Atmospheric River Observations: A Summary of Recent Results

F. M. Ralph

Director, Center for Western Weather and Water Extremes (CW3E) at
UC San Diego's Scripps Institution of Oceanography

Western States Water Council Workshop on S2S Precipitation Forecasting
San Diego California, 7 June 2016

Outline

- The role of atmospheric rivers and Sierra barrier jet in extreme precipitation in Northern California
- Summary of Water year 2016 "Top-10" precipitation events in Northern California
- Airborne AR observations

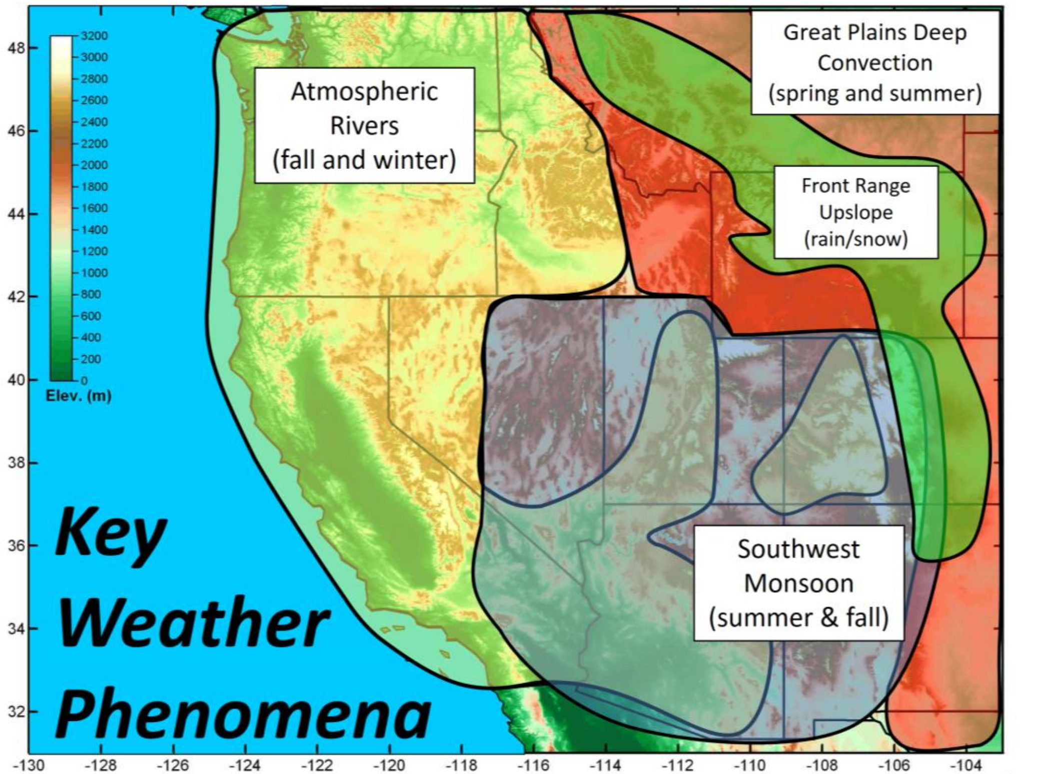
CW3E

Universities Council on Water Resources
Journal of Contemporary Water Research & Education
Issue 153, Pages 16-32, April 2014

A Vision for Future Observations for Western U.S. Extreme Precipitation and Flooding

F.M. Ralph[1], M. Dettinger[2], A. White[3], D. Reynolds[4], D. Cayan[2], T. Schneider[5], R. Cifelli[3], K. Redmond[6], M. Anderson[7], F. Gherke[7], J. Jones[7], K. Mahoney[4], L. Johnson[8], S. Gutman[9], V. Chandrasekar[10], J. Lundquist[11], N. Molotch[12], L. Brekke[13], R. Pulwarty[14], J. Horel[15], L. Schick[16], A. Edman[17], P.Mote[18], J. Abatzoglou[19], R. Pierce[20], G. Wick[3]

Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation, flooding and contribute to water supply in the Western U.S. (Ralph et al. 2014)



Landfalling Atmospheric Rivers, the Sierra Barrier Jet and Extreme Daily Precipitation in Northern California's Upper Sacramento River Watershed

F. M. Ralph, J. Cordeira, P. Neiman, M. Hughes

In Press at J. Hydrometeorology

Supported by DWR
Data from HMT and DWR

Sierra Barrier Jets, Atmospheric Rivers, and Precipitation Characteristics in Northern California: A Composite Perspective Based on a Network of Wind Profilers

Neiman, Hughes, Moore, Ralph, and Sukovich , MWR 2013

Based on observations from the CalWater field campaign 2009-2011; described in Ralph et al. (2016), *BAMS*

*Schematic based on a composite of the 13 strongest SBJ cases observed at the SHS profiler between 2009-2011.

*Profilers at CCO, CFC, and CCR also recorded data and composited during these SBJ cases.

*A 6-km regional reanalysis dataset from the WRF model provided additional information.

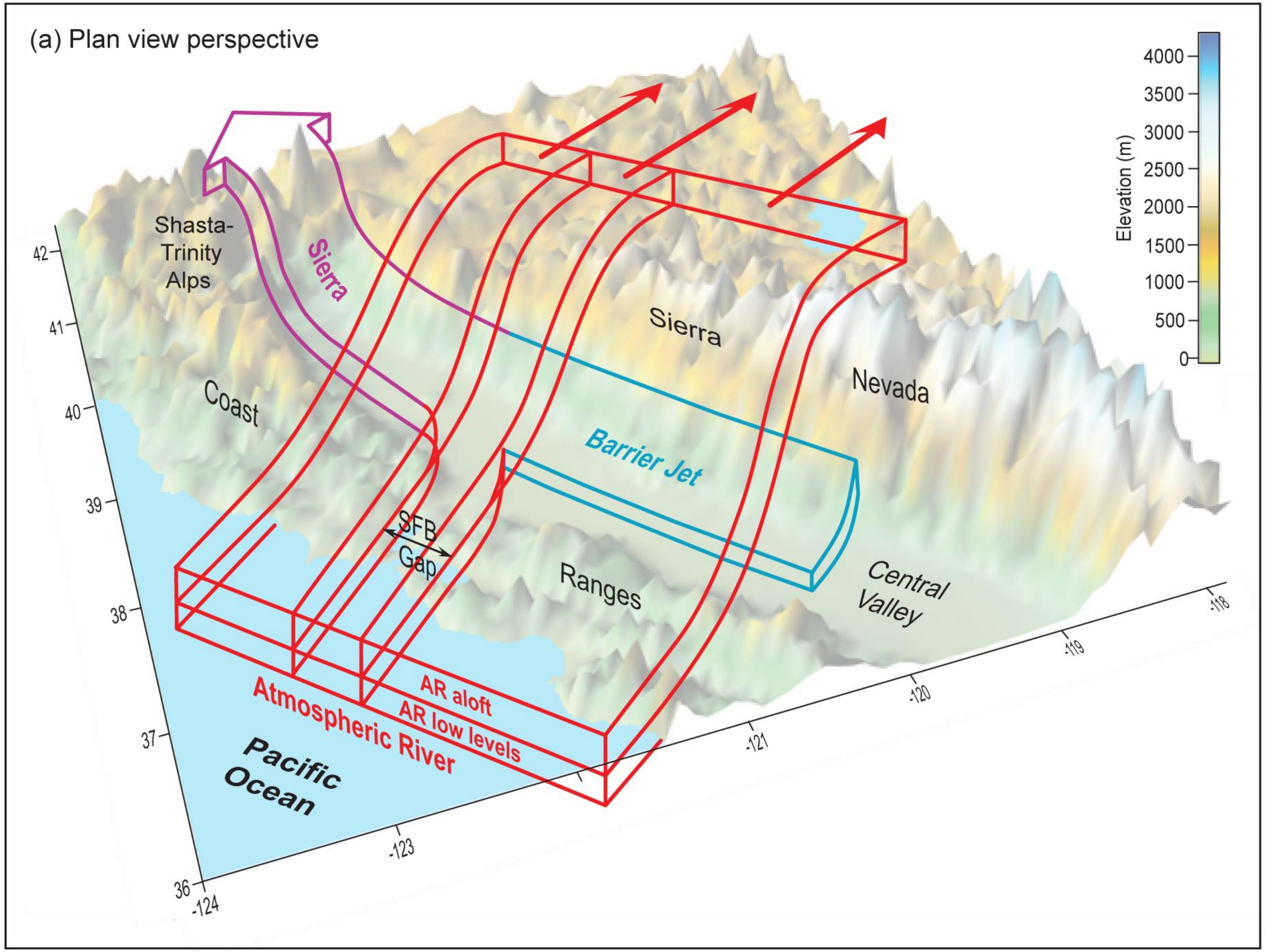
*The SBJ parallels the Sierra over the eastern Central Valley (CV): core 1 km above ground.

*The SBJ core increases in altitude up Sierra windward slope and poleward over Northern CV.

*Inland penetration of AR through San Francisco Bay gap contributes to SBJ deepening/moistening over Nern CV.

*Aloft, AR airstream rides over SBJ.

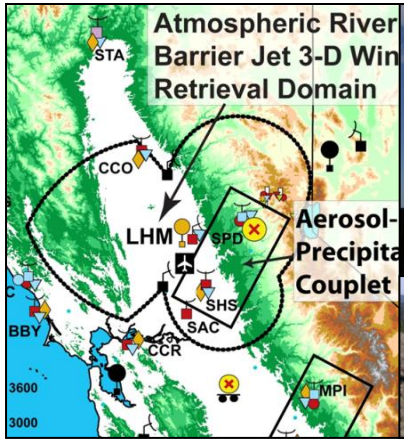
*Sierra-perpendicular vapor fluxes linked to heavy precip. along Sierra's windward slope, & SBJ-parallel fluxes tied to heavy precip. at N end of CV.



Kinematic and Thermodynamic Structures of Sierra Barrier Jets and Overrunning Atmospheric Rivers during a Land-falling Winter Storm in Northern California

Kingsmill, Neiman, Moore, Hughes, Yuter and Ralph

Journal of Hydrometeorology, 2013

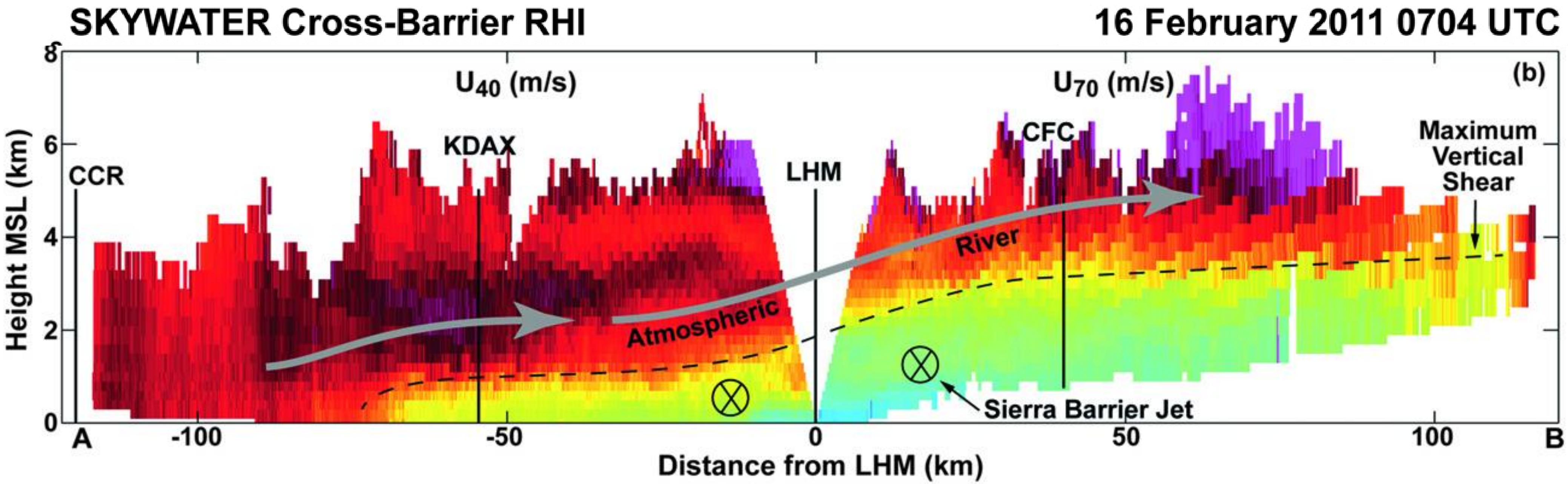


Landfalling storm 14-16 February 2011

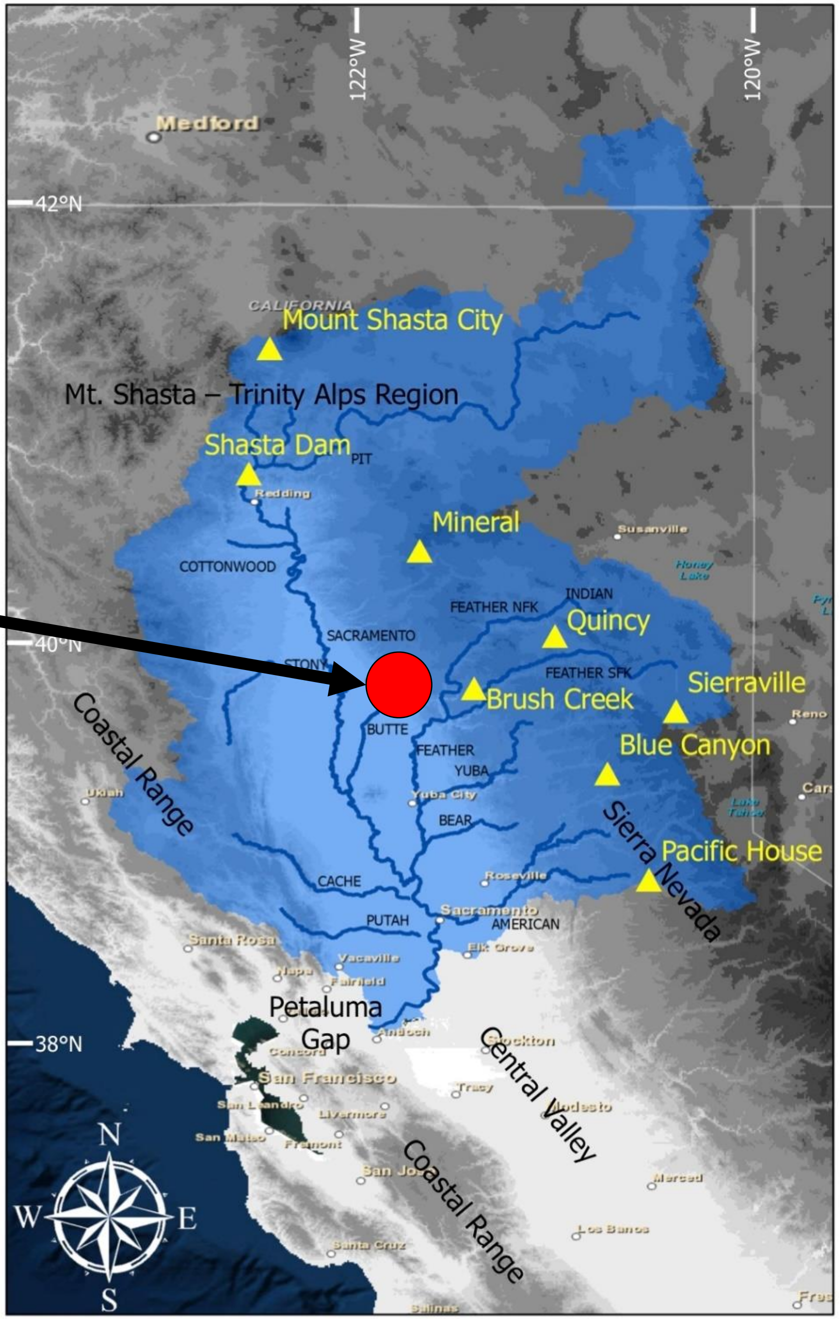
- Multi-Doppler scanning-radar retrievals
- Multi-wind-profiler time series diagnostics
- Balloon soundings

Observing network clearly monitored both the AR and SBJ during two sub-periods within the 2-day IOP

- SBJ western edge detected
- SBJ deepened toward the north
- AR rode up and over the SBJ



Chico wind profiling radar (NOAA/HMT)



Key:

- N. Sierra 8 Stations
- Rivers and Creeks
- Sacramento Watershed

Elevation (m):

0 - 100	1,501 - 2,000
101 - 200	2,001
201 - 300	2,001 - 2,500
301 - 400	2,501 - 3,000
401 - 500	3,001 - 3,500
501 - 1,000	3,501 - 4,000
1,001 - 1,500	4,001 - 4,500

Scale (km): 0 37.5 75 150

Stations of the Northern Sierra 8 Station Index

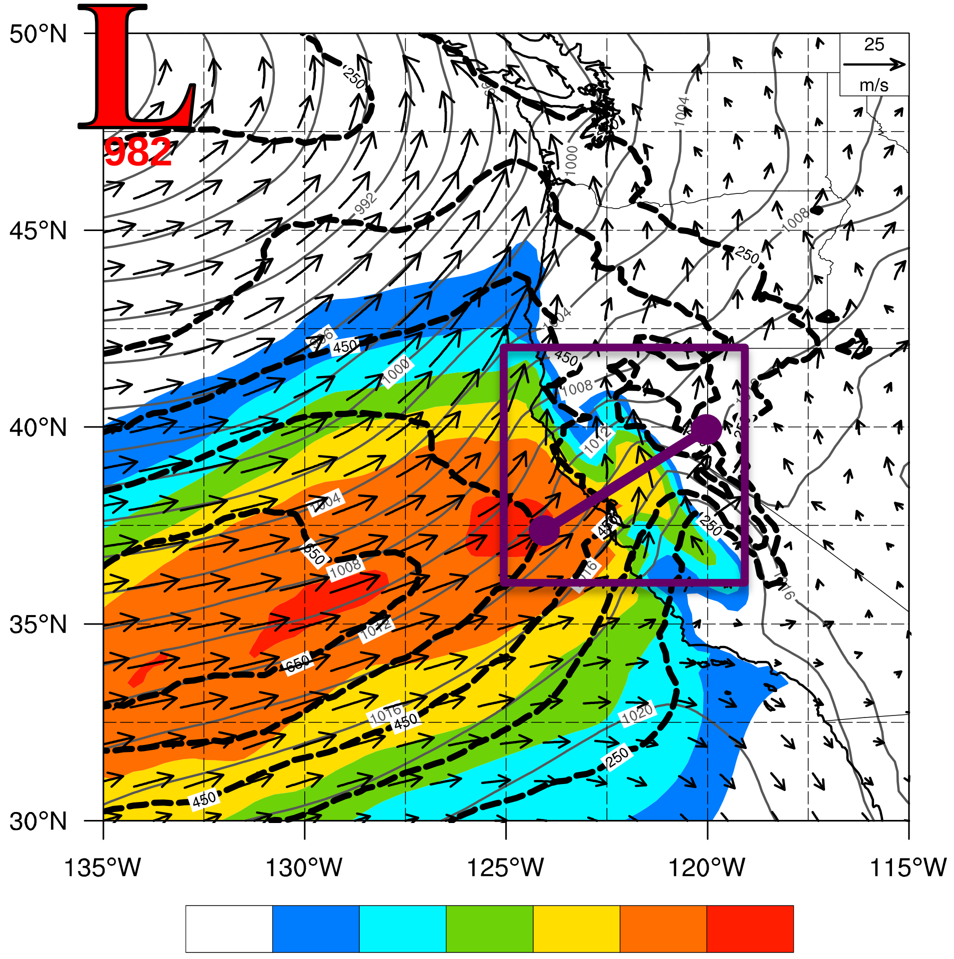
Name	ID	Location	Altitude
Pacific House	PCF	38.77°N, 120.50°W	1036
Blue Canyon	BYM	39.28°N, 120.70°W	1609
Sierraville	SRR	39.58°N, 120.37°W	1516
Brush Creek	BCM	39.69°N, 121.34°W	1085
Quincy	QRD	39.94°N, 120.95°W	1042
Mineral	MNR	40.35°N, 121.60°W	1486
Shasta Dam	SHA	40.72°N, 122.42°W	325
Mount Shasta City	MSC	41.32°N, 122.32°W	1094

Compiled from the following data sources:

Esri ArcMap 10.3.1 basemap and cities
NOAA NGDC "ETOPO1 Global Relief" 1-km terrain
NOAA NOHRSC Major Rivers GIS dataset
USDA NRCS Watershed Boundary Dataset

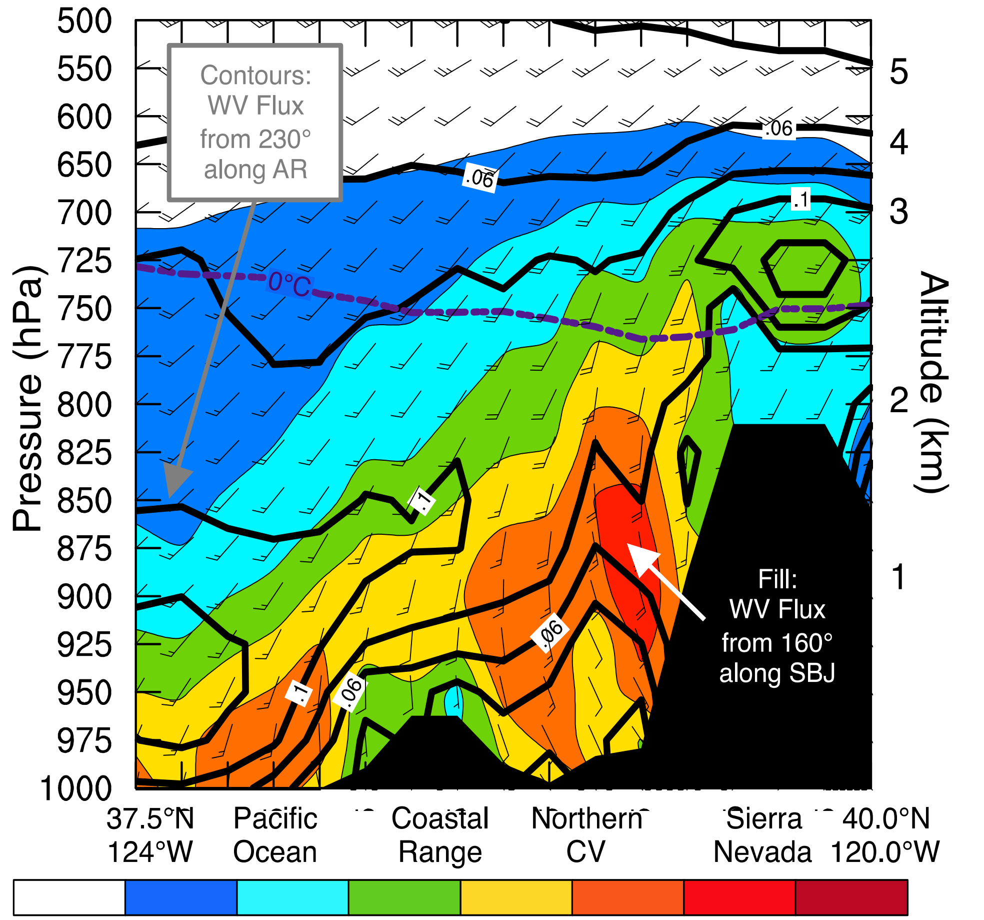
Composites of Top-10 Extreme Daily Precipitation from NARR Reanalyses

(c) Top 10 EDP: Large Domain



Integrated water vapor – IWV (cm)

(b) Top 10 EDP AR-Parallel Cross Section



Horizontal water vapor transport

Ralph et al. (*J. Hydrometeor.*, 2016, in press)

Conclusions – Part 1

92% 46 of 50 extreme daily precipitation events are associated with landfalling ARs on either the day before or the day of precipitation.

90% 45 of 50 extreme daily precipitation events are associated with SBJ conditions on either the day before or the day of precipitation.

76% 38 of 50 extreme daily precipitation events are associated with **both** landfalling ARs and SBJ conditions on either the day before or the day of precipitation.

Conclusions – Part 2

100%

The 10 wettest days in the Northern Sierra 8-station Index (i.e., the top 0.3% of all days in 10 years) were **all associated with both a landfalling AR and an SBJ**.

Can we build a tool that uses this result to produce an alert of high risk based on associated diagnoses of forecast model output?

And uses ARO and SSM/I data to validate and monitor in real-time?

Representation of the Sierra Barrier Jet in 11 years of a high-resolution dynamical reanalysis downscaling compared with long-term wind profiler observations.

Hughes, M., P. J. Neiman, E. Sukovich and F. M. Ralph, 2012, *J. Geophys. Res. – Atmos.,* **117**

Method

- 11 years of profiler-observed SBJs (256)
- Compared with reanalyses ranging from 275 km, 32 km, 10 km to 6 km grid sizes

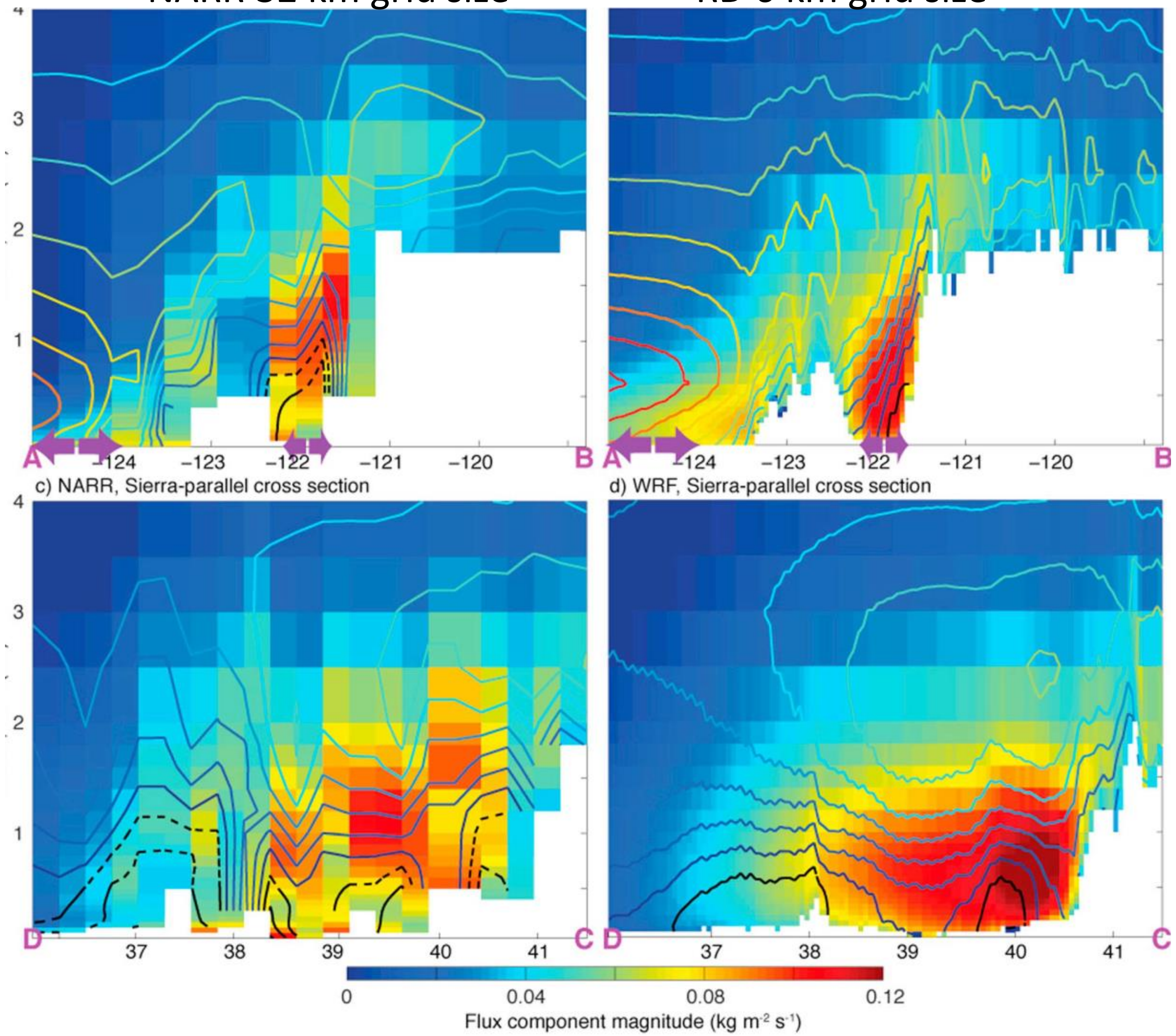
Results

- NNRP (275 km) does not have SBJs
- NARR (32 km) and CARD (10 km) SBJ is 2 times as deep as observed
- WRF RD (6 km) has 80% of SBJs
- **SBJs in WRF RD (6 km) are best match to observed strength and depth**
- WRF RD misses stable layer below 500 m MSL in SBJs (compared to radiosondes)

- **Vapor transport in 6-km WRF-RD differs greatly from 32-km NARR**
- NARR 35% too much flux into Sierra
- NARR 20% too little flux along Sierra

NARR 32 km grid size

RD 6 km grid size



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

Top Ten Precipitation Events in Water Year 2016: Northern Sierra 8-Station Index

Prepared by Brian Kawzenuk, Marty Ralph, Julie Kalansky

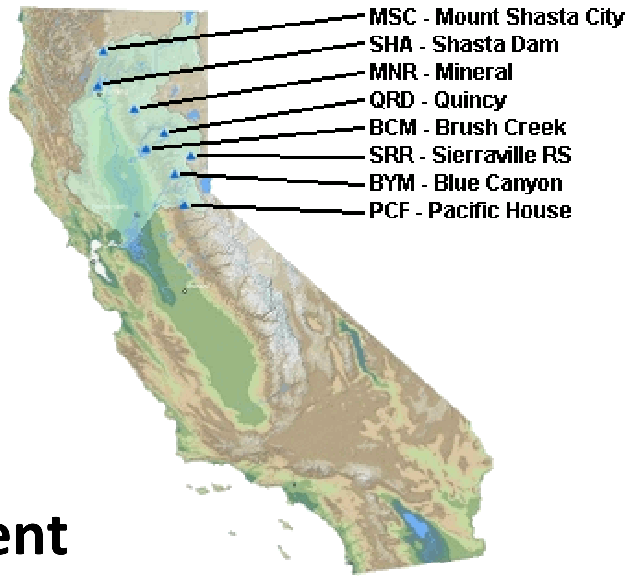
Per request from DWR and building on Elissa Lynn example from 2005

NS8SI Top-Ten Precipitation Events – Water Year 2016

- Top precipitation events were determined based on storm total precipitation measured by the Northern Sierra 8-Station Index

- All events were analyzed to determine if an Atmospheric River was present
  - defined by IVT >250 kg m^{-1} s^{-1} and
  - IWV >20 mm in a long narrow feature*
  - **All top-10 precip events included AR conditions during the event**
  - 8 were considered moderate ARs (IVT >500 kg m^{-1} s^{-1} over land)
  - 6 were considered strong ARs (IVT >750 kg m^{-1} s^{-1} over land)

Precipitation gages included in the "Northern Sierra 8-Station Index"



*See Ralph et al. 2004; Rutz et al. 2014 for the bases of these thresholds defining AR conditions

CW3E

Top-Ten NS8SI Precipitation Events – Water Year 2016

Date	Rank	Precipitation (8-Station Index; in/cm)			AR Conditions	
		Max Daily	Storm Total	% of WY16*	Max IVT (kg m^{-1} s^{-1})	Max IWV (mm)
3/12-3/14	1	**2.33** / 5.91	**4.78** / 12.15	8.6%	516	30
3/4-3/6	2	**2.33** / 5.93	**4.67** / 11.85	8.4%	1029	32
12/20-12/23	3	**1.93** / 4.91	**3.86** / 9.80	6.9%	688	32
1/29-1/31	4	**1.49** / 3.79	**3.08** / 7.83	5.5%	769	35
3/9-3/11	5	**1.69** / 4.29	**2.78** / 7.07	5.0%	1075	32
1/17-1/18	6	**1.67** / 4.24	**2.74** / 6.97	4.9%	827	32
12/10-12/11	7	**1.66** / 4.21	**2.87** / 5.81	4.1%	988	33
1/21-1/23	8	**1.09** / 2.77	**2.04** / 5.18	3.6%	922	30
3/21-3/22	9	**1.11** / 2.81	**2.01** / 5.11	3.6%	393	26
1/5-1/6	10	**1.02** / 2.59	**1.84** / 4.67	3.3%	497	29
		Total	**30.01** / 76.44	**54%**		

*Data through May 31, 2016

Maximum IWV/IVT values are calculated along the U.S. West Coast and may not be at the same time or location

IVT/IWV data from GFS analysis

CW3E

Top-Ten NS8SI Precipitation Events – Water Year 2016

Date	Rank	Precipitation (8-Station Index; in/cm)			AR Conditions	
		Max Daily	Storm Total	% of WY16*	Max IVT (kg m^{-1} s^{-1})	Max IWV (mm)
3/12-3/14	1	**2.33** / 5.91	**4.78** / 12.15	8.6%	516	30
3/4-3/6	2	**2.33** / 5.93	**4.67** / 11.85	8.4%	1029	32
12/20-12/23	3	**1.93** / 4.91	**3.86** / 9.80	6.9%	688	32
1/29-1/31	4	**1.49** / 3.79	**3.08** / 7.83	5.5%	769	35
3/9-3/11	5	**1.69** / 4.29	**2.78** / 7.07	5.0%	1075	32
1/17-1/18	6	**1.67** / 4.24	**2.74** / 6.97	4.9%	827	32
12/10-12/11	7	**1.66** / 4.21	**2.87** / 5.81	4.1%	988	33
1/21-1/23	8	**1.09** / 2.77	**2.04** / 5.18	3.6%	922	30
3/21-3/22	9	**1.11** / 2.81	**2.01** / 5.11	3.6%	393	26
1/5-1/6	10	**1.02** / 2.59	**1.84** / 4.67	3.3%	497	29
		Total	**30.01** / 76.44	**54%**		

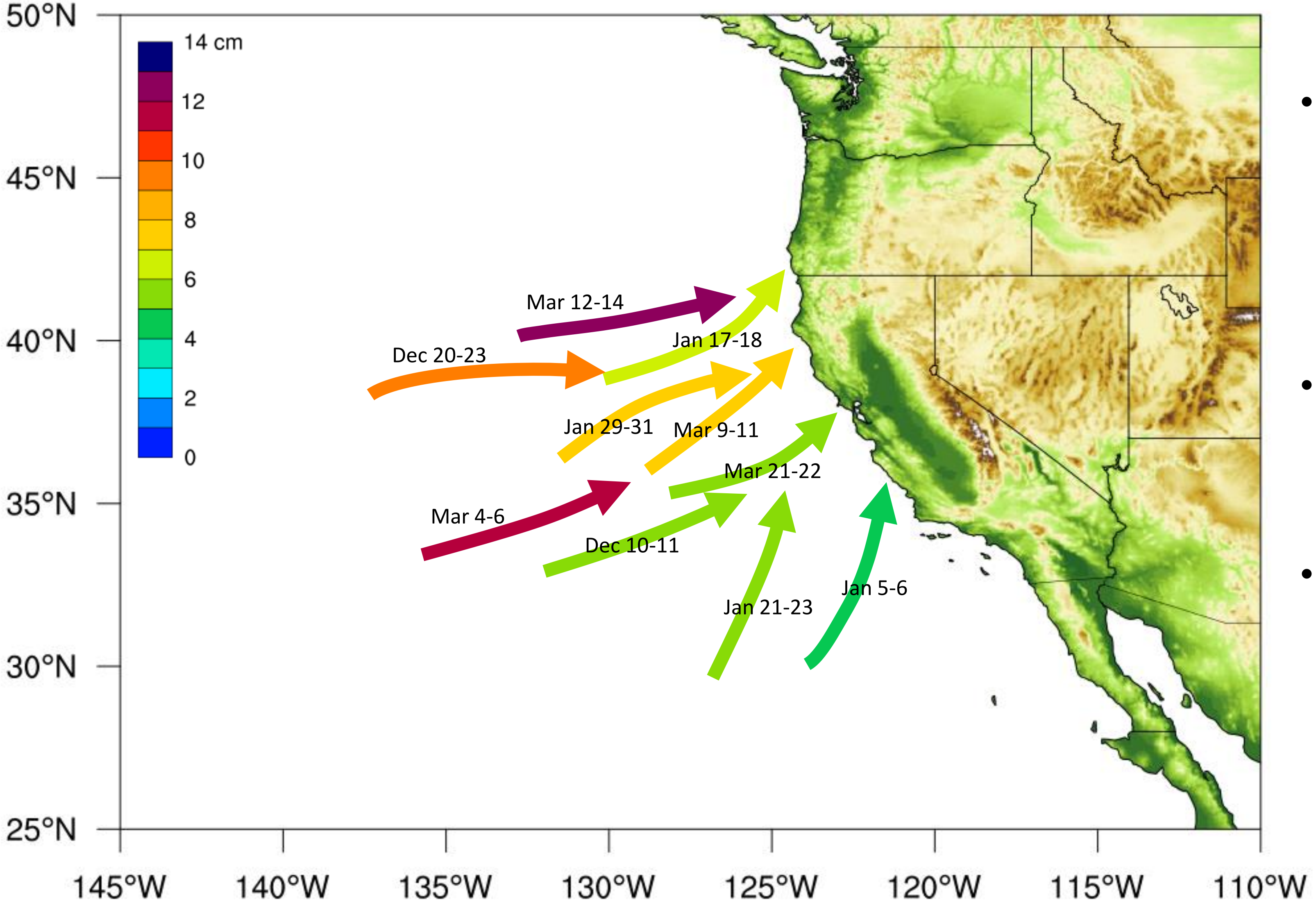
22% of WY in 10 days in March

*Data through May 31, 2016

Maximum IWV/IVT values are calculated along the U.S. West Coast and may not be at the same time or location
IVT/IWV data from GFS analysis

CW3E

AR Tracks – Preliminary schematic

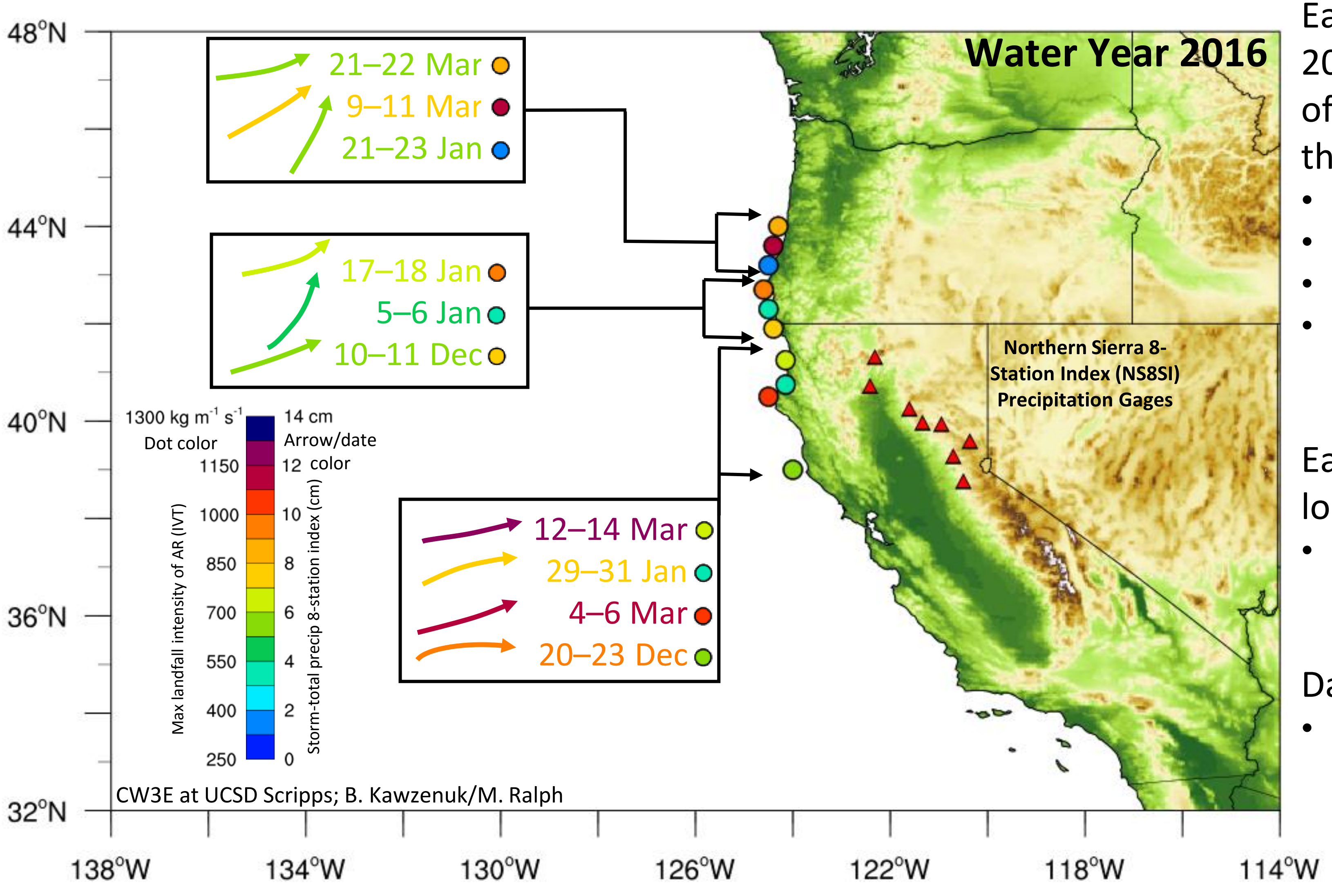


- Each arrow is representative of an AR associated with one of the top ten precipitation events in the Northern Sierra Nevada during the cool season of water year 2016.
- Each arrow represents the approximate AR corridor and initial landfall location at the time of initial landfall
- Color of each arrow represents the accumulated precipitation measured by the 8-Station Index during the event (48,72, or 96 hours)

CW3E

WY 2016 Storm Summary: Top-10 Wettest Events - Northern Sierra 8-Station Index

Dates, Landfall Locations, Storm Orientations – All Were Atmospheric Rivers



Each of the top-10 wettest events of WY 2016 were identified and examined in terms of their strength and nature of the storms that produced them

- The 10 events produced 54% of WY16 precip.
- All 10 were atmospheric river (AR) events*
- All 10 had winds from west or southwest
- All struck NorCal or OR coast and forced water vapor into the northern Sierra/Shasta area

Each dot represents the central landfall location of the associated atmospheric river

- Dot's color represents the maximum AR strength (i.e., its water vapor transport – IVT)

Dates and AR orientations are shown

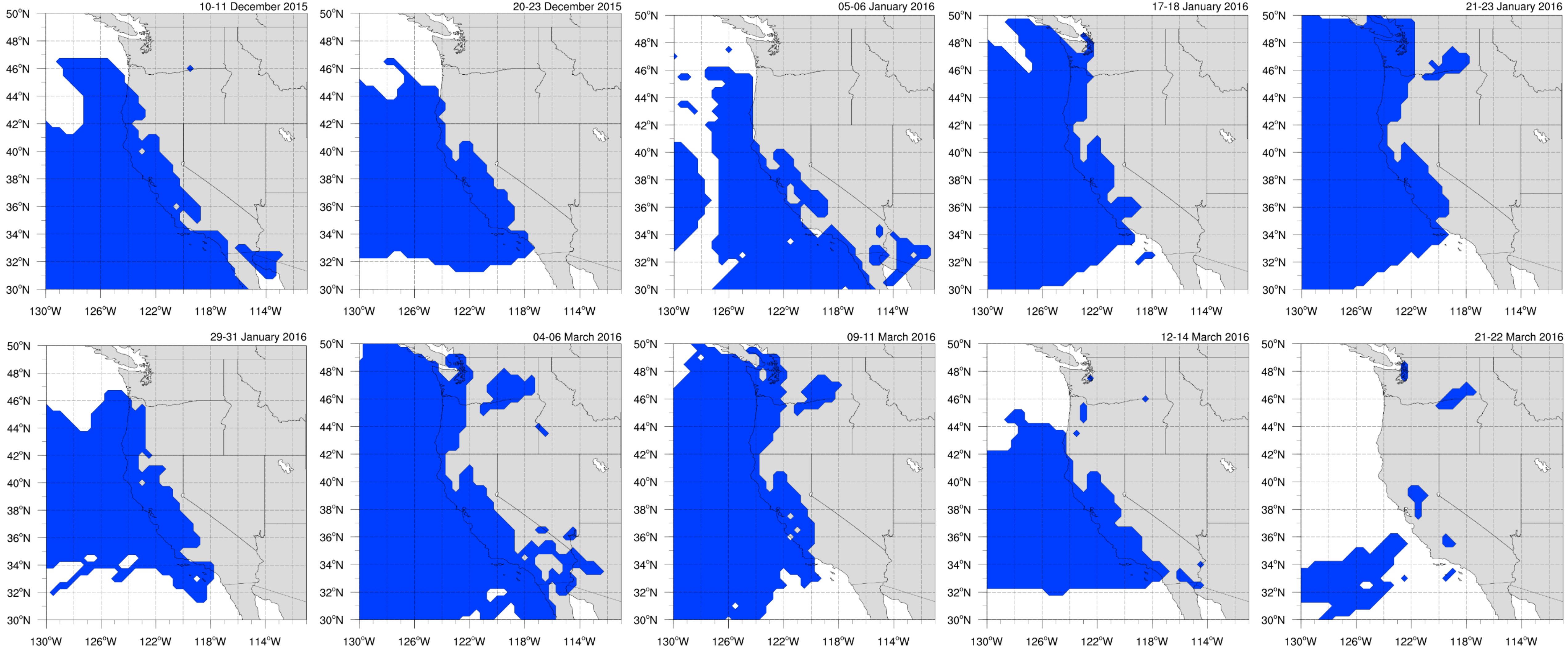
- Arrow's color represents total precip. measured by the 8-Station Index in that event (over 48,72, or 96 hours)

*See Ralph et al. 2016 for study of the relationship between NS8SI extreme events and landfalling ARs

CW3E

Location of All AR Conditions

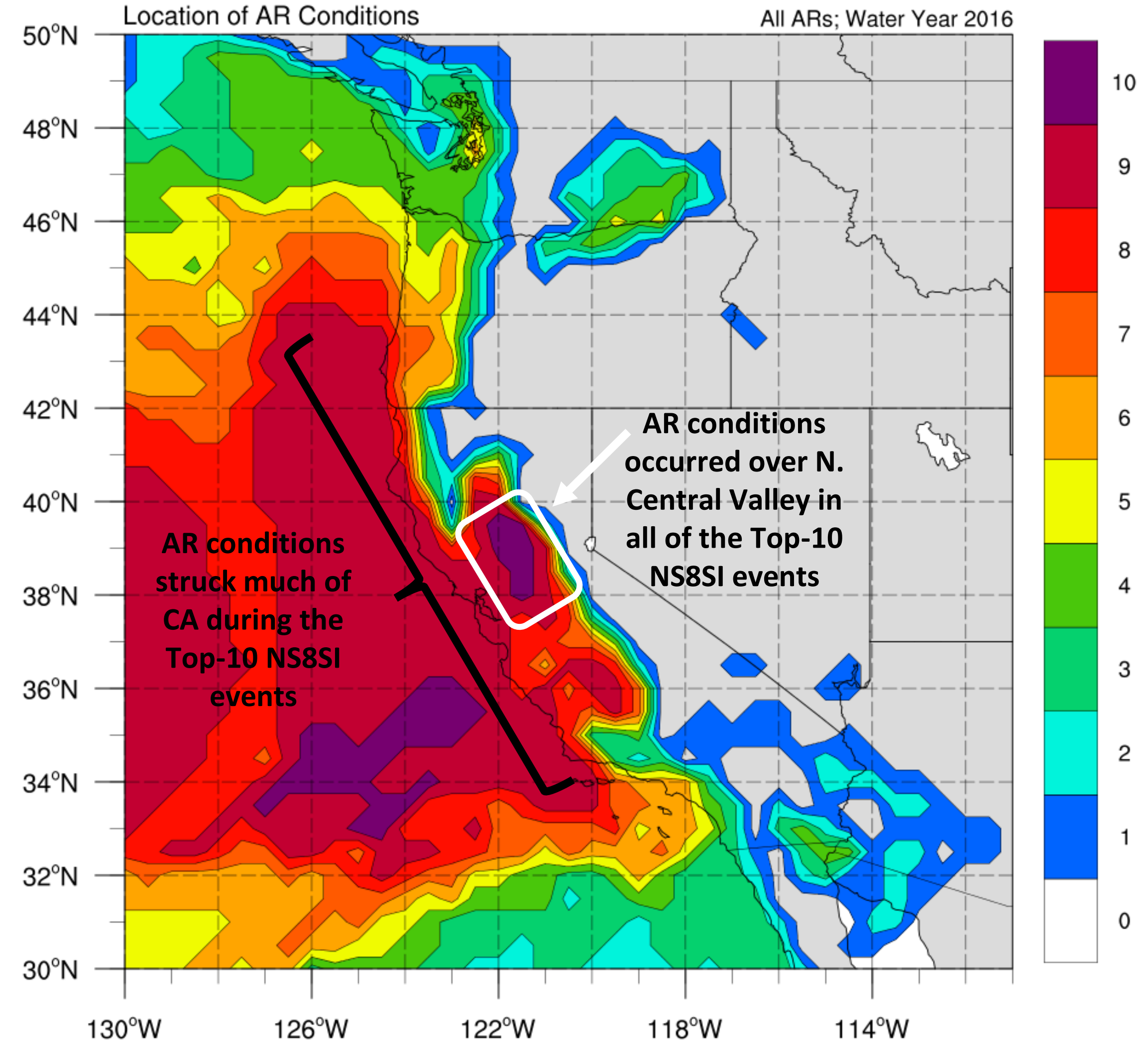
AR conditions are defined as IWV >20 mm and IVT >250 kg m^{-1} s^{-1}. Data from the GFS 0.5° analysis



CW3E

Location of AR Conditions Associated with the Top-10 NS8SI Precip. Events

AR conditions are defined as IWV >20 mm and IVT >250 kg m^{-1} s^{-1}. Data from the GFS 0.5° analysis



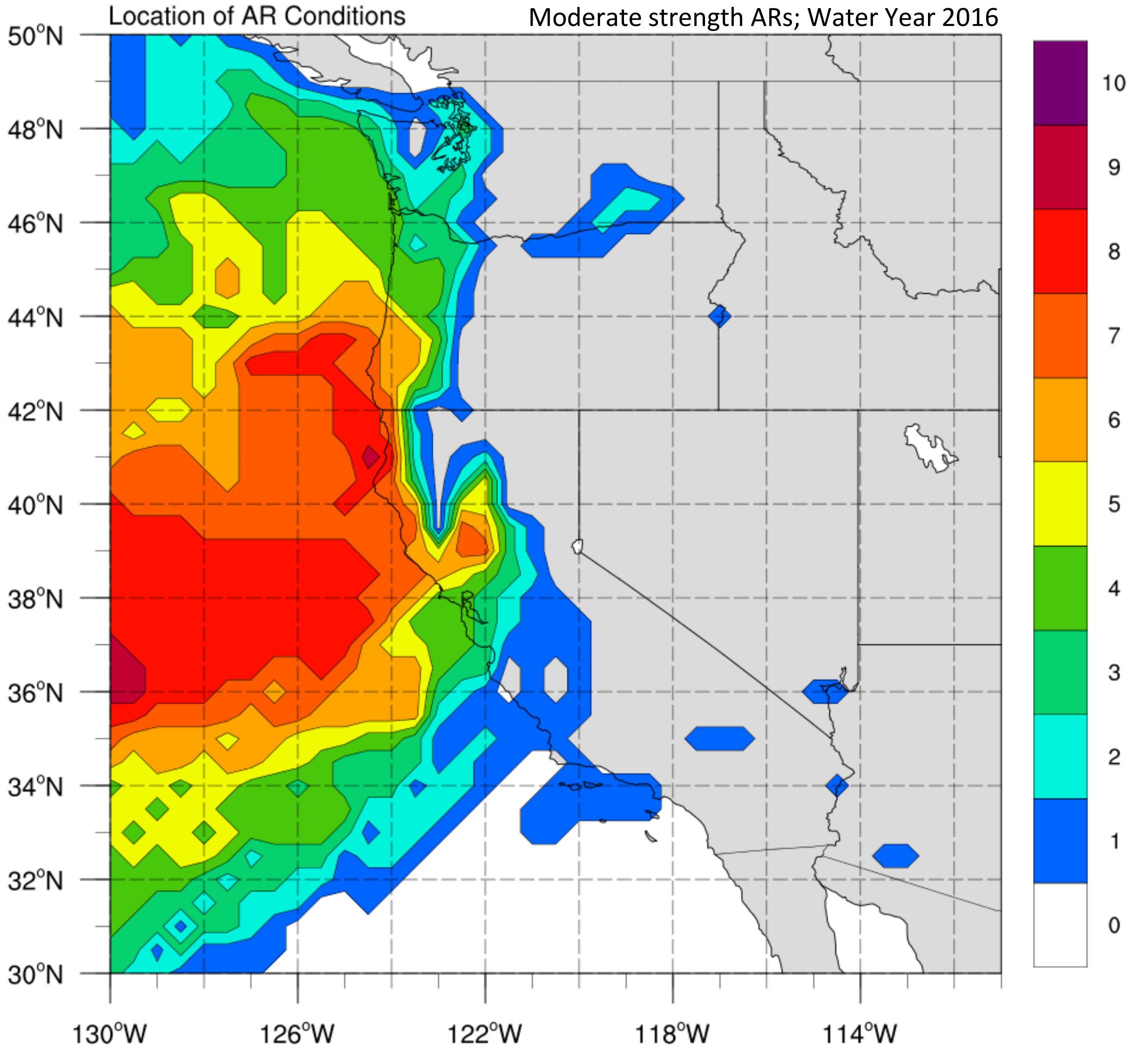
- Shading shows where AR criteria were met during the Top-10 NS8SI events*
- Locations within the ten contour (purple) experienced AR conditions during all ten events
    - AR conditions penetrated inland to the north central valley in all cases
- 90% of these ARs also made landfall over central and northern California

*See Ralph et al. 2016 for study of the relationship between NS8SI extreme events and landfalling ARs

CW3E

Location of Moderate Strength AR Conditions

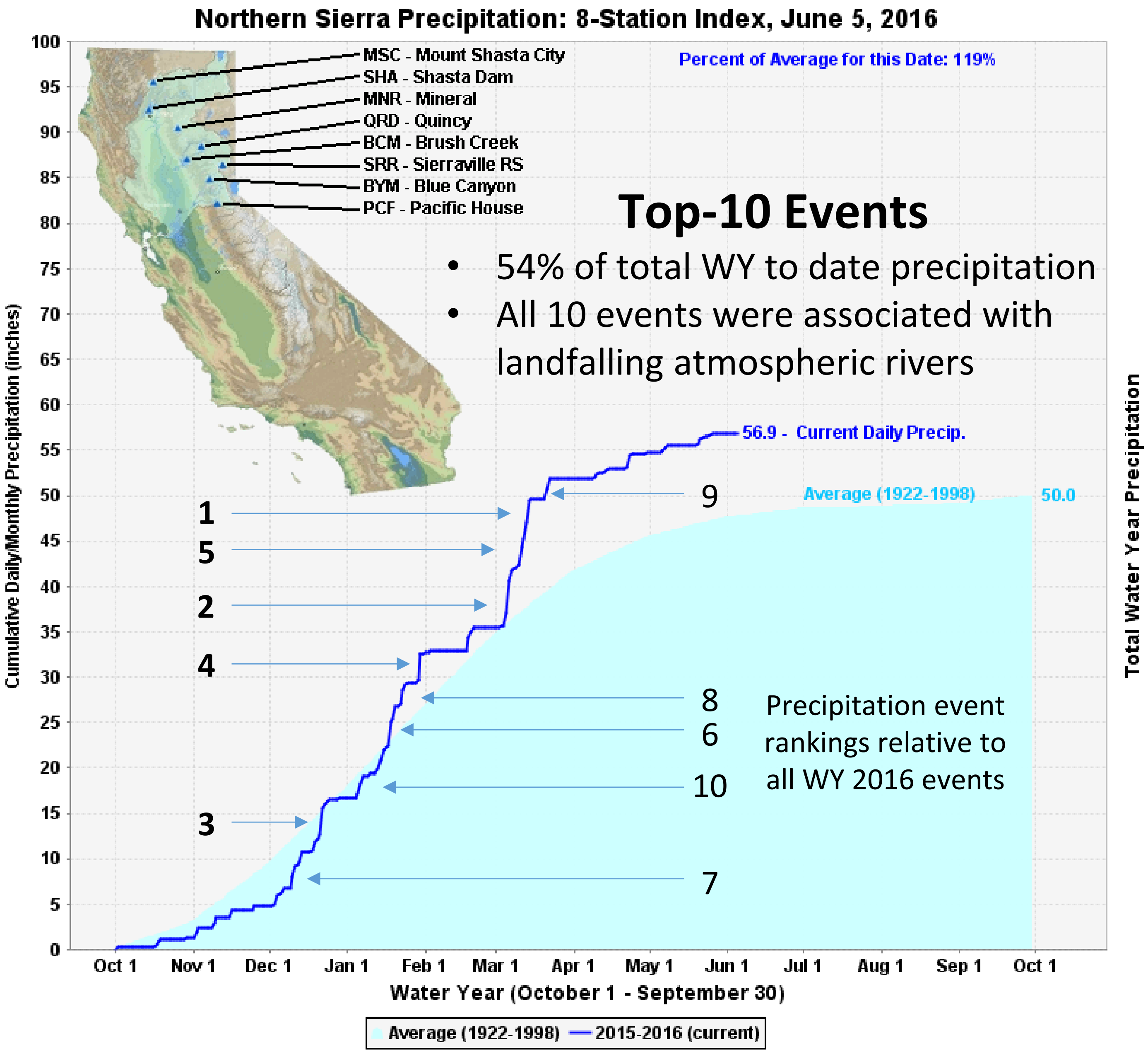
AR conditions are defined as IWV >20 mm and IVT >500 kg m^{-1} s^{-1}. Data from the GFS 0.5° analysis



- Shading shows where moderate strength AR conditions were met during the ten events
- Moderate strength AR conditions penetrated inland to the northern central valley and northern Sierra Nevada during 7 events
- Eight ARs made landfall over central/northern CA with moderate strength

Top-10 Events

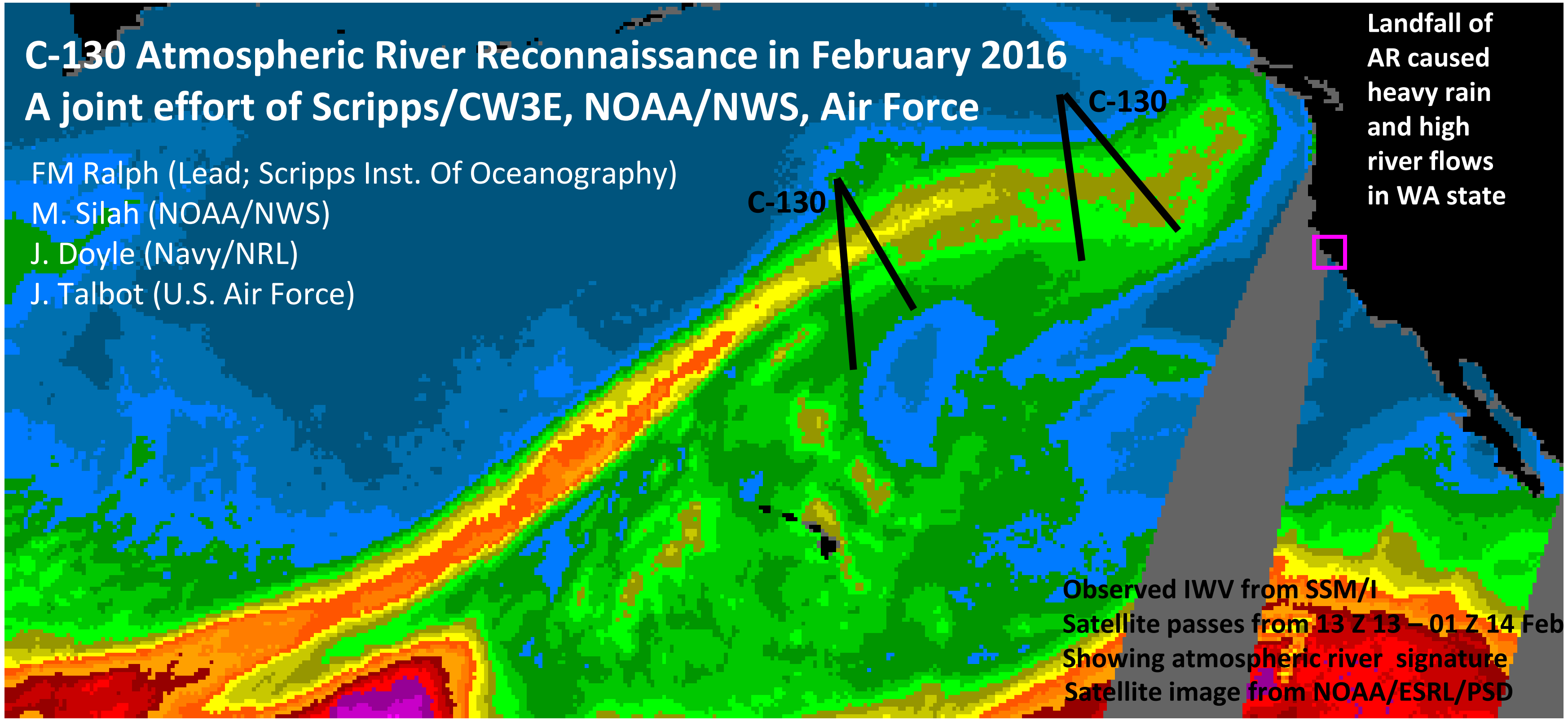
- 54% of total WY to date precipitation
- All 10 events were associated with landfalling atmospheric rivers



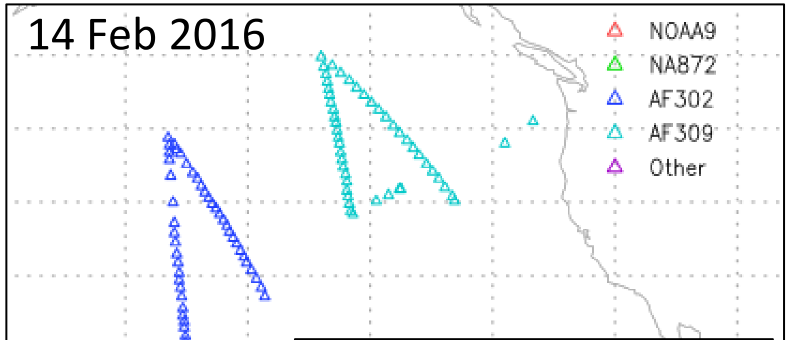
CW3E

C-130 Atmospheric River Reconnaissance in February 2016
A joint effort of Scripps/CW3E, NOAA/NWS, Air Force

FM Ralph (Lead; Scripps Inst. Of Oceanography)
M. Silah (NOAA/NWS)
J. Doyle (Navy/NRL)
J. Talbot (U.S. Air Force)



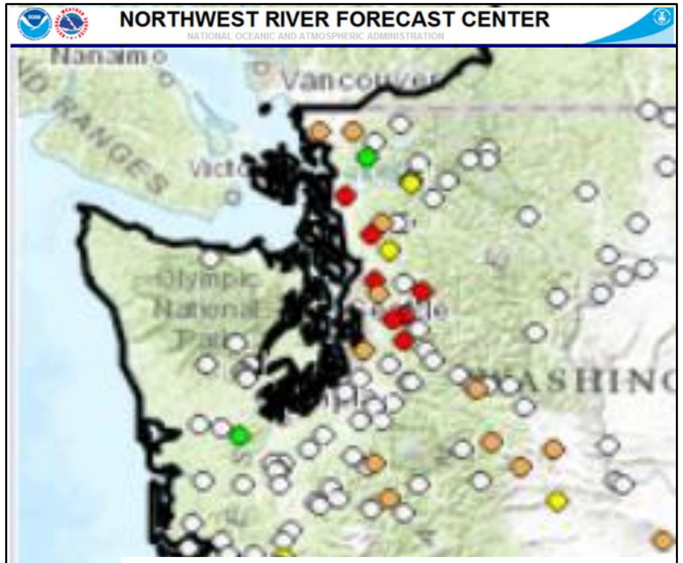
1st C-130 AR Recon Mission
13-14 Feb 2016
Dropsondes released for the 0000 UTC 14 Feb 2016 GFS data assimilation window



Locations of C-130 AR Recon dropsondes received and successfully decoded into NCEP's production bufr data tanks for assimilation into NCEP/GFS

Air Force C-130 Aircraft – Weather Recon' Squadron

Center for Western Weather and Water Extremes



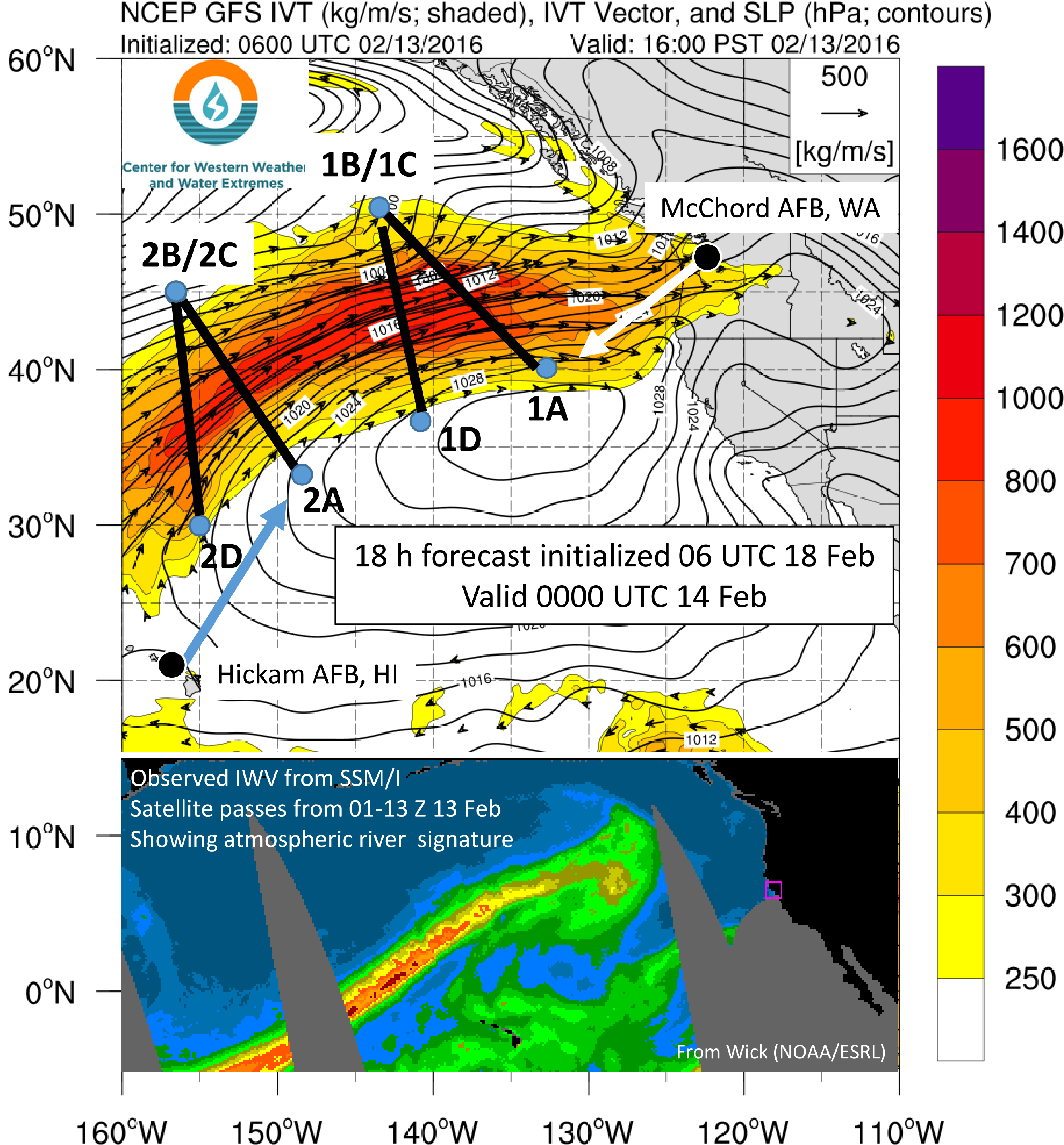
NWRFC flood forecast map as of 1500 UTC 15 Feb showing several rivers predicted to reach flood stage on 15-16 Feb (red dots)

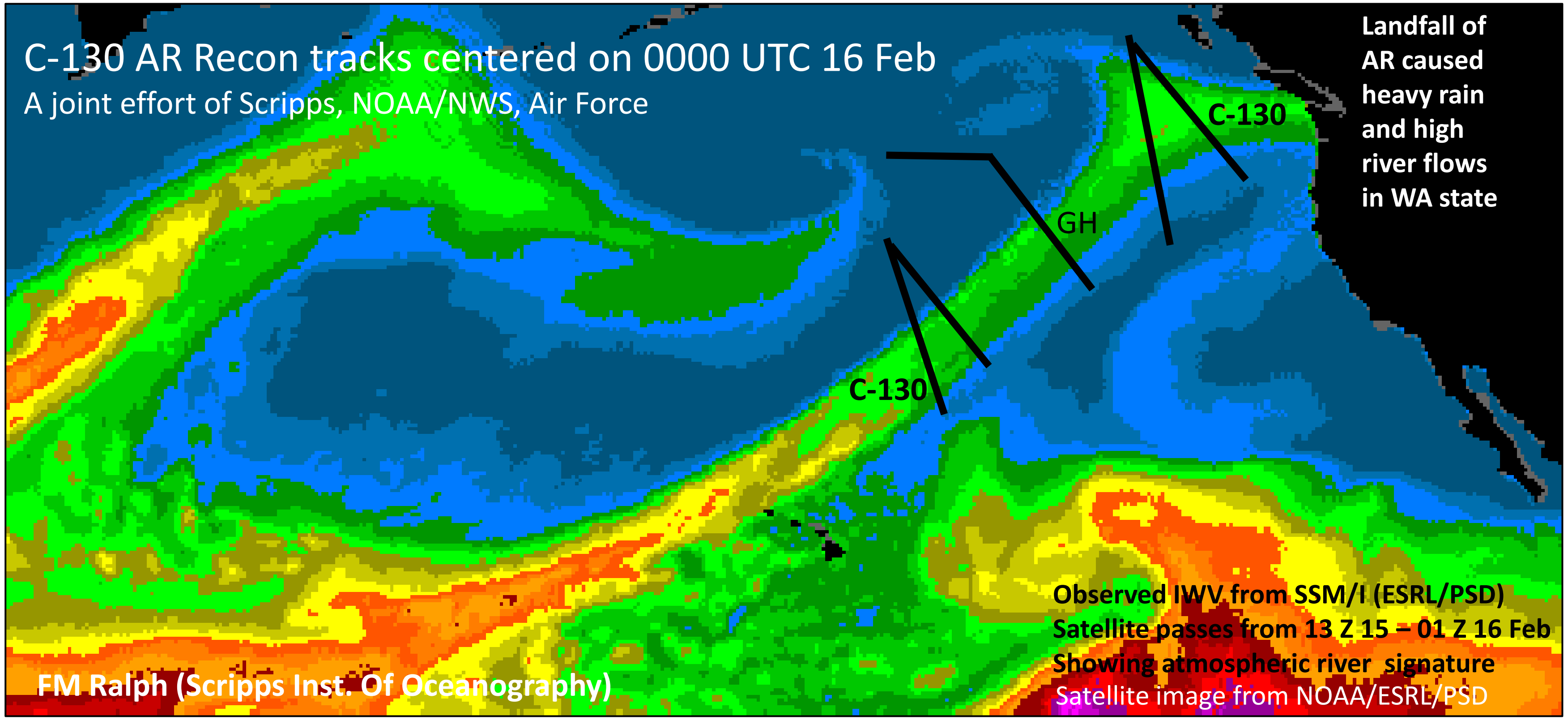
C-130 Atmospheric River Reconnaissance Mission
Flights centered on 0000 UTC 14 Feb

A joint effort of Scripps Institution of Oceanography/CW3E, US Air Force/Weather Recon. Squadron and NOAA/NWS

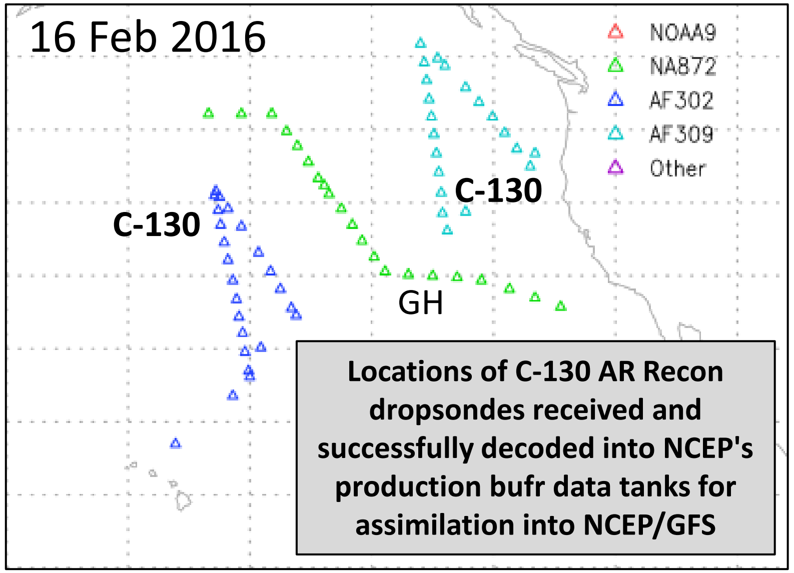
Summary by F. Martin Ralph

C-130 base	Waypoint	Lat (deg N)	Long (deg W)	Distance (time at 300 kt)
McChord AFB WA	TO: 1810 UTC	47.14	122.48	To 1A:
	1A: 2041	40	133	
	No Pt 1B			
	1C: 2340	50	144	
49 sondes	1D: 0157	39.1	141.6	
10.6 h	Ld: 0445			To McChord:
Hickam AFB HI	TO: 1721 UTC	21.34	157.95	To 2A:
	2A: 2032	33.5	148.5	
	No pt 2B			
	2C: 2322	45	157	
53 sondes	2D: 0318	30	155	
12.3 h	Ld: 0537			To Hickam:





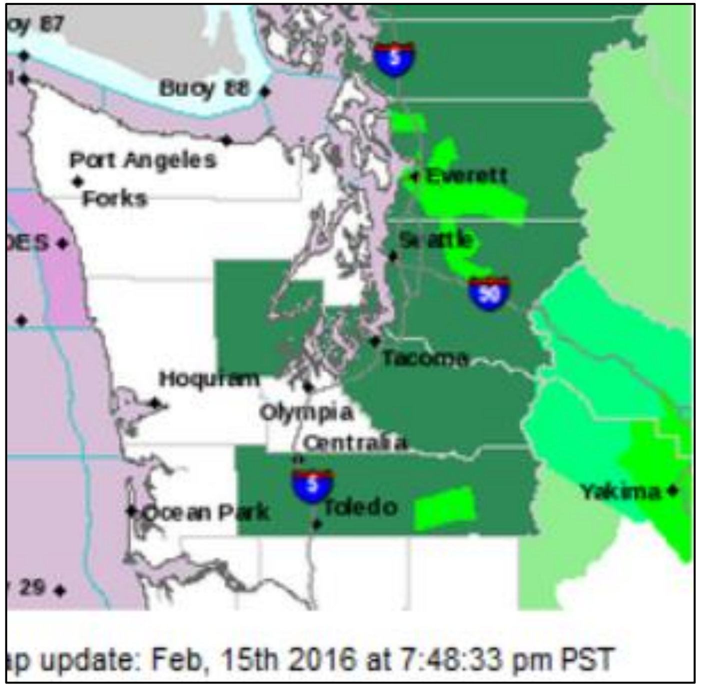
2nd C-130 AR Recon Mission
15-16 Feb 2016
Dropsondes released for the
0000 UTC 16 Feb 2016
GFS data assimilation window



Locations of C-130 AR Recon dropsondes received and successfully decoded into NCEP's production bufr data tanks for assimilation into NCEP/GFS

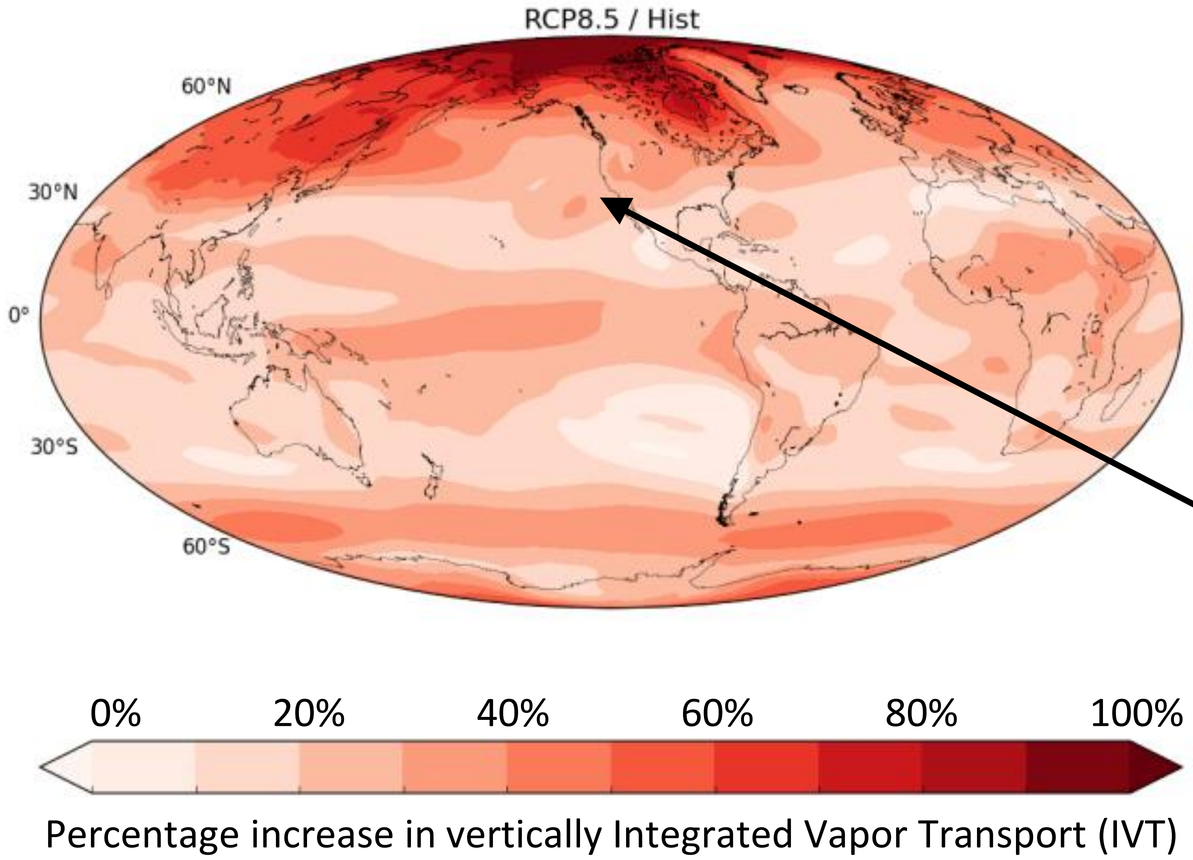
http://www.emc.ncep.noaa.gov/cmb/stokes/drops/maps/

Seattle NWS Office flood warnings, watches and advisories at 0400 UTC 16 Feb 2016

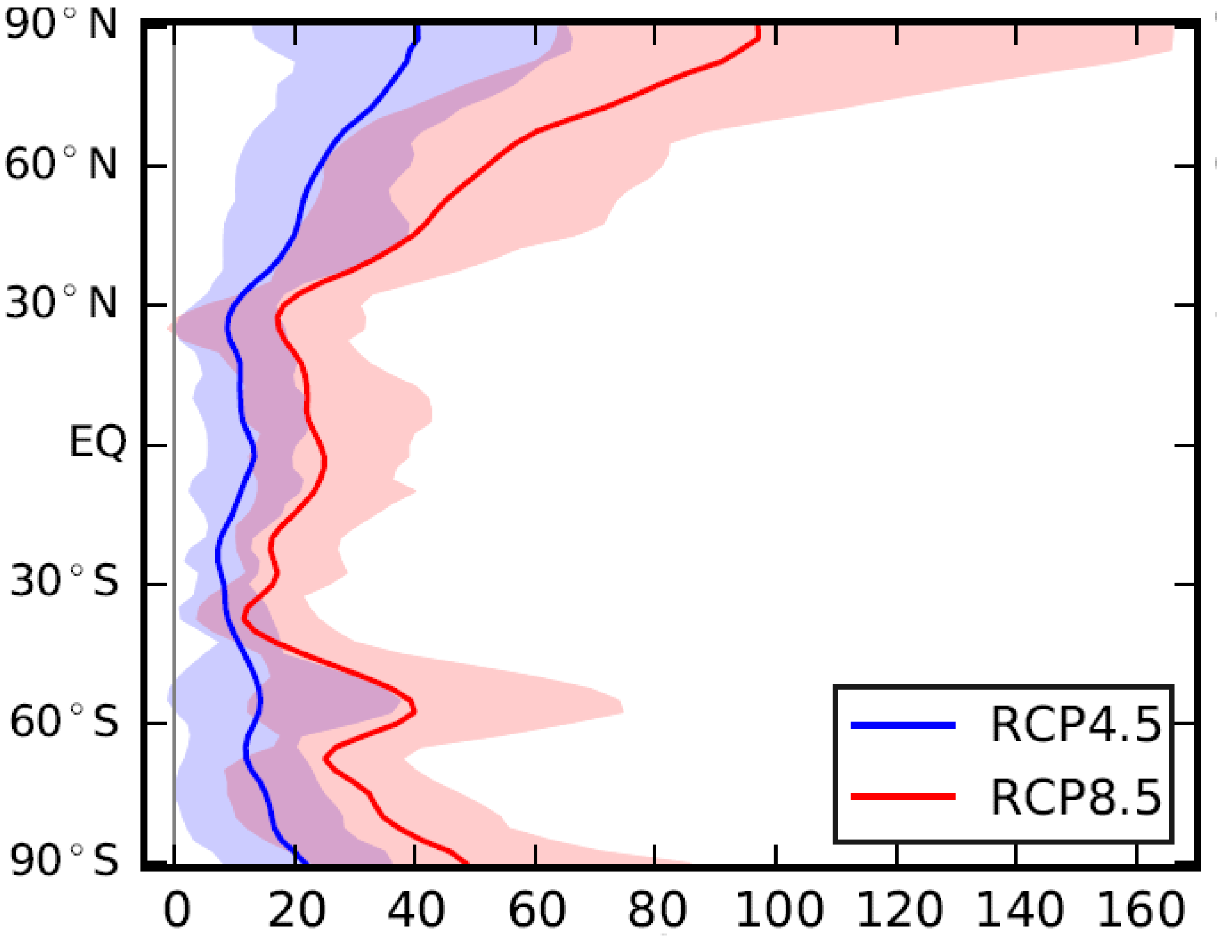


Climate change intensification of horizontal water vapor transport in CMIP5

D.A. Lavers, F.M. Ralph, D.E. Waliser, A. Gershunov, and M.D. Dettinger
Geophysical Research Letters (2015)



- 22 CMIP-5 GCM runs
- 2073-2099 (RCP4.5 and 8.5) vs 1979-2005 ("HIST")
- Percentage mean IVT increase (RCP8.5 / HIST) in Dec/Jan/Feb.
- 20-30% increases near CA



Percentage zonal-averaged mean IVT change in DJF

1. The mean and variance of atmospheric water vapor flux will intensify under projected climate change.

2. In key areas this flux will directly increase orographic precipitation.

3. The high-latitude (Arctic) water vapor flux exhibits the largest percentage increases.

4. The increased water vapor flux is almost exclusively due to increased low-level specific humidity.

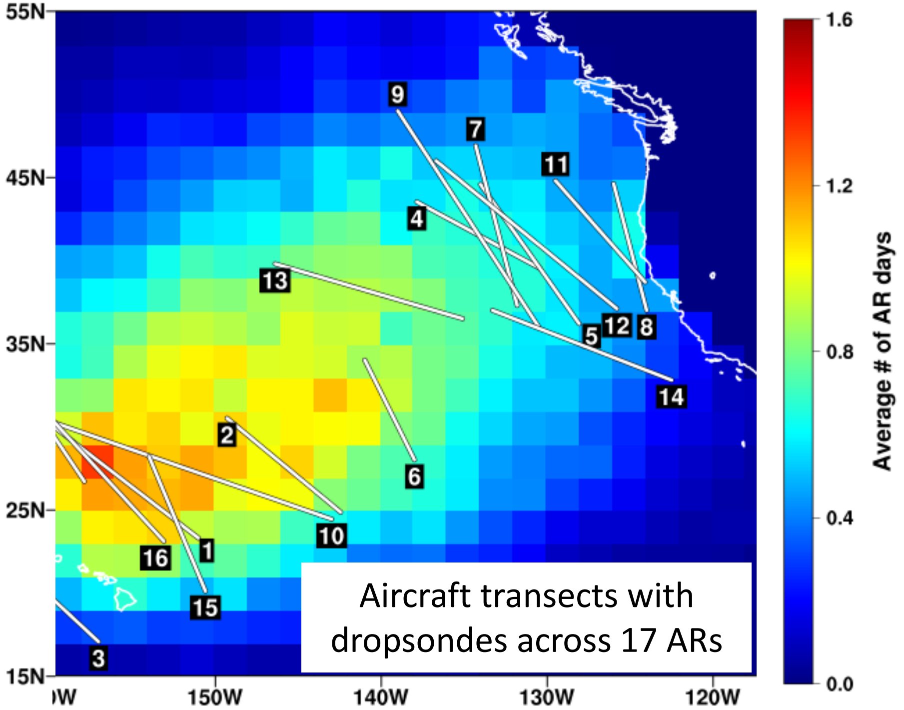
Lavers et al (*Geophys. Res.Lett., 2015)*

Center for Western Weather and Water Extremes

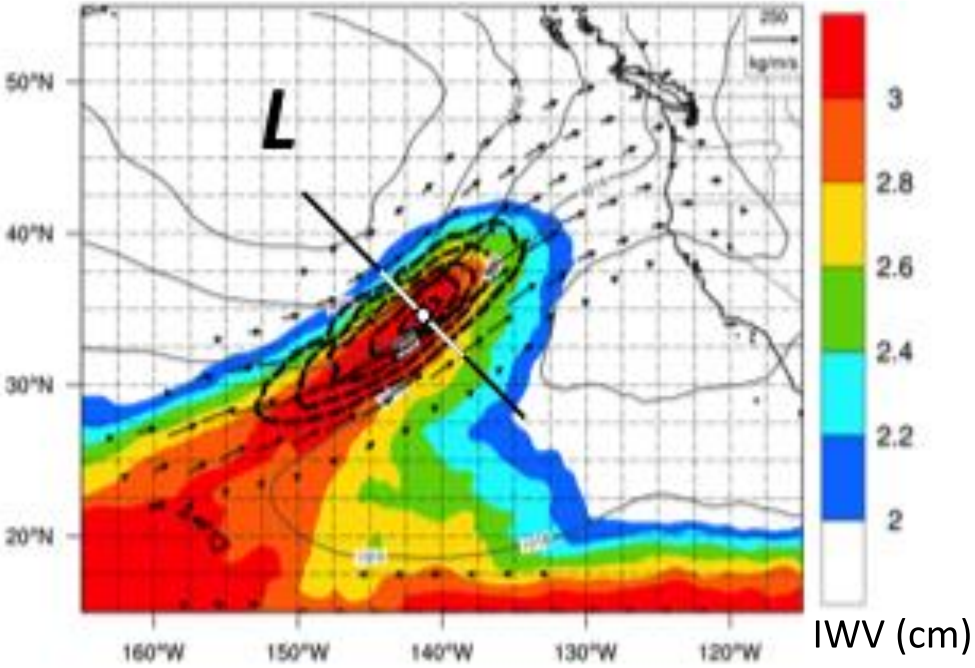
Observations of Water Vapor Transport by North Pacific Atmospheric Rivers

F.M. Ralph, S. Iacobellus, P.J. Neiman, J. Cordeira, J.R. Spackman, D. Waliser, G. Wick, A.B. White, C. Fairall

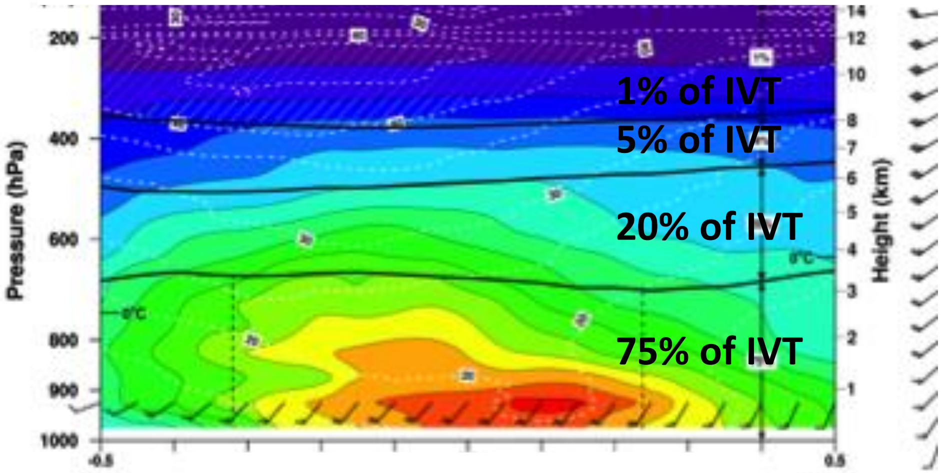
In Preparation



Composite AR Plan View (Color fill IWV; dashed lines IVT)



Composite AR Cross section (26 Mississippi's)

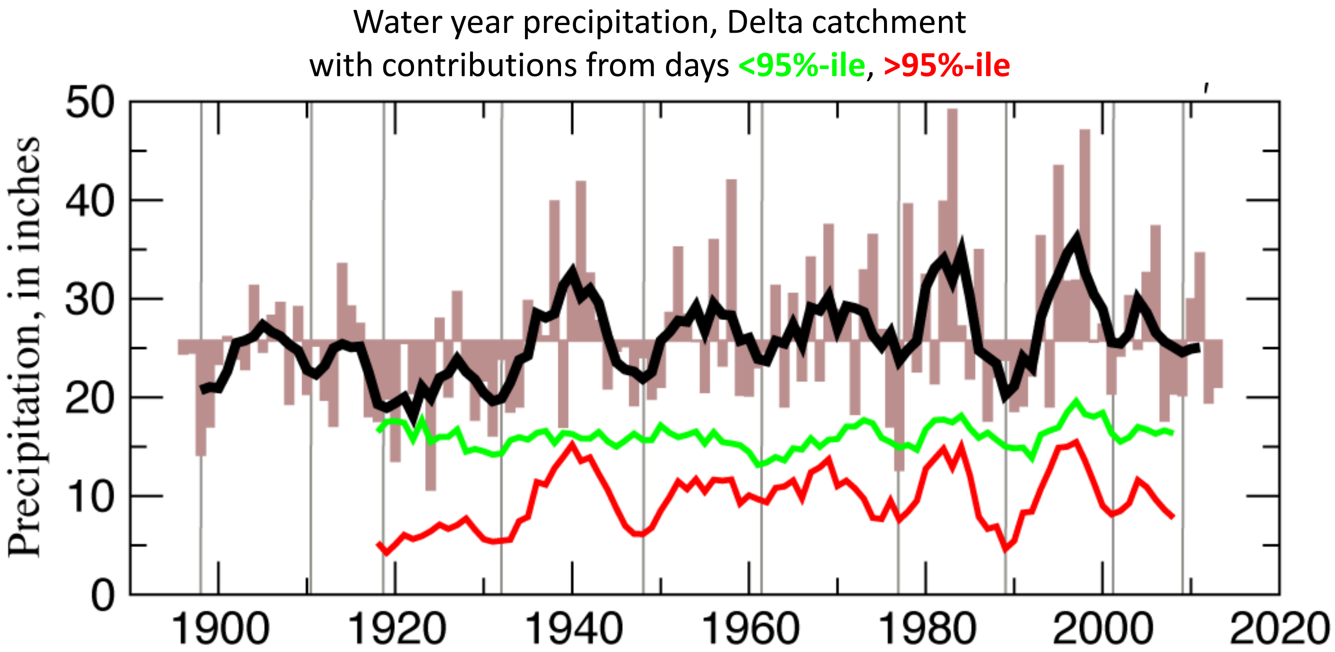


Normalized AR width (860 km)

Vapor transport (color fill)

A few large storms (or their absence)

Account for a disproportionate amount of California's precipitation variability



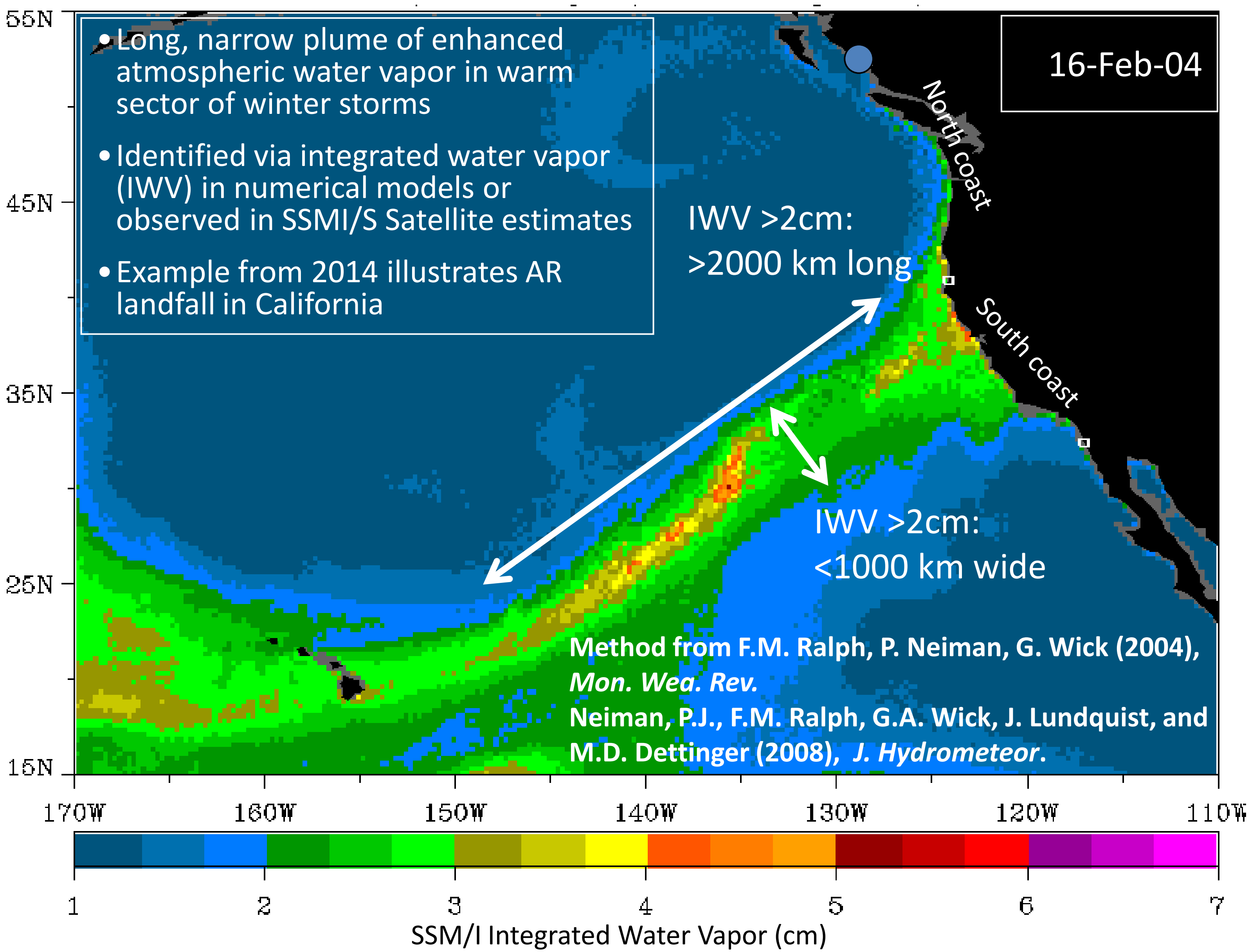
Dettinger and Cayan 2014, *San Francisco Estuary and Watershed Science*

Thank you

mralph@ucsd.edu
cw3e.ucsd.edu

Center for Western Weather and Water Extremes

NorCal Landfalling Atmospheric River Events Identified Using SSM/I IWV Data

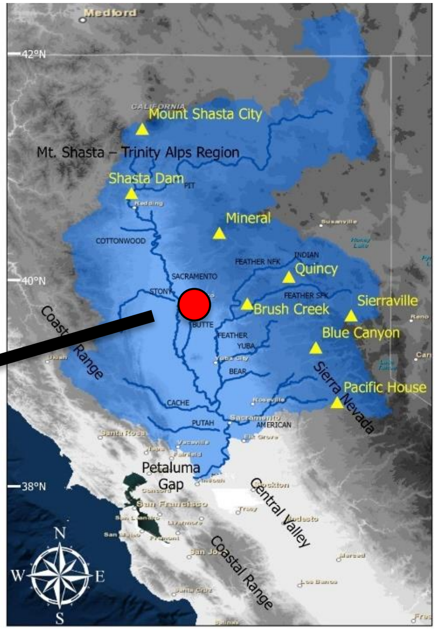


- Long, narrow plume of enhanced atmospheric water vapor in warm sector of winter storms
- Identified via integrated water vapor (IWV) in numerical models or observed in SSMI/S Satellite estimates
- Example from 2014 illustrates AR landfall in California

Method from F.M. Ralph, P. Neiman, G. Wick (2004), *Mon. Wea. Rev.*
Neiman, P.J., F.M. Ralph, G.A. Wick, J. Lundquist, and M.D. Dettinger (2008), *J. Hydrometeor.*

A seven-year wind profiler-based climatology of the windward barrier jet along California's Sierra Nevada

Neiman, Sukovich, Ralph and Hughes, *Mon. Wea. Rev., 2010*

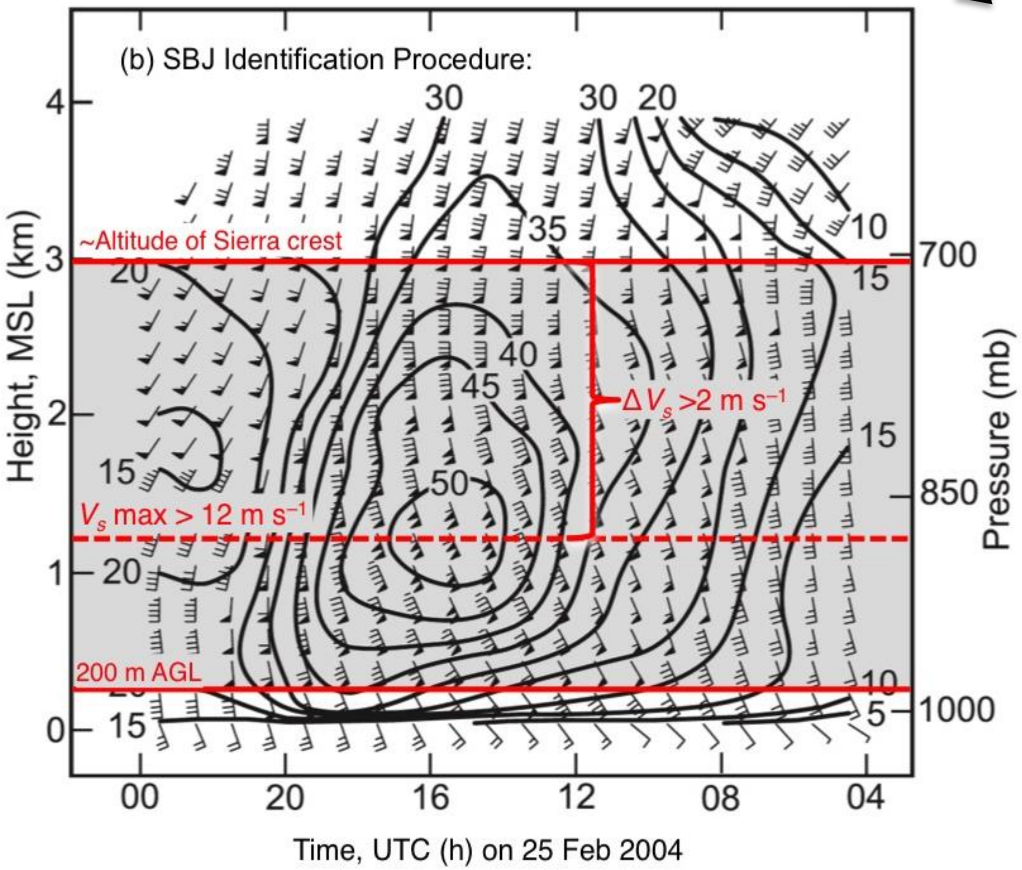


Sierra Barrier Jet Identification

- A barrier jet is a low-level, barrier-parallel core of locally strong winds composed primarily of ageostrophic flow at ~1 km AGL.

- SBJs are identified from data collected from a 915-MHz radar wind profiler at Chico (CCO), CA deployed by NOAA/ESRL.

- SBJs are identified using the Neiman et al. (2010) methodology: (1) meridional (V) wind component >12 m s^{-1} below 3 km, (2) maximum V-wind (V_{max}) must be located ≥200 m AGL, and (3) V-wind must decrease by >2 m s^{-1} between level of V_{max} and 3 km.



Time–height section of hourly averaged wind profiles (every other range gate shown) and barrier-parallel isotachs (m s^{-1}; directed toward 340°) at Chico (CCO), CA on 25 Feb 2004 (wind flags = 25 m s^{-1}, barbs = 5 m s^{-1}, half barbs = 2.5 m s^{-1}). Figure from Neiman et al. (2010).

SBJ Identification Criteria