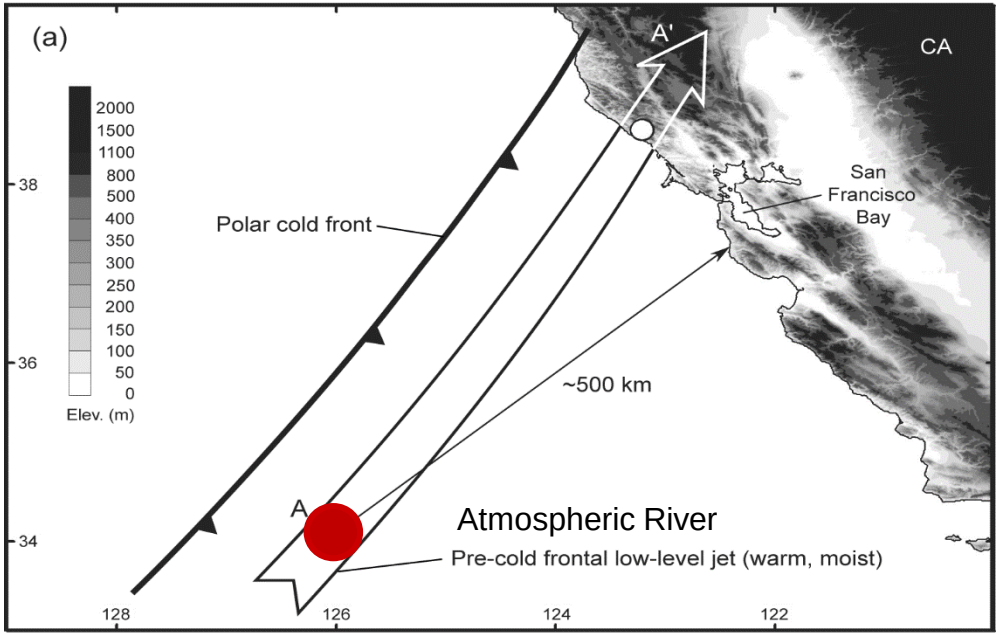
Center for Western Weather and Water Extremes

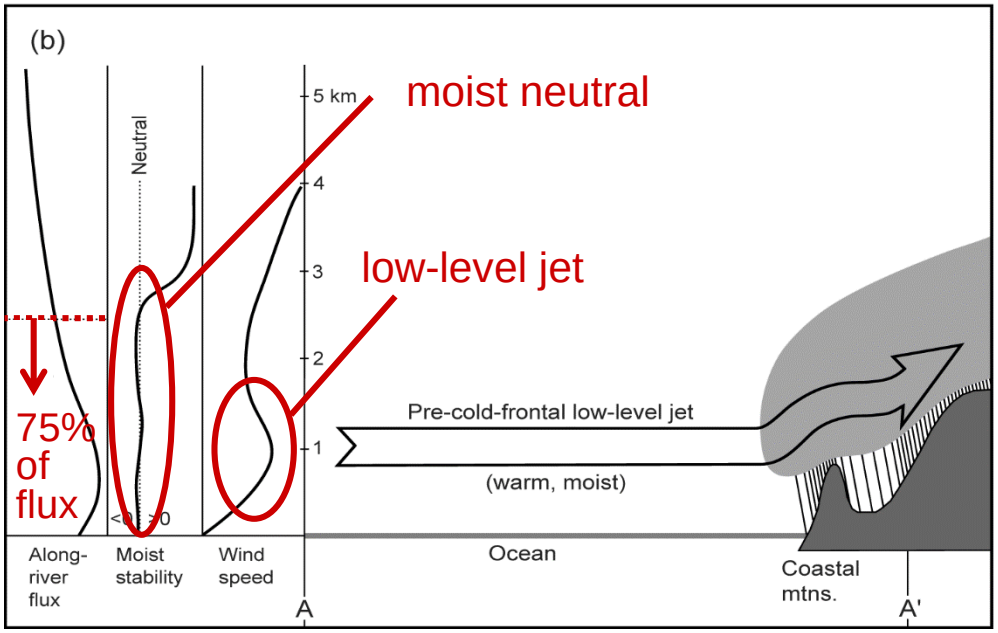
Observations of Water Vapor Transport by North Pacific Atmospheric Rivers

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

International Atmospheric Rivers Conference
Scripps Inst. Oceanography, La Jolla
11 August 2016

Experiments in 1998,2001 provided a mean vert profile in ARs

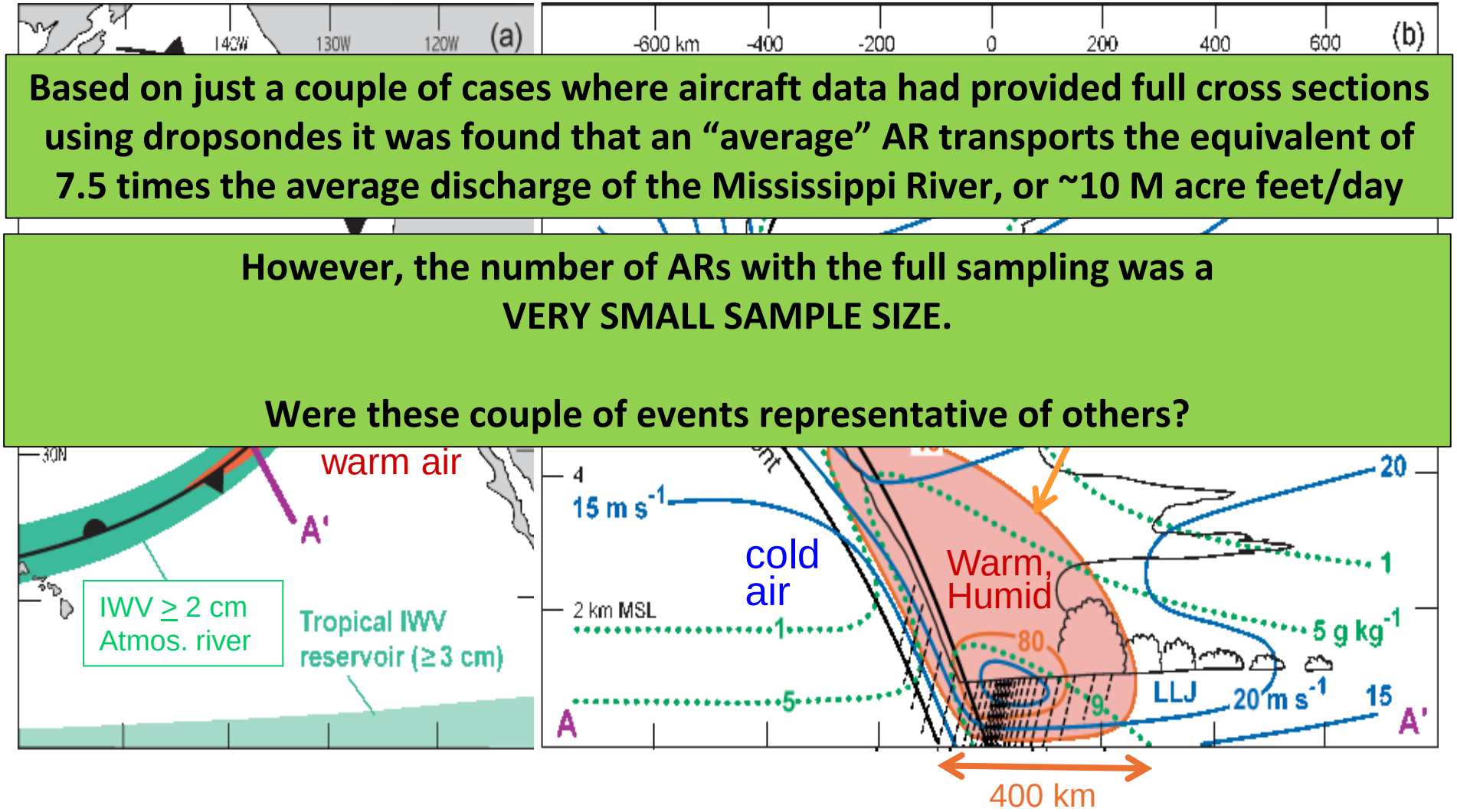




- CALJET and PACJET field experiments used the NOAA P-3 aircraft to profile ARs
- Composite sounding located 500 km off CA coast in atmos. river & pre-cold-frontal LLJ
- LLJ directed toward coast and situated at 1 km MSL
- Most (75%) of pre-cold-frontal along-river moisture flux is below 2.5 km MSL
- Moist neutral stratification below 2.8 km MSL, hence no resistance to orographic lifting
- Overlapping set of conditions conducive to orographic rain enhancement in coastal mtns

Ralph et al. (2005), *MWR*

Ralph et al. 2004 and 2011 (Mon. Wea. Rev.)
presented two detailed cross sections from two field experiments



Based on just a couple of cases where aircraft data had provided full cross sections using dropsondes it was found that an "average" AR transports the equivalent of 7.5 times the average discharge of the Mississippi River, or ~10 M acre feet/day

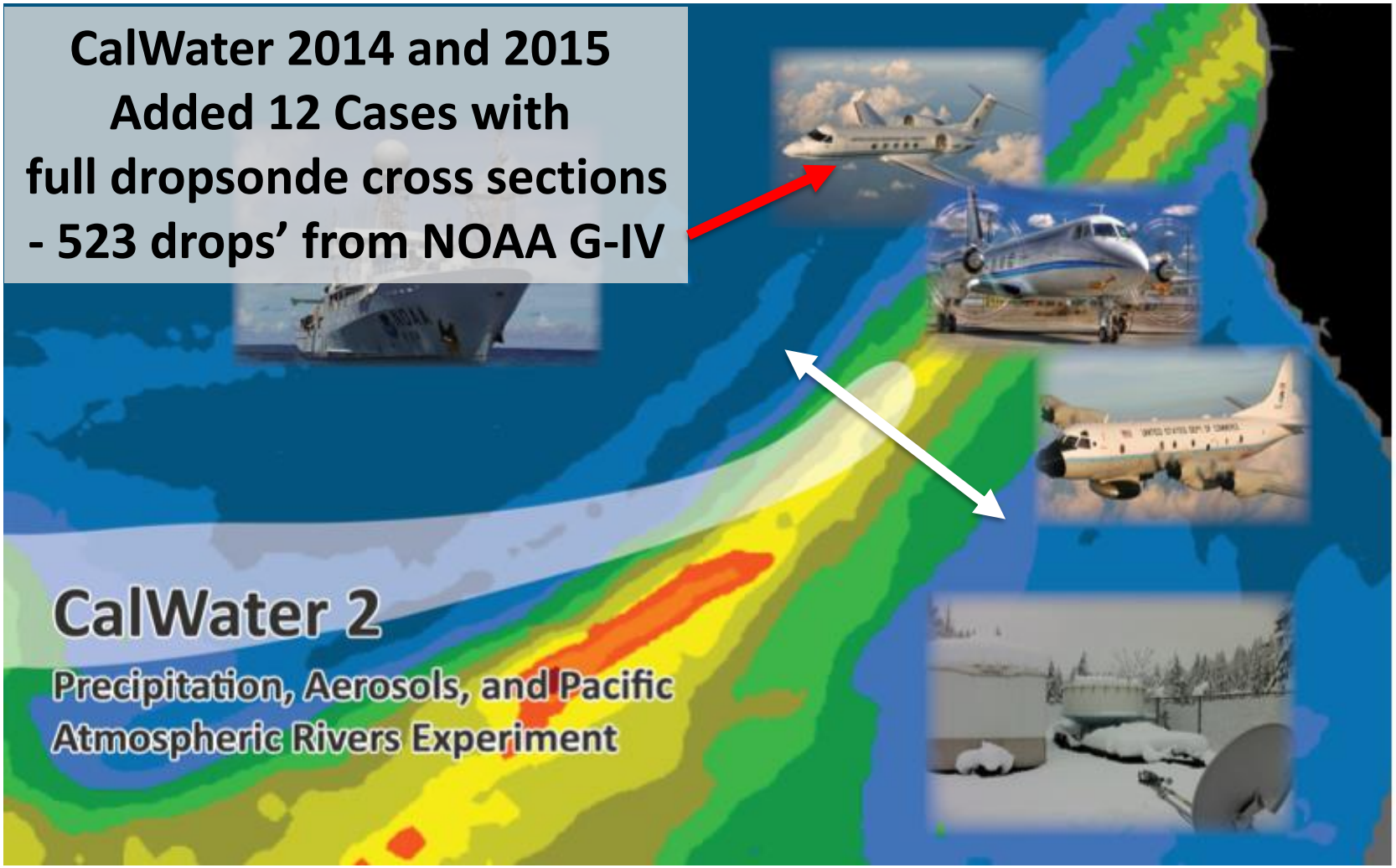
However, the number of ARs with the full sampling was a VERY SMALL SAMPLE SIZE.

Were these couple of events representative of others?

CalWater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in Modulating U.S. West Coast Precipitation in a Changing Climate

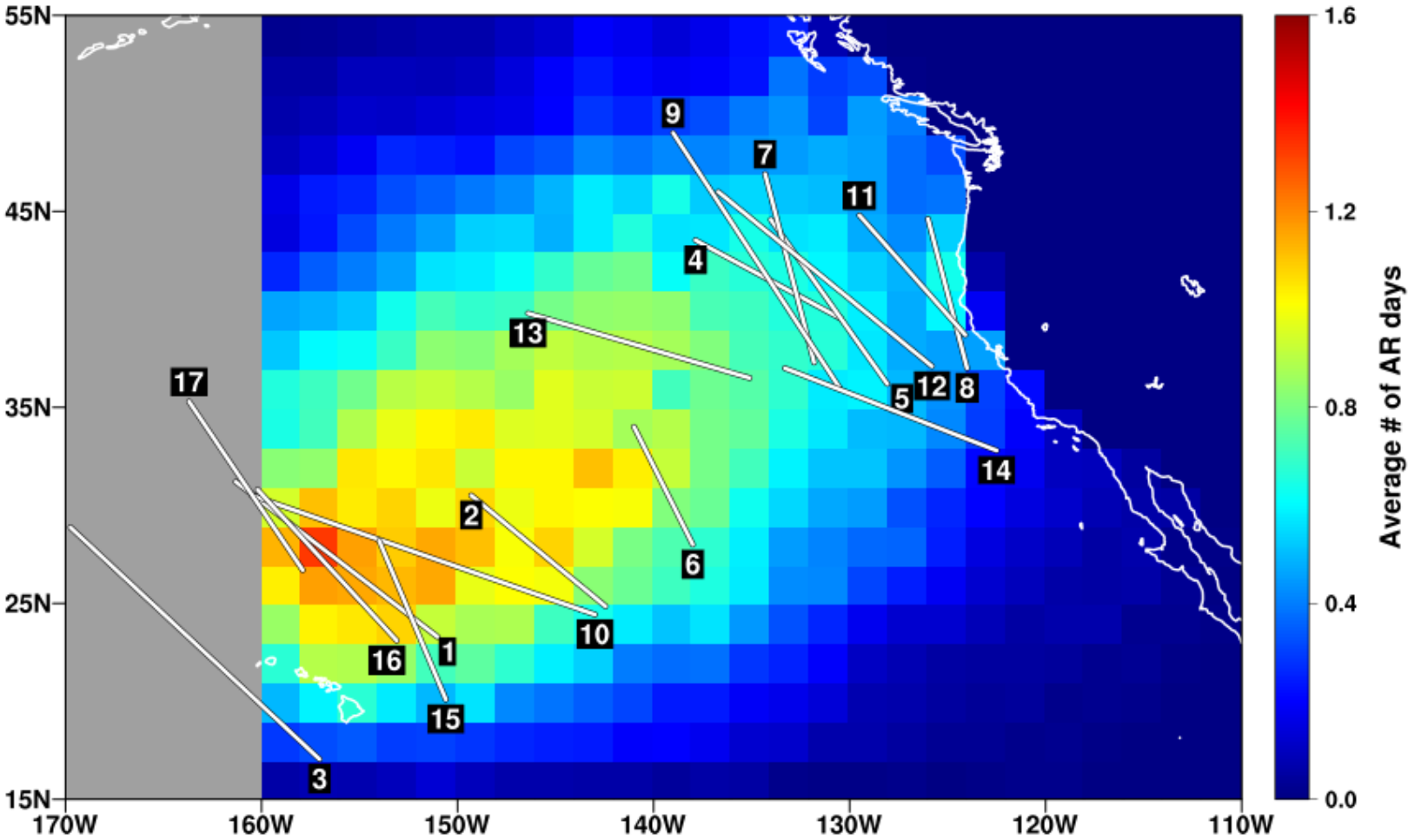
Ralph, F.M, K. A. Prather, D. Cayan, J.R. Spackman, P. DeMott, M. Dettinger, C. Fairall, R. Leung, D. Rosenfeld, S. Rutledge, D. Waliser, A. B. White, J. Cordeira, A. Martin, J. Helly, and J. Intrieri,.

Bull. Amer. Meteor. Soc. (July 2016)



17 AR Cases now available with full dropsonde cross-sections

(includes 5 from flights prior to CalWater2)



Location of the dropsonde transects listed in Table 1. The background image denotes weekly AR frequency calculated using the AR Detection Tool of Wick et al (2013) applied during the 2003-2012 cool seasons (November-February). AR frequency data west of 160°W was not available.

Typical Dropsonde Retrieval from G-IV Aircraft

- data starts ~ 175-200 hPa and down to surface

- generally ~1500-2000 levels with 5-10 meter resolution

- takes ~ 15 minutes to reach surface

- measurements of P, T, Z, RH, U, and V

- allows calculation of integrated water vapor (IWV)
  and integrated vapor transport (IVT)

$$\mathrm{IWV} = \frac{1}{g}\int_{p_{sfc}}^{p_{top}} q\, dp$$

$$\mathrm{IVT} = \frac{1}{g}\int_{p_{sfc}}^{p_{top}} q\boldsymbol{V}\, dp$$

Examined Dropsondes for Transects Across ARs

AR Boundaries defined using:

IWV > 20 mm
or
IVT > 250 kg m^{-1} sec^{-1}

- Test sensitivity of calculated AR properties to threshold method

- Not all flight missions were designed to transect an AR

- Some transects did not completely cross the AR

	Date	Aircraft	Central Latitude	No. of Sondes@	Mean Dir.	IWV_{MAX} (mm)	IVT_{MAX} (kg m^{-1} s^{-1})	$TIVT_a$ (10^8 kg s^{-1})	$Width_a$ (km)	$TIVT_b$ (10^8 kg s^{-1})	$Width_b$ (km)
	Subtropical										
1	25-Mar-2005	P-3	27.2°N	16	233	41.2	674	4.26	1196	3.96	1016
2	12-Feb-2011	G-Hawk	27.7°N	9	237	41.0	585	2.37	811	1.77	415
3	04-Mar-2011	G-IV	23.0°N	17	220	48.9	725	4.85	1539	4.24	849
6	08-Feb-2014	G-IV	31.0°N	9	230	41.7	1029	3.44	602	3.56	611
10	18-Feb-2014	G-IV	27.5°N	11	203	39.6	314	3.54	1802	1.33	477
15	14-Feb-2015	G-IV	24.2°N	11	229	46.1	1204	6.62	846	6.87	917
16	20-Feb-2015	G-IV	27.0°N	13	240	41.7	861	5.19	964	5.63	1092
17	22-Feb-2015	G-IV	31.0°N	17	232	39.1	926	6.94	1334	6.30	1026
			Mean (subtropical cases)	13	228	42.4	790	4.65	1137	4.21	800
			Standard Deviation	3	11	3.1	259	1.48	380	1.88	247
	Mid-latitude										
4	04-Mar-2011	G-Hawk	41.5°N	10	231	18.1	531	NA*	NA*	2.46	687
5	09-Mar-2011	G-Hawk	40.4°N	15	226	25.0	622	1.92	382	3.26	723
7	11-Feb-2014	G-IV	42.1°N	23	232	37.4	1296	7.94	1035	8.05	1067
8	12-Feb-2014	G-IV	40.8°N	14	245	32.0	636	3.21	808	2.80	619
9	13-Feb-2014	G-IV	42.5°N	21	220	33.2	789	4.39	733	6.90	1371
11	15-Jan-2015	G-IV	41.8°N	9	219	27.4	733	3.21	639	3.45	692
12	17-Jan-2015	G-IV	41.6°N	10	236	28.4	831	4.17	603	6.11	1154
13	24-Jan-2015	G-IV	38.2°N	12	203	29.9	607	2.58	534	3.74	868
14	08-Feb-2015	G-IV	34.9°N	11	216	34.8	938	4.35	774	5.96	1054
			Mean (midlatitude cases)	14	225	29.6	776	3.97	689	4.75	915
			Standard Deviation	5	12	5.4	219	1.71	184	1.91	244
			Overall Mean	13.4	227	35.6	782	4.31	913	4.49	861
			Standard Deviation	4.2	12	8.1	247	1.69	385	1.97	260

Summary of Statistics from 17 AR Transects

	No. of Sondes	Mean Dir.	IWV max (mm)	IVT max (kg m^{-1} s^{-1})	$TIVT_1$ (10^8 kg s^{-1})	$Width_1$ (km)	$TIVT_2$ (10^8 kg s^{-1})	$Width_2$ (km)
Overall Mean	13.4	227	35.6	782	**4.3**	**910**	**4.5**	**860**
Standard Deviation	4.2	12	8.1	247	1.7	390	2.0	260

TIVT = Total Integrated Vapor Transport (10^8 kg sec^{-1})
TIVT1: AR defined using IWV > 20 mm threshold
TIVT2: AR defined using IVT > 250 kg m^{-1} sec^{-1} threshold

TIVT using IVT threshold within ~ 3% of IWV threshold method
AR Width within ~ 6% between the two threshold methods

- **IVT threshold of 250 kg m^{-1} s^{-1} corresponds well to established IWV threshold of 20mm**
- **Additionally IVT threshold:**
  - **produces more consistent results between sub-tropical and mid-latitude ARs**
  - **more relevant to orographic precipitation than IWV**

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TIVT = Total Integrated Vapor Transport (10^8 kg sec^{-1})
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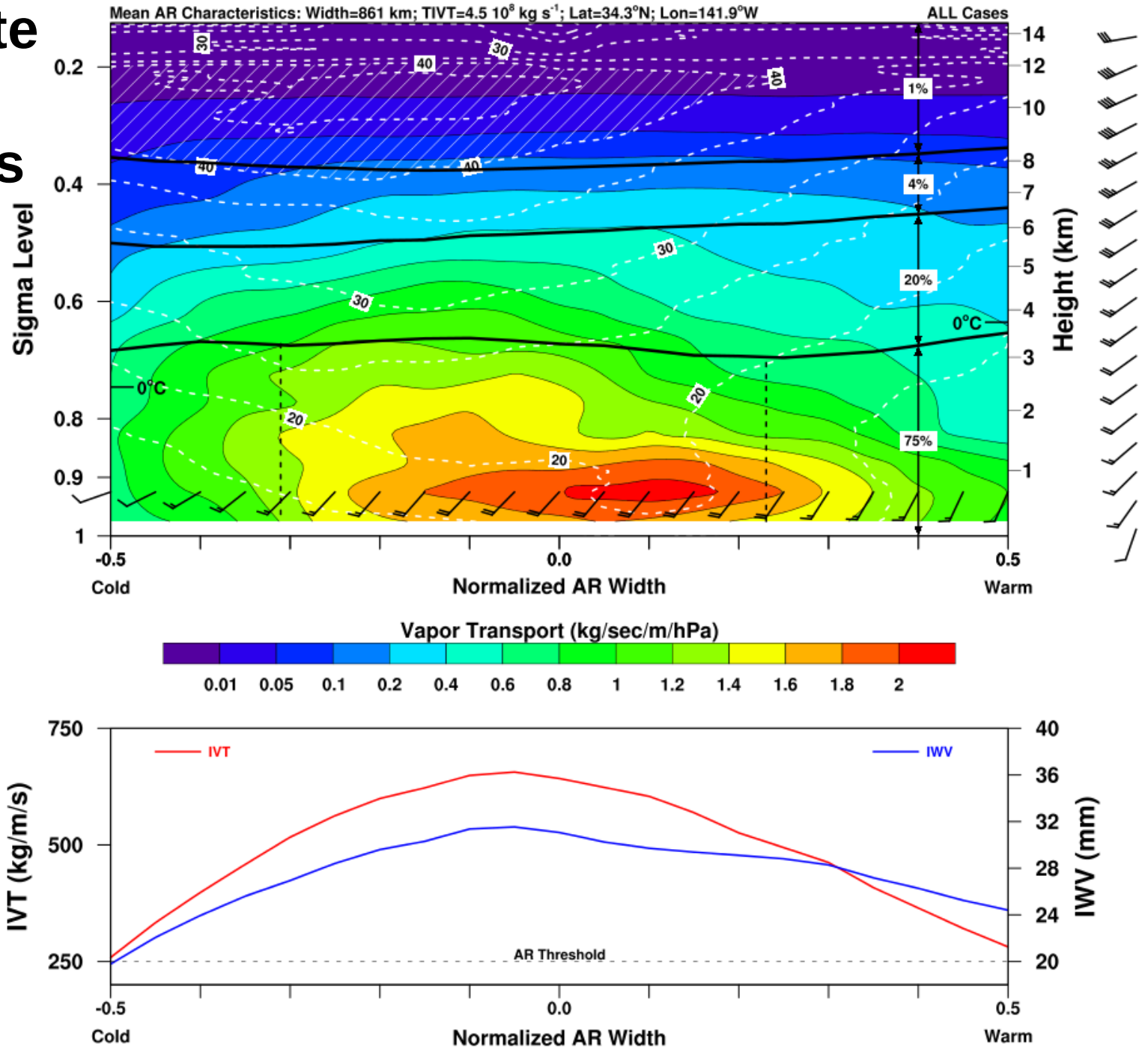
Maximum Values over all 17 ARs:

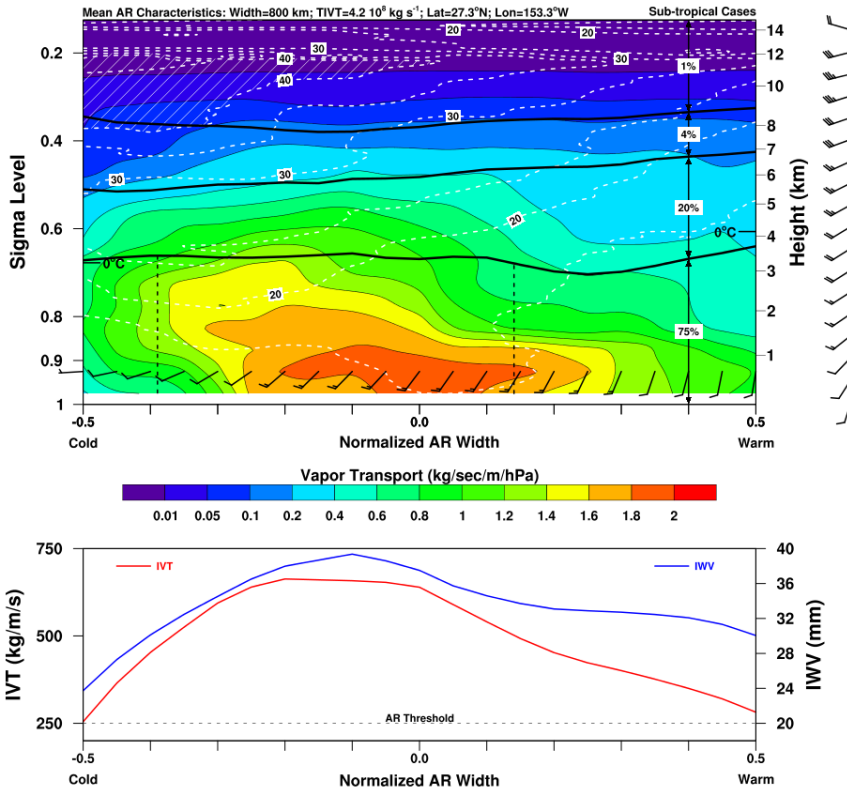
Max IWV = 48.9 mm
Max IVT = 1296 kg m^{-1} s^{-1}
Max TIVT = 8.05 x 10^8 kg s^{-1}

Average AR TIVT equivalent to ~ flow rate of 27 Mississippi Rivers (2.6 Amazons)
Maximum AR TIVT equivalent to ~ flow rate of 47 Mississippi Rivers (4.5 Amazons)

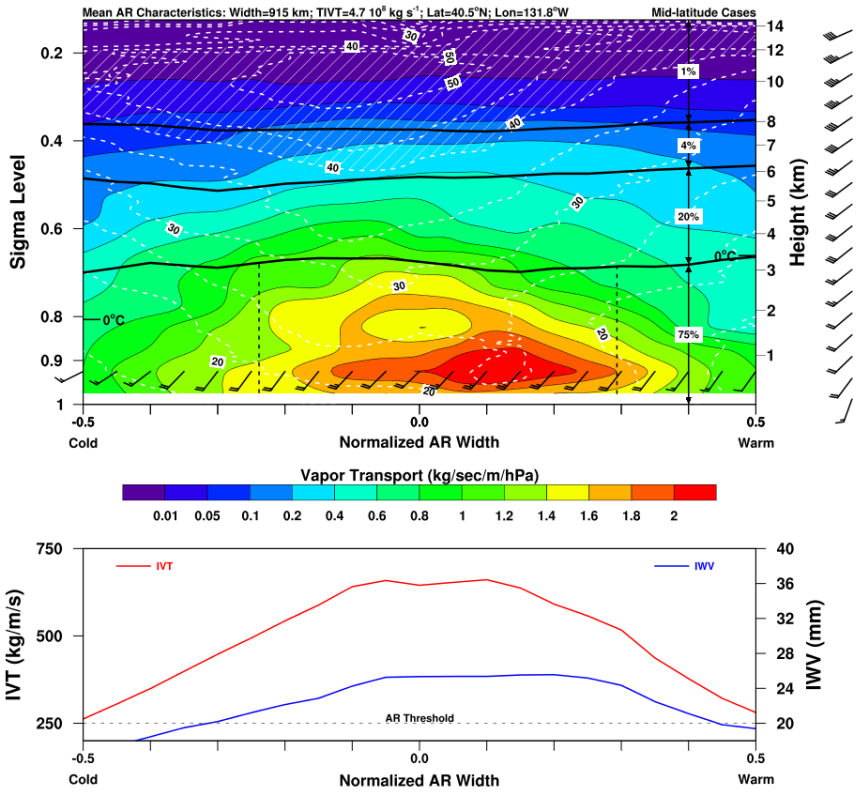
Composite of All 17 AR Cases



Sub-tropical ARs Only (latitude < 35°N)



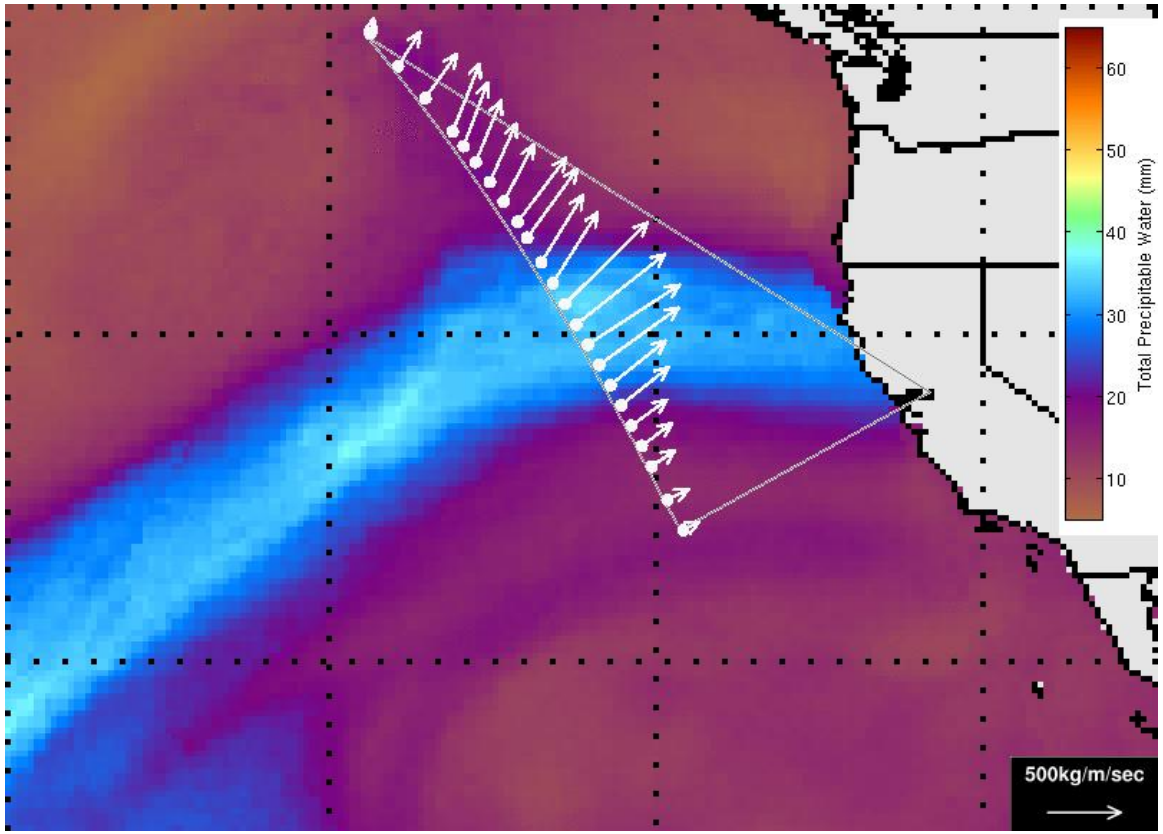
Mid-latitude ARs Only (latitude > 35°N)



Comparison to GFS Products

Example: 2015 IOP 5

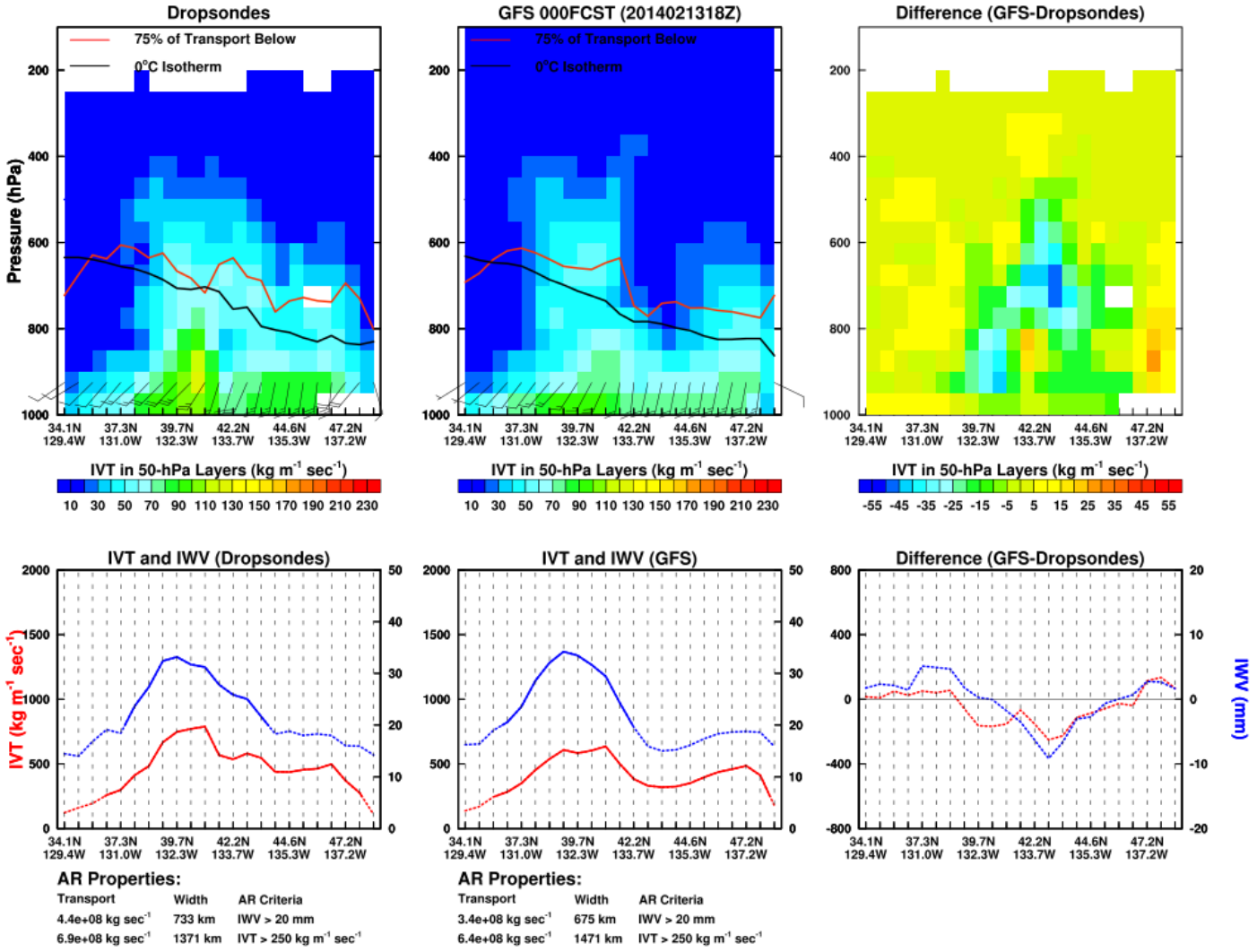
Arrows: IVT Background: SSMI IWV



Start: 13-Feb-2014 18:33Z End: 13-Feb-2014 20:58Z

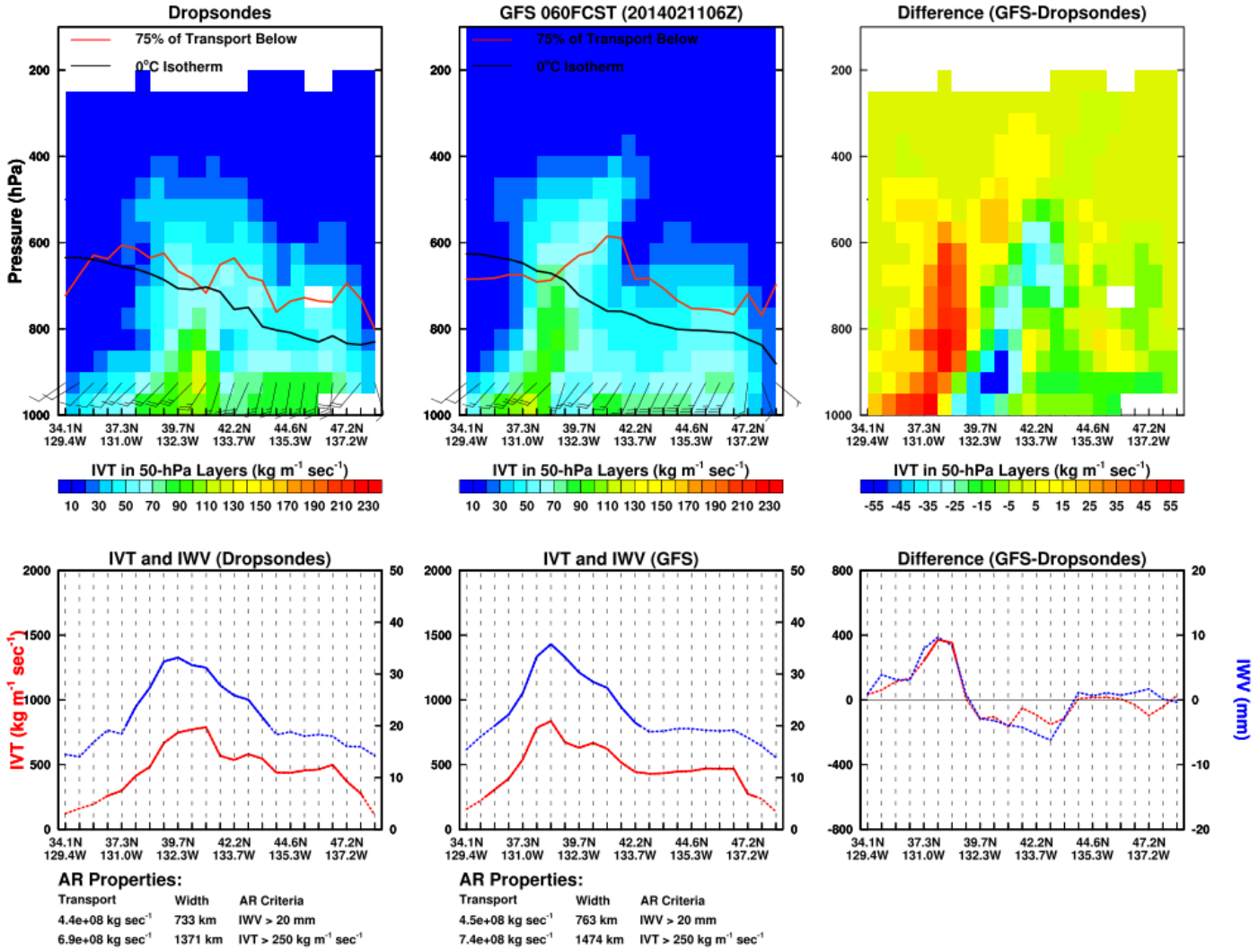
Comparison to GFS Products

Analysis (0hr Lead):



Comparison to GFS Products

60-Hour Forecast:

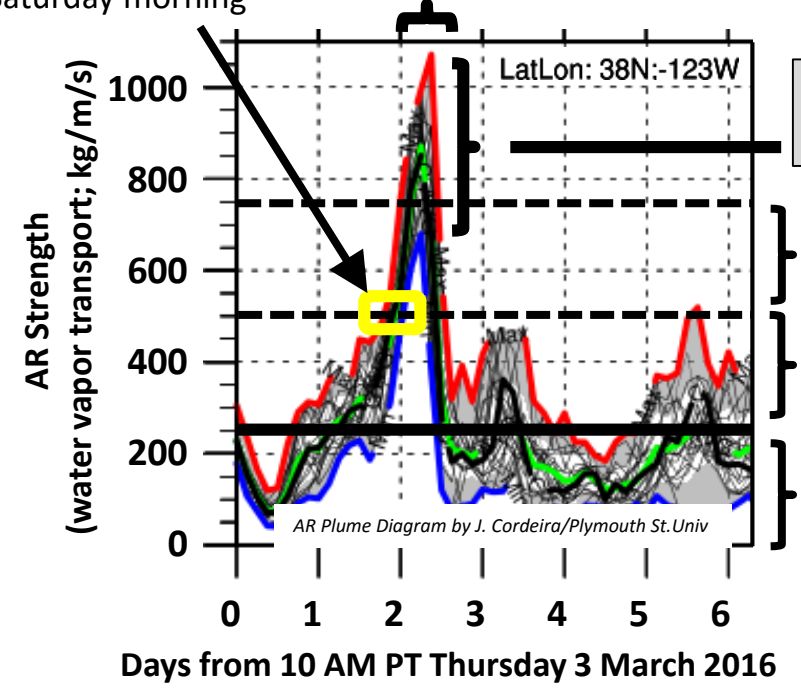


AR Outlook for Pt Reyes, CA area, including Russian River

Summary by F.M. Ralph 8 AM PT Fri 4 March 2016

Onset of moderate-strength AR conditions Saturday morning

Normal-duration AR landfall (12-24 hours)



Max AR strength is uncertain by +/- 20%

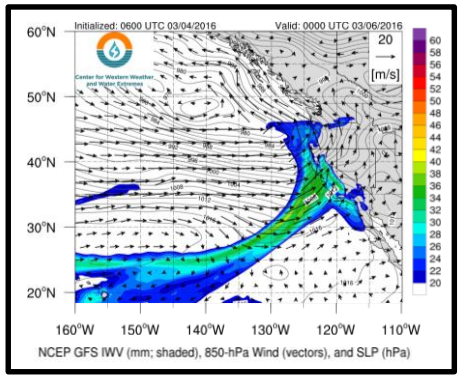
General Risk Levels

Hazardous

Moderate strength AR — **Beneficial & Hazardous**

Minimal strength AR — **Beneficial**

Not an AR



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

	Date	Aircraft	Central Latitude	No. of Sondes@	Mean Dir.	IWV_{MAX} (mm)	IVT_{MAX} (kg m^{-1} s^{-1})	$TIVT_a$ (10^8 kg s^{-1})	$Width_a$ (km)	$TIVT_b$ (10^8 kg s^{-1})	$Width_b$ (km)
	Overall Mean			**13.4**	**227**	**35.6**	**782**	**4.31**	**913**	**4.49**	**861**
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			Standard Deviation	4.2	12	8.1	247	1.69	385	1.97	260

An average AR is 860 km wide and
Transports 4.5 ± 2.0 x 10^8 kg/s of water vapor

Using IVT or IWV as the basis for defining the "edges" of an AR changed the TIVT by only 4%

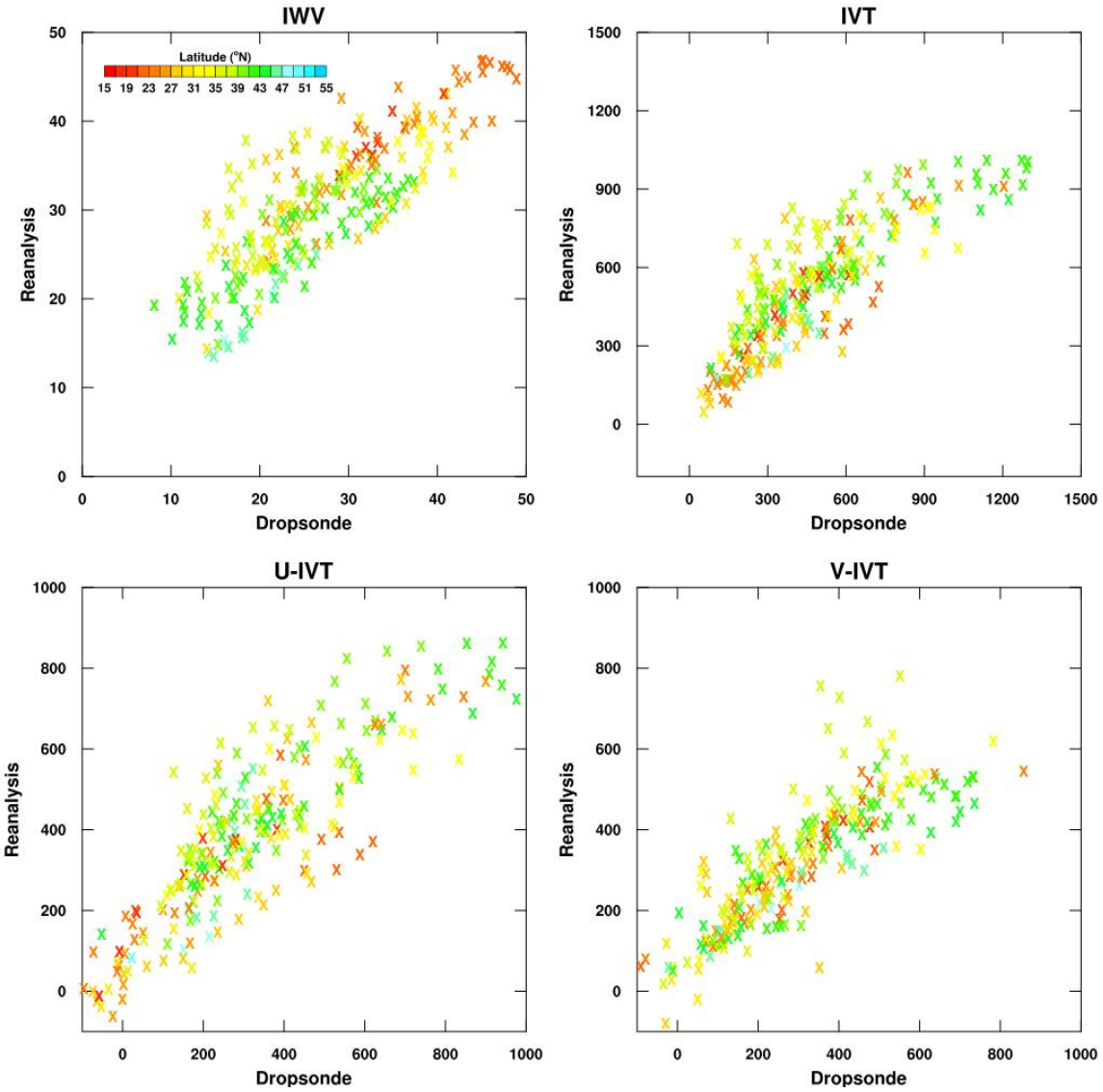
Thus, for these purposes, either IVT or IWV provide very similar results, though IVT was more robust in other ways

An average AR transports 27 MISSISSIPPIS

Comparison to Reanalysis Products

- compare sonde IWV and IVT to interpolated Reanalysis values

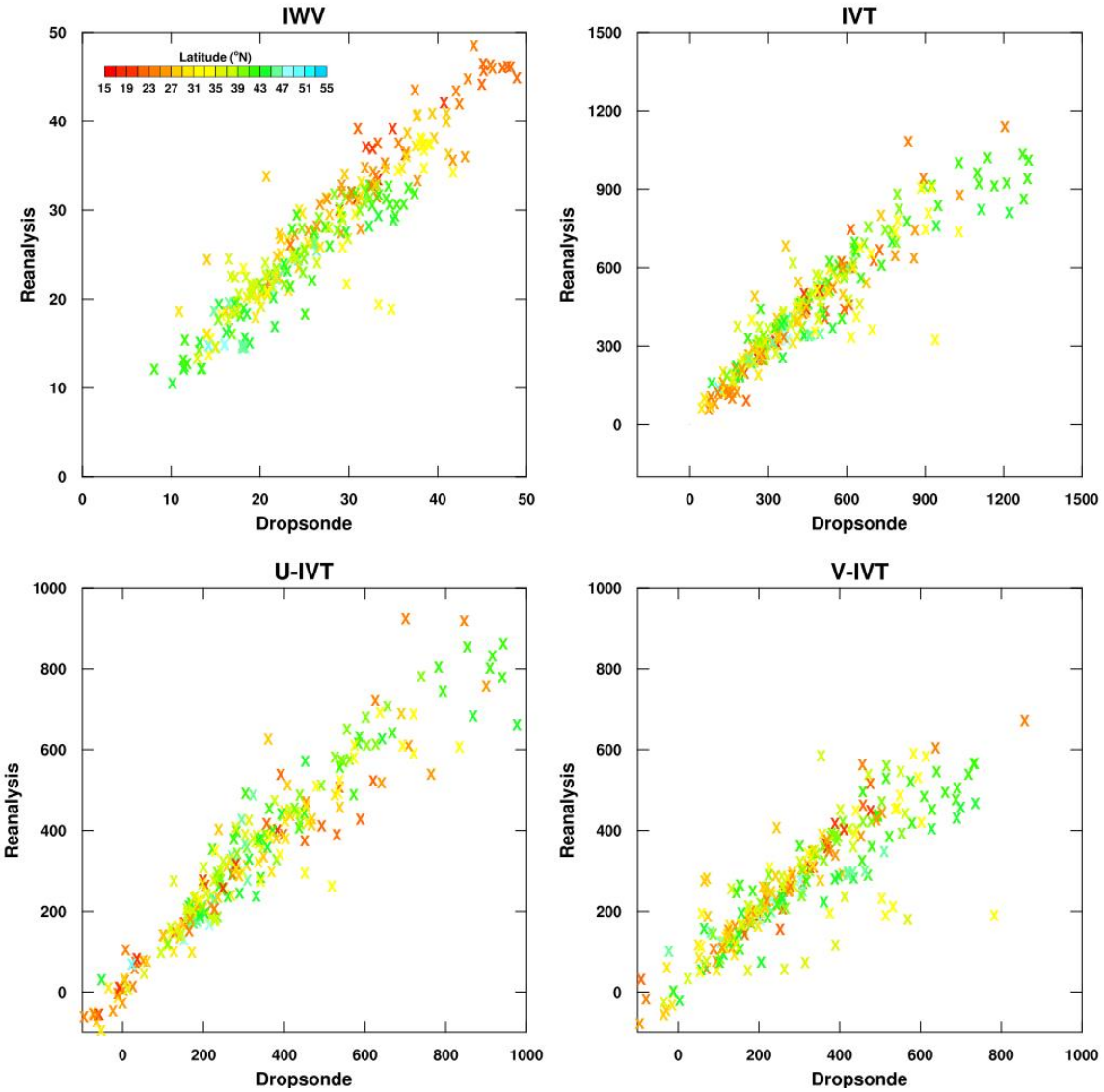
NCAR Reanalysis: 2.5°x2.5°, 6 hourly



Comparison to Reanalysis Products

- compare sonde IWV and IVT to interpolated Reanalysis values

ERA-Interim: 1.0°x1.0°, 6 hourly

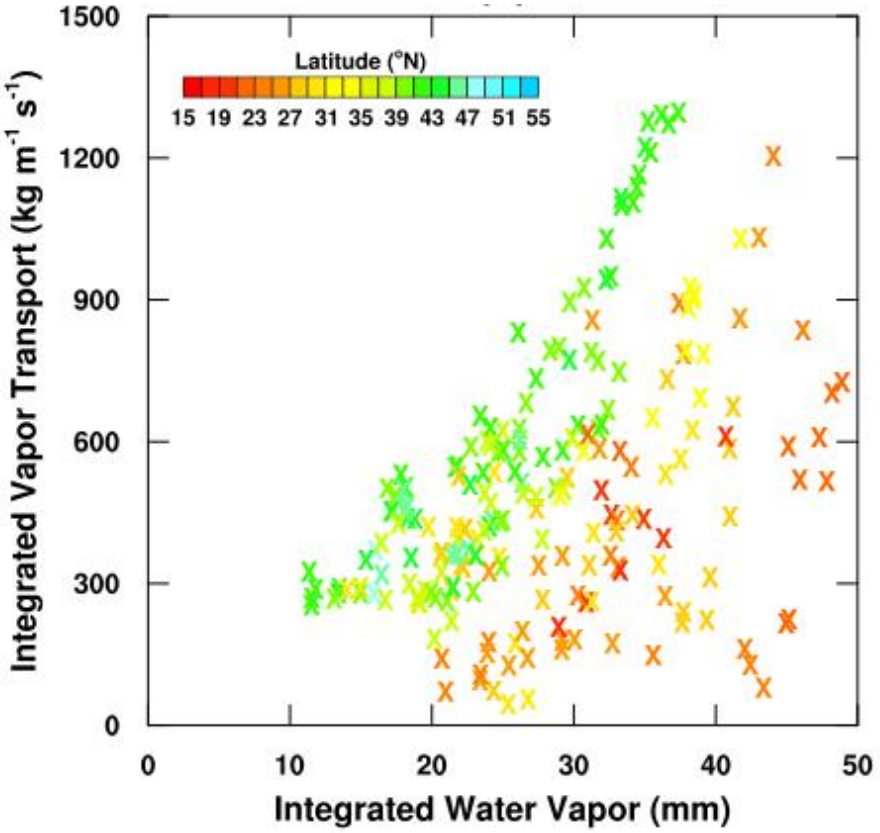


Summary

- CalWater2 program provided a large and very useful dropsonde data set
- Performed analysis of transects across 17 ARs
- Using IVT threshold to define AR boundaries compares well to IWV threshold
- Composite AR cross-section constructed and displays distinct "*AR features*"

IWV vs. IVT

Data from individual dropsondes with IWV > 20 mm or IVT > 250 kg m^{-1} s^{-1}



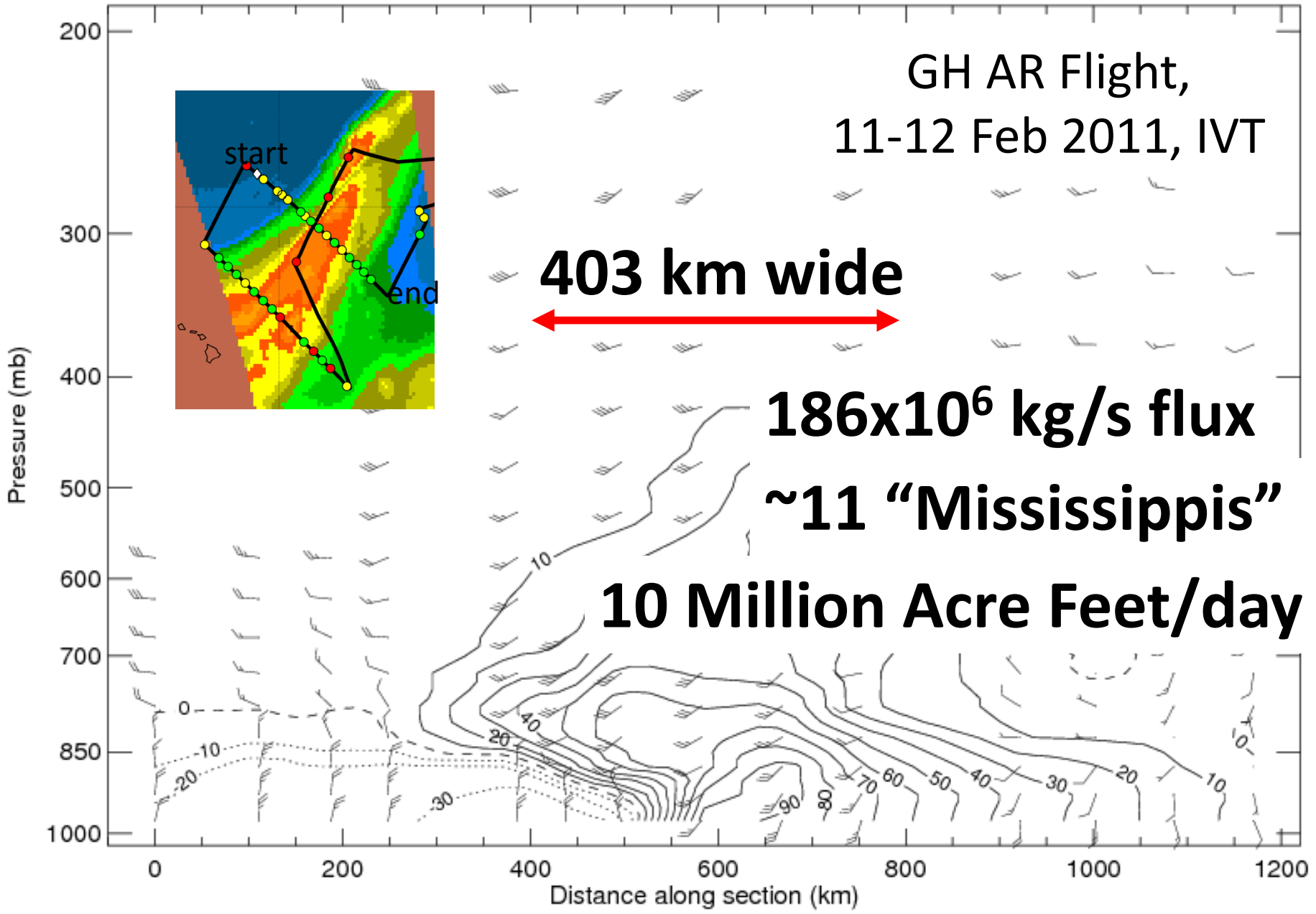
- IWV not well correlated with IVT when all latitudes considered

Winter Storms and Pacific Atmospheric Rivers (WISPAR)

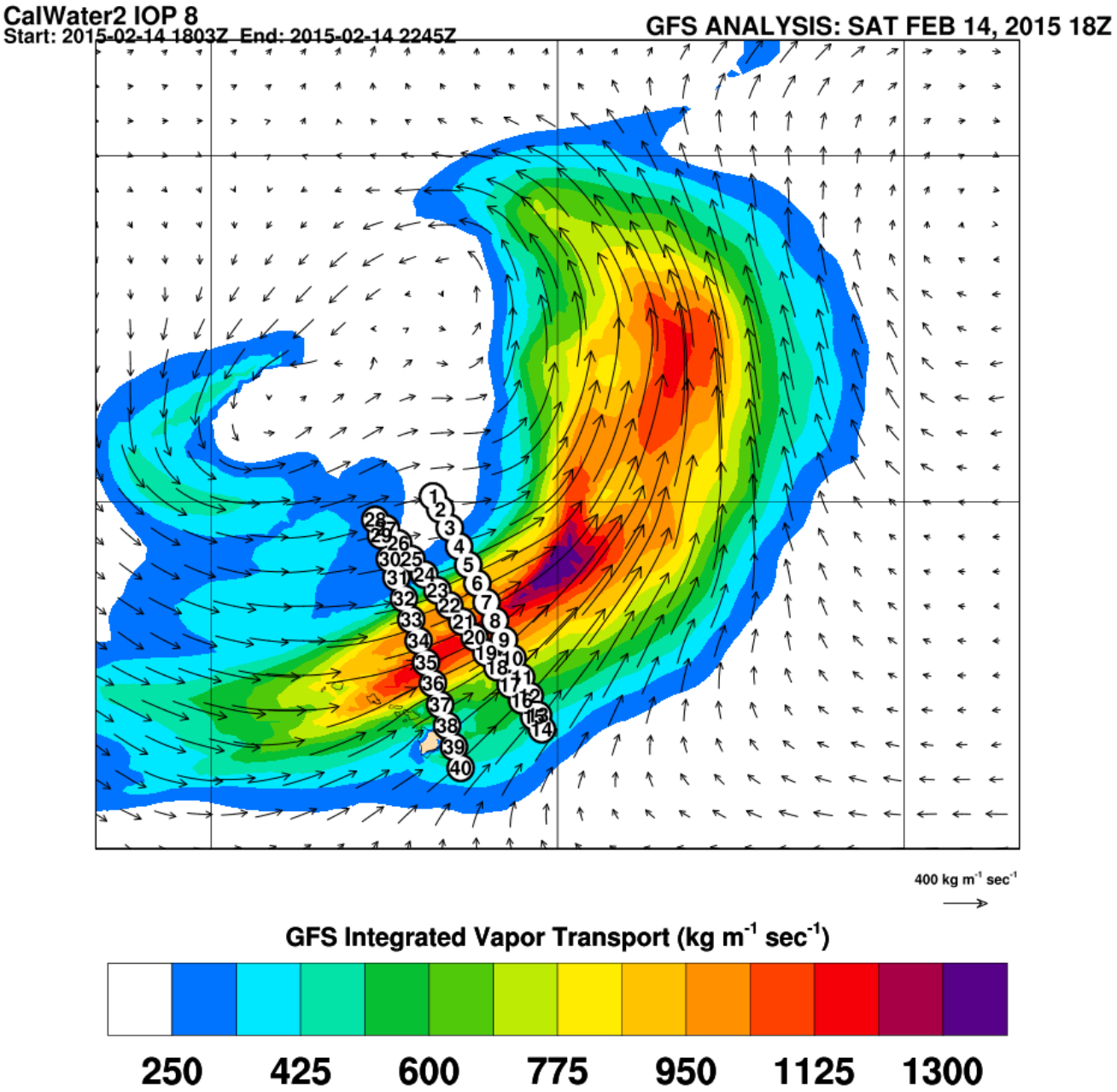
J. R. Spackman[1,2], G. A. Wick[1], M. L. Black[3], F. M. Ralph[1], Y. Song[4], Y. Zhu[4], P. J. Neiman[1], J. Intrieri[1], T. Hock[5], B. H. Lambrigtsen[6], R. E. Hood[7]

[1]NOAA Earth System Research Laboratory
[2]Science and Technology Corporation
[3]NOAA AOML Hurricane Research Division
[4]NCEP Environmental Modeling Center
[5]National Center for Atmospheric Research
[6]NASA Jet Propulsion Laboratory
[7]NOAA Unmanned Aircraft Systems Program

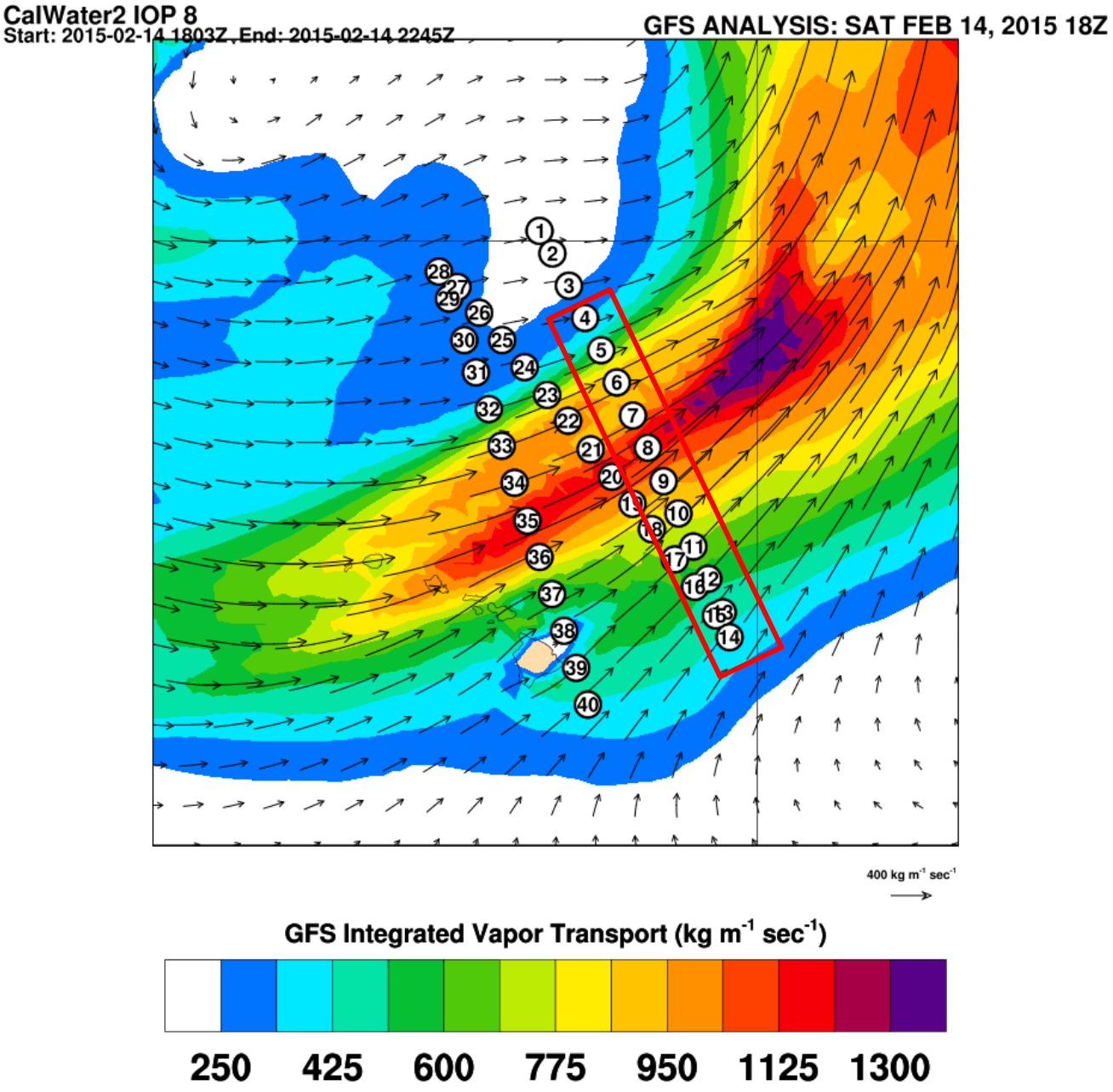
Photo Credit: NASA


GH AR Flight,
11-12 Feb 2011, IVT
start
end
403 km wide
186x10⁶ kg/s flux
~11 "Mississippis"
10 Million Acre Feet/day
Pressure (mb)
Distance along section (km)
200
300
400
500
600
700
850
1000
0
200
400
600
800
1000
1200

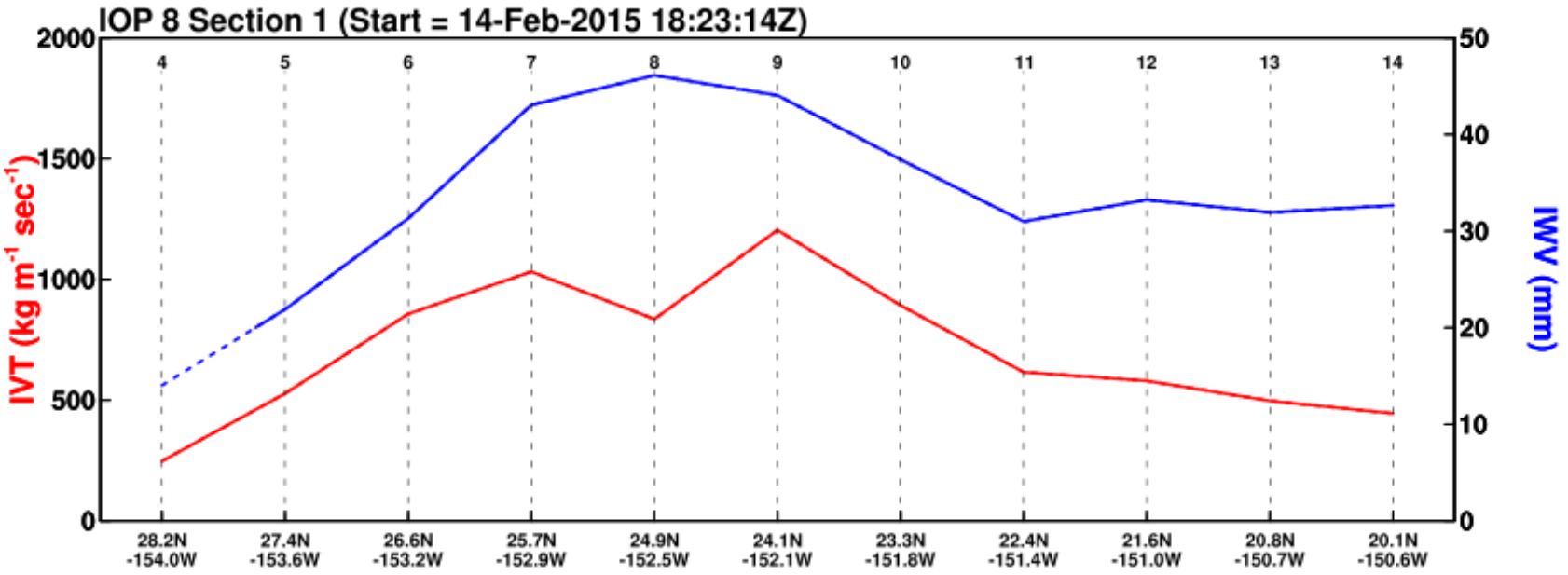
Example: FEBRUARY 14, 2015 IOP8



Example: FEBRUARY 14, 2015 IOP8



IWV and IVT along Transect



AR Properties:

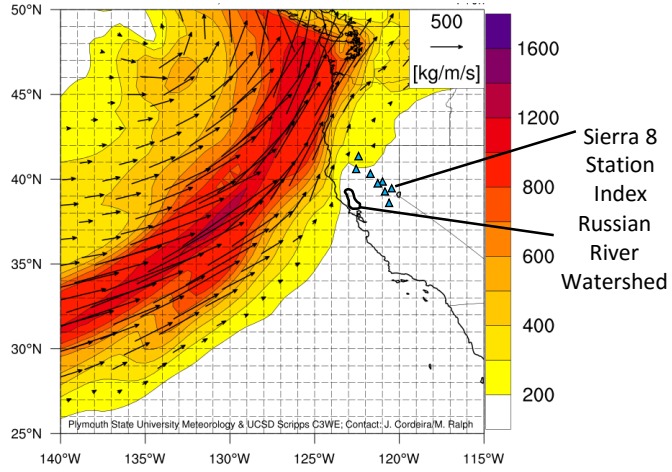
Transport	Width	AR Criteria
6.62e+08 kg sec^{-1}	846 km	IWV > 20 mm
6.87e+08 kg sec^{-1}	917 km	IVT > 250 kg m^{-1} sec^{-1}

Note: AR Boundary not defined on southern edge using either IWV or IVT threshold

Integrate IVT along transect to get total transport

NCEP GFS IVT Evolution

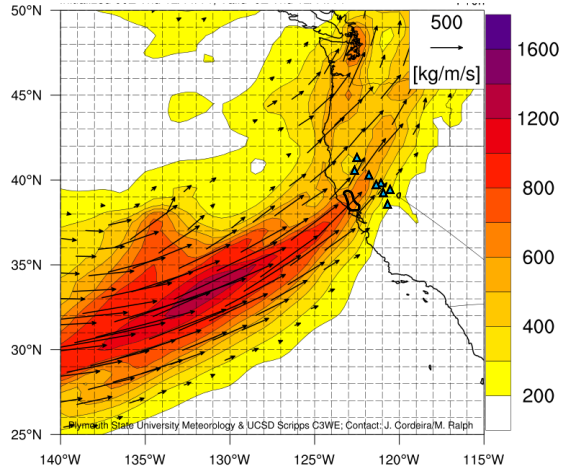
4 AM PT 10 Dec



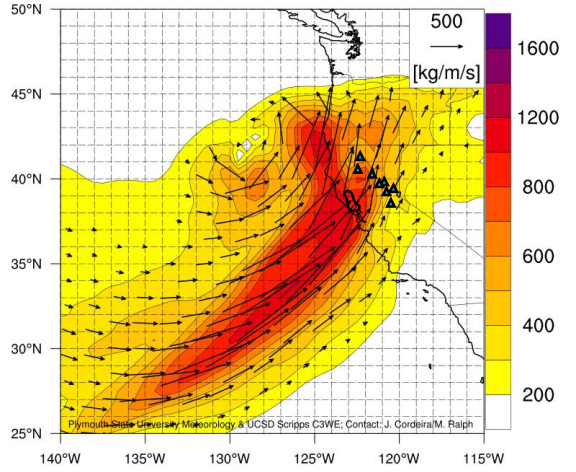
Sierra 8 Station Index

Russian River Watershed

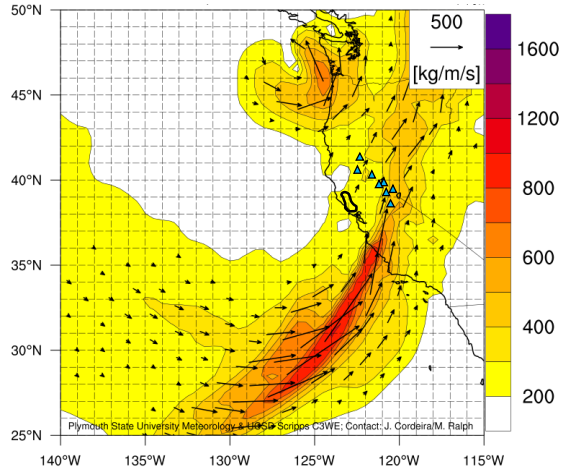
4 PM PT 10 Dec



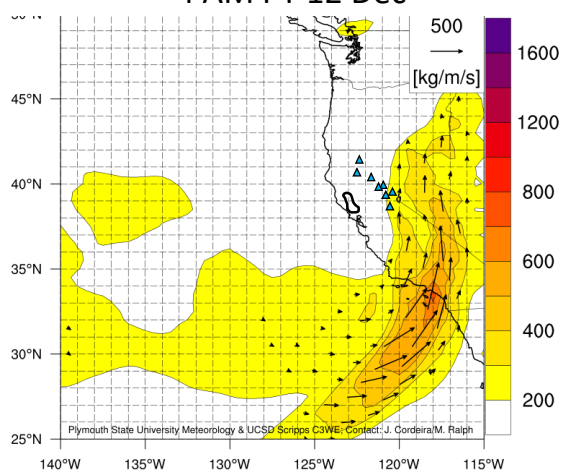
4 AM PT 11 Dec



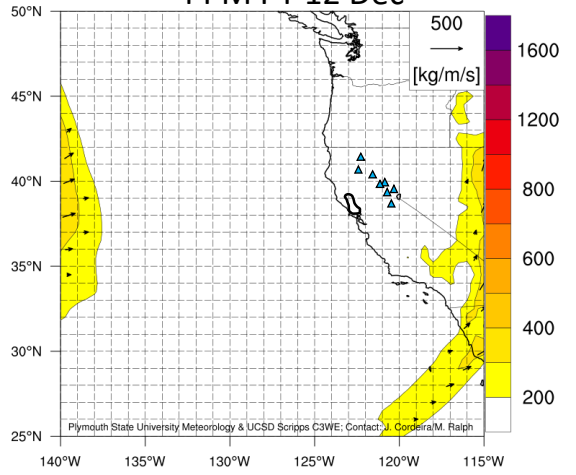
4 PM PT 11 Dec

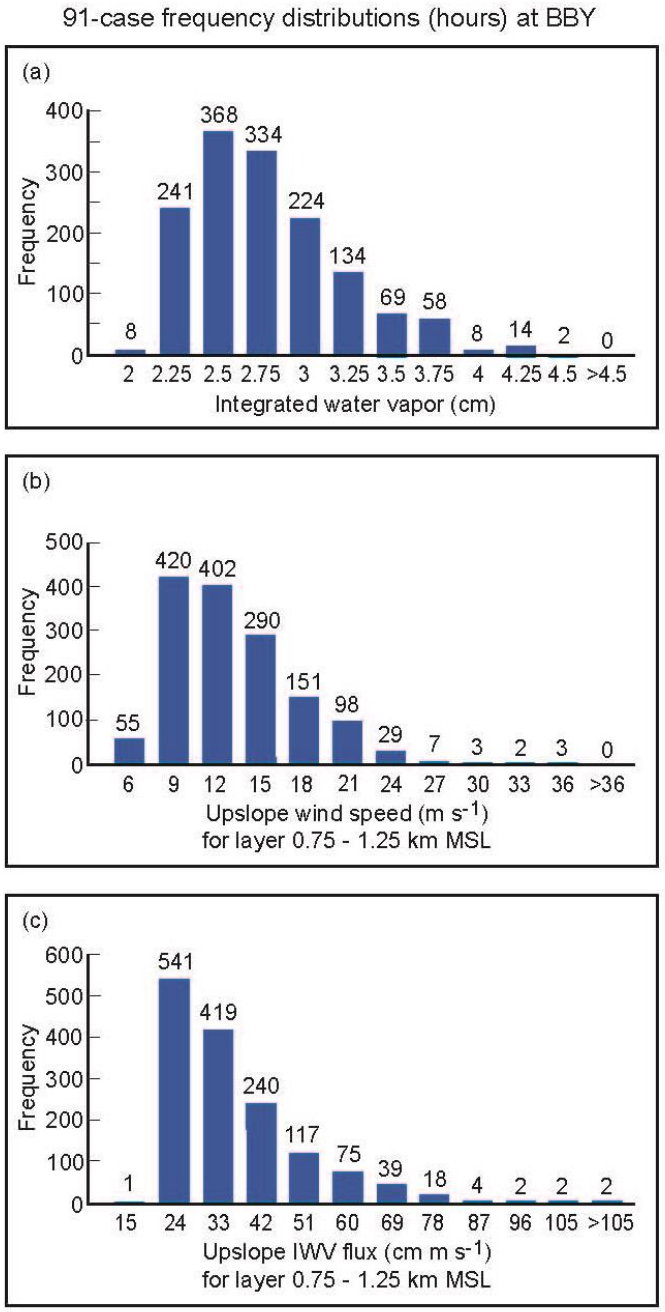


4 AM PT 12 Dec



4 PM PT 12 Dec





Rankings of key characteristics

- Histograms showing the frequency distribution of hourly observations of
  - (a) IWV,
  - (b) upslope wind speed, and
  - (c) upslope IWV flux during the 1460 hours of AR conditions within the 91 AR events.
- This enables comparisons between current or predicted events to assess how extreme they are relative to past events.

Ralph et al. 2013 J. Hydrometeorology

Upper 1% and 10% Thresholds for Key Variables

Parameter	Top 10% Threshold	Top 1% Threshold
Integrated Water Vapor (cm)	3.3	4.1
Total Wind Speed (m/s)	22.2	30.6
Total Integrated Water Vapor Flux (cm)(m/s)	61.0	83.0
Upslope Wind Speed (m/s)	17.9	24.0
Upslope Integrated Water Vapor Flux (cm)(m/s)	50.8	74.4
CZC Rain Rate (mm)	8.7	16.0
HBG Soil Moisture	51.6%	56.8%
Russion River Stream Flow (1000 cfs)	13.3	36.9
Austin Creek Stream Flow (1000 cfs)	4.1	12.1

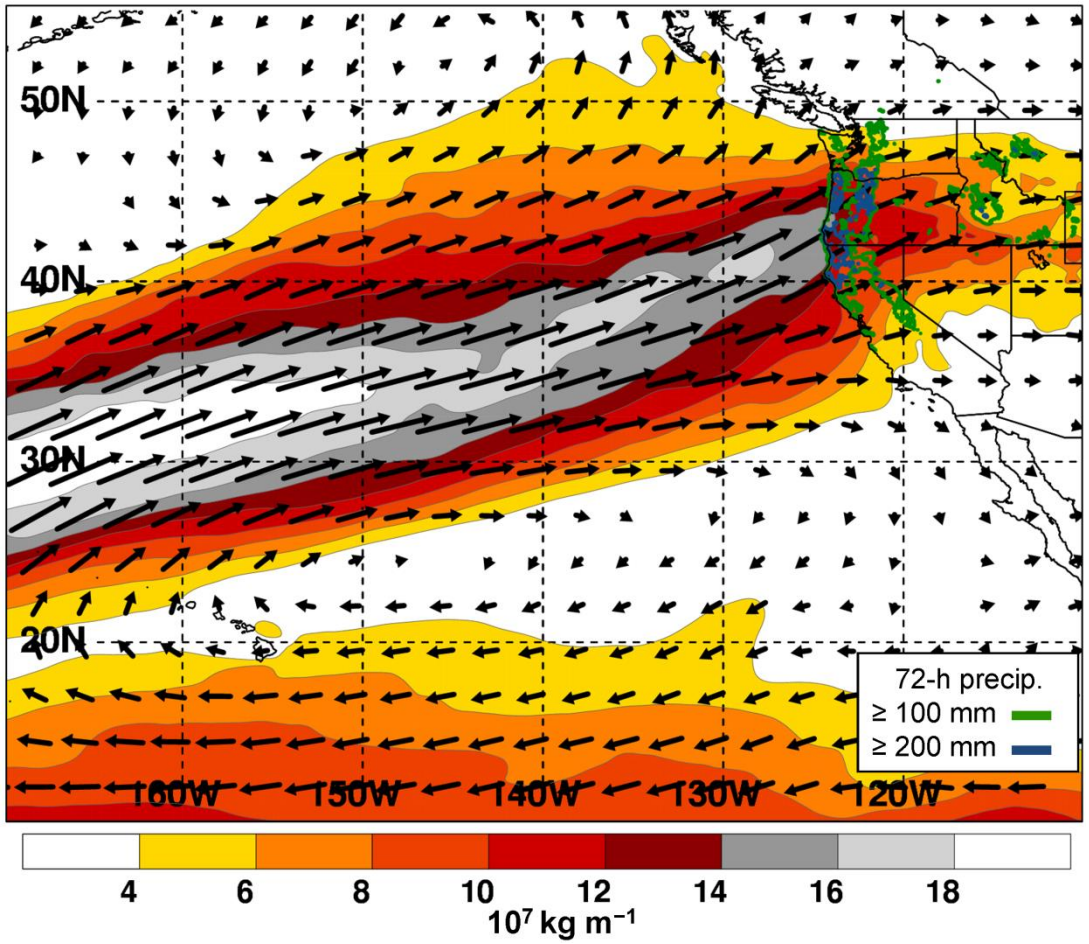
Upper 10% and 1% thresholds for hourly values of each key variable from within the 1460 AR hours during the 6-year study period.

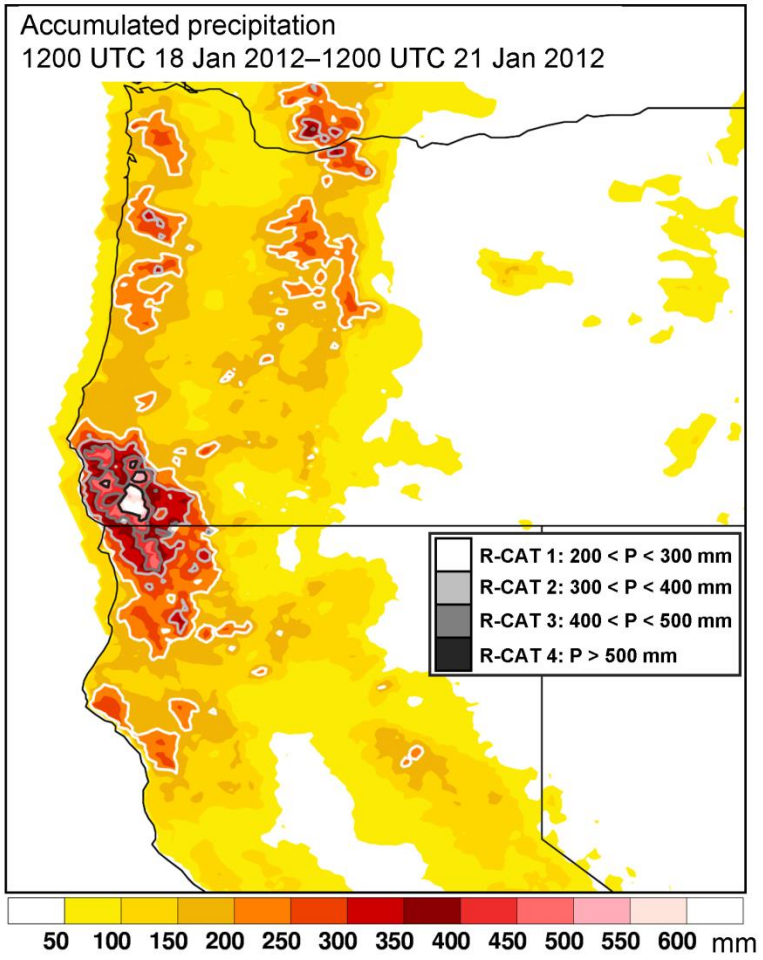
Ralph et al. 2013 J. Hydrometeorology

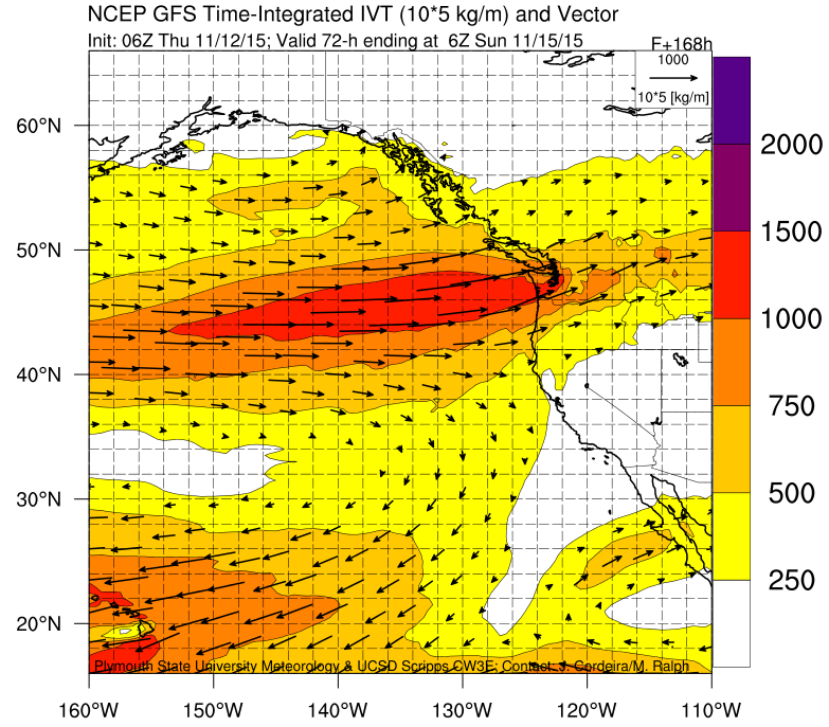
18–21 Jan 2012 AR Event

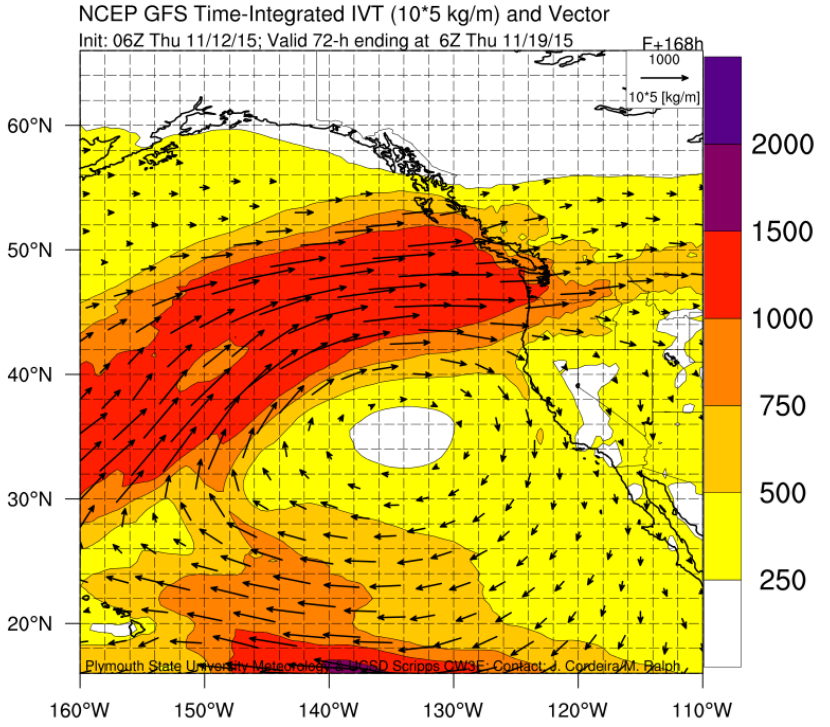
- The long duration of AR conditions in Oregon and northern California supported widespread heavy rainfall
- 72-h precipitation totals exceeding 100 mm were common along the west coast, with largest amounts observed in southwestern Oregon and northwestern CA
- Localized precip. totals ranged from 400 mm to >500 mm (R-CATs 3–4) in this region

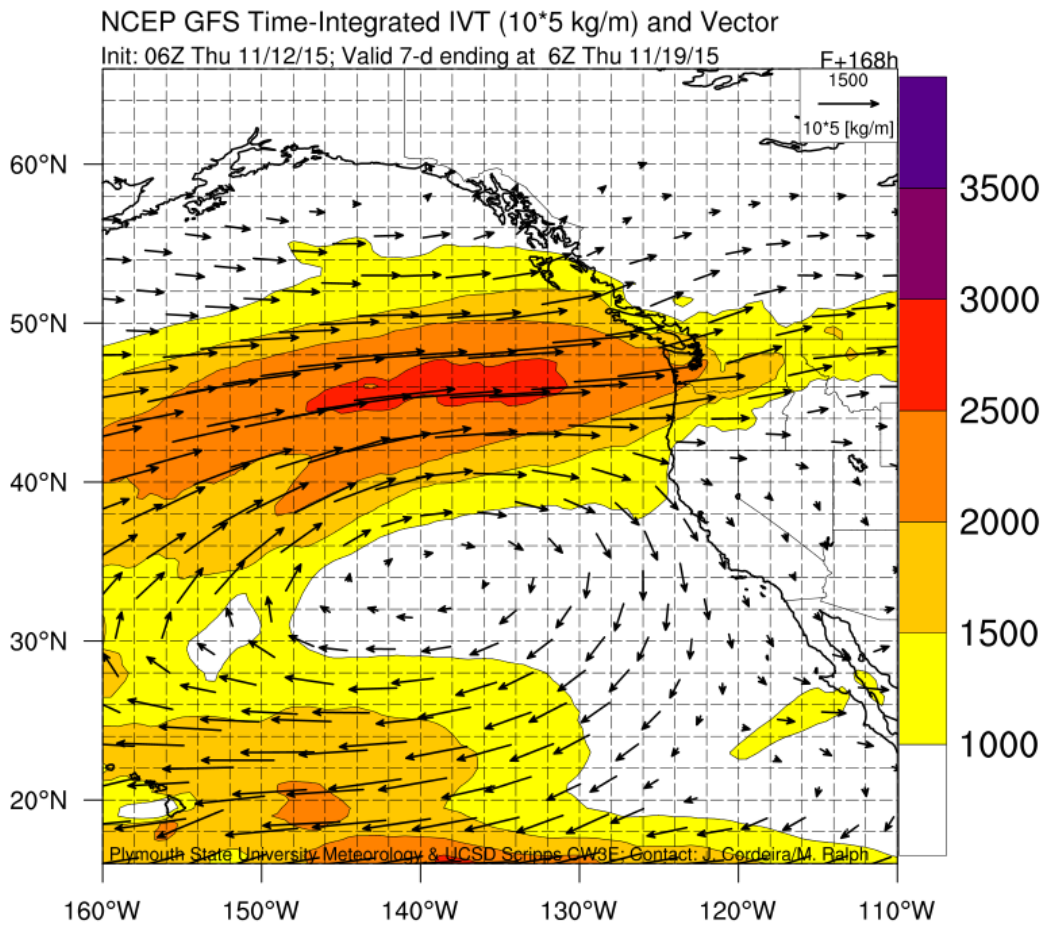
Time-integrated IVT 12 UTC 18 Jan–12 UTC 21 Jan

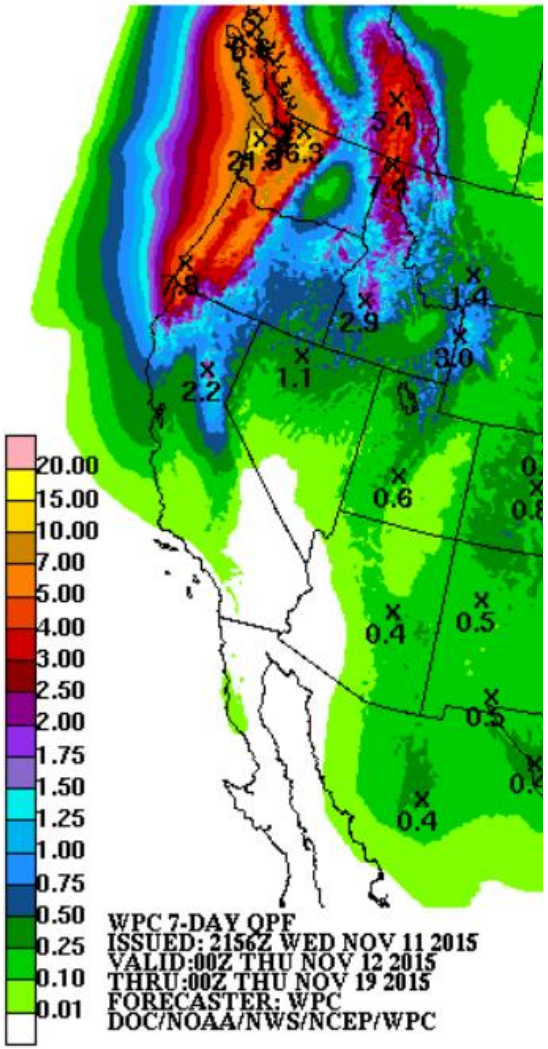


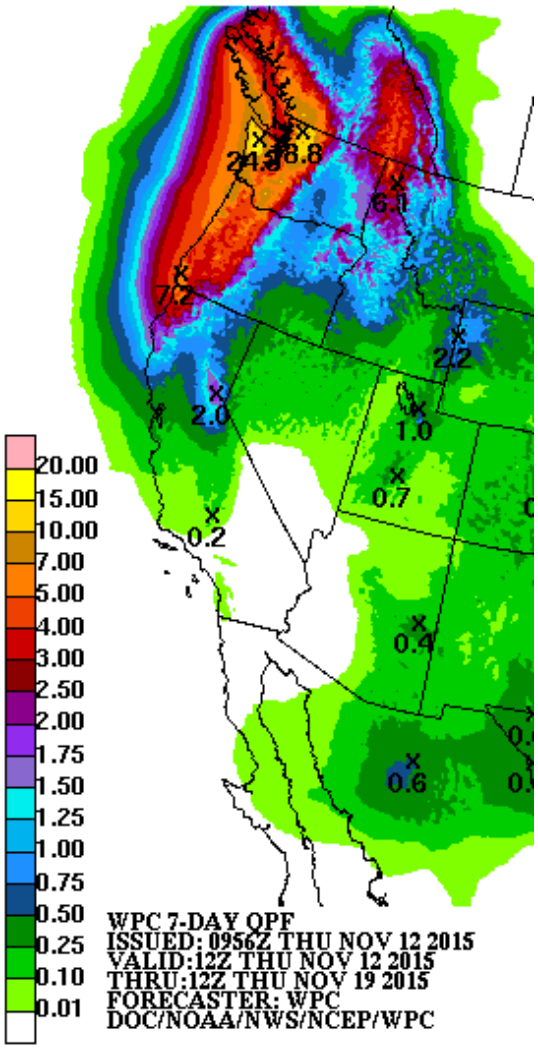



NCEP GFS Time-Integrated IVT (10*5 kg/m) and Vector
Init: 06Z Thu 11/12/15; Valid 72-h ending at 6Z Sun 11/15/15
F+168h
1000
10*5 [kg/m]
2000
1500
1000
750
500
250
60°N
50°N
40°N
30°N
20°N
160°W
150°W
140°W
130°W
120°W
110°W
Plymouth State University Meteorology & UCSD Scripps CW3E; Contact: J. Cordeira/M. Ralph

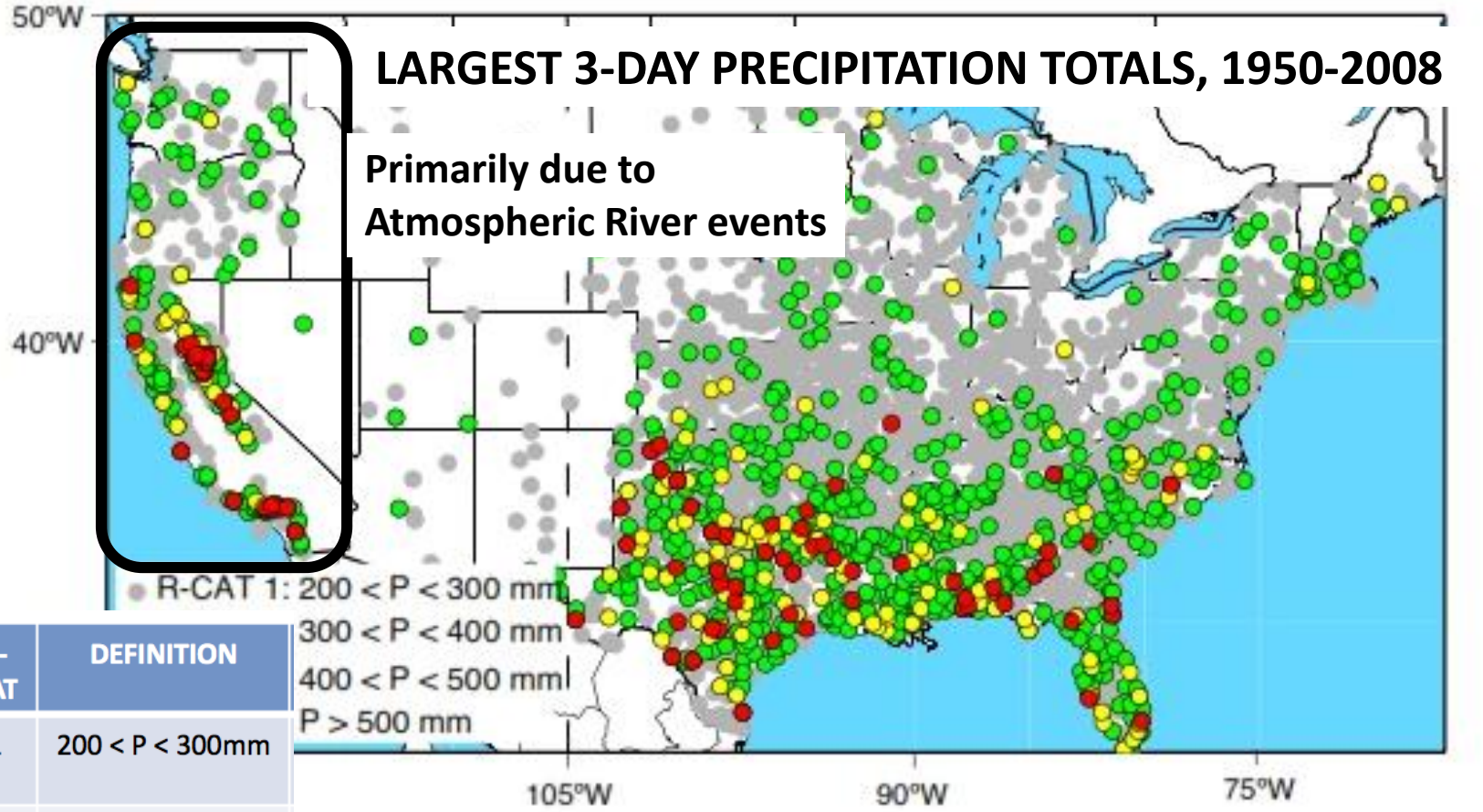

NCEP GFS Time-Integrated IVT (10*5 kg/m) and Vector
Init: 06Z Thu 11/12/15; Valid 72-h ending at 6Z Thu 11/19/15
F+168h
1000
10*5 [kg/m]
2000
1500
1000
750
500
250
60°N
50°N
40°N
30°N
20°N
160°W
150°W
140°W
130°W
120°W
110°W
Plymouth State University Meteorology & UCSD Scripps CW3E; Contact: J. Cordeira/M. Ralph


NCEP GFS Time-Integrated IVT (10*5 kg/m) and Vector
Init: 06Z Thu 11/12/15; Valid 7-d ending at 6Z Thu 11/19/15
F+168h
1500
10*5 [kg/m]
60°N
50°N
40°N
30°N
20°N
160°W
150°W
140°W
130°W
120°W
110°W
3500
3000
2500
2000
1500
1000
Plymouth State University Meteorology & UCSD Scripps CW3E: Contact: J. Cordeira/M. Ralph


20.00
15.00
10.00
7.00
5.00
4.00
3.00
2.50
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.10
0.01
WPC 7-DAY QPF
ISSUED: 2156Z WED NOV 11 2015
VALID:00Z THU NOV 12 2015
THRU:00Z THU NOV 19 2015
FORECASTER: WPC
DOC/NOAA/NWS/NCEP/WPC


20.00
15.00
10.00
7.00
5.00
4.00
3.00
2.50
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.10
0.01
WPC 7-DAY QPF
ISSUED: 0956Z THU NOV 12 2015
VALID:12Z THU NOV 12 2015
THRU:12Z THU NOV 19 2015
FORECASTER: WPC
DOC/NOAA/NWS/NCEP/WPC

A scale for maximum 3-day rainfall "R-Cat"



R-CAT	DEFINITION
1	200 < P < 300mm
2	300 < P < 400mm
3	400 < P < 500mm
4	P > 500mm

Ralph, F.M., and Dettinger, M.D., Historical and national perspectives on extreme west-coast precipitation associated with atmospheric rivers during December 2010: *Bulletin of the American Meteorological Society,* (2012)

Some Options for an AR Intensity Scale

- Maximum IVT offshore and at landfall
- Total IVT offshore and at landfall
- Time-integrated (3-day) IVT offshore and at landfall
- Maximum 3-day rainfall onshore
- Other

Composite Cross-Section of an AR

- Normalize using width of AR and Total IVT across AR.