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

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NOAA/ESRL/PSD and U. of Colorado/CIRES

Annual Progress Meeting on Reclamation Climate and Hydrology Research. October 3, 2012

Motivation

- 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?

Wenden Arizona, Jan 24, 2010

Project Purpose

Develop a better understanding extreme precipitation events in the intermountain west:

(1) What are the preferred pathways for moisture to reach the inter-mountain west?

(2) What atmospheric processes including atmospheric rivers, influence extreme precipitation events?

(3) How well do high-resolution models simulate heavy precipitation events? How can model diagnostics and sensitivity experiments be used to better understand of the processes that result in intense precipitation?

(4) How are the pathways/extreme events influenced by climate factors such as ENSO and the MJO?

(5) How can the results best be used to address water resource management and dam safety issues?

Project Tasks

- Obtain precipitation data and other relevant meteorological variables to identify extreme events
- Perform In-depth case studies of known extreme events and events occurring in specific USBR locations of interest
- Diagnose processes contributing to extreme precipitation events using back trajectories and weather diagnostics based on recent reanalysis data sets.
- Perform high-resolution simulations and sensitivity studies
- Create climatology and investigate interannual variability (Yr 2)

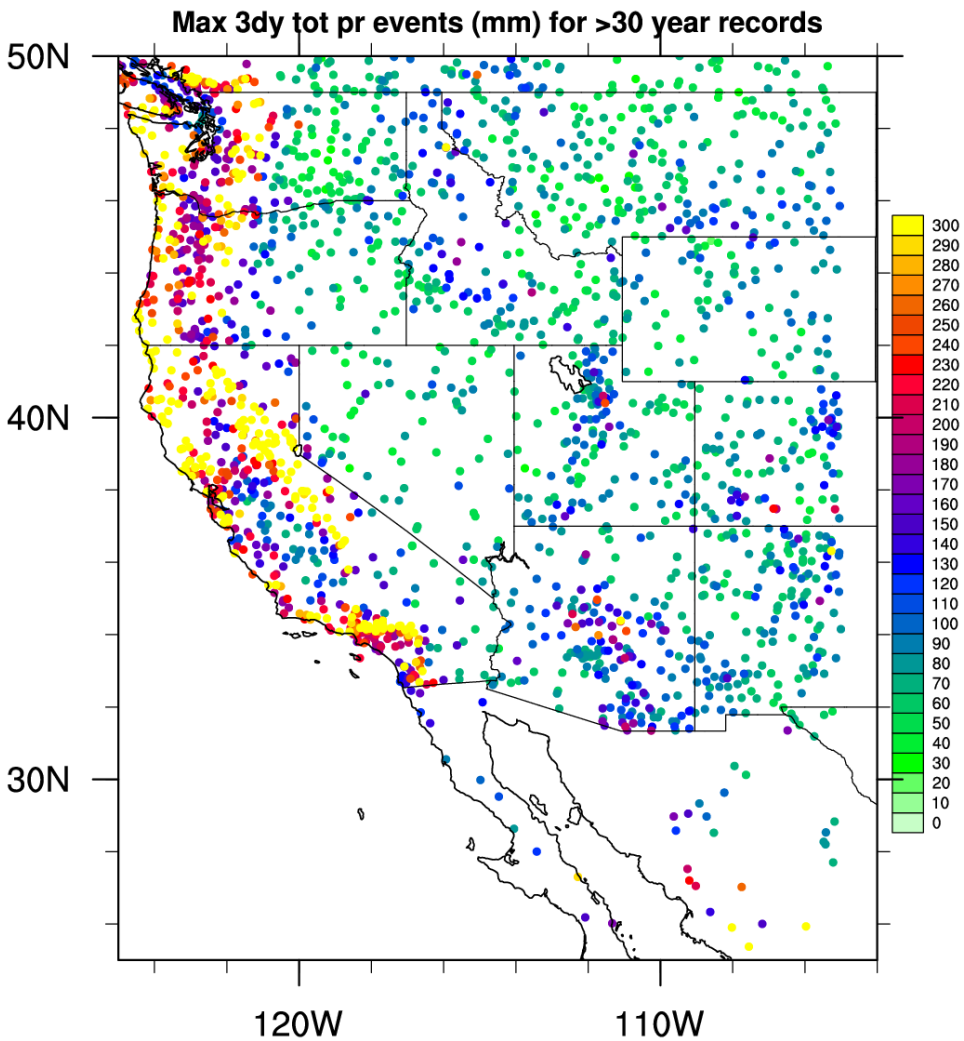
Integrated approach: Choose cases and regions for more intensive study where Reclamation has a management interest **and** where the exposure to extreme precipitation events is high

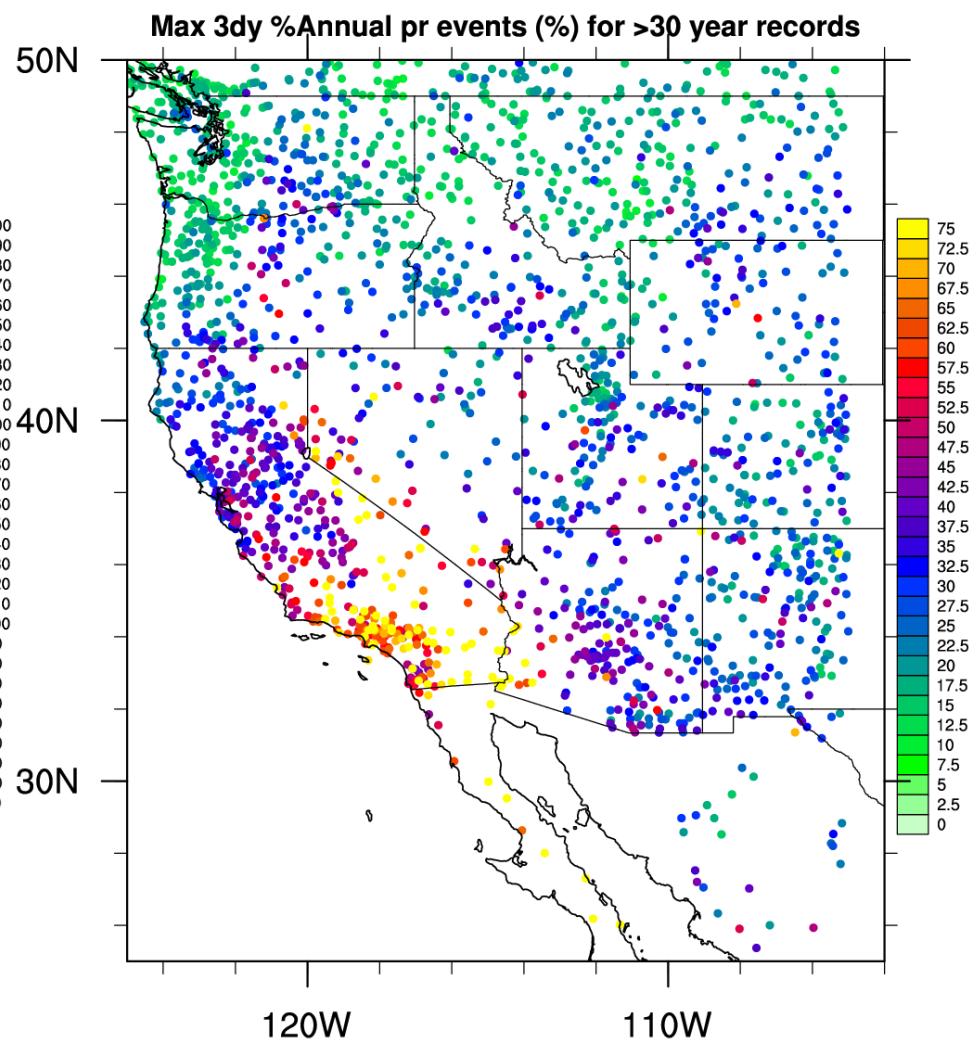
Intermountain West US Cold Season Extreme Precipitation Events

- Identify events using using Global Daily Climatology Precipitation Network
- Augment with Snowtel data (case studies)
- North American Regional Reanalysis and Climate Forecast System Reanalysis (CFSR)
- Back Trajectories from Hysplit trajectory code

Maximum 3-day precipitation (Oct-Apr)

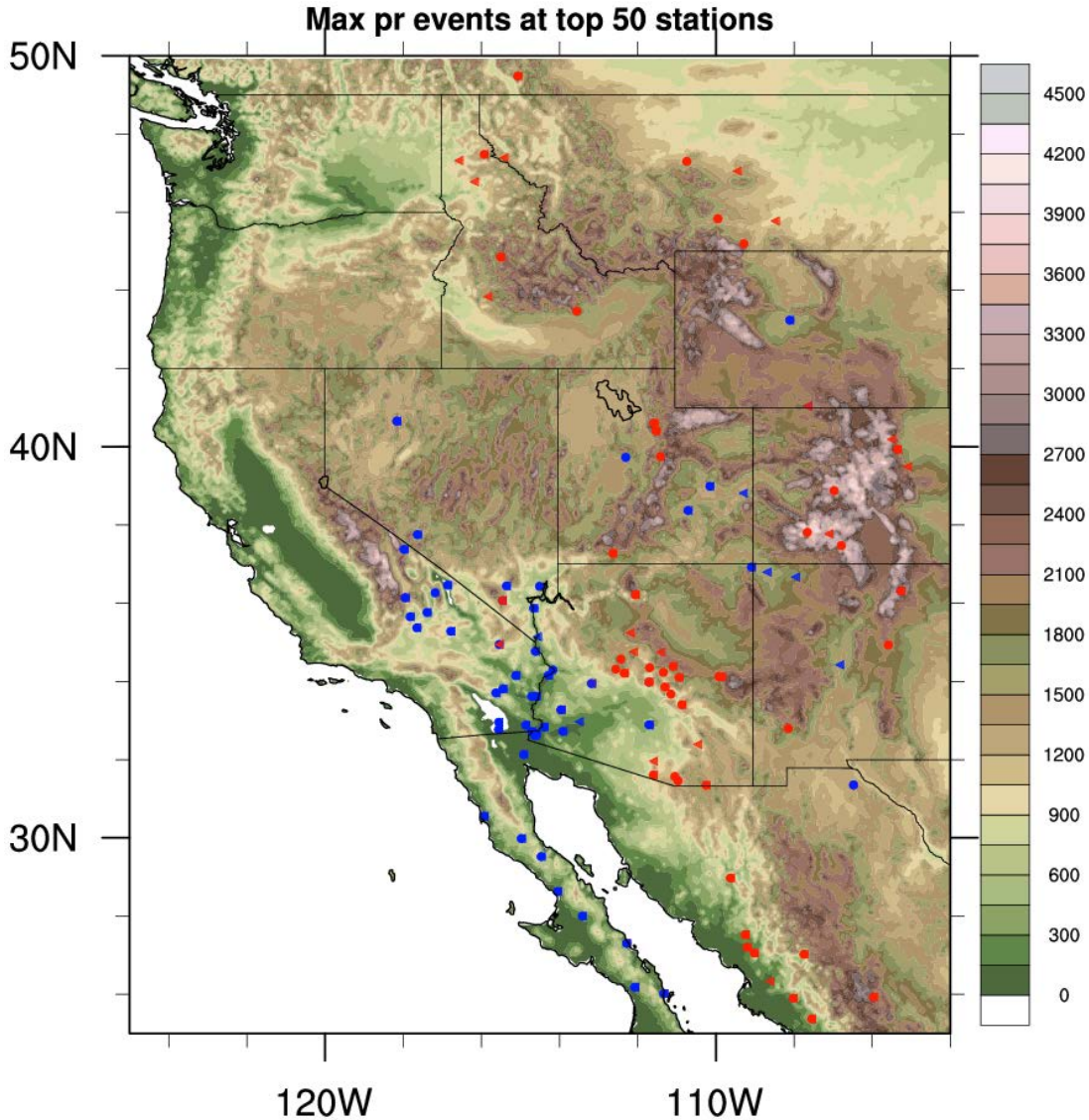
all stations with at least a 30-year record (and 80% report rate). 1832-2011 (2167 stations)
The size of the event is shown in mm (on left) and in % of Annual mean (on right)





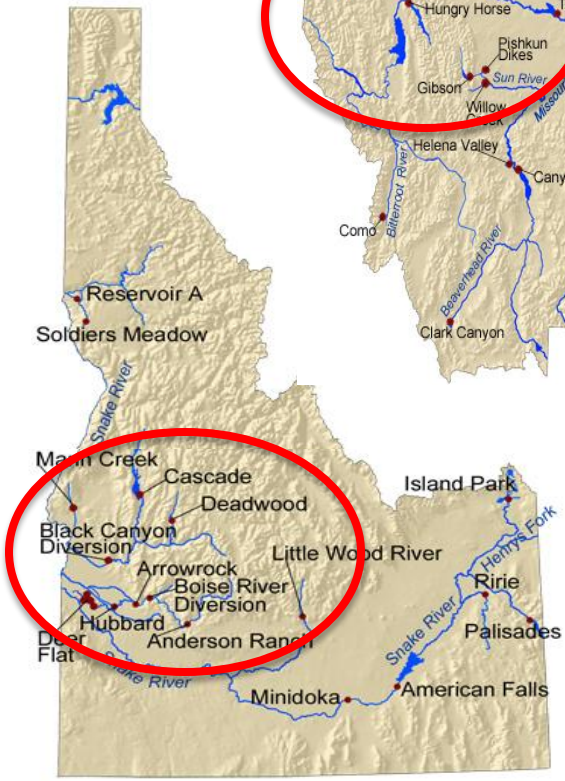
Max Precip events at each station are sorted 4 ways. 1-day and 3-day events, total precip and fraction of annual precip. Red events are total precip and blue events are based on % annual precip. Triangles are 1-day events and circles are 3-day. Top 50 events shown for each method. West Coast stations excluded to focus on intermountain region.

- 1 day TOT
- 1 day %ANN
- 3 day TOT
- 3 day %ANN



USBR Dam locations in West US

Arizona



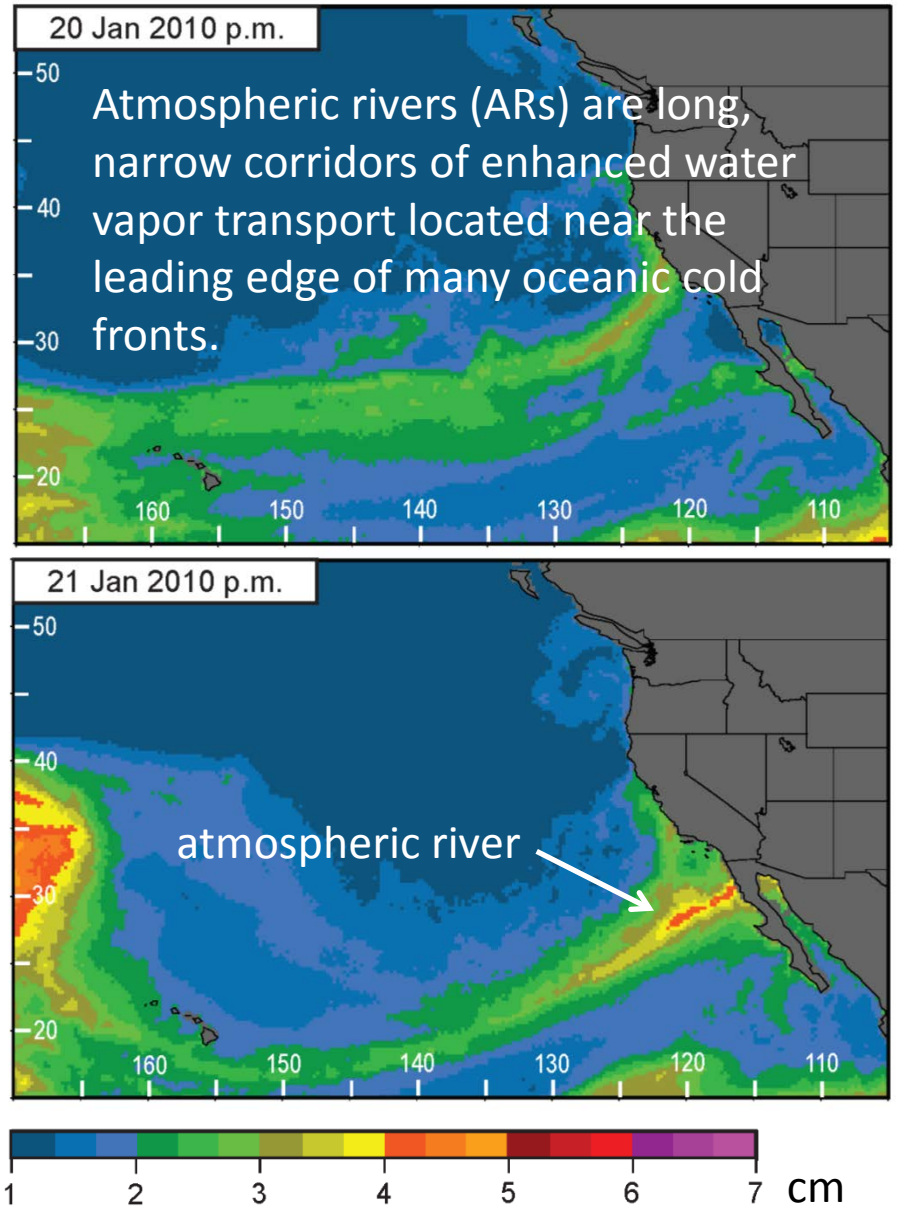
Idaho

Montana

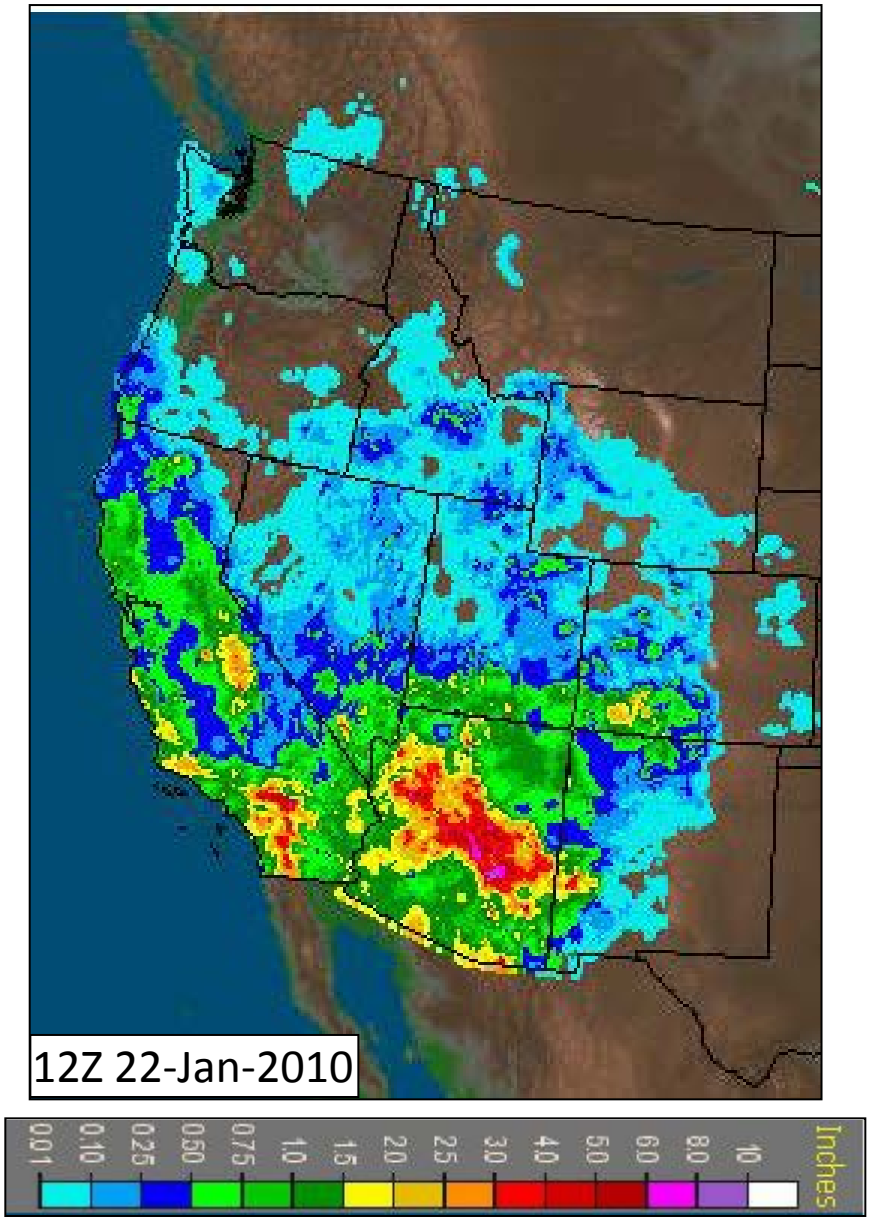
Case Study I – Central Arizona Jan 2010

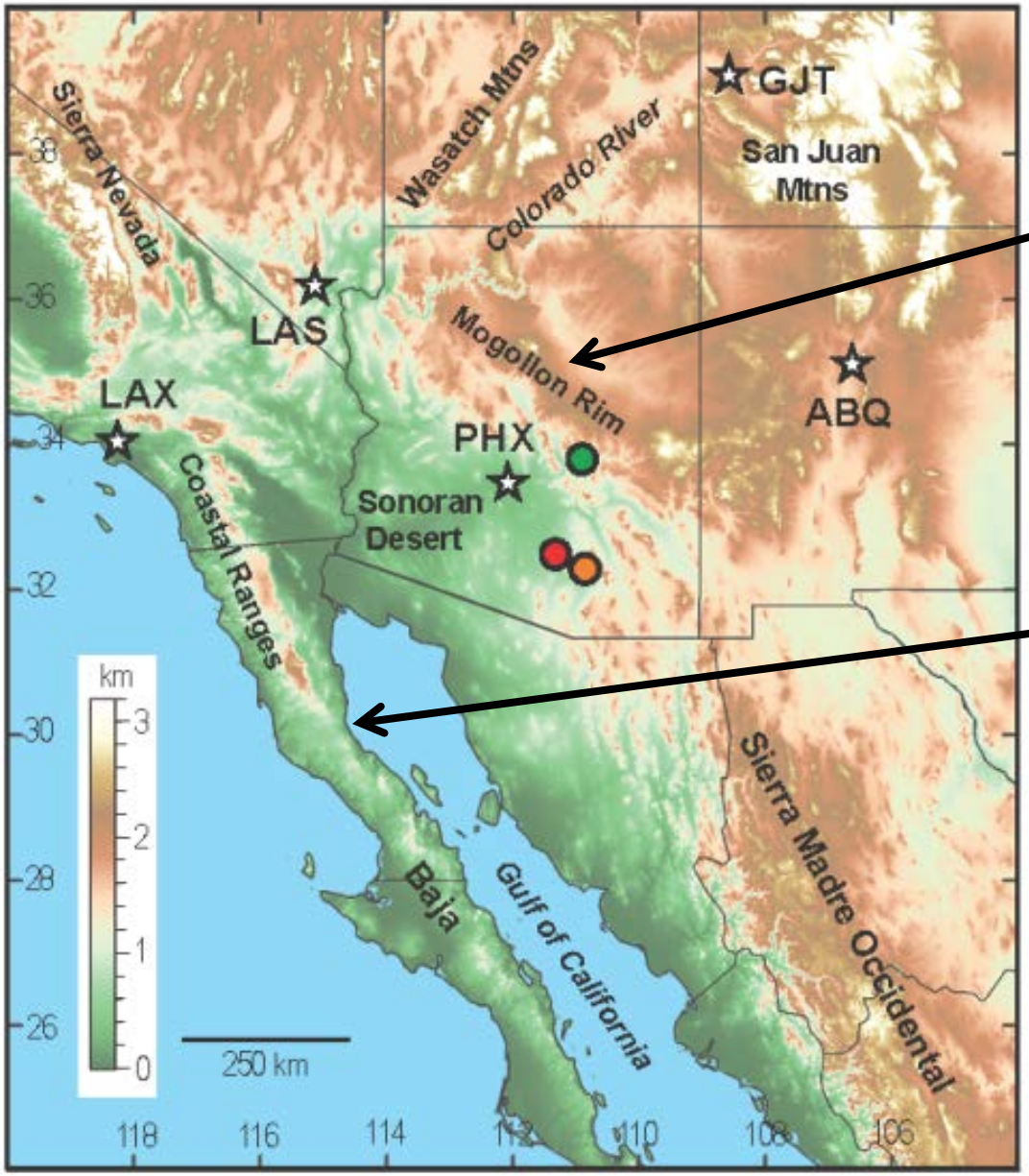
- Detailed case study to test the hypothesis that an AR can penetrate inland from the Pacific Ocean.
  - “The Landfall and Inland Penetration of a Flood-Producing Atmospheric River in Arizona. Part 1: Observed Synoptic-Scale, Orographic, and Hydrometeorological Characteristics" by Paul J. Neiman; F. Martin Ralph; Benjamin J. Moore; Mimi Hughes; Kelly M. Mahoney; Jason M. Cordeira; Michael D. Dettinger. Submitted to J. Hydrometeorology.

SSM/I IWV satellite imagery 20-21 Jan. 2010 depicts a strengthening AR making landfall



24-h precip ending 12Z 22 Jan. 2010: Advanced Hydrological Prediction Services

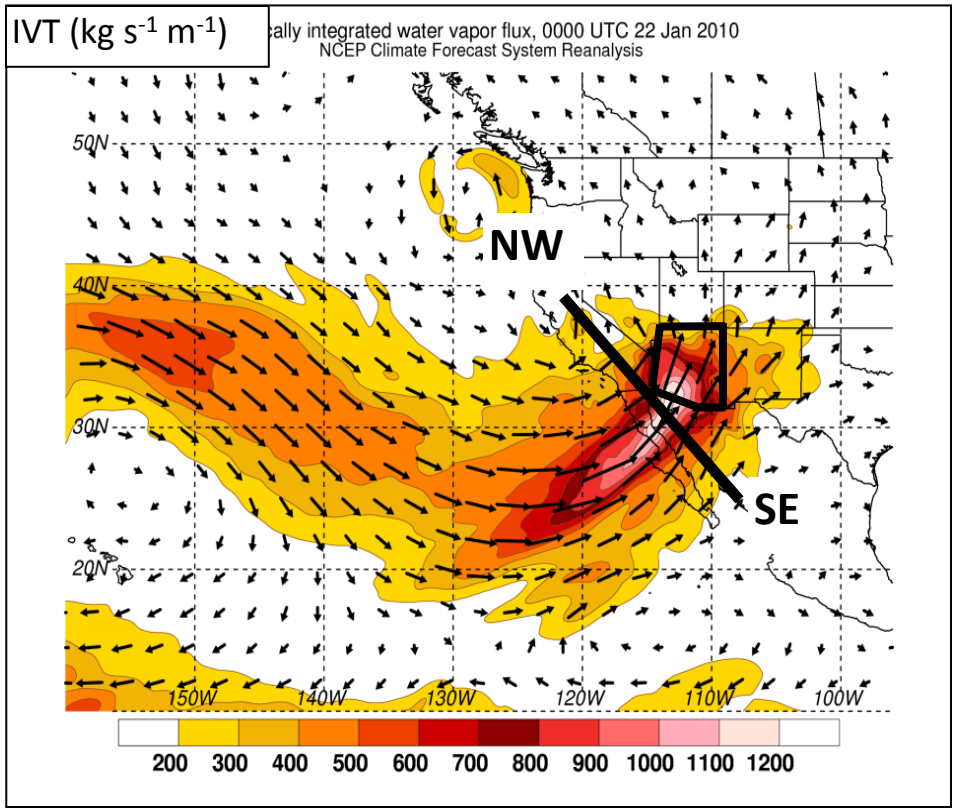


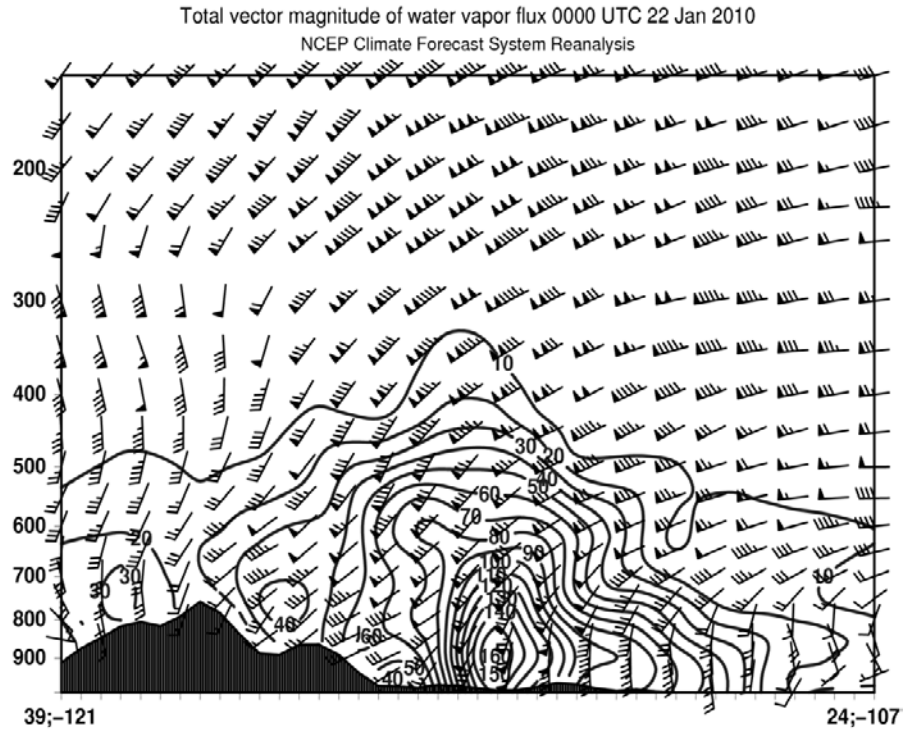


Note the NW-SE orientation of the Mogollon Rim: Orthogonal to the incoming AR

Note gaps in mountains

NCEP's CFSR: 0000 UTC 22 January 2010

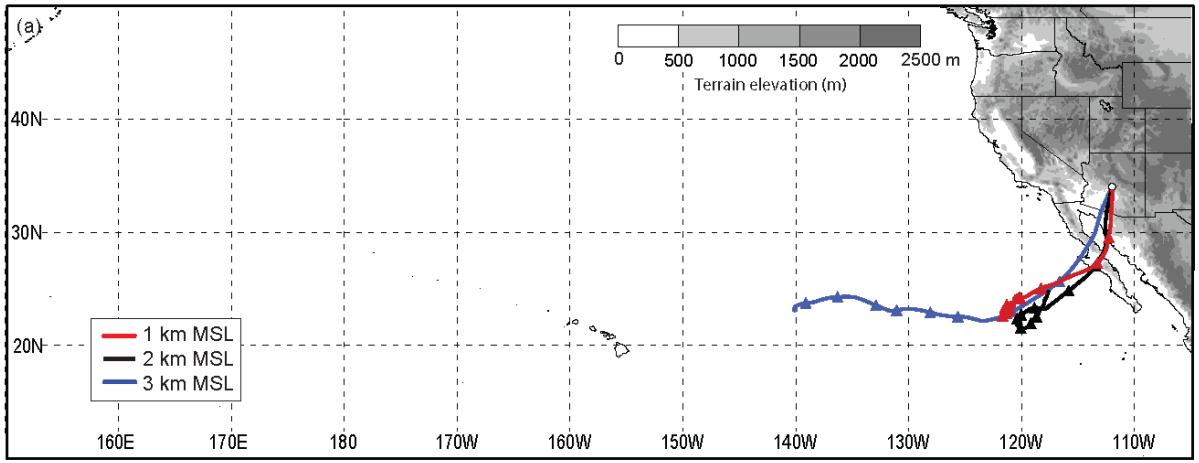


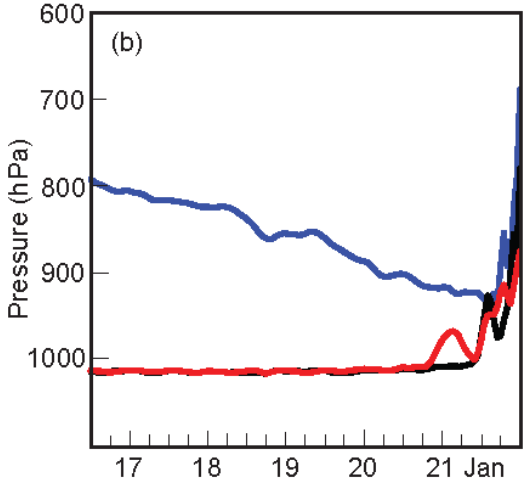


NW Water vapor flux (kg s^{-1} m^{-1}) **SE**

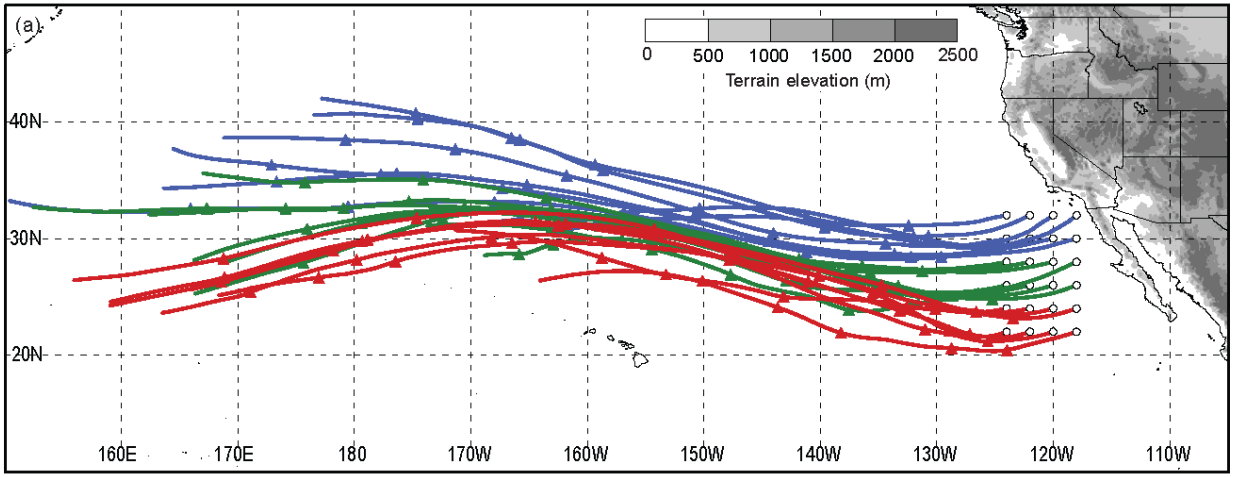
Back Trajectories using Hysplit

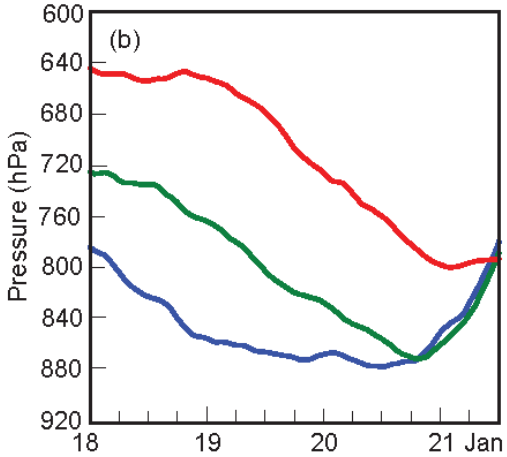
trajectories (132 hr) ending at 2 km MSL at 00Z 22 January 2010



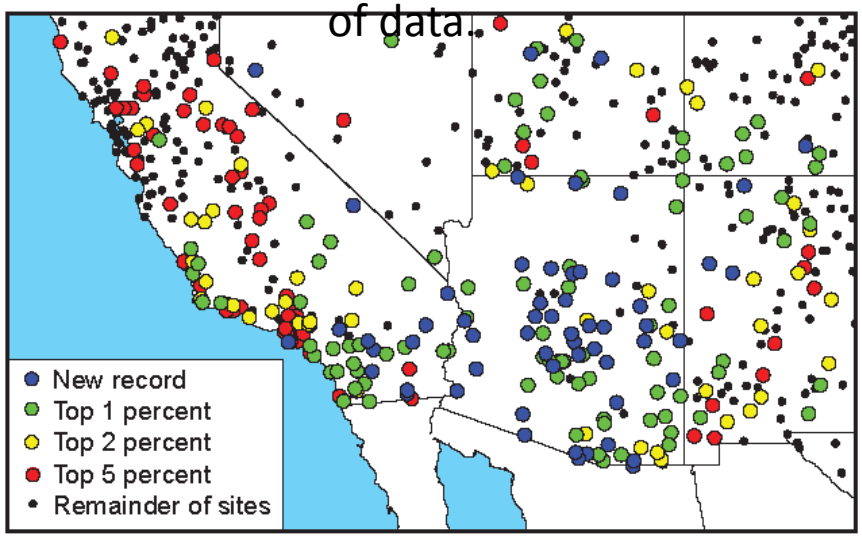


trajectories (84 h) ending at 2 km MSL at 12Z 21 January 2010

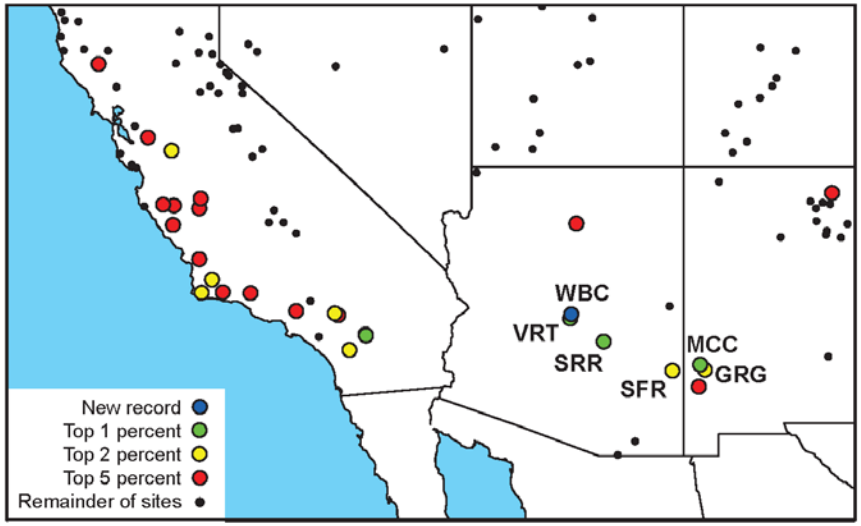




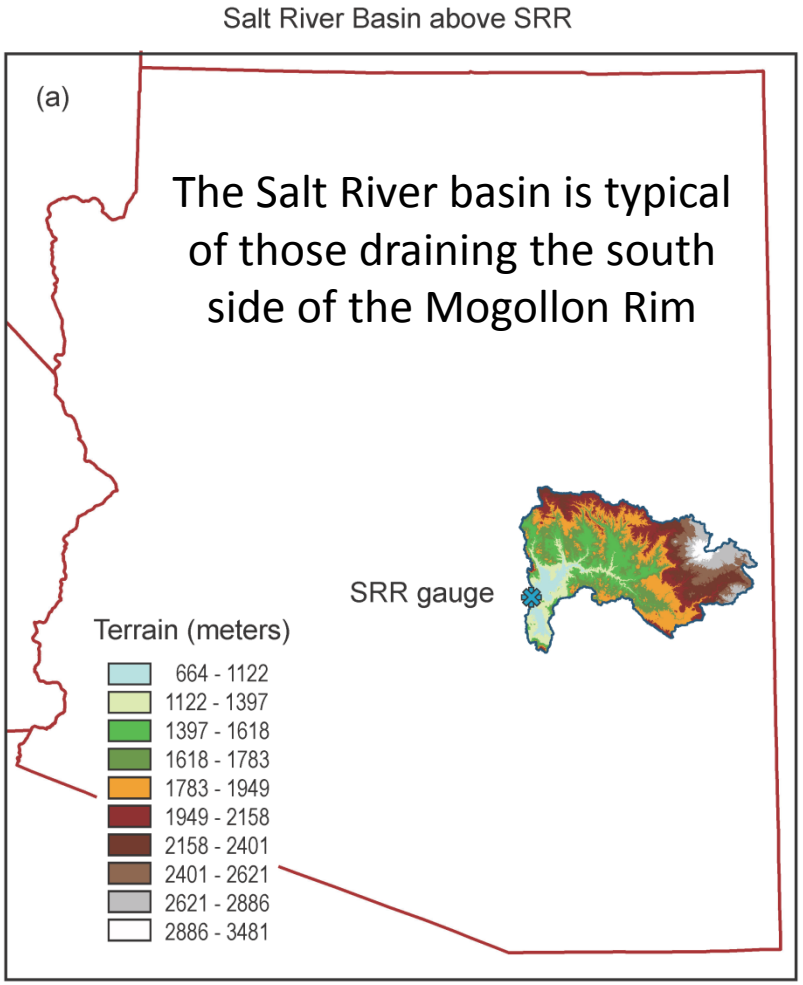
COOP precipitation on 21-22 Jan. 2010: Rank relative to all January pairs (2-day average) of days between 1950-2009 for gauges with >25 Januarys of data.

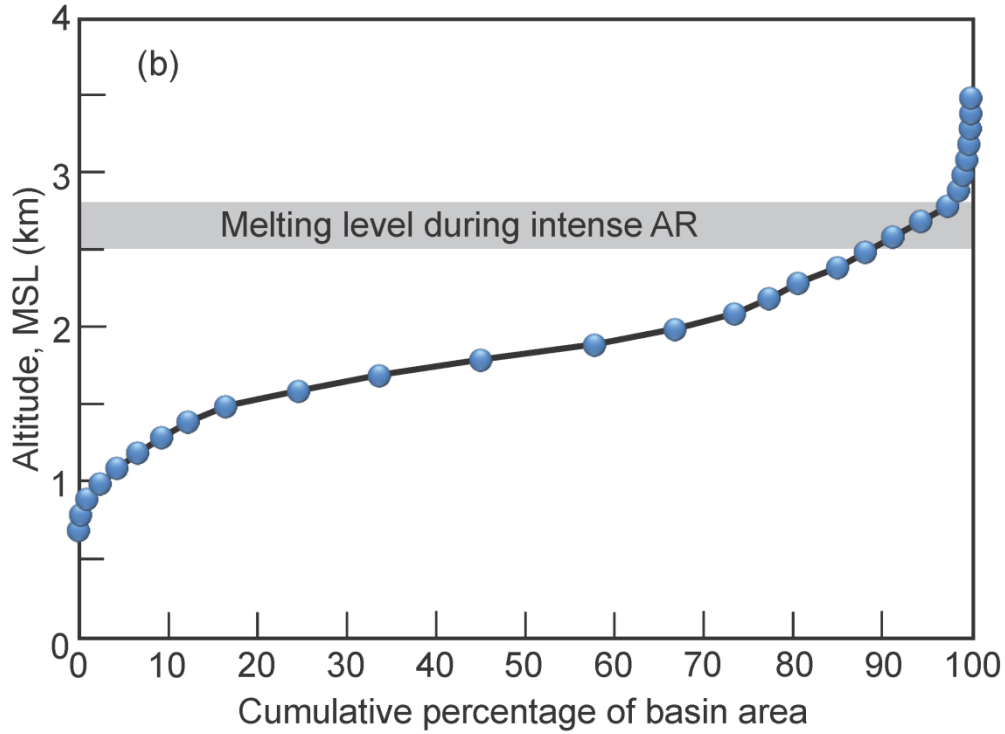


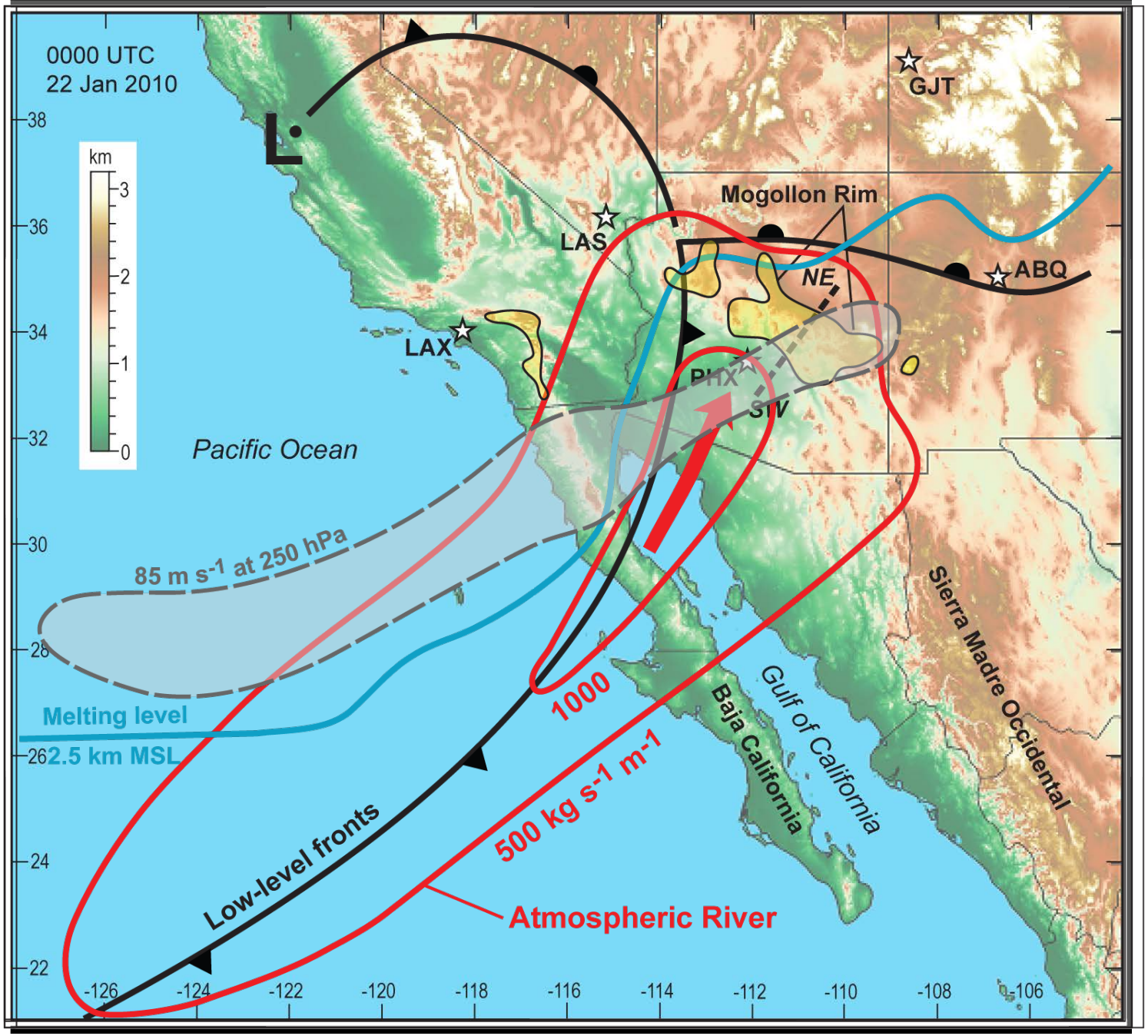
USGS streamflow on 21-22 Jan. 2010 for unregulated channels: Rank relative to all January pairs of days between 1901-2009 for gauges with >25 Januarys of data.



Catchment basin characteristics, local meteorology, and implications for flooding







Summary
Central Arizona
Jan 2010 Case

Neiman et al. 2012, J. Hydrometerology

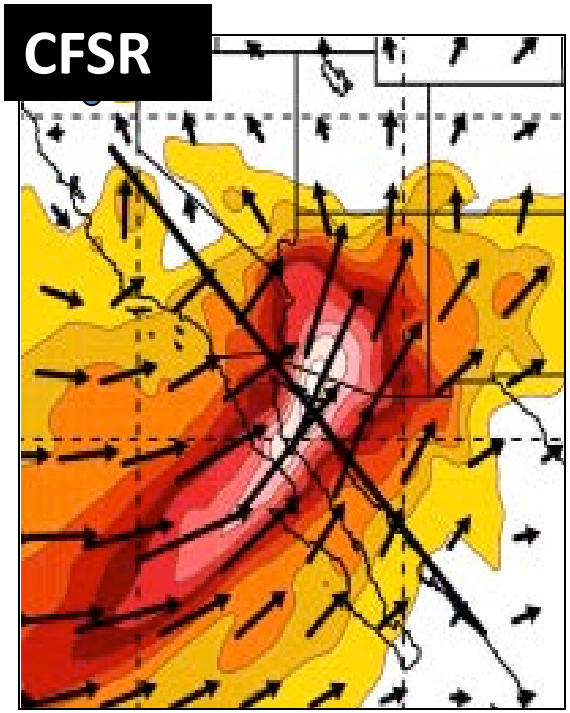
Model Simulations of Arizona Storm

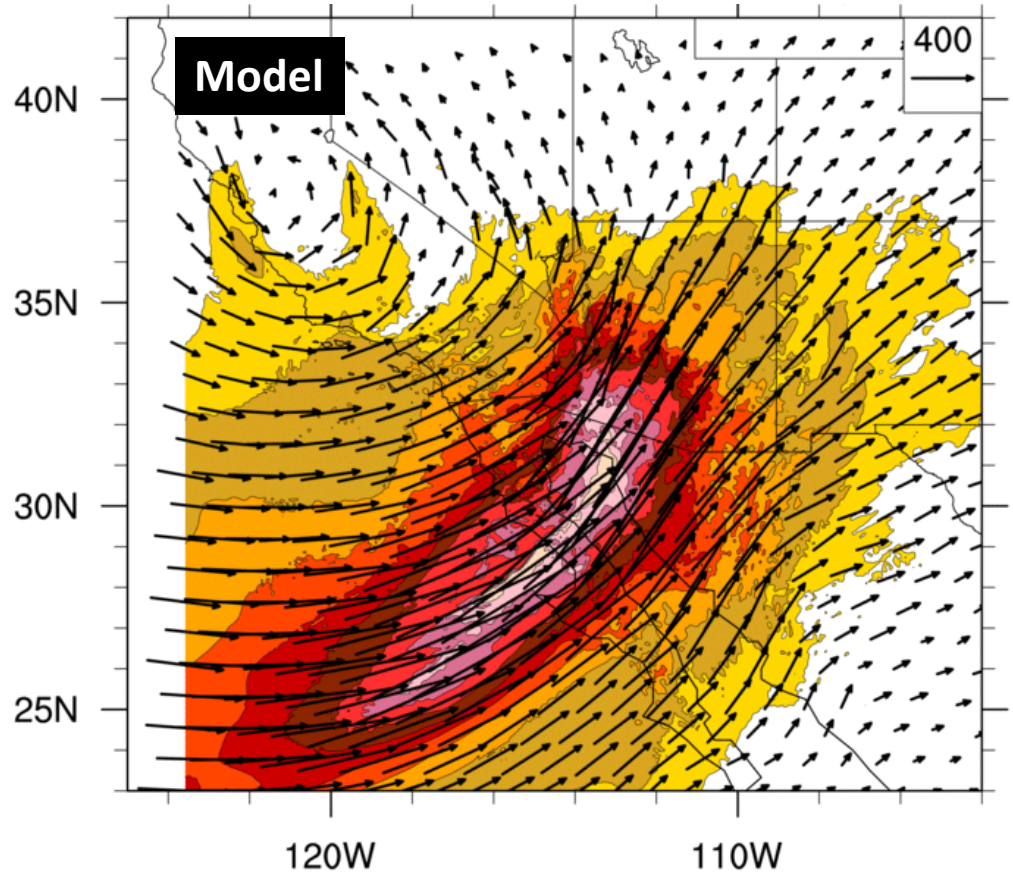
- Weather Research and Forecast Model (WRF)
  - Initialized with CFSR
  - Run for 48 hours
- How well does the model match nature
- Sensitivity to resolution
- Role of modeling small-scale vertical motion
  - w/wo convective parameterization
- Role of topography

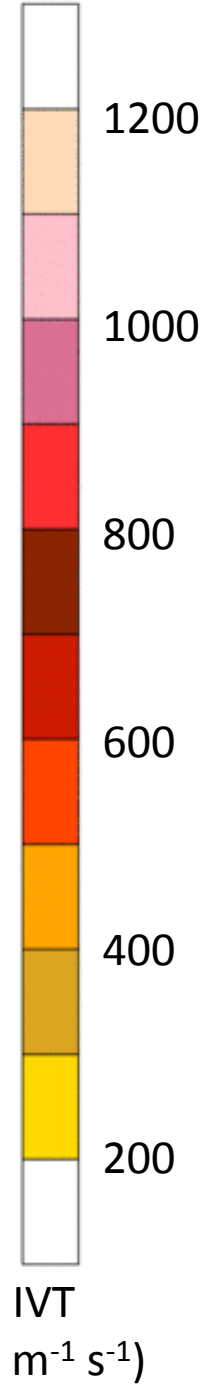
Hughes M: Presented at the AMS Mountain Meteorology Conference, Steamboat Springs, CO August 2012

Observed (CFSR) & Simulated "Control" (3km) Integrated Water Vapor Transport (IVT)

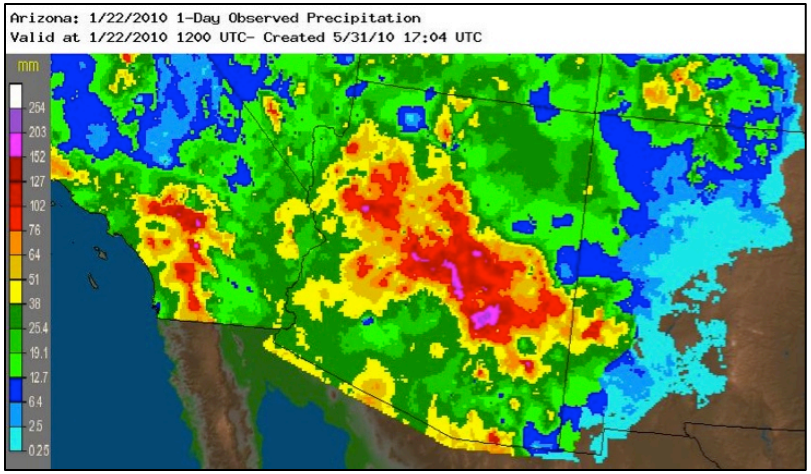
3 km domain IVT, 1/22/2010, 0Z



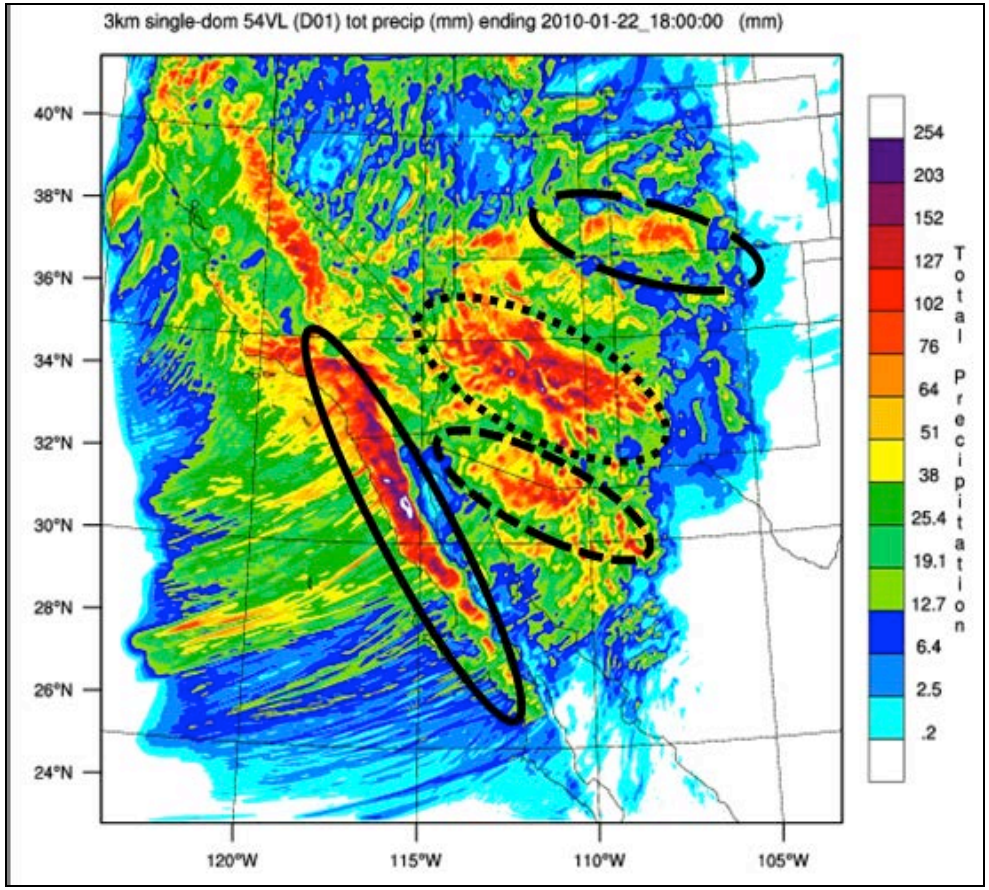




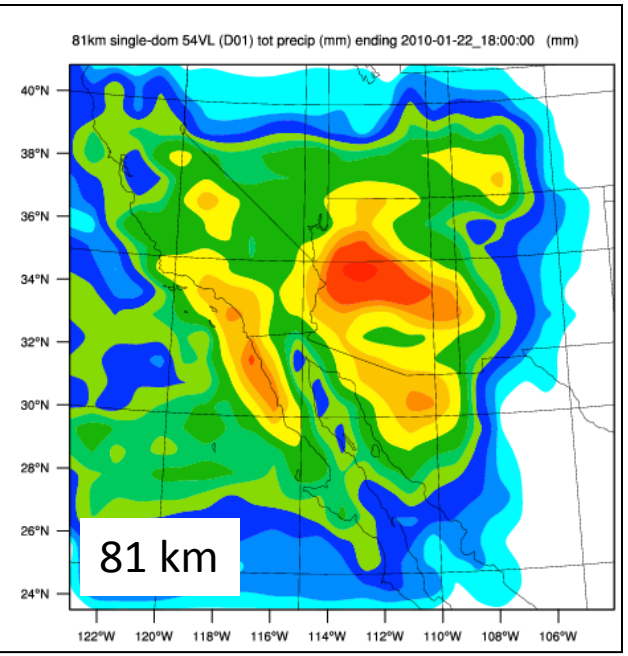
Observed and Simulated Precipitation

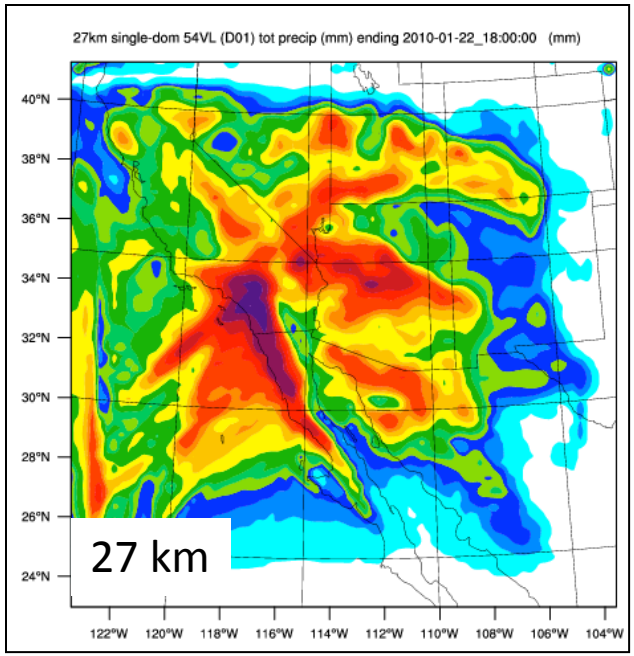


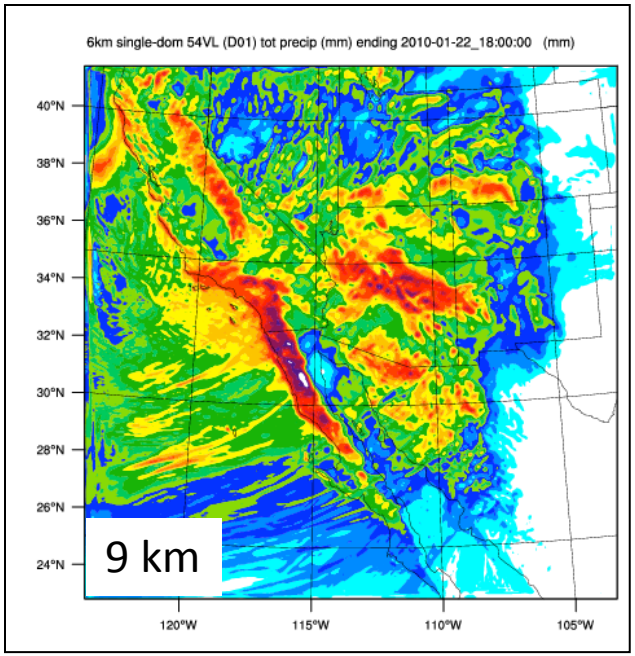
NMQ Stage IV QPE
24-hour ending Jan 22 12Z

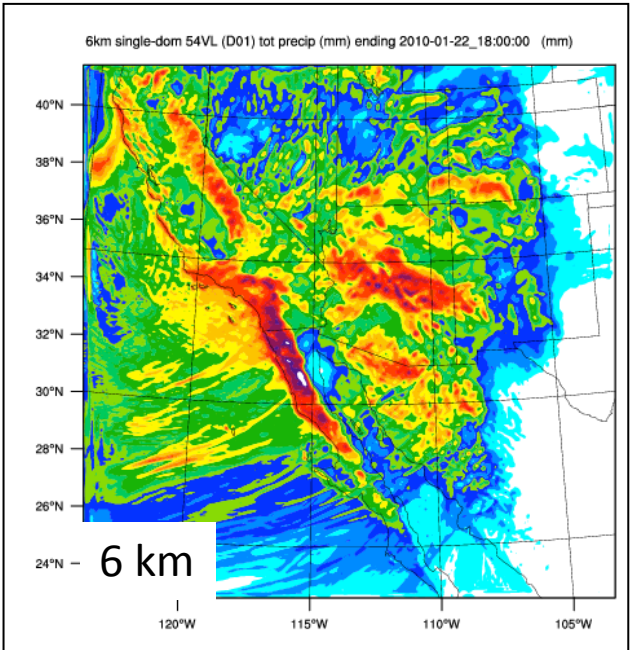


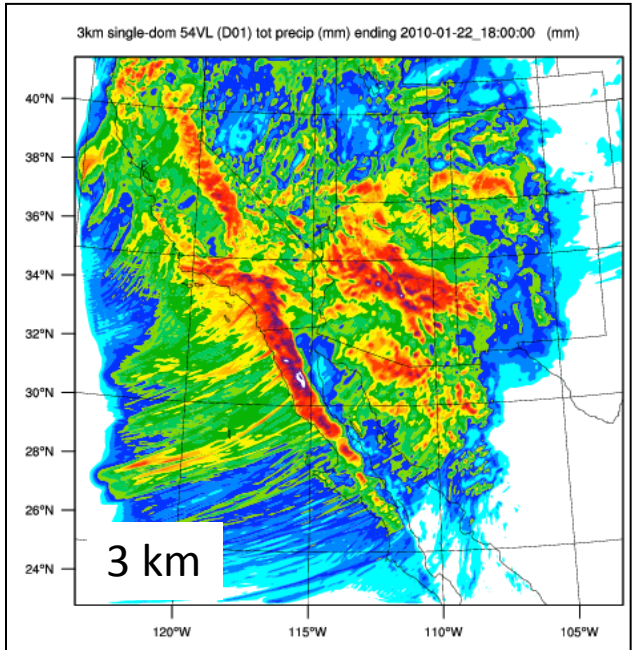
Precipitation at Different Model Resolutions

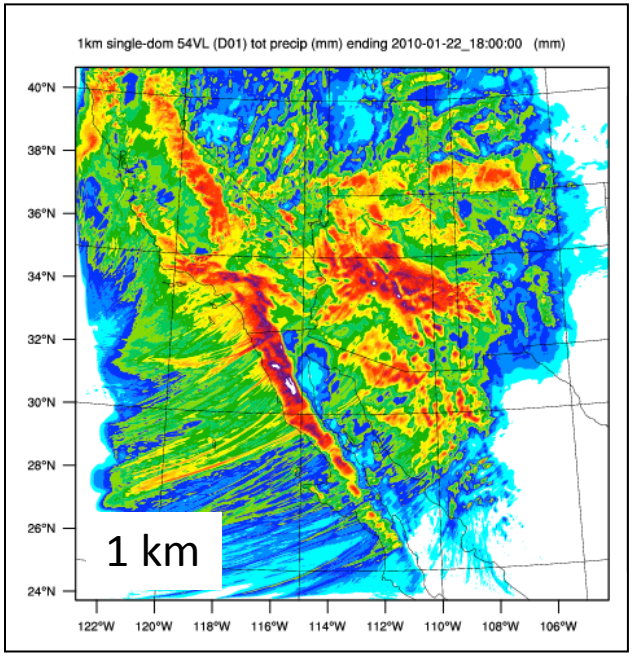




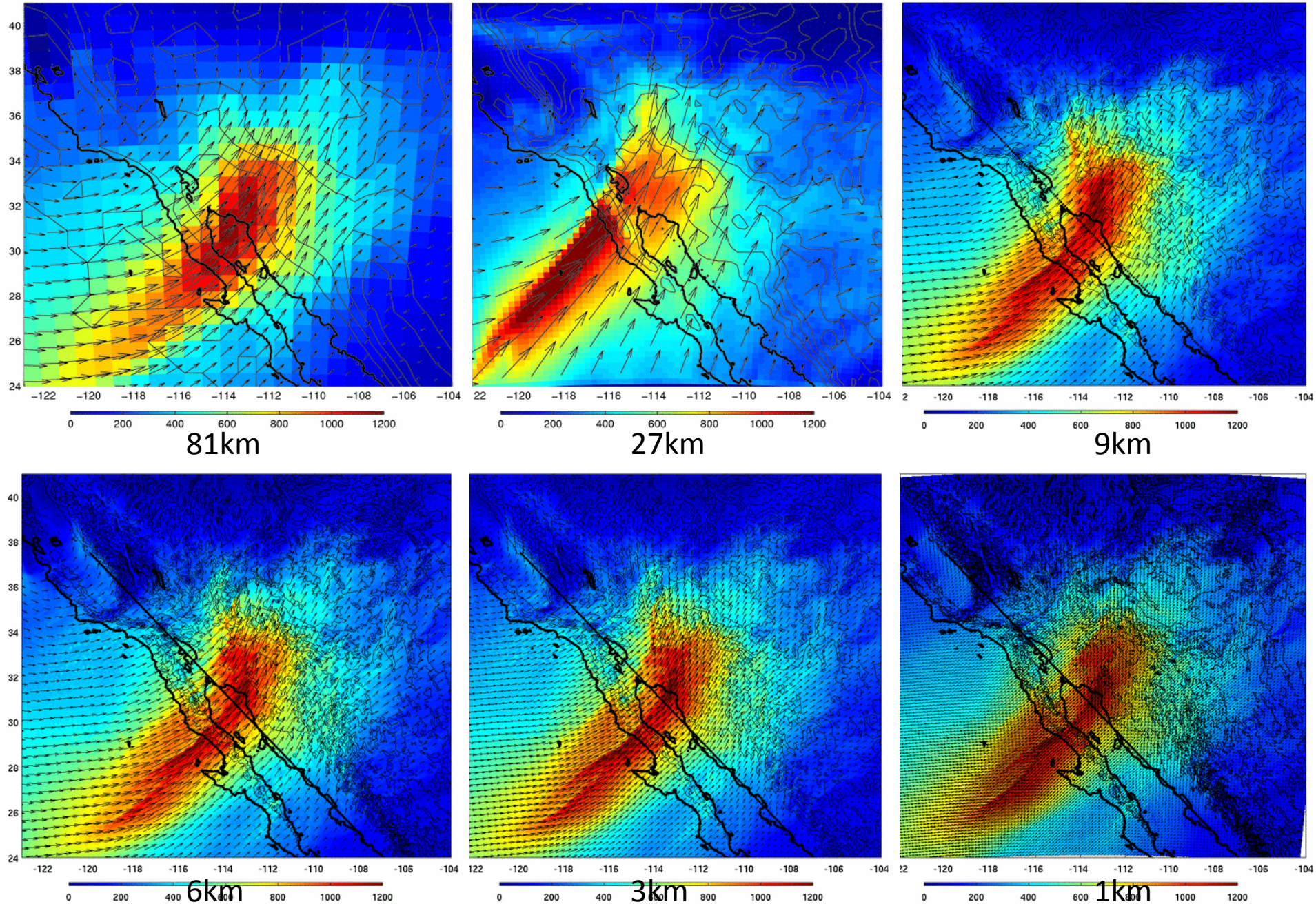




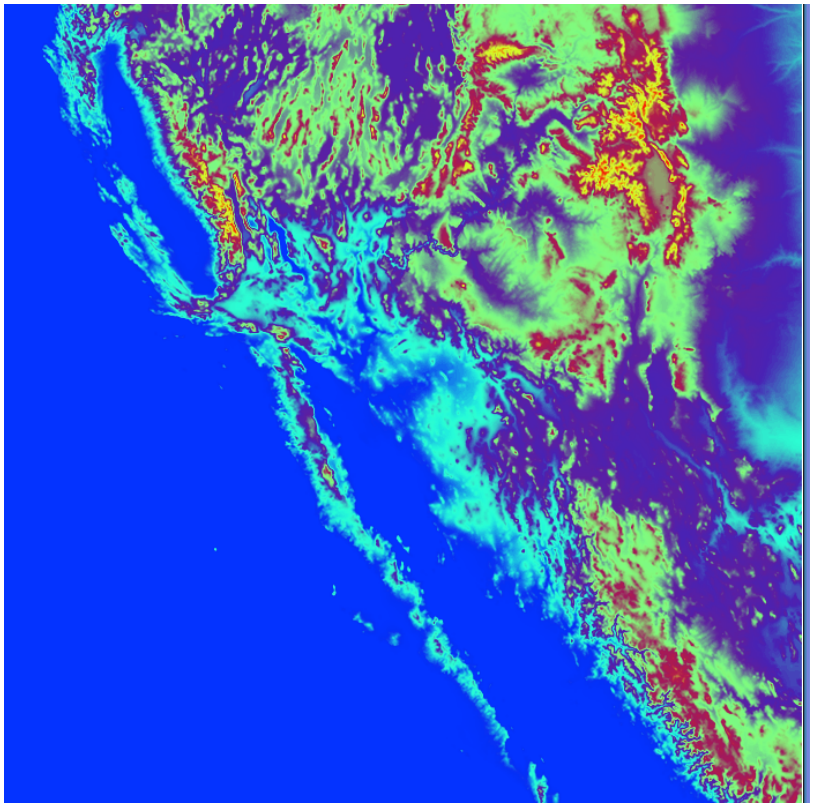


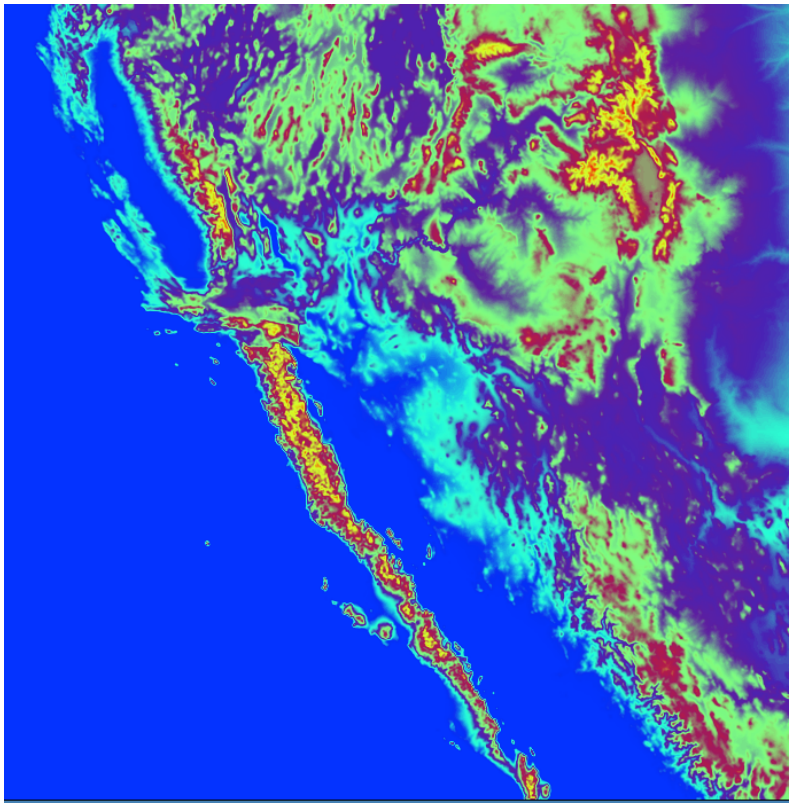


IVT planviews (kg m^{-1} s^{-1}) (color fill shows magnitude, arrows show magnitude and direction)



To what extent does Baja's terrain 'channel' water to AZ/ CO?

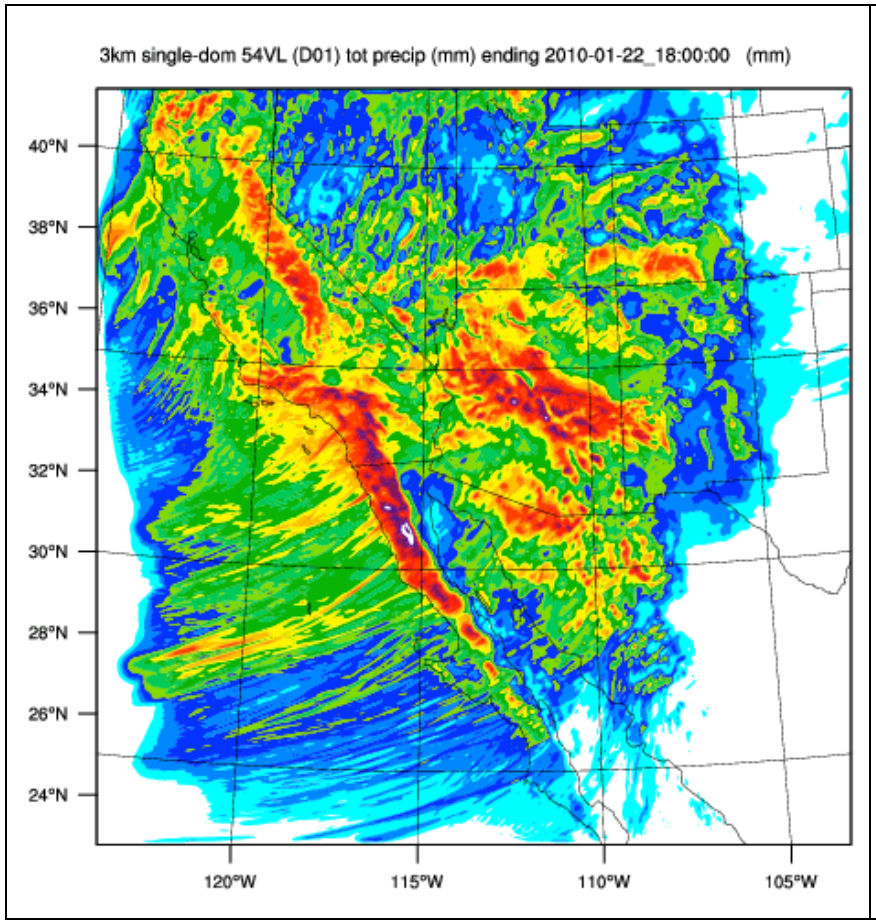


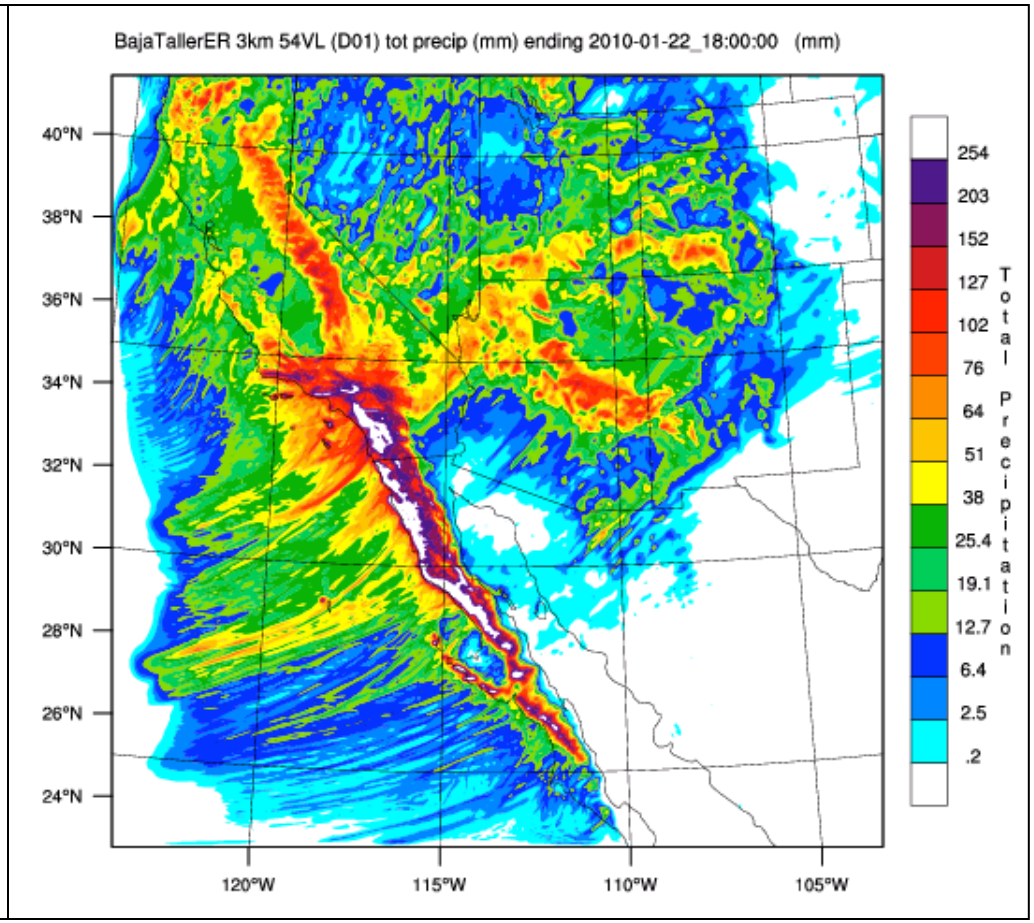


3 km CTRL terrain height

Tall Baja terrain height

To what extent does Baja's terrain 'channel' water to AZ/ CO?





3 km CTRL precipitation

Tall Baja precipitation

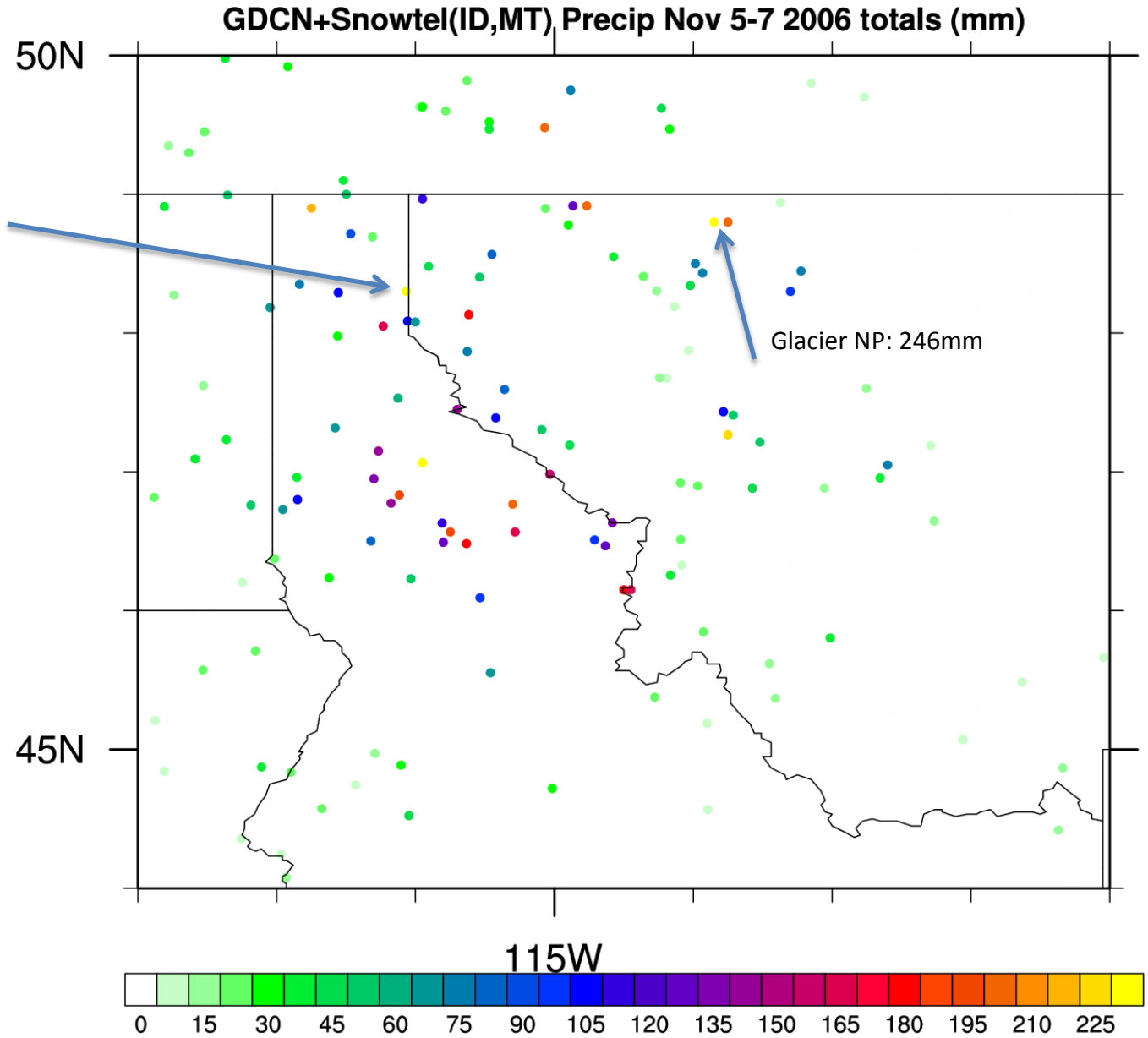
Case Study # 2

- Northern Idaho and Montana
  - November 6-7, 2006
  - Includes snowtel stations

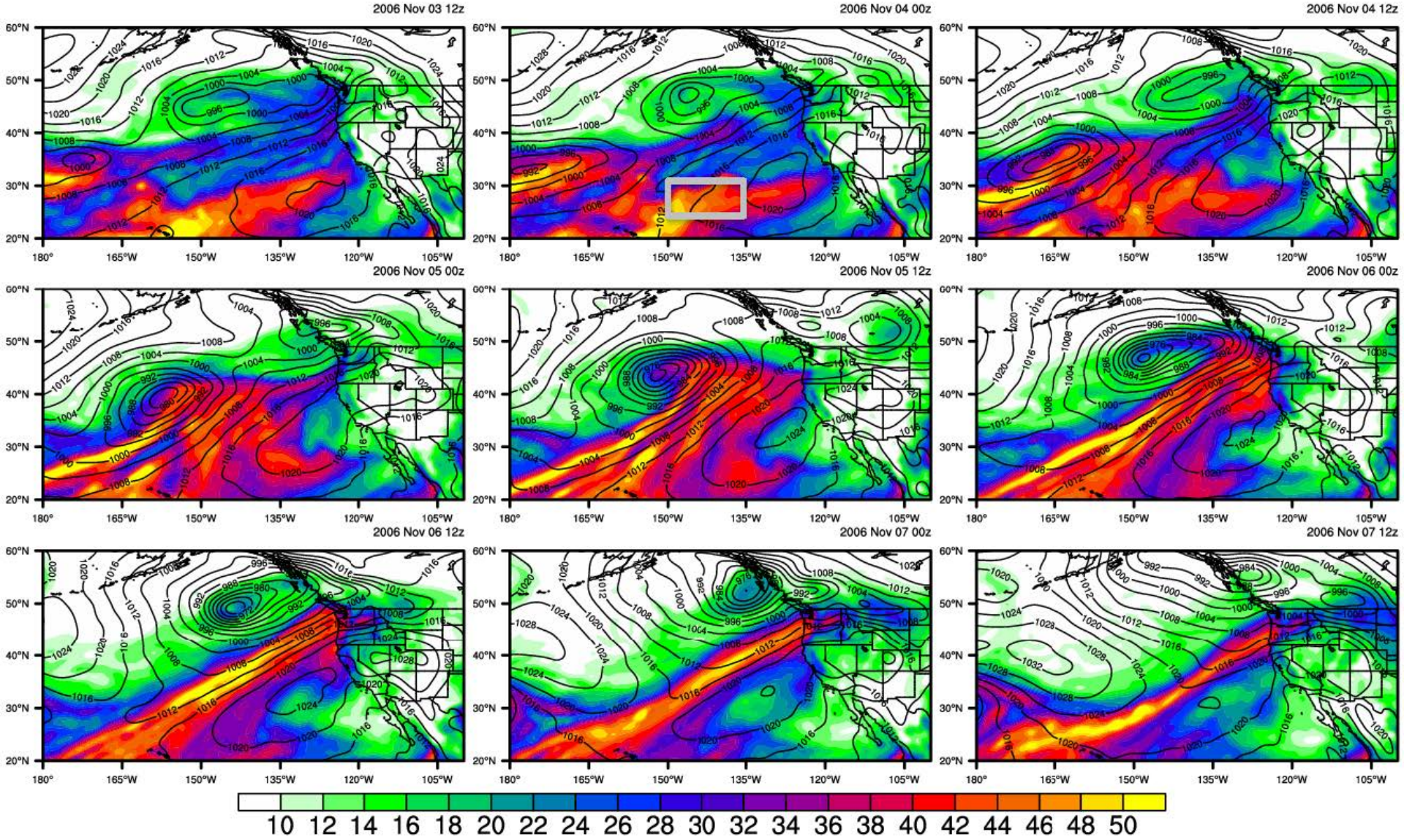
Northern ID, MT: November 5-7 2006

8 stations > 200mm
~ 8 in

388 mm @ Bear Mtn, ID



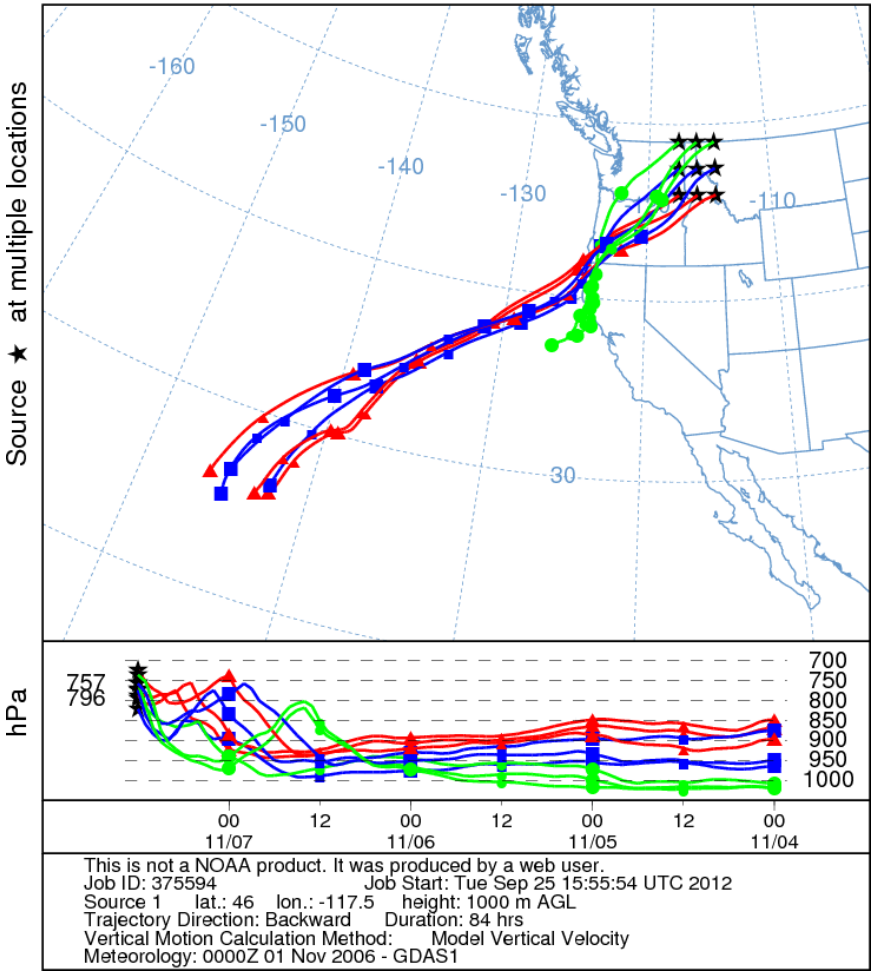
SLP (mb) & Precipitable Water (mm)



Back trajectories using Hysplit Model

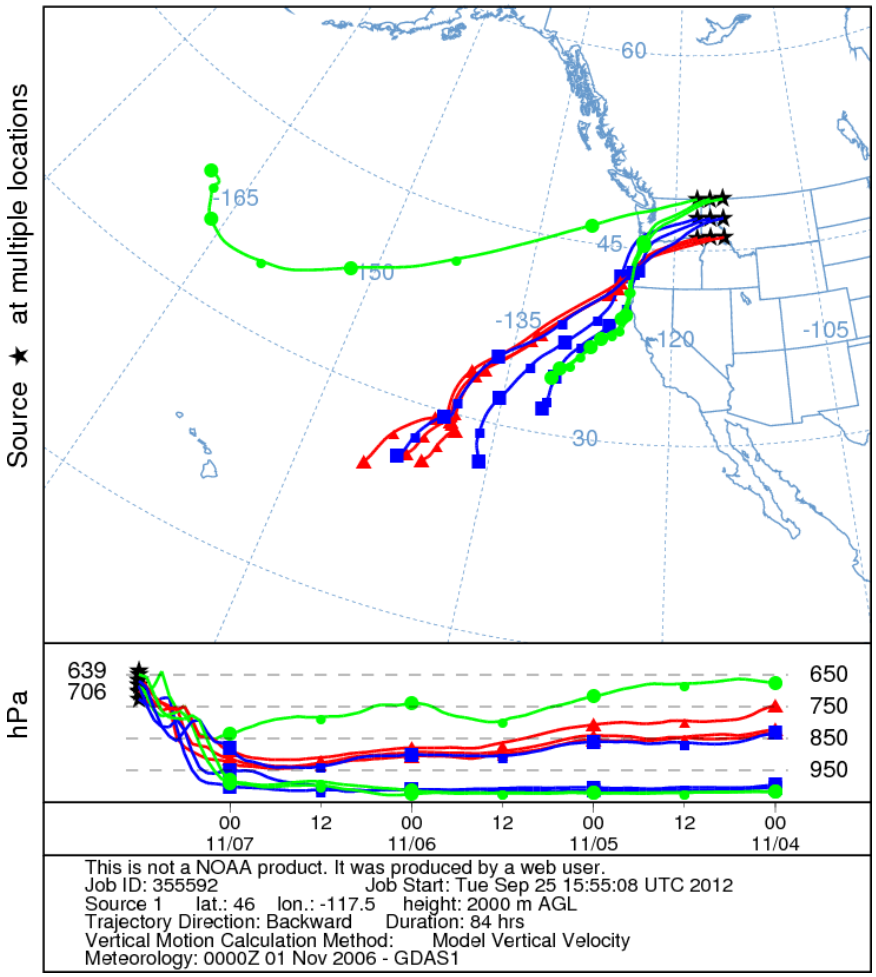
1KM AGL target

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 07 Nov 06
GDAS Meteorological Data



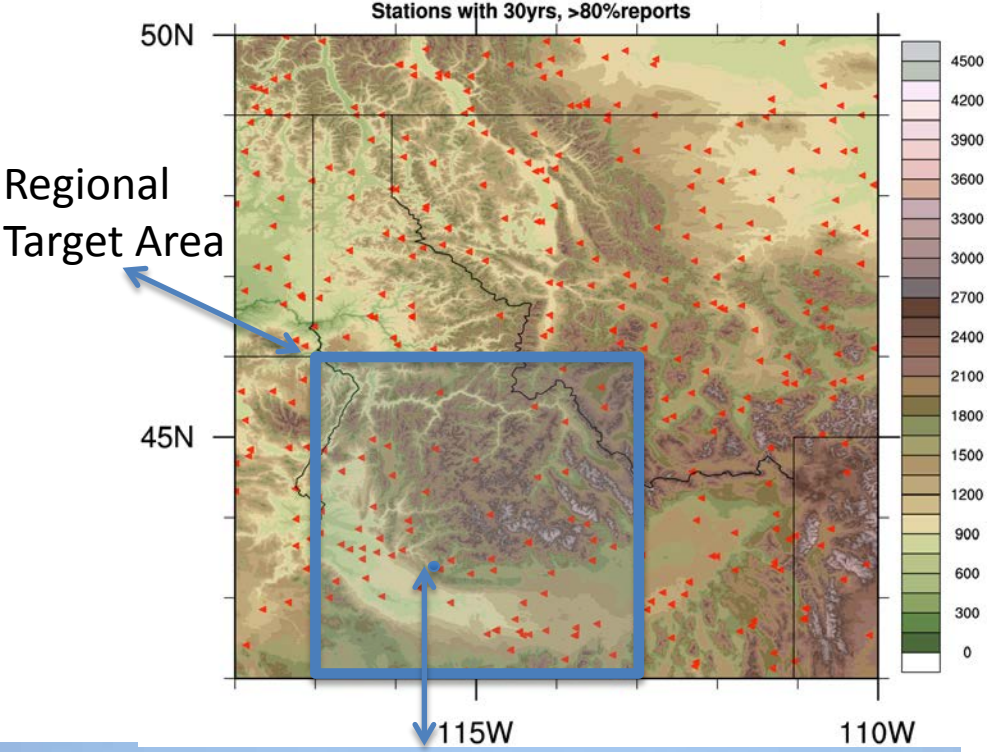
2KM AGL target

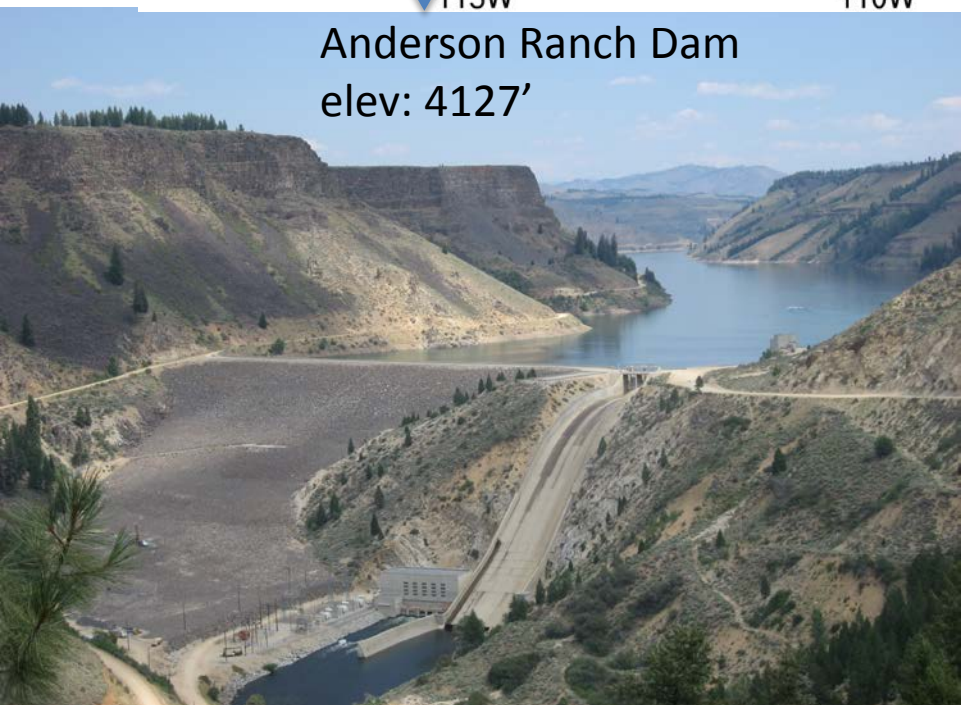
NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 07 Nov 06
GDAS Meteorological Data

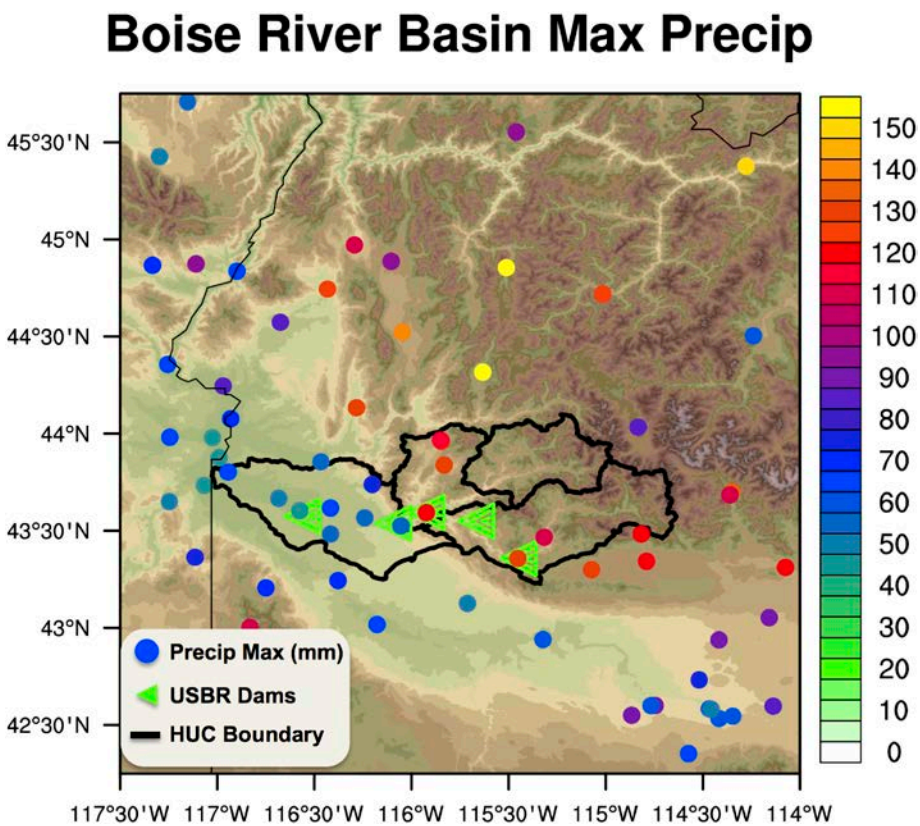


Southern Idaho – regional study

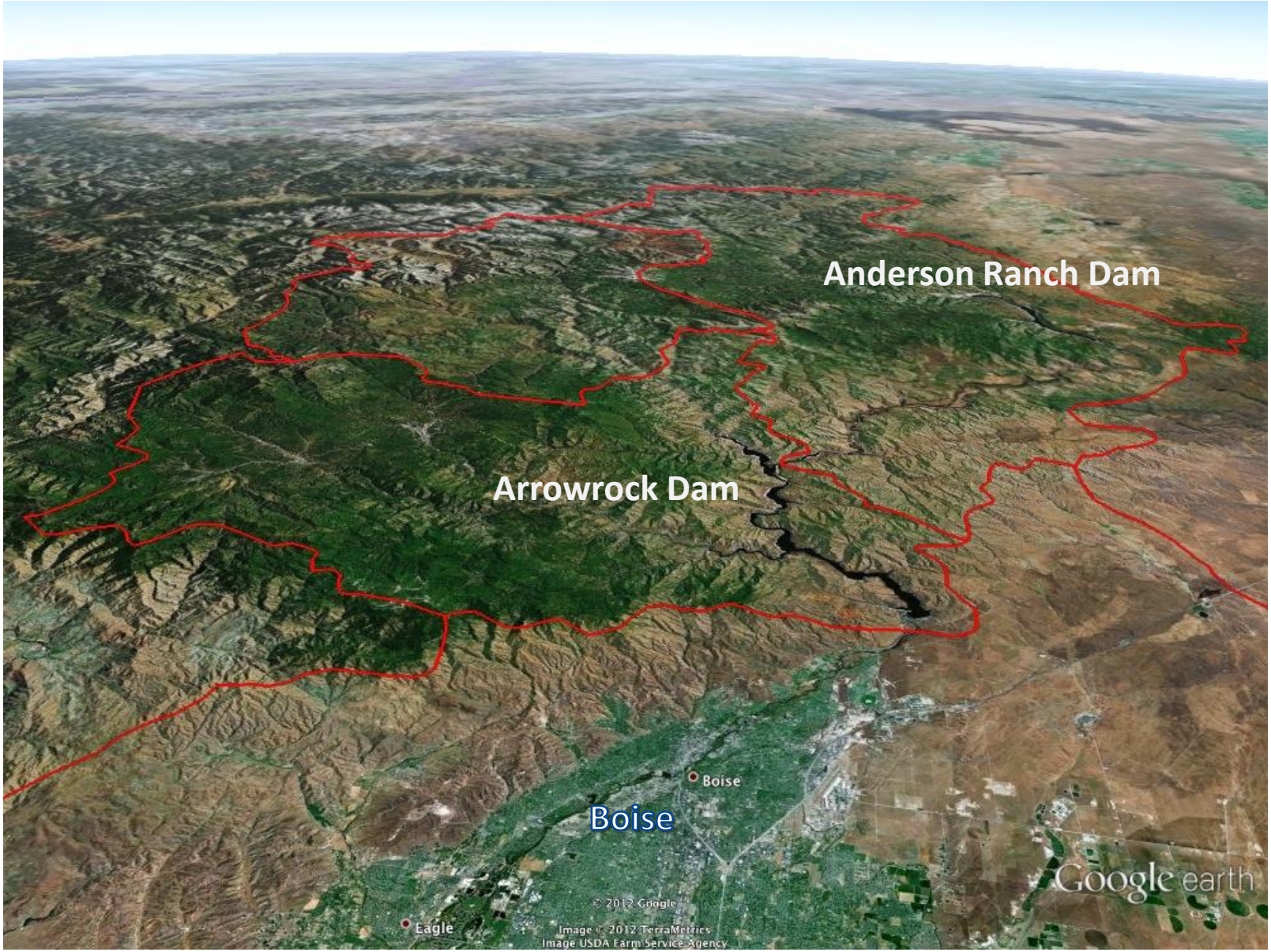
- Develop understanding of the types of storm that result in heavy precipitation
- Develop methods for grouping storms


Stations with 30yrs, >80%reports
50N
45N
115W
110W
4500
4200
3900
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0
Regional
Target Area


Anderson Ranch Dam
elev: 4127'

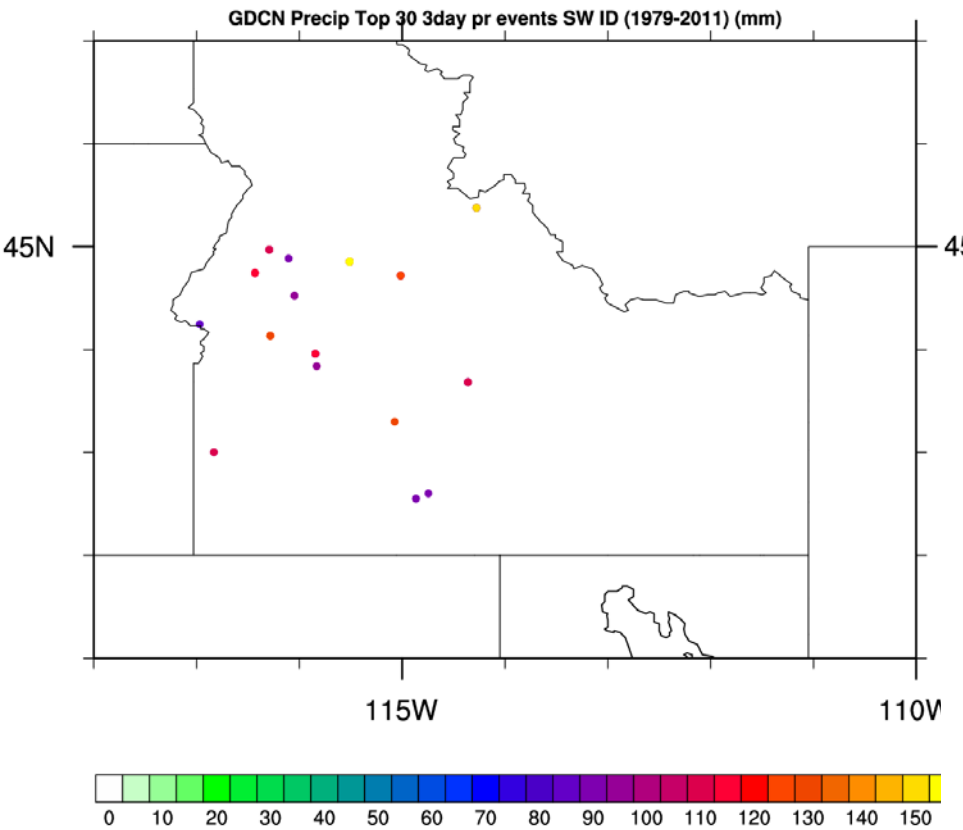

Boise River Basin Max Precip
45°30'N
45°N
44°30'N
44°N
43°30'N
43°N
42°30'N
117°30'W
117°W
116°30'W
116°W
115°30'W
115°W
114°30'W
114°W
Precip Max (mm)
USBR Dams
HUC Boundary
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0

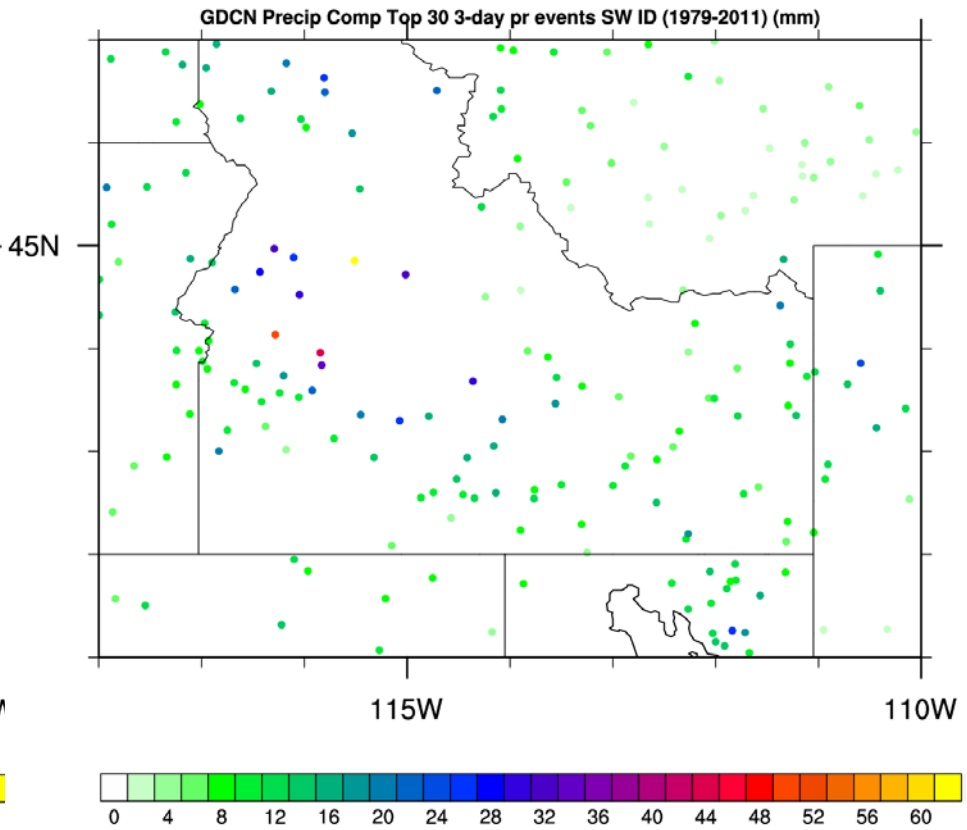
Boise River Watershed

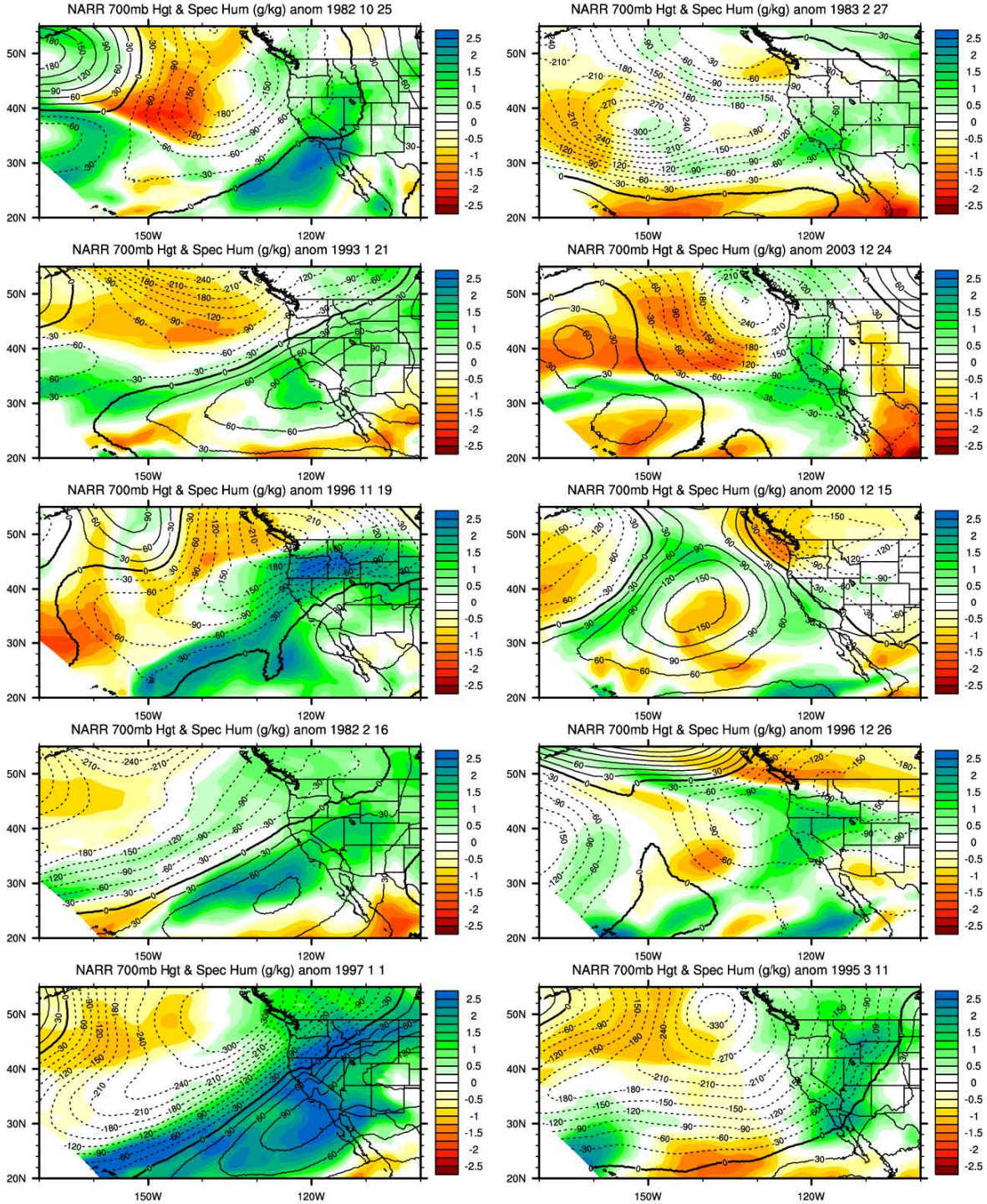


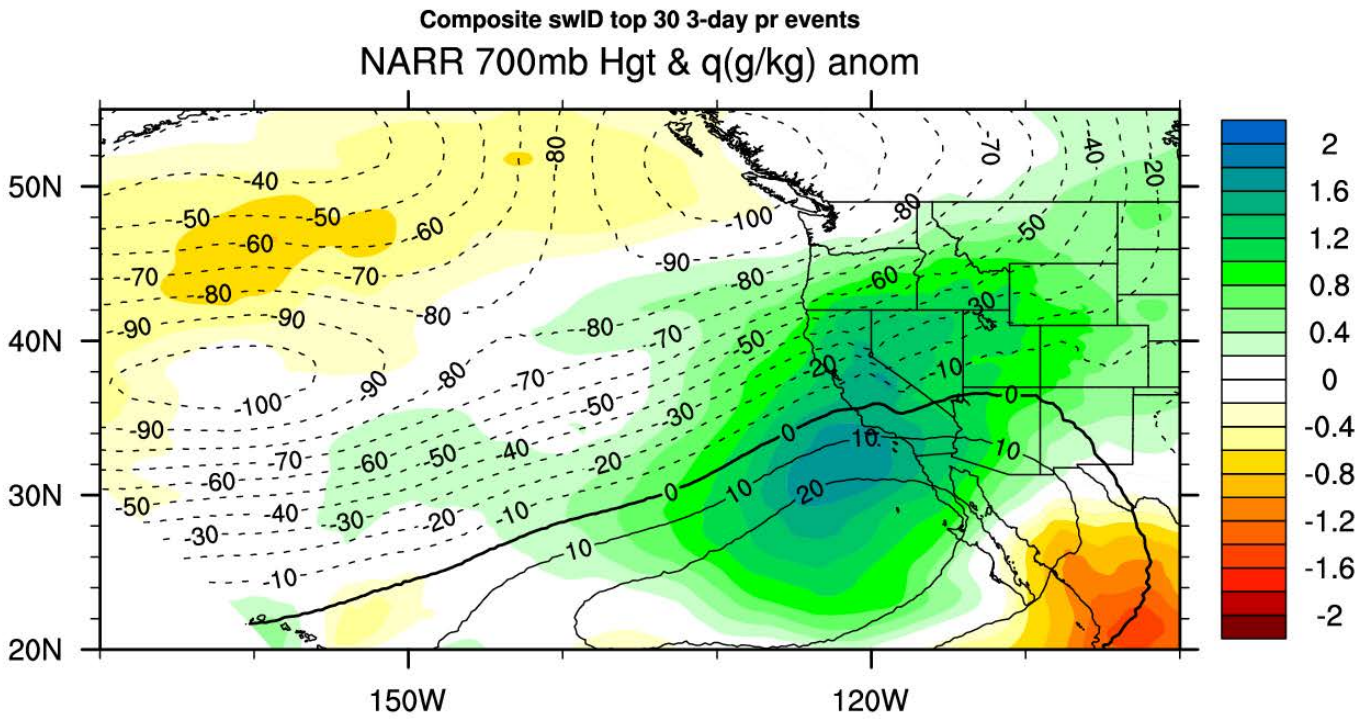
Top 30 Precipitation events (Oct-Apr) in regional target (SW ID) occurs at 15 stations

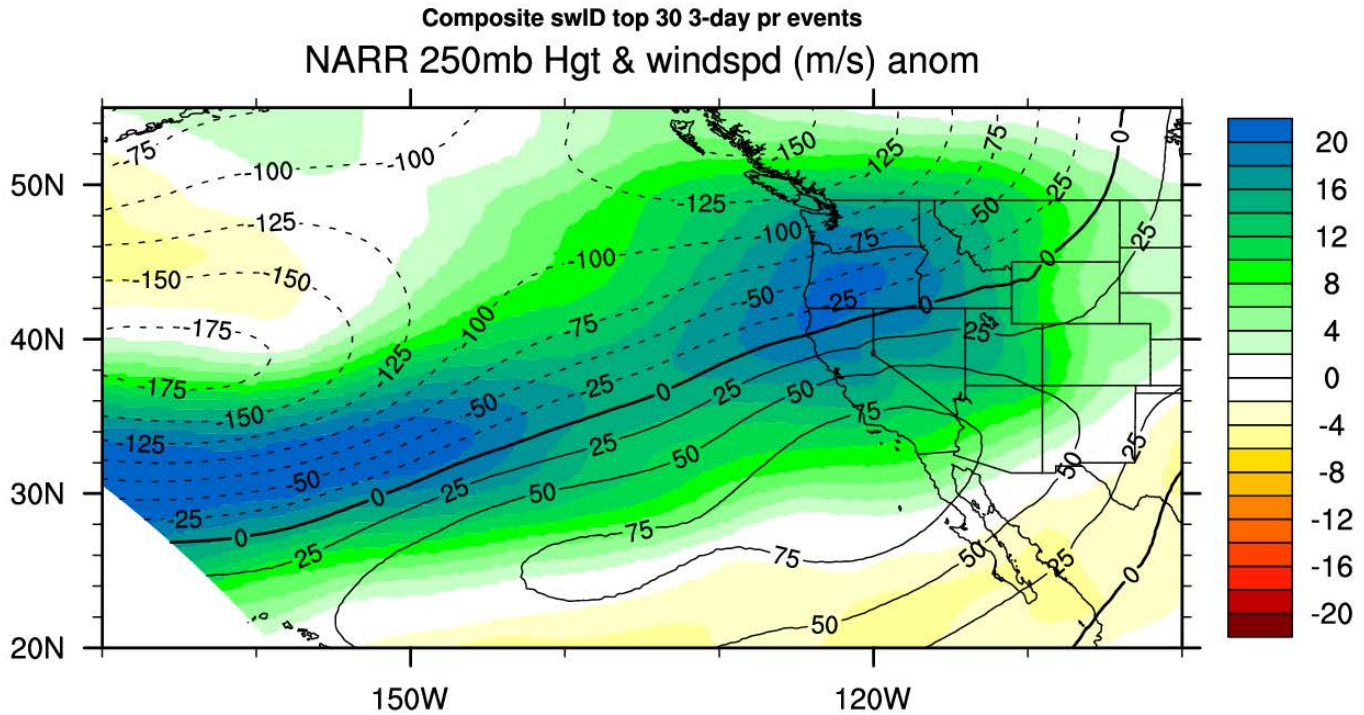
Most events are localized => Regional composite precipitation signal is relatively weak.






NARR 700mb Hgt & Spec Hum (g/kg) anom 1982 10 25
NARR 700mb Hgt & Spec Hum (g/kg) anom 1983 2 27
NARR 700mb Hgt & Spec Hum (g/kg) anom 1993 1 21
NARR 700mb Hgt & Spec Hum (g/kg) anom 2003 12 24
NARR 700mb Hgt & Spec Hum (g/kg) anom 1996 11 19
NARR 700mb Hgt & Spec Hum (g/kg) anom 2000 12 15
NARR 700mb Hgt & Spec Hum (g/kg) anom 1982 2 16
NARR 700mb Hgt & Spec Hum (g/kg) anom 1996 12 26
NARR 700mb Hgt & Spec Hum (g/kg) anom 1997 1 1
NARR 700mb Hgt & Spec Hum (g/kg) anom 1995 3 11
50N
40N
30N
20N
150W
120W
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5


Composite swID top 30 3-day pr events
NARR 700mb Hgt & q(g/kg) anom
50N
40N
30N
20N
150W
120W
2
1.6
1.2
0.8
0.4
0
-0.4
-0.8
-1.2
-1.6
-2


Composite swID top 30 3-day pr events
NARR 250mb Hgt & windspd (m/s) anom
50N
40N
30N
20N
150W
120W
20
16
12
8
4
0
-4
-8
-12
-16
-20

Summary

- Used Station data to identify extreme events
- Performed analyses using station data, atmospheric reanalysis and back trajectories
- Case studies
  - Jan 2010 event in Arizona
    - Detailed observational and model study
    - Penetration of extratropical AR through gaps in mountains in Baja into AZ
  - Nov 2006 event
    - Northern Idaho/Montana event
      - Preliminary – moisture flow through Columbia river and over Cascades
- Regional analyses in southern Idaho
  - Composite analysis indicates strong jet from the south west moisture transported from off California coast

Future Research

- Broader scale implications
  - ways to define a region of interest
    - e.g. cluster analysis
  - Are there better ways to group similar storms?
    - self organizing maps
    - EOFs
    - Trajectory density
    - Forward trajectories based on land falling
- Modeling work
  - Publish Arizona case study case
  - Trajectories
  - Role of topography, wind direction, SSTs
- Impact of climate factors (ENSO) on moisture pathways

Backup slides

Integrated Approach

We want to choose cases and regions for more intensive study where Reclamation has a management interest **and** where the exposure to extreme precipitation events is high

Reclamation assets potentially at risk

Reclamation has a diversity of interests (Dam Safety office, Regional Offices, R&D) and facilities throughout the Intermountain West.

Reclamation has expressed a continuing interest in better understanding the potential flood risk at several of its locations.

Reclamation conducts periodic dam safety reviews -- choose regions where these reviews are imminent.

Exposure to extreme precipitation events

Historical study of precipitation to determine where large storms have occurred

Numerical modeling case studies of recent extreme storms to better understand the reasons for the extreme precipitation

Determine whether there are preferred locations where AR's may penetrate inland.

Background & Motivation

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

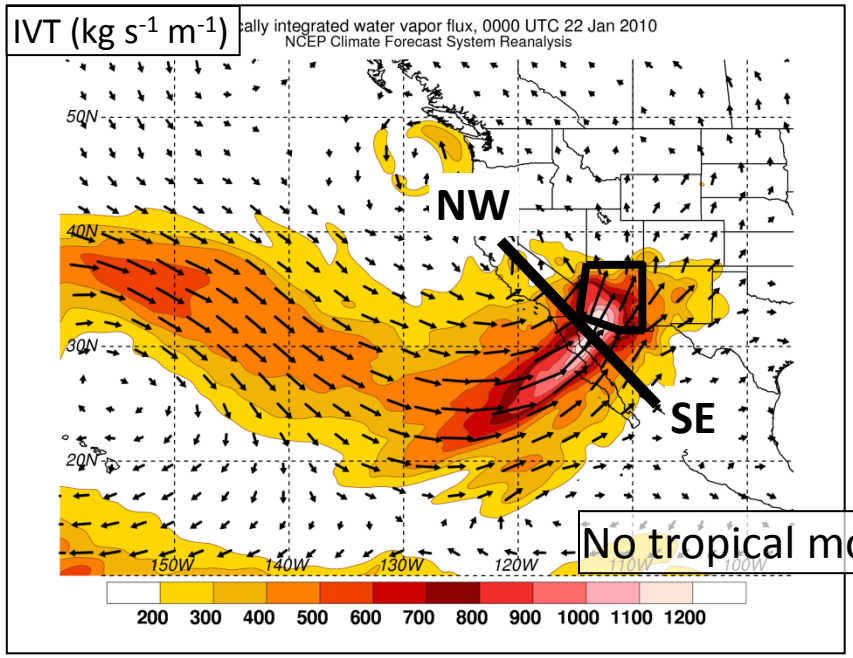
- ARs contribute significantly to the annual precipitation and snowpack in the West Coast States via orographic processes.

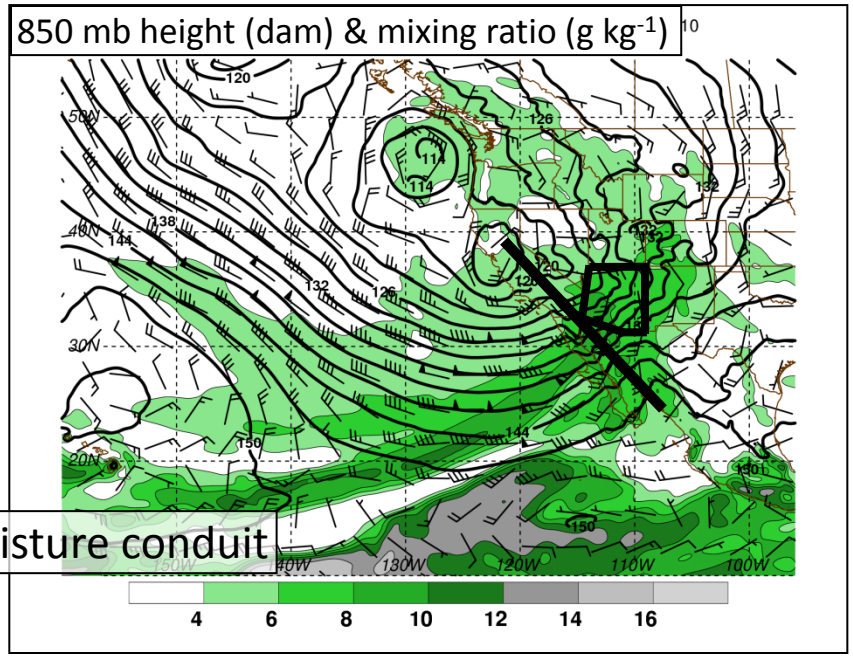
- Less certain are the hydrometeorological impacts of ARs as they migrate inland into the Intermountain West.

- 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.

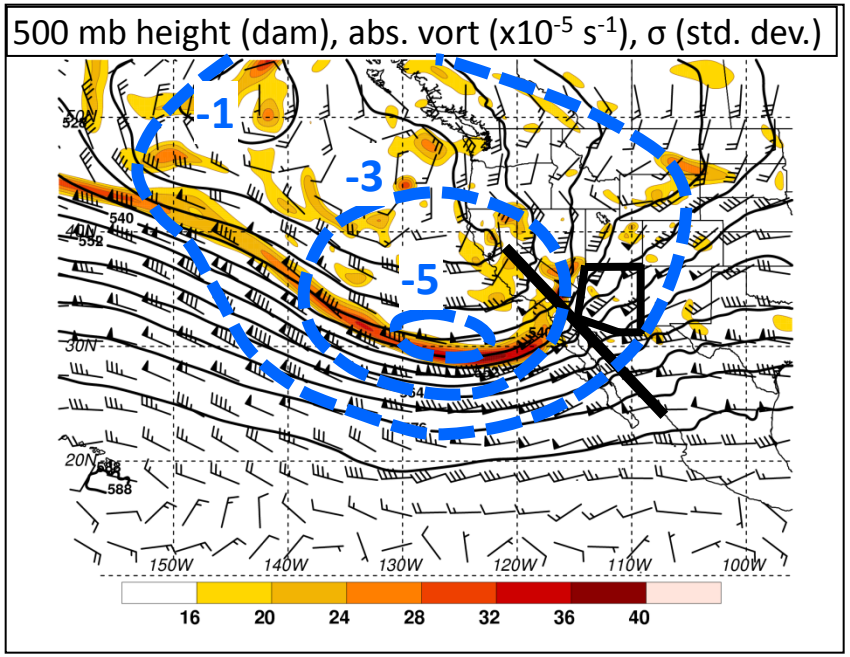
- The research presented here provides the first detailed case study to test the hypothesis that an AR and its impacts can penetrate inland from the Pacific Ocean.

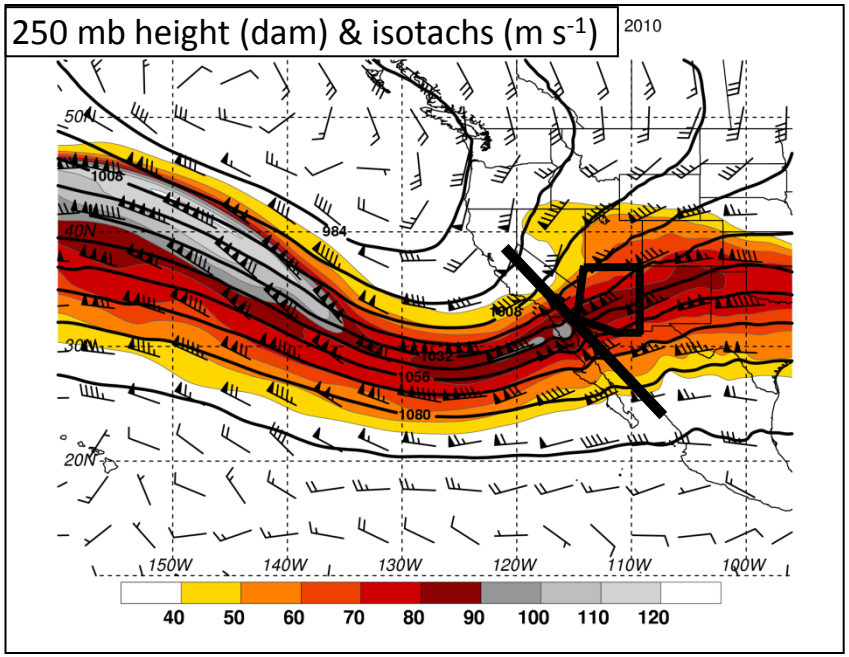
NCEP's CFSR: 0000 UTC 22 January 2010



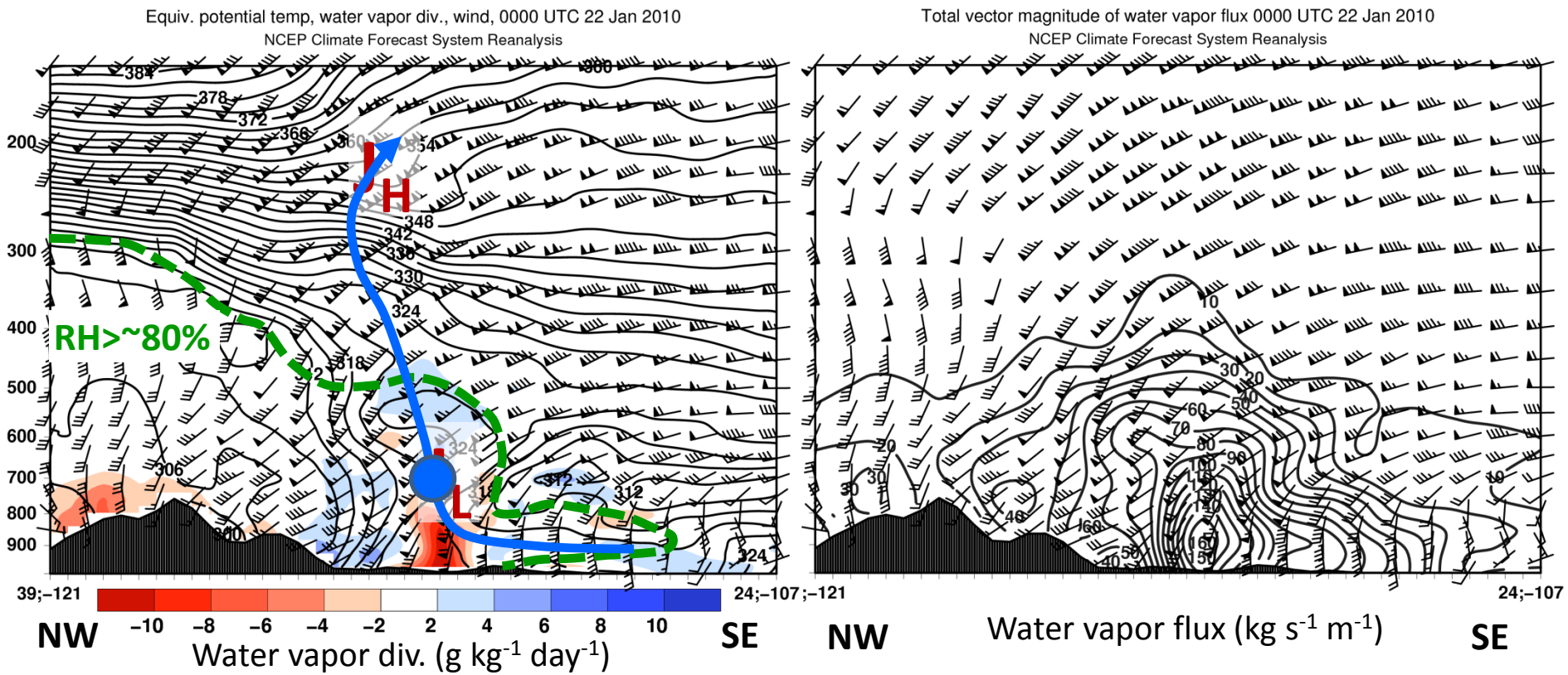


No tropical moisture conduit



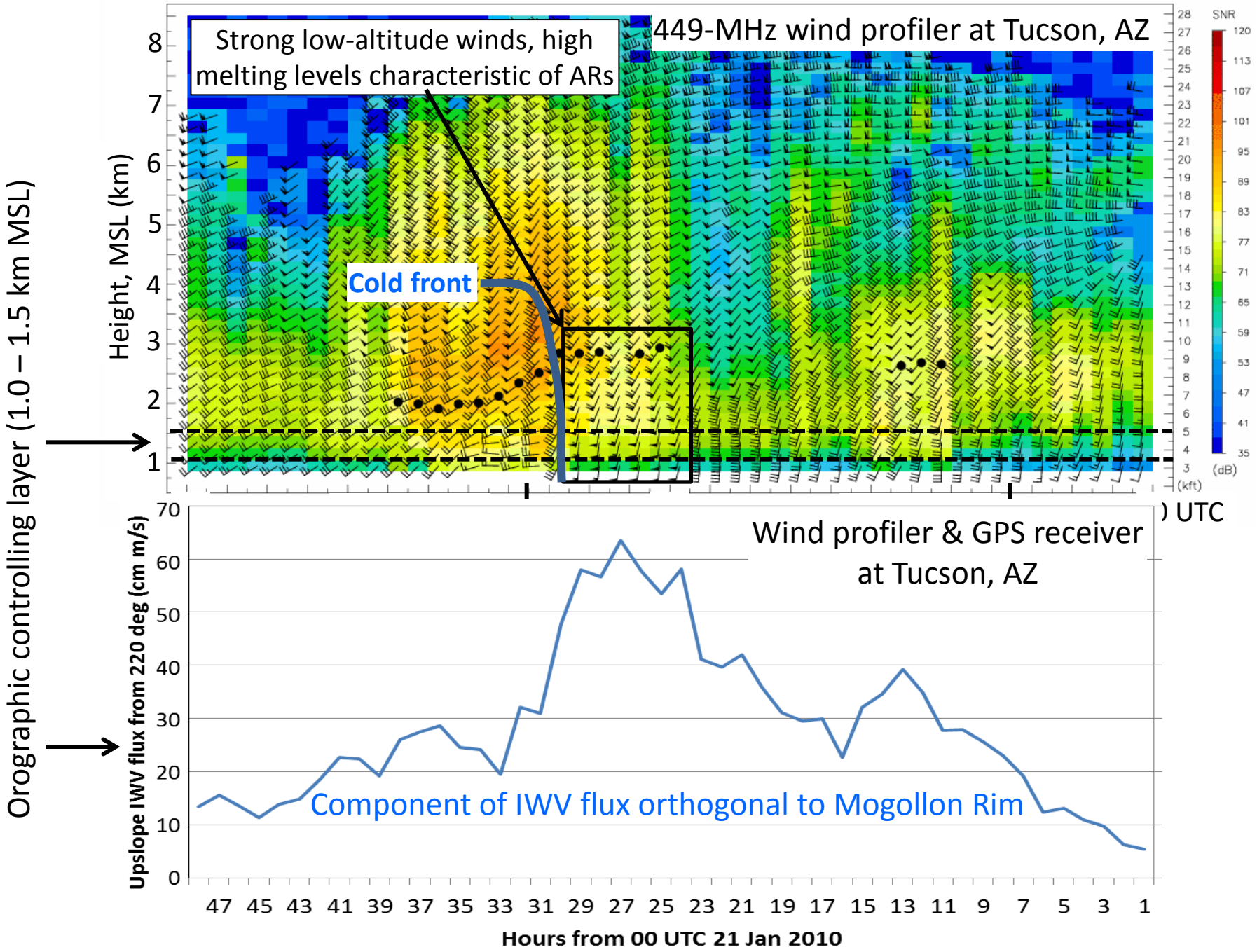


NCEP's CFSR: Cross section NW – SE on 00Z 22 January 2010

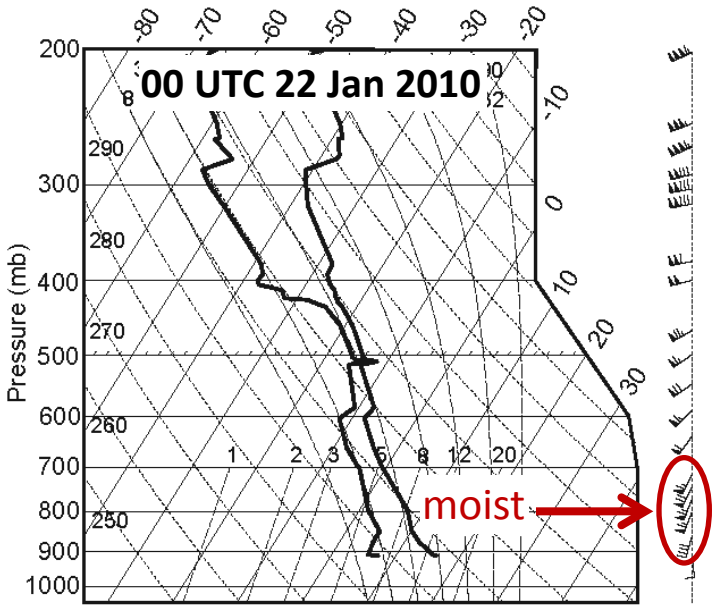


J_H = 85+ m s^{-1} ω_{max} < -25 µb s^{-1}

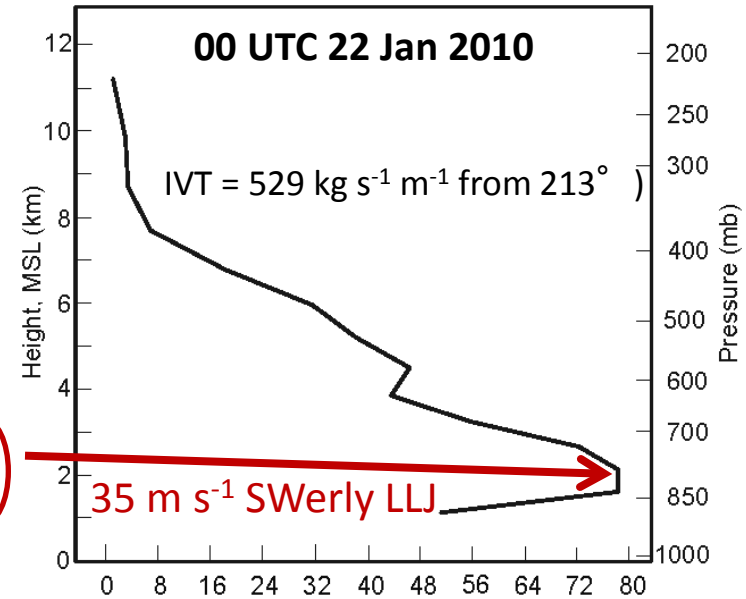
J_L = 35+ m s^{-1}


449-MHz wind profiler at Tucson, AZ
Strong low-altitude winds, high melting levels characteristic of ARs
Cold front
Height, MSL (km)
SNR
(dB)
(kft)
Orographic controlling layer (1.0 – 1.5 km MSL)
Wind profiler & GPS receiver at Tucson, AZ
Component of IWV flux orthogonal to Mogollon Rim
Upslope IWV flux from 220 deg (cm m/s)
Hours from 00 UTC 21 Jan 2010

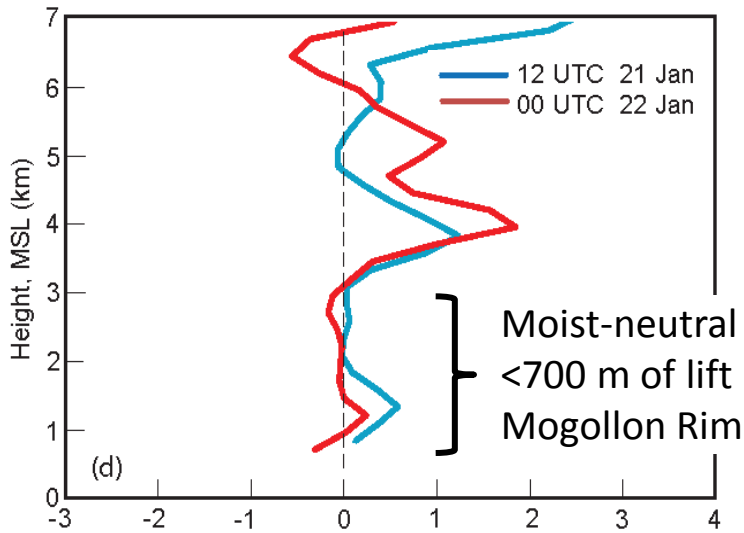
Rawinsonde observations from Tucson, AZ



Skew T – Log P diagram



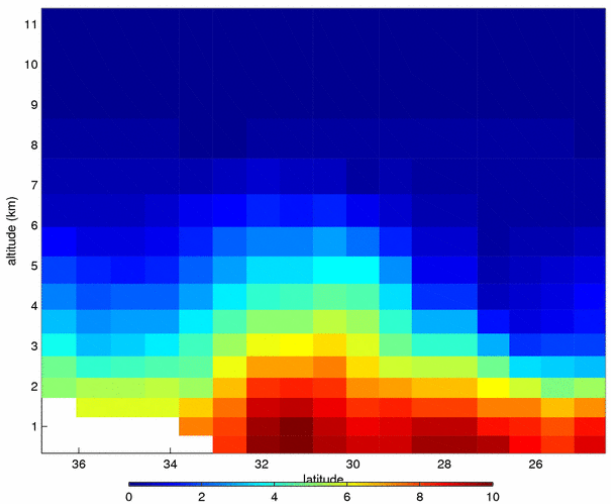
Water vapor flux (kg s^{-1} m^{-1}; from 220˘)



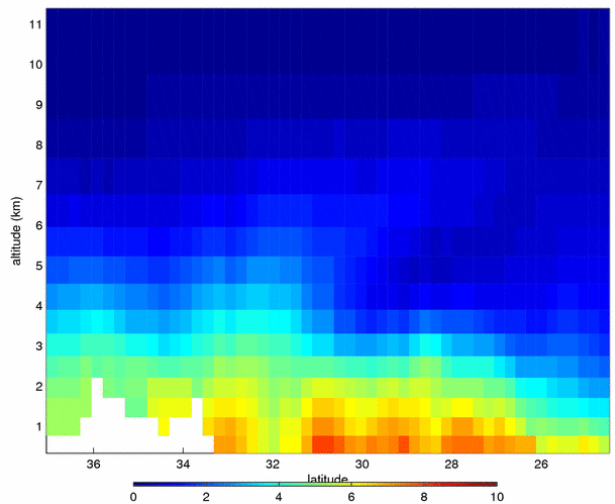
Moist-neutral below 3 km MSL.
<700 m of lift needed to saturate.
Mogollon Rim rises >1 km.

Moist B-V frequency squared (x10^4 s^{-2})

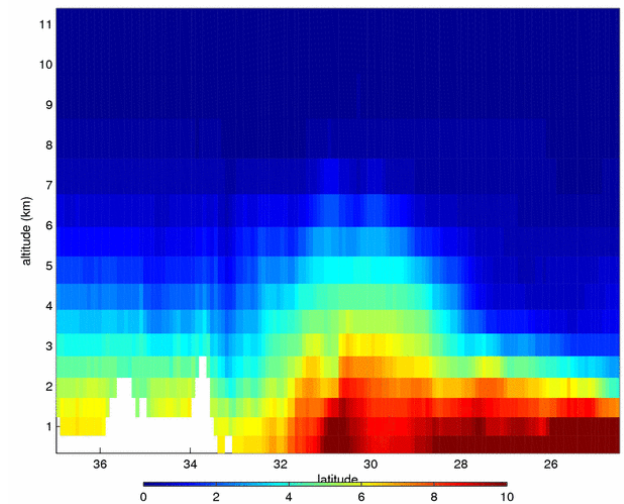
Water vapor cross sections (NW to SE) (g/kg)
Color fill is water vapor content



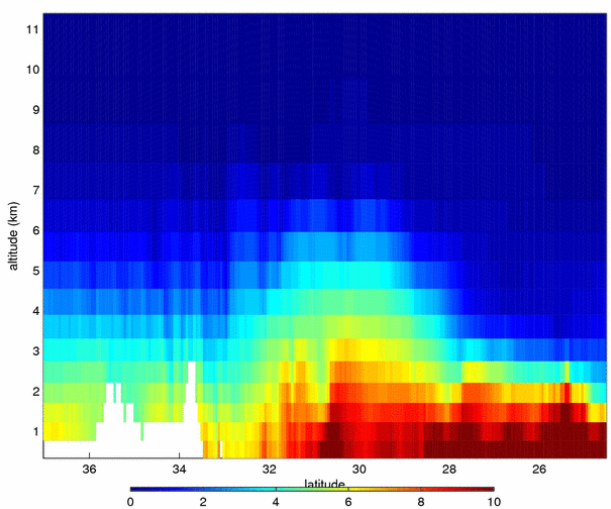
81km



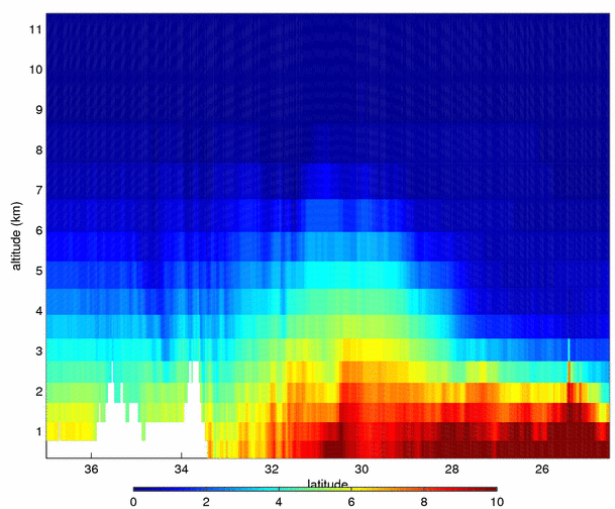
27km



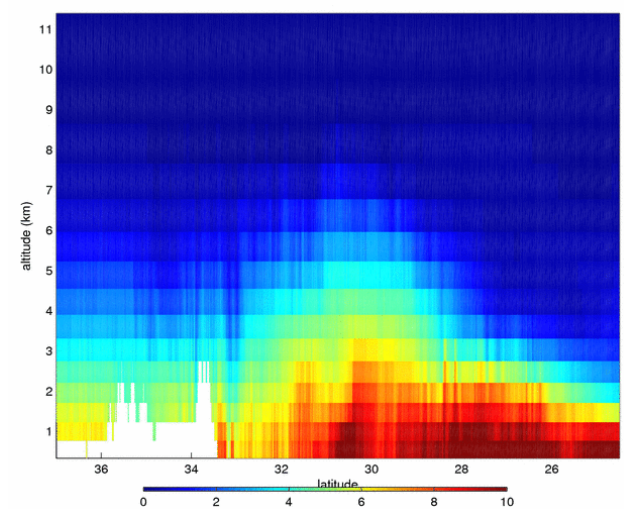
9km



6km



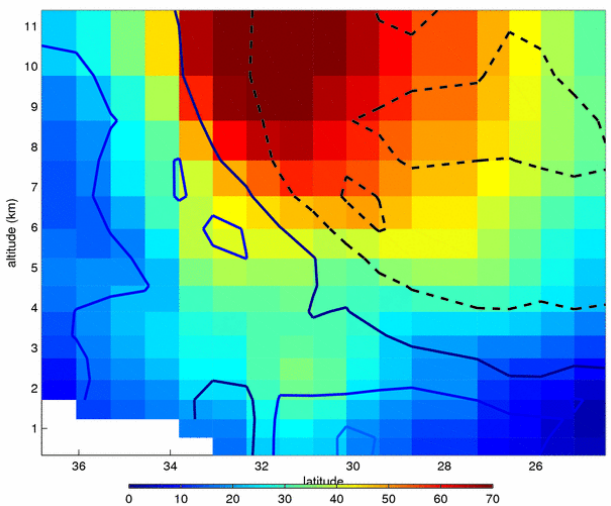
3km



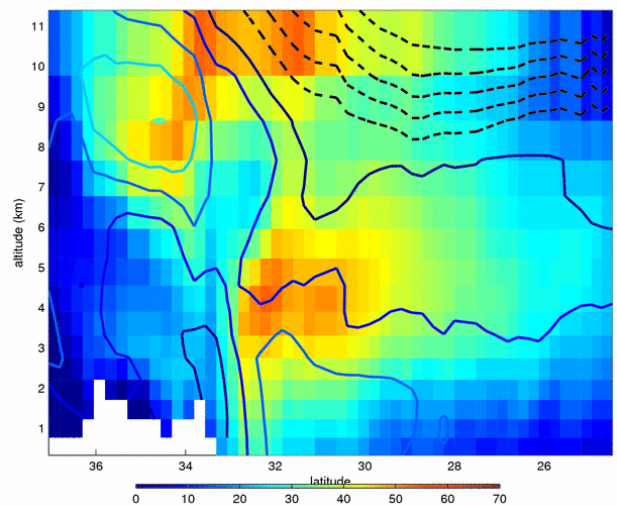
1km

Wind cross sections (NW to SE) (m s^{-1})

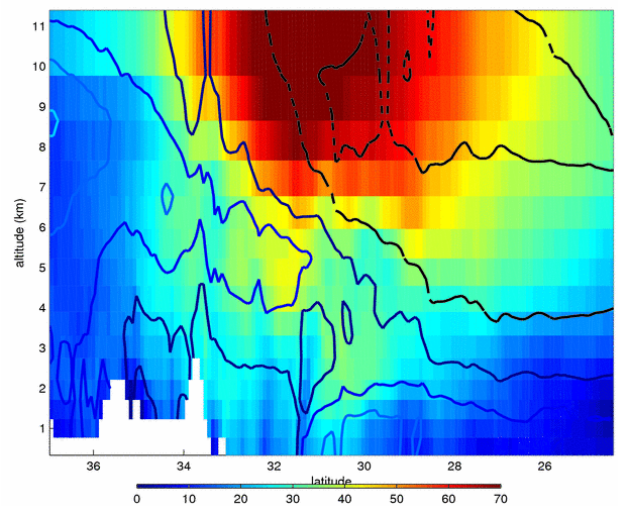
Color fill is 'AR parallel' component (from 230 degrees), contours are 'AR perpendicular'



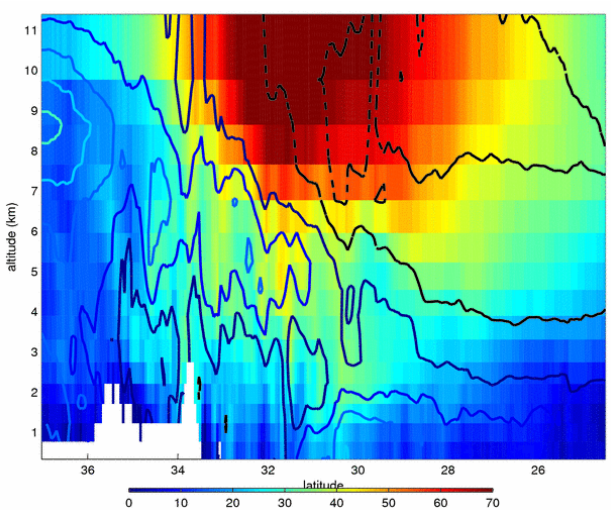
81km



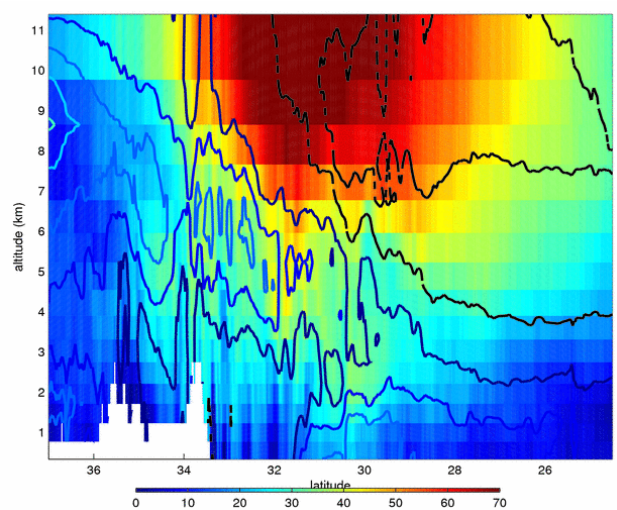
27km



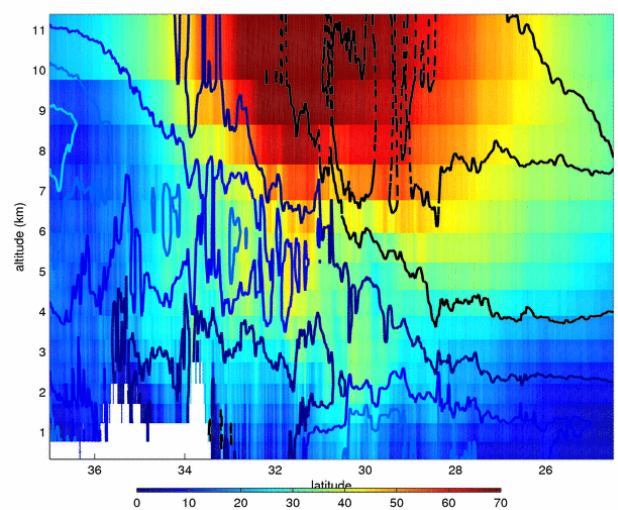
9km



6km



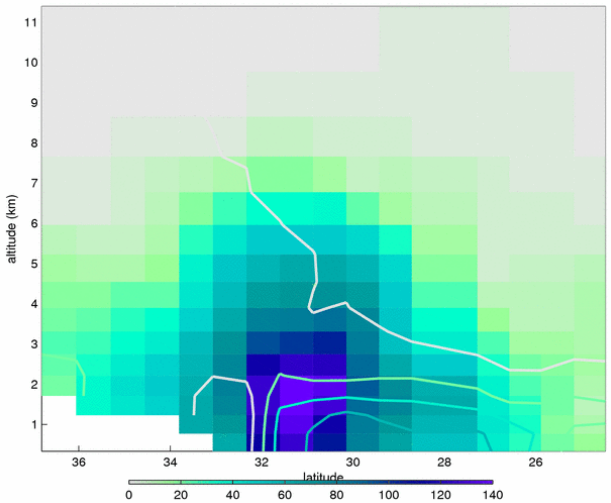
3km



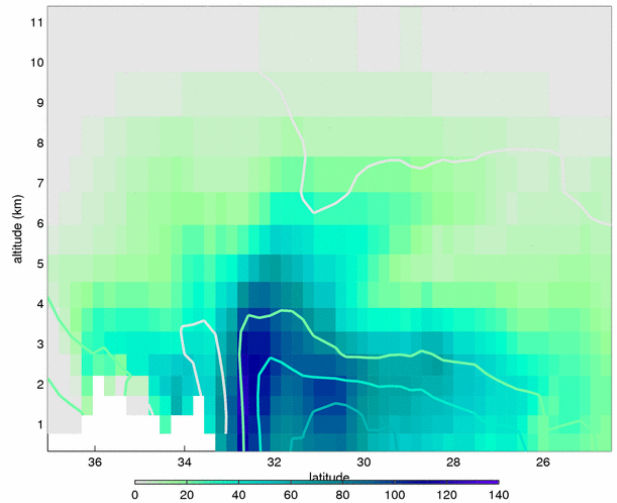
1km

IVT cross sections (NW to SE) (kg m^{-1} s^{-1})

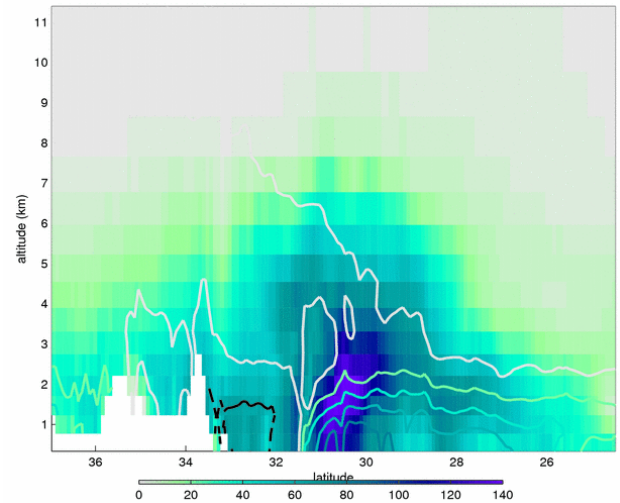
Color fill is 'AR parallel' component (from 230 degrees), contours are 'AR perpendicular'



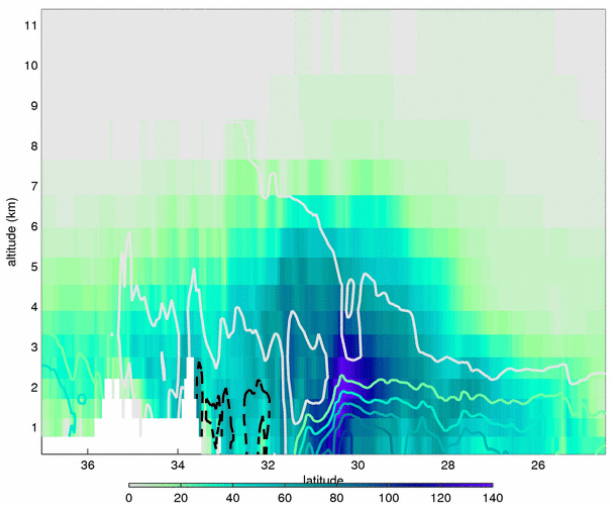
81km



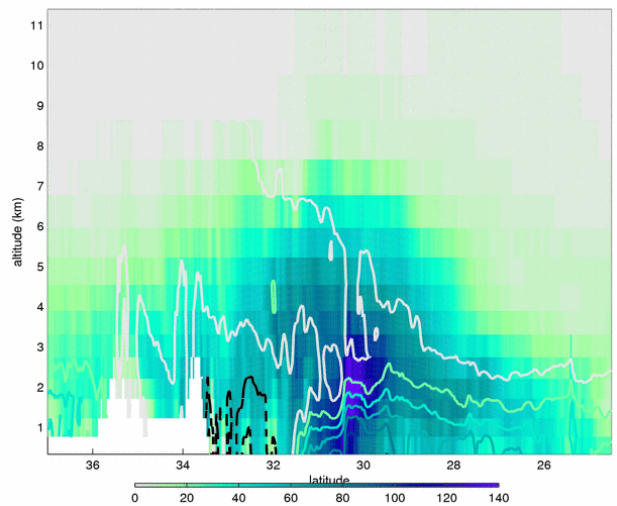
27km



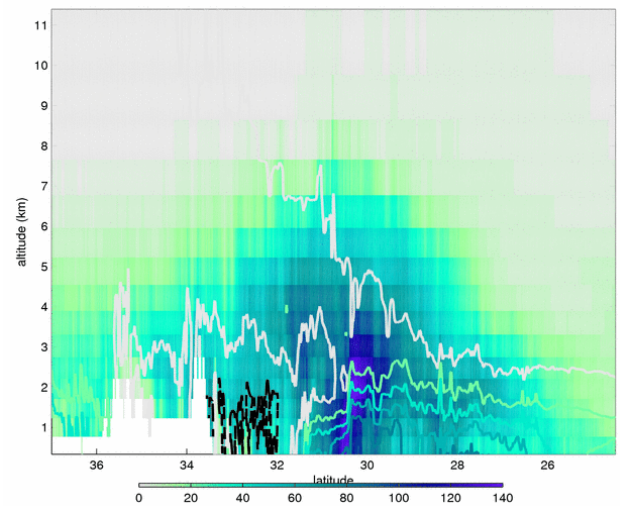
9km



6km

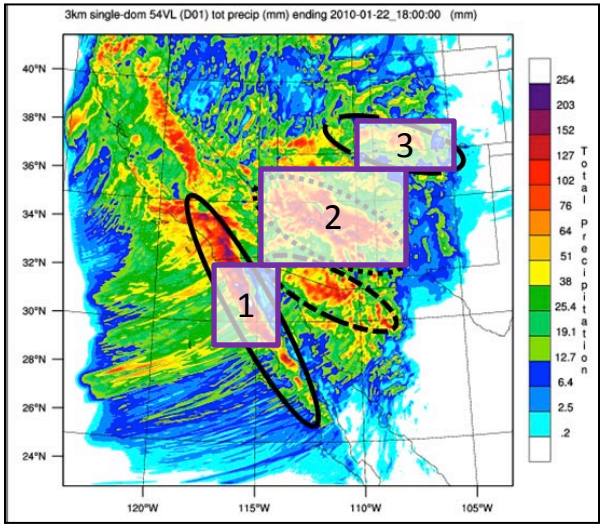


3km



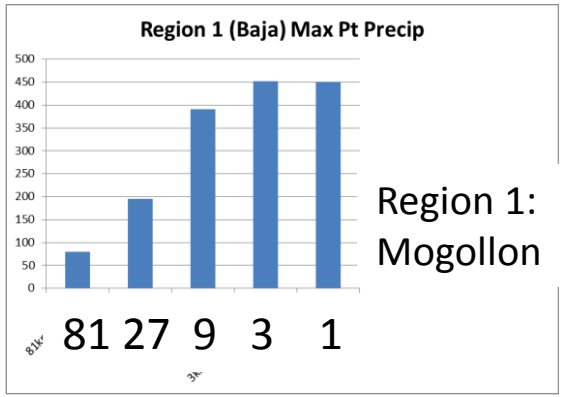
1km

Differences due to resolution in resultant precipitation

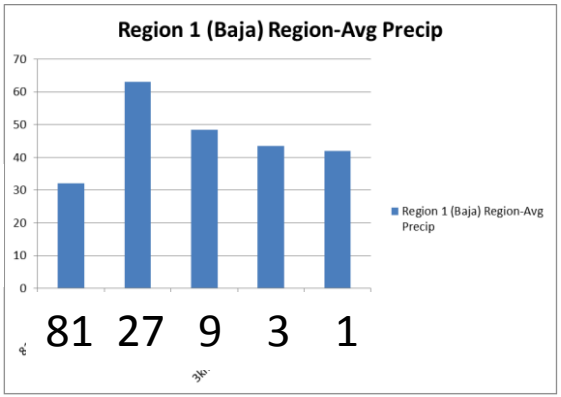


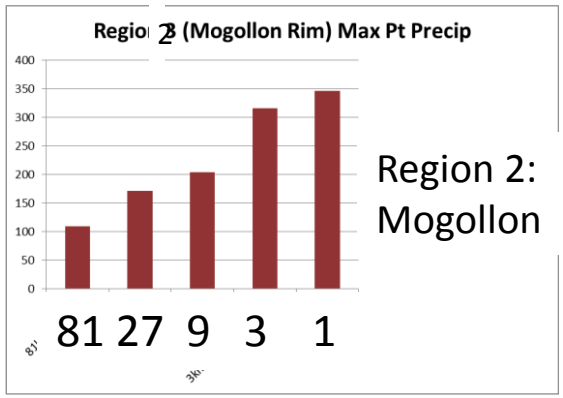
Region maximum precip

Region average precip

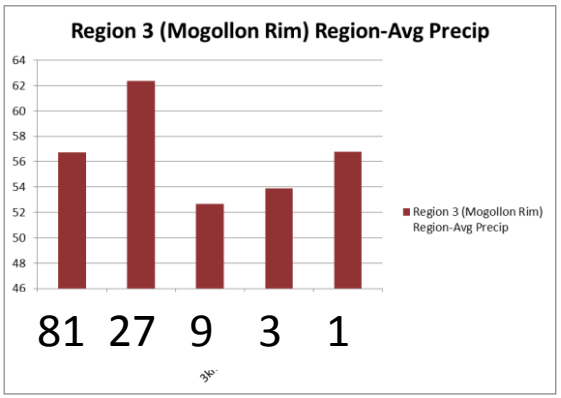


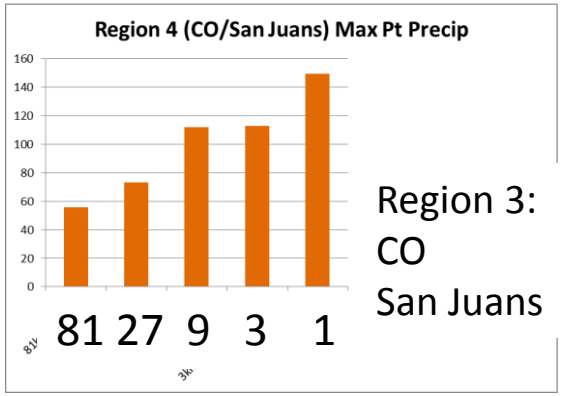
Region 1: Mogollon



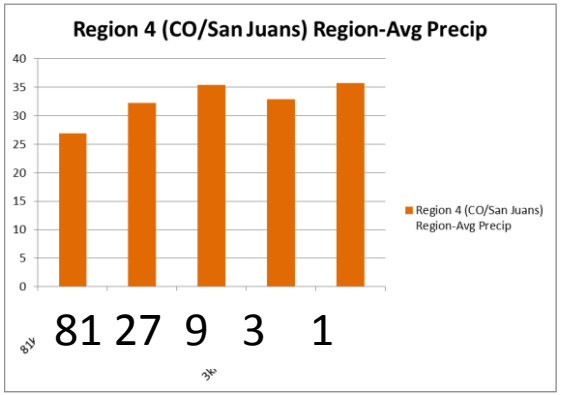


Region 2: Mogollon

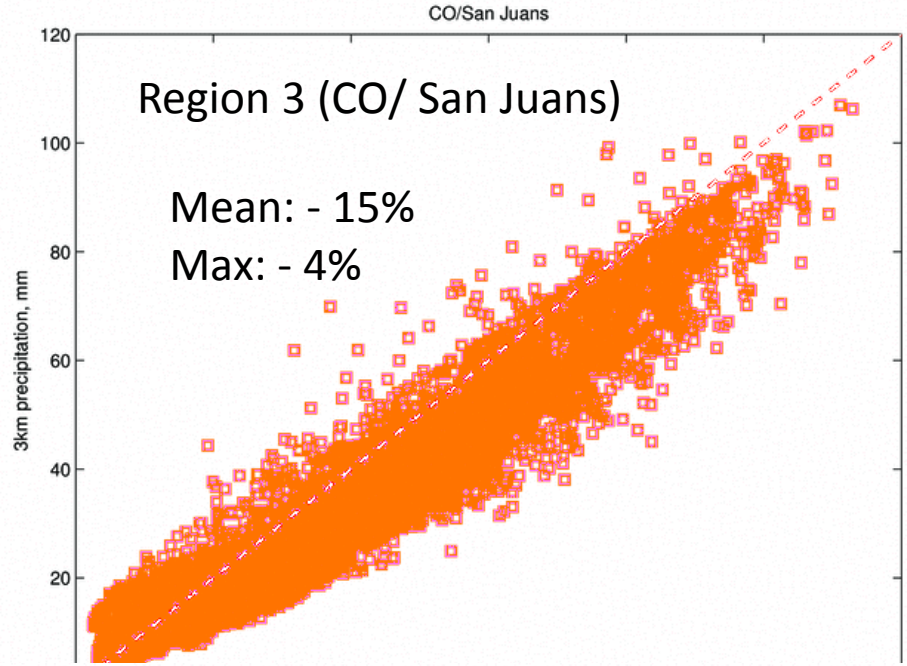


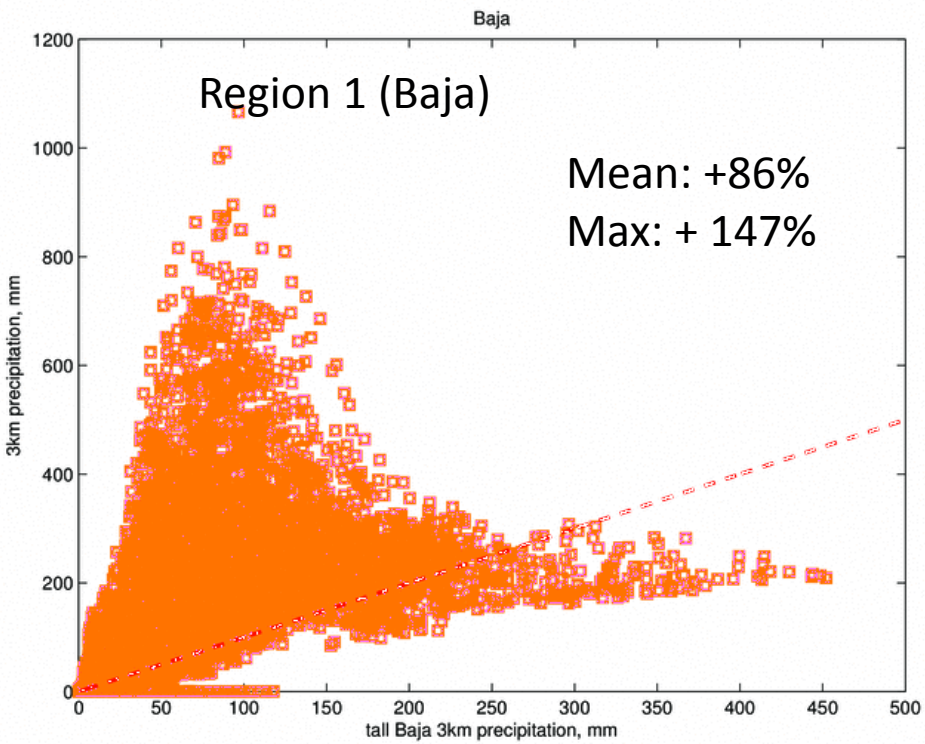


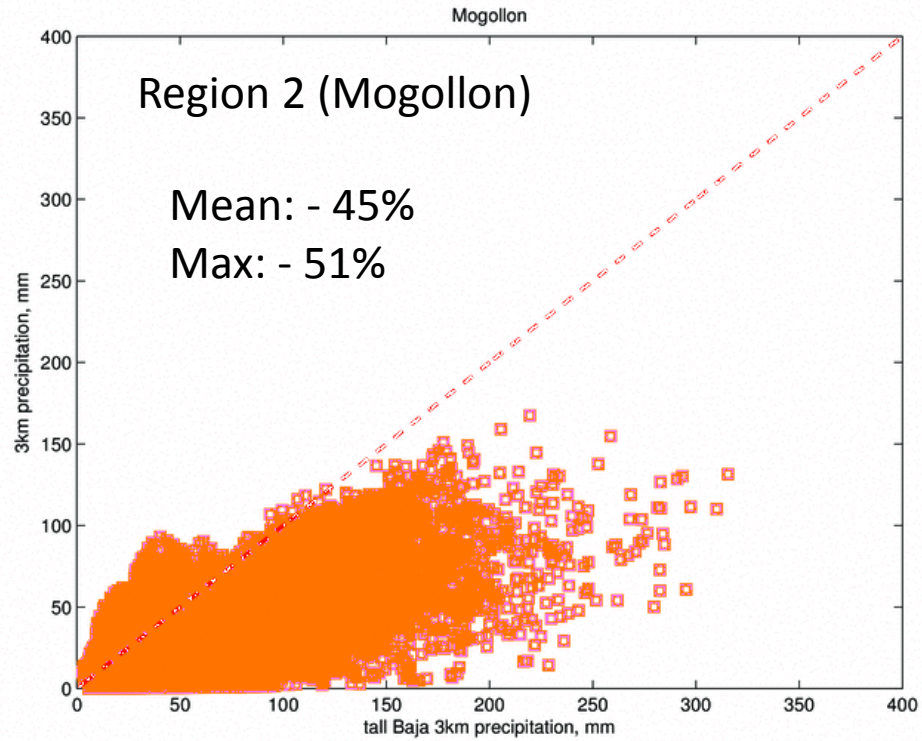
Region 3: CO San Juans



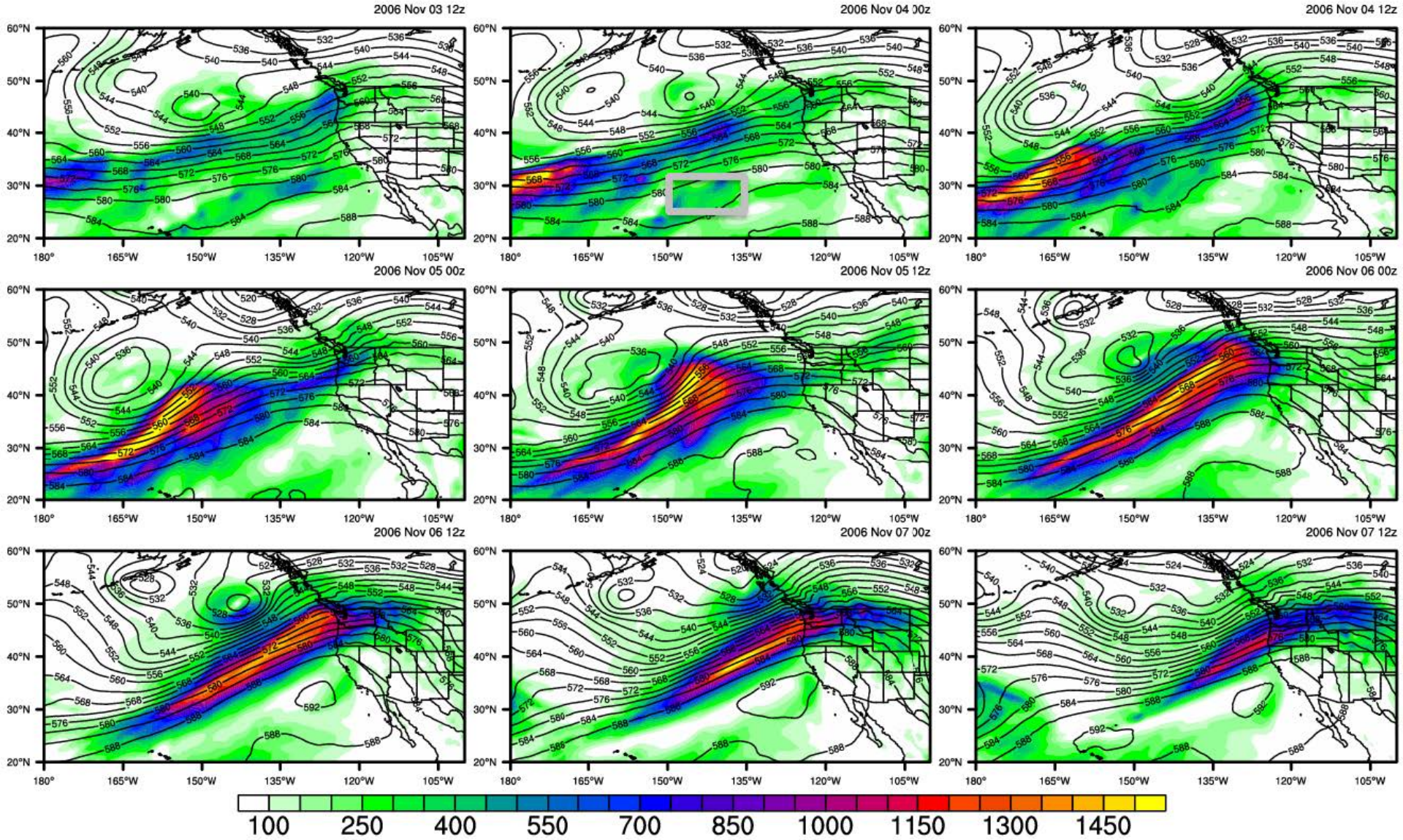
Tall Baja resultant precipitation, compared against CTRL



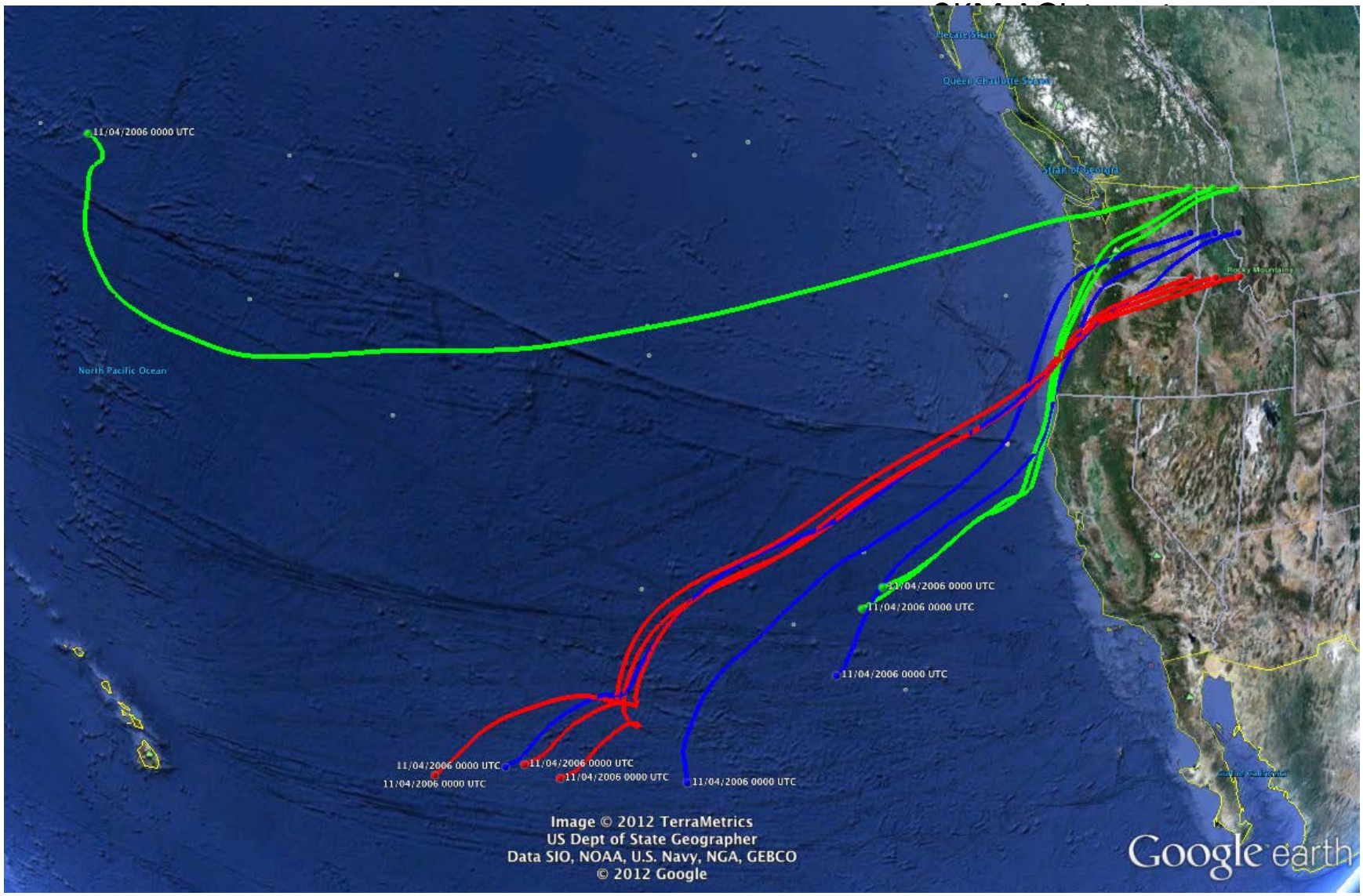




Total IVT (kg m^{-1} s^{-1}) & 500mb Hgt (dm)

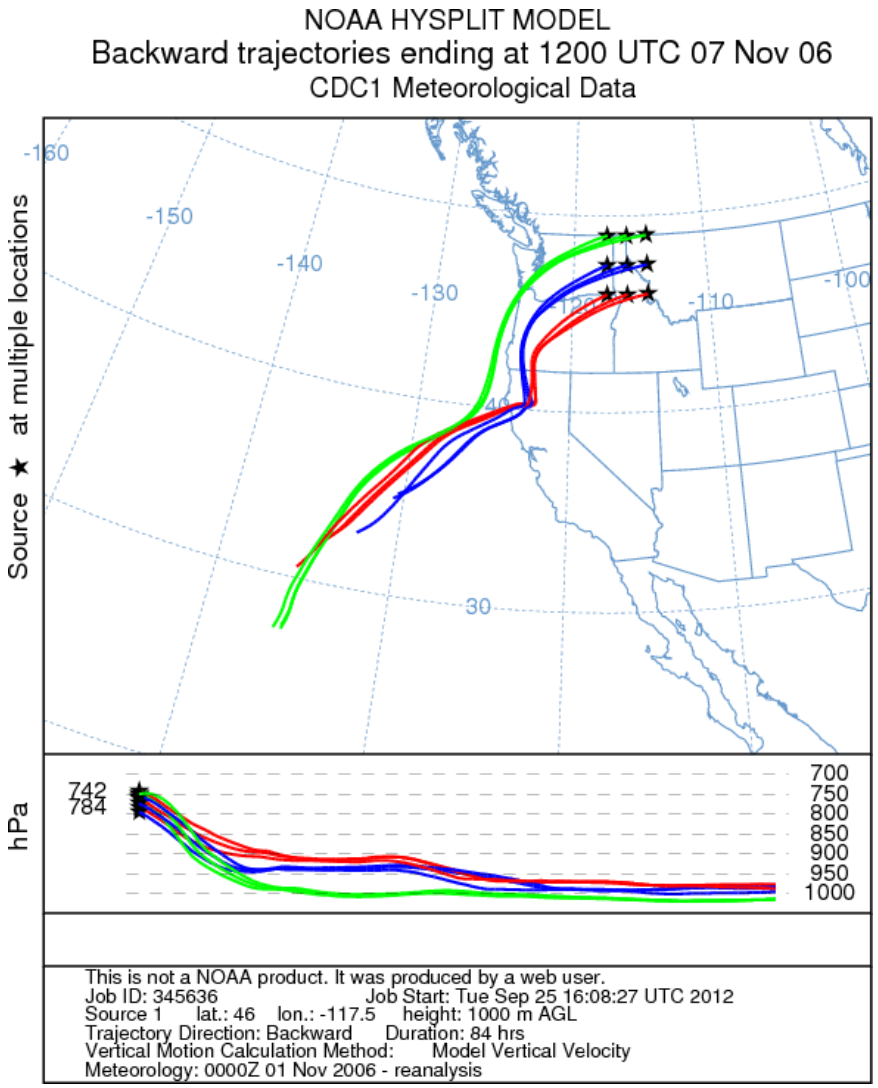


Back trajectories using Hysplit Model
Nov 4-7, 2006. 2KM target

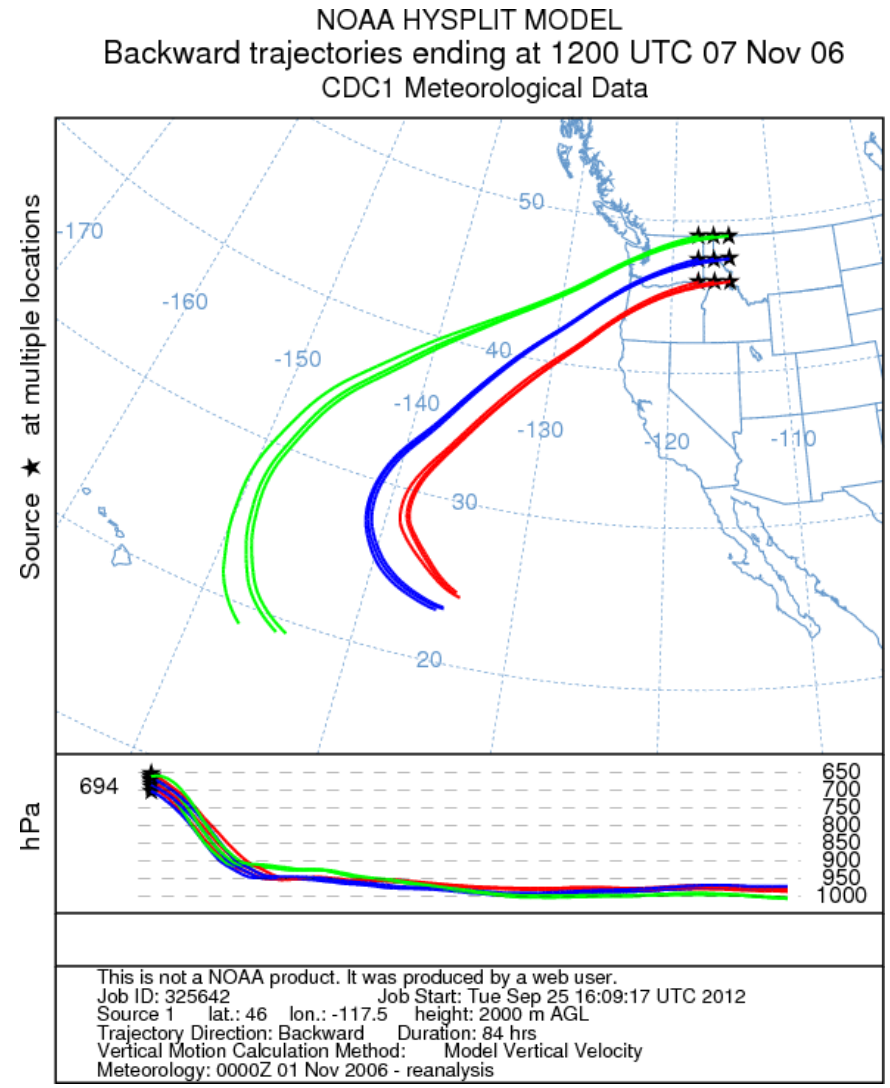


Lower resolution Trajectories (NCEP R1)

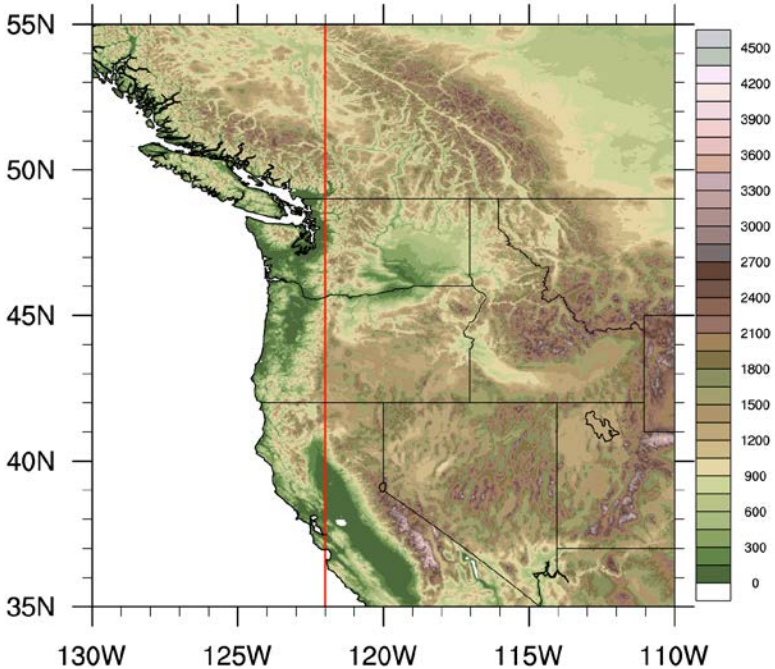
1KM AGL target



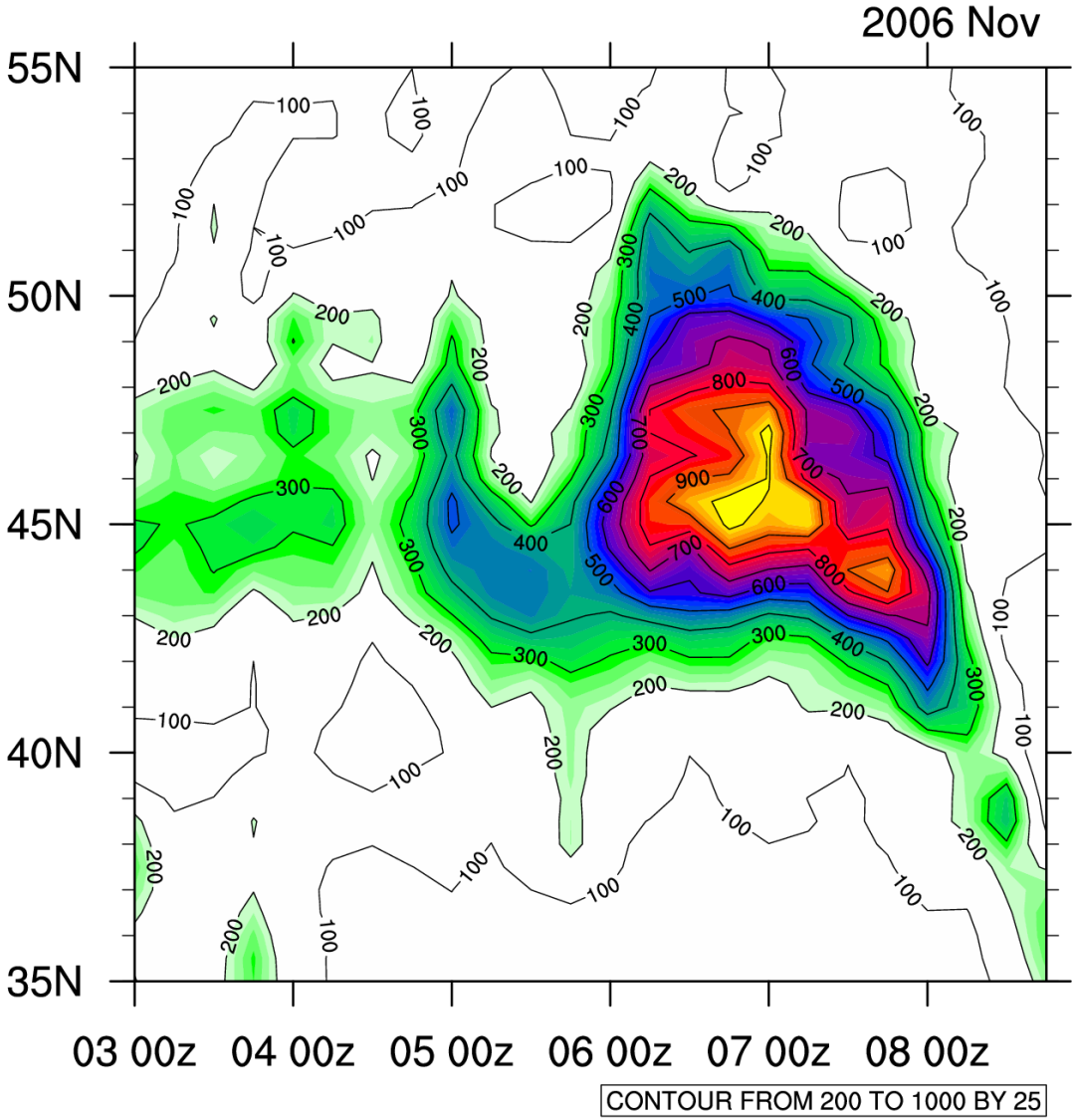
2KM AGL target

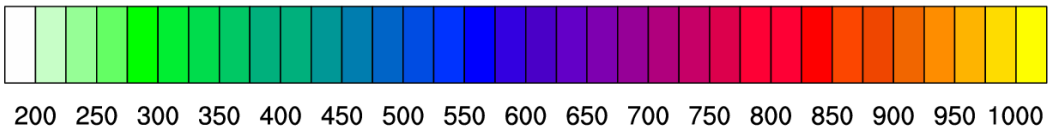


Latitude vs Time IVT along 122° W

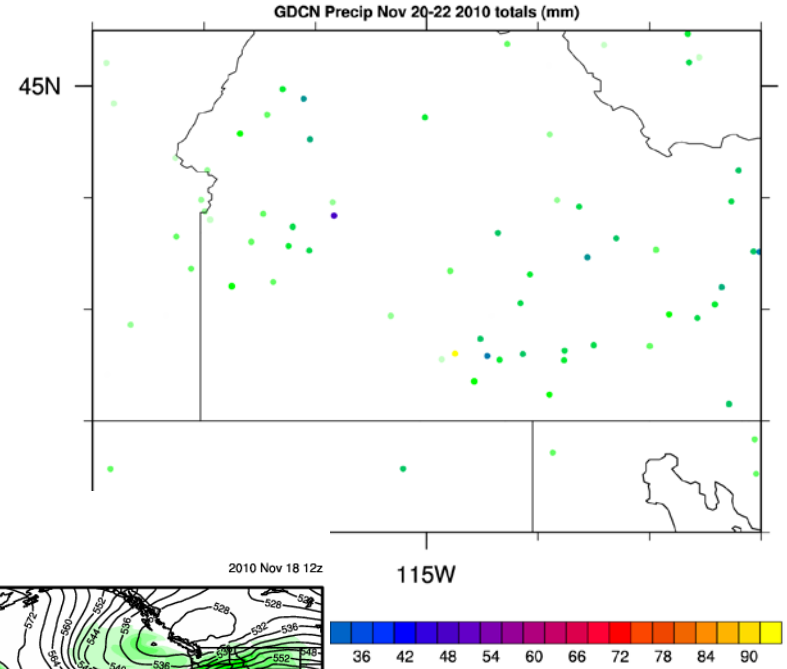


Eastward IVT (kg m^{-1} s^{-1}) @ 122° W

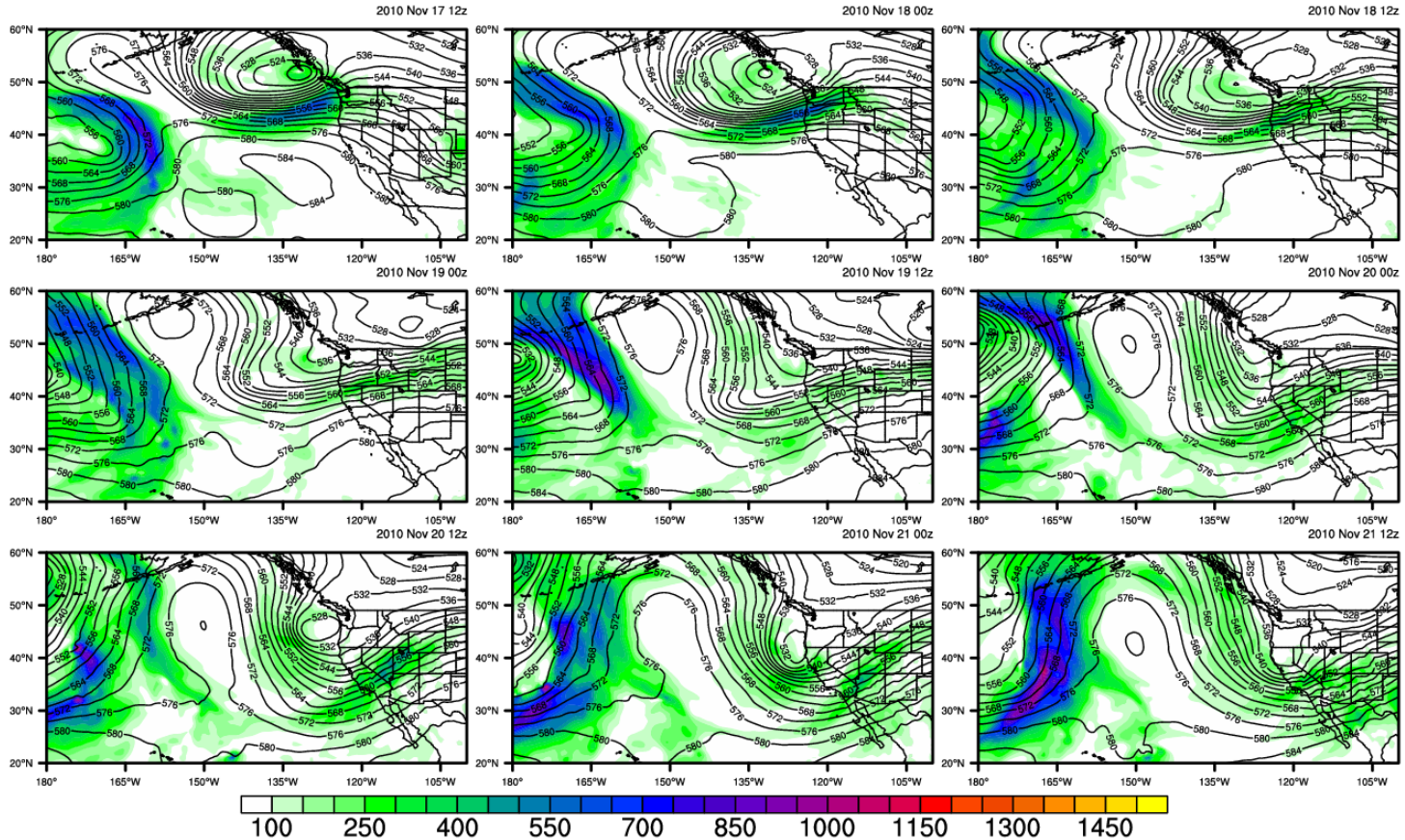




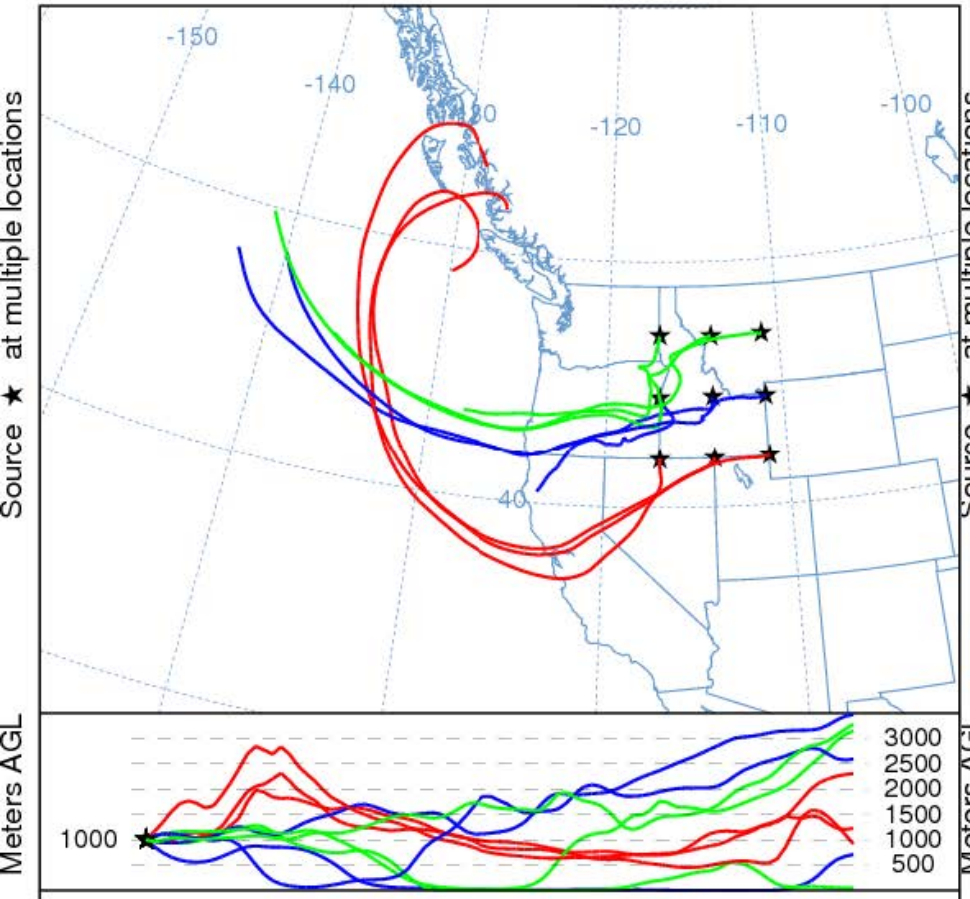
90mm event in S. ID with Gulf of AK source region
Nov 20-22, 2010



Total IVT (kg m^{-1} s^{-1}) & 500mb Hgt (dm)

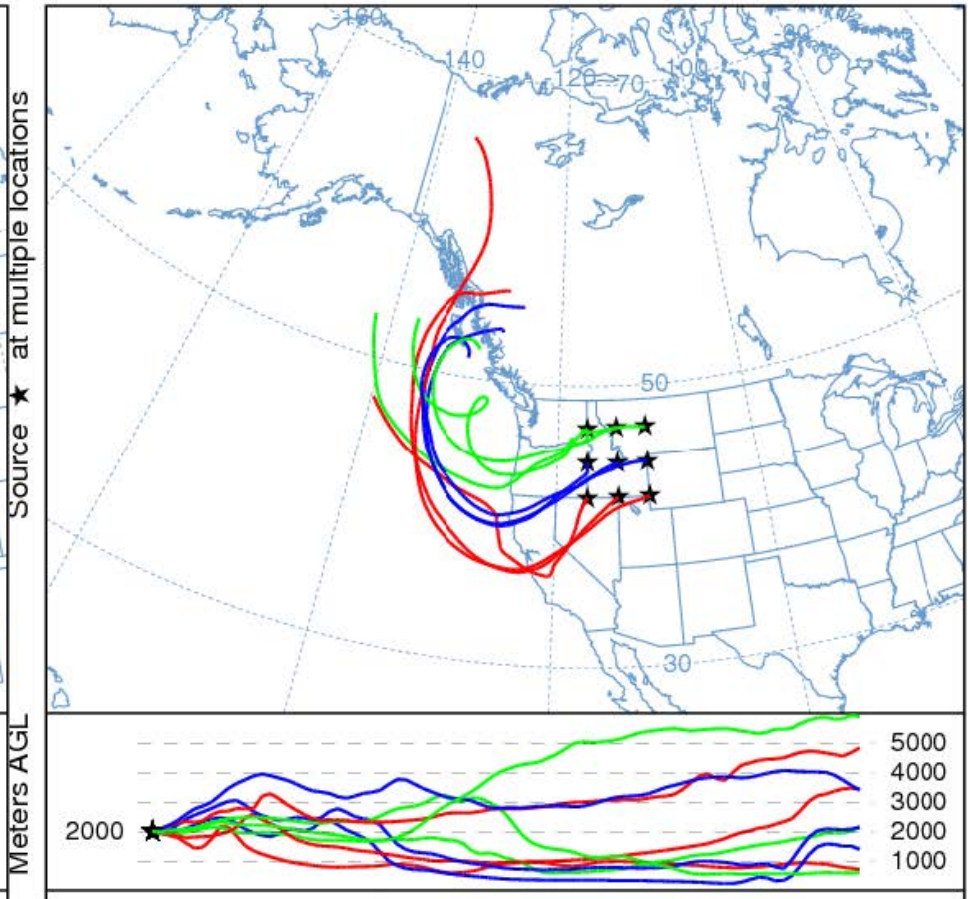


NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 21 Nov 10
GDAS Meteorological Data

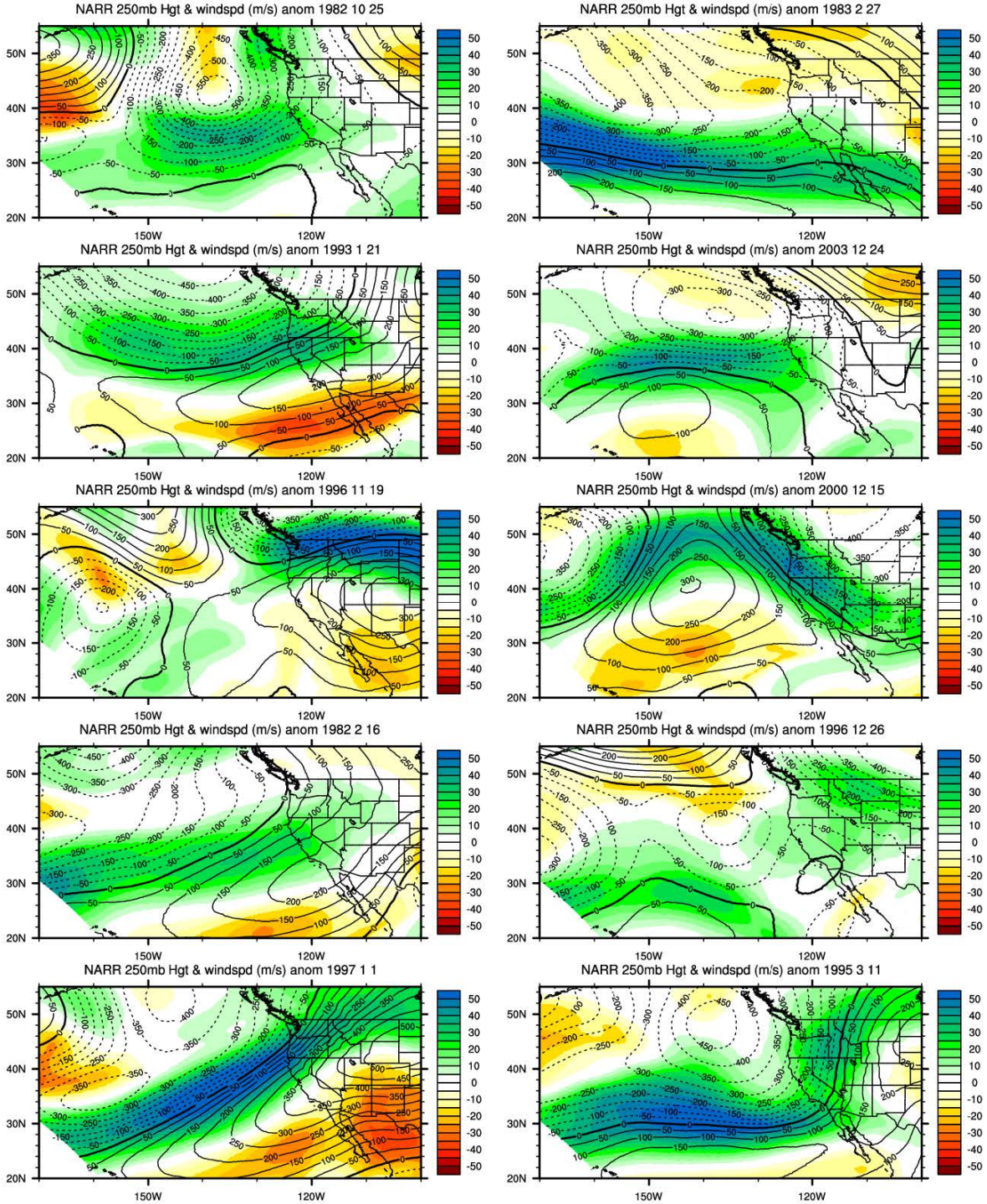


This is not a NOAA product. It was produced by a web user.
Job ID: 366071 Job Start: Tue Sep 25 21:35:36 UTC 2012
Source 1 lat.: 42 lon.: -117 height: 1000 m AGL
Trajectory Direction: Backward Duration: 84 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 15 Nov 2010 - GDAS1

NOAA HYSPLIT MODEL
Backward trajectories ending at 1200 UTC 21 Nov 10
GDAS Meteorological Data



This is not a NOAA product. It was produced by a web user.
Job ID: 376073 Job Start: Tue Sep 25 21:38:29 UTC 2012
Source 1 lat.: 42 lon.: -117 height: 2000 m AGL
Trajectory Direction: Backward Duration: 84 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 15 Nov 2010 - GDAS1


NARR 250mb Hgt & windspd (m/s) anom 1982 10 25
NARR 250mb Hgt & windspd (m/s) anom 1983 2 27
NARR 250mb Hgt & windspd (m/s) anom 1993 1 21
NARR 250mb Hgt & windspd (m/s) anom 2003 12 24
NARR 250mb Hgt & windspd (m/s) anom 1996 11 19
NARR 250mb Hgt & windspd (m/s) anom 2000 12 15
NARR 250mb Hgt & windspd (m/s) anom 1982 2 16
NARR 250mb Hgt & windspd (m/s) anom 1996 12 26
NARR 250mb Hgt & windspd (m/s) anom 1997 1 1
NARR 250mb Hgt & windspd (m/s) anom 1995 3 11
50N
40N
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150W
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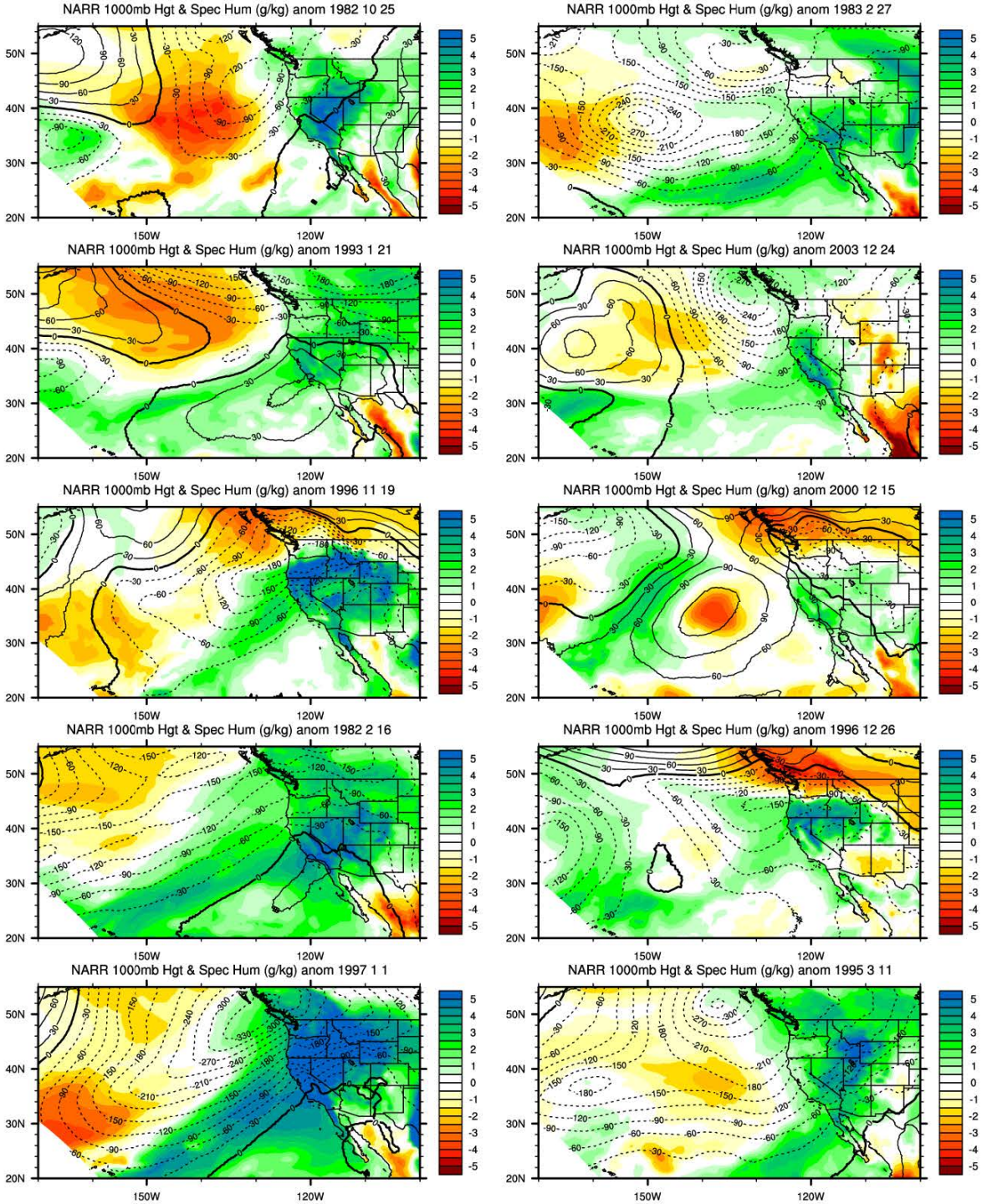
NARR 1000mb Hgt & Spec Hum (g/kg) anom 1982 10 25
NARR 1000mb Hgt & Spec Hum (g/kg) anom 1983 2 27
NARR 1000mb Hgt & Spec Hum (g/kg) anom 1993 1 21
NARR 1000mb Hgt & Spec Hum (g/kg) anom 2003 12 24
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50N
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Concluding 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.