Atmospheric Rivers over the Western United States:

Comparing the Cool-Season Events of 2016/17 to the 1980-2017 Mean

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With acknowledgements to Ben Hatchett (DRI),
Andy Edman (NWS) and Brian Kawzenuk (UCSD)

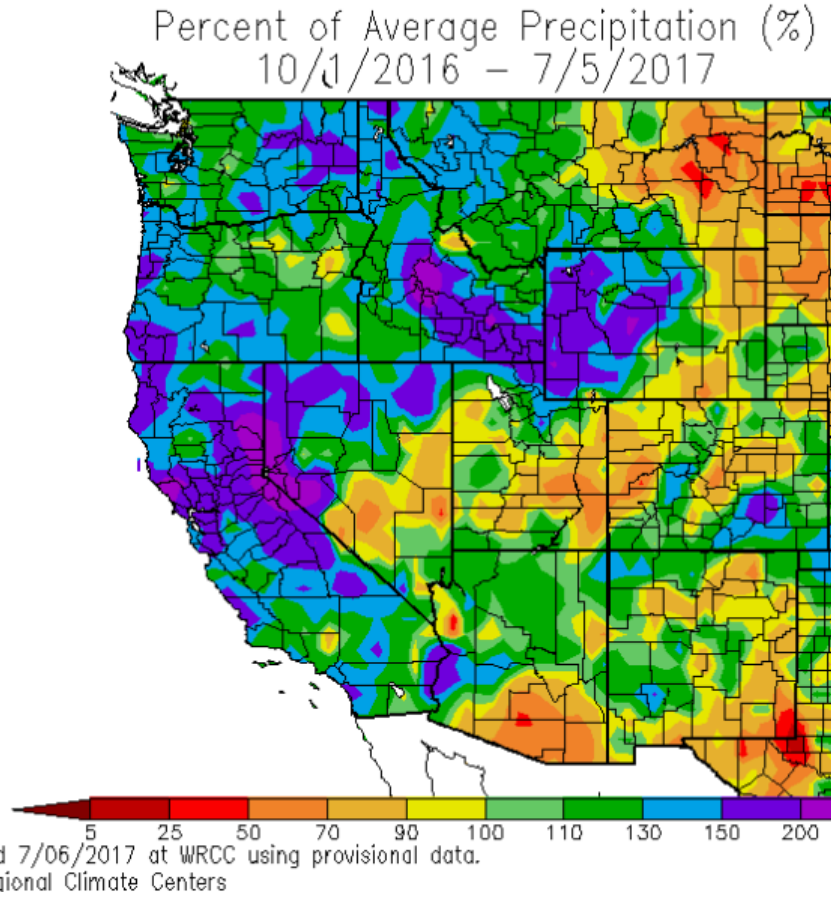
Weather Prediction Center Seminar
NOAA Center for Weather and Climate Prediction – July 17th, 2017

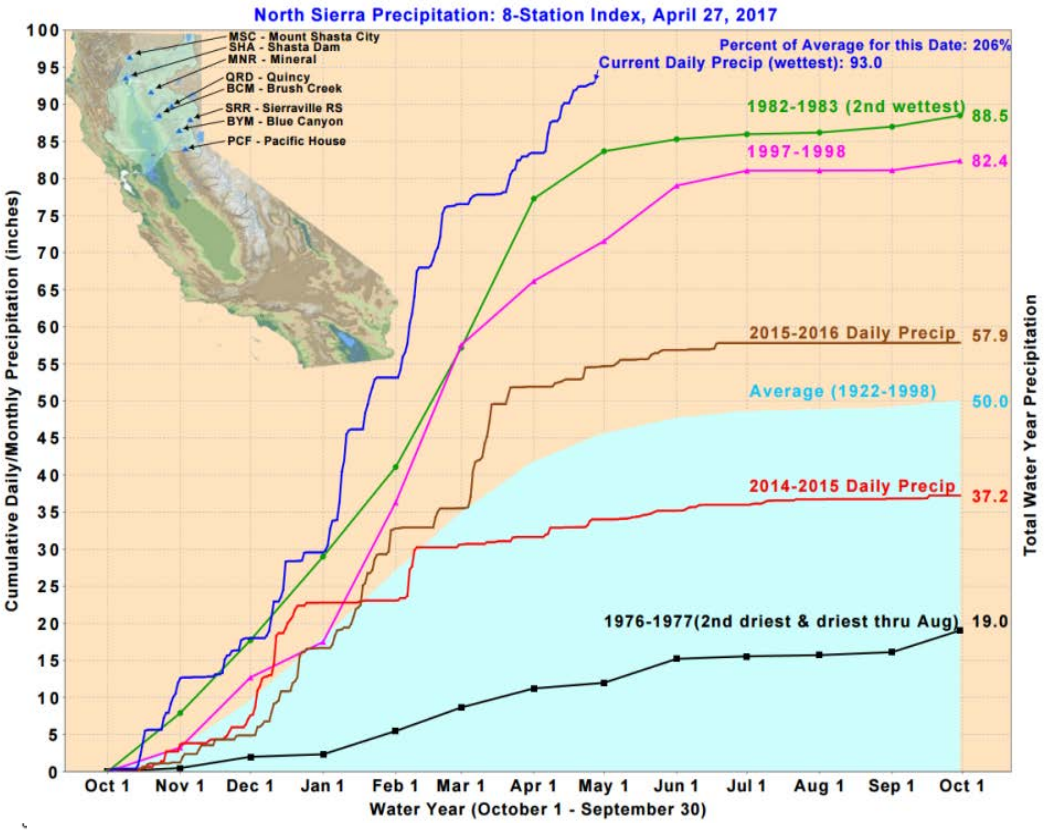
Outline

- Motivation
- Atmospheric Rivers
  - What are they and why do we care?
- Data and Methods
- Results
  - Statistics over the western U.S.
  - ARs and Precipitation
  - Statistics at Selected Points

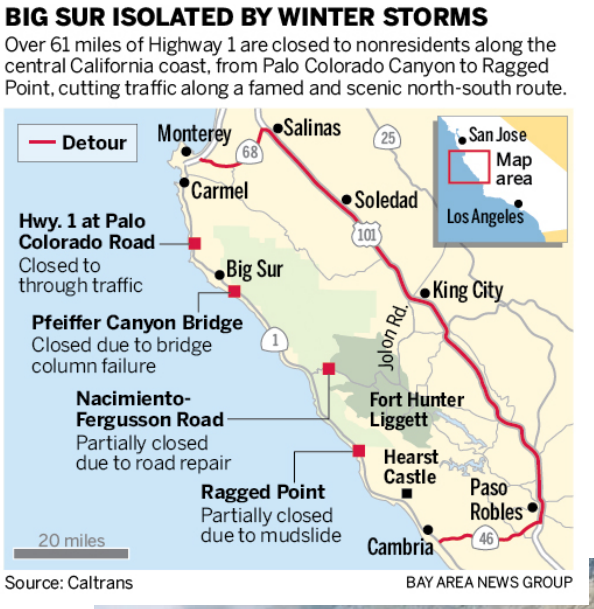
Motivation – Hazards

Incredibly wet and snowy year for the western U.S.





Motivation – Hazards

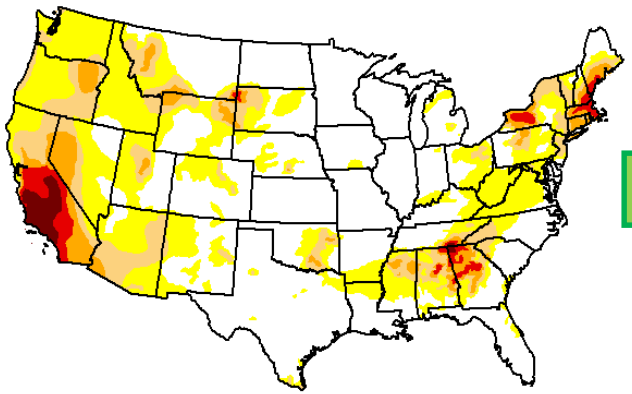



Mammoth Mountain Resort, CA (Jan 2017)

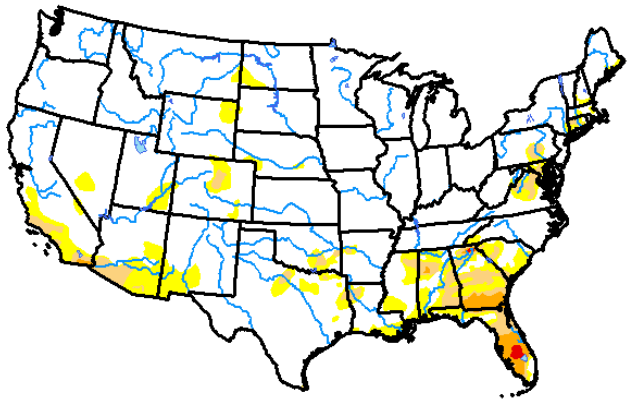

Big Sur, CA (May 2017)


Oroville Dam Spillway, CA (Feb 2017)

Motivation – Benefits



2016/17 Cool Season



September 27, 2016
(Released Thursday, Sep. 29, 2016)
Valid 8 a.m. EDT

Drought Conditions (Percent Area)

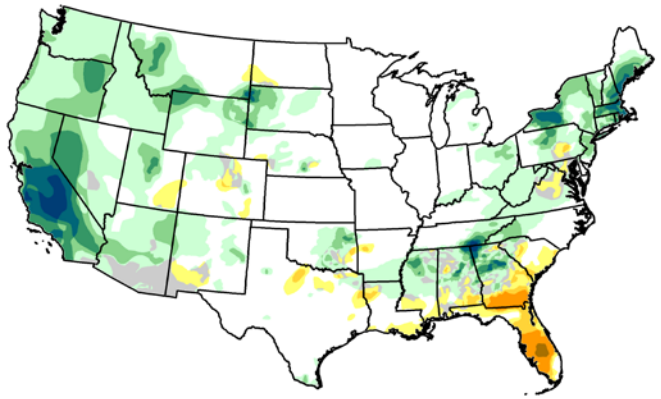
	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	53.60	46.40	18.96	8.10	3.20	1.16
Last Week 9/20/2016	54.97	45.03	18.82	7.76	2.94	1.11
3 Months Ago 6/28/2016	56.61	43.39	16.18	5.43	2.36	1.11
Start of Calendar Year 12/29/2015	66.99	33.01	18.74	11.56	6.28	2.70
Start of Water Year 9/29/2015	44.91	55.09	31.36	20.09	11.45	3.00
One Year Ago 9/29/2015	44.91	55.09	31.36	20.09	11.45	3.00

Intensity:

- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

U.S. Drought Monitor Class Change - CONUS
Start of Water Year



May 2, 2017
compared to
September 27, 2016

May 2, 2017
(Released Thursday, May. 4, 2017)
Valid 8 a.m. EDT

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	85.69	14.31	4.98	1.30	0.13	0.00
Last Week 04-25-2017	78.33	21.67	6.11	1.07	0.03	0.00
3 Months Ago 01-31-2017	68.02	31.98	14.55	3.83	0.41	0.00
Start of Calendar Year 01-03-2017	53.89	46.11	22.53	8.63	3.15	0.96
Start of Water Year 09-27-2016	53.60	46.40	18.96	8.10	3.20	1.16
One Year Ago 05-03-2016	66.11	33.89	14.56	5.46	3.44	1.11

Intensity:

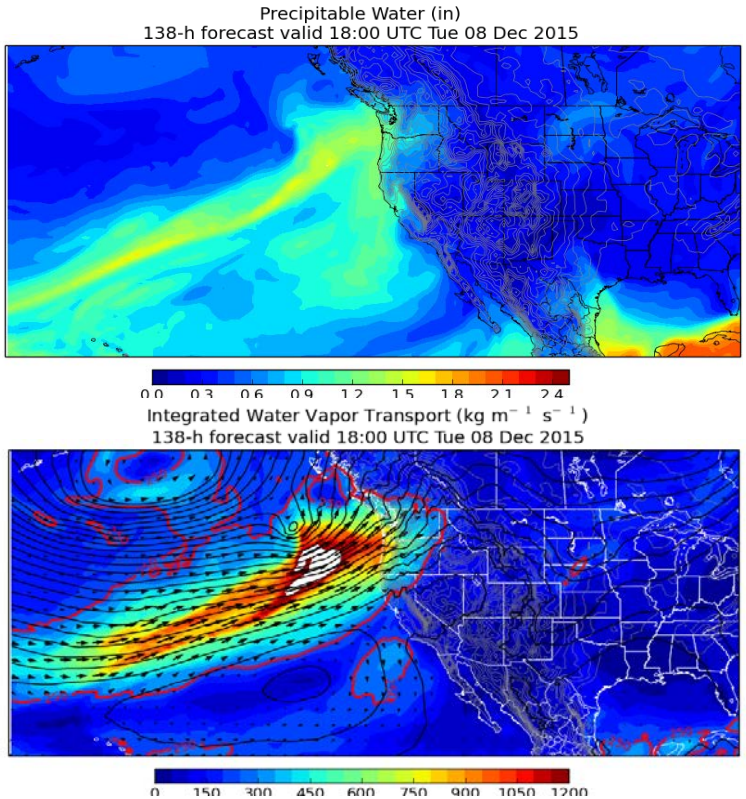
- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

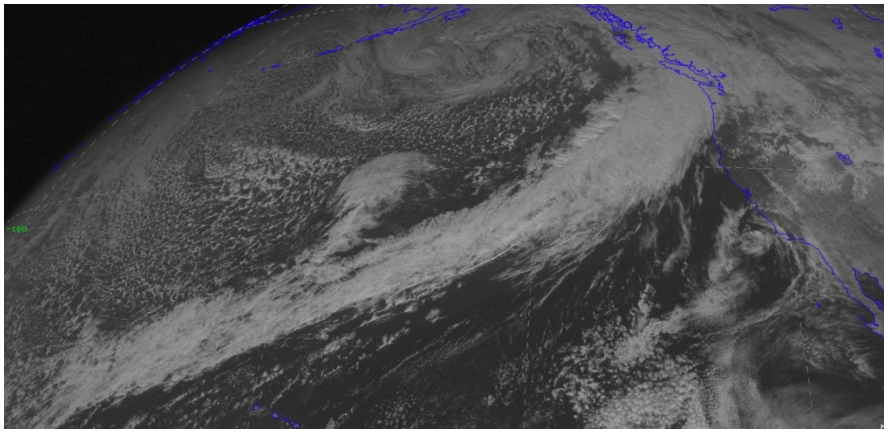
The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

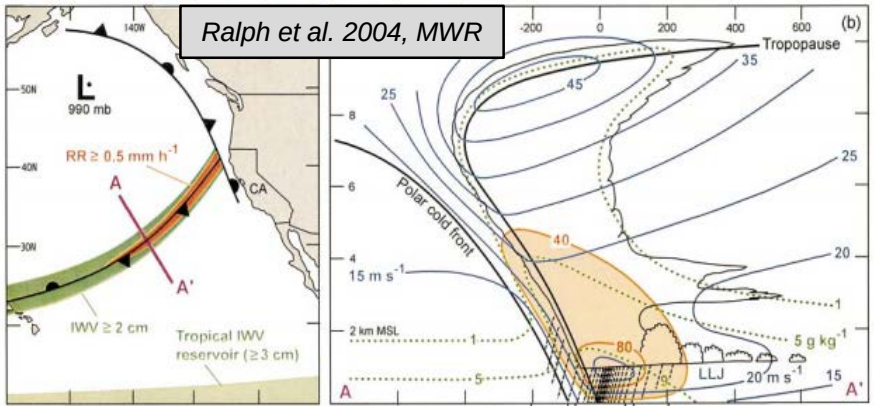
Atmospheric Rivers – What Are They?

- Atmospheric rivers (ARs): elongated regions of intense vertically integrated water vapor transport (IVT). They are…
  - **Long (> 2000 km)**
  - **Narrow (< 1000 km)**
  - **Large IVT (> 250 kg m^{-1} s^{-1})**

→ **Length/Width > 2/1**



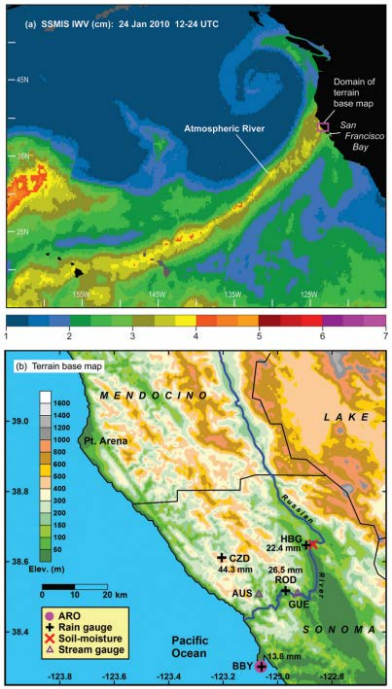


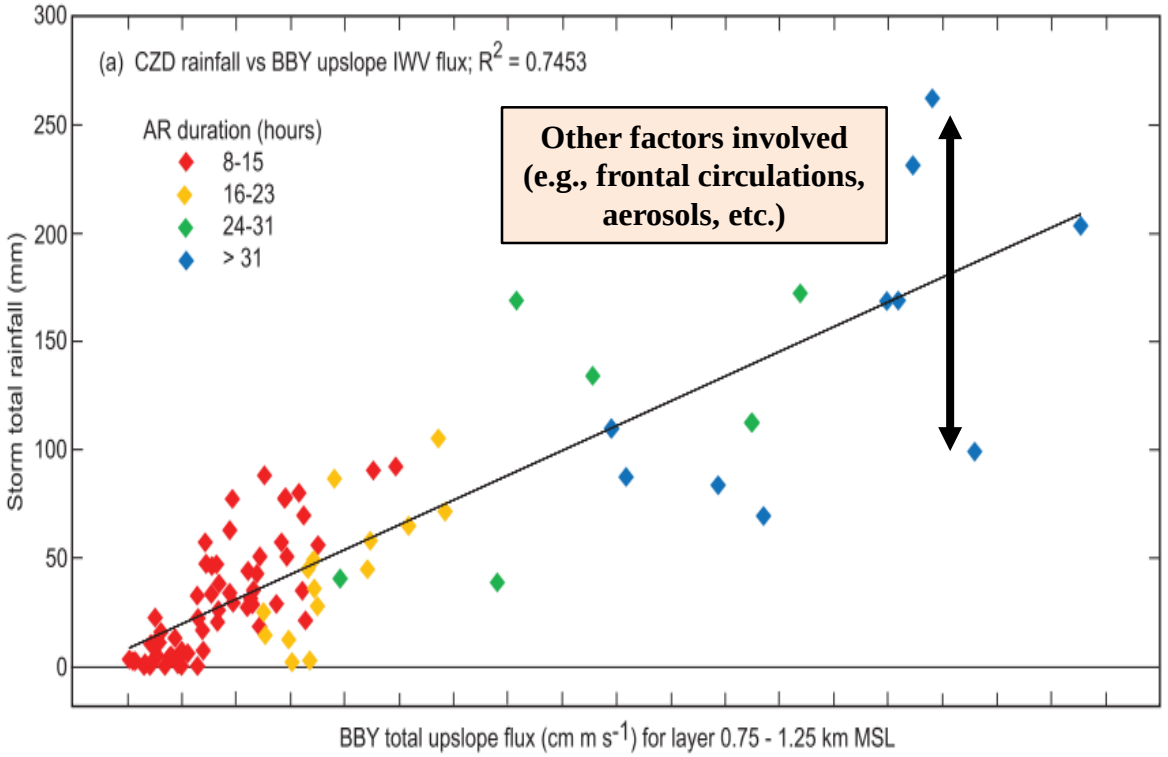


Atmospheric Rivers – Why Do We Care?

Observed impacts of duration and seasonality of atmospheric-river landfalls on soil moisture and runoff in coastal northern California

Ralph, F. M., T. Coleman, P. J. Neiman, R. Zamora, and M. D. Dettinger, J. Hydrometeorology, 2013





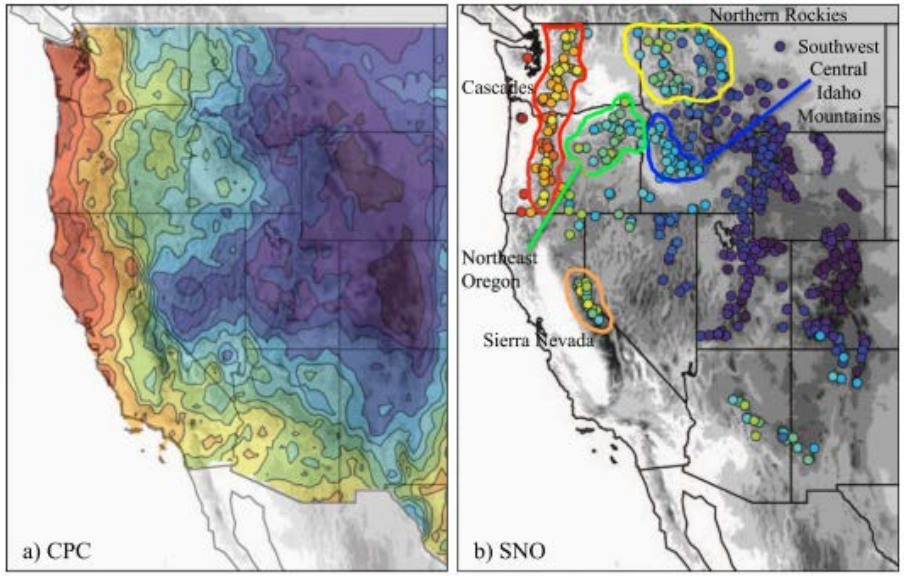
The greater the precipitation

The greater the AR strength and duration

Atmospheric Rivers – Why Do We Care?

Climatological characteristics of atmospheric rivers and their inland penetration over the western United States

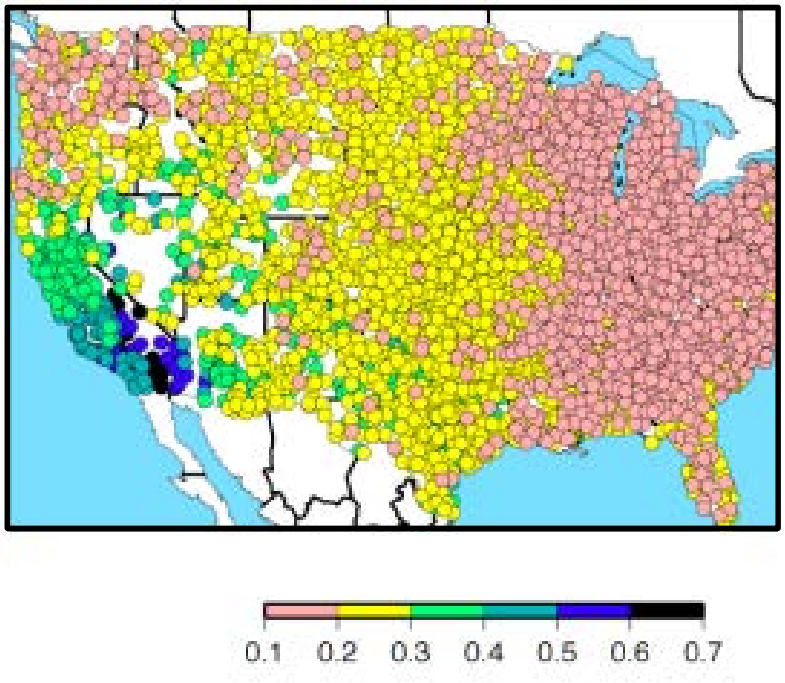
Rutz, J. J., W. J. Steenburgh, and F. M. Ralph, Mon. Wea. Rev., 2014



Fraction of cool-season (Nov – Apr) precipitation attributable to ARs based on (left) CPC analysis and (right) SNOTEL data

Atmospheric rivers, floods, and the water resources of California

Dettinger, M. D., F. M. Ralph, T. Das, P. J. Neiman, and D. R. Cayan, Water, 2011



Coefficient of variation for annual precipitation

Key Science Questions for 2016/17

- ***How*** was 2016/17 different from average?
  - Were there simply more AR events?
  - Were they longer-lived AR events?
  - Were they more intense AR events?
  - Or maybe all 3?

- ***What*** was the relationship between ARs and precipitation during the 2016/17 cool season?

- ***Why*** was 2016/17 different from average?
  - More on this at the end

Data and Analysis

- MERRA v2 Reanalysis used to calculate IVT and ARs from **Jan 1980 – Apr 2017**
  - 0.5°×0.625° horizontal grid
  - 25 hPa from 1000-700 hPa
  - 50 hPa from 500-200 hPa
  - 3-hour time steps
  - Most of CONUS and AK
  - example shown at right

123.125°W, 38.5°N

yyyy	mm	dd	hh	AR?	new AR?	AR duration	ivt
2017	2	5	9	0	0	0	182.80
2017	2	5	12	0	0	0	177.52
2017	2	5	15	0	0	0	196.64
2017	2	5	18	1	1	3	268.17
2017	2	5	21	1	0	6	350.94
2017	2	6	0	1	0	9	462.30
2017	2	6	3	1	0	12	531.89
2017	2	6	6	1	0	15	325.53
2017	2	6	9	1	0	18	274.47
2017	2	6	12	1	0	21	279.71
2017	2	6	15	1	0	24	302.33
2017	2	6	18	1	0	27	279.04
2017	2	6	21	1	0	30	366.22
2017	2	7	0	1	0	33	420.16
2017	2	7	3	1	0	36	474.17
2017	2	7	6	1	0	39	717.14
2017	2	7	9	1	0	42	766.54
2017	2	7	12	1	0	45	680.94
2017	2	7	15	1	0	48	800.43
2017	2	7	18	1	0	51	486.54
2017	2	7	21	1	0	54	353.27
2017	2	8	0	1	0	57	297.10
2017	2	8	3	0	0	0	208.20
2017	2	8	6	0	0	0	234.37
2017	2	8	9	1	1	3	395.92
2017	2	8	12	1	0	6	563.81

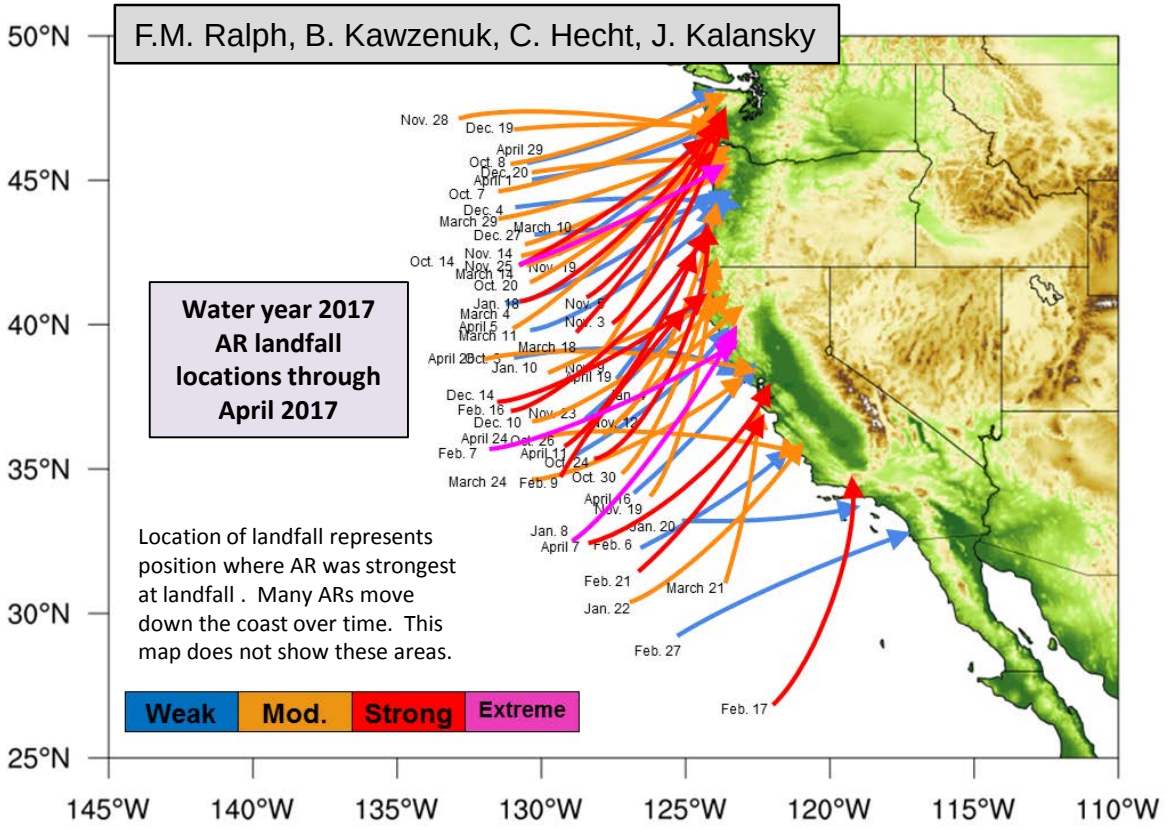
Data Available at: http://www.inscc.utah.edu/~rutz/ar_catalogs/

2016/17 Cool Season ARs

Ralph/CW3E AR Strength Scale

- Weak: IVT=250–500 kg m^{-1} s^{-1}
- Moderate: IVT=500–750 kg m^{-1} s^{-1}
- Strong: IVT=750–1000 kg m^{-1} s^{-1}
- Extreme: IVT>1000 kg m^{-1} s^{-1}

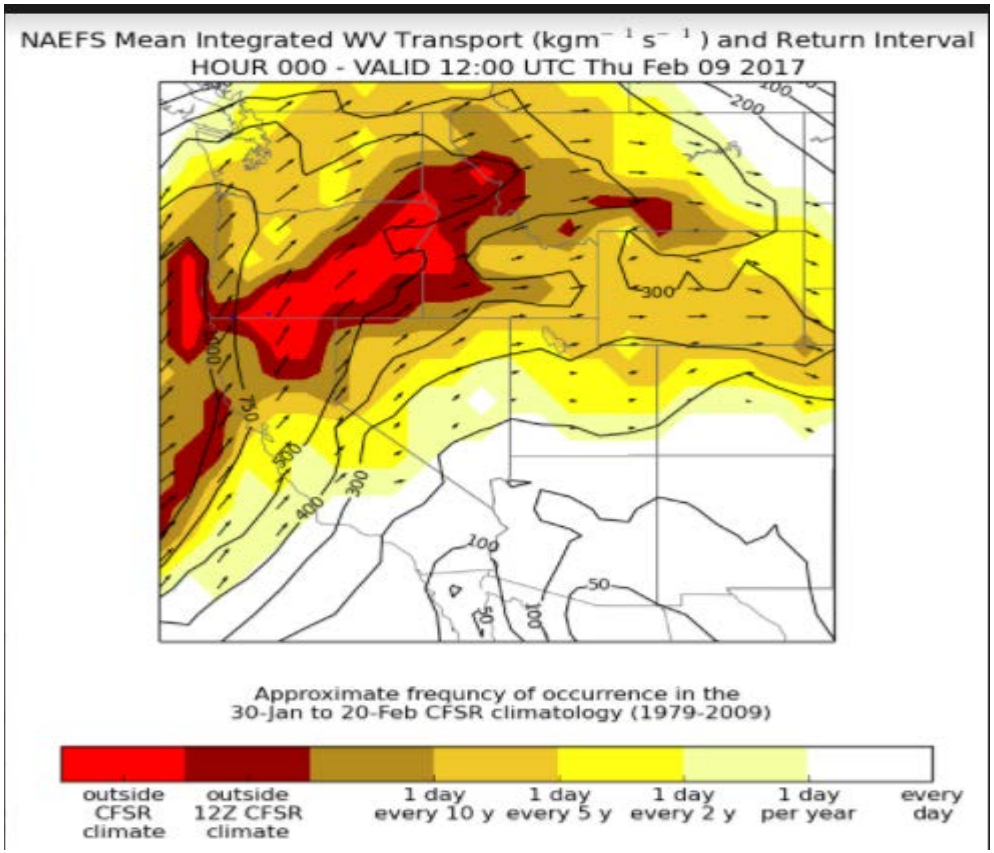
AR Strength	AR Count*
Weak	15
Moderate	23
Strong	13
Extreme	3



*Radiosondes at Bodega Bay, CA indicated the 10–11 Jan AR was strong (noted as moderate based on GFS analysis data) and 7–8 Feb AR was extreme (noted as strong)

- 54 ARs have made landfall on the West Coast thus far during the 2017 water year (1 Oct. – 1 May 2017)
- This is much greater than normal
- 1/3 of the landfalling ARs have been “strong” or “extreme”

AR Examples

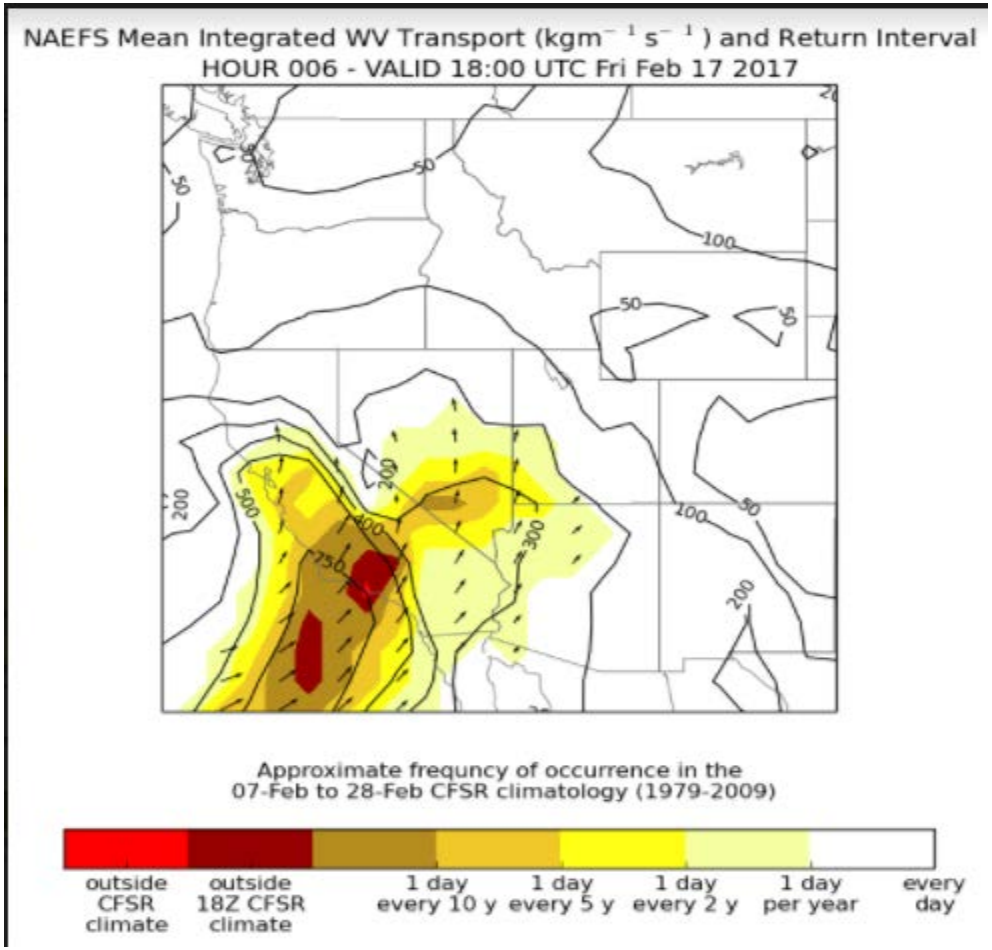


MIMIC TPW
ftp://ftp.ssec.wisc.edu/pub/ssec/edman1
Courtesy of Anthony Wimmers/Chris Veldon - UW – Jon Rutz WR/STID

Feb 6-10, 2016

- 12" over the Feather River Basin led to the Oroville Dam crisis
- ftp://ftp.ssec.wisc.edu/pub/ssec/edman1/mimic_epac0207-0211.gif

AR Examples



MIMIC TPW

ftp://ftp.ssec.wisc.edu/pub/ssec/edman1

Courtesy of Anthony Wimmers/Chris Veldon - UW – Jon Rutz WR/STID

Feb 17-18 2016

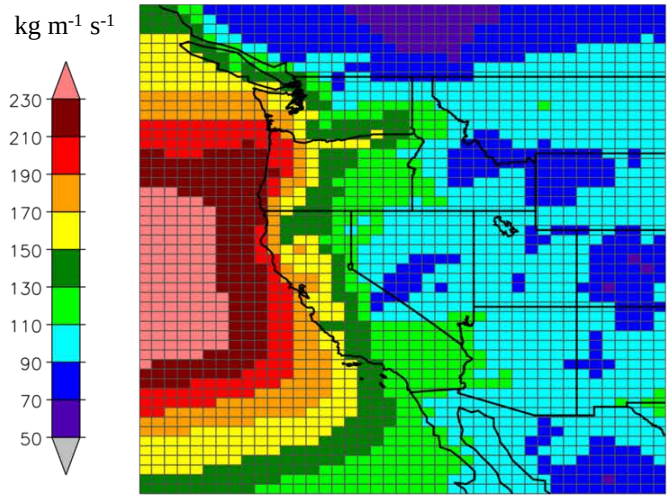
- Much more quickly progressing AR, but heavy rain and landslides in the LA and surrounding mountains... talking to folks at Oxnard and San Diego... probably most significant SoCal event since 2010/11.12" over the Feather River Basin led to the Oroville Dam crisis
- ftp://ftp.ssec.wisc.edu/pub/ssec/edman1/mimic_epac0214-0218.gif

AR Examples

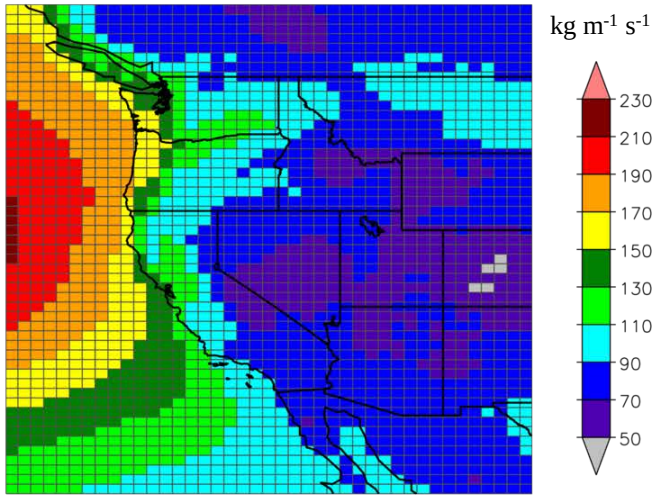
- Early Jan AR event
  - ftp://ftp.ssec.wisc.edu/pub/ssec/edman1/170106-11_mimic_tpw_EPAC_CA_anim.gif

- Early Season Trpoical Transition
  - ftp://ftp.ssec.wisc.edu/pub/ssec/edman1/161010-15_mimic_tpw2_Songda_to_PacNW_anim.gif

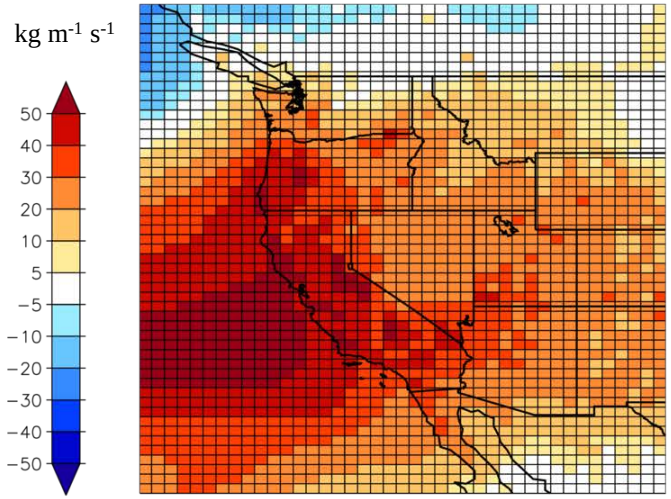
Integrated Water Vapor Transport (IVT)



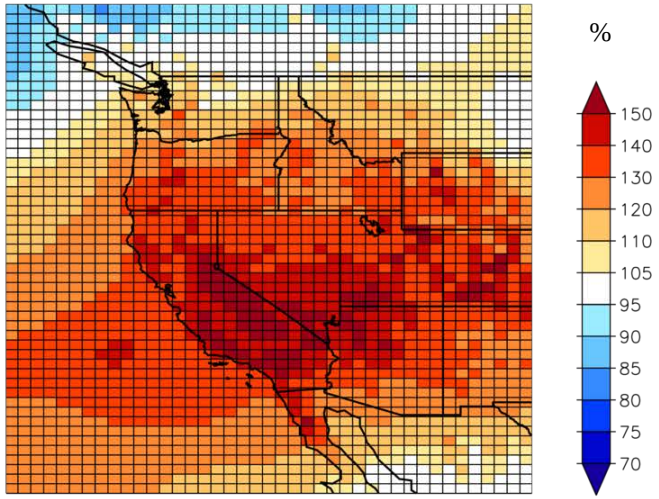
2016/17 Cool Season



1980-2017 Cool Season Mean

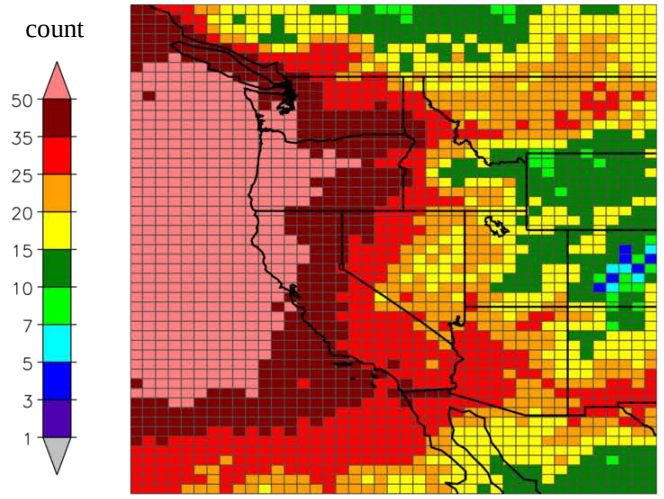


Difference (2016/17 – Mean)

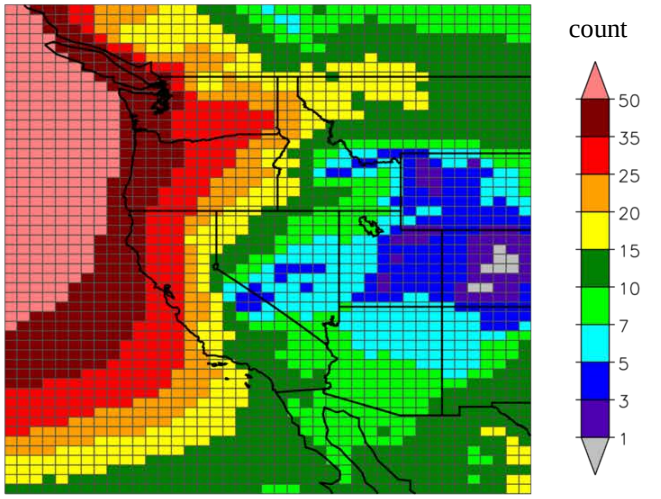


Percentage (2016/17 ÷ Mean)

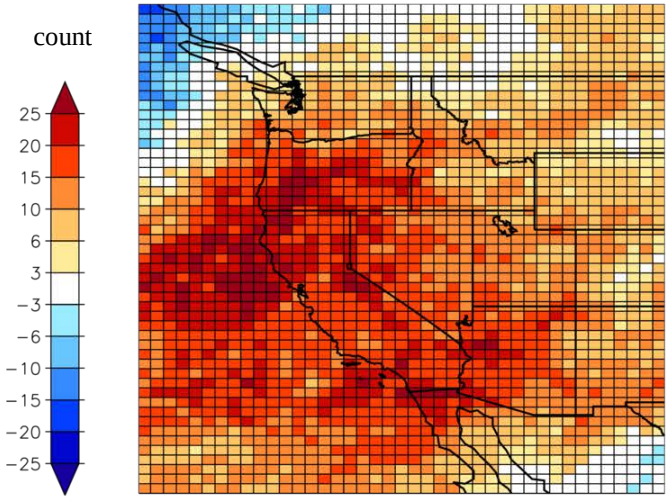
Atmospheric River Events (IVT ≥ 250)



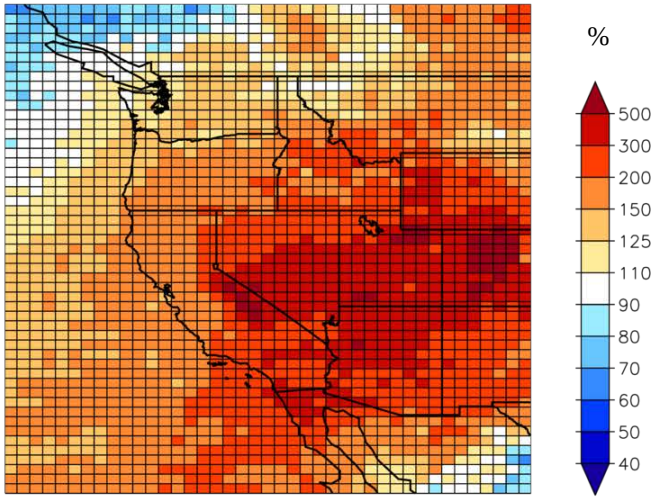
2016/17 Cool Season



1980-2017 Cool Season Mean

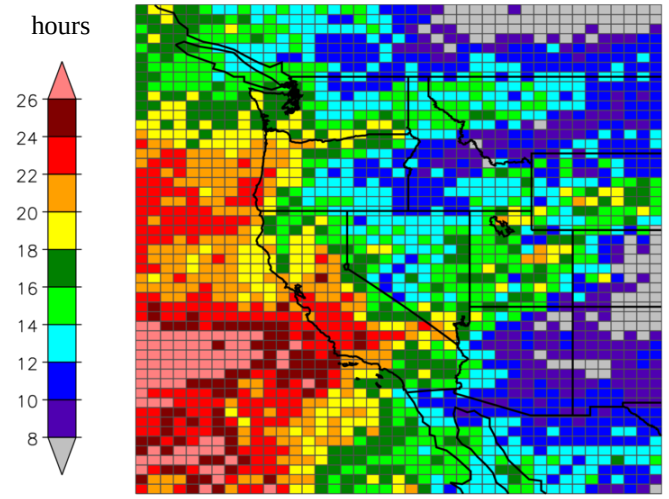


Difference (2016/17 – Mean)

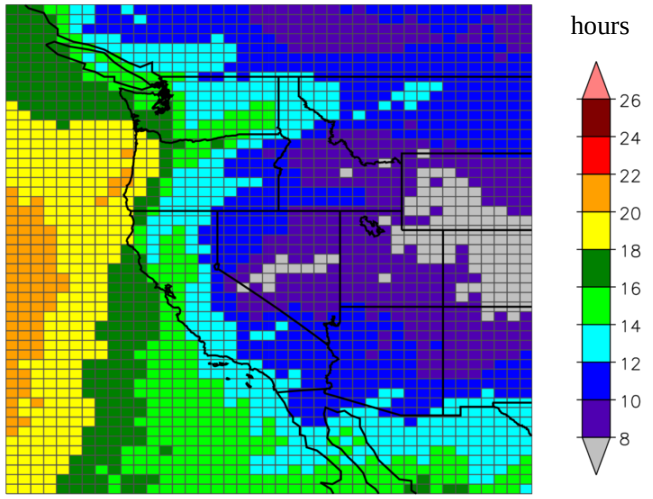


Percentage (2016/17 ÷ Mean)

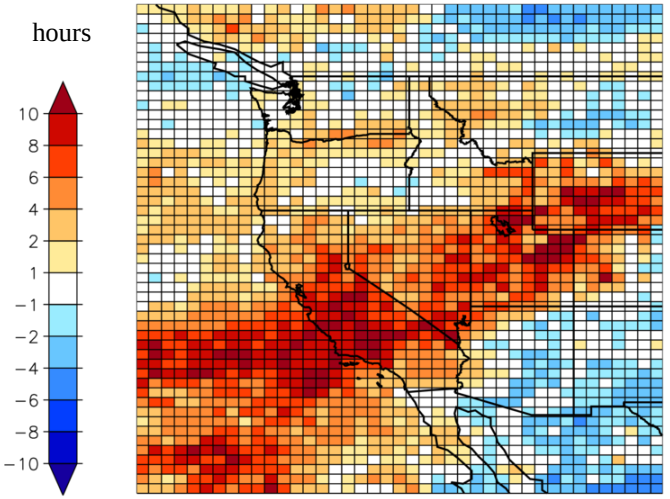
Atmospheric River Mean Duration



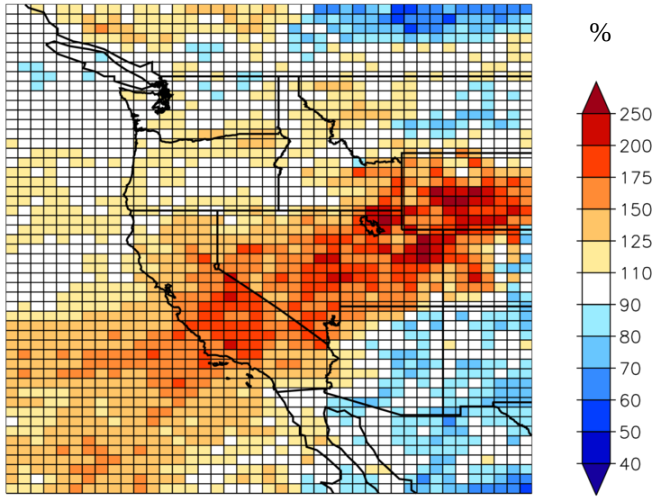
2016/17 Cool Season



1980-2017 Cool Season Mean



Difference (2016/17 – Mean)

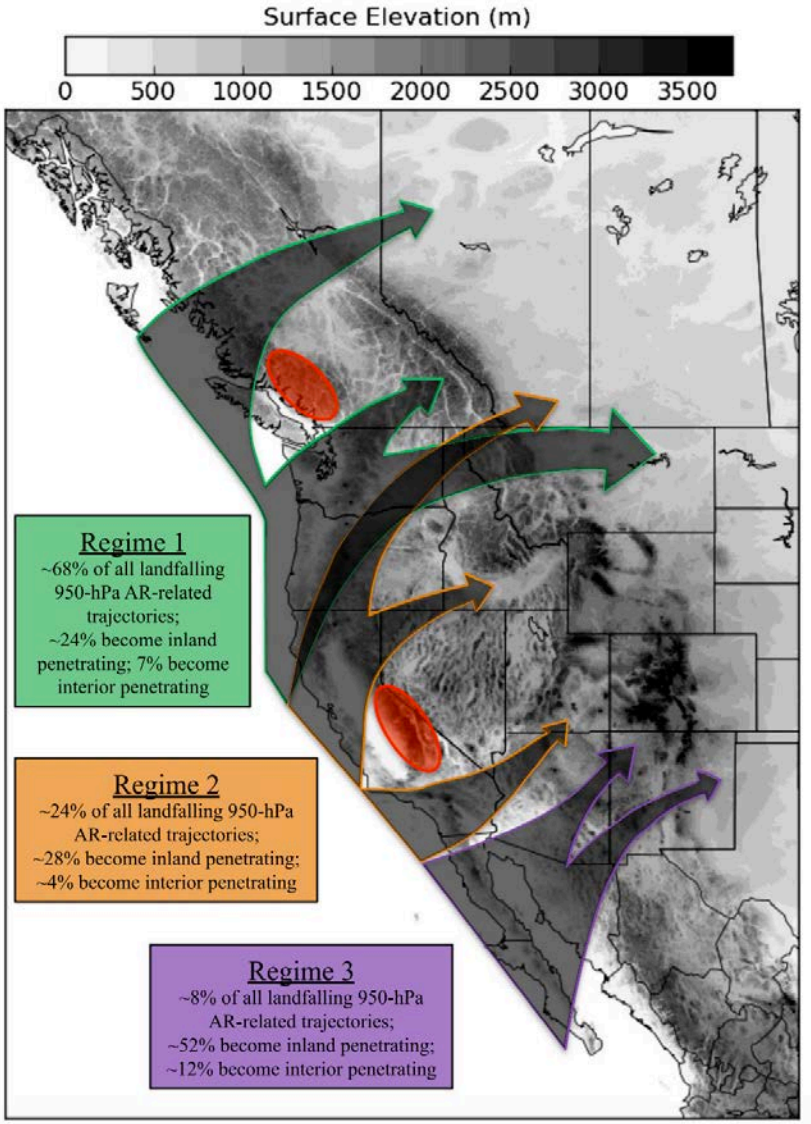


Percentage (2016/17 ÷ Mean)

What Explains Great Basin Anomalies?

Typically, the high Sierra are strongly conducive to AR decay via water vapor depletion, as well as flow blocking and deflection (Rutz et al. 2015 Mon. Wea. Rev.; Swales et al. 2016 Geophys. Res. Lett.; Hudson et al. in prep).

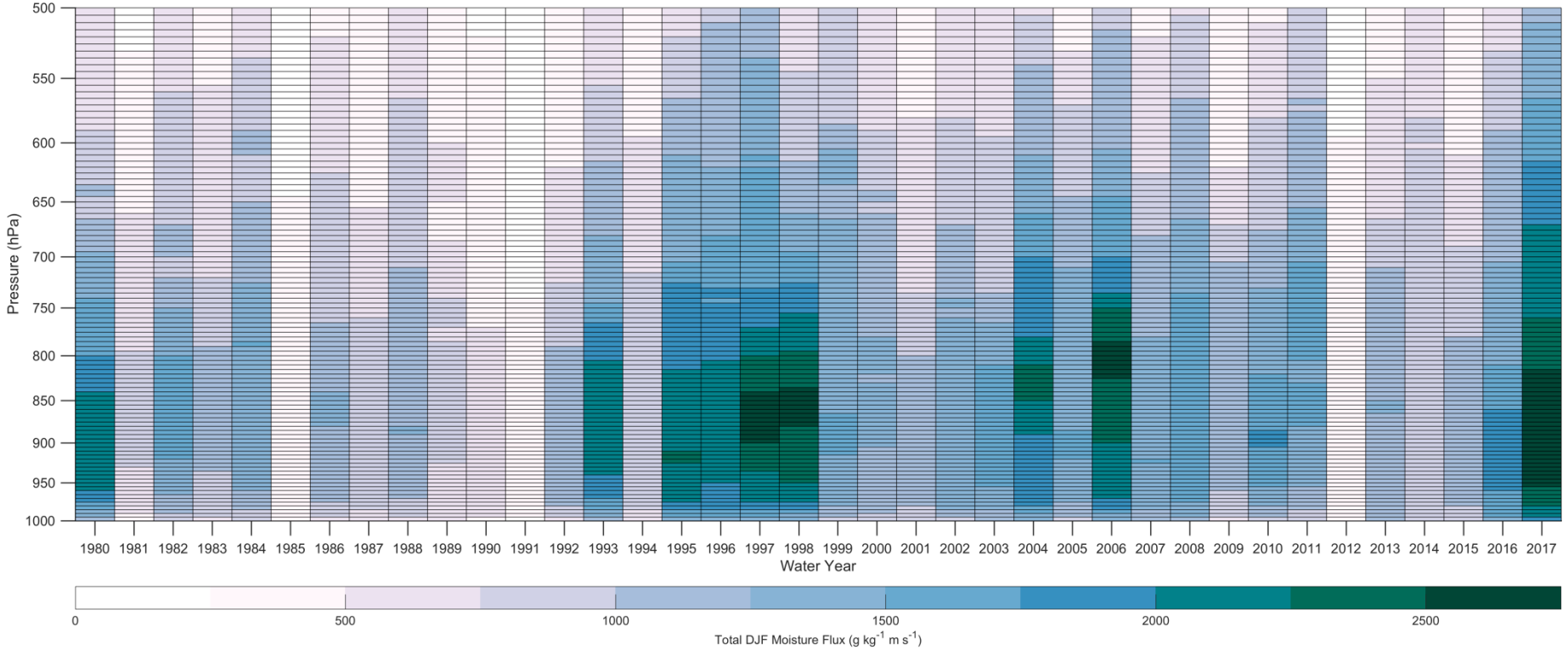
So what explains the huge anomalies over the Great Basin?



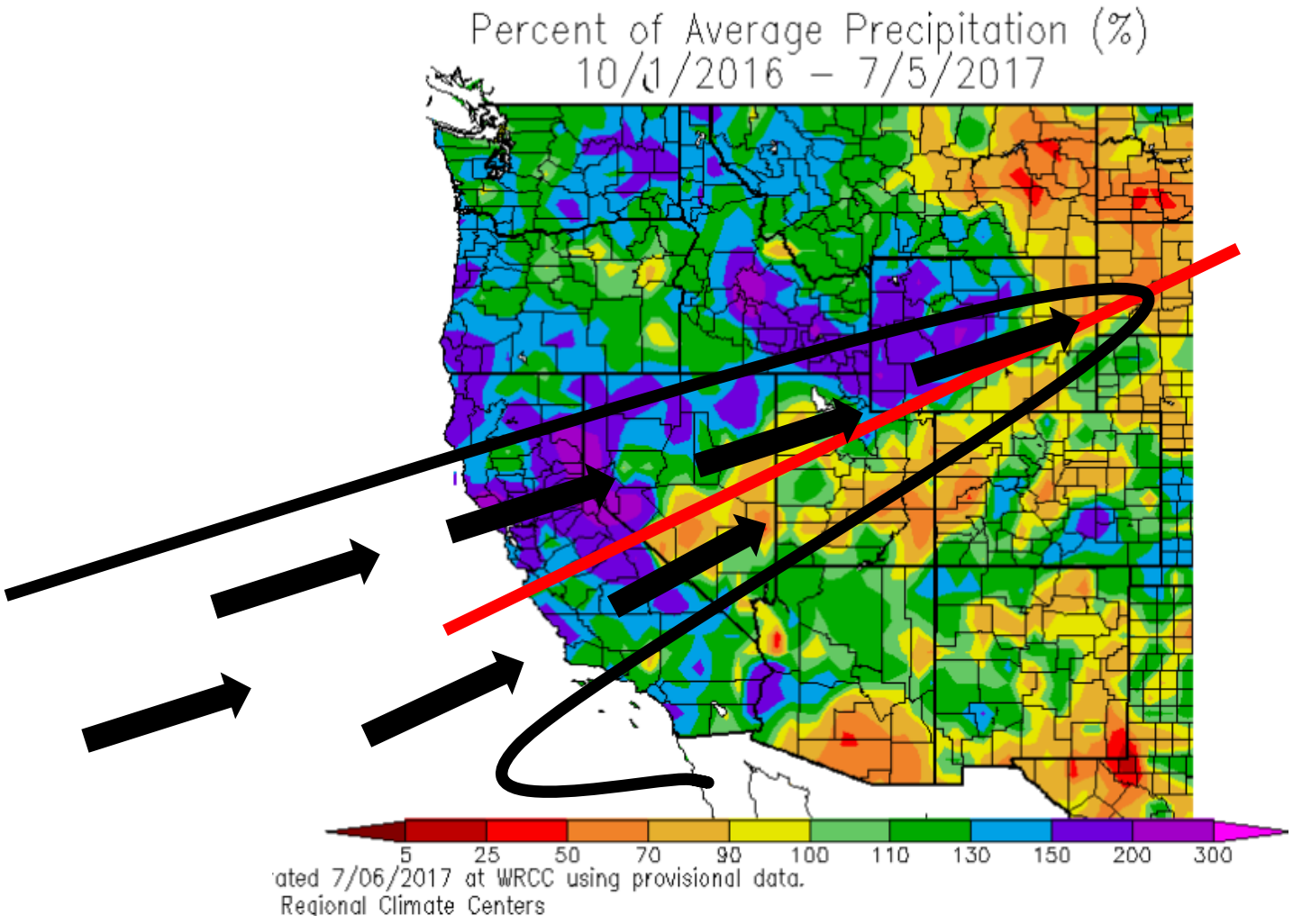
Mid-Level Moisture Transport

One strong candidate is mid-level moisture transport (Kaplan et al. 2012 J. Hydromet.); also the frequency and intensity of landfalling ARs.

Moisture Flux at Oakland For DJF (caveat: some 1980s years missing or suspicious)

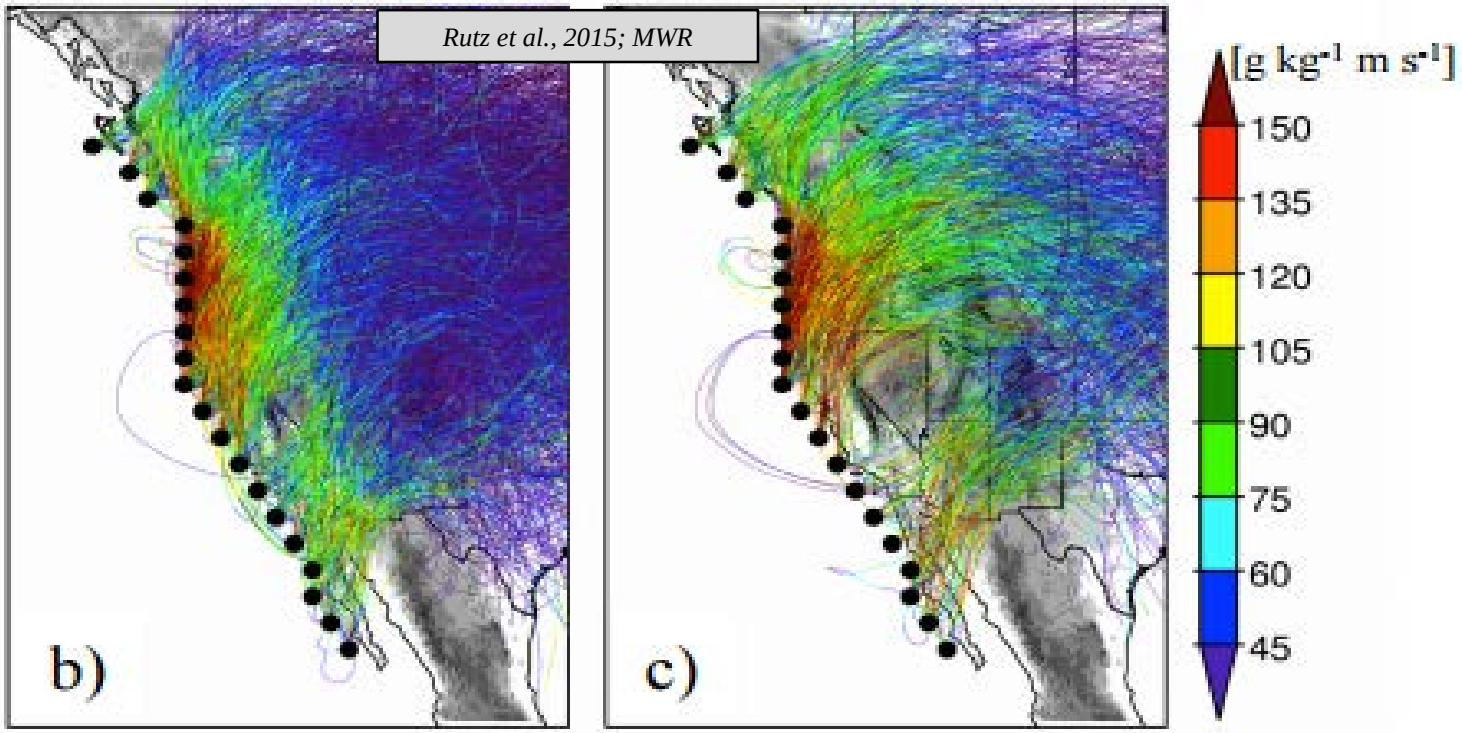


ARs and Precipitation

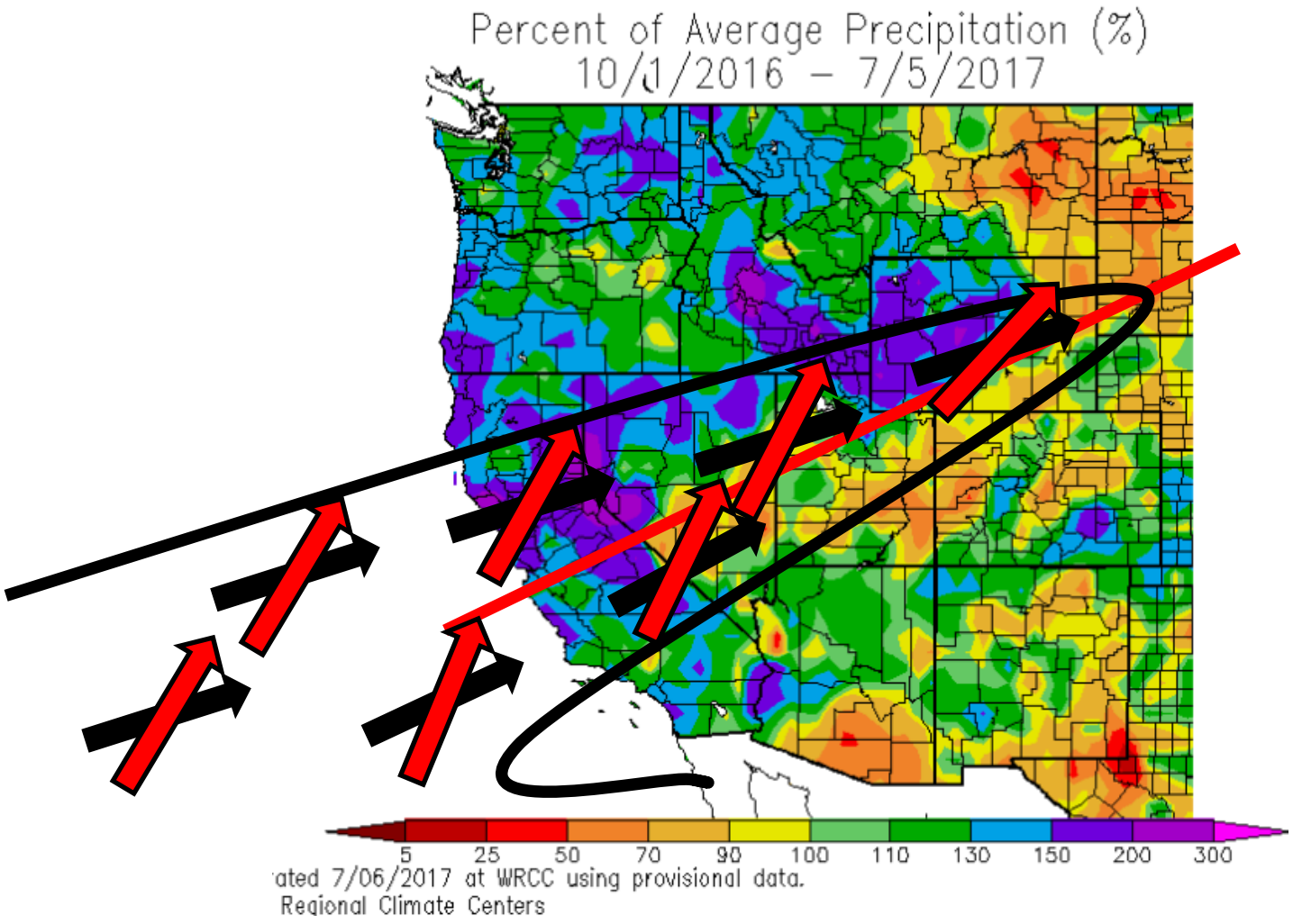


ARs and Precipitation

Transport within ARs is much more poleward than parallel to the AR, especially at lower levels where greater moisture is present.

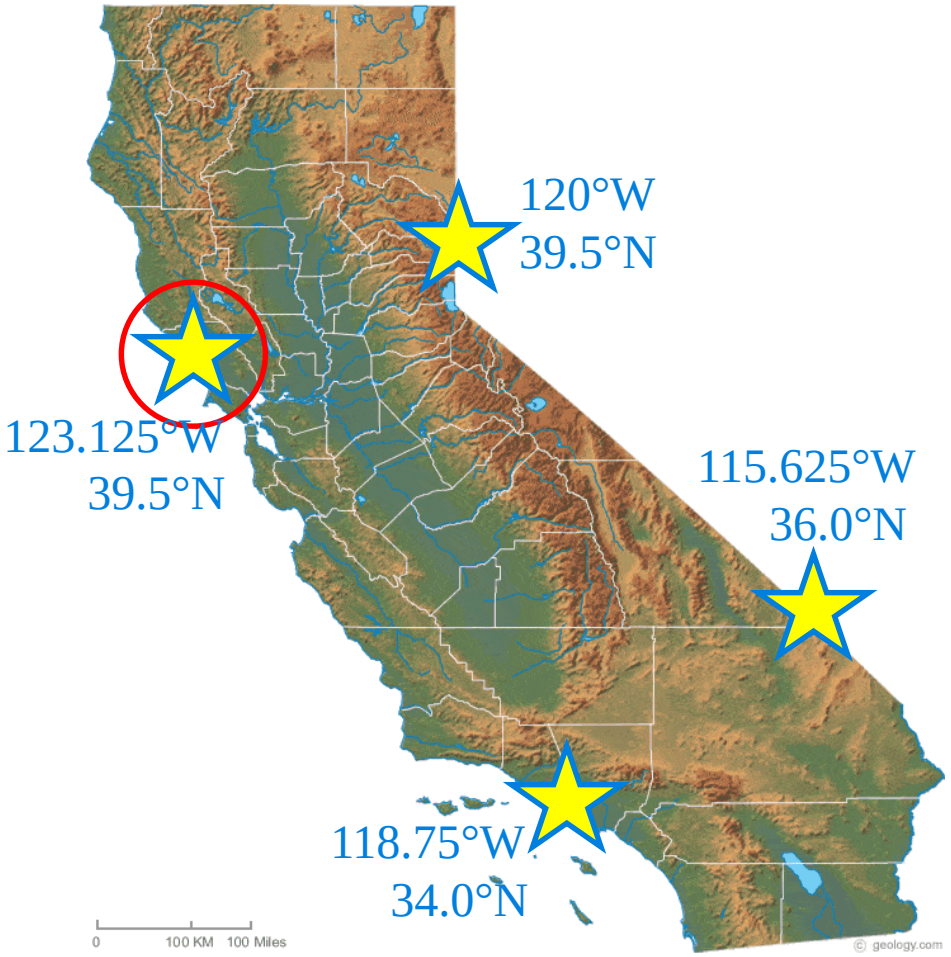


ARs and Precipitation



And Now For A Closer Look…

- Using MERRA v2 Catalogs
- Compare AR climatology of 2016-2017 cool season to the 1980-2017 mean
  - 2 locations along CA coast
  - 2 location at CA/NV border
- I can quickly provide data and graphics for other locations



AR Timeseries 1980–2017

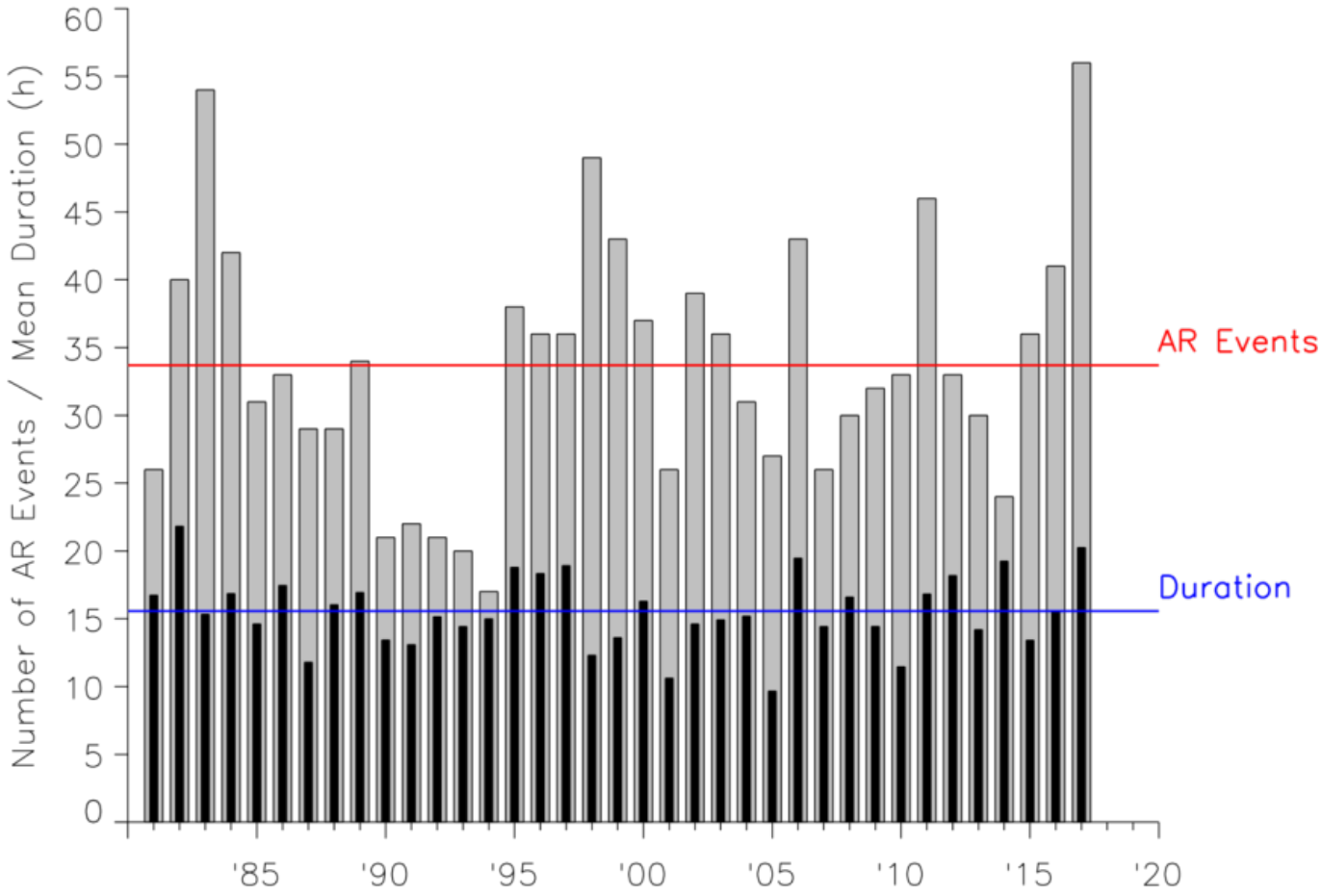


Figure Description: Number of AR events (grey) and mean annual duration (black).

AR Timeseries 1980–2017

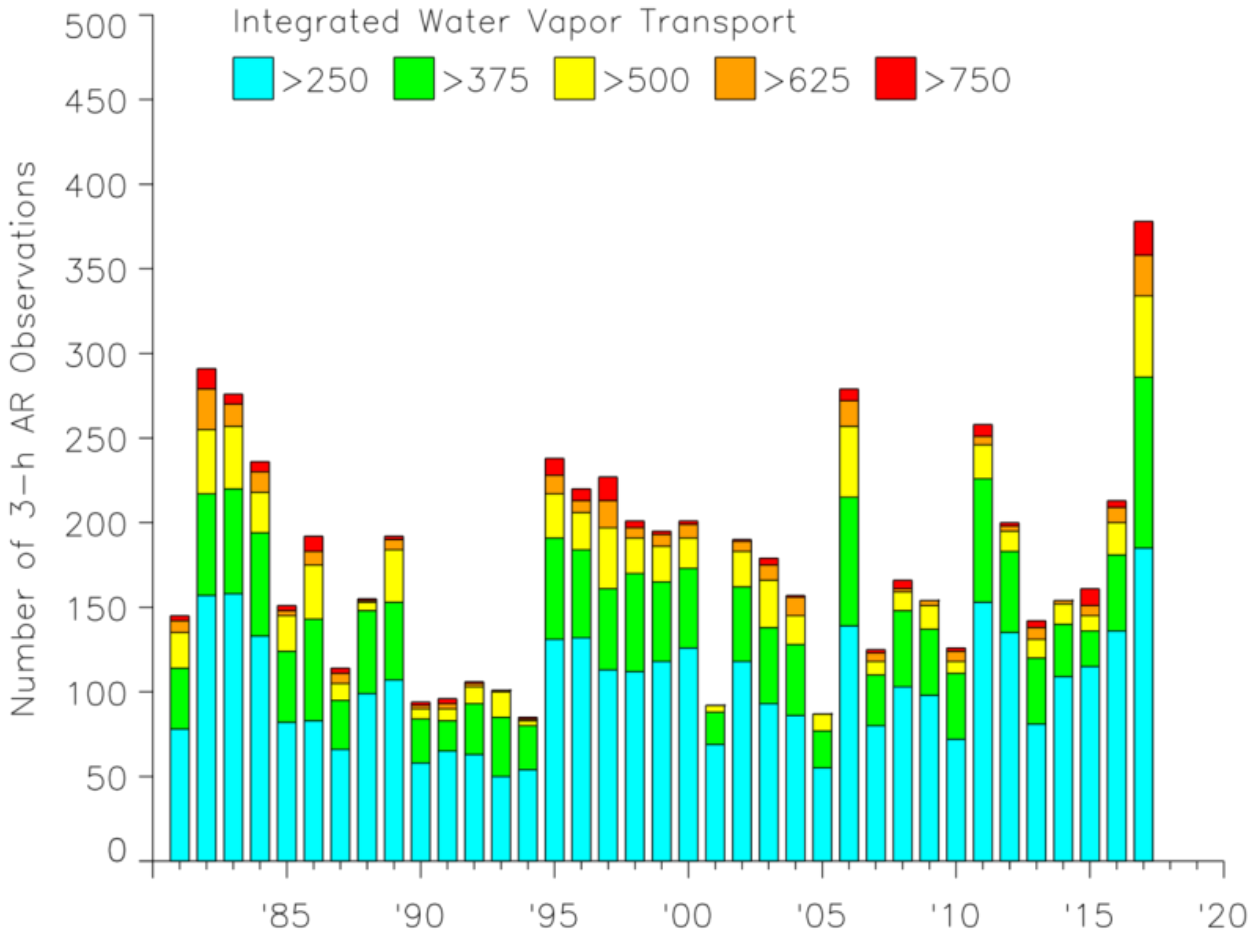


Figure Description: AR Observations as a function of IVT (solid fill).

AR Intensity by Month

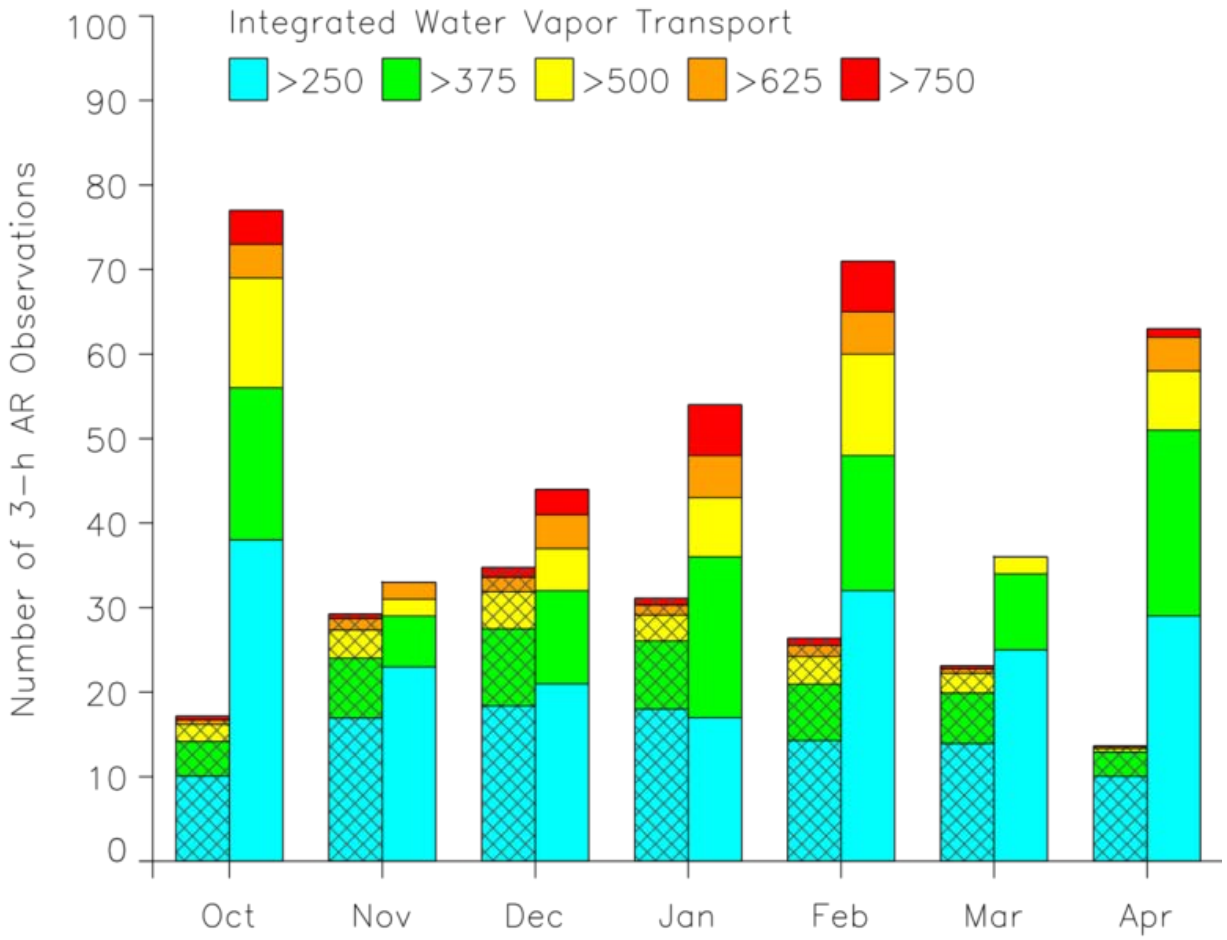


Figure Description: 2016/17 AR Observations as a function of IVT (solid fill) and 1980-2017 mean (cross hatched).

Inland Impacts – Feb/Mar 2017

Marsh Creek near Inkom, ID (16 Feb 2017)

Cottonwood, ID (3 Mar 2017)

Southern ID (11 Feb 2017)

Summary

- The 2016/17 cool season saw widespread impacts – both hazardous and beneficial – across the western U.S.
  - Landslides, flooding, emergency dam releases, drought reduction

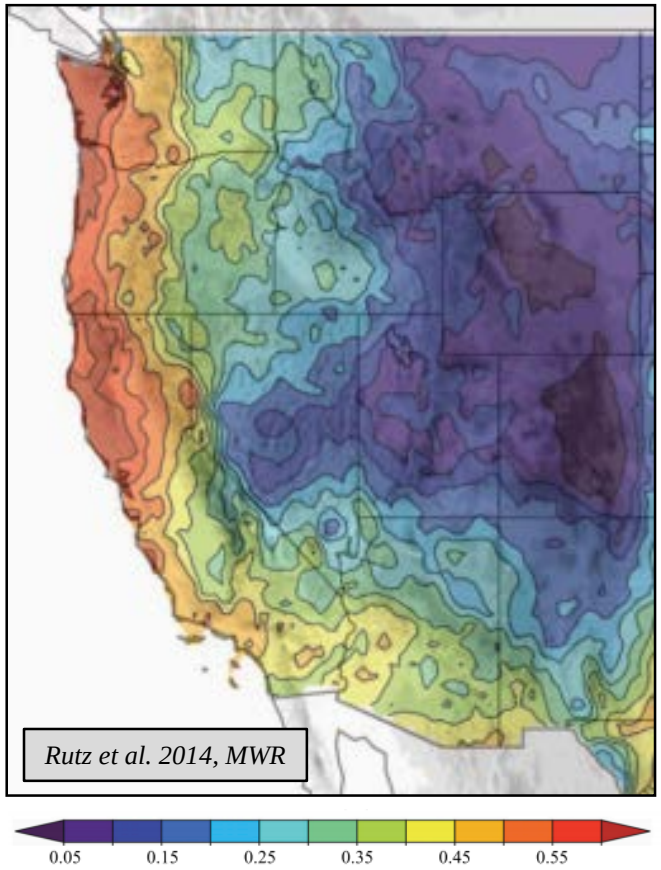
- During this time, atmospheric rivers (ARs) were ***more frequent***, ***longer-lived***, and ***more intense*** than the 1980–2017 average
  - Although other years can compete on one or two of these metrics, none can compete on all three
  - These ARs and their impacts were not limited to coastal regions, but extended (and were actually most anomalous) further inland

Ongoing Work

- ***Why*** were the climatological characteristics of ARs so extreme during 2016/17?
  - Corresponding w/ group at ESRL working to answer this question

- Can forecast skill be improved at various lead times?

- Did the greater frequency, duration, and intensity of ARs during the 2016/17 cool season actually alter the relative contribution of ARs to precipitation?

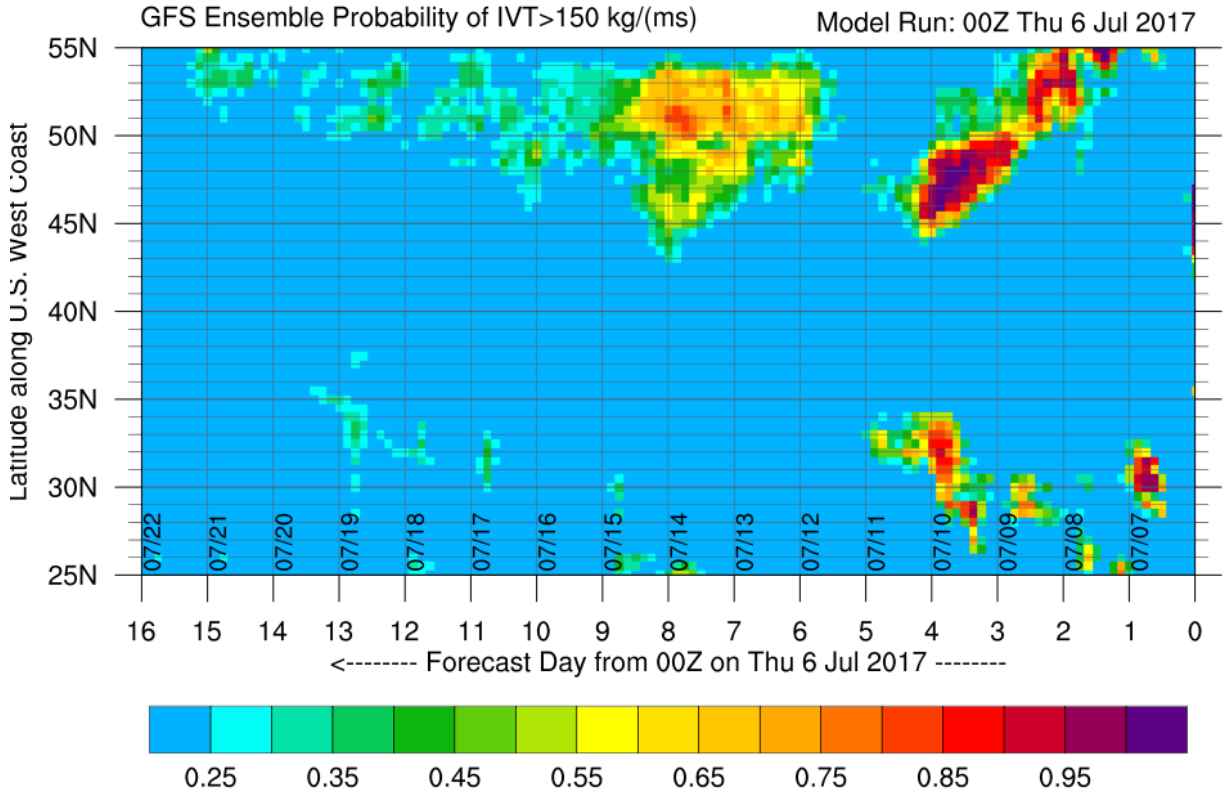


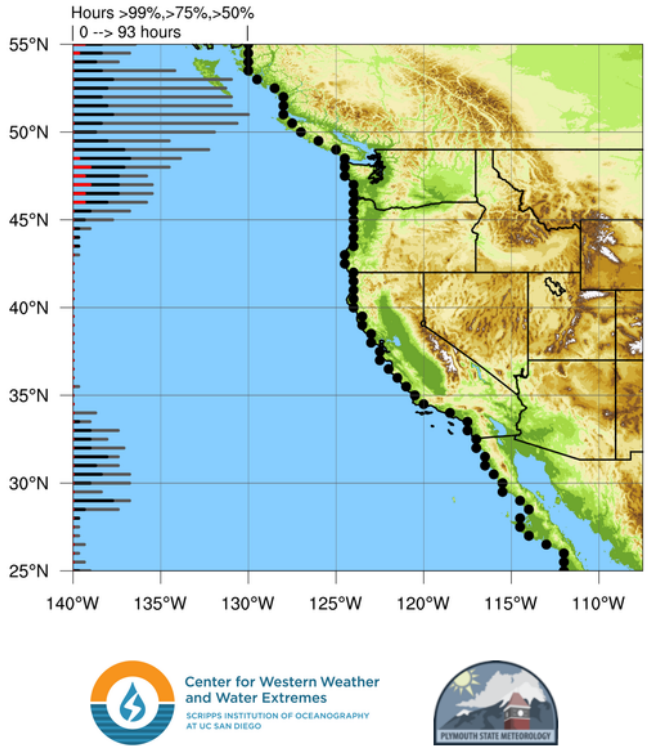
Atmospheric River Forecast Tools

Atmospheric River Forecast Tools

UCSD / Scripps / CW3E

http://cw3e.ucsd.edu/iwv-and-ivt-forecasts/





Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

PLYMOUTH STATE METEOROLOGY

Atmospheric River Forecast Tools

NWS Situational Awareness Tables

http://esatqa.ncep.noaa.gov/

ENSEMBLE SITUATIONAL AWARENESS TABLE ARCHIVE
NOAA / NATIONAL WEATHER SERVICE

Verification

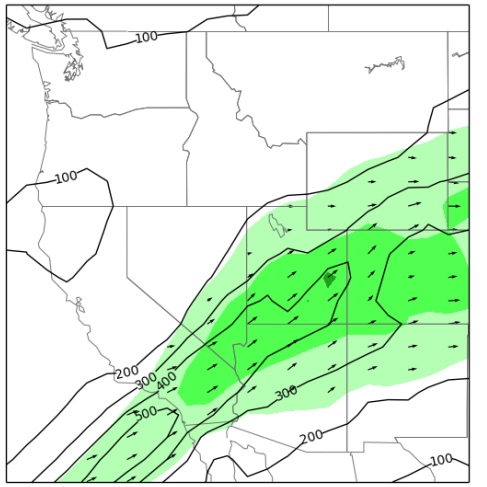
Type: NAEFS Standardized Anomaly | Recent Cases | Historic Cases | Date: 02/08/2017 | 12Z | Region: Western U.S. | View Table

Fcst Hr: 72 Valic

Western U.S. Table Feb 8, 2017 00Z Run

			Z	T	U	V	WSP	SLP	Q	PW	IVT
0	Wed 8th	00Z	-2.0	2.7	4.1	-2.7	4.3	-2.3	3.9	4.3	5.8
6		06Z	2.0	2.9	4.3	-2.7	4.5	-1.9	3.3	3.5	5.8
12		12Z	2.1	2.7	3.5	-2.9	3.7	-1.4	3.1	3.2	4.1
18		18Z	2.2	2.4	3.7	-2.9	3.6	-1.4	3.2	3.3	4.3
24	Thu 9th	00Z	2.4	2.5	3.8	2.3	3.8	-1.7	3.2	3.2	4.9
30		06Z	2.4	2.5	3.6	2.9	3.8	-2.1	3.5	3.3	5.6
36		12Z	-2.5	2.5	3.9	3.4	3.6	-2.5	3.8	3.3	5.8
42		18Z	-2.7	2.8	4.3	3.6	4.6	-2.7	4.1	3.6	6.3
48	Fri 10th	00Z	-2.8	2.7	4.6	3.7	5.1	-2.6	4.3	3.7	6.2
54		06Z	-2.7	2.6	4.3	3.2	3.7	-2.5	4.1	3.7	6.3
60		12Z	2.6	2.8	4.5	2.9	4.1	-2.5	4.1	3.6	5.7
66		18Z	2.6	2.6	4.3	2.6	4.1	-2.2	3.9	3.4	6.1
72	Sat 11th	00Z	2.5	2.6	4.2	2.5	4.1	-1.9	3.4	3.1	6.2
78		06Z	2.3	2.3	3.9	2.3	4.2	-1.7	3.3	3.0	5.9
84		12Z	2.2	2.3	3.7	2.3	4.2	-1.6	3.1	2.6	5.1
90		18Z	2.0	2.2	2.5	2.2	2.7	1.5	2.6	2.5	4.2
96	Sun 12th	00Z	1.8	2.1	1.6	2.1	1.8	1.6	2.3	2.2	3.2
102		06Z	1.7	2.2	-1.9	2.1	1.7	1.9	2.1	2.1	2.1
108		12Z	1.8	1.8	-2.0	-2.2	2.2	1.9	2.0	1.8	1.3
114		18Z	1.9	-1.8	-3.0	-2.2	2.4	2.0	-2.0	1.4	1.2
120	Mon 13th	00Z	2.0	-1.8	-3.0	-2.3	2.0	2.0	1.9	1.3	1.5
126		06Z	2.1	-1.8	-2.8	-2.4	2.2	1.8	2.0	1.7	1.5
132		12Z	2.1	1.8	-2.7	-2.1	2.0	1.7	2.3	1.7	1.1
138		18Z	1.9	1.9	-2.6	-2.2	2.1	1.7	2.0	1.5	0.8
144	Tue 14th	00Z	1.8	-1.7	-2.0	-2.0	0.9	1.6	-1.9	1.3	0.9
150		06Z	1.9	1.6	-1.6	-1.7	1.0	1.3	1.9	1.4	0.9
156		12Z	2.0	1.7	-1.6	-1.5	0.9	1.3	1.9	1.5	0.8
162		18Z	2.0	1.8	-1.5	-1.4	0.6	1.0	1.7	1.3	0.8
168	Wed 15th	00Z	2.2	1.8	-1.6	-1.3	0.8	0.9	-1.6	0.9	0.8
174		06Z	2.3	1.9	-1.6	1.4	1.0	0.9	1.9	1.3	1.4
180		12Z	2.4	2.0	-1.6	1.5	1.3	1.1	2.6	1.7	1.9
186		18Z	2.4	2.0	-1.5	1.9	1.7	0.7	2.8	2.1	2.7
192	Thu 16th	00Z	2.5	2.0	-1.6	1.9	1.6	0.7	2.5	2.1	2.5
198		06Z	2.5	2.1	-1.6	2.0	1.8	0.9	2.6	2.1	2.5
204		12Z	2.5	2.1	-1.6	2.0	1.7	-1.0	2.5	2.1	2.2
210		18Z	2.4	2.1	-1.7	1.9	1.3	-1.1	2.7	2.2	1.8

NAEFS Mean Integrated WV Transport ($kgm^{-1}s^{-1}$) and Standardiz
HOUR 072 - VALID 00:00 UTC Sat Feb 11 2017



Relative to the 31-Jan to 21-Feb 1979-2009 CFSR climatology

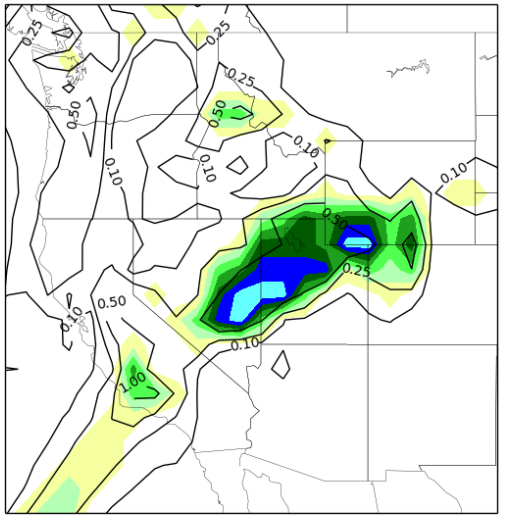
ENSEMBLE SITUATIONAL AWARENESS TABLE ARCHIVE
NOAA / NATIONAL WEATHER SERVICE

Type: GEFS M-Climate QPF | Recent Cases | Historic Cases | Date: 02/08/2017 | 12Z | Region: Western U.S. | View Table

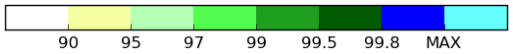
Western U.S. Table Feb 8, 2017 12Z Run

			6-h	12-h	24-h	48-h	72-h
6	Wed 8th	18Z	99.0				
12	Thu 9th	00Z	99.8	99.6			
18		06Z	MAX	99.9			
24		12Z	MAX	MAX	MAX		
30		18Z	MAX	MAX	MAX		
36	Fri 10th	00Z	MAX	MAX	MAX		
42		06Z	99.9	99.9	MAX		
48		12Z	99.9	MAX	MAX	MAX	
54		18Z	MAX	MAX	MAX	MAX	
60	Sat 11th	00Z	MAX	MAX	99.9	MAX	
66		06Z	MAX	MAX	MAX	MAX	
72		12Z	MAX	MAX	MAX	MAX	MAX
78		18Z	MAX	MAX	MAX	MAX	MAX
84	Sun 12th	00Z	99.4	99.8	MAX	MAX	MAX
90		06Z	96.8	98.9	MAX	MAX	MAX
96		12Z	98.6	98.1	99.4	MAX	99.9
102		18Z	99.3	99.5	98.9	MAX	MAX
108	Mon 13th	00Z	MAX	MAX	99.7	MAX	MAX
114		06Z	98.1	99.8	99.9	99.8	MAX
120		12Z	96.6	97.7	99.9	99.5	MAX
126		18Z	93.4	97.9	99.6	99.8	MAX
132	Tue 14th	00Z	93.8	93.8	97.7	99.7	MAX
138		06Z	<90	93.1	97.7	99.6	99.7
144		12Z	91.3	90.1	96.0	99.6	99.4
150		18Z	91.0	93.9	97.1	98.9	99.5
156	Wed 15th	00Z	<90	<90	94.1	98.8	99.5
162		06Z	93.7	90.0	91.7	98.1	99.4
168		12Z	<90	<90	<90	96.7	99.4
174		18Z	98.1	94.4	<90	95.1	98.6
180	Thu 16th	00Z	99.2	99.2	95.3	91.8	98.1

GEFS Mean QPF (in) and M-Climate percentile
48-72-h forecast valid
12Z Fri Feb 10 2017 to 12Z Sat Feb 11 2017



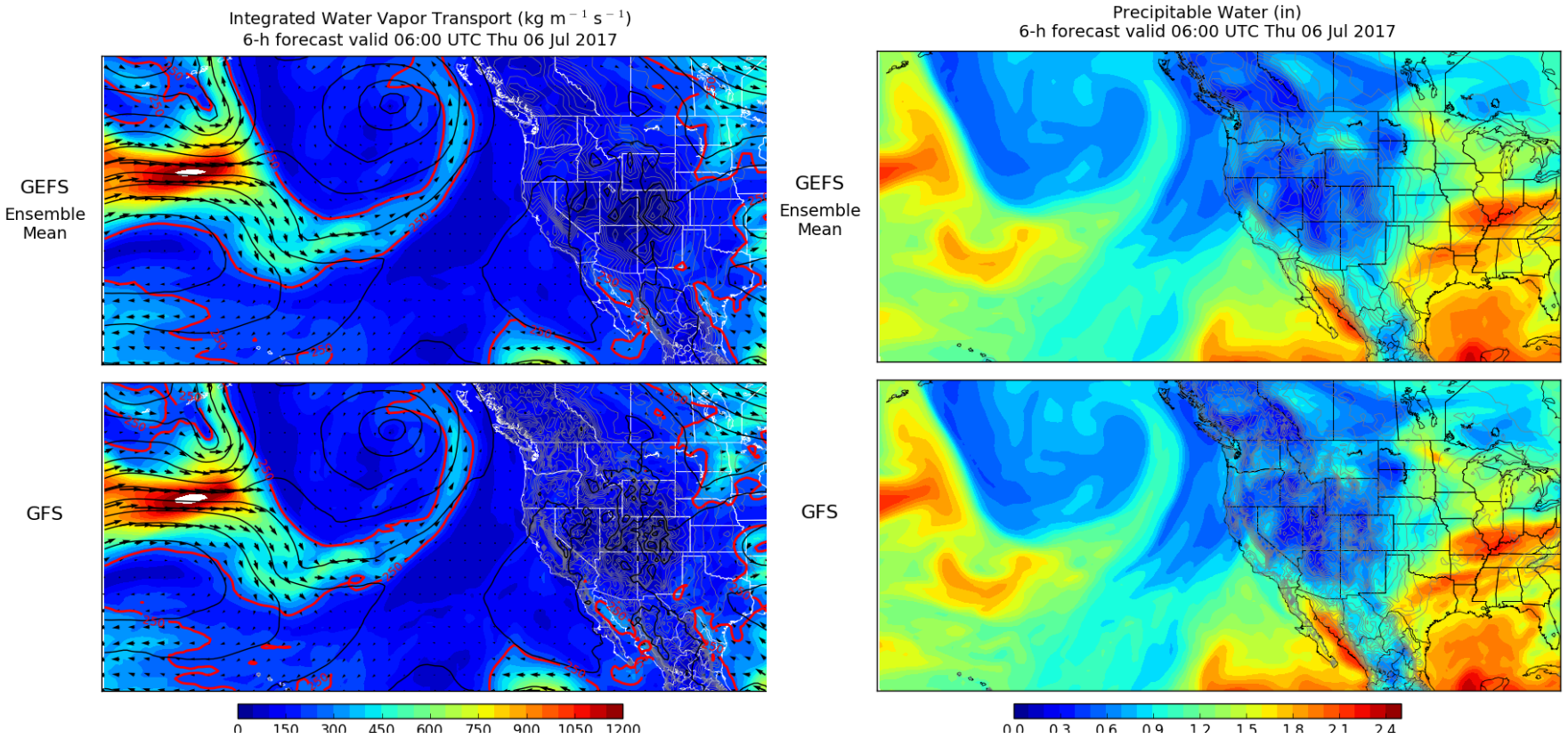
relative to GEFS reforecasts initialized
25-Dec to 25-Mar (1985-2012)



Atmospheric River Forecast Tools

NWS WRHQ

http://ssd.wrh.noaa.gov/naefs/?type=ivtw

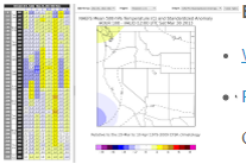


Atmospheric River Forecast Tools

NWS WRHQ "Forecast Confidence Toolkit"

https://sites.google.com/a/noaa.gov/nws-wr-stid/projects/forecast-confidence

Large-Scale Pattern Tools

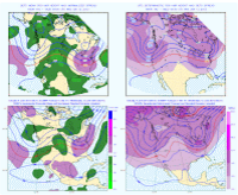


Ensemble Situational Awareness Table

- WR Version | NCEP Version (w/ECens Data)
- Penn State Anomaly Page

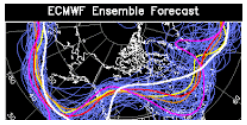
Contact/training: Randy Graham

- Provides a framework for quickly identifying significant events in the forecast.
- NAEFS ensemble mean fields are compared to the 1979-2009 CFSR reanalysis climatology to highlight potentially significant features in the forecast.
- The NAEFS ensemble consists of a control run and 20 perturbed members from each of the Canadian and GEFS models.
- Only presents the ensemble mean-- no explicit confidence information.
- Large anomalies in an ensemble mean at long lead times suggest a higher likelihood of significant events, but not if the model is underdispersive or "overconfident"
- See the Projects Page for more details.



STID Ensemble Graphics

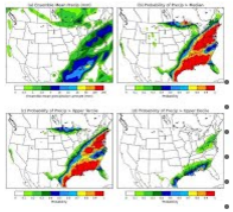
- GFS/GEFS 500mb Heights
- Contact/training: Trevor Alcott
- Gathers several confidence tools (normalized spread, GFS deterministic versus GEFS ensemble, model climate QPF, ensemble IVT) in one place.
- Normalized spread is especially tricky, and can highlight strong gradients or pattern changes rather than low predictability.



ECMWF Ensemble Graphics

- HPC Spaghetti Plots
- ECMWF Normalized Spread Maps

Impact Probabilities and Forecast Analogs

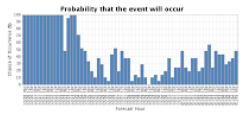


GEFS Reforecast V2 & Climatology-Calibrated Precipitation Analysis

- ESRL SA Table
- QPF Analogs and EFI
- High-Res QPF Analogs
- Extreme Percentile Plots
- Z500/T850/T2
- Teleconnections

Contact/training: Trevor Alcott
Data outages: Reforecast Admin

- Reforecast analogs are used to calibrate the real-time GEFS forecast, which shows considerable skill over raw ensemble probabilities.
- Uses a GEFS reforecast dataset covering 1984 to 2012 at ~50km (~70 km) resolution for days 1-8 (8-16).
- Precipitation forecasts are subject to the quality of the NARR reanalysis precipitation (32-km resolution).



NCEP / EMC Ensemble Tools

- NAEFS / GEFS / SREF Graphics
- NOMADS Probability Tool

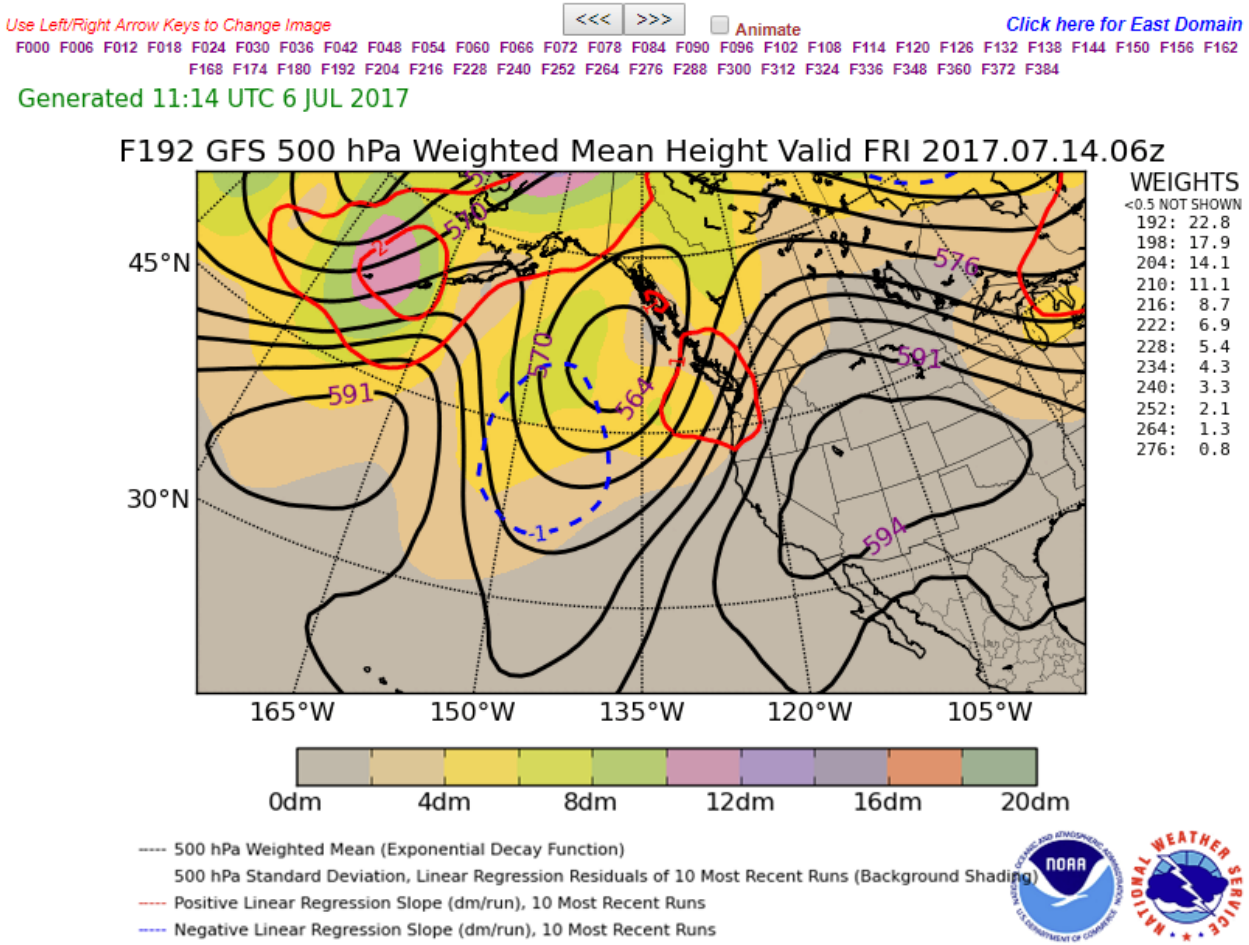
Contact/training: JJ Brost

- Show the raw probability of exceeding various thresholds (% of 21 GEFS members).
- Point-based and plan view graphics available. One-stop shop for raw ensemble mean/spread data and probabilities.
- Use raw ensemble probabilities at your peril. Particularly for high precipitation thresholds, these uncalibrated values are unreliable in complex terrain.

Atmospheric River Forecast Tools

"ModTrend" Tool

http://www.wrh.noaa.gov/hnx/modTrend/



Questions or comments?