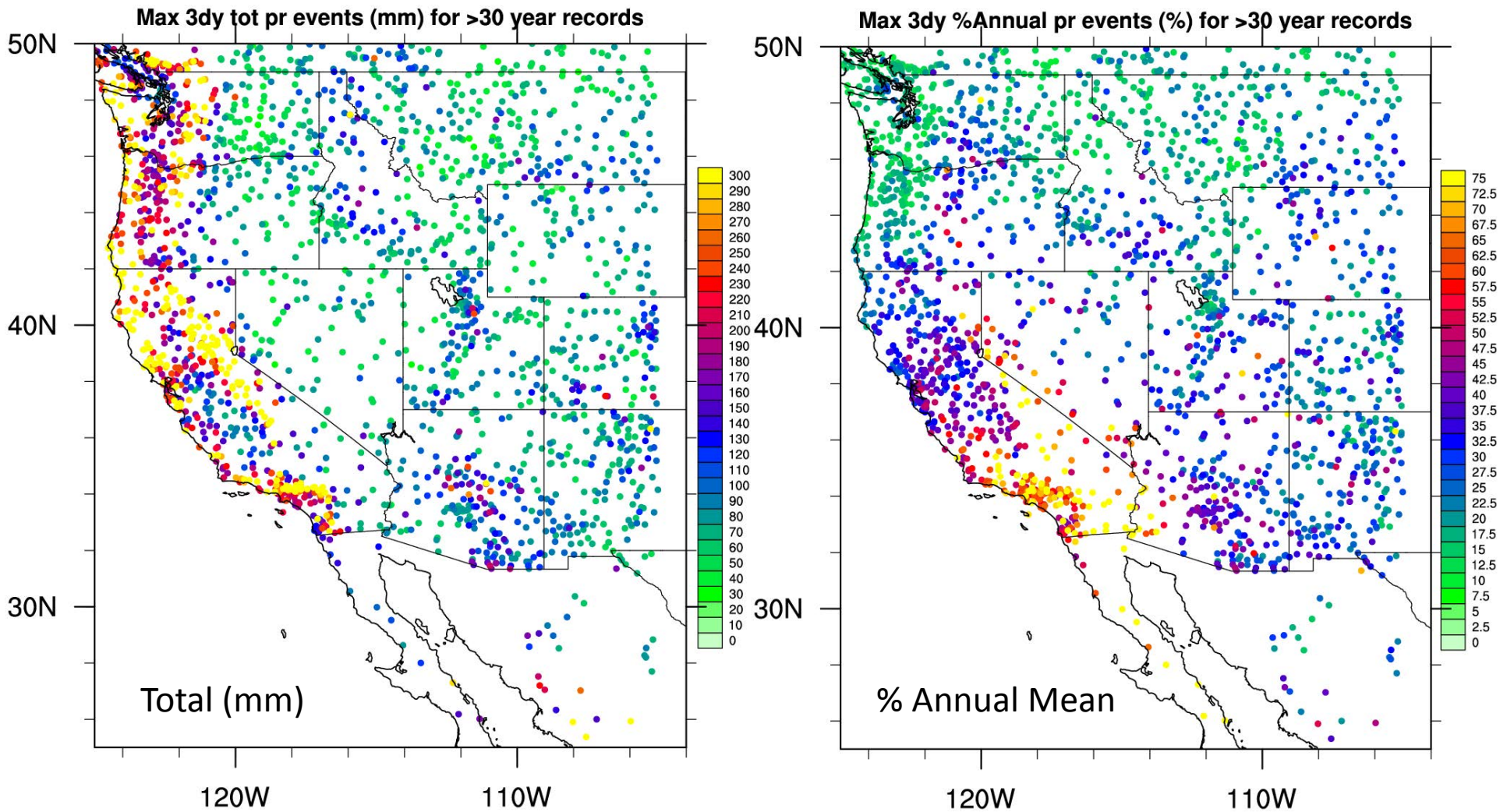


- Flow over mountains causes air to cool and hold less moisture.
- Where does the moisture for intense precipitation events in the Inter mountain west Sierra come from in winter?
- Do air parcels may take unique pathways to reach states such as Arizona, Idaho and Colorado?

Project Tasks

- Obtain precipitation data and other relevant meteorological variables to identify extreme events
- Diagnose processes contributing to extreme precipitation events using back trajectories and diagnostics based on recent reanalysis data sets.
- Perform In-depth case studies of known extreme events and events occurring in specific USBR locations of interest
- Perform high-resolution simulations and sensitivity studies
- Create climatology and investigate interannual variability
  - Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, 2014: Climatological characteristics of atmospheric rivers and their inland penetration over the western United States, Monthly Weather Review, 142, 905-921

Example: Maximum 3-day precipitation (Oct-Mar)



Based on daily precipitation data from the Global Historical Climatology Network (GHCN; Menne et al. 2012). All (2167) stations with at least a 30-year record and 80% report rate during 1832-2011.

Methods for identifying moisture pathways during heavy precipitation events

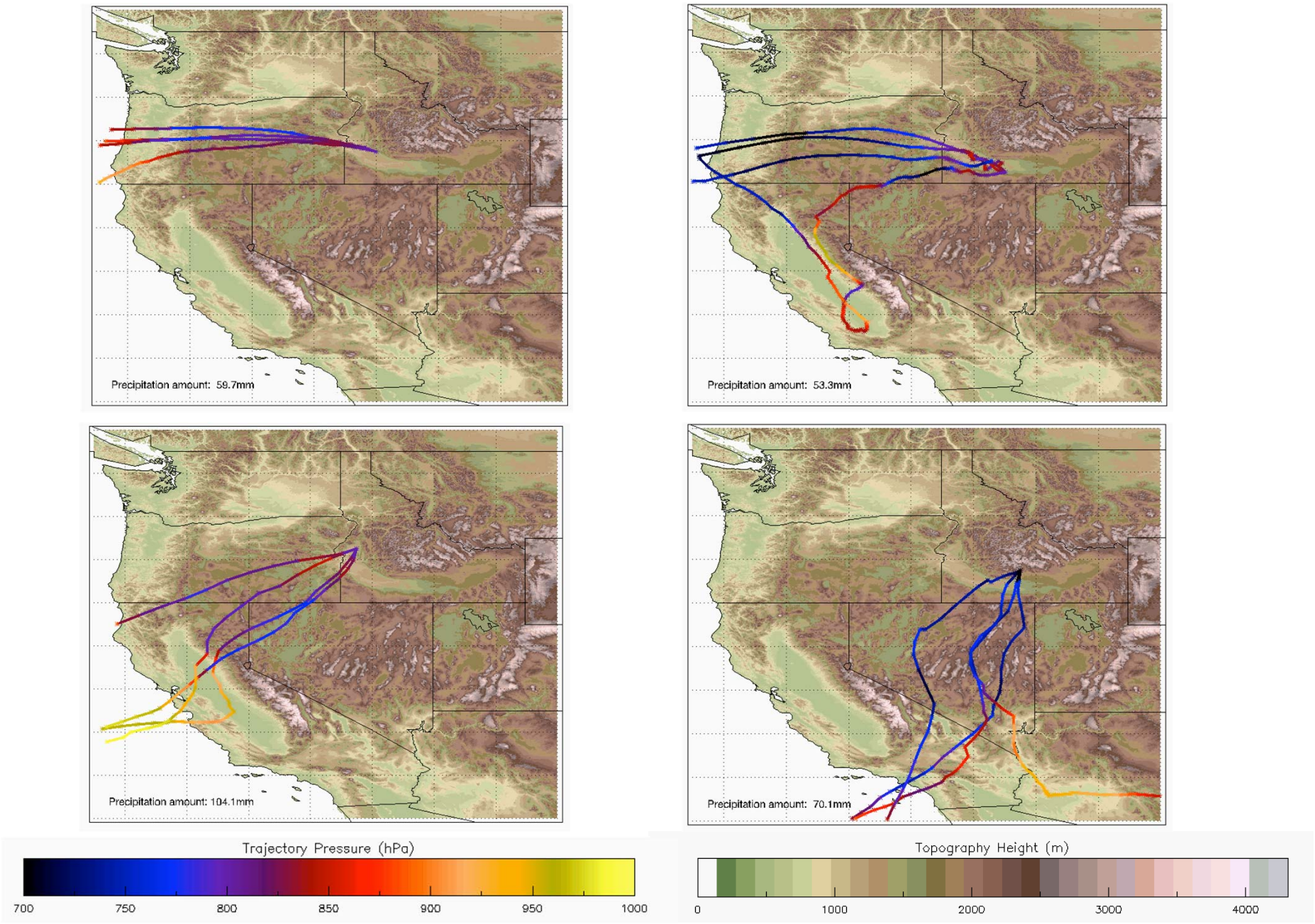
Two semi-independent methods for identifying moisture pathways

- Backward trajectories
  - Initiated during a heavy precipitation event as indicated by daily precipitation data from stations in the west

- EOFs of the Vertically Integrated Water Transport (IVT) from the Climate forecast System Reanalysis (CFSR) fields
  - Reanalysis combination of observations & model
  - CFSR Resolution ~40 km

- All results are for 1979-2010 (When CFSR is available)
- in winter (Oct-Mar)

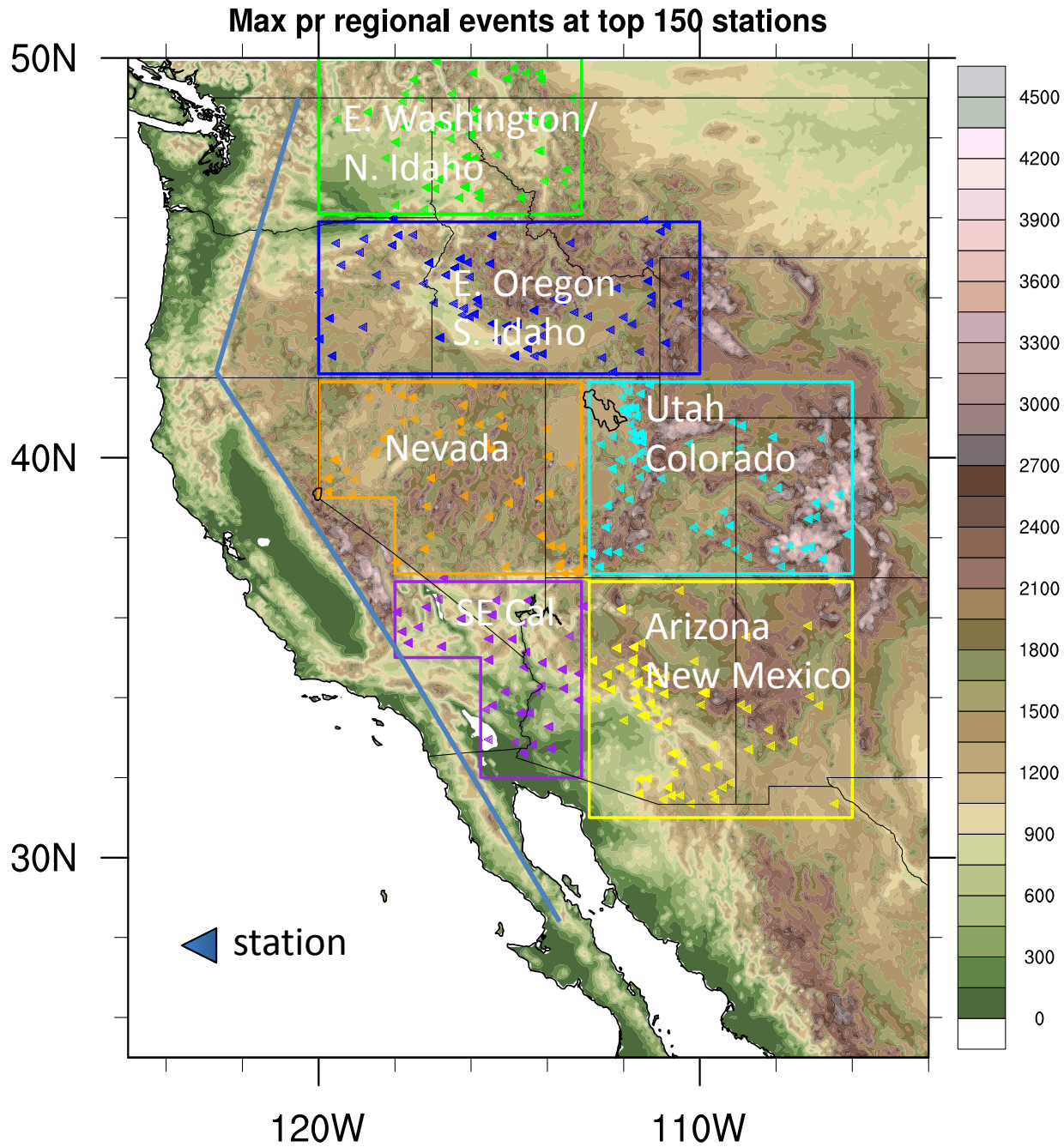
Example of Back Trajectories for S. Idaho Region



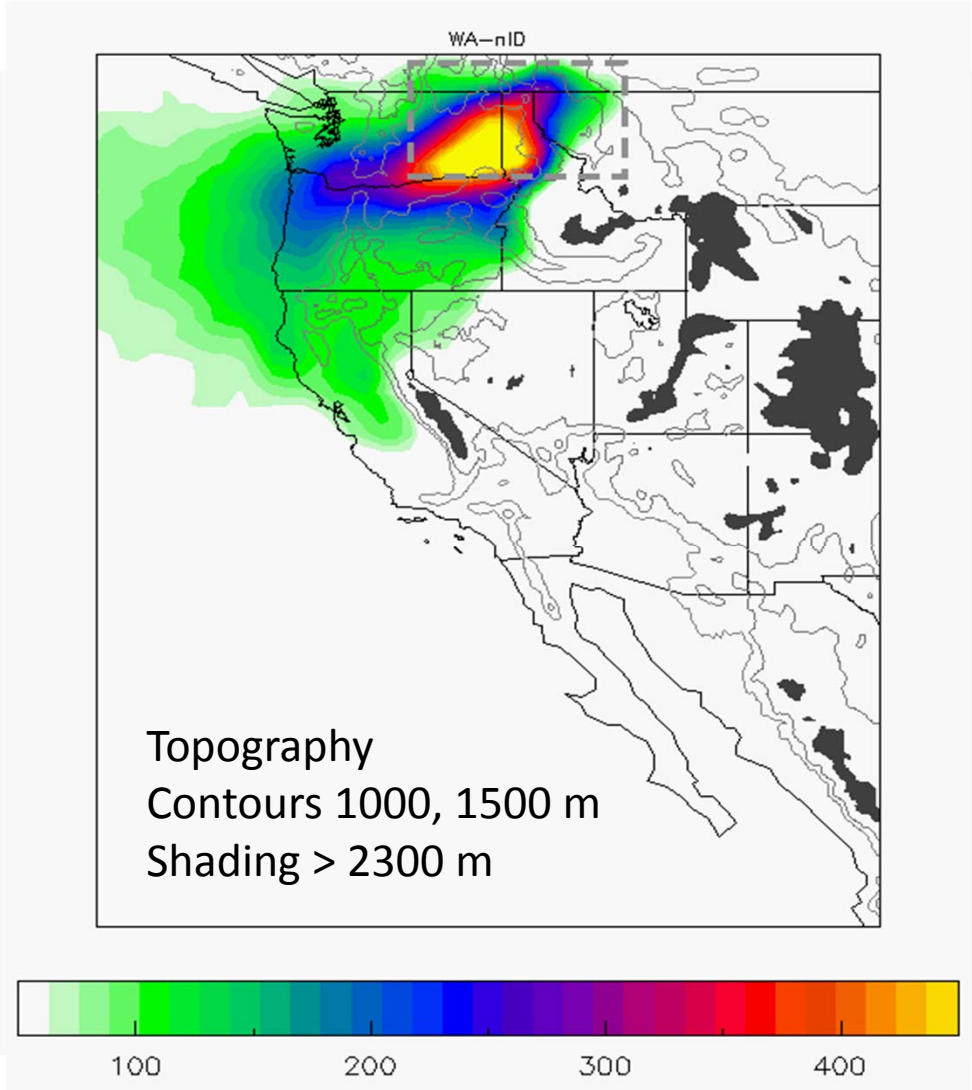
Backward Trajectory Analysis

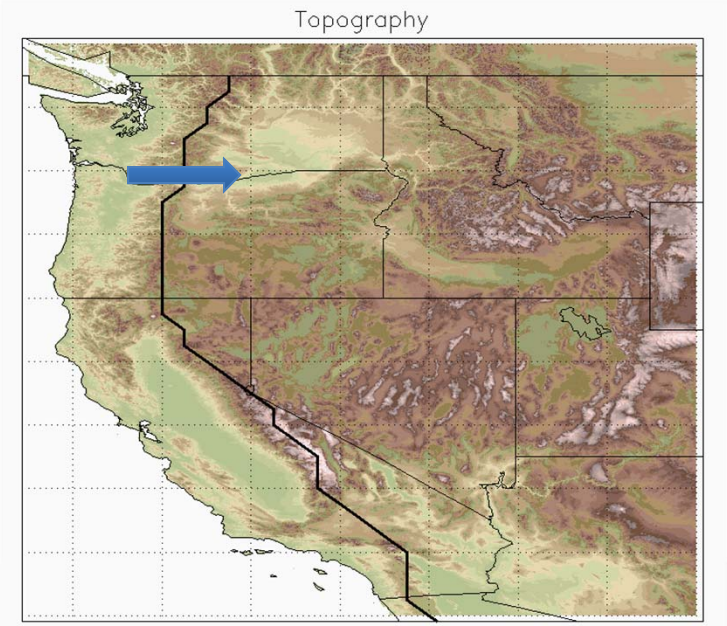
- Six regions selected chosen subjectively based on:
  - Adequate number of stations
  - Topographic features (e.g. not dividing mountain gaps)
  - Grouping stations that exhibit similar precipitation maxima
  - Contain heavy precipitation events
  - Reclamation Interest
  - Guided by IVT EOF Analysis
- 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

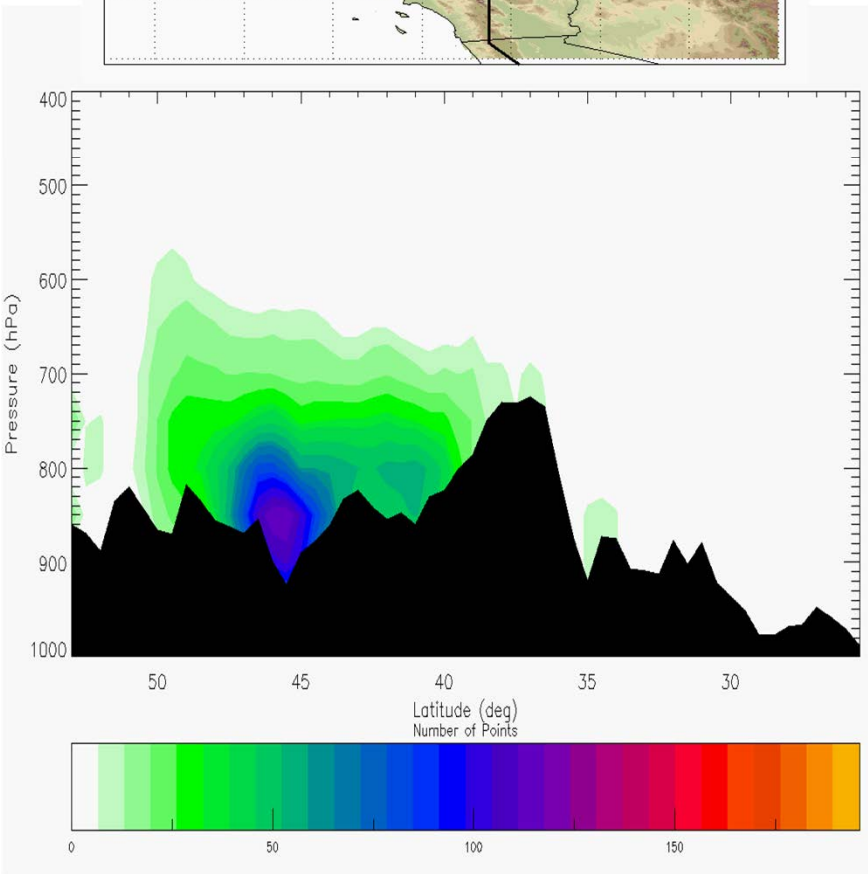
Regions for trajectory count maps and cross sections



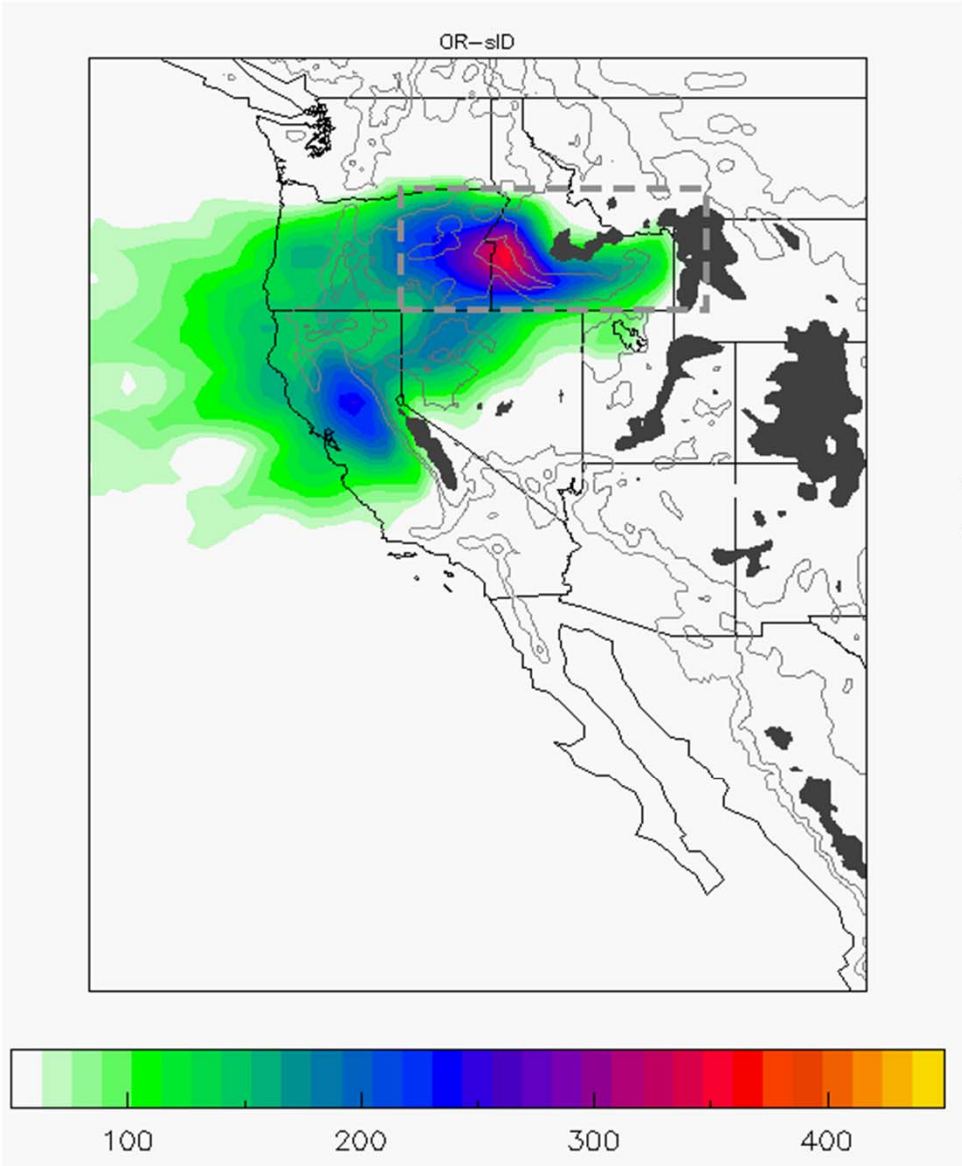
Washington & N. Idaho Count Maps/x-section

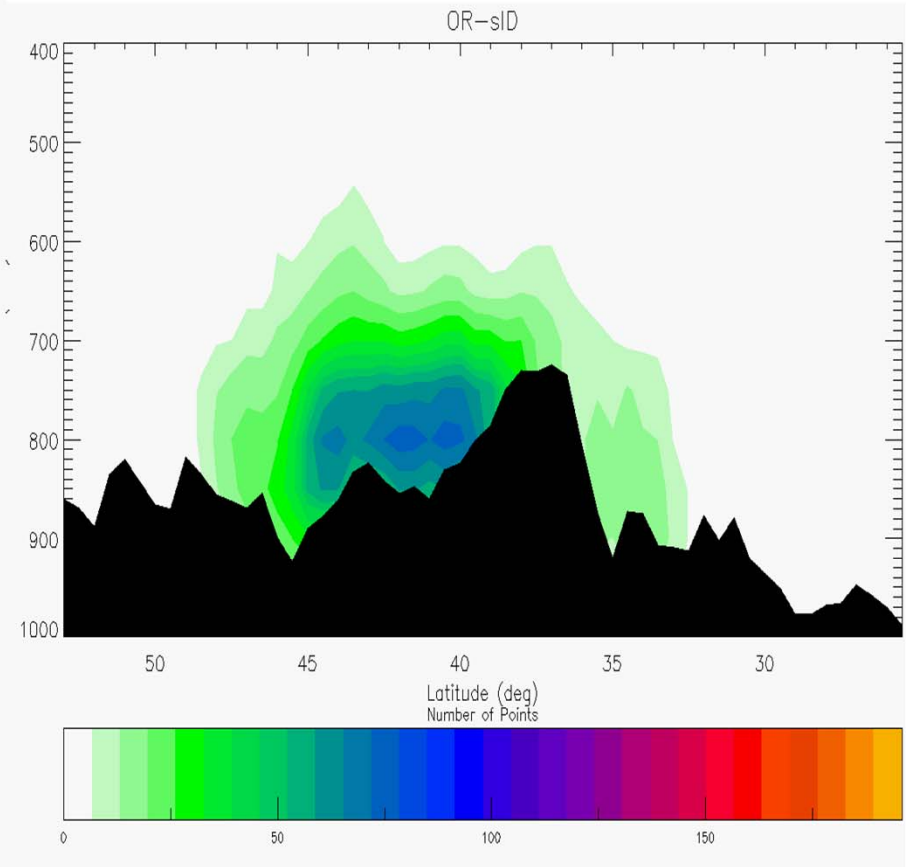




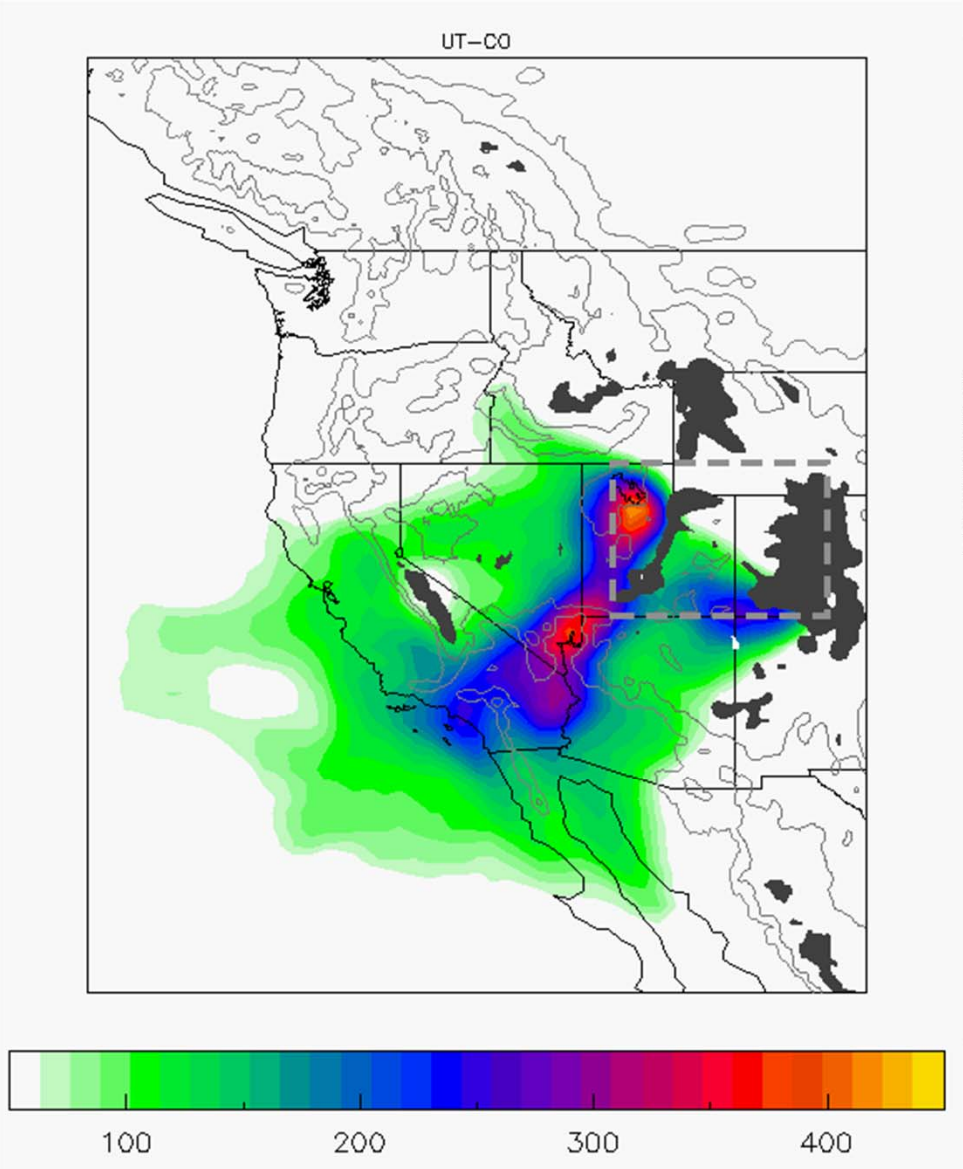


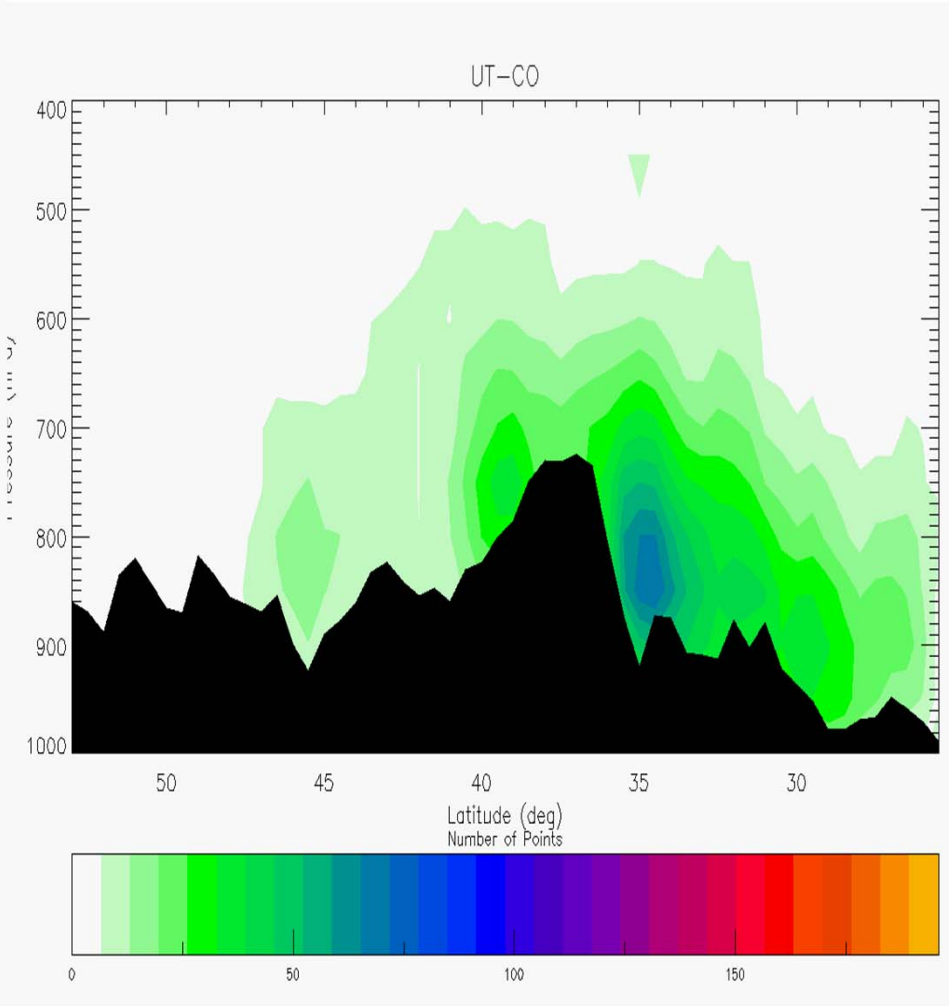
E. Oregon/S. Idaho



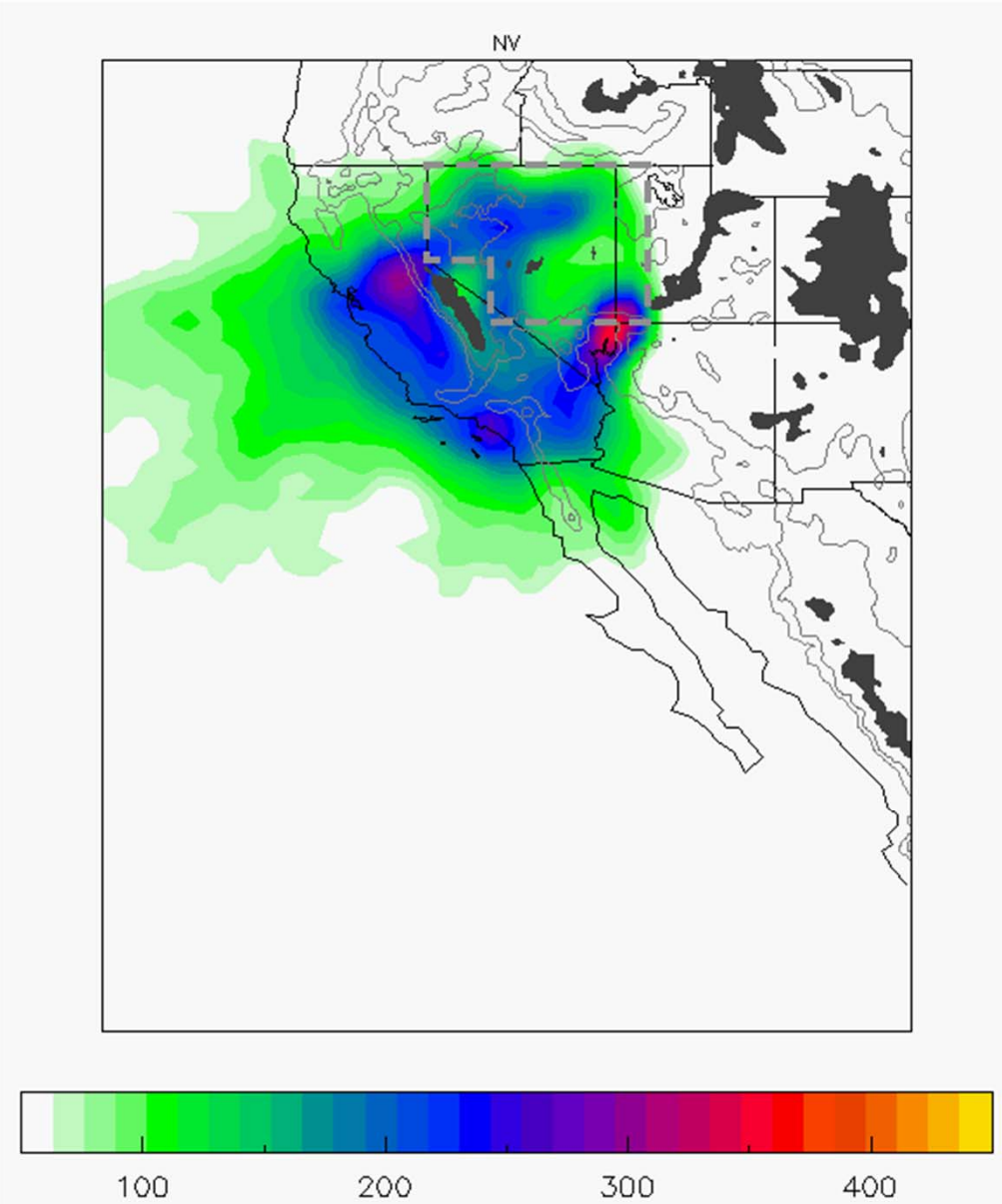


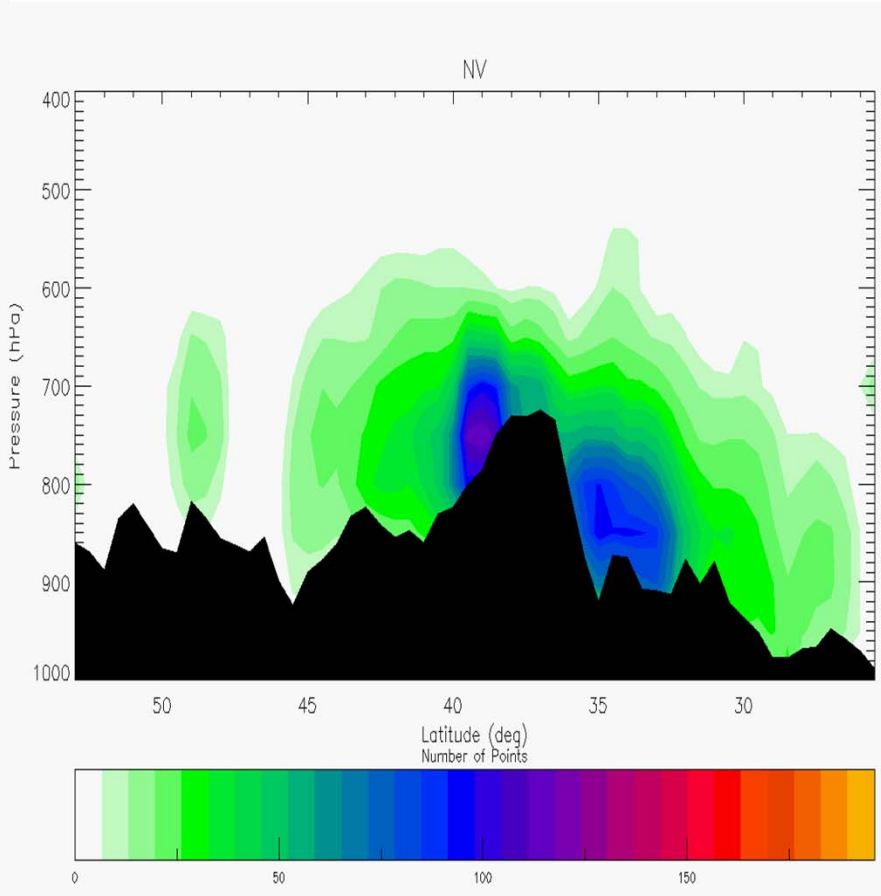
Utah/Colorado



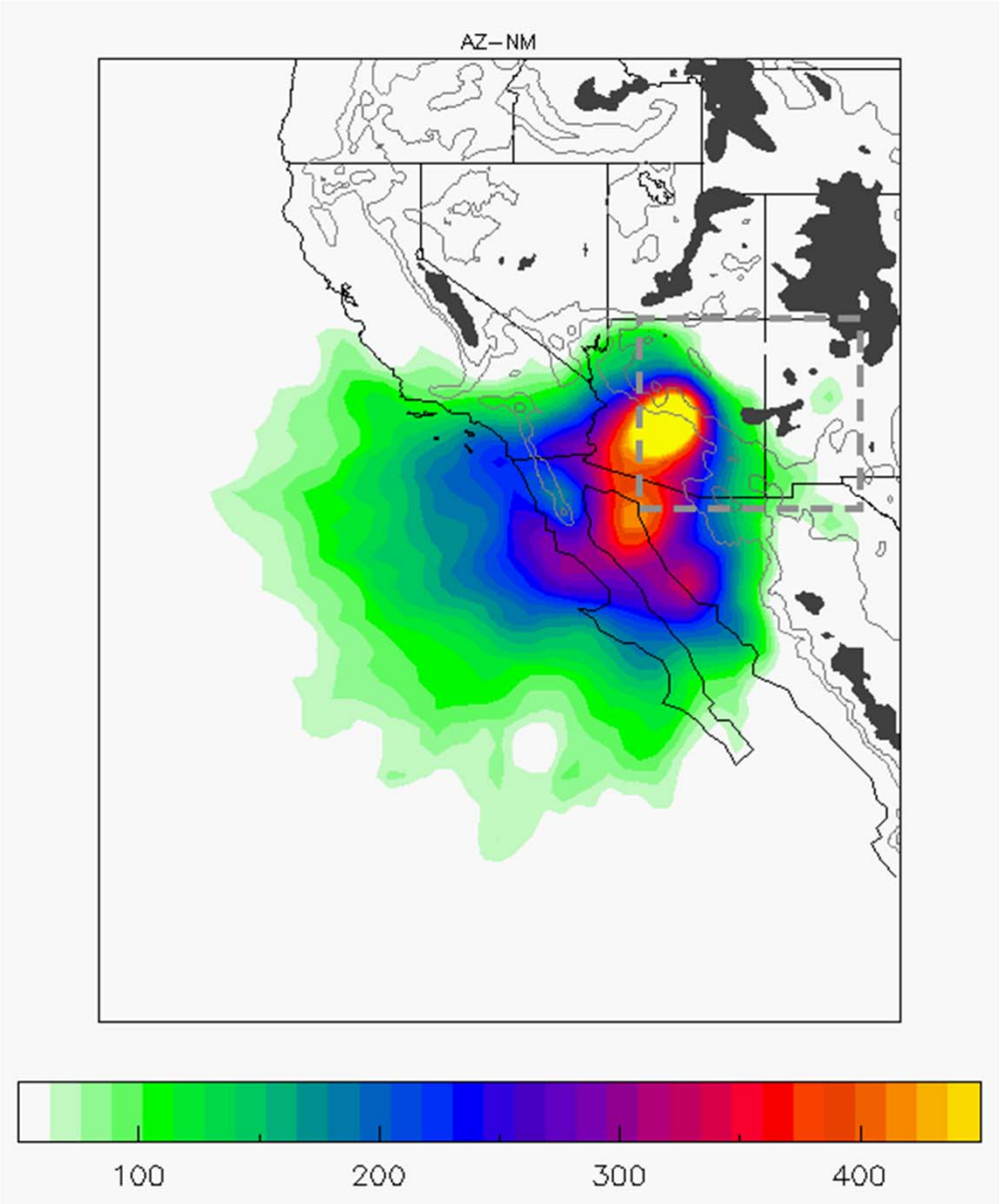


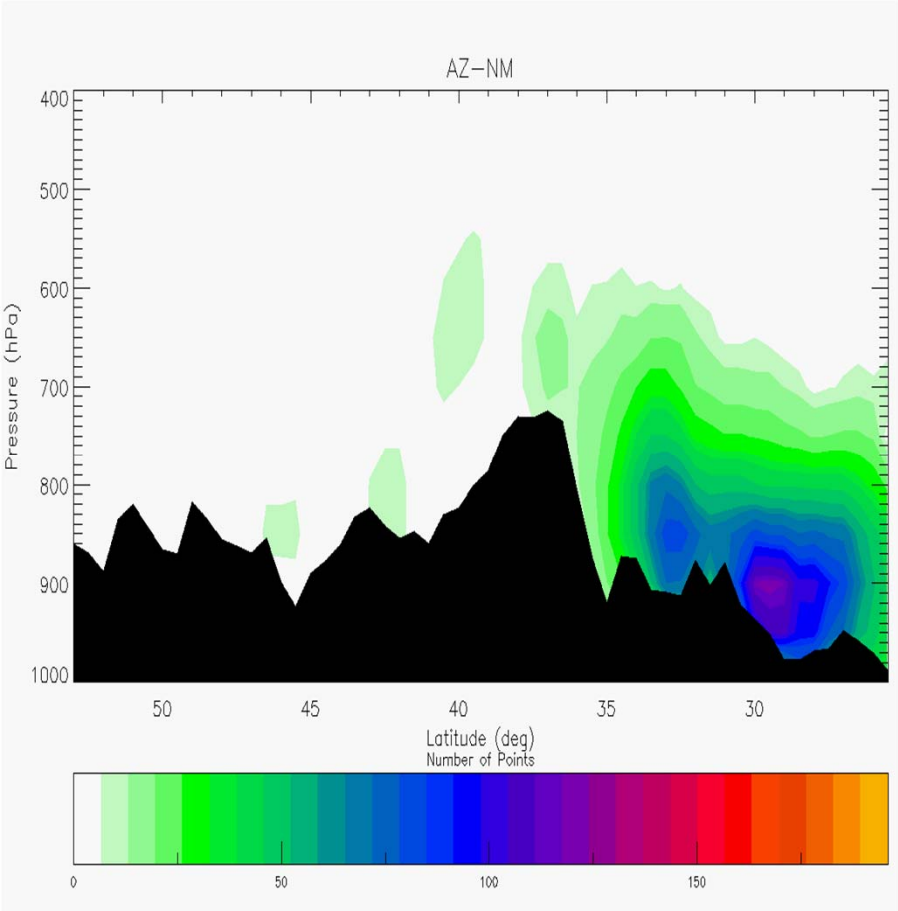
Nevada


NV
100
200
300
400

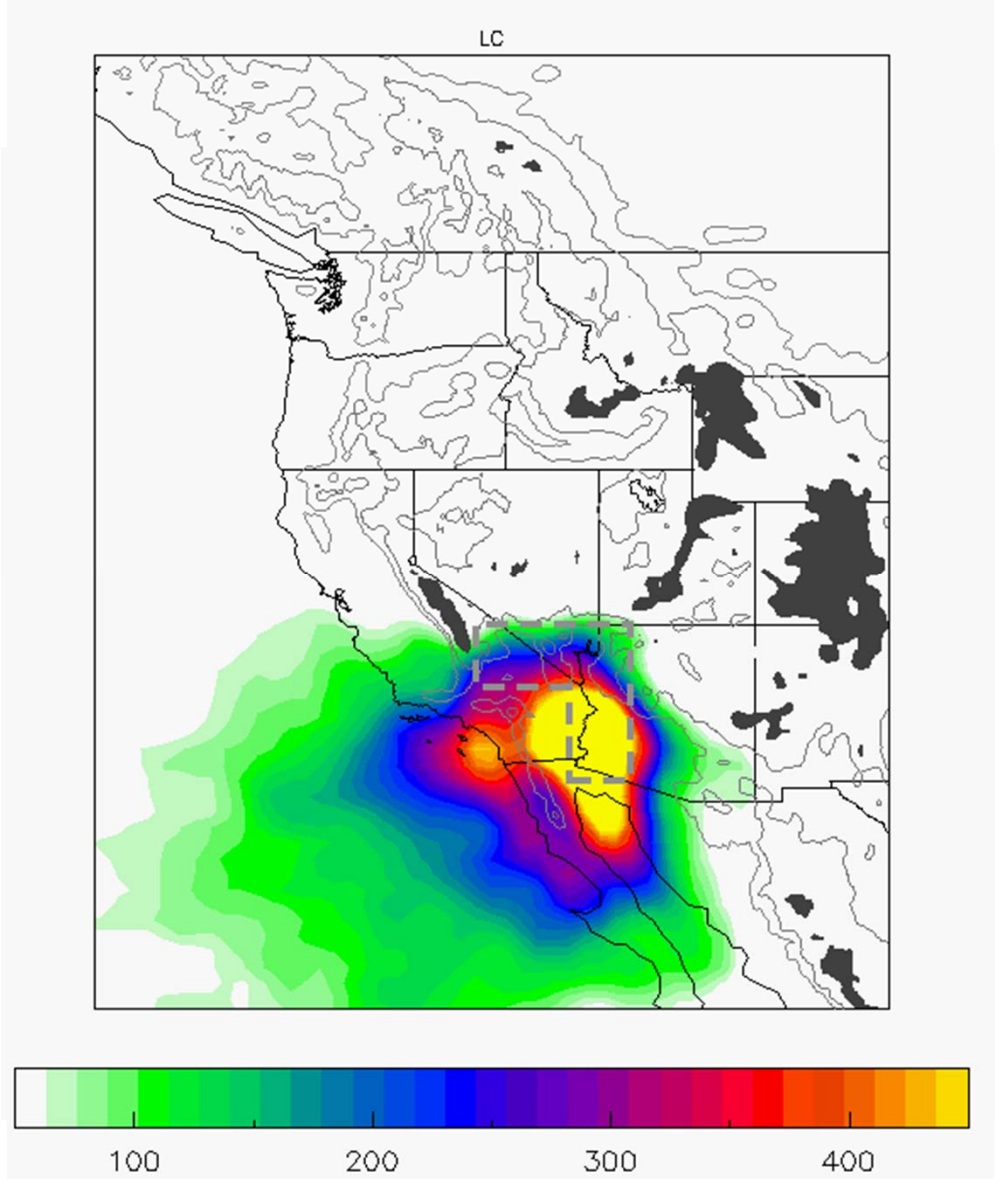

NV
400
500
600
700
800
900
1000
Pressure (hPa)
50
45
40
35
30
Latitude (deg)
Number of Points
0
50
100
150

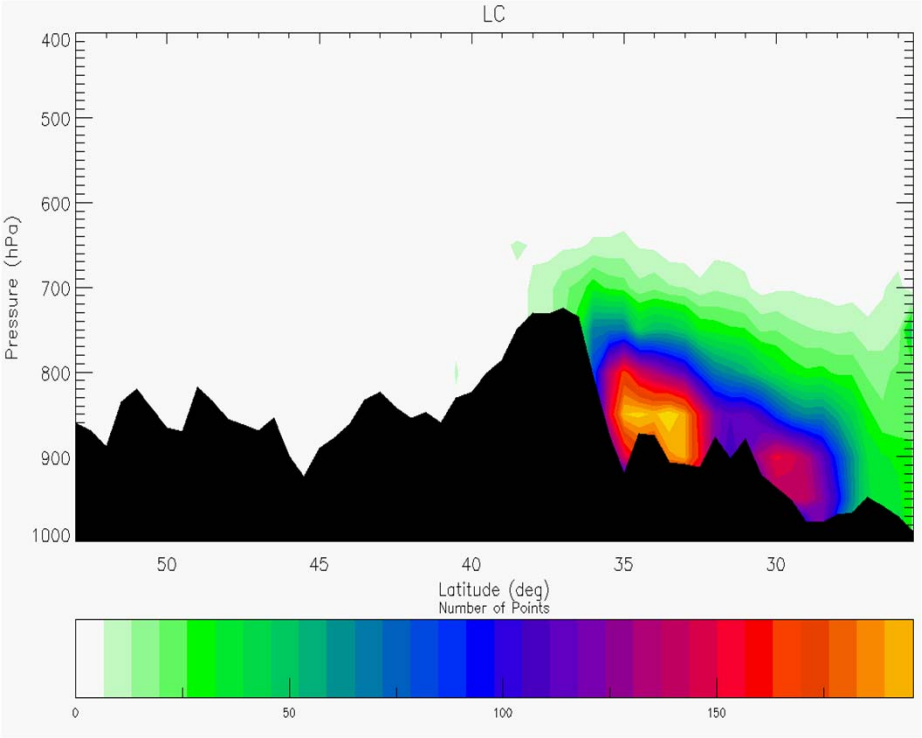
Arizona/New Mexico



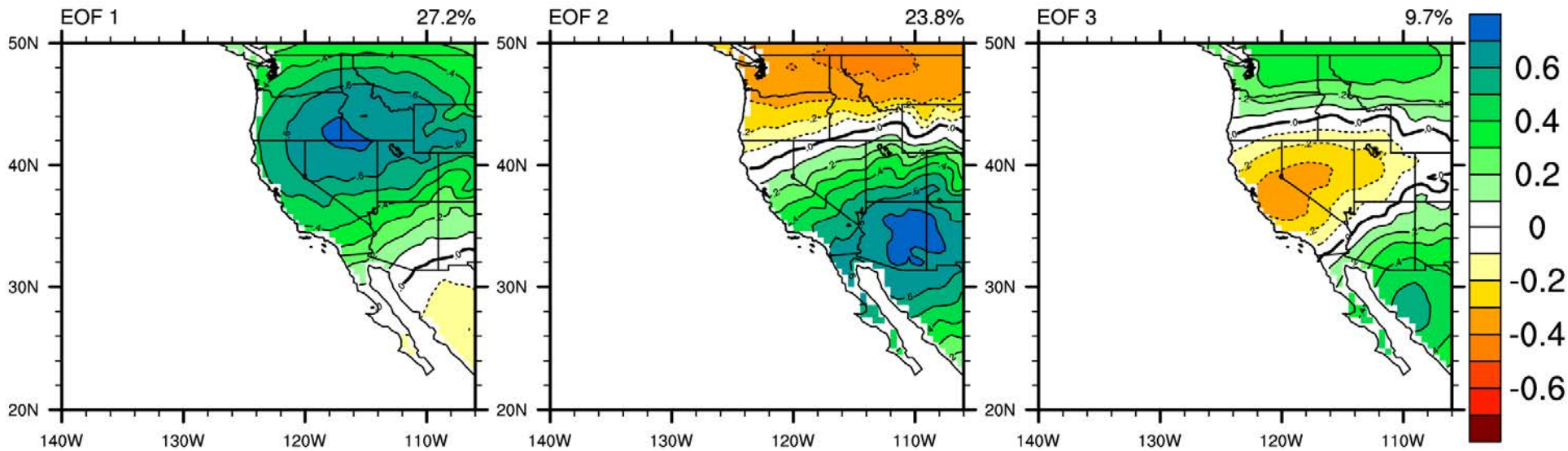


Lower (Southeast) California



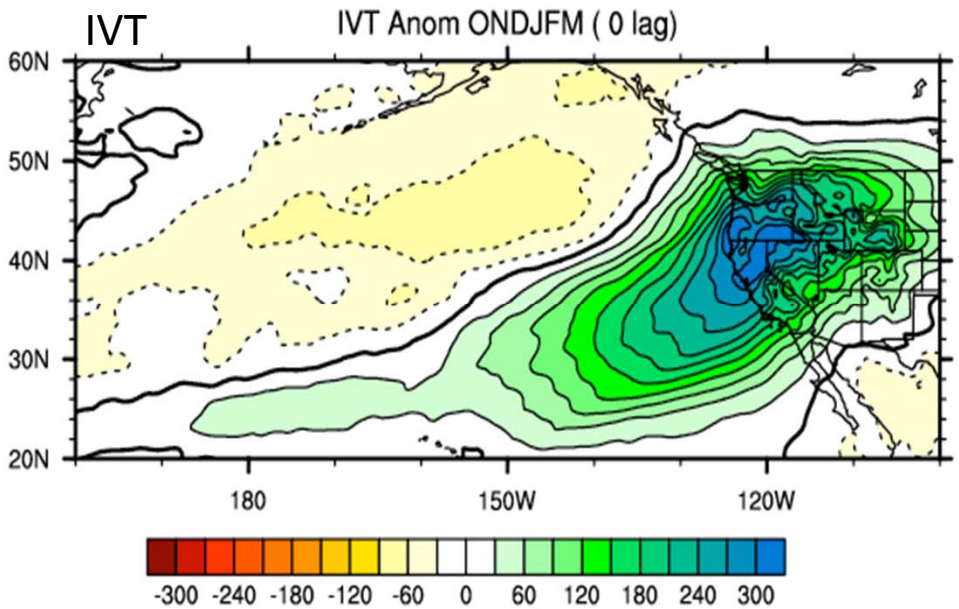


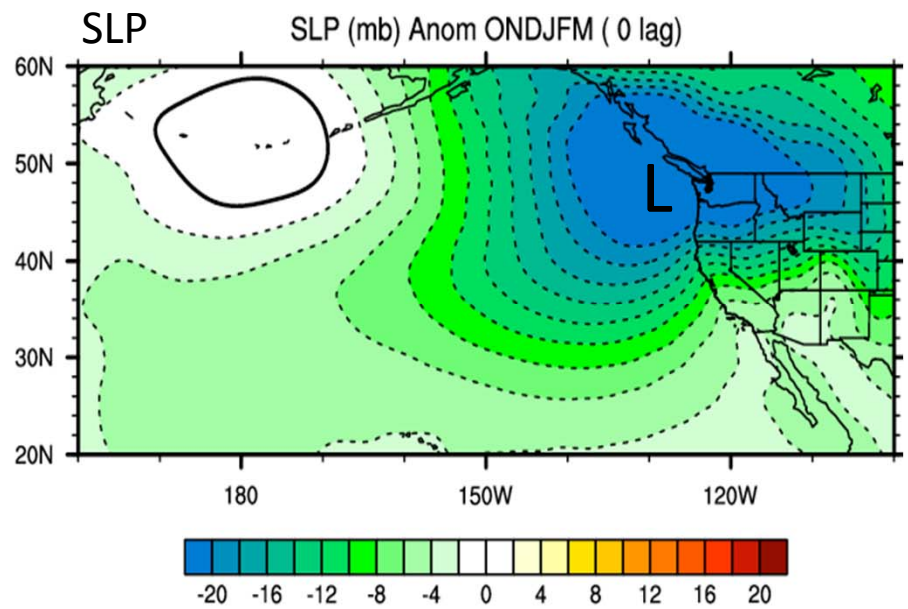
EOFs of Winter CFSR IVT anomalies

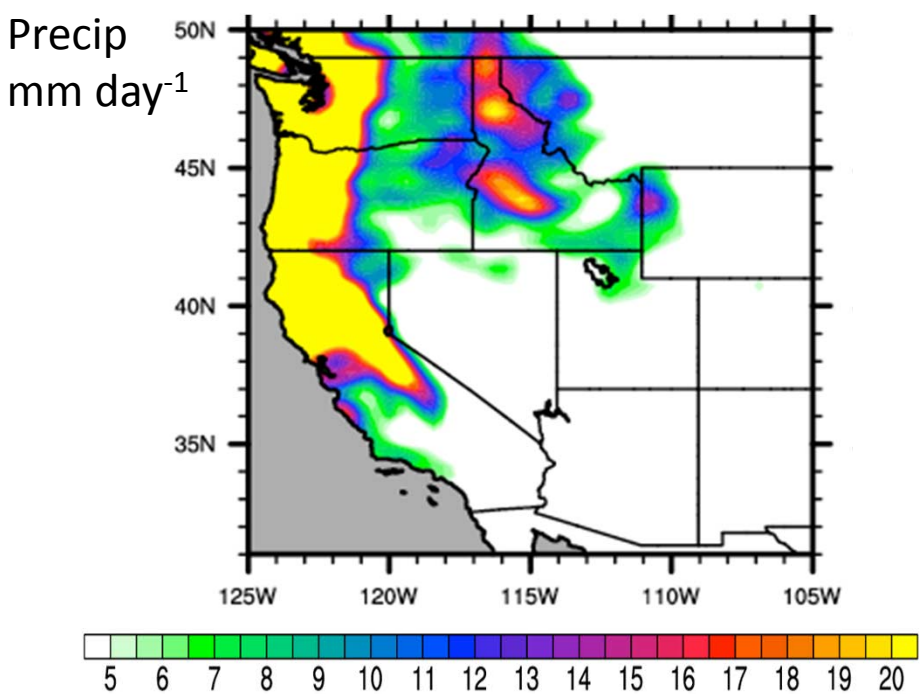


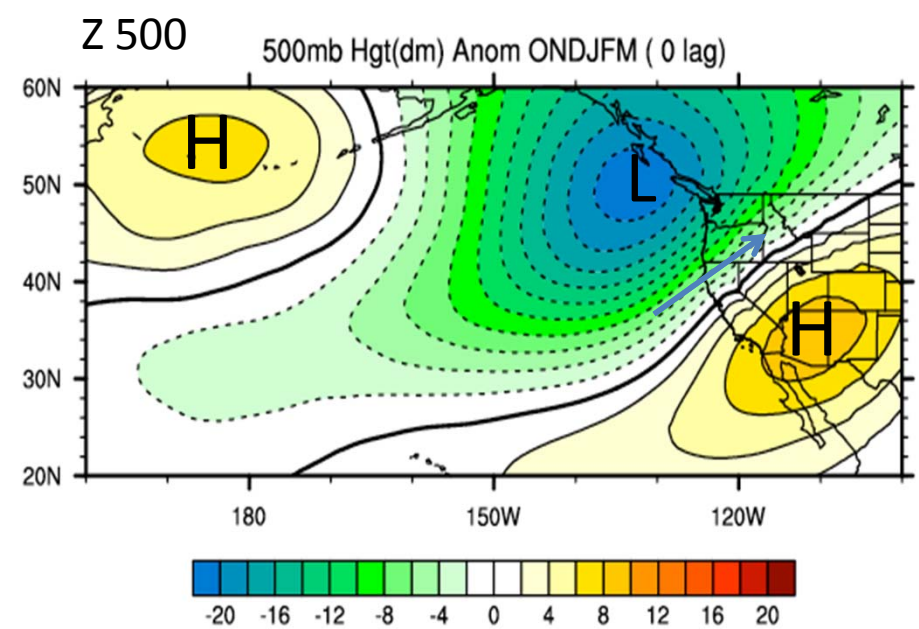
- Obtained from CFSR 1979-2010
- 6 hourly (4x day) normalized anomalies by IVT standard deviation
- EOFs based on land only and normalized Precipitation
  - By normalizing and using land only emphasizes variability in the interior.
  - Can use composites to show the full fields (including over the ocean) based on the value of the principal component (PC, time series):
  - PC 1, 2, 3 (positive, “high” or “top”), PC2 (negative, “low” or “bot”)

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

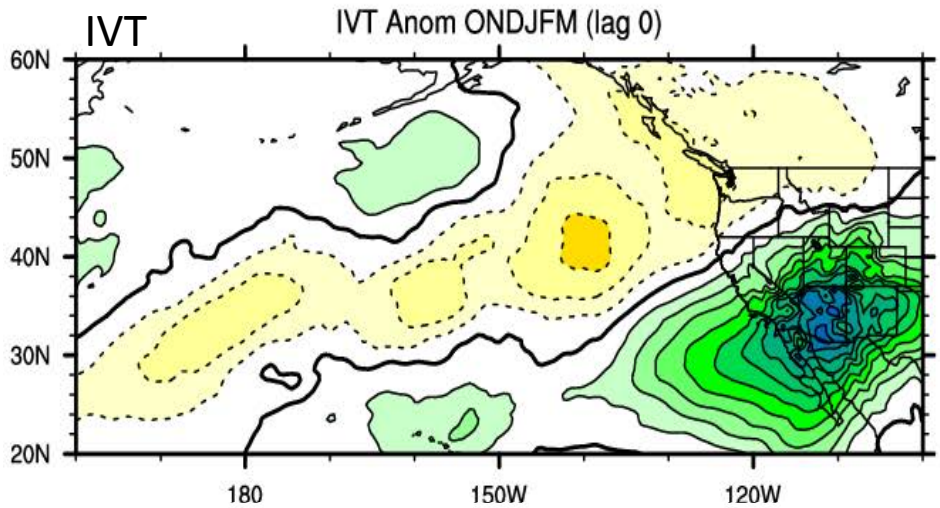


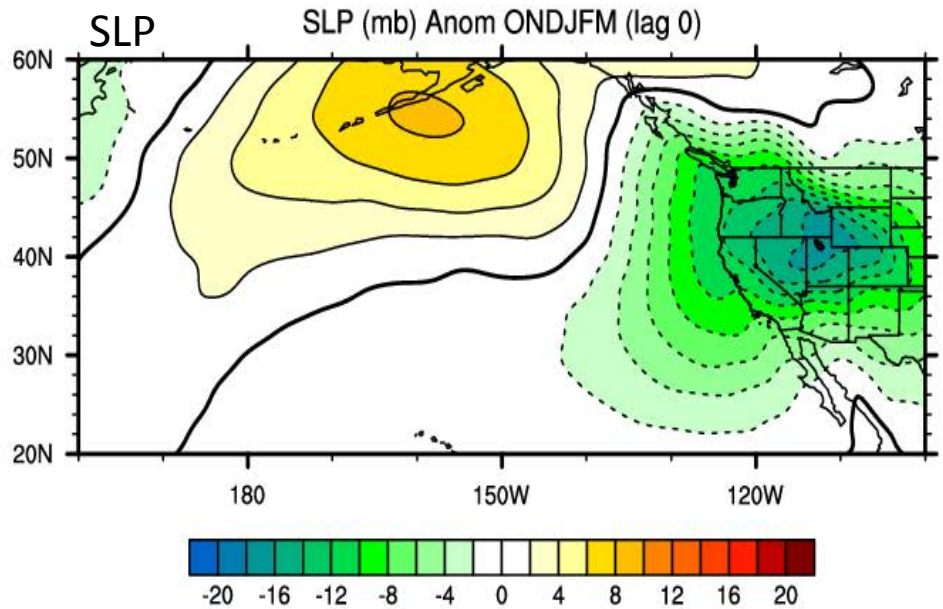


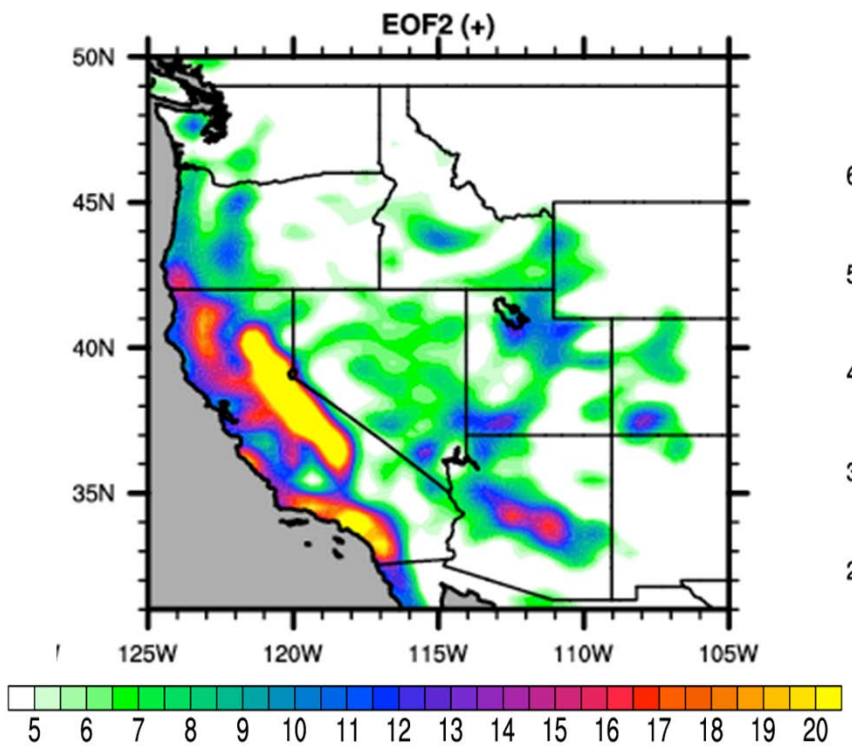


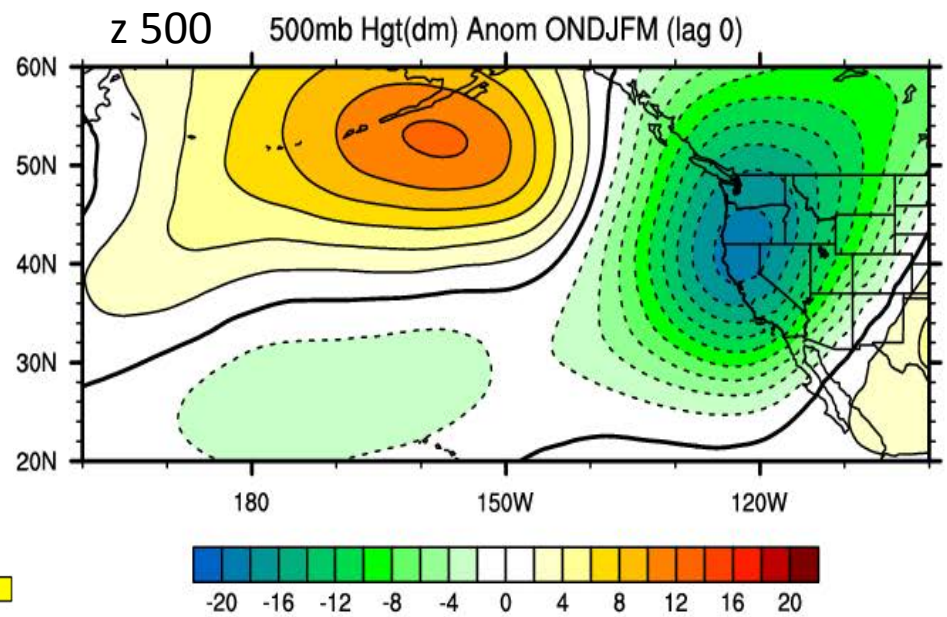


EOF 2 “high” composite IVT

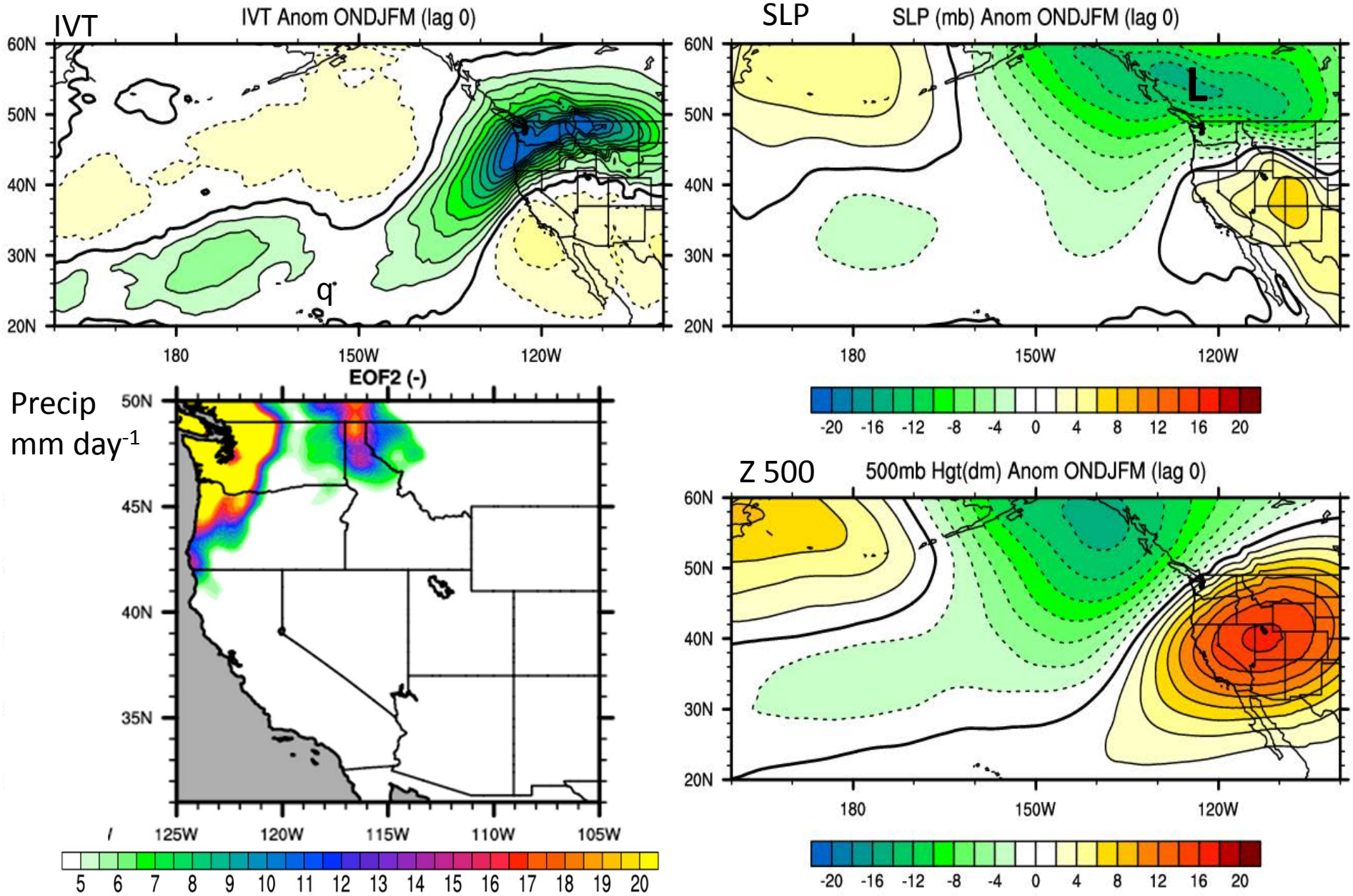




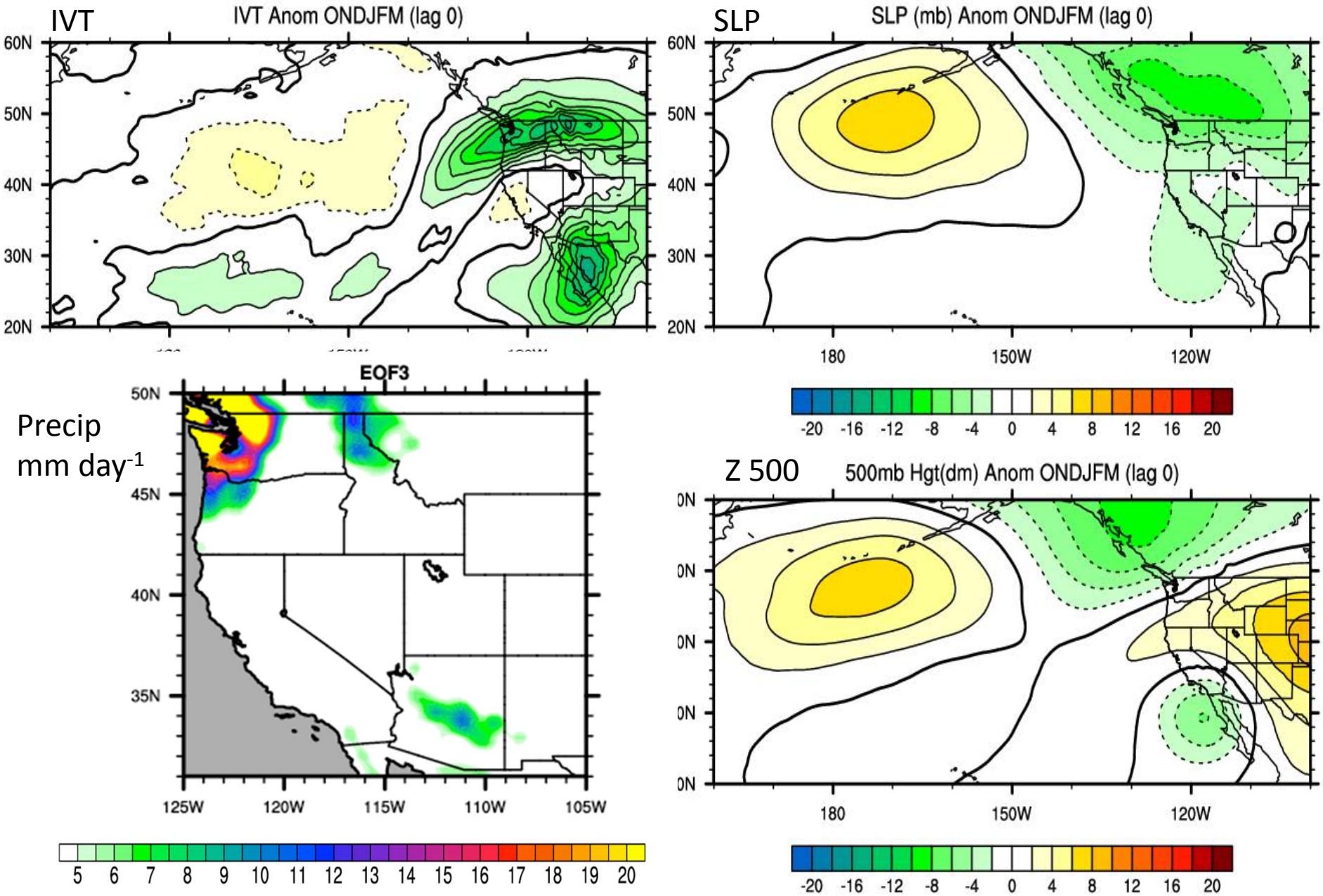




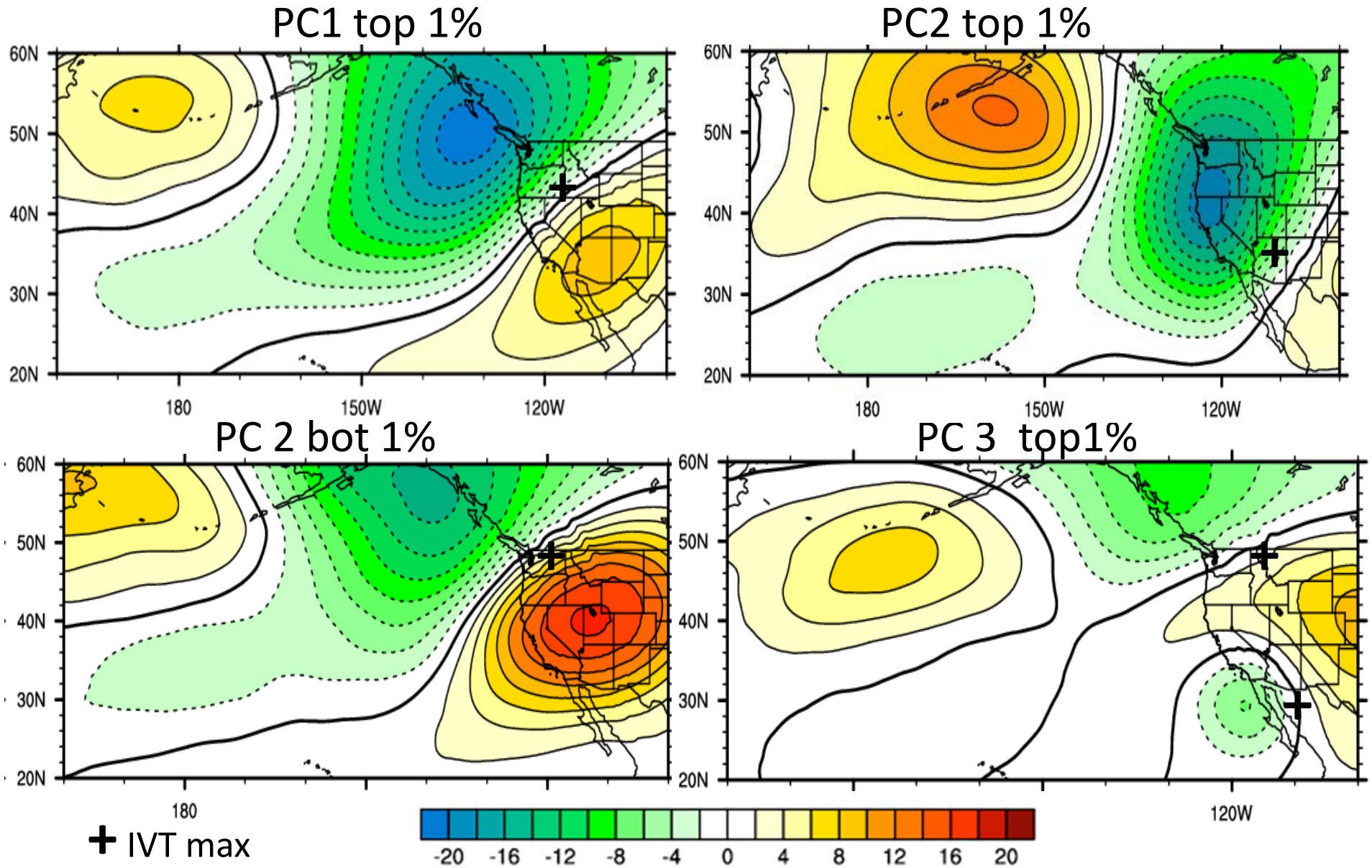
EOF2/PC2 "Low"Composite



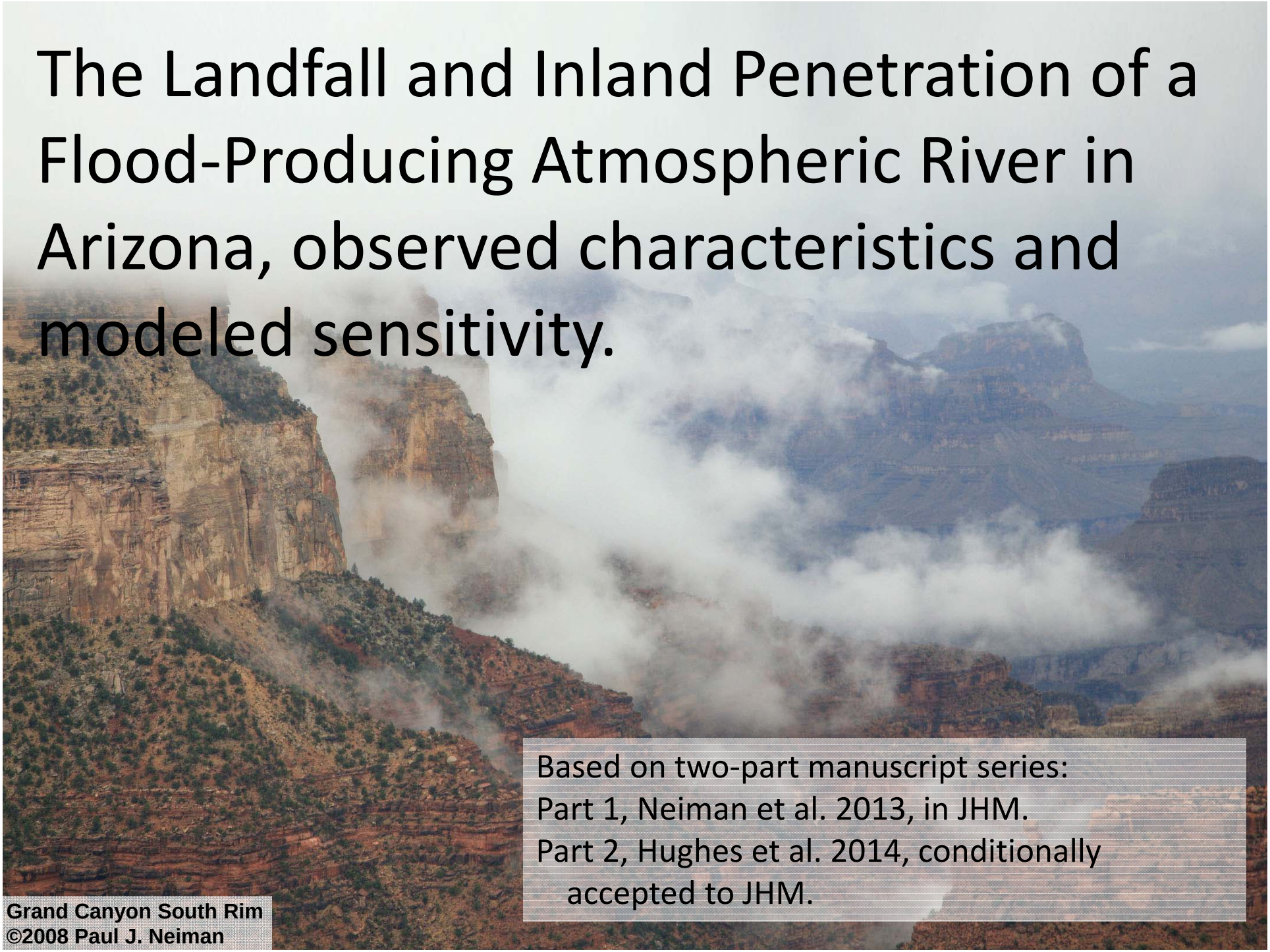
EOF 3 “TOP” composite 0 lag



PC-based 500 hPa Anomaly (dm) Composite 0 lag



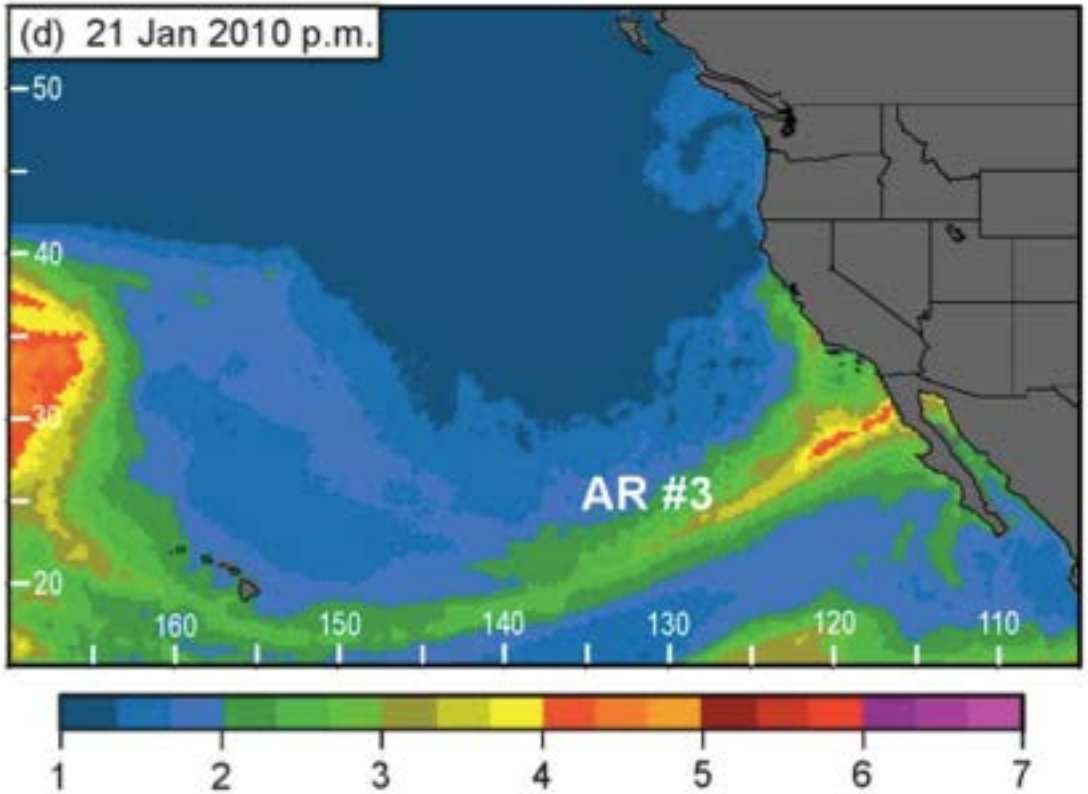
The Landfall and Inland Penetration of a Flood-Producing Atmospheric River in Arizona, observed characteristics and modeled sensitivity.



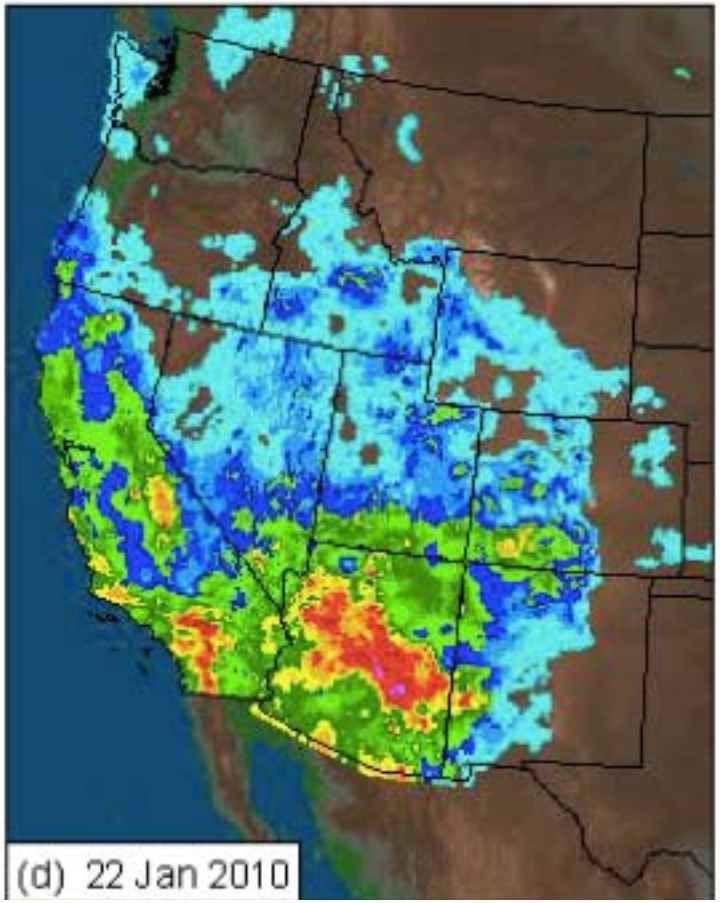
Based on two-part manuscript series:
Part 1, Neiman et al. 2013, in JHM.
Part 2, Hughes et al. 2014, conditionally accepted to JHM.

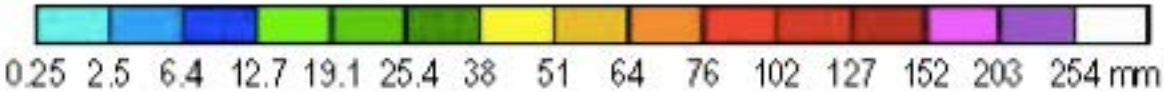
Grand Canyon South Rim
©2008 Paul J. Neiman

Landfalling Atmospheric River -> Extreme Precipitation amounts in Arizona



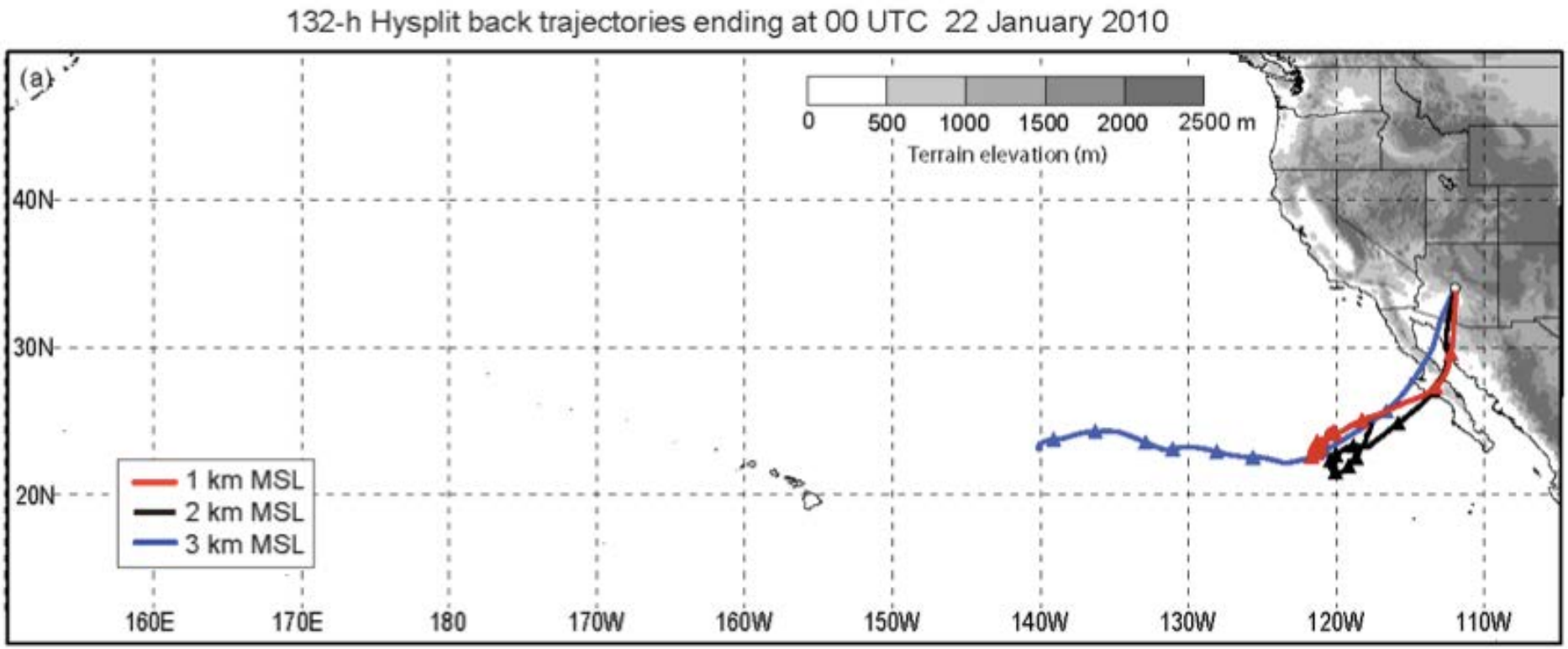
Integrated Water Vapor (cm)



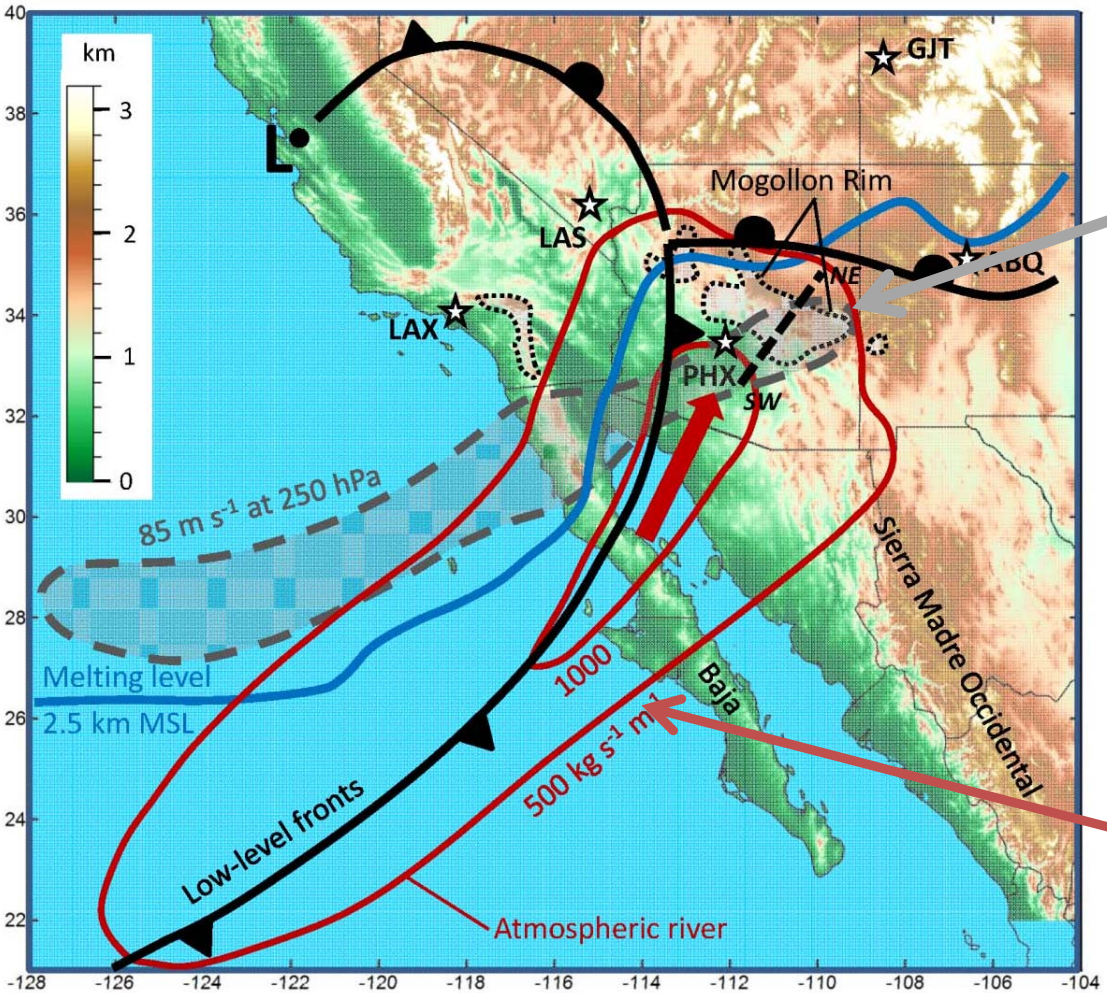


Quantitative precipitation estimation (mm)

Back trajectories show a path across Baja



Motivation and questions addressed

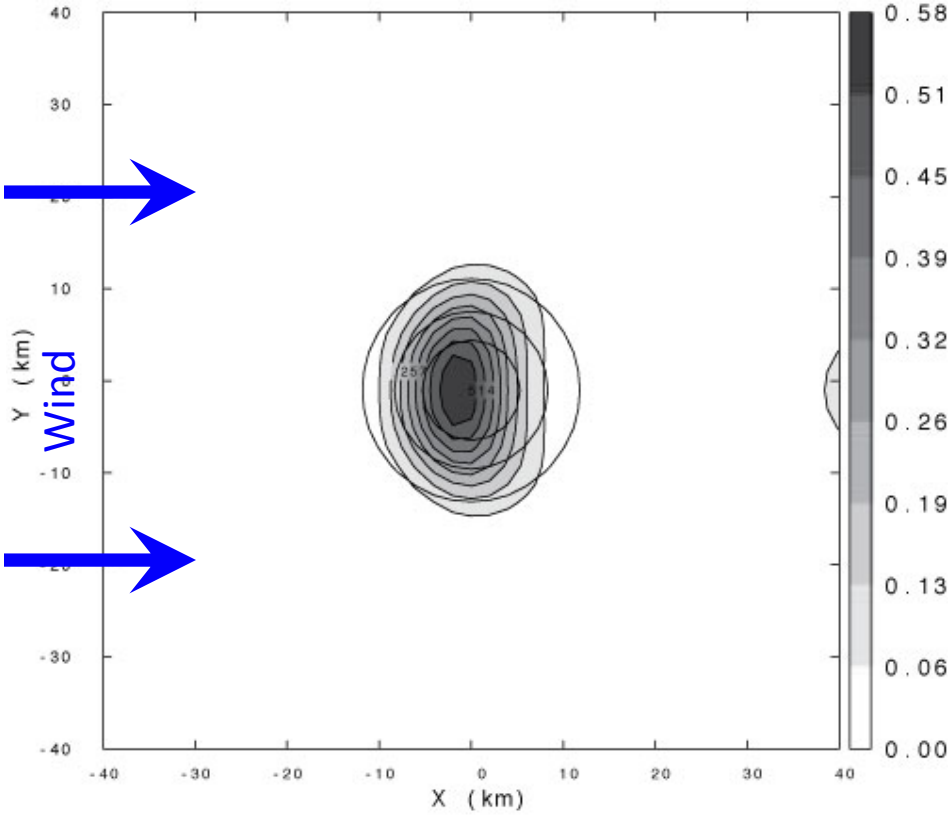


Precipitation: 13th largest in entire Intermountain West from 1979-2013

AR = atmospheric river (region of strong water vapor fluxes)

From Neiman… Hughes… et al. 2013

Moist air flowing over a mountain



Precipitation (grayscale) and topography (contours) for an idealized numerical study. From Jiang (2003)

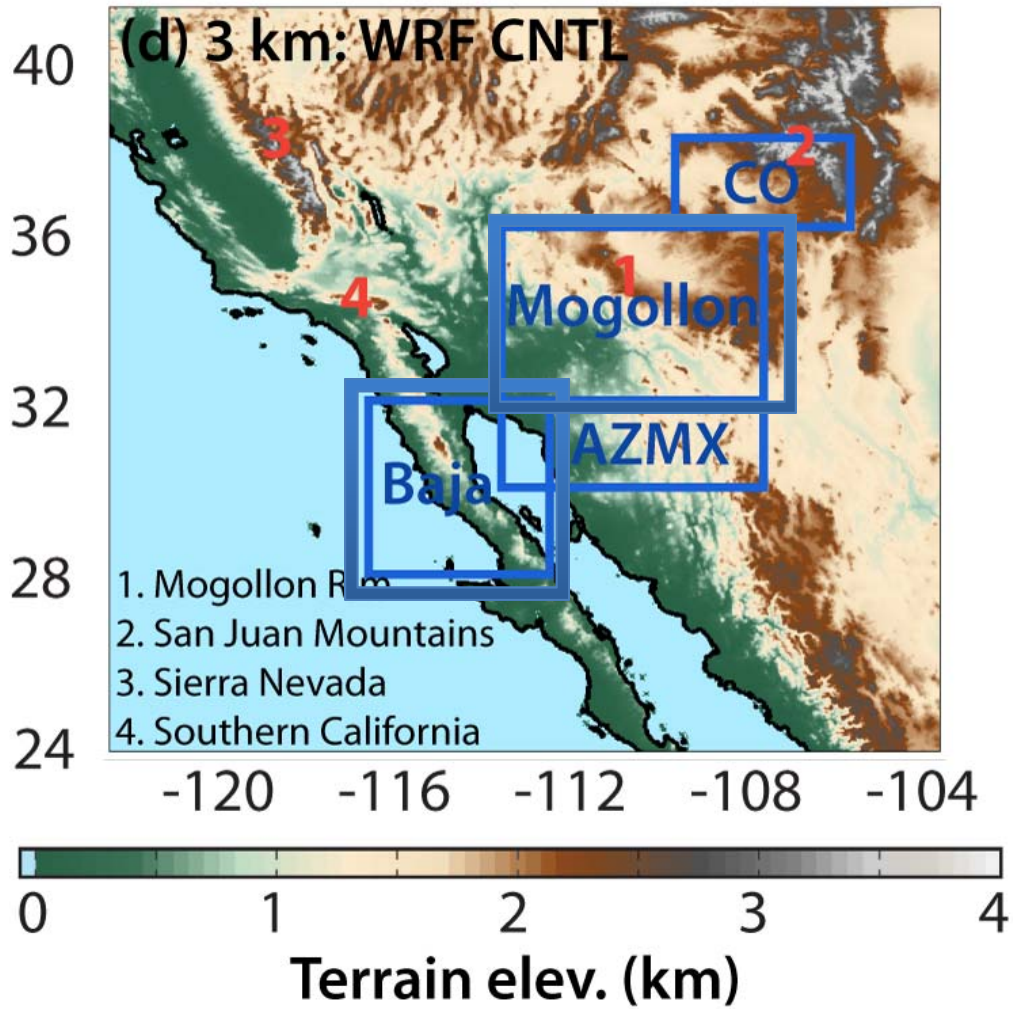
Upslope model of orographic precipitation:

$$P \propto \boxed{q\vec{U}} \bullet \boxed{\nabla h}(x,y)$$

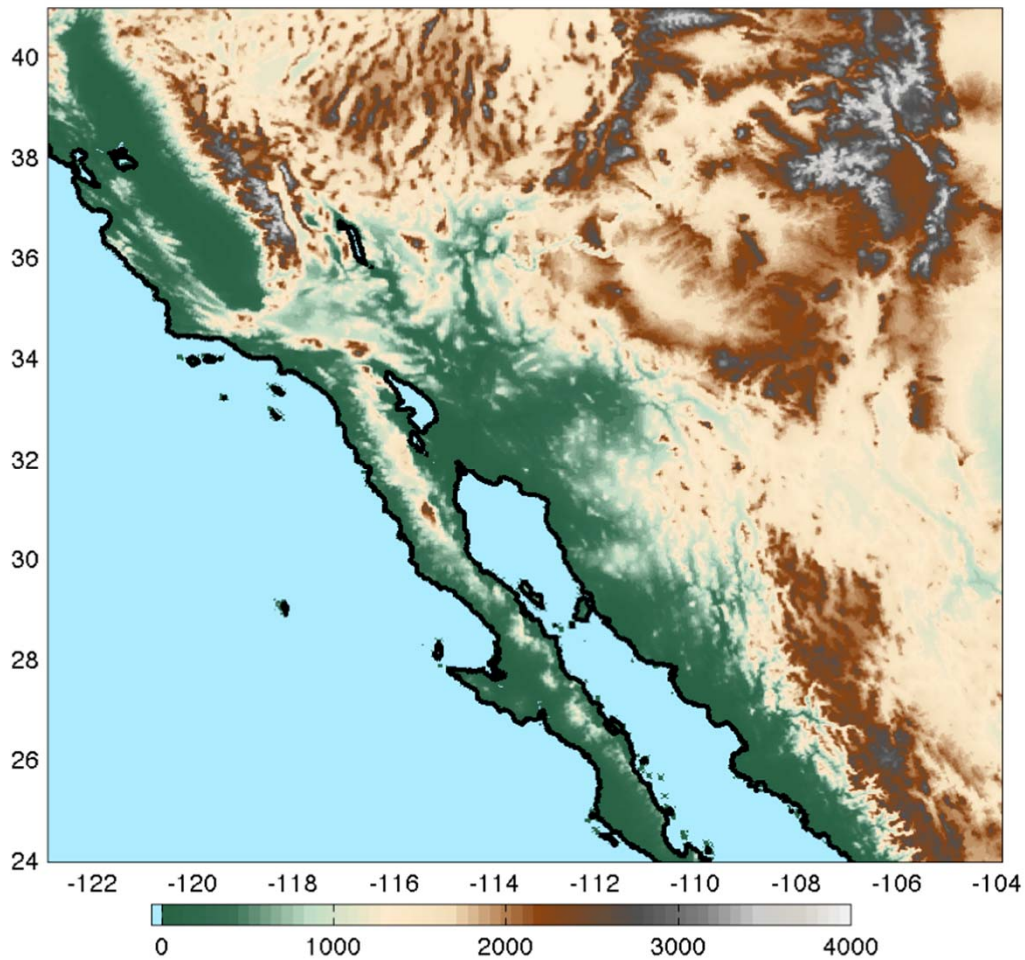
P: Precipitation
qU: Water vapor flux (specific humidity times wind)
h(x,y): Terrain height

See Smith (1979), Roe (2005), etc.

Locations and mountain ranges discussed

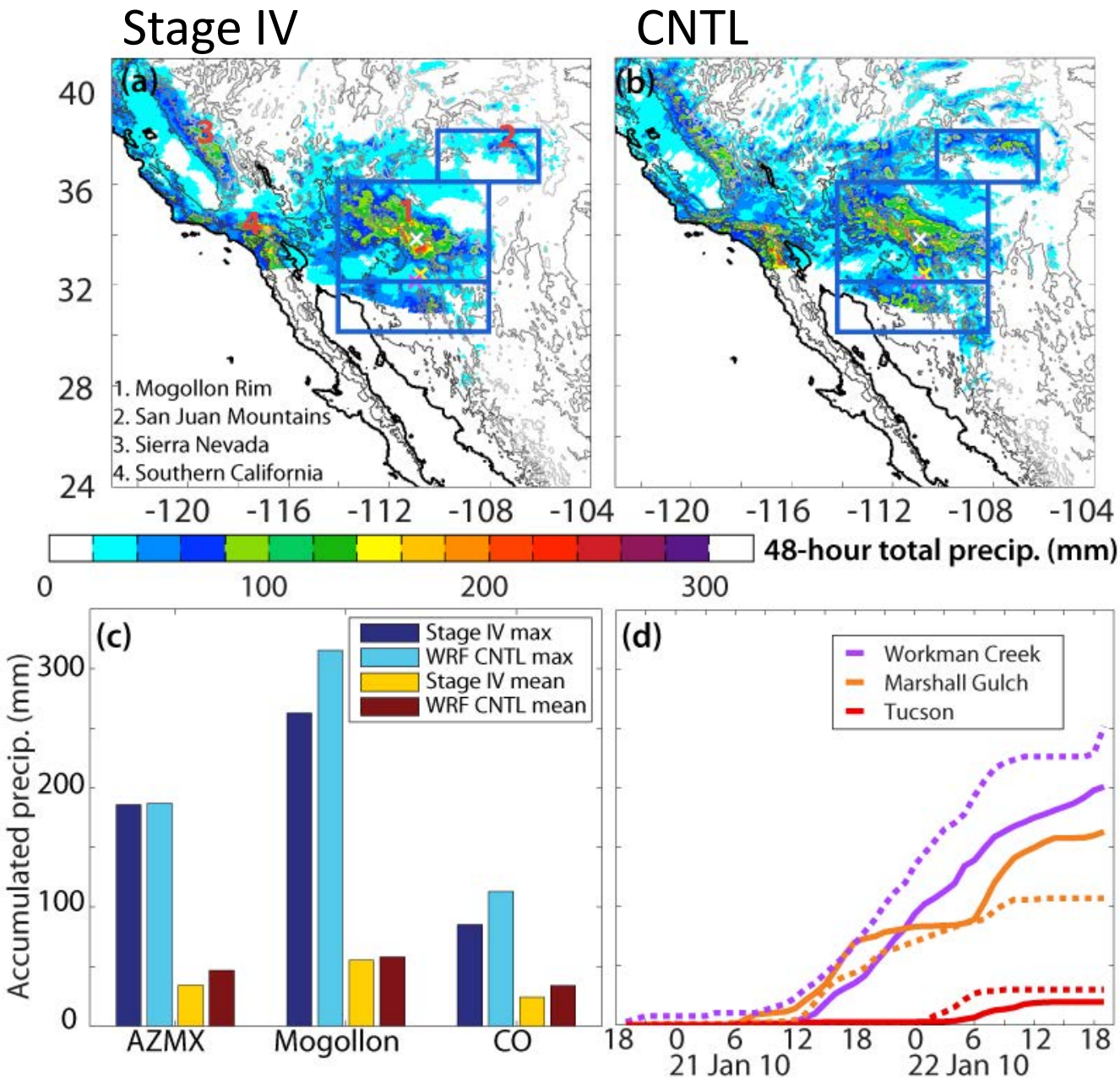


Experimental design: Control simulation

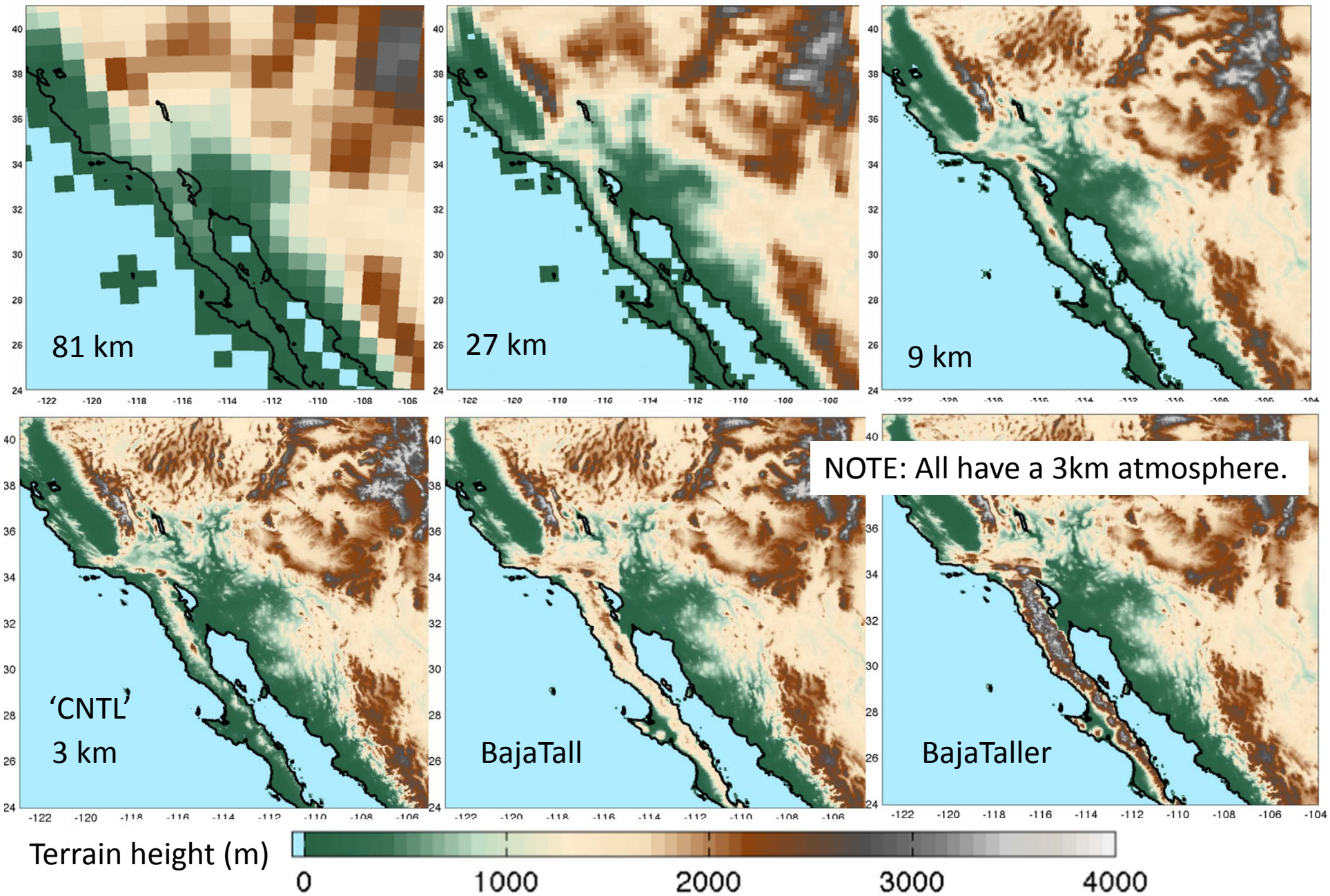


- Climate Forecast System Reanalysis -> Weather, Research, and Forecast model (WRF)
- 3km grid spacing
- Explicit convection
- 54 vertical levels

Control simulation: verification

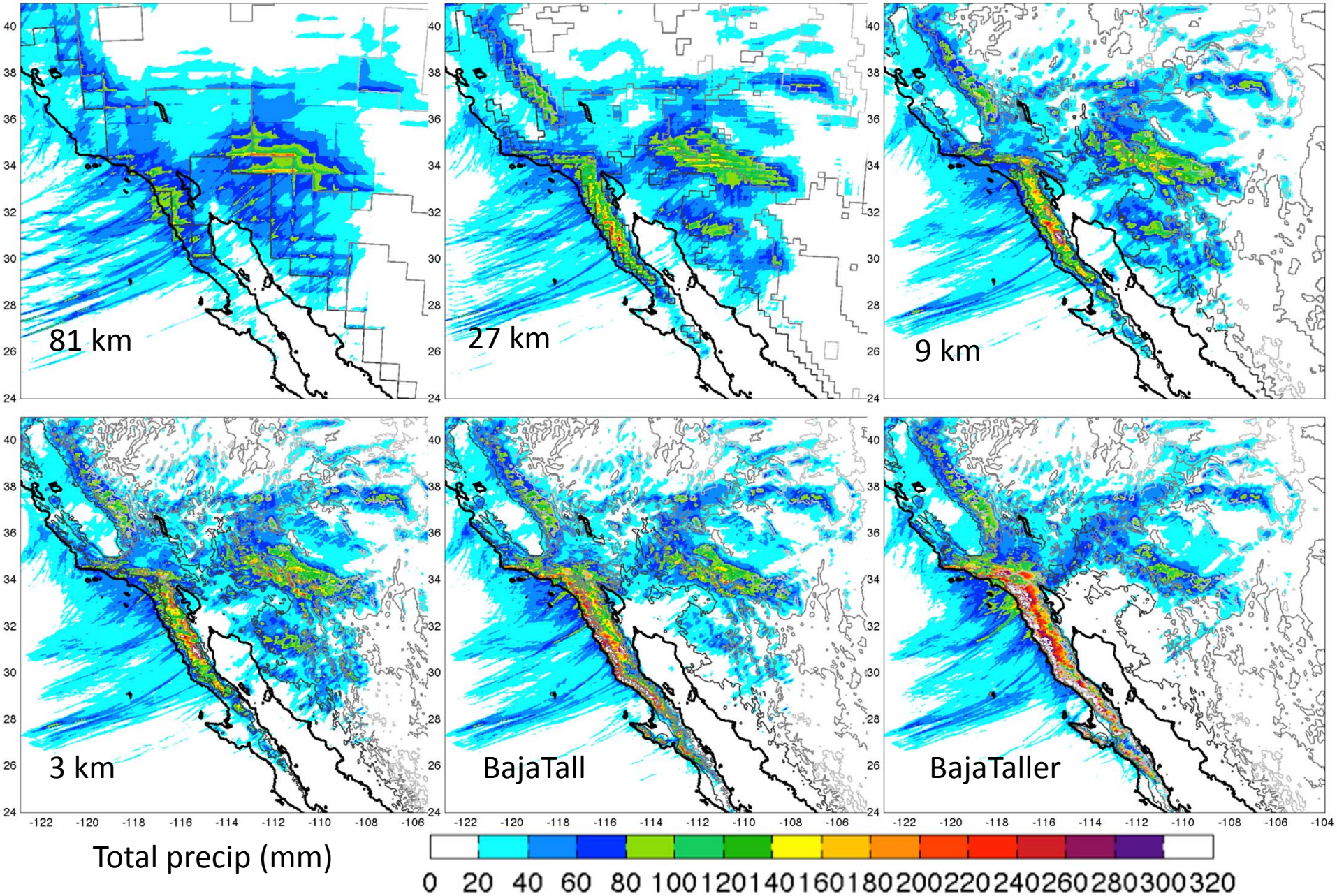


Weather, Research, and Forecast (WRF) simulations

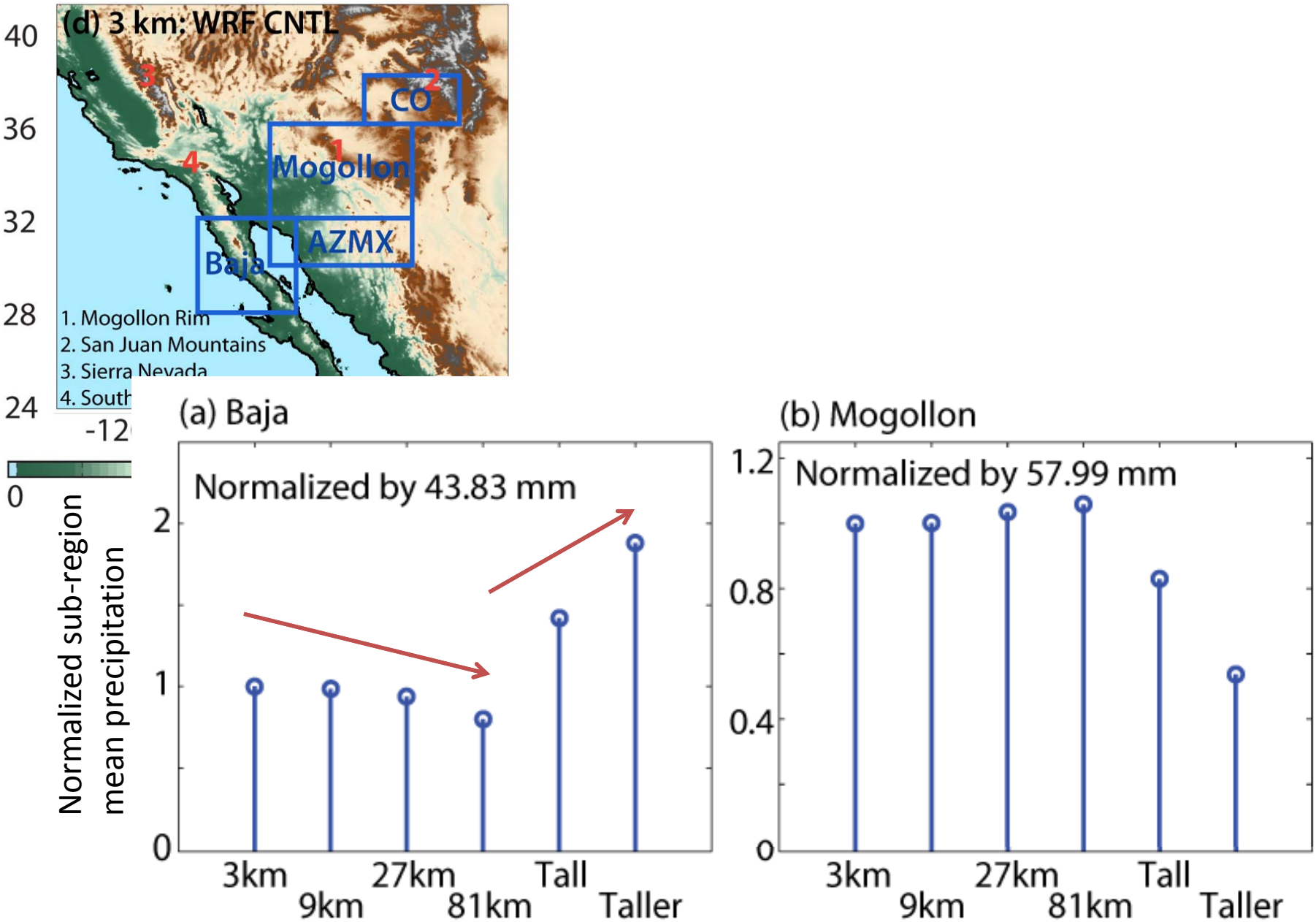


Simulated 48-hour total precipitation

(reminder: all have 3km atmosphere)

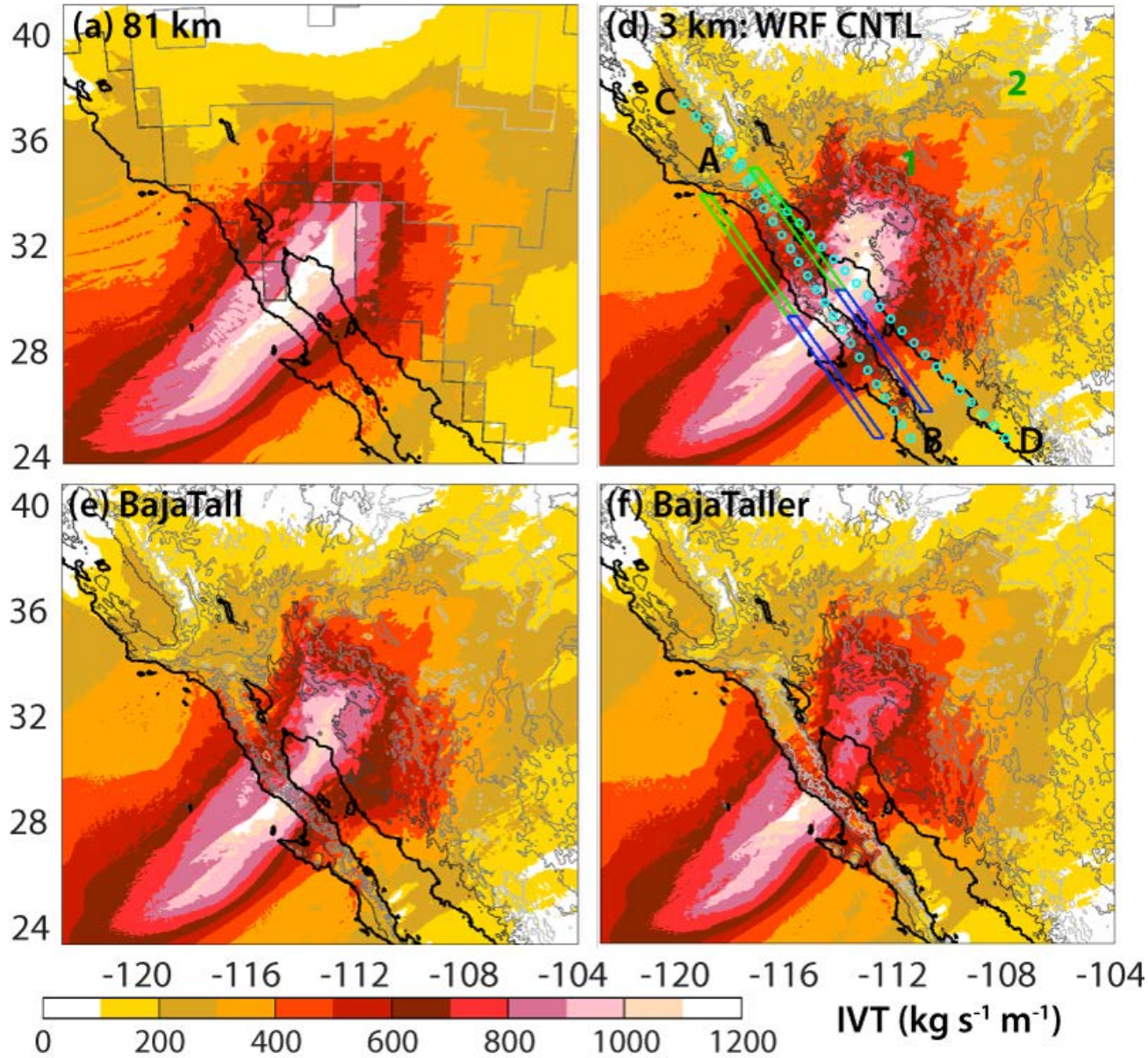


Precipitation in sub-regions

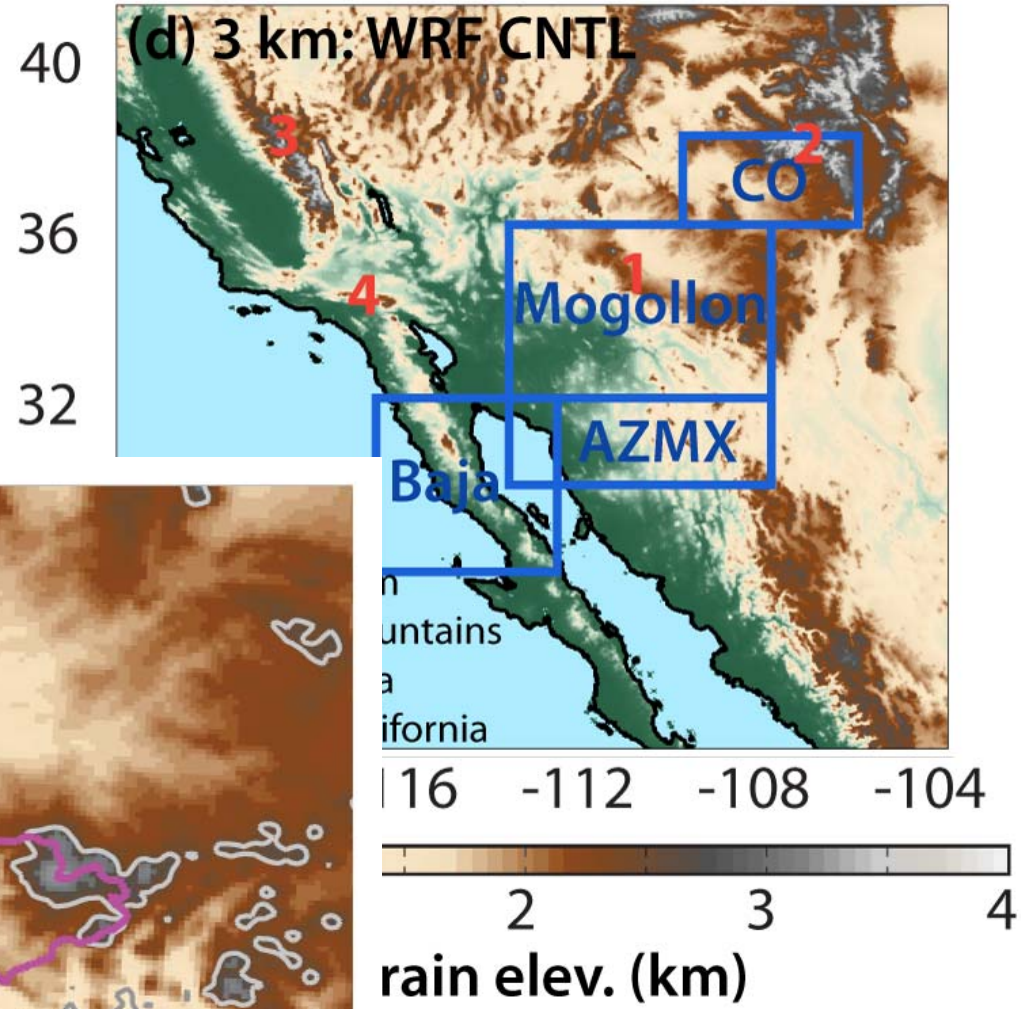


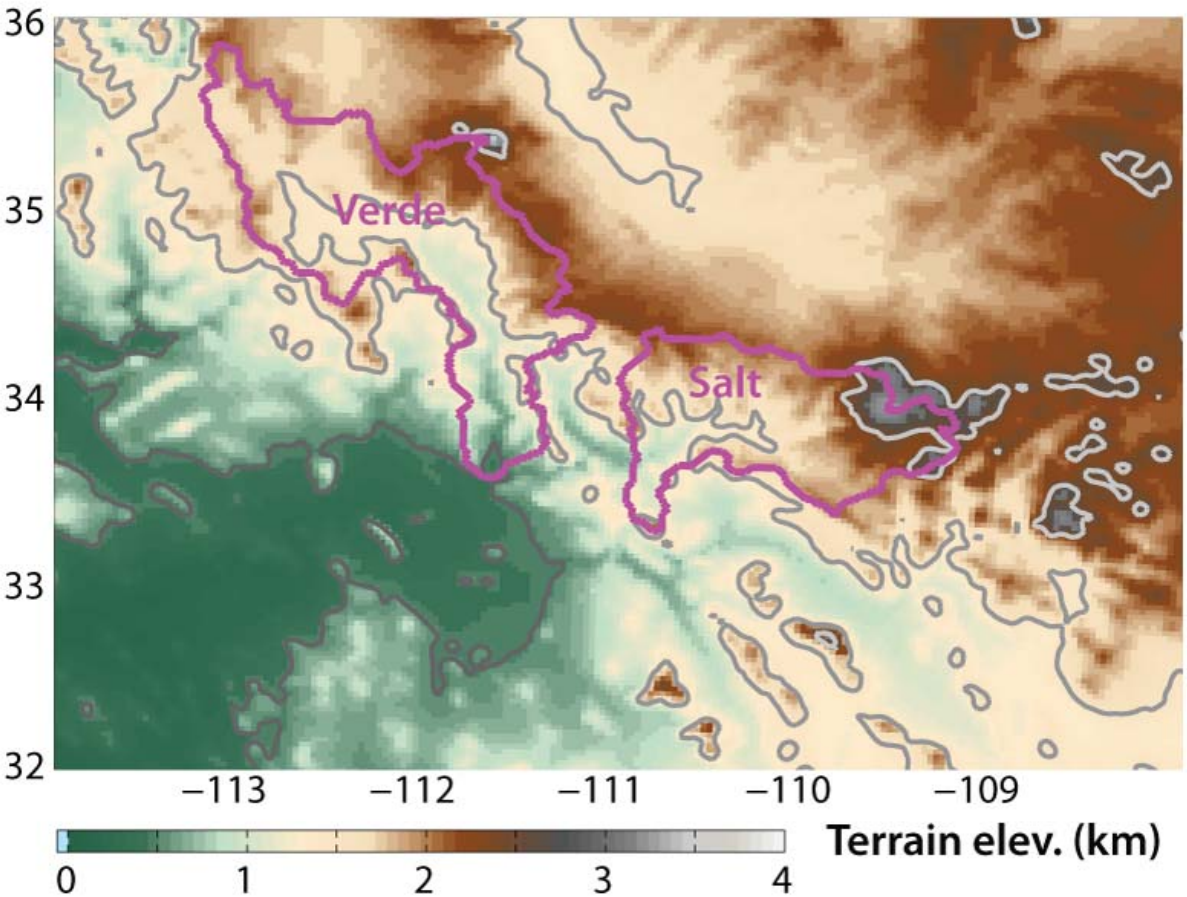
Investigating water vapor pathways: Impact of Baja's Terrain on 'downstream' IVT magnitude

Integrated water vapor transport (IVT) magnitude in four of the six simulations on 0Z Jan. 22, 2010



Water vapor flux magnitude (and thus AR trajectory) matters, what about flux direction?

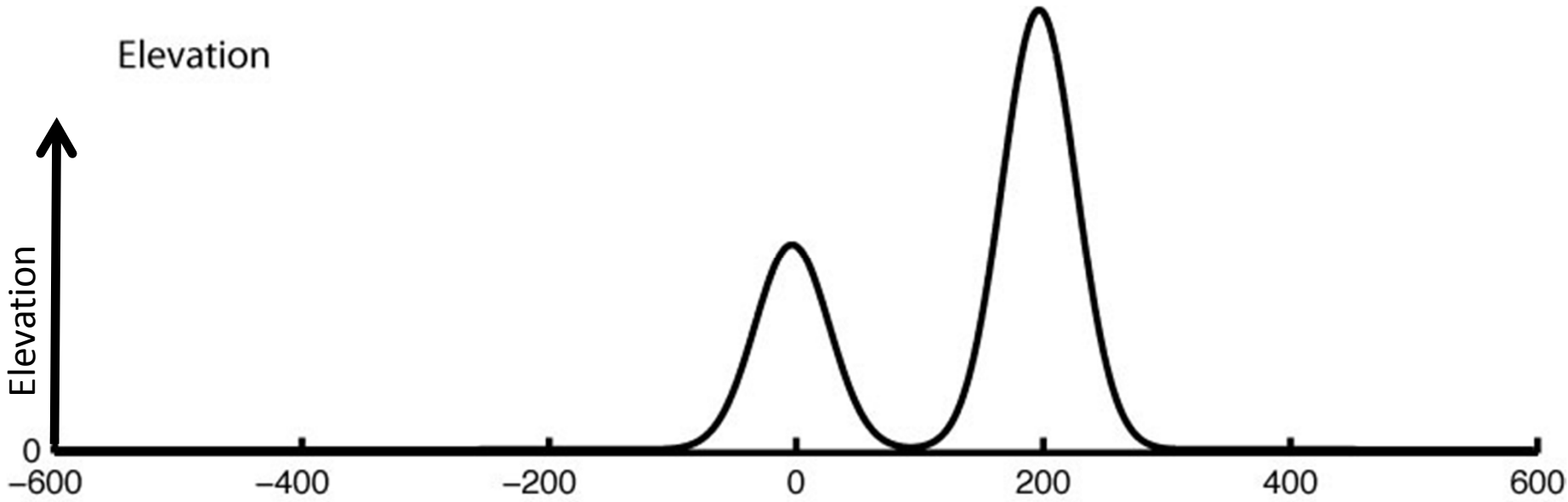




Reminder:

$$P \propto q\vec{U} \bullet \nabla h(x,y)$$

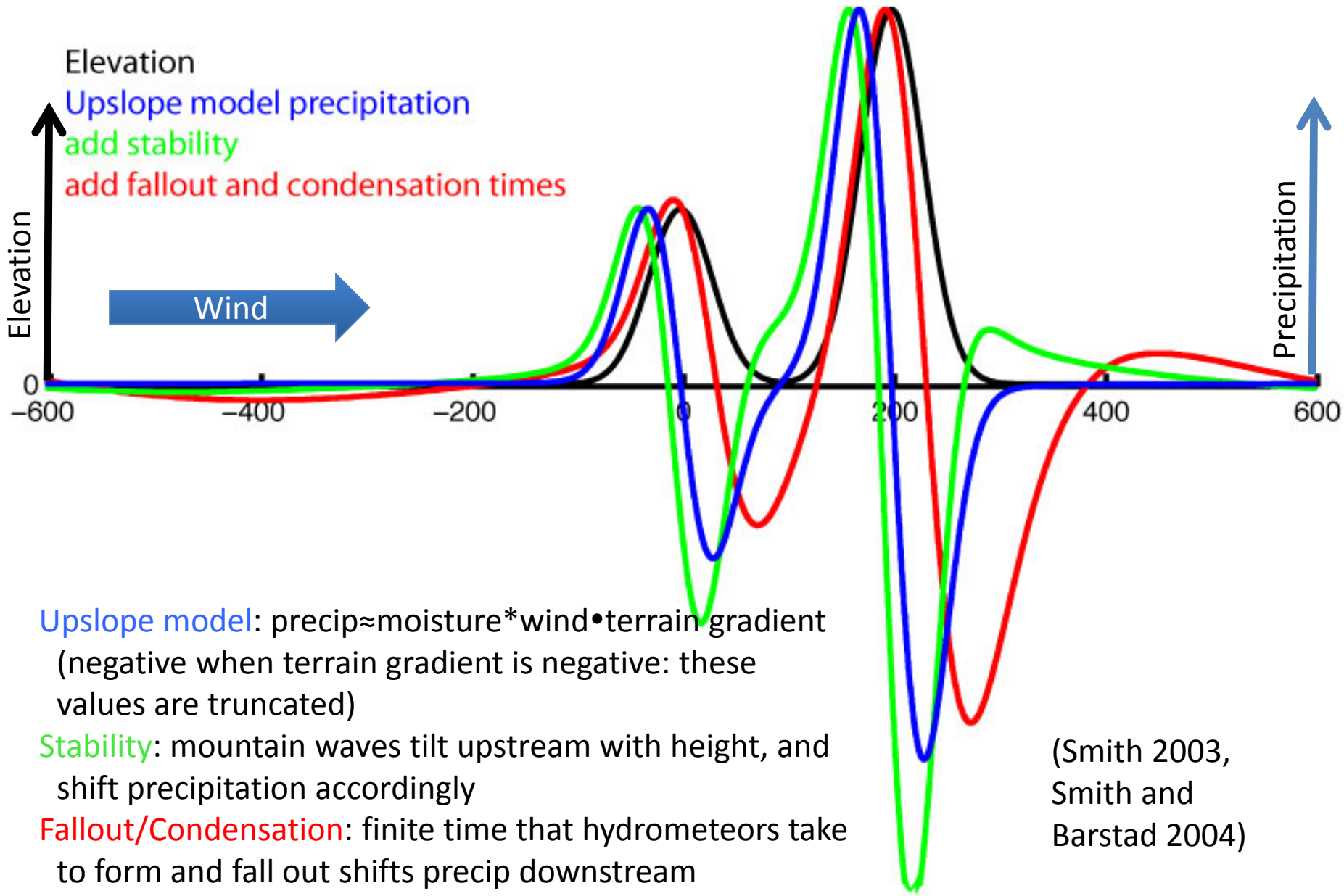
Linear model (LM) of orographic precipitation



Two, two-dimensional idealized mountains

(Smith 2003, Smith and Barstad 2004)

Linear model (LM) of orographic precipitation



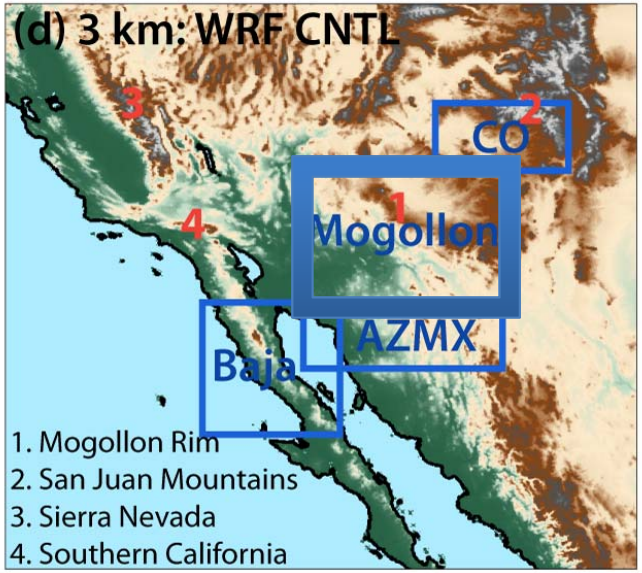
Upslope model: precip≈moisture*wind•terrain gradient (negative when terrain gradient is negative: these values are truncated)

Stability: mountain waves tilt upstream with height, and shift precipitation accordingly

Fallout/Condensation: finite time that hydrometeors take to form and fall out shifts precip downstream

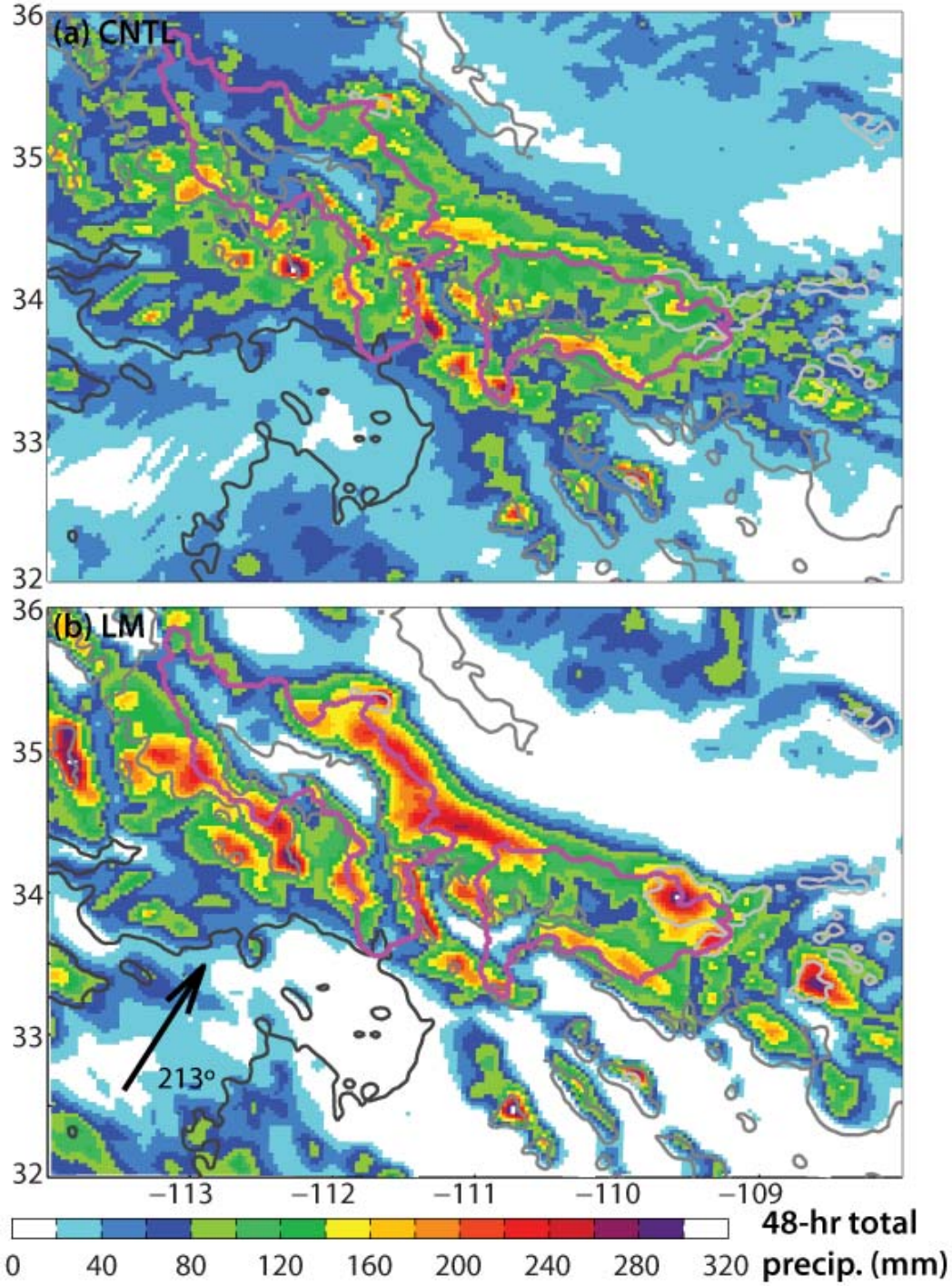
(Smith 2003, Smith and Barstad 2004)

LM applied

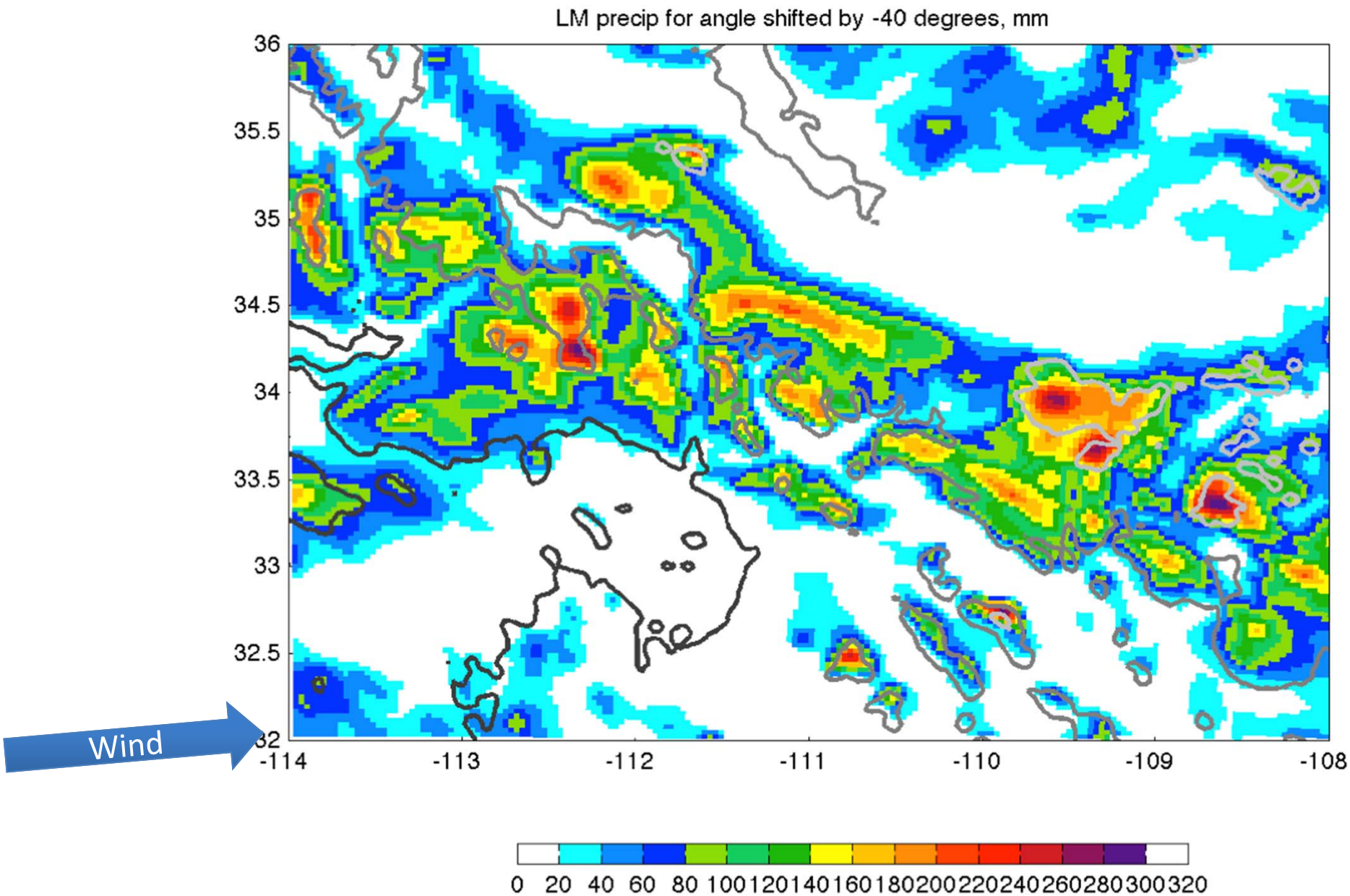


Spatial correlation coefficient
= 0.83

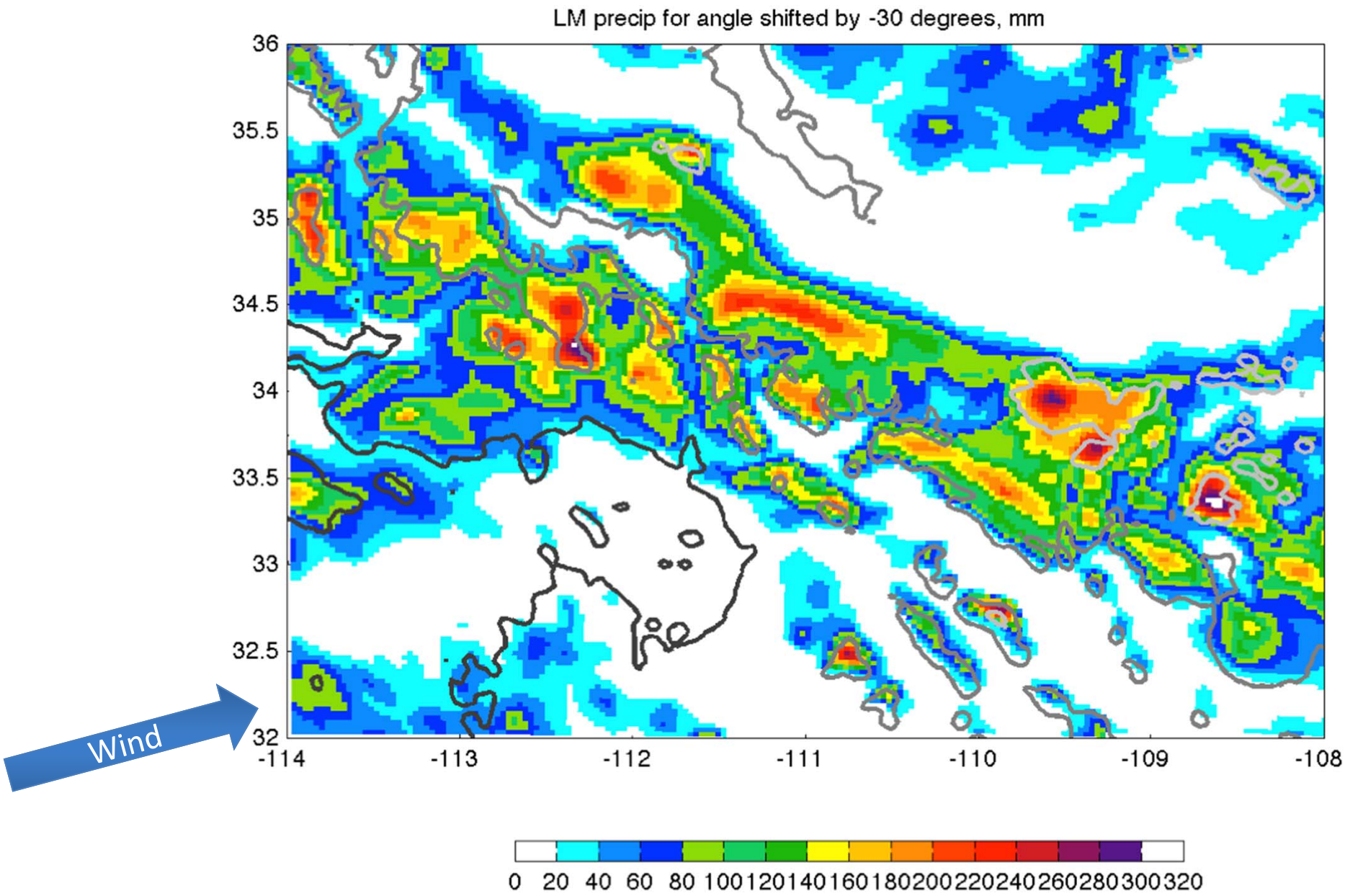
Means (mm):
57.9 CNTL
56.6 LM
Maximum (mm):
315.5 CNTL
310.6 LM



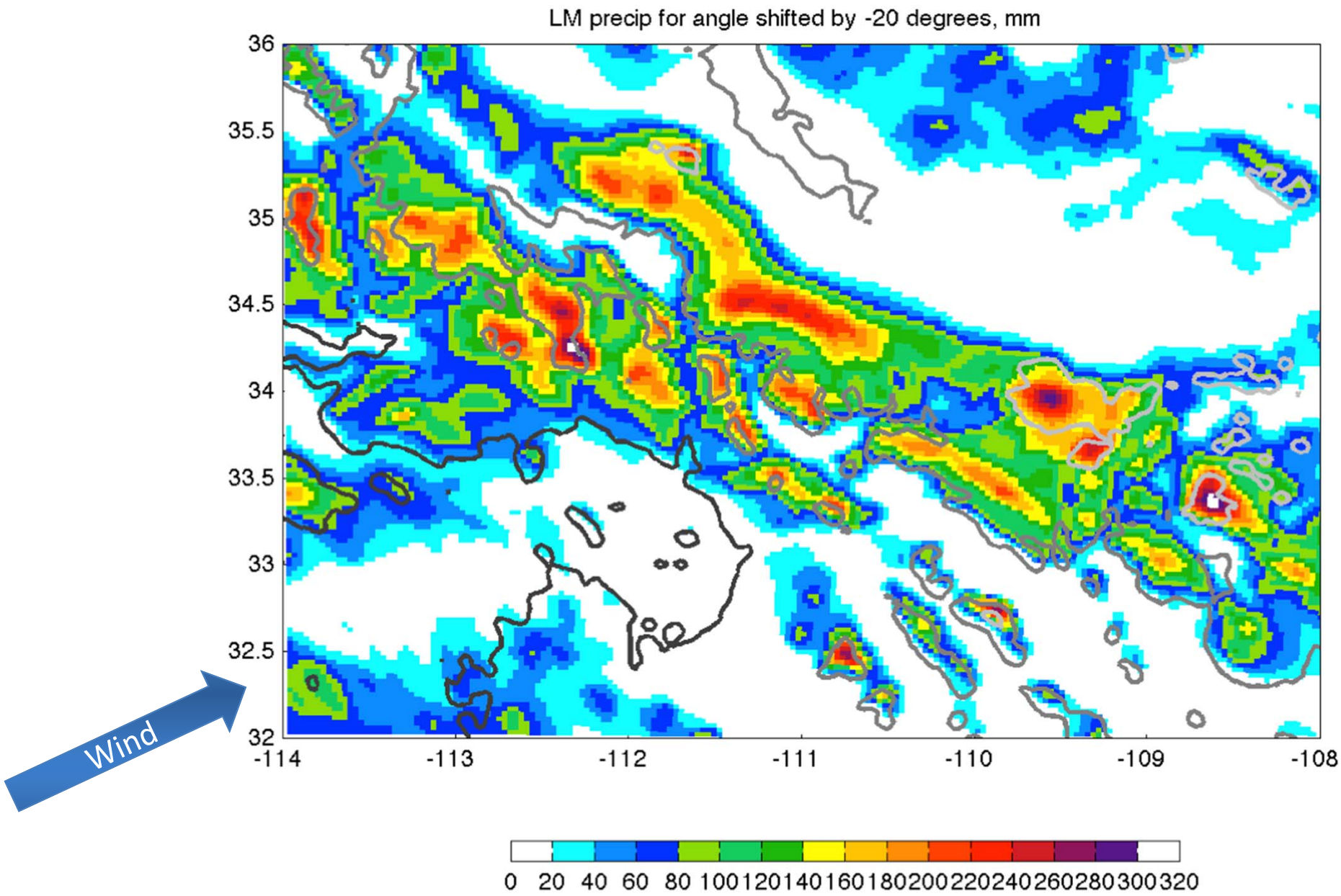
Linear Model applied



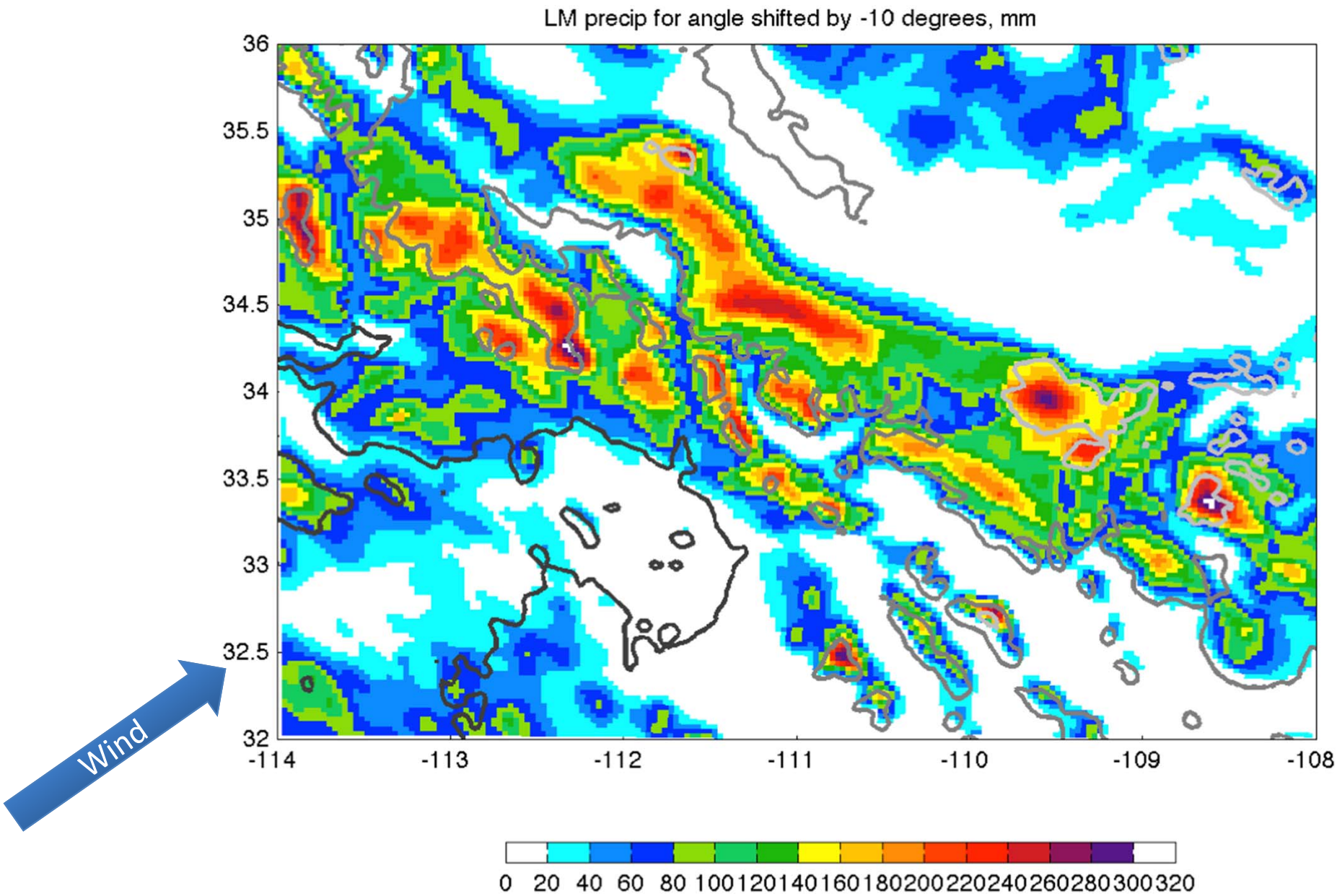
Linear Model applied



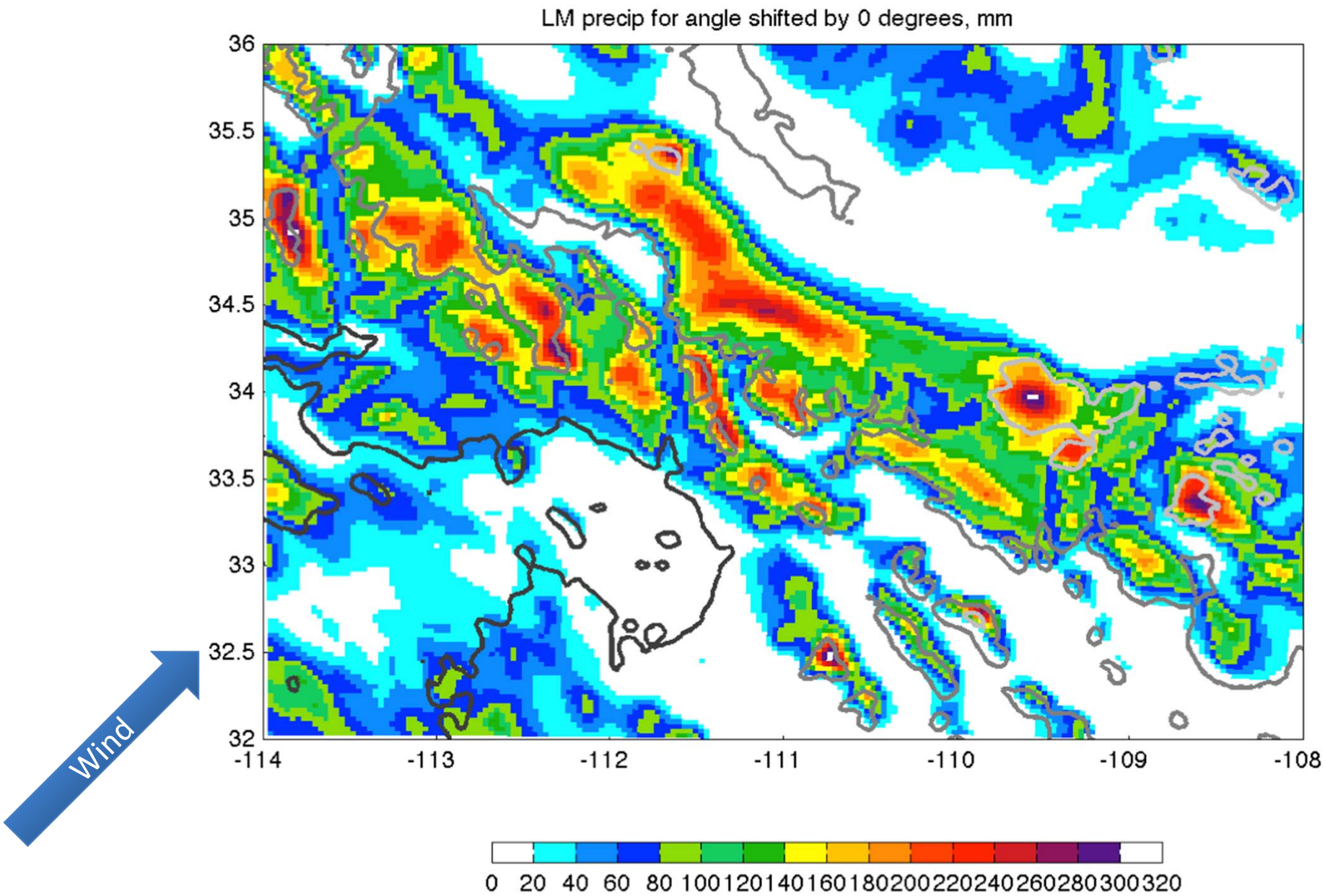
Linear Model applied



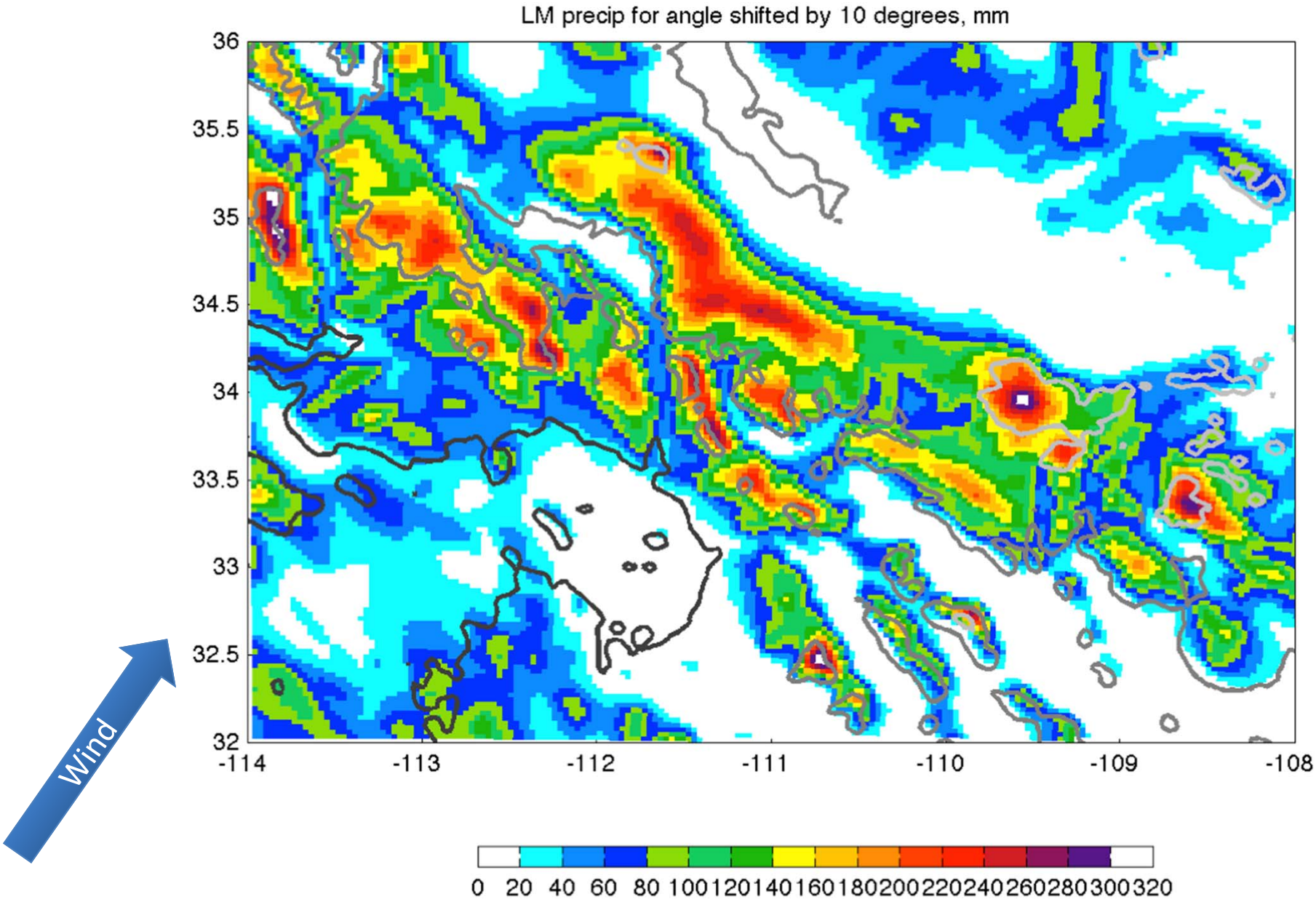
Linear Model applied



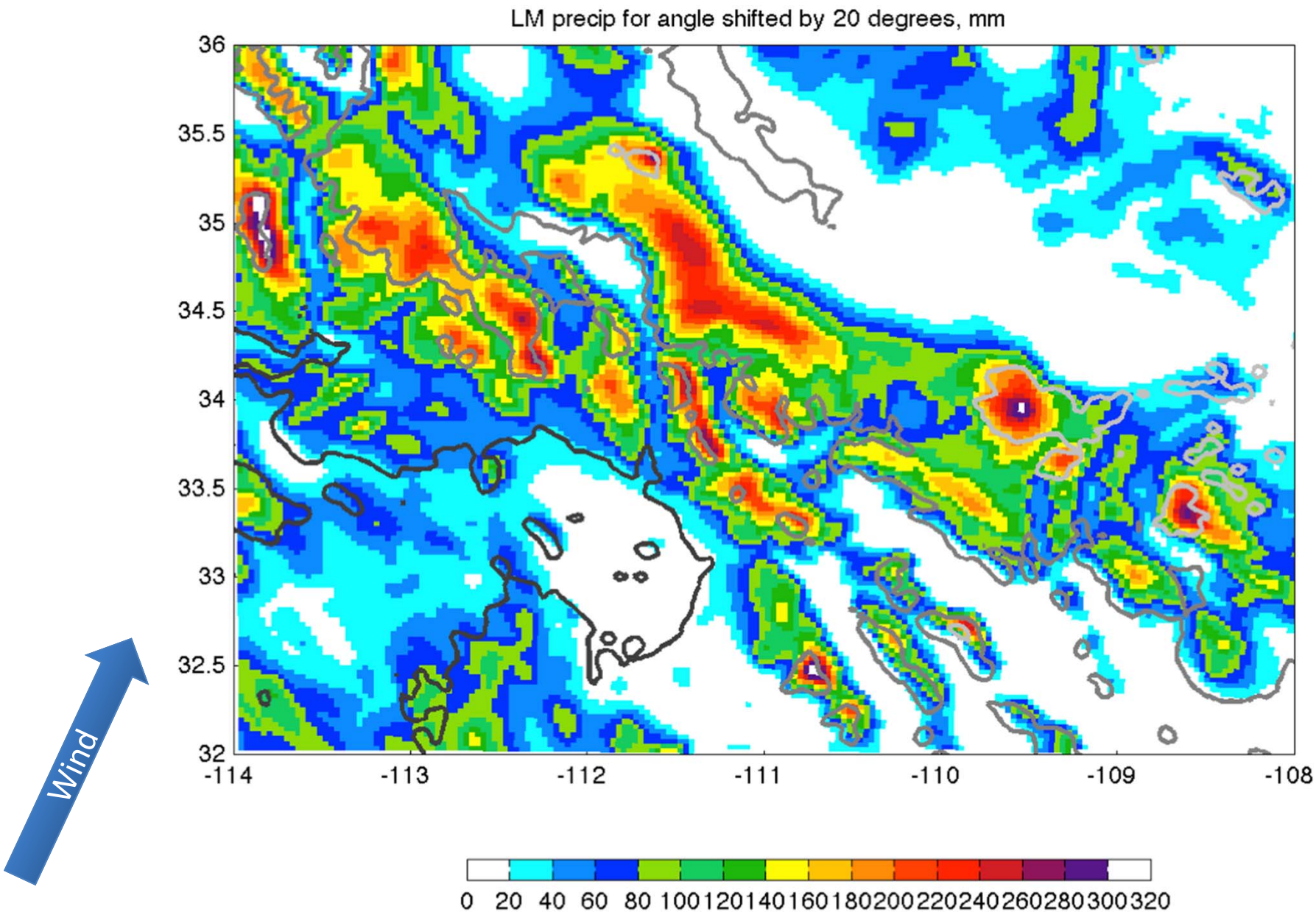
Linear Model applied



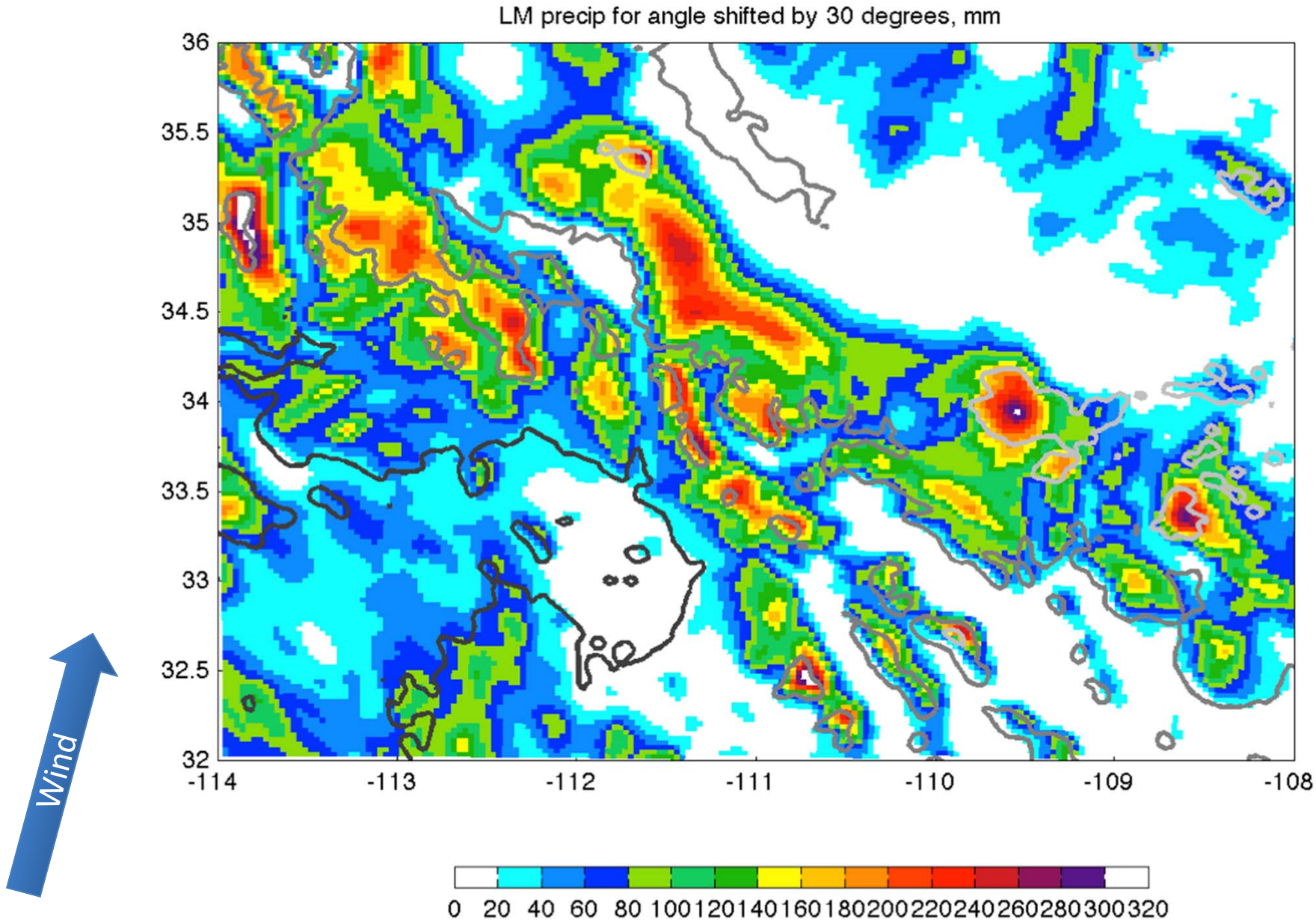
Linear Model applied



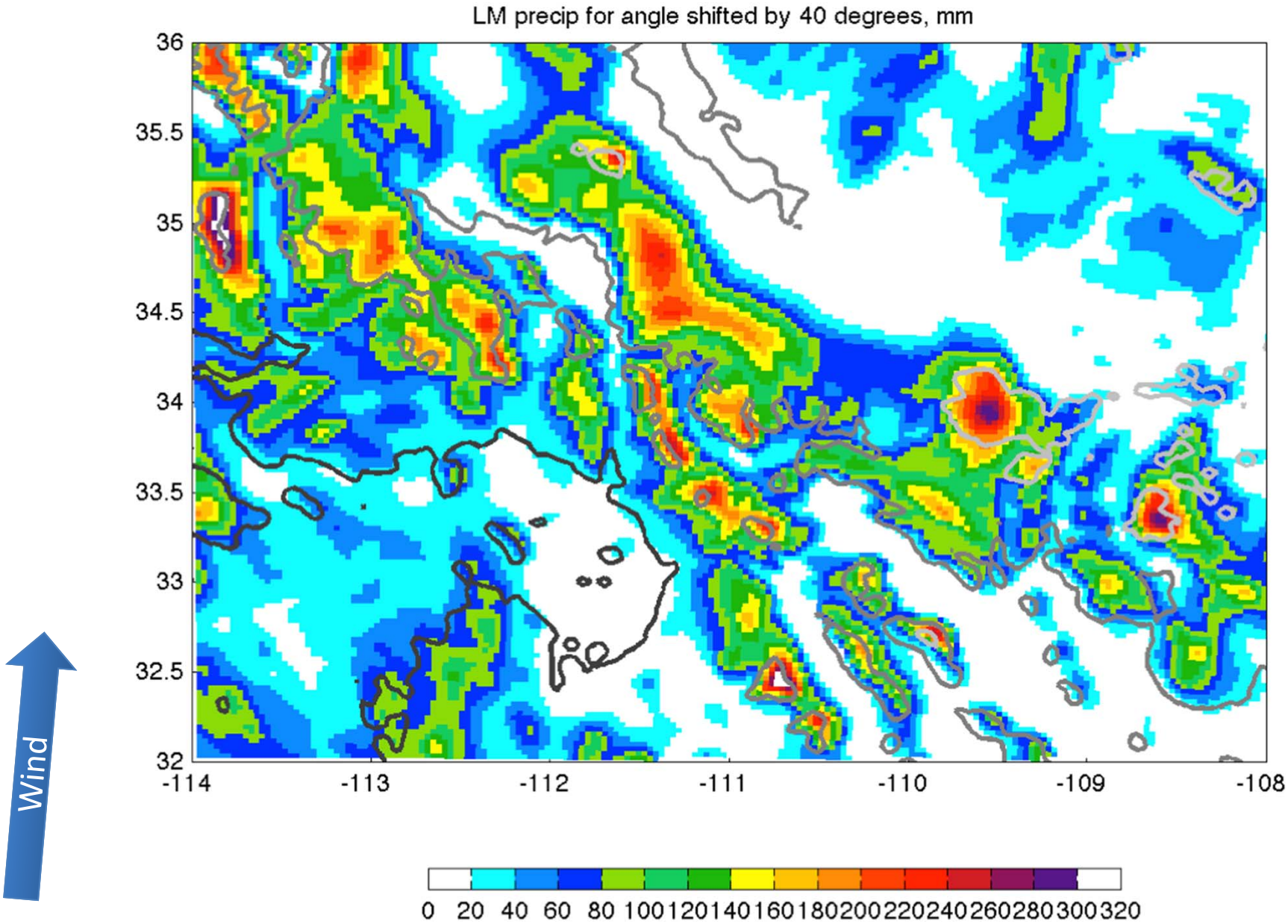
Linear Model applied



Linear Model applied



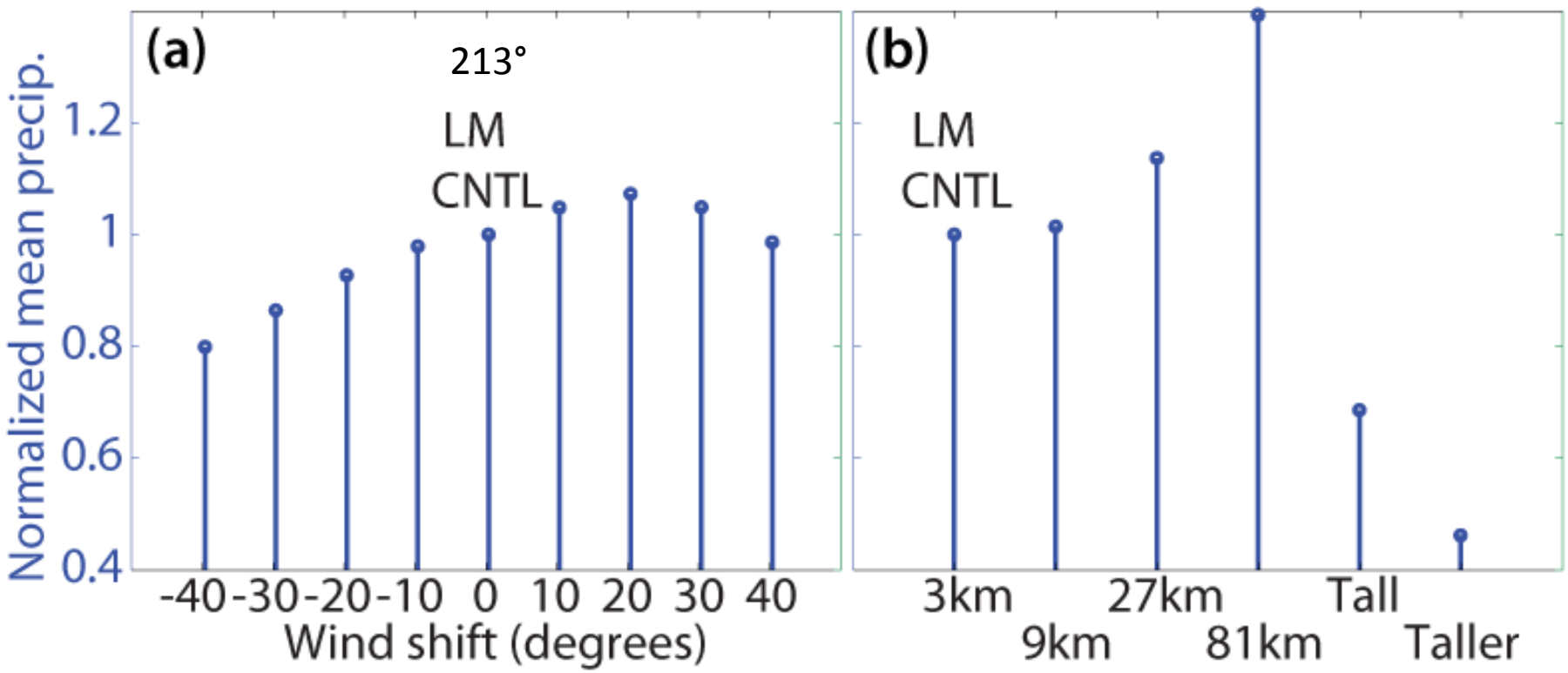
Linear Model applied



LM precipitation: Comparing IVT rotation to impact of upstream topography

Water vapor flux **angle**

Water vapor flux **magnitude**

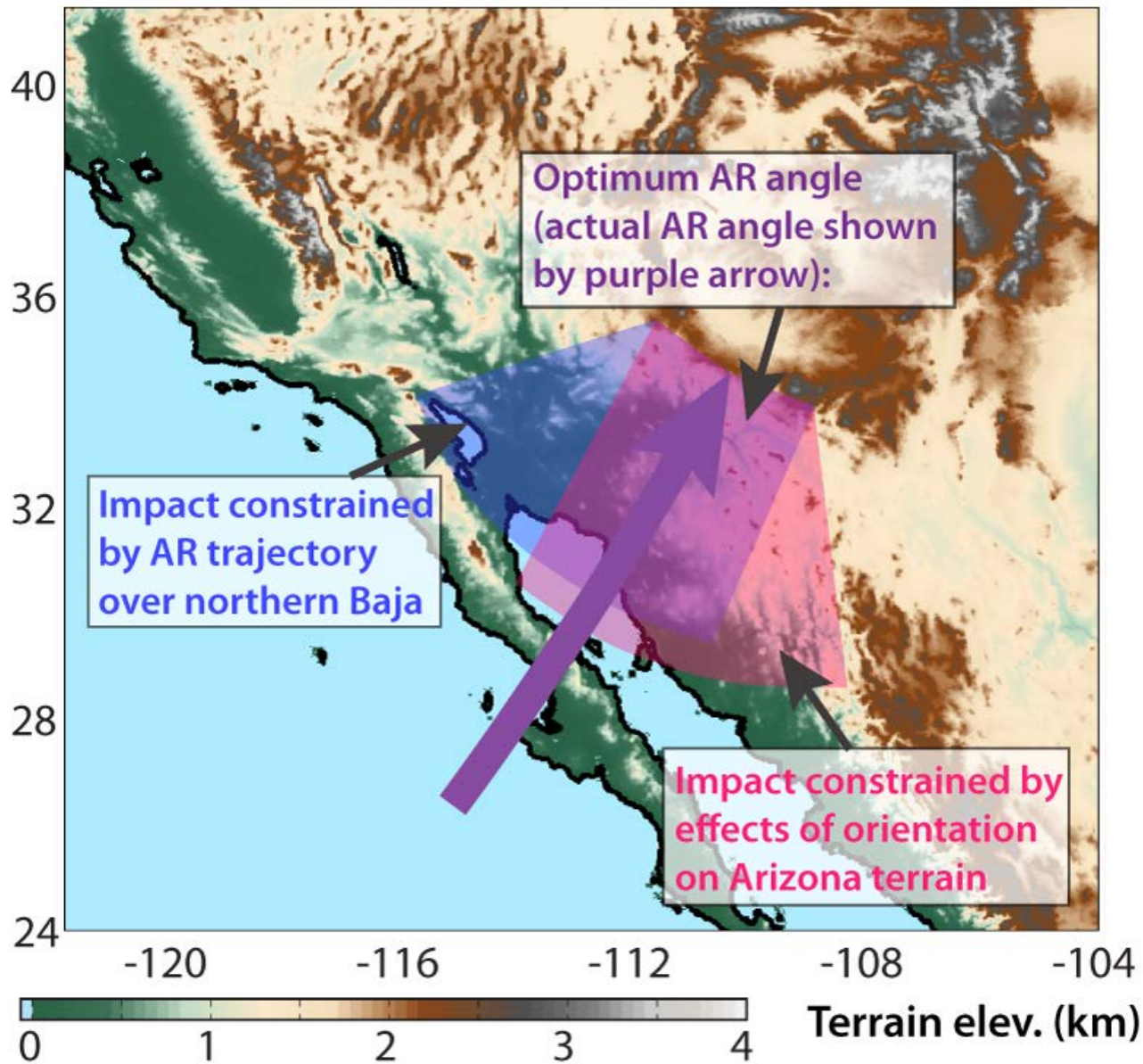


Up to 34% difference region-wide

Up to 200% difference region-wide

Optimum AR ‘angle’ for extreme precipitation

AR = atmospheric river (region of strong water vapor transport/flux)



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

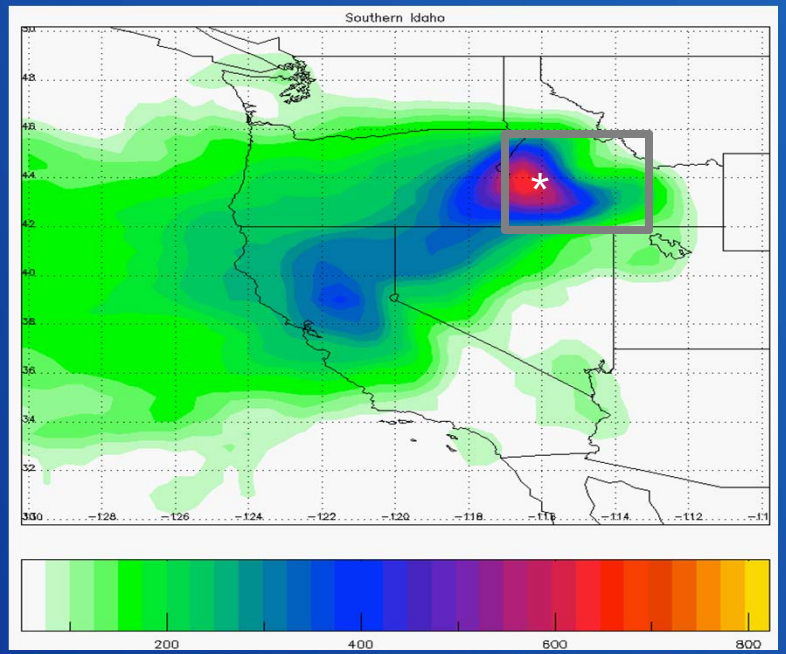
* case study/WRF simulation

Key Lessons Learned

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

Next Steps/Future Work (next talk)

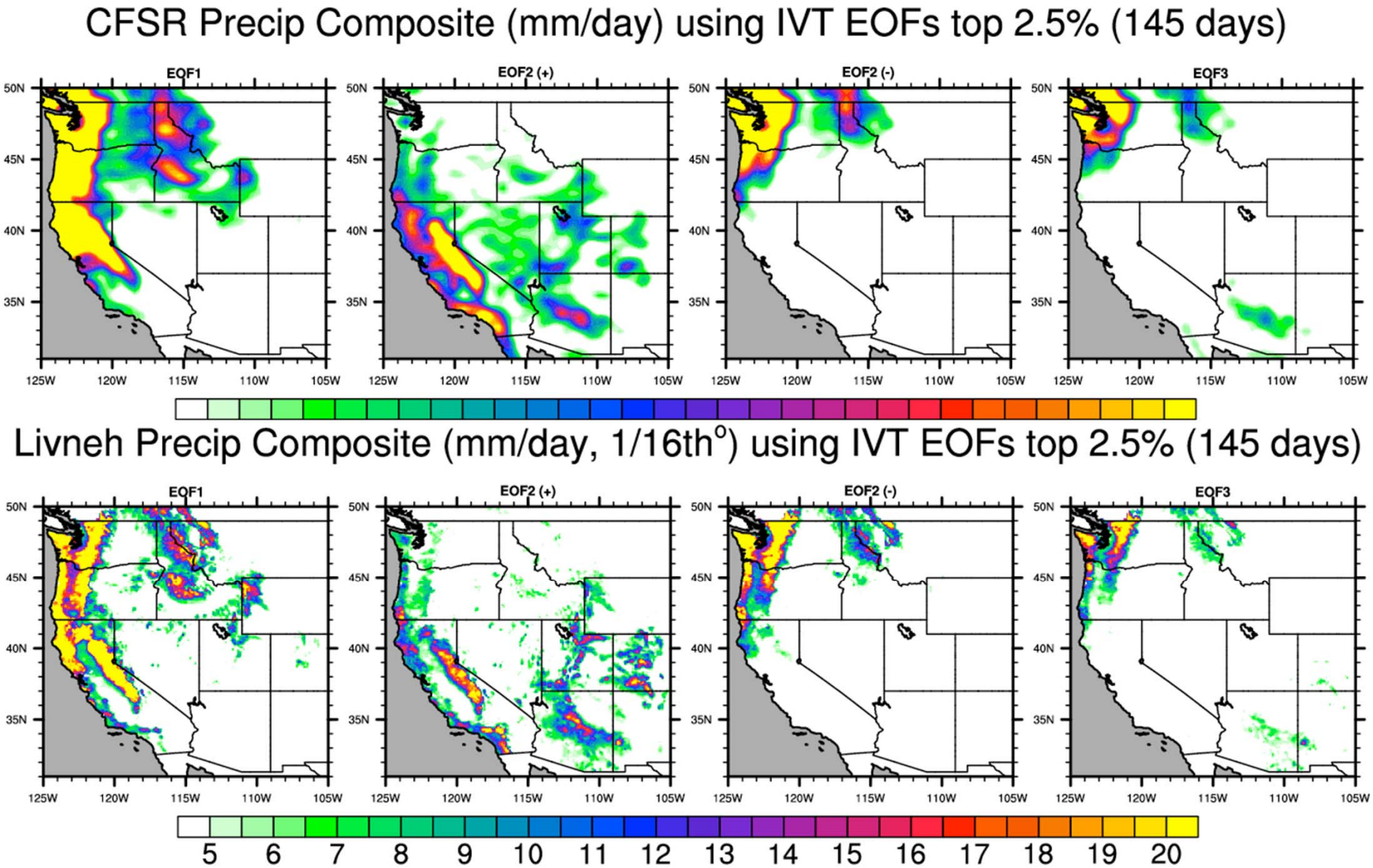
- Transfer to data & methods to Reclamation
- Additional methods for grouping storms
- Generate/analyze ensemble of high-resolution simulations of heavy precip events
- Examine Impact of climate change on ARs



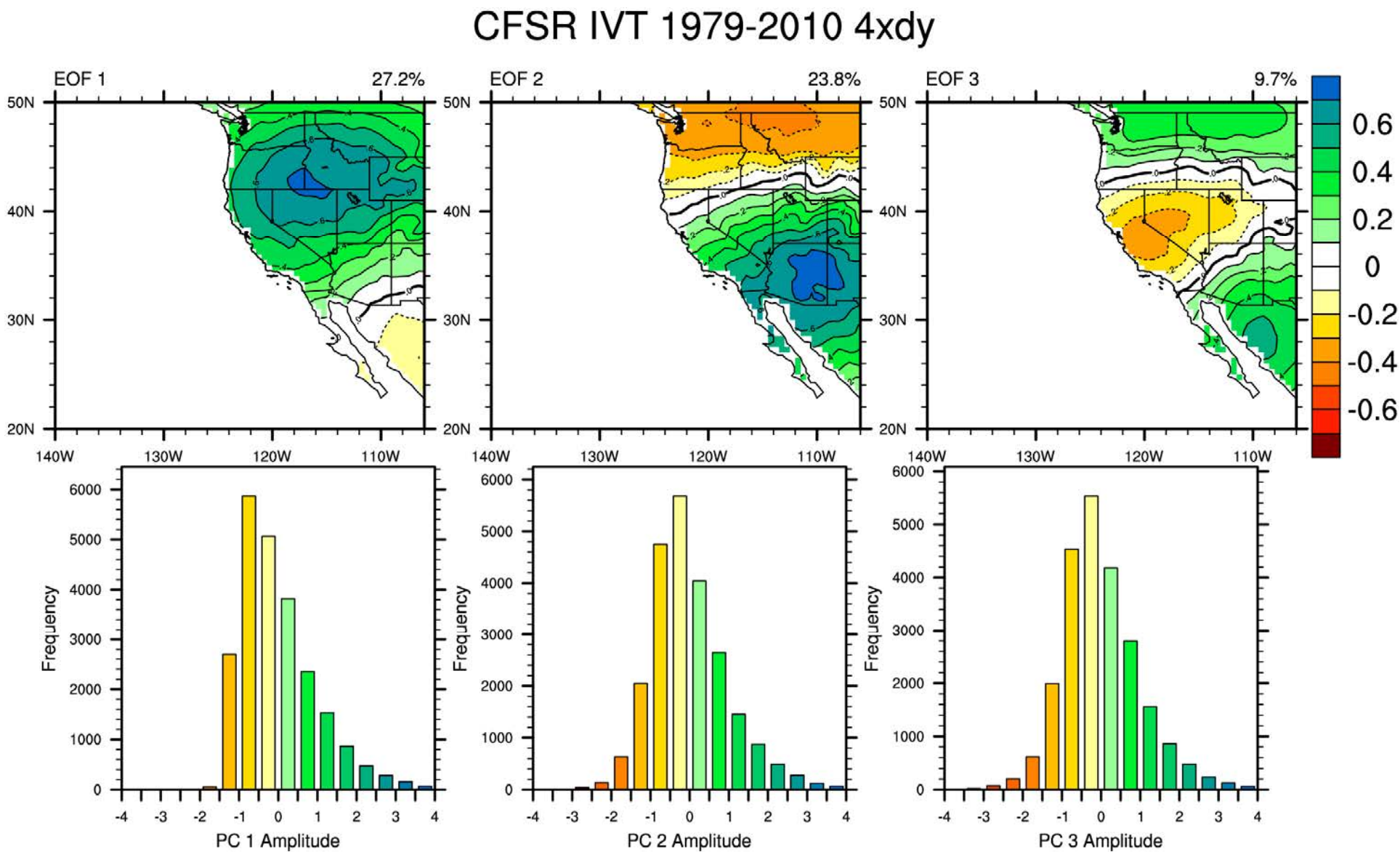
RECLAMATION

Backup slides

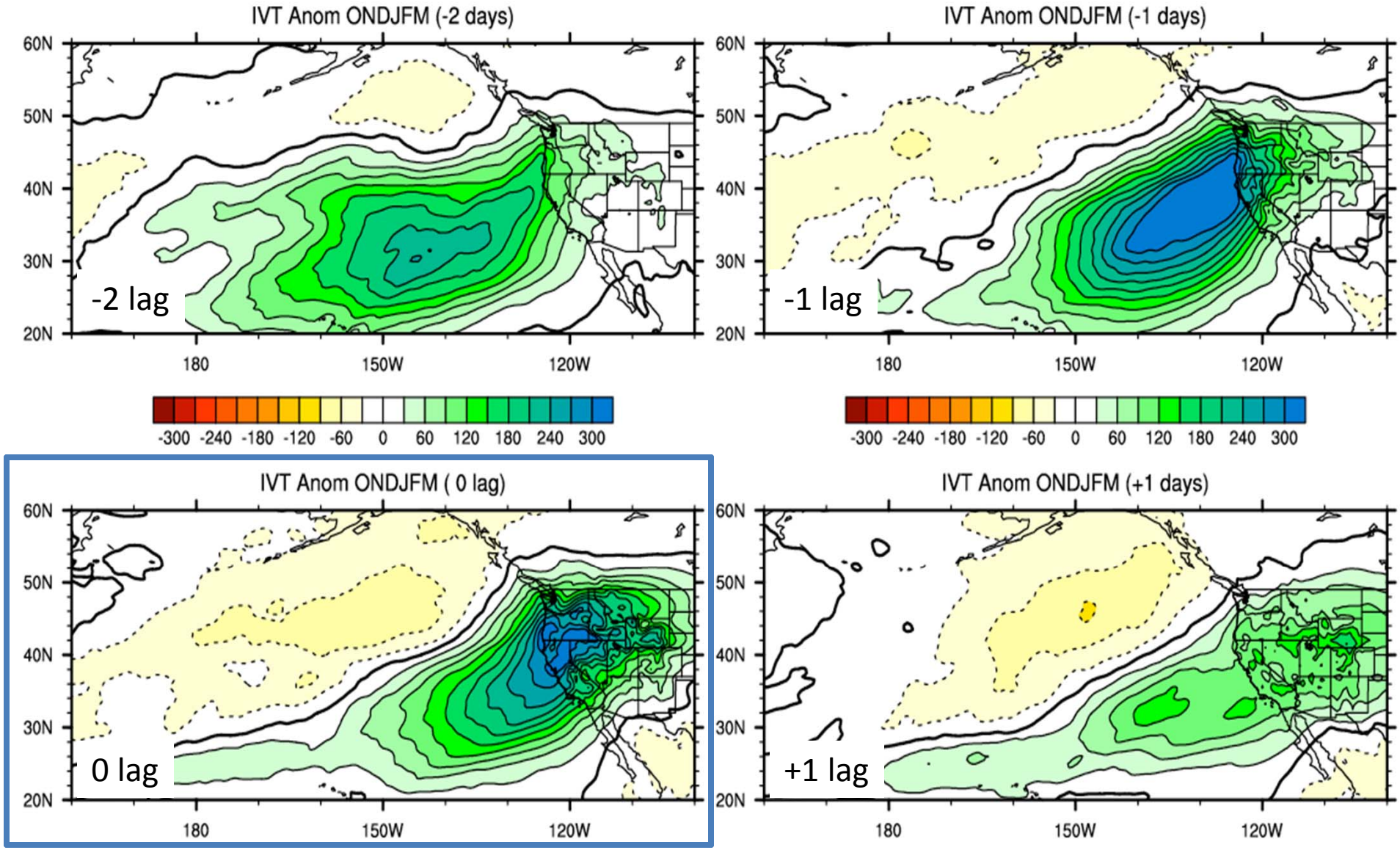
Daily precip that's why 2.5%



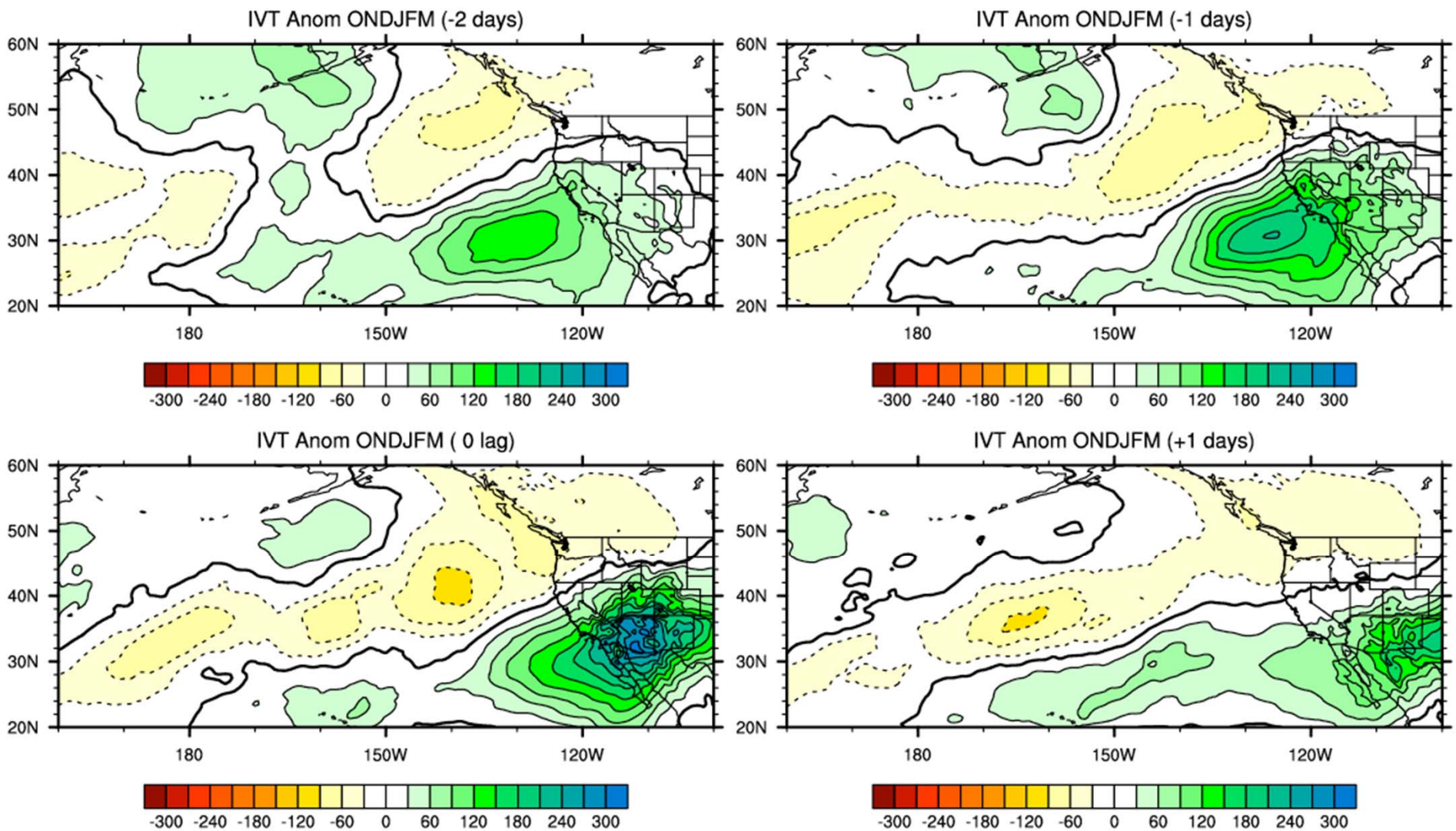
Top: 3 leading IVT EOFs shown as regression on PC
Bot: Histogram of the associated normalized PC values



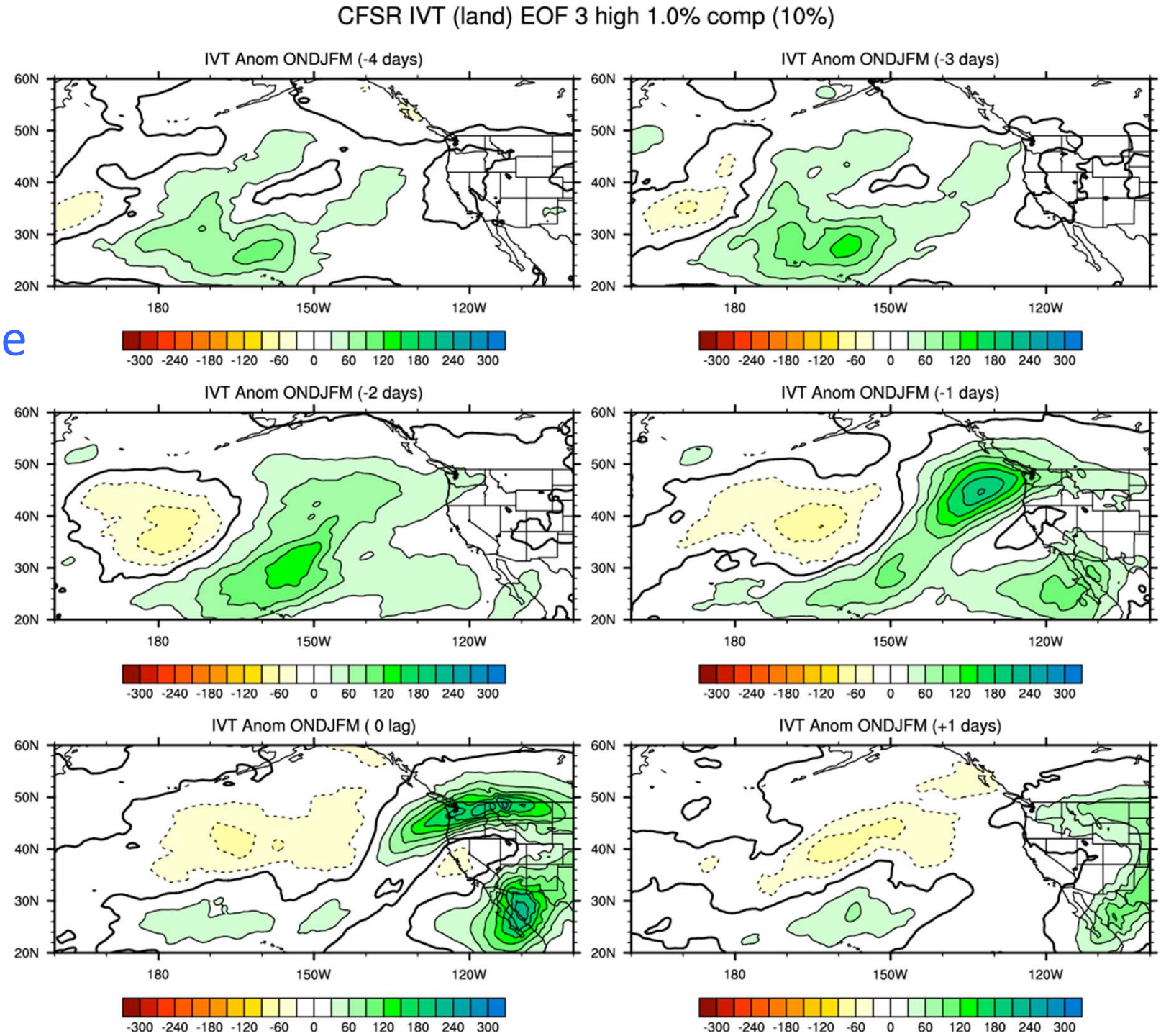
Composite of lead/lag IVT top 1% of PC 1



EOF 2 “high”composite IVT lags -2 to +1 days



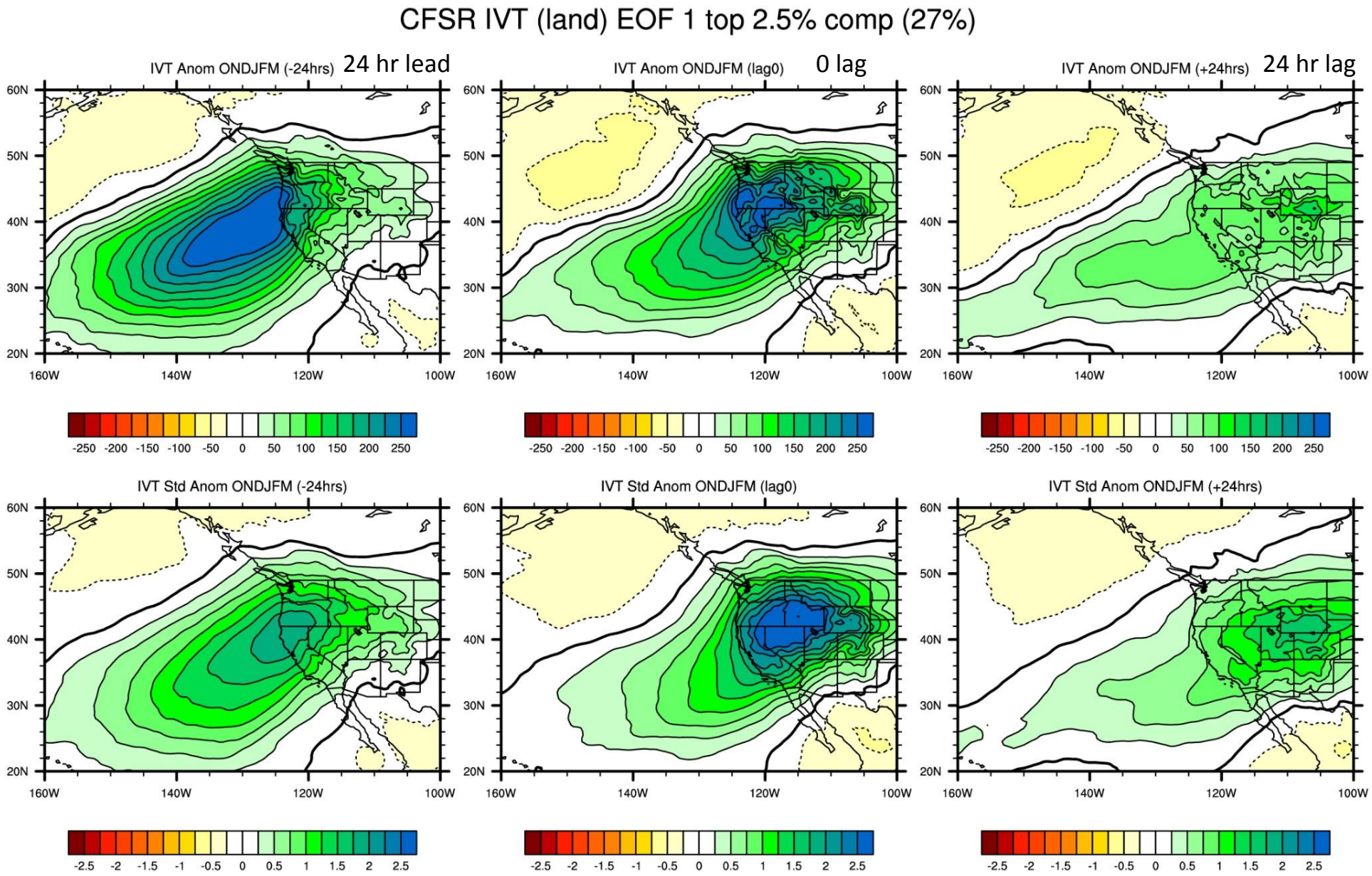
EOF 3 "high" composite IVT lags -4 to +1 days



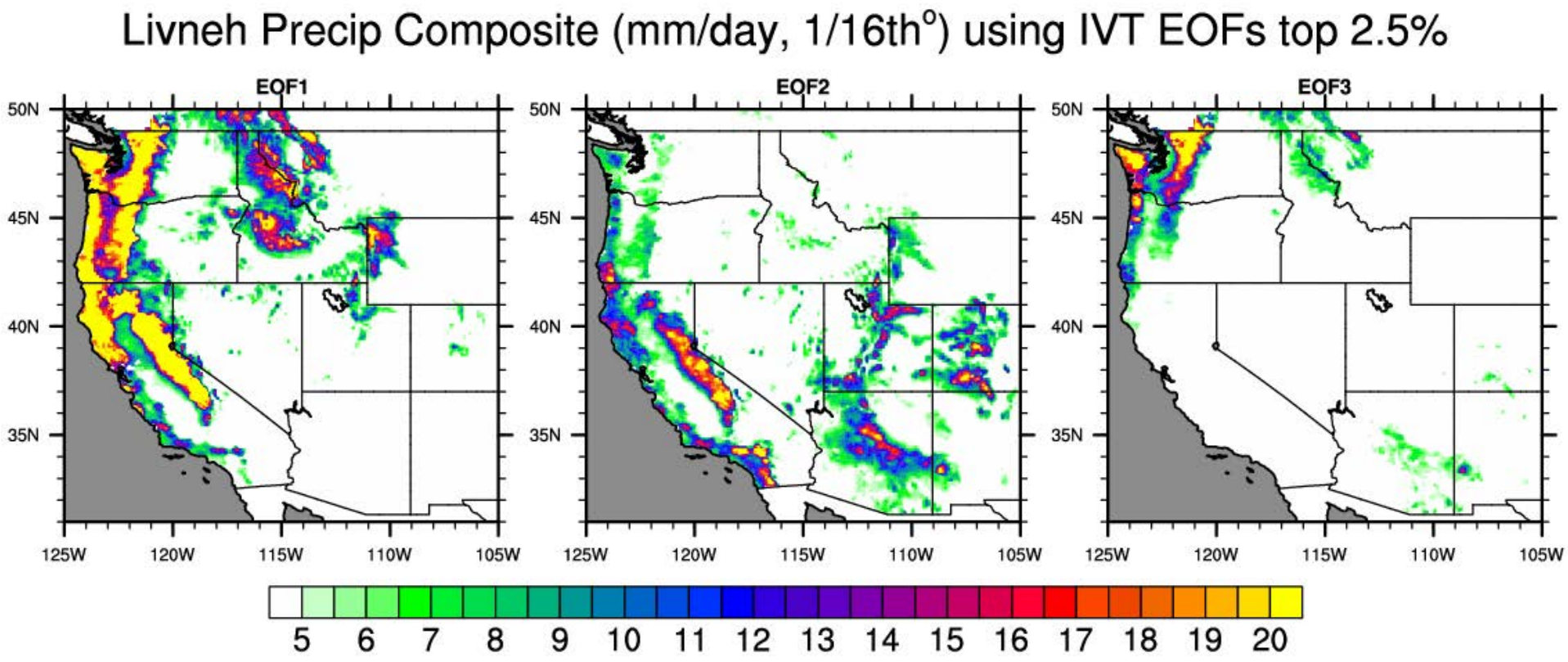
New AR/Trajectory Proposal Tasks

1. Transfer to Reclamation the data, information, methods and documentation we have developed. (all of us)
2. Develop additional methods (other than EOFs) for diagnosing and grouping storms
    1. Cluster analysis (possible to identify regions)
        1. Trajectory Similarity Score (Joe, Dustin?)
    2. SOMS of IVT? (Mimi, Dustin?)
        1. Menounos Poster presentation at AGU
3. Generate/analyze ensemble of high-resolution WRF simulations of 1-2 heavy precip events (likely an AR)
    1. Methodology developed in extremes project (Kelly)
4. Impact of climate change on ARs
    1. Diagnose CMIP5 models (Mike, Jamie)
        1. Eric Salathé (U Washington) gave a talk on this at AGU
    2. WRF simulations, e.g. delta method
        1. Salathé et al. paper submitted: 12 km WRF 1970-2070 ECHAM5 (BCs) => VIC

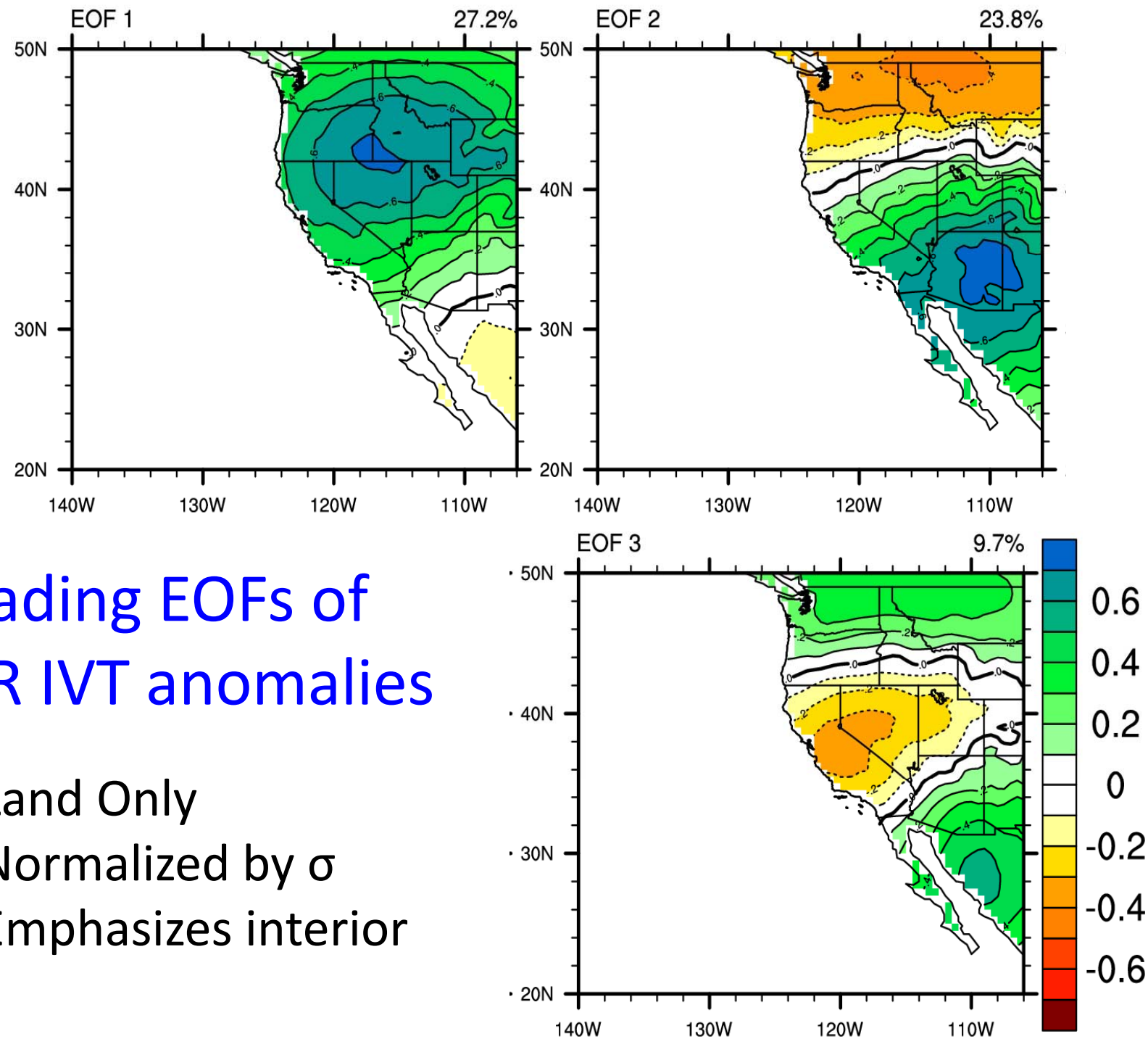
IVT Composites based on top 2.5% (~550) of PC1



Precipitation Composites (Livneh dataset) based on IVT top 2.5% of PC values



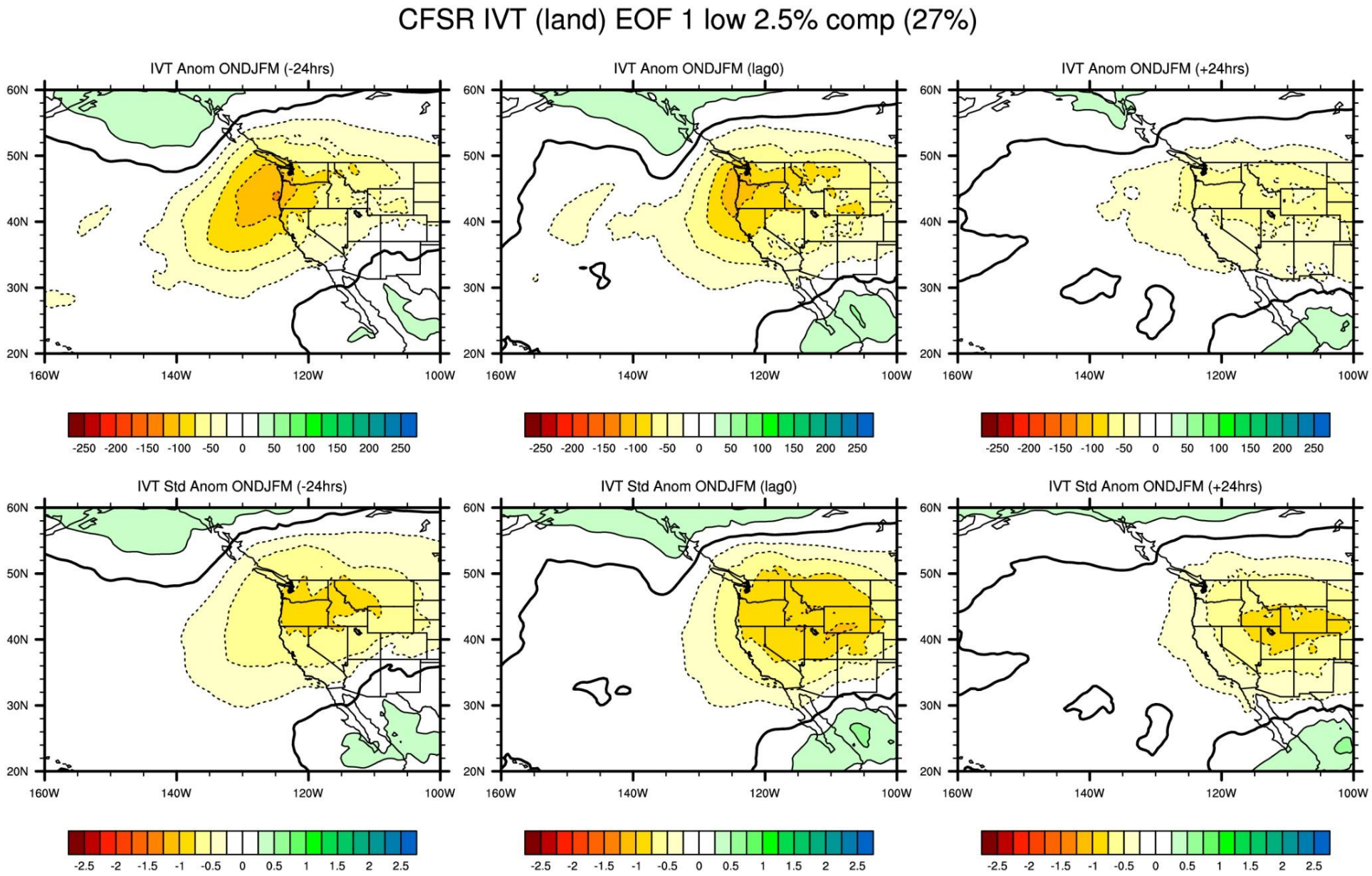
Livneh et al. 2013 (J. Climate in review), update to Mauer 2002 dataset)



3 leading EOFs of CFSR IVT anomalies

- Land Only
- Normalized by σ
  Emphasizes interior

IVT Composites based on lowest 2.5% (~550) of PC1



EOFs of Cold Season CFSR IVT anomalies

- Empirical Orthogonal Functions (EOFs) – used to identify patterns
- Associated time series or principal components (PC) show phase an amplitude of that pattern
- 3 leading EOFs of Integrated water vapor transport (IVT)
- Cold Season: October - March
- Obtained from new NCEP reanalysis (CFSR) 1979-2010
- 6 hourly (4x day) normalized anomalies by standard deviation
- Here, showing EOFs based on land only
  - By normalizing and using land only emphasizes variability in the interior.
  - Can use composites or regressions to show the full fields (including over the ocean)

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

Partnership between CIRES, NOAA, and Reclamation to better understand the processes responsible for heavy precipitation events, including atmospheric rivers, in the intermountain west for use in dam safety and flood hydrology assessments.

Background & Motivation

- Atmospheric rivers (ARs) are long, narrow corridors of enhanced water vapor transport located near the leading edge of many oceanic cold fronts.

- ARs contribute significantly to the annual precipitation and snowpack in the West Coast States via orographic processes.

- Less certain are the hydrometeorological impacts of ARs as they migrate inland into the Intermountain West.

- A recent modeling study by Leung and Qian (2009) and an observational compositing study by Rutz and Steenburgh (2012) show the potential importance of landfalling ARs in the interior.

- The research presented here provides the first detailed case study to test the hypothesis that an AR and its impacts can penetrate inland from the Pacific Ocean.

Concluding Remarks

- An atmospheric river (AR) with strong dynamics and water vapor fluxes penetrated inland and severely impacted Arizona on 21 – 22 January 2010.

- The AR's water vapor transport plume intensified via extratropical dynamical processes rather than by entrainment of tropical water vapor over the eastern North Pacific.

- The AR was oriented orthogonal to Arizona's Mogollon Rim escarpment and, combined with weak stratification, resulted in strong orographic forcing and heavy precipitation there… similar to that observed with ARs along the U.S. West Coast.

- Heavy precip. fell during warm conditions and high melting levels, resulting in widespread flooding because catchment basins on the Mogollon received mostly rain instead of snow … similar to that observed with ARs along the U.S. West Coast.

- The follow-on study presented by Mimi Hughes uses high-resolution WRF simulations to explore case-specific AR water vapor pathways from the Pacific to Arizona and how the terrain upstream of Arizona modulated these pathways.