Pacific Atmospheric Rivers: Impacts on Extreme Rainfall, Flooding and Water Supply

YOTC International Science Symposium and 8th AMY International Workshop

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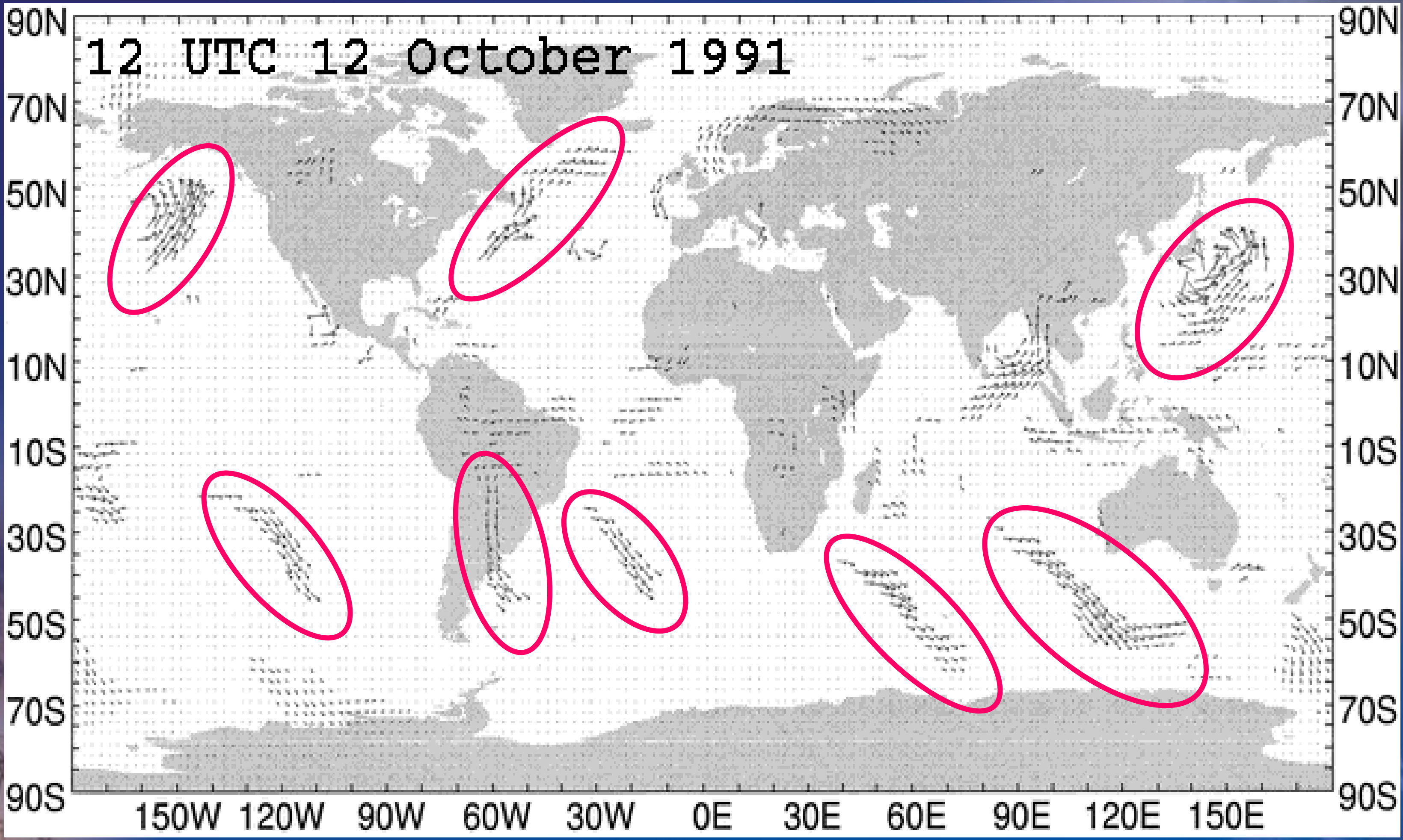
Major Talking Points

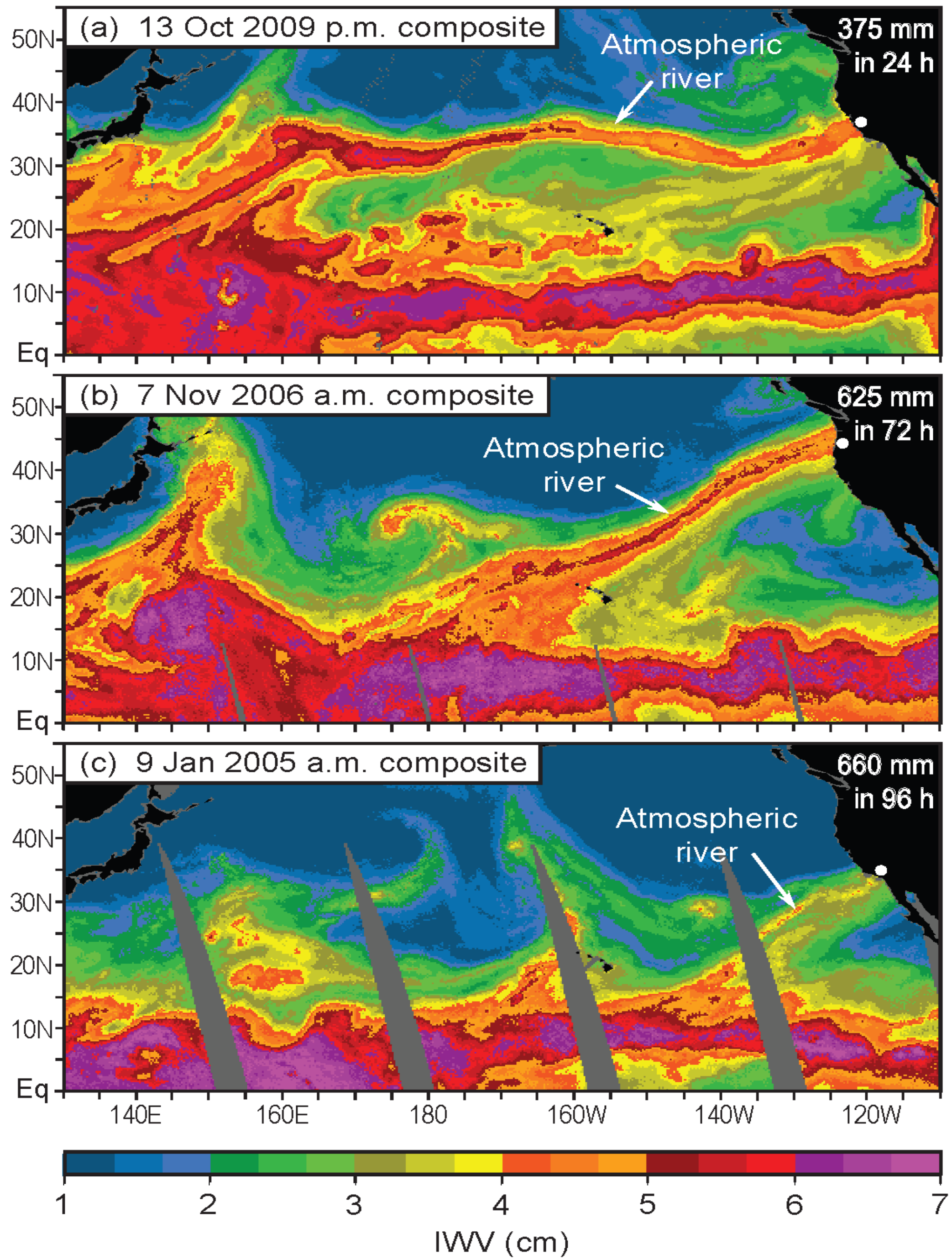
- Pacific ARs are critical phenomena impacting the West Coast of North America
  - formation and physical processes
  - contribution to water supply
  - contribution to flooding
- Outstanding Forecast Challenges
  - Role of intra-seasonal tropical forcing on ARs
    - MJO - tropical /extra-tropical interactions and West Coast outcomes
    - When can we use MJO projections for 7-10 day lead-time for heavy rain
      - Forecast based reservoir operation s
  - Classifying strength of AR offshore – scaling factor
  - QPF for land-falling ARs still poor – timing and locations
- Hydrometeorological Testbed
  - Its purpose
  - Its contributions to understanding and forecasting impacts of ARs
  - Research to Operations
    - progress and future plans

Zhu & Newell (in Monthly Weather Review, 1998) concluded that

1) Most water vapor transport occurs in only a few narrow regions
2) There are 4-5 of these within a hemisphere at any one moment
3) They are part of extratropical cyclones and move with the "storm track"



Coined the term "atmospheric river"

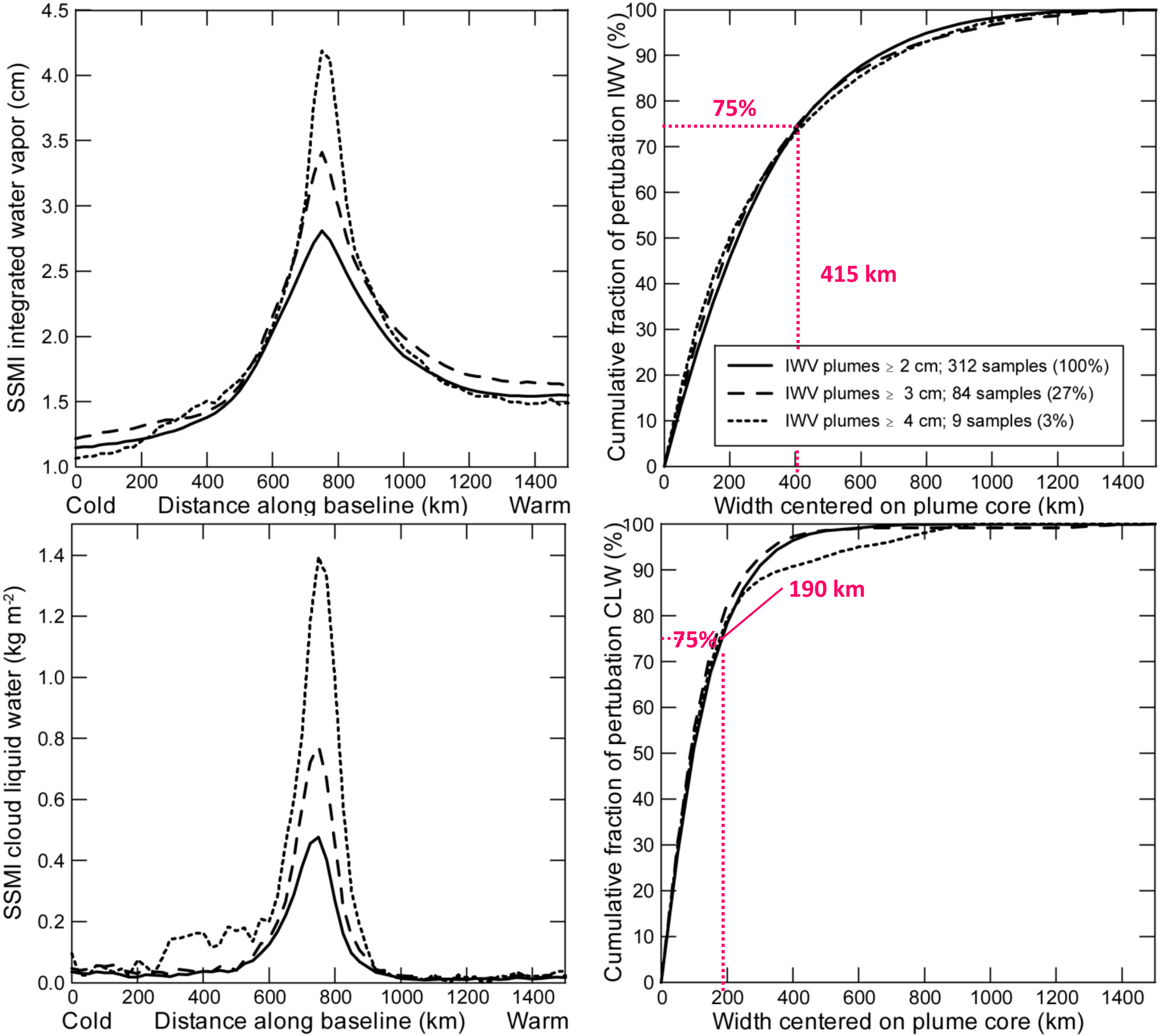


A Key Finding:

- atmospheric rivers are a key to extreme precipitation and flooding, as well as water supply and stream flow on the U.S. West Coast

Examples of AR events that produced extreme precipitation on the US West Coast, and exhibited spatial continuity with the tropical water vapor reservoir as seen in SSM/I satellite observations of IWV.

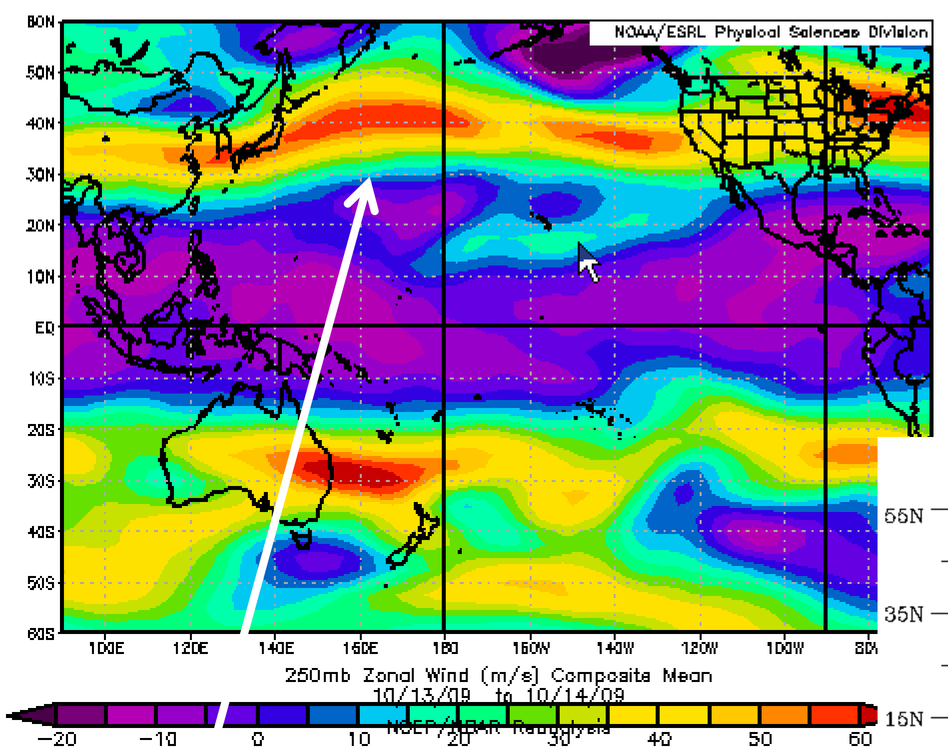
Observations of many atmospheric rivers were composited and define the average width and strength of atmospheric rivers (from Ralph et. al. 2004).

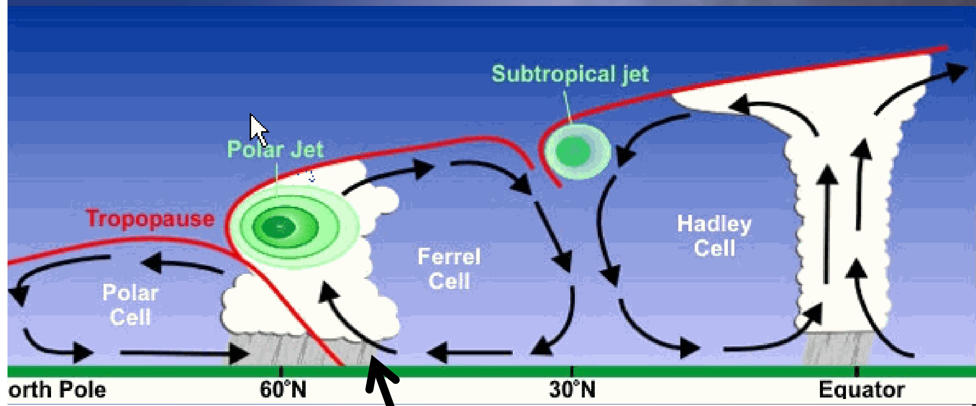


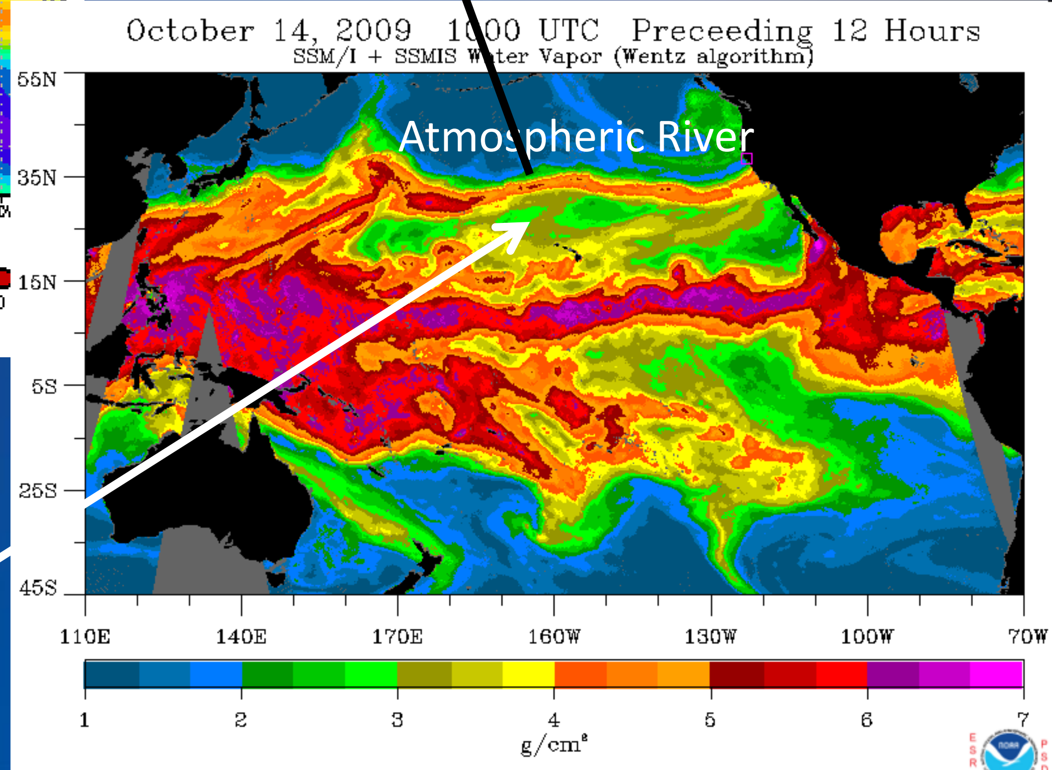
The average width of an AR is roughly 400 km in terms of water vapor, and 150-200 km in terms of clouds and precipitation.

This is important partly because it defines the spatial scales for which coastal monitoring is needed.

SSM/I shows AR stretching across Pacific to Central California





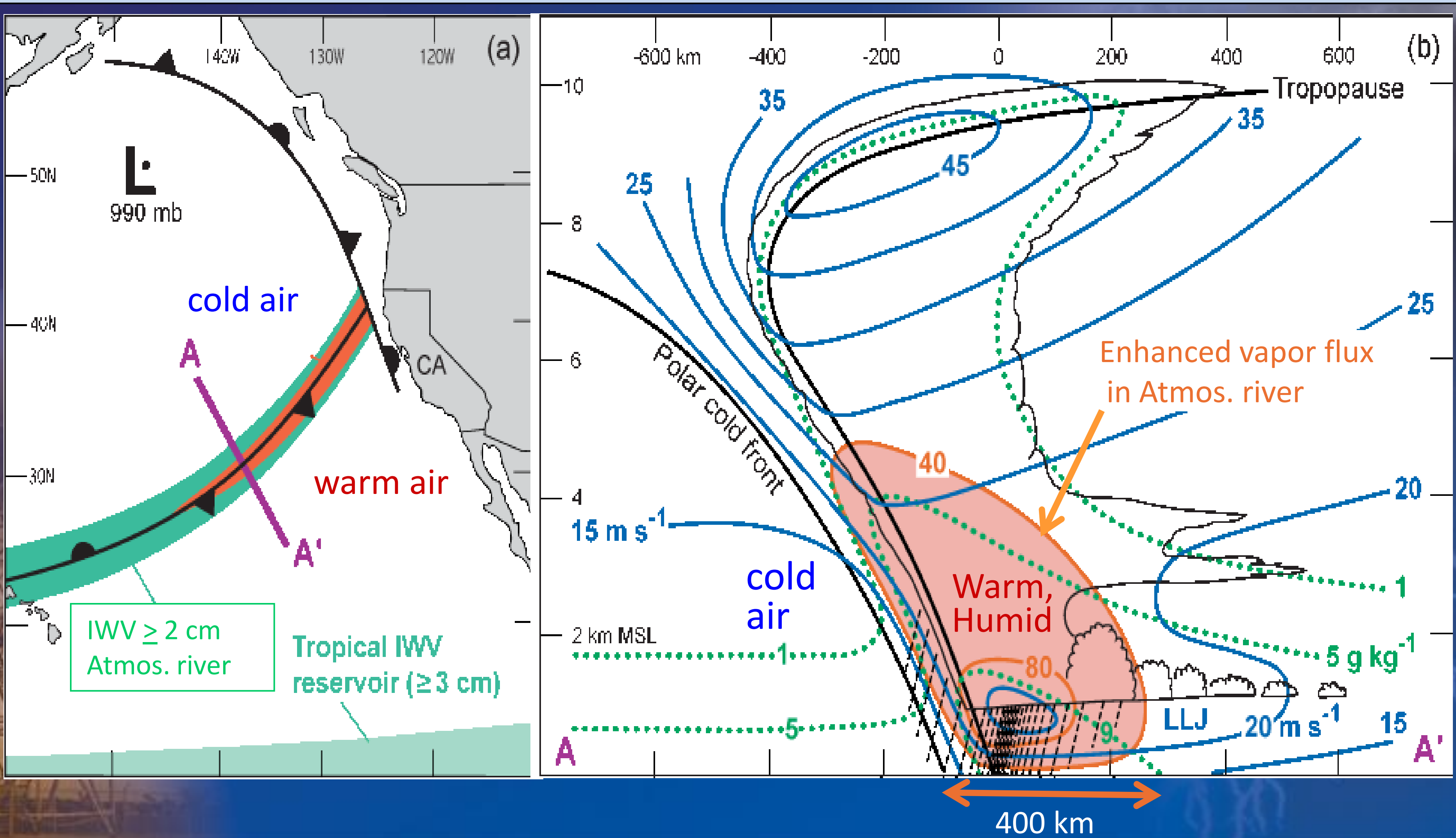


Extended East-Asian Jet

Cycle time of IWV in AR ?

Observational studies by Ralph et al. (2004, 2005, 2006) extend model results:

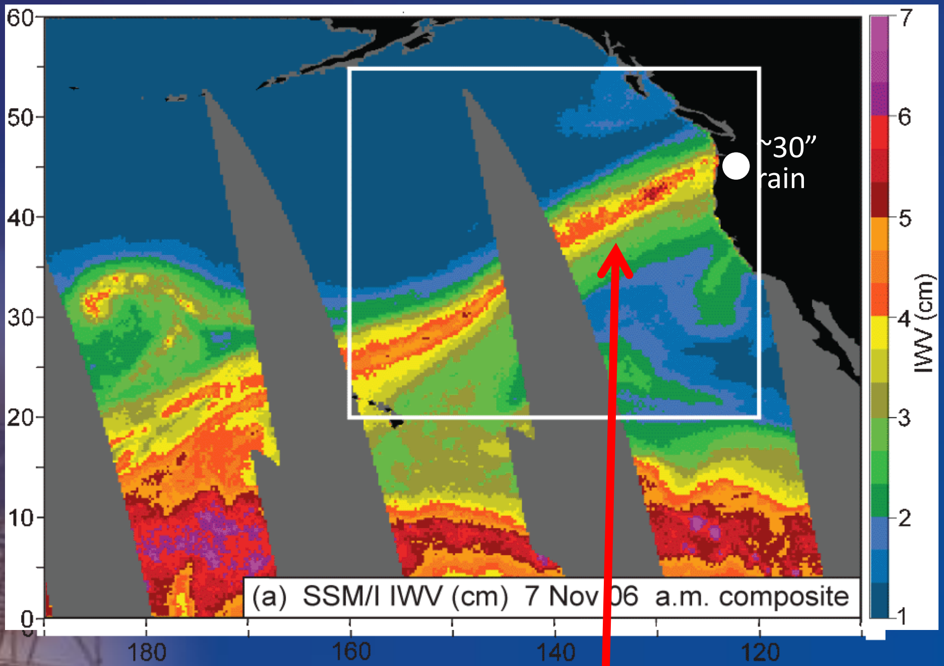
1) Long, narrow plumes of IWV >2 cm measured by SSM/I satellites considered proxies for ARs.
2) These plumes (darker green) are typically situated near the leading edge of polar cold fronts.
3) P-3 aircraft documented strong water vapor flux in a narrow (400 km-wide) AR; See section AA'.
4) Airborne data also showed 75% of the vapor flux was below 2.5 km MSL in vicinity of LLJ.



Diagnosis of an Intense Atmospheric River Impacting the Pacific Northwest: Storm Summary and Offshore Vertical Structure Observed with COSMIC Satellite Retrievals

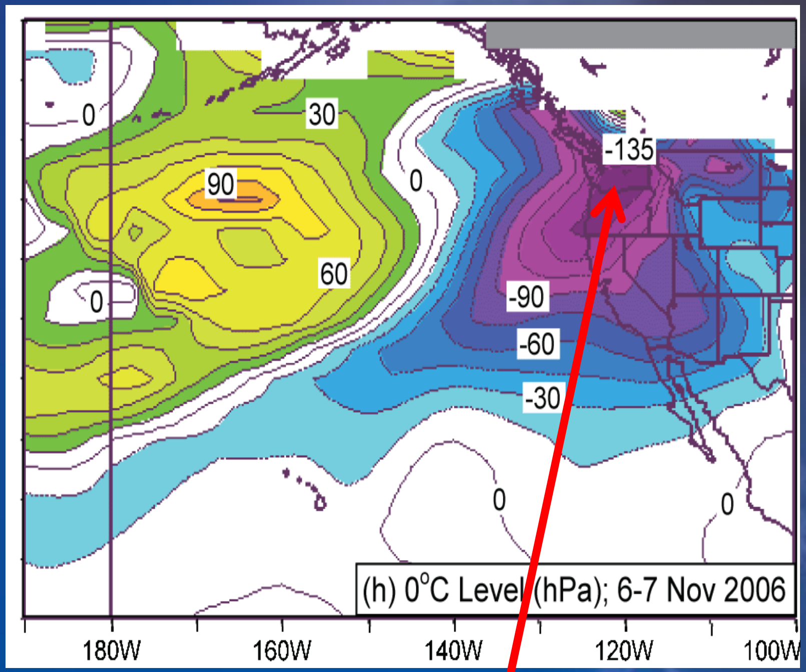
by Paul J. Neiman, F. Martin Ralph, Gary A. Wick, Y.-H. Kuo, T.-W. Wee, Z. Ma, G. H. Taylor, M.D. Dettinger
Monthly Weather Review, **136**, 4398-4420.

SSM/I satellite imagery of integrated water vapor (IWV, cm)



This AR is also located near the leading edge of a cold front, with strong vapor fluxes (as per reanalysis diagnostics)

Global reanalysis melting-level anomaly (hPa; rel. to 30-y mean)

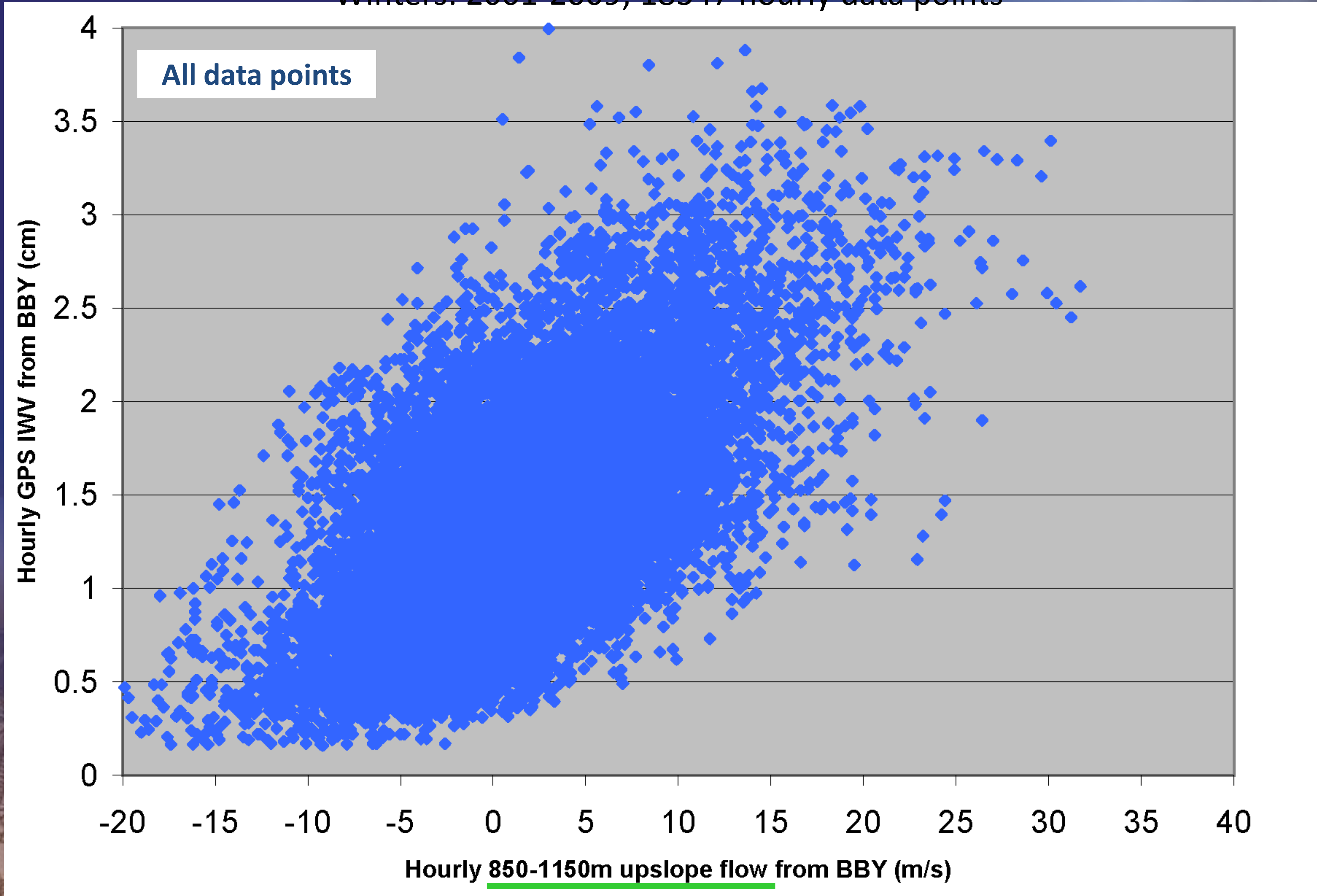


Melting level ~4000 ft (1.2 km) above normal across much of the PacNW during the landfall of this AR

Thresholds in water vapor and wind are key in determining heavy hourly rainfall

- The next 4 graphs each show 8 winters of hourly observations from an atmospheric river observatory near Bodega Bay operated in HMT.
- Over 18,000 hourly measurements of
  - Water vapor
  - Winds at 1 km above sea level
  - Coastal mountain rainfall
- Conclusions are that the heaviest hourly rain rates occur when
  - Water vapor (IWV) exceeds 2 cm, and
  - Upslope winds at 1 km altitude exceed 12 m/s

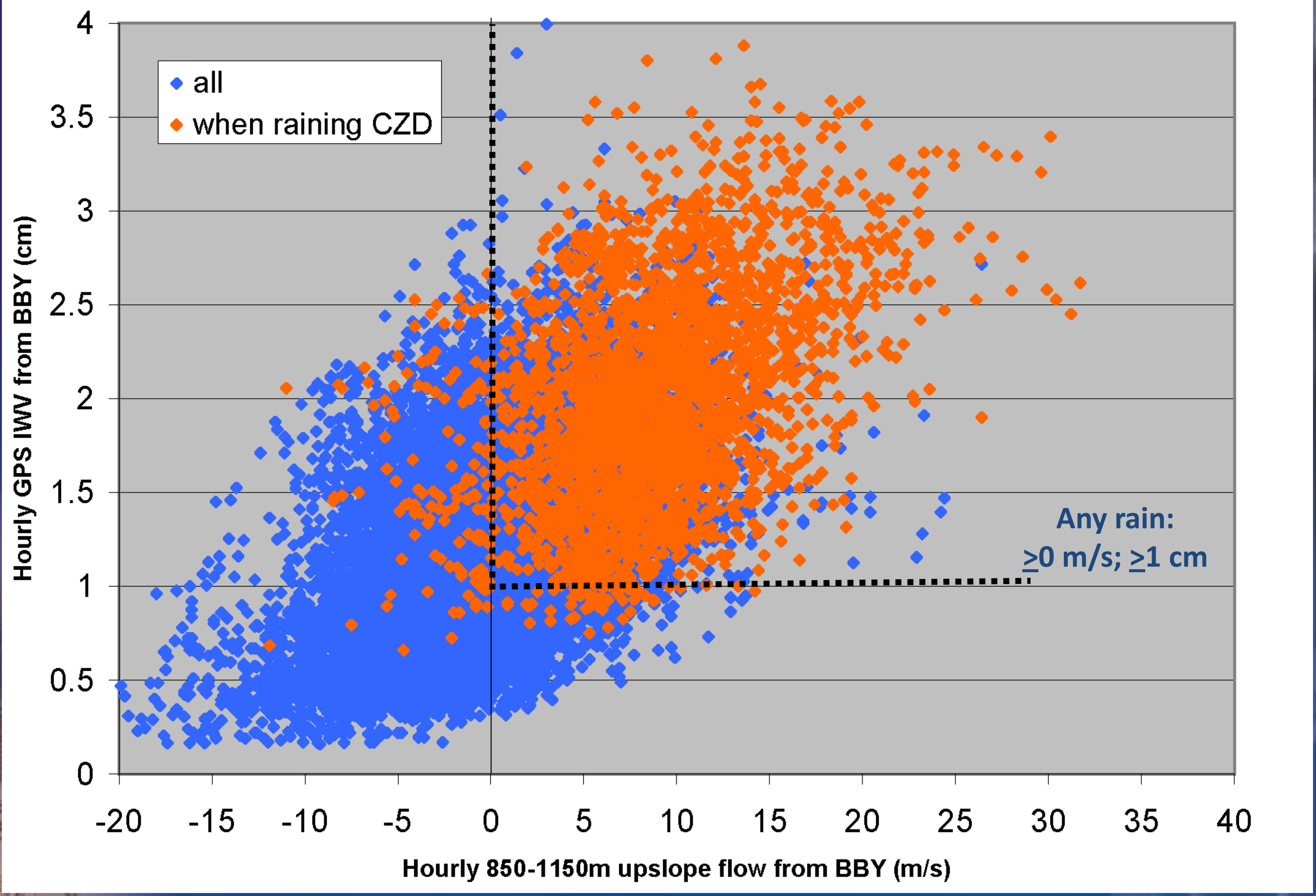
Winters: 2001-2009; 18347 hourly data points



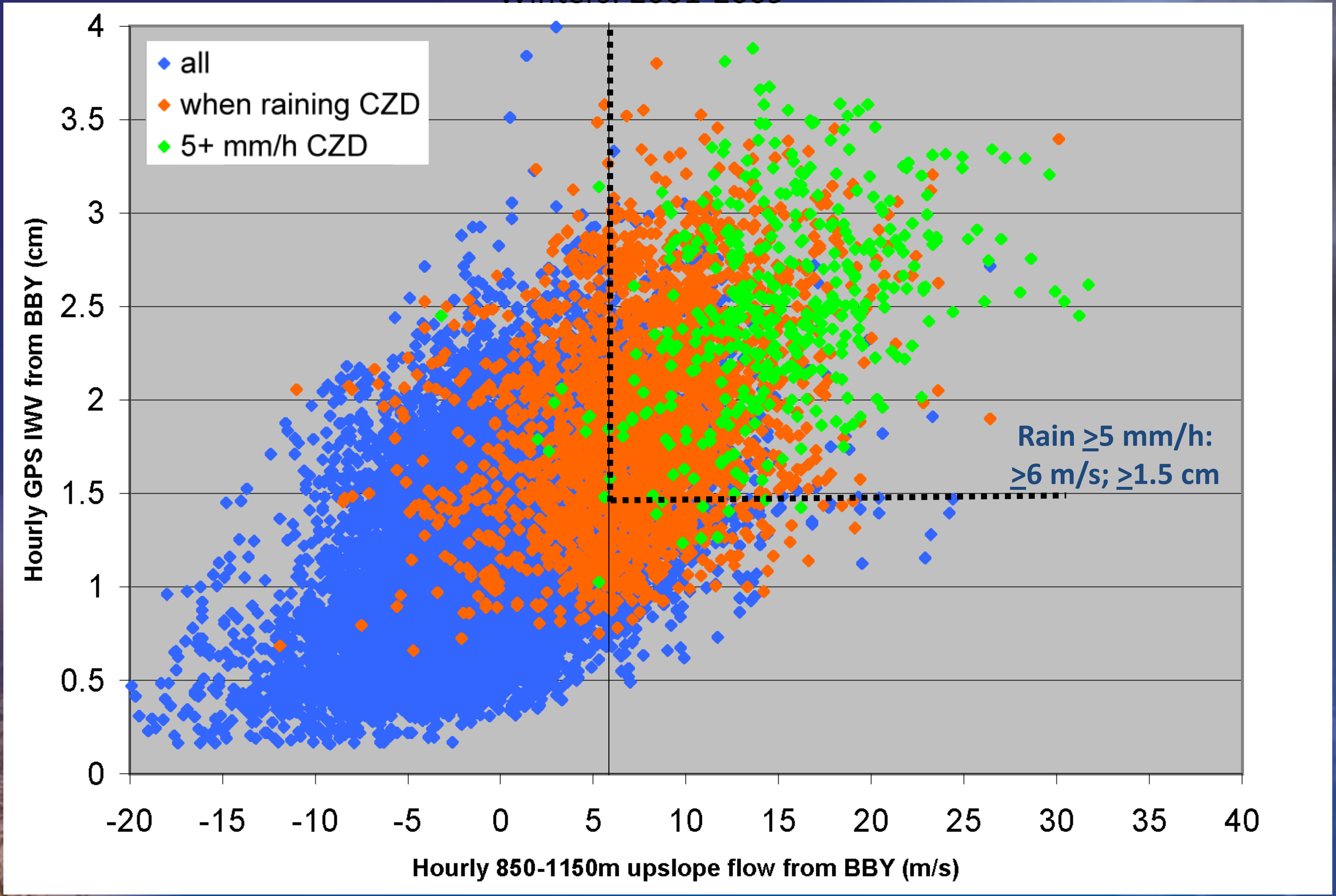
Component of the flow in the orographic controlling layer directed from 230 ,
i.e., orthogonal to the axis of the coastal mtns

Neiman et al. (2008), *Water Management*

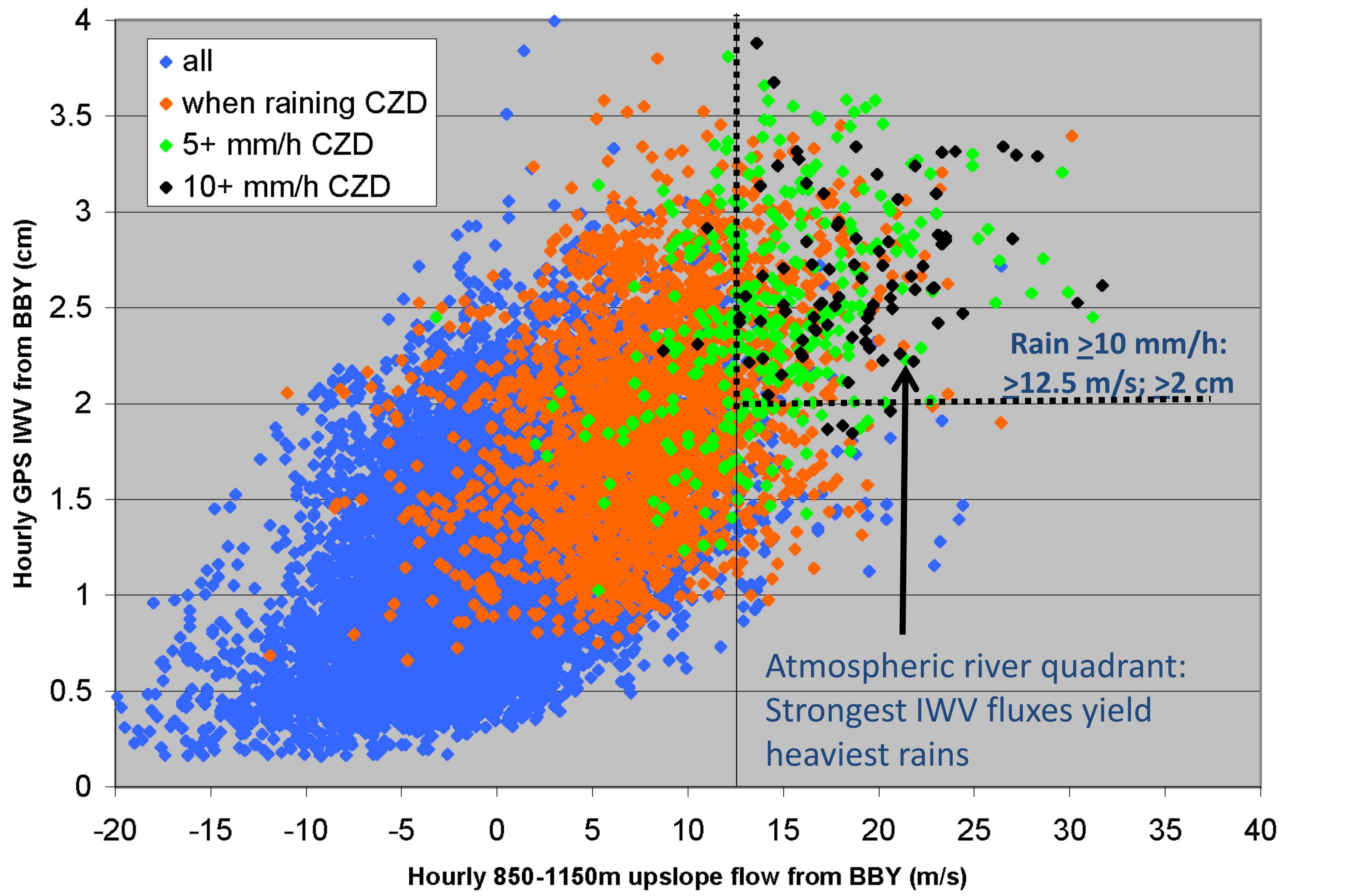
Winters: 2001-2009



Winters: 2001-2009



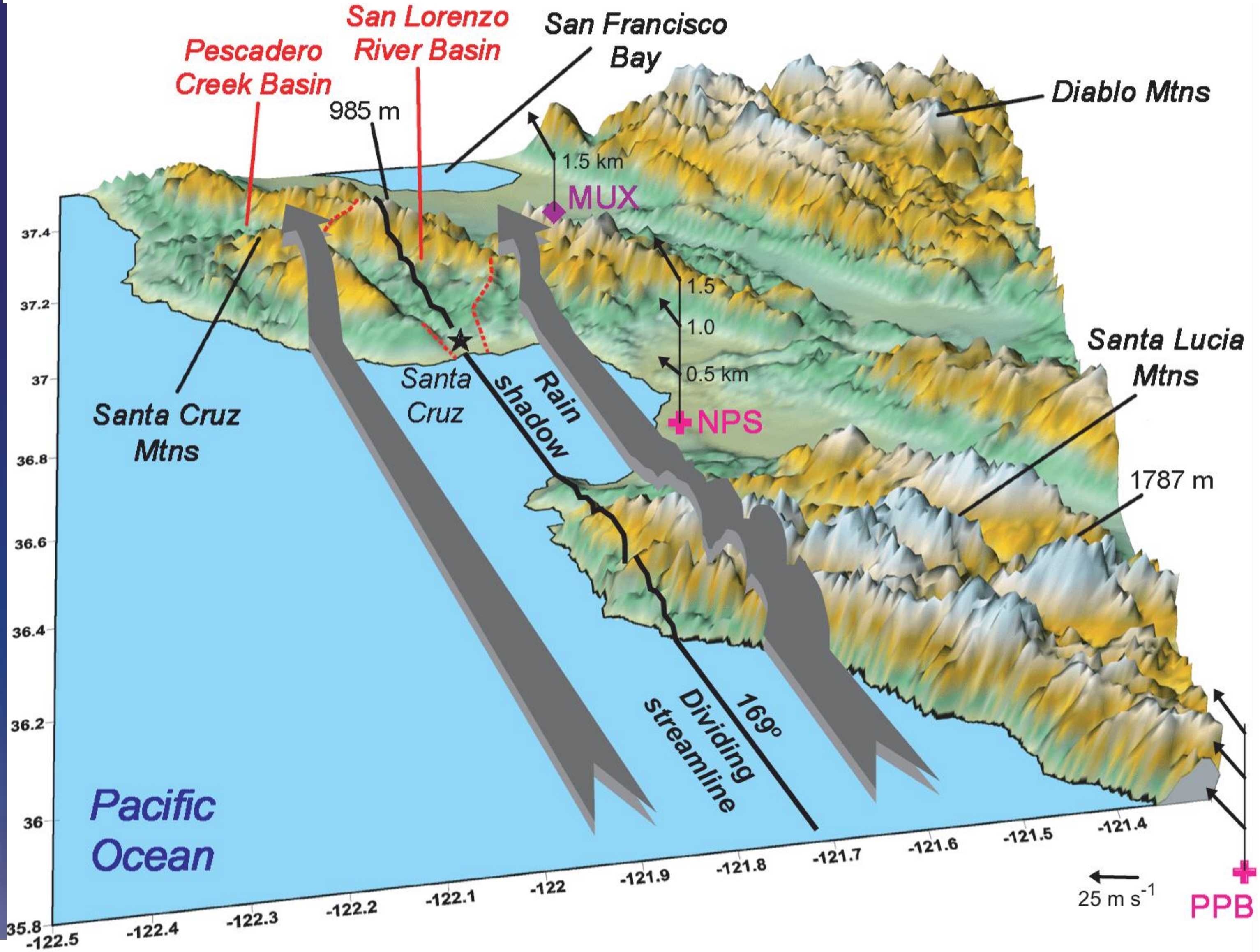
Winters: 2001-2009



*Nearly 2/3 of tropospheric water vapor is in the lowest 2 km MSL.
Hence, to first order, the IWV flux provides a close estimate
of the low-level water-vapor transport into the coastal mountains.

Physical variables required for extreme precipitation (includes AR conditions)

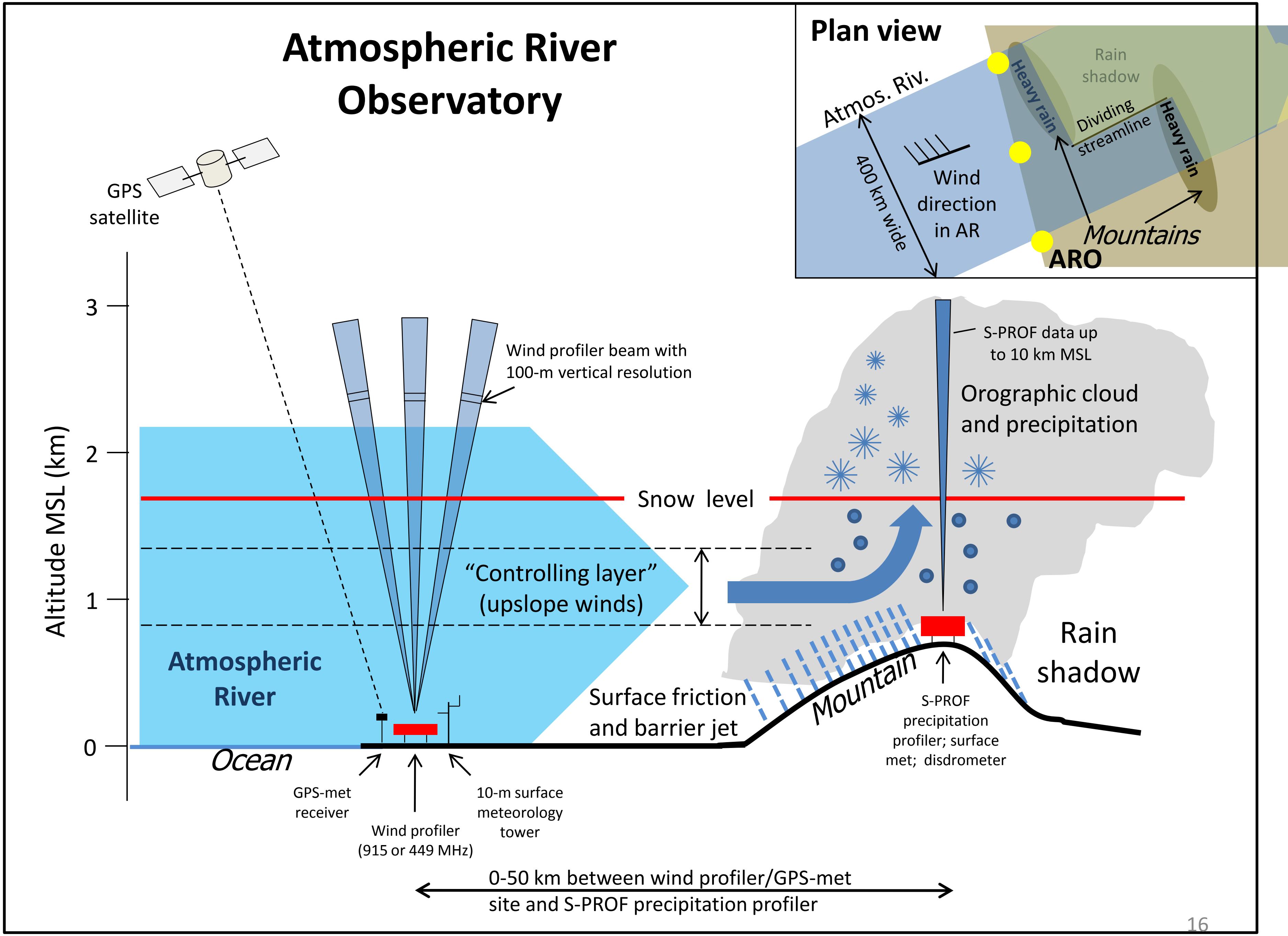
- Wind in the controlling layer near 1 km MSL
  - speed > 12.5 m/s
  - direction (determines location of rain shadow)
- Water vapor content
  - vertically integrated water vapor (IWV) > 2 cm
- Snow level
  - Above top of watershed



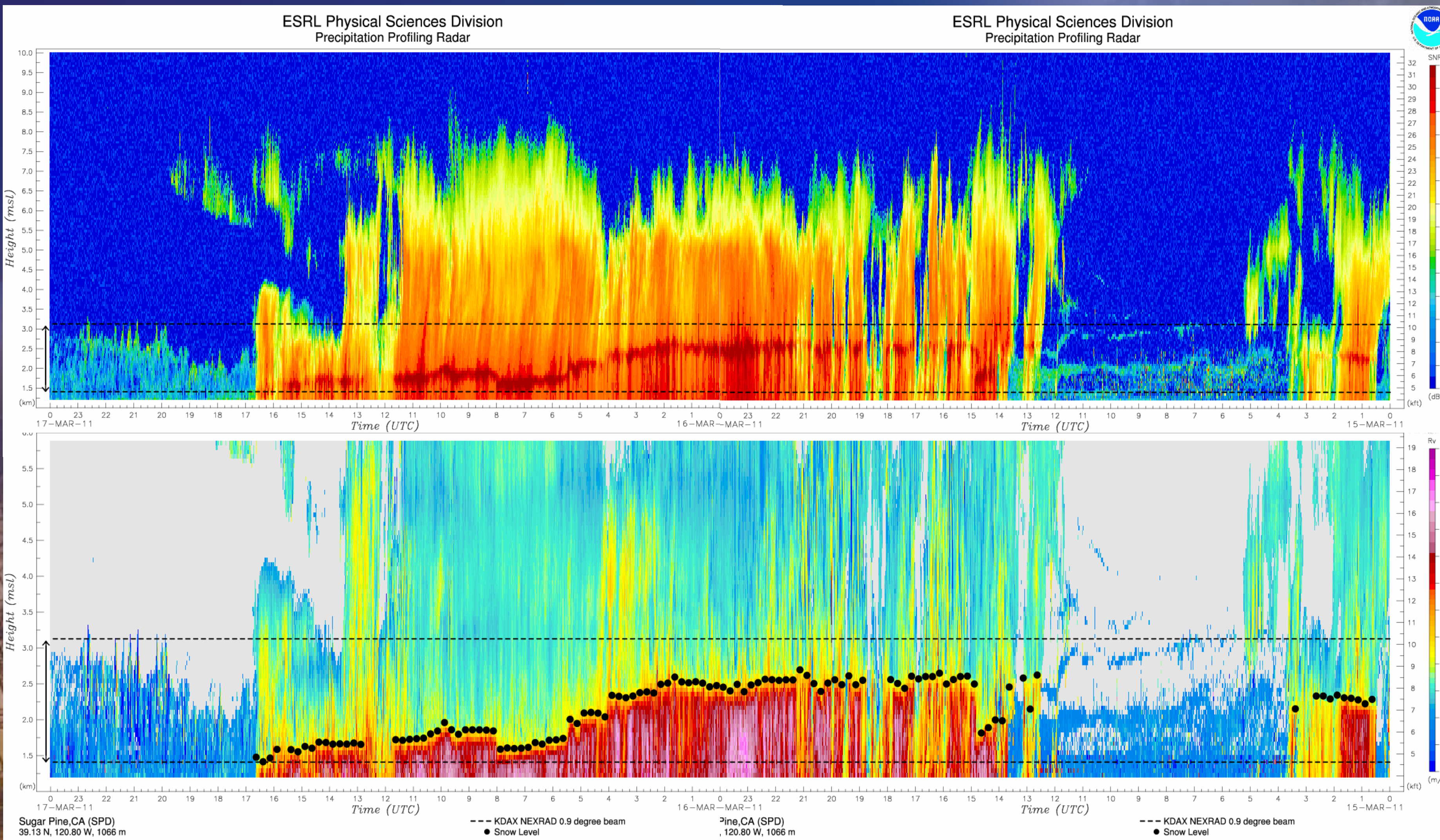
When atmospheric rivers strike coastal mountains (Ralph et al. 2003)

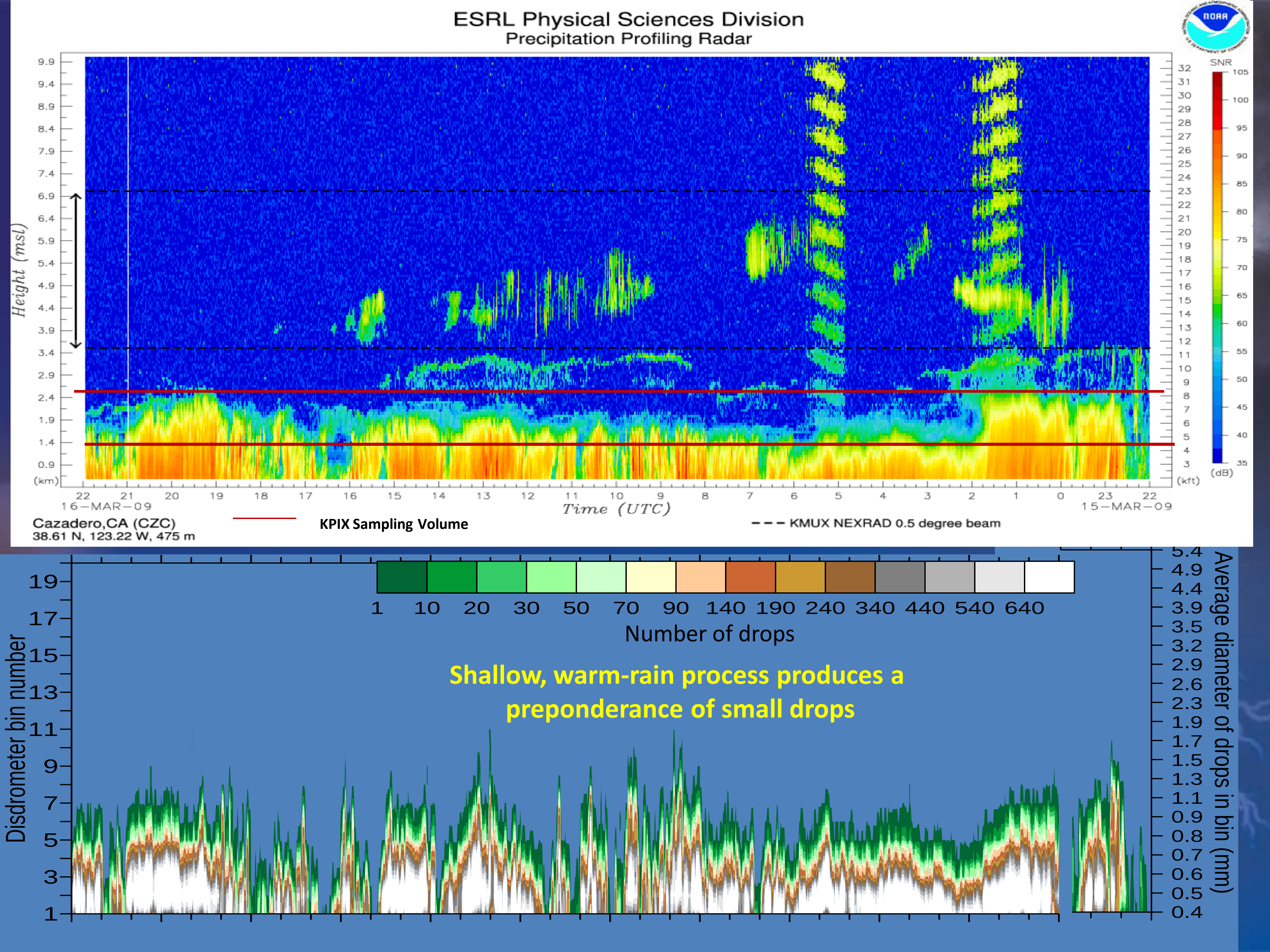
- Details (e.g., wind direction) of the atmospheric river determine which watersheds flood

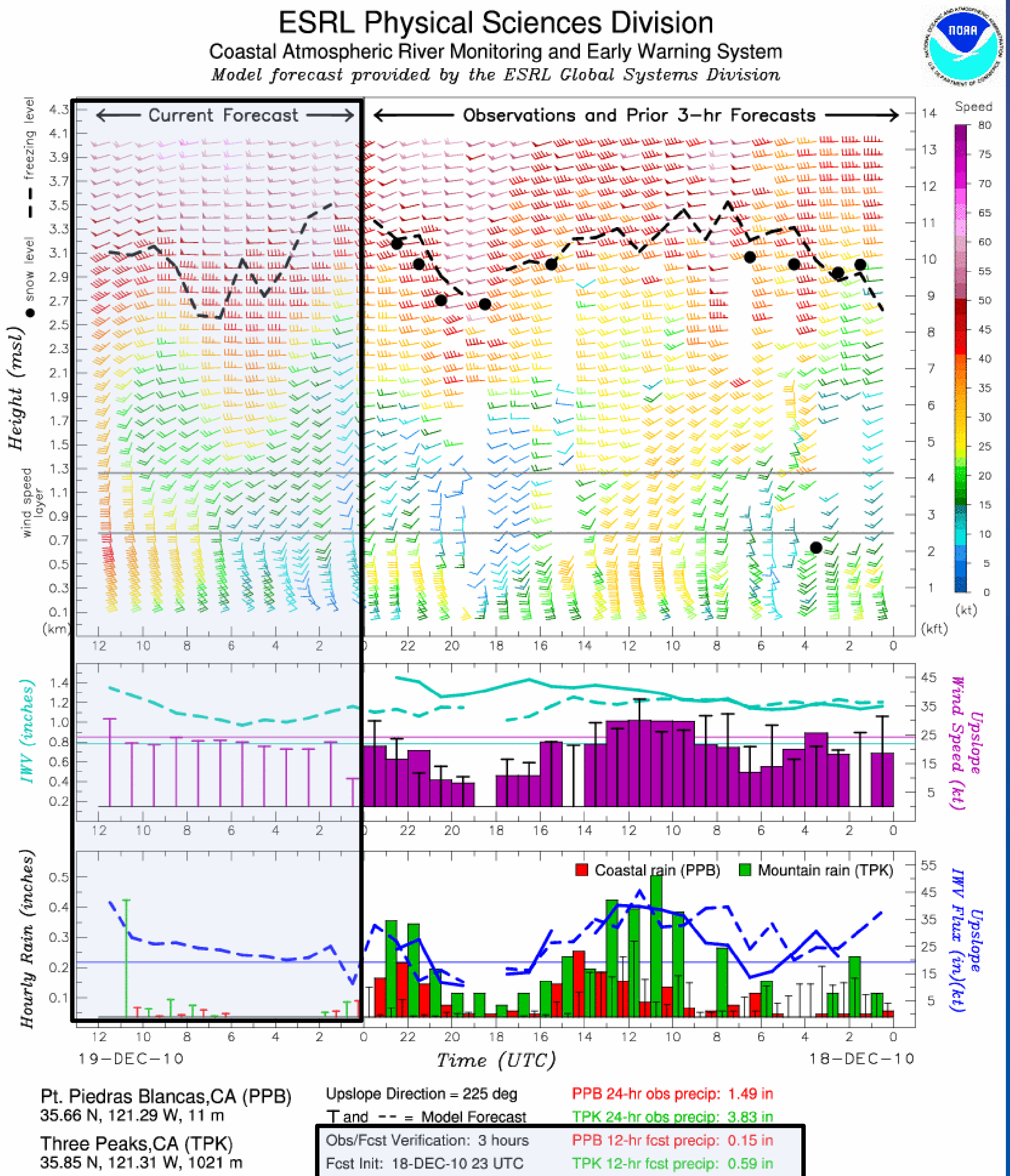
Atmospheric River Observatory



Snow level was 8000-9000 ft initially
Sugar Pine Dam received 5 inches of rain in 27 hours




ESRL Physical Sciences Division
Precipitation Profiling Radar
Height (msl)
(km)
(kft)
SNR
(dB)
Time (UTC)
16−MAR−09
15−MAR−09
Cazadero,CA (CZC)
38.61 N, 123.22 W, 475 m
KPIX Sampling Volume
KMUX NEXRAD 0.5 degree beam
1 10 20 30 50 70 90 140 190 240 340 440 540 640
Number of drops
Shallow, warm-rain process produces a preponderance of small drops
Disdrometer bin number
Average diameter of drops in bin (mm)

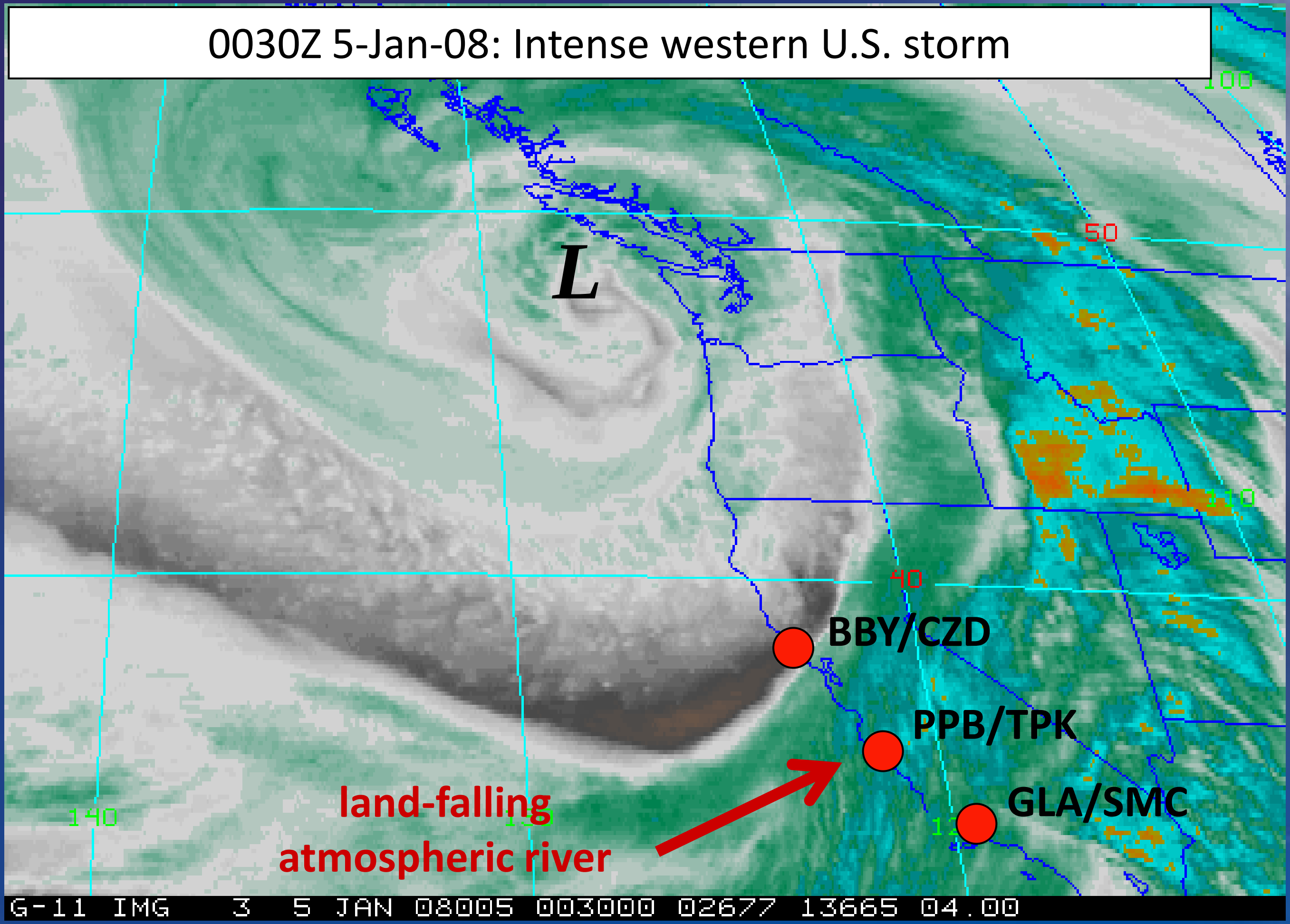


Predictive capability added to ARO at request of NWS

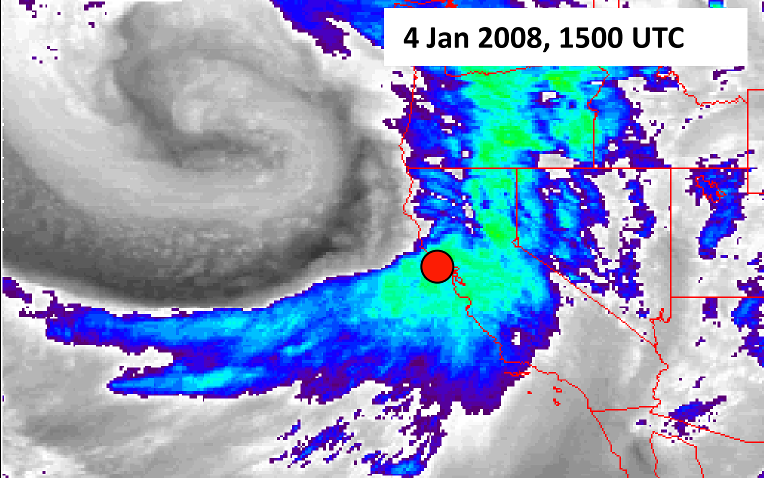
The left side of the figure represents forecasts of AR conditions from a specialized numerical model.

Note that time increases from right to left in this display, which is a meteorological style.

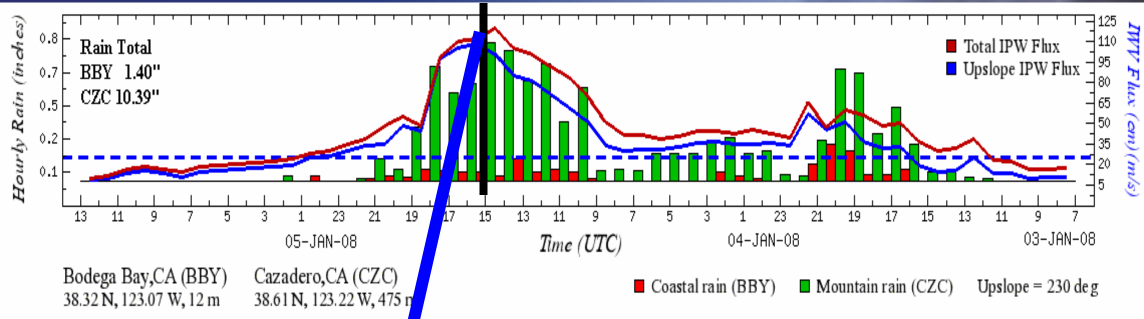
Prototype forecast tool tested at 3 CA couplets during NOAA's HMTs

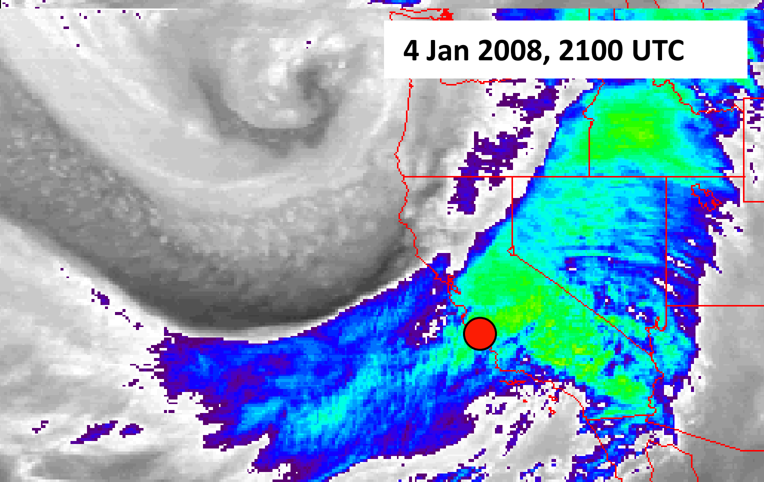


Couplet	Coast (*profiler, GPS, rain gauge*):	Mountains (*rain gauge*):
North:	Bodega Bay (BBY; 12 m MSL)	Cazadero (CZD; 475 m MSL)
Central:	Piedras Blancas (PPB; 11 m MSL)	Three Peaks (TPK; 1021 m MSL)
South:	Goleta (GLA; 3 m MSL)	San Marcos Pass (SMC; 701 m MSL)

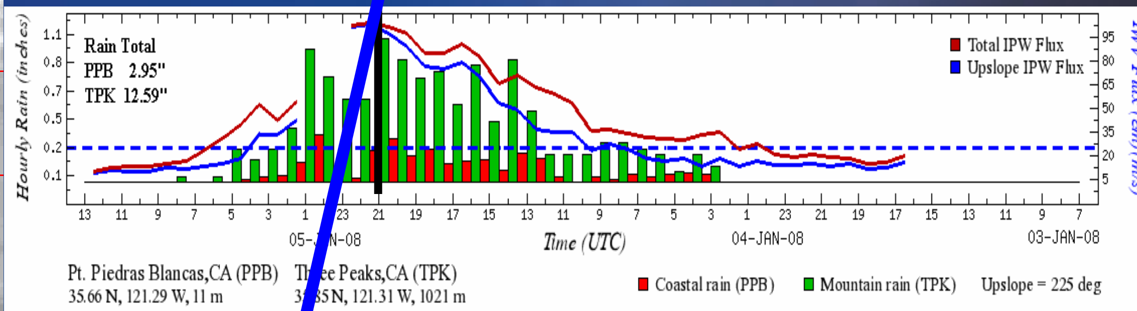


Time of max AR bulk flux at BBY: 1500 UTC 4 Jan



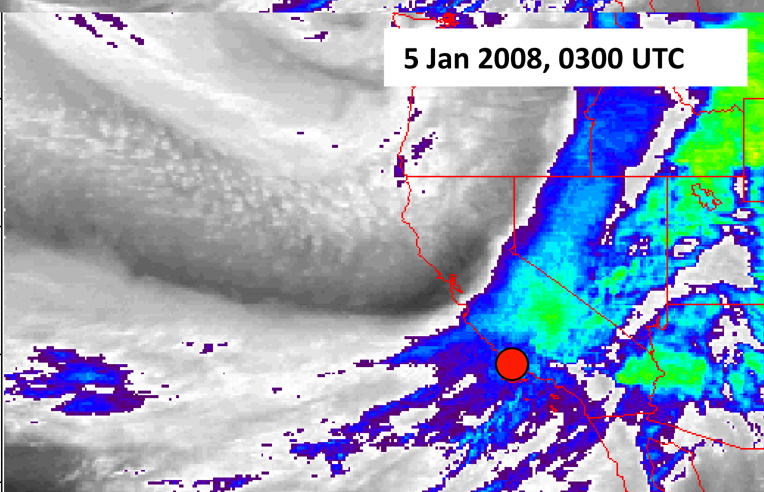


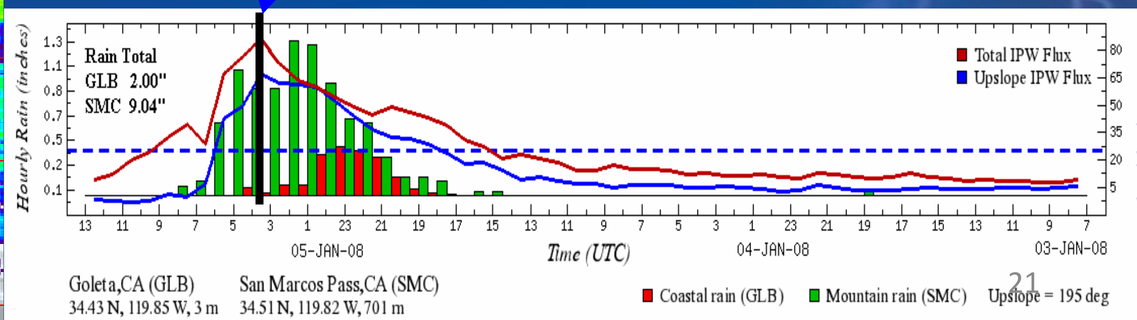
Time of max AR bulk flux at PPB: 2100 UTC 4 Jan



AR Propagation: ~12 m s^{-1}.
½-day lead time for SoCal

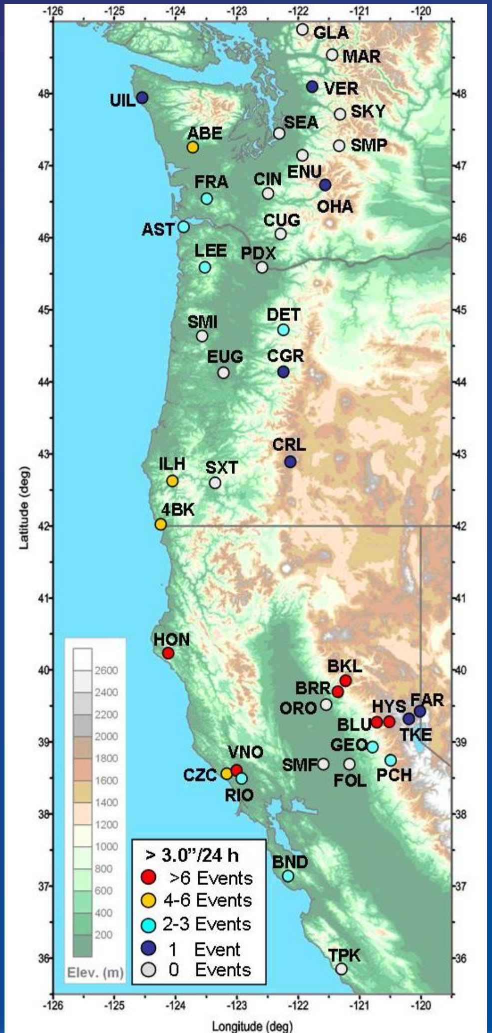
Time of max AR bulk flux at GLA: 0300 UTC 5 Jan

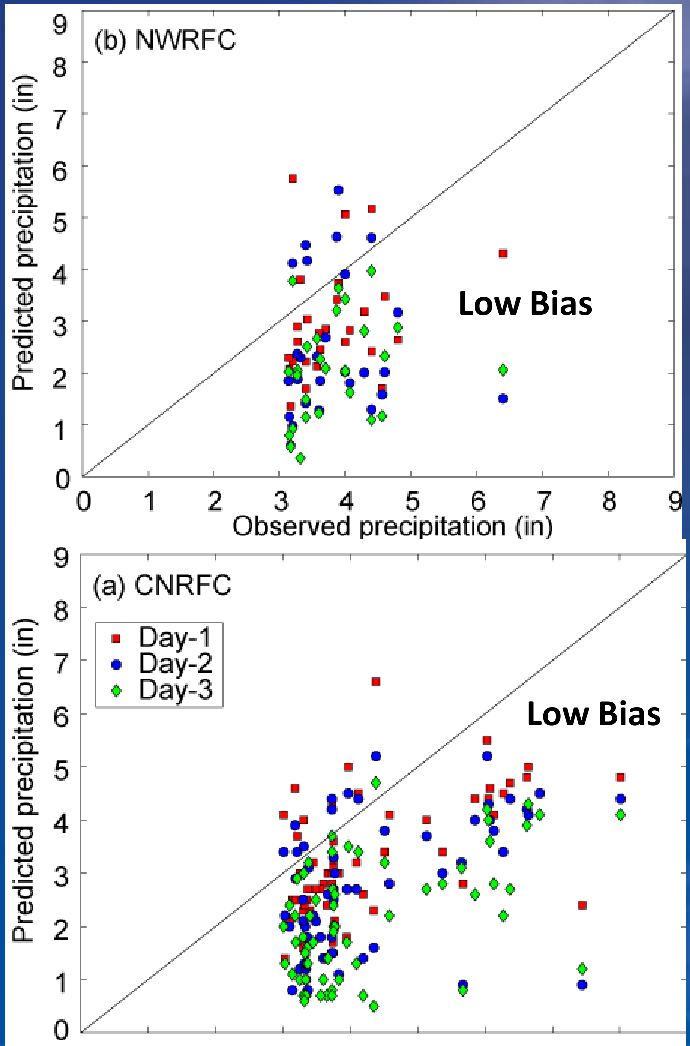




Frequency of Occurrence for Observed and Predicted 3” Precipitation Events

Ralph, F. M., E. Sukovich, D. Reynolds, M. Dettinger, S. Weagle, W. Clark and P.J.Neiman, 2010: Assessment of Extreme Quantitative Precipitaiton Forecasts and Development of Regional Extreme Event Thresholds Using Data from the HMT-2006 and COOP Observers. J. HydroMet.

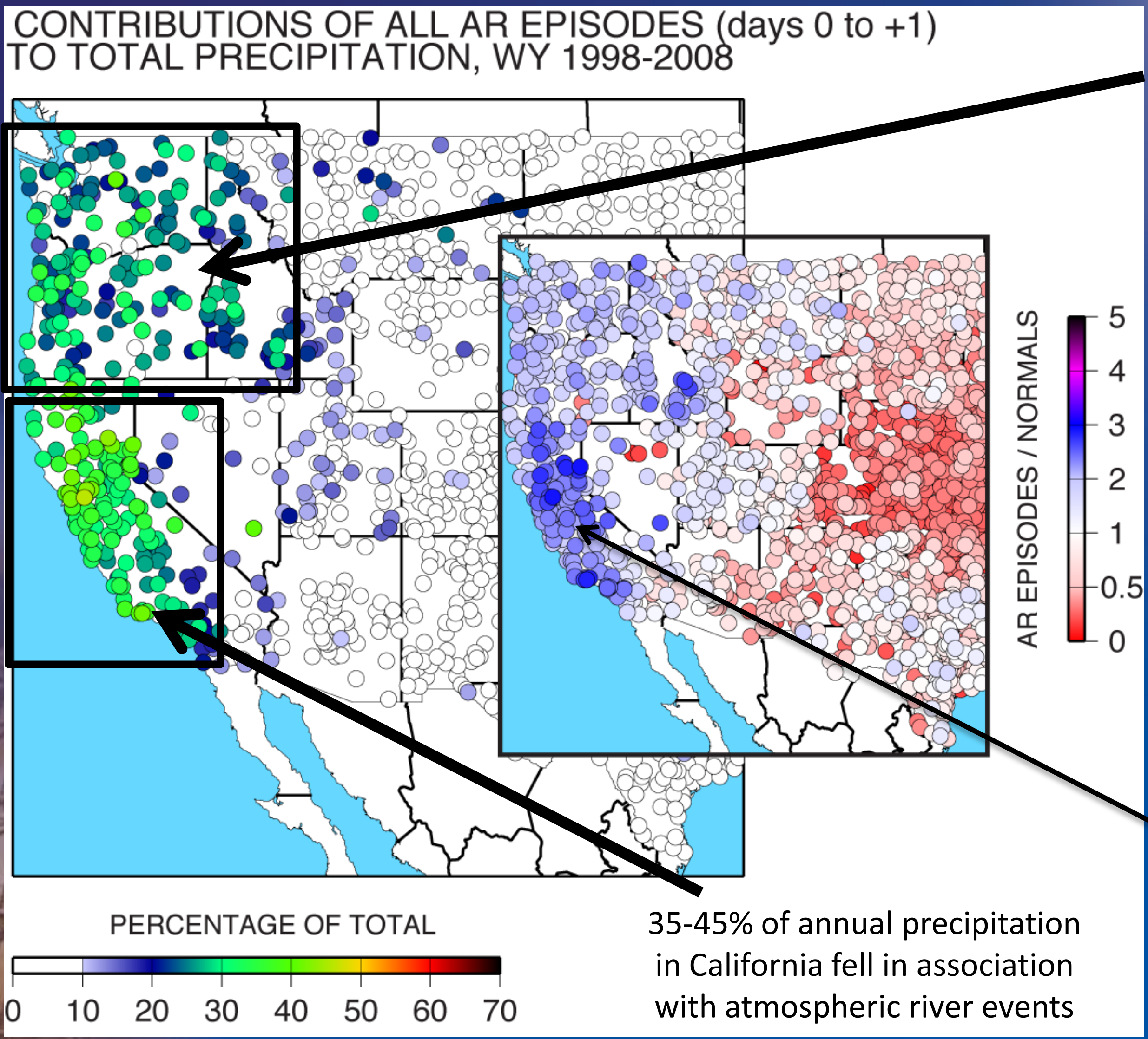




Atmospheric Rivers, Floods and the Water Resources of California

by Mike Dettinger, Marty Ralph, , Tapash Das, Paul Neiman, Dan Cayan

Water, 2011 (in Press)



25-35% of annual precipitation in the Pacific Northwest fell in association with atmospheric river events

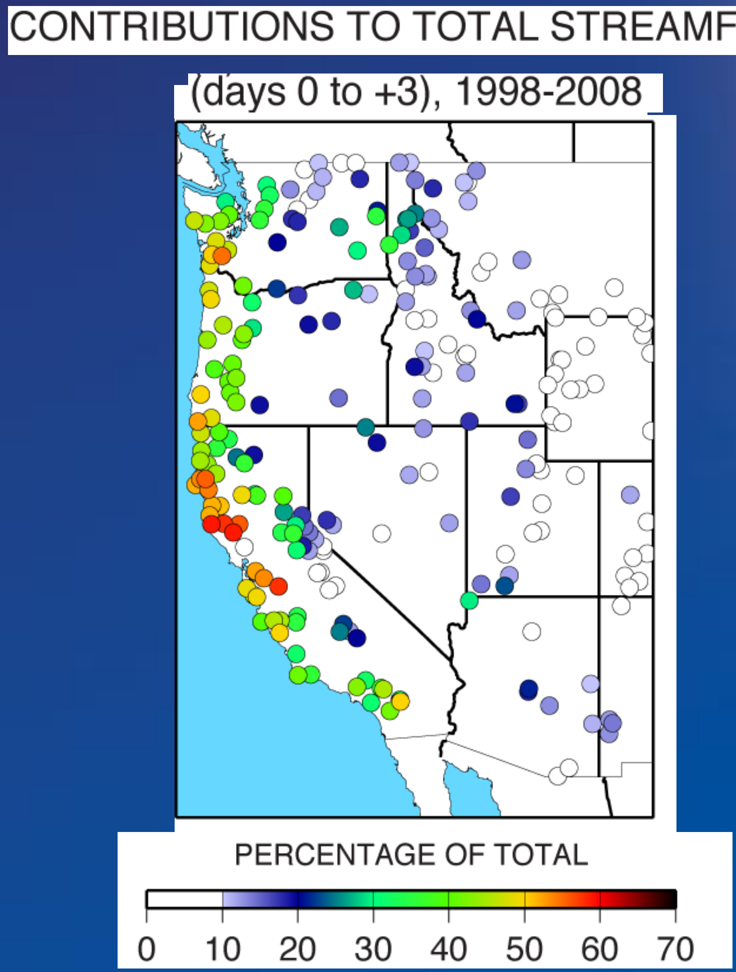
An average AR transports the equivalent of 7.5 times the average discharge of the Mississippi River, or ~10 M acre feet/day

2 -3x more rainfall on an AR day

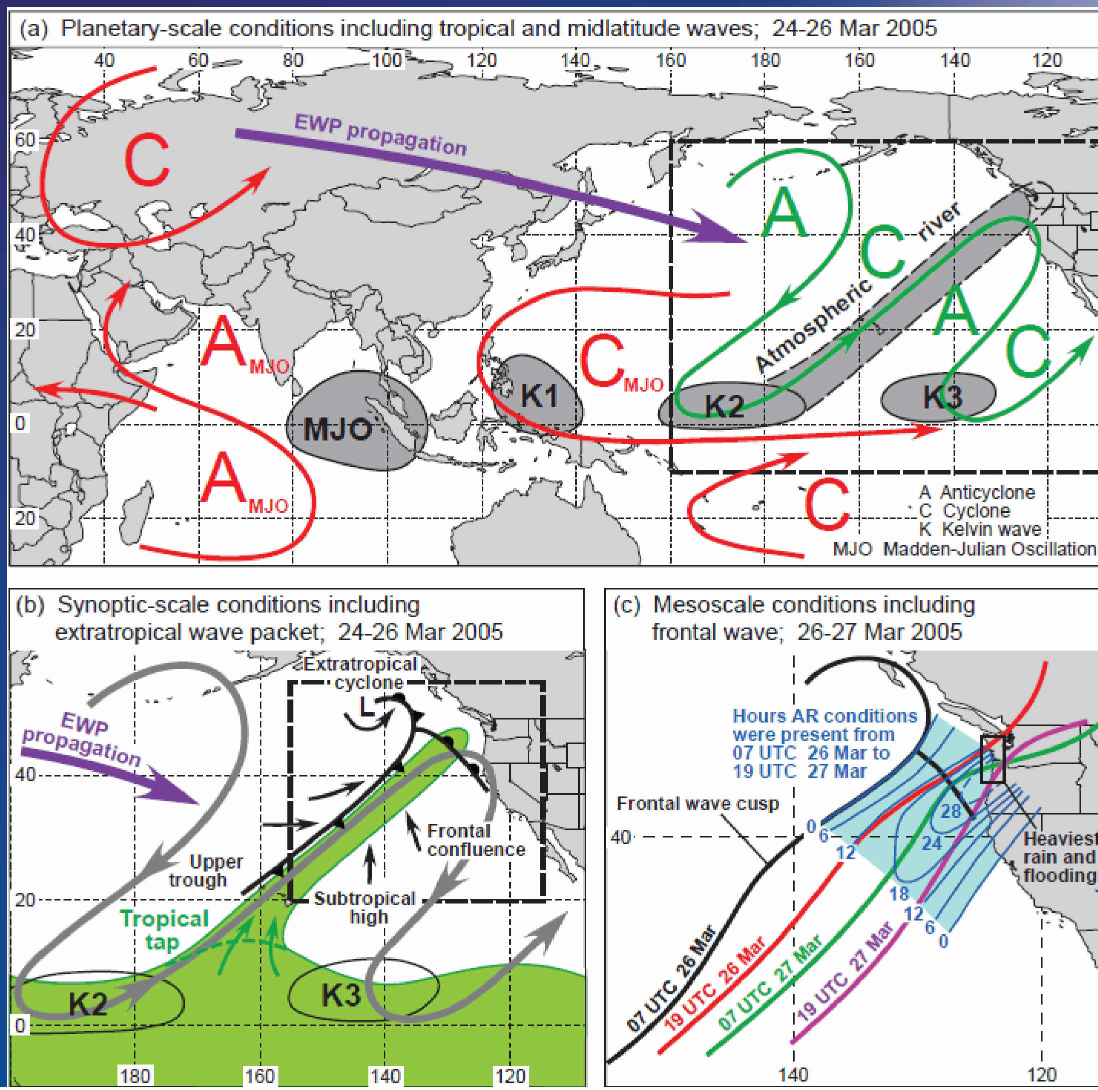
Atmospheric Rivers, Floods and the Water Resources of California

by Mike Dettinger, Marty Ralph, , Tapash Das, Paul Neiman, Dan Cayan

Accepted in ***Water***



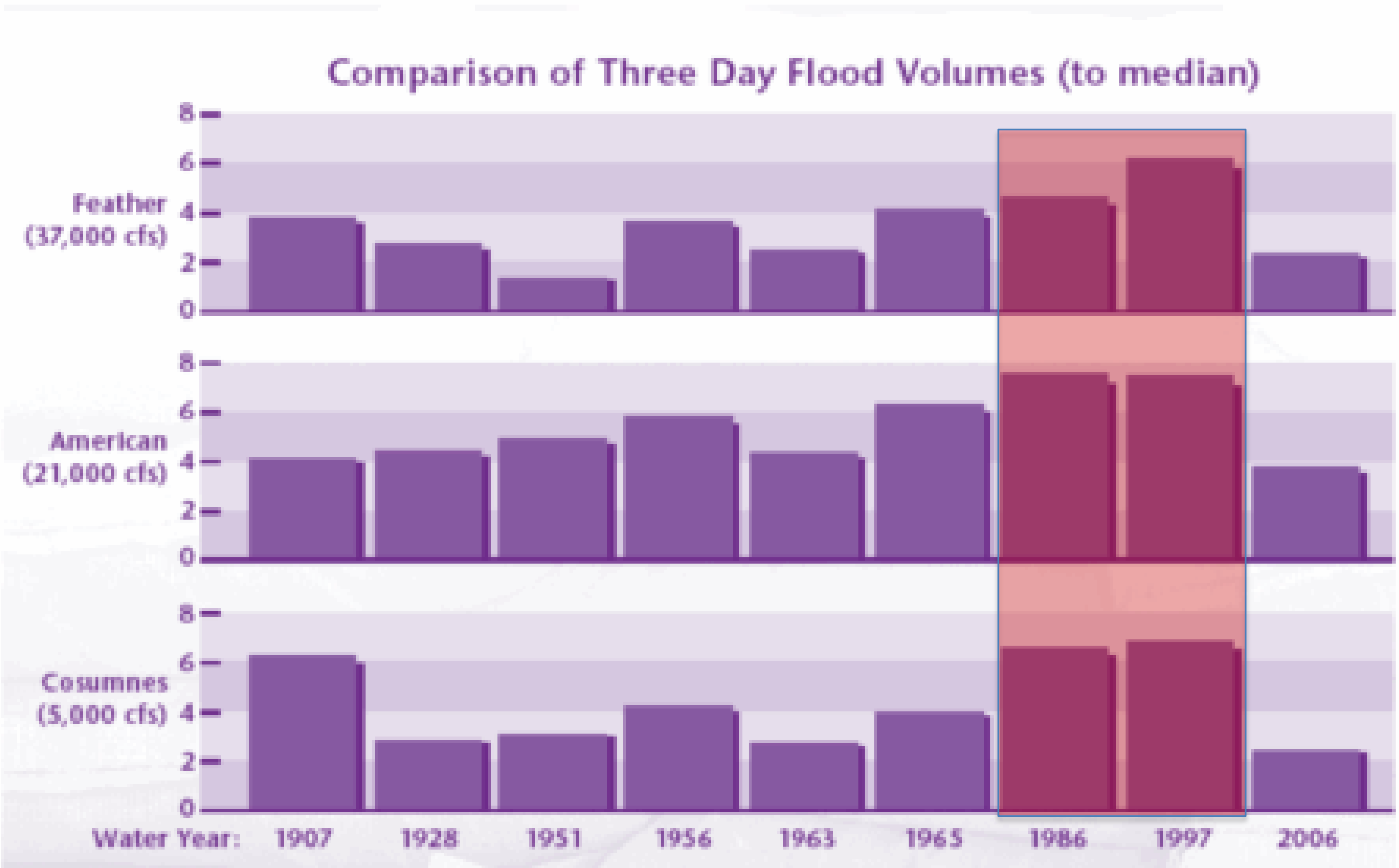
Evolution of a Pacific Atmospheric River and Subsequent Extreme Rainfall in PacNW



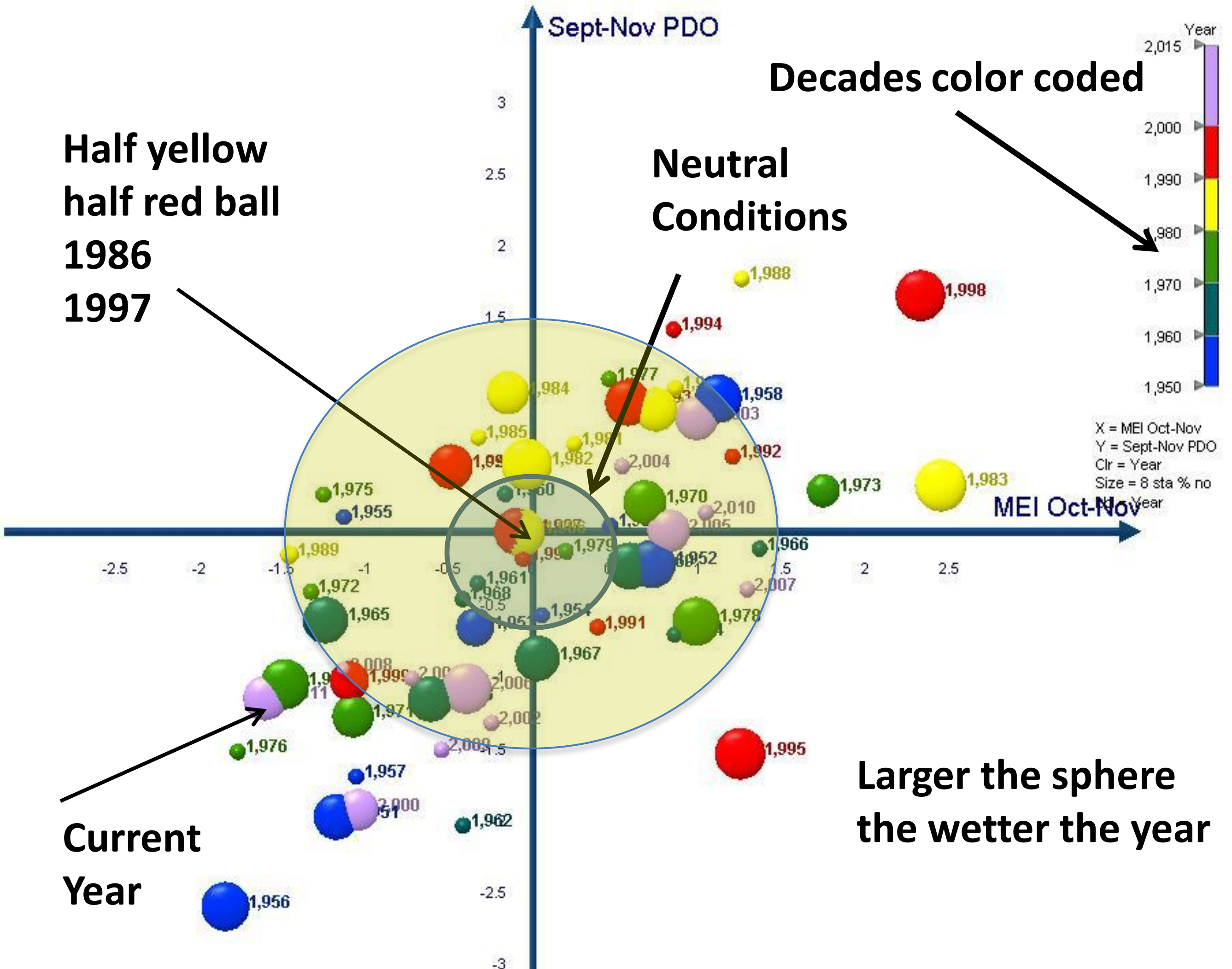
Ralph, F. Martin, P.J.Neiman, G. N. Kiladis, K. Weickman, D.W. Reynolds, 2011: A Planatery-to-Mesoscale Case Study of a Pacific Atmospheric River that Caused Extreme Precipitation in Oregon: Impacts of Tropical Forcings and a Mesoscale Frontal Wave. MWR, 139, 1169-1189.

Major 3-day flood volumes CA

From Roos 2007

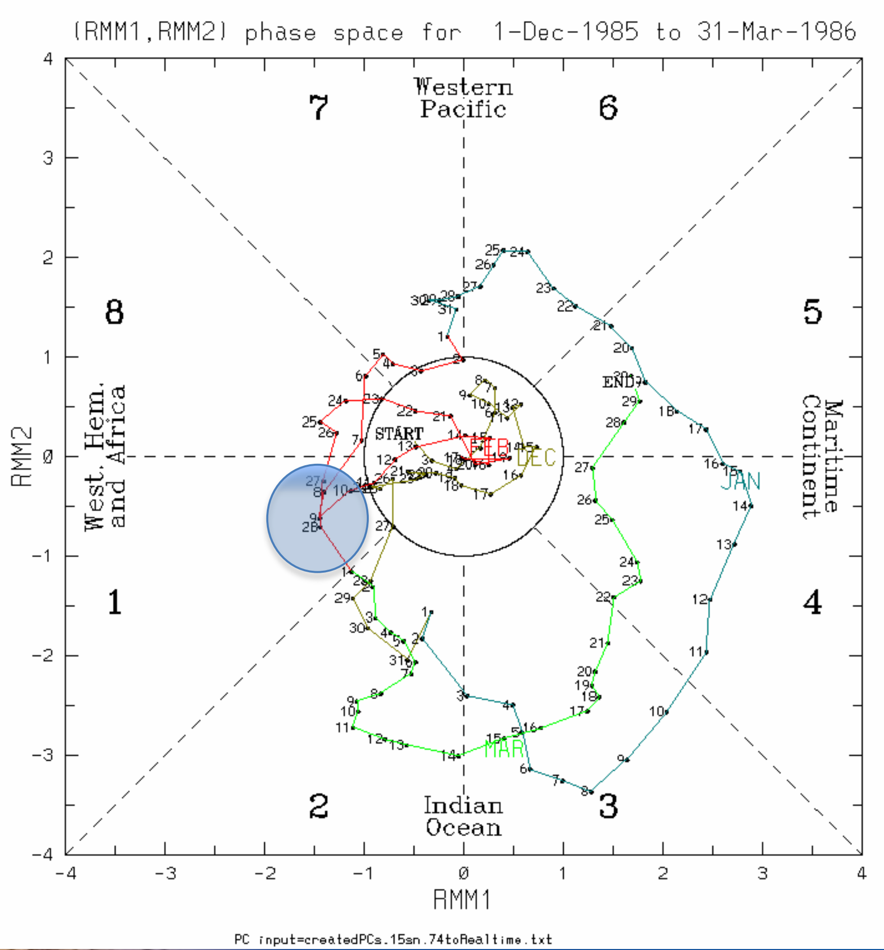


8-station WY rainfall related to Phase of PDO and ENSO

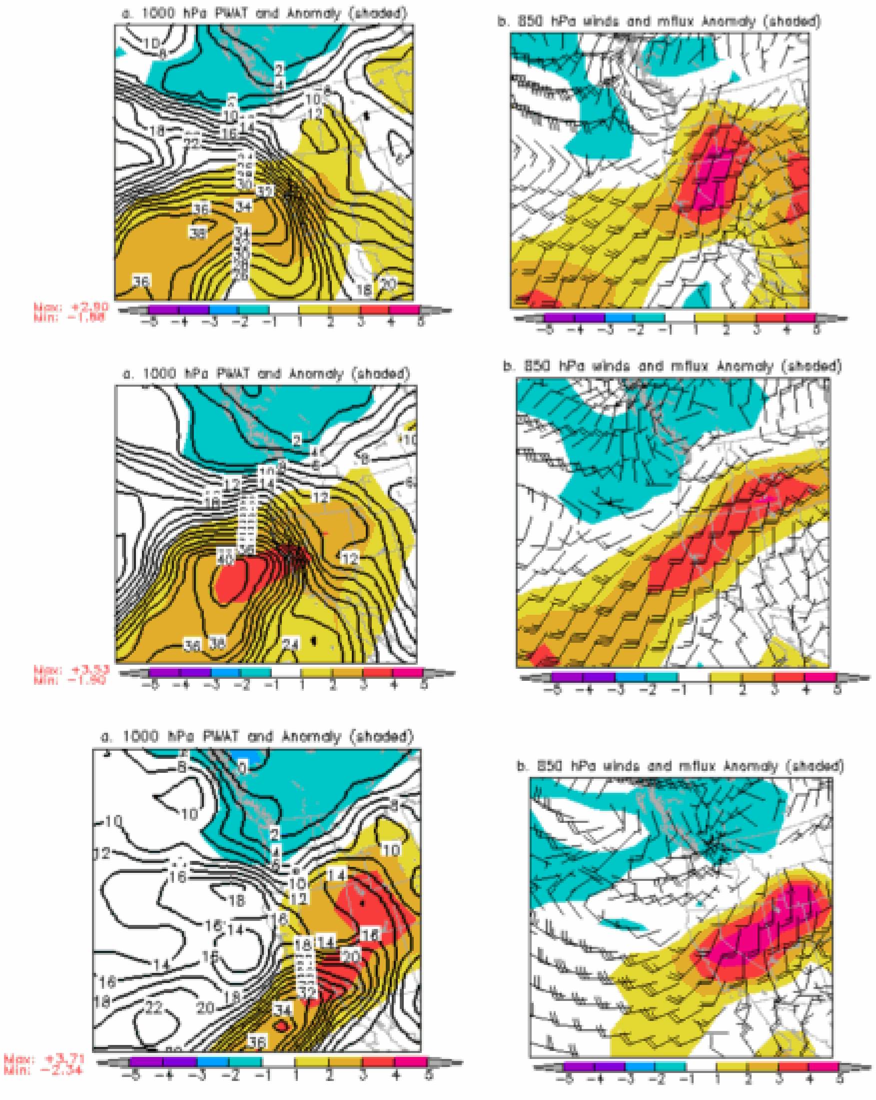


Roundy, P.E., K. MacRitchie, J. Asuma, and T. Melino, 2010: Modulation of the Global Atmospheric Circulation By Combined Activity in the Madden-Julian Oscillation and the El-Nino-Southern Oscillation during Boreal Winter. J. Clim, 29, 4045-4059.

Feb 1986

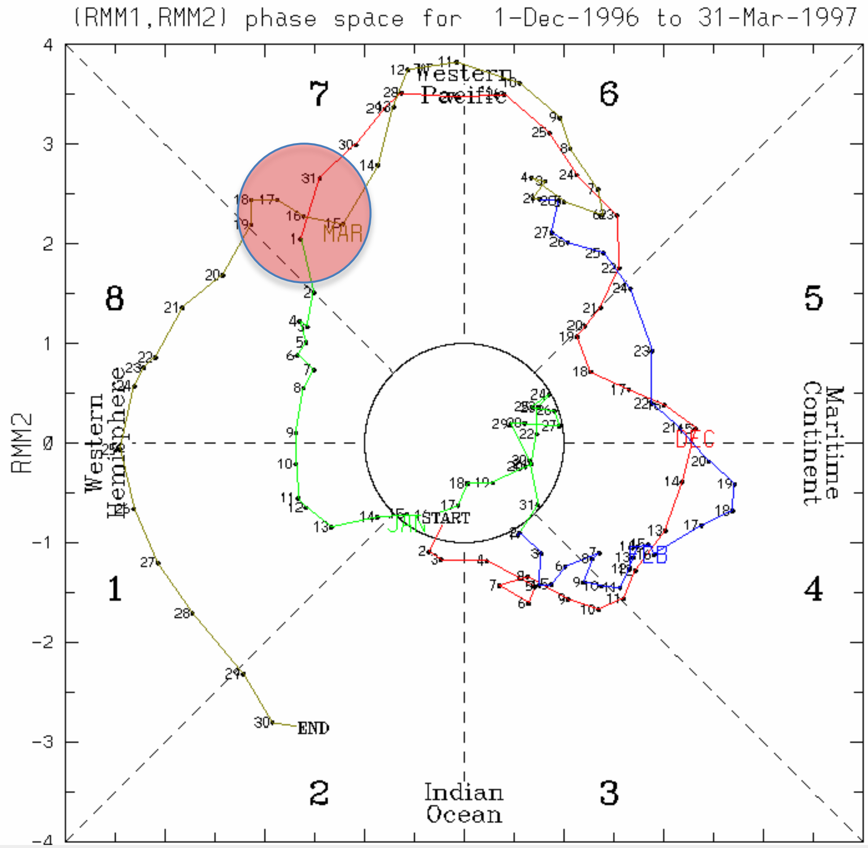


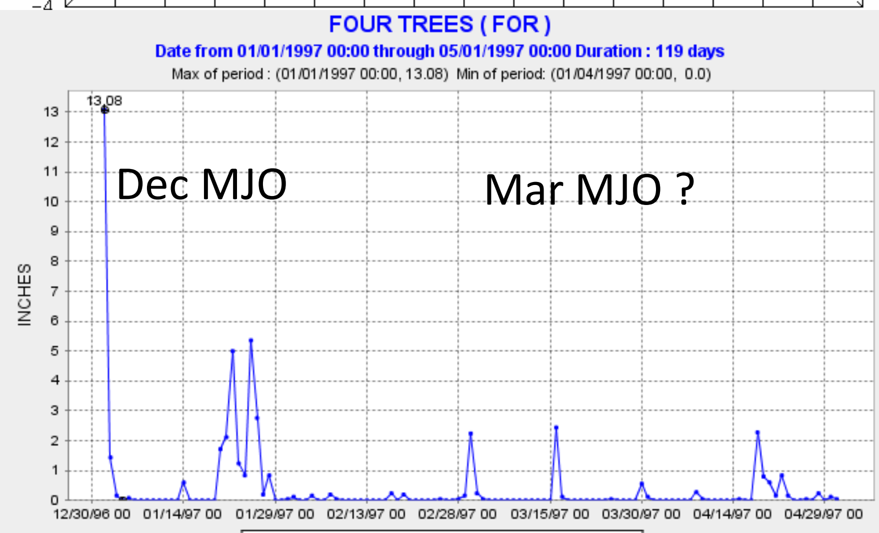
Max of 55" rain in 7 days Northern Sierra

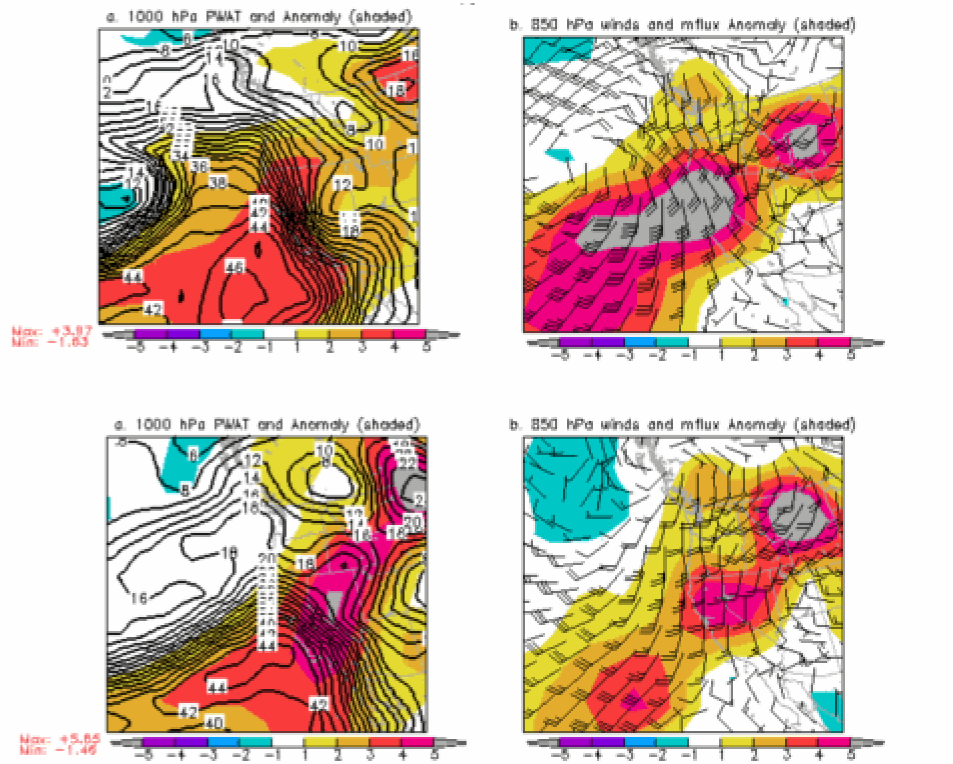


PW (mm) and normalized PW anomaly (magnitude of the anomaly scale is shown on the scale at the bottom of the figure) valid 0000 UTC 17 Feb. 1986 (top panel), 1200 UTC 17 Feb. 1986 (middle panel) and 1200 UTC 19 Feb 1986 (bottom panel).

850-hPa winds (standard barbs and flags) and normalized anomaly of 850-hPa moisture flux (magnitude is given by the color fill from the bar at the bottom of the figure) valid 0000 UTC 17 Feb. 1963 (top panel), 1200 UTC 17 Feb. 1963 (bottom panel).





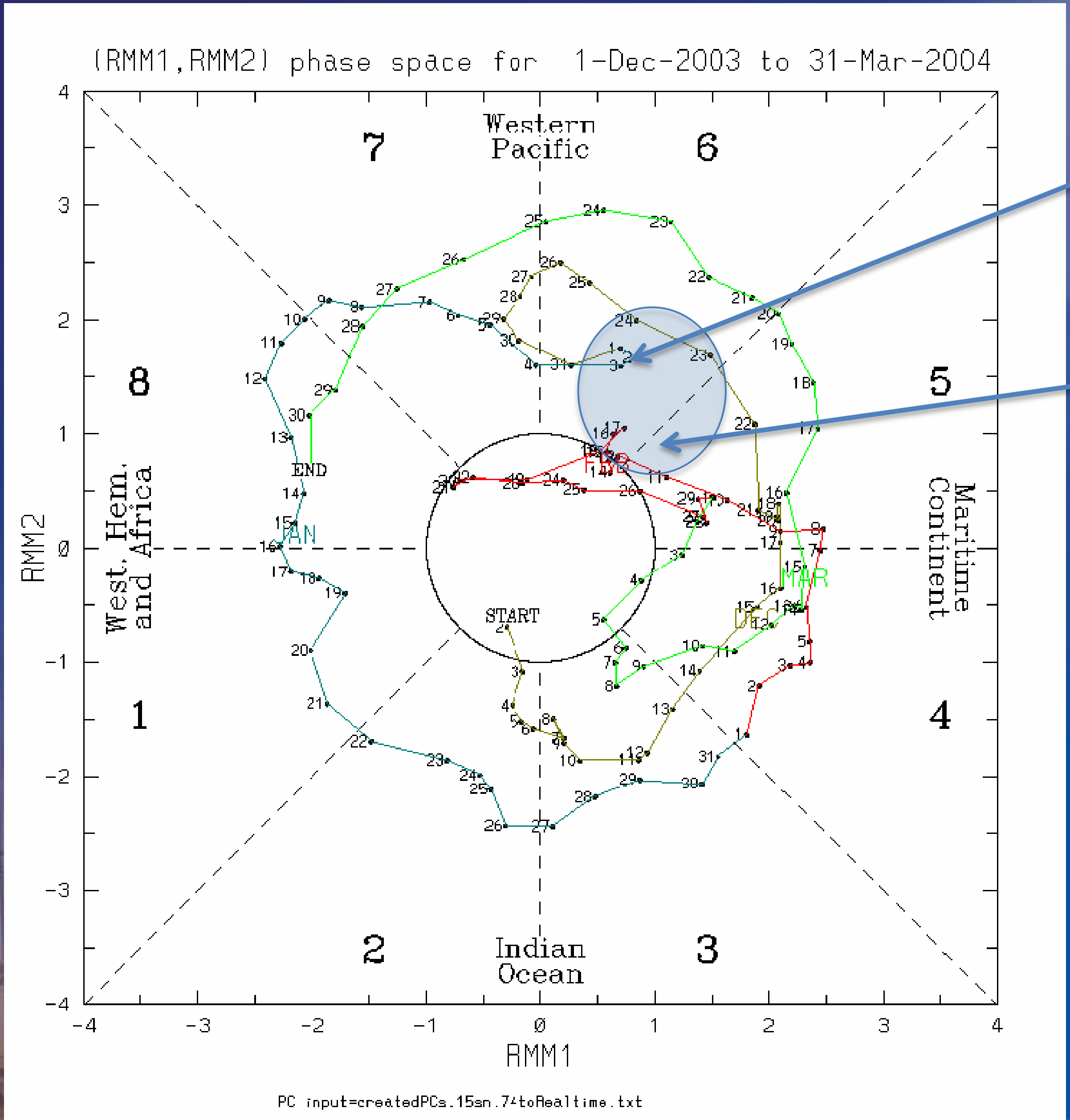


PW (mm) and normalized PW anomaly (magnitude of the anomaly scale is shown on the scale at the bottom of the figure) valid 1800 UTC 31 Dec. 1996 (top panel), 1800 UTC 01 Jan. 1997 (bottom panel).

850-hPa winds (standard barbs and flags) and normalized anomaly of 850-hPa moisture flux (magnitude is given by the color fill from the bar at the bottom of the figure) valid 1800 UTC 31 Dec. 1996 (top panel), 1800 UTC 01 Jan. 1997 (bottom panel).

New Years 1997

Napa River Flooding ~45 days apart

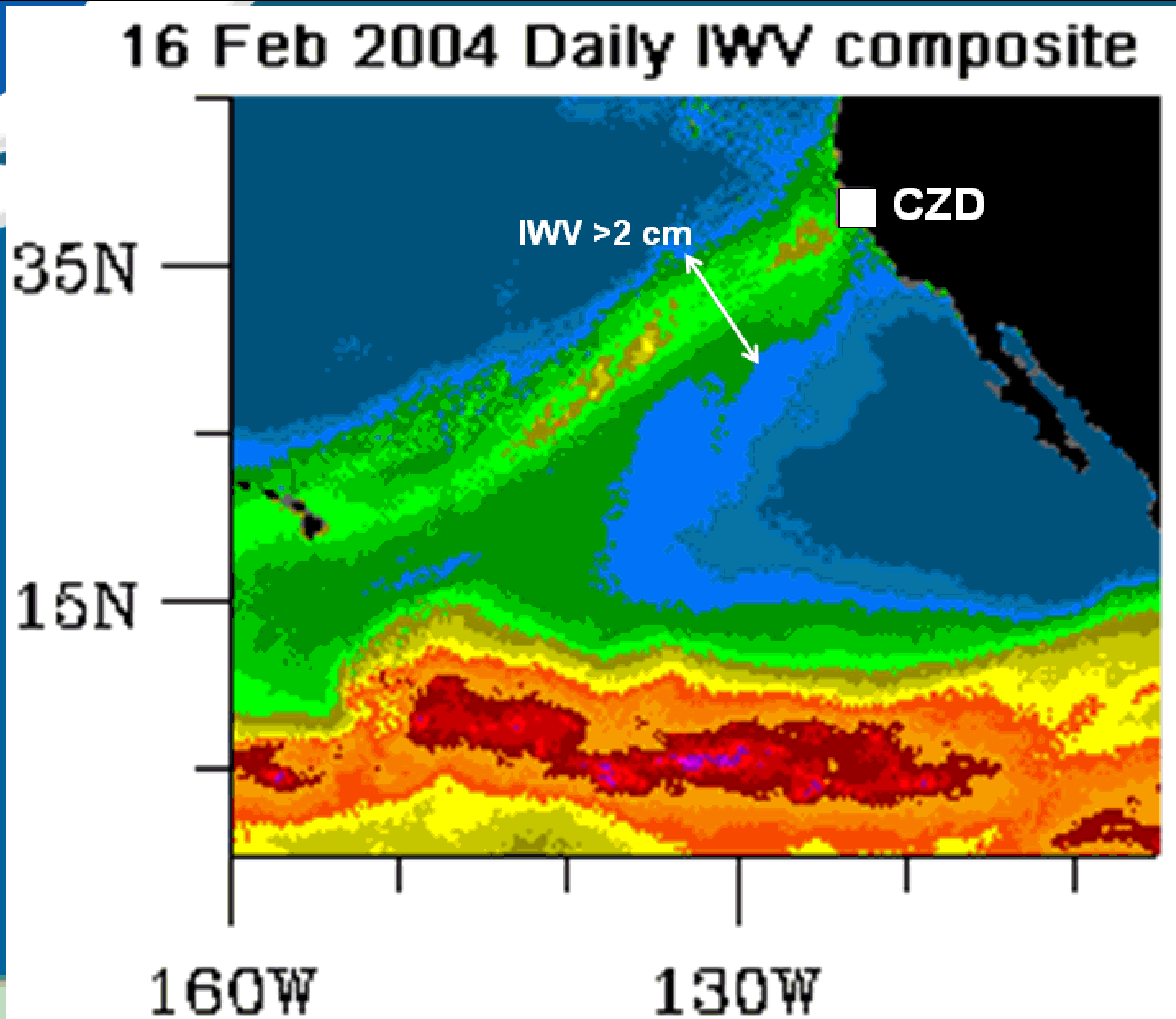


Jan 1-3

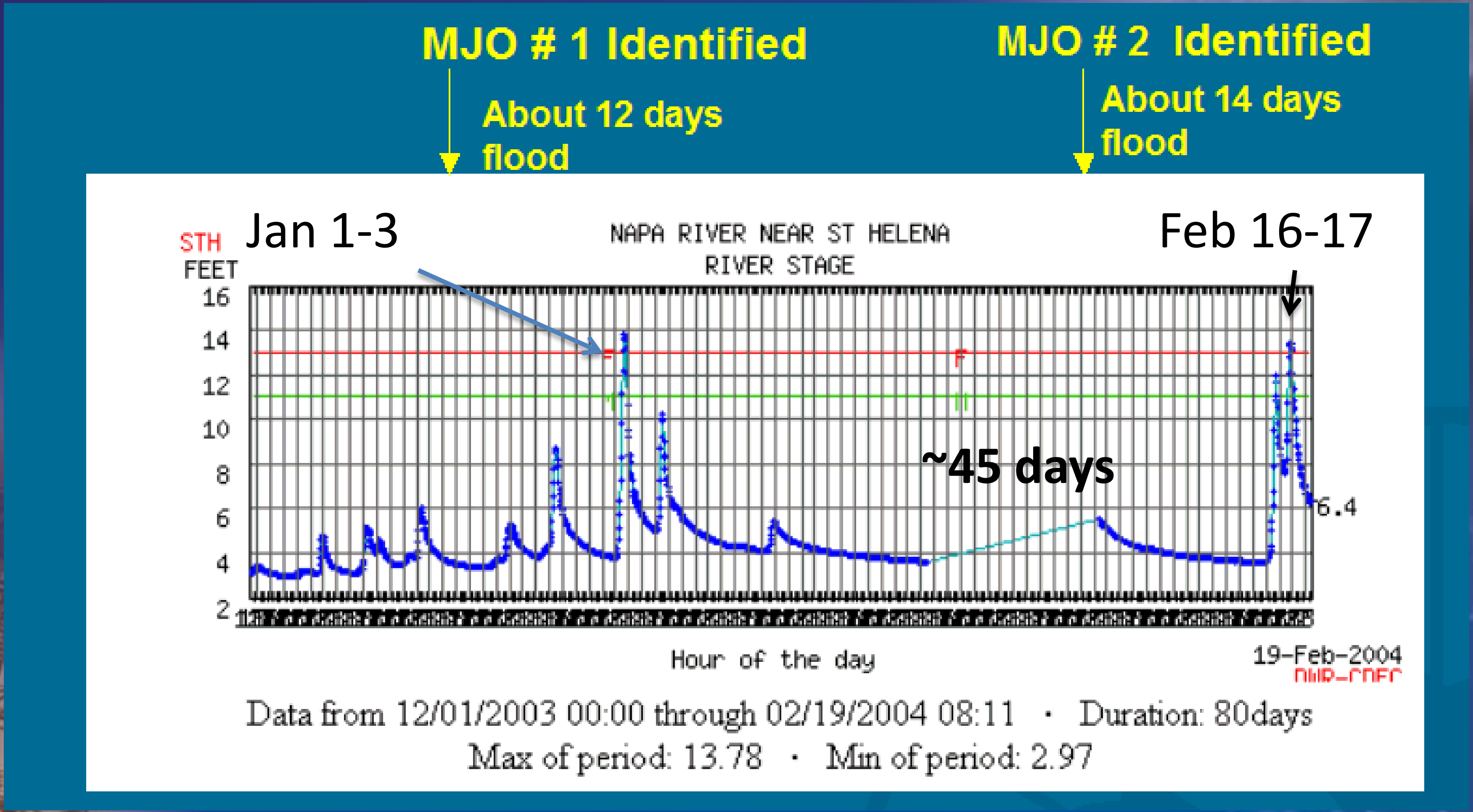
Flooding North Bay

Feb 16-17

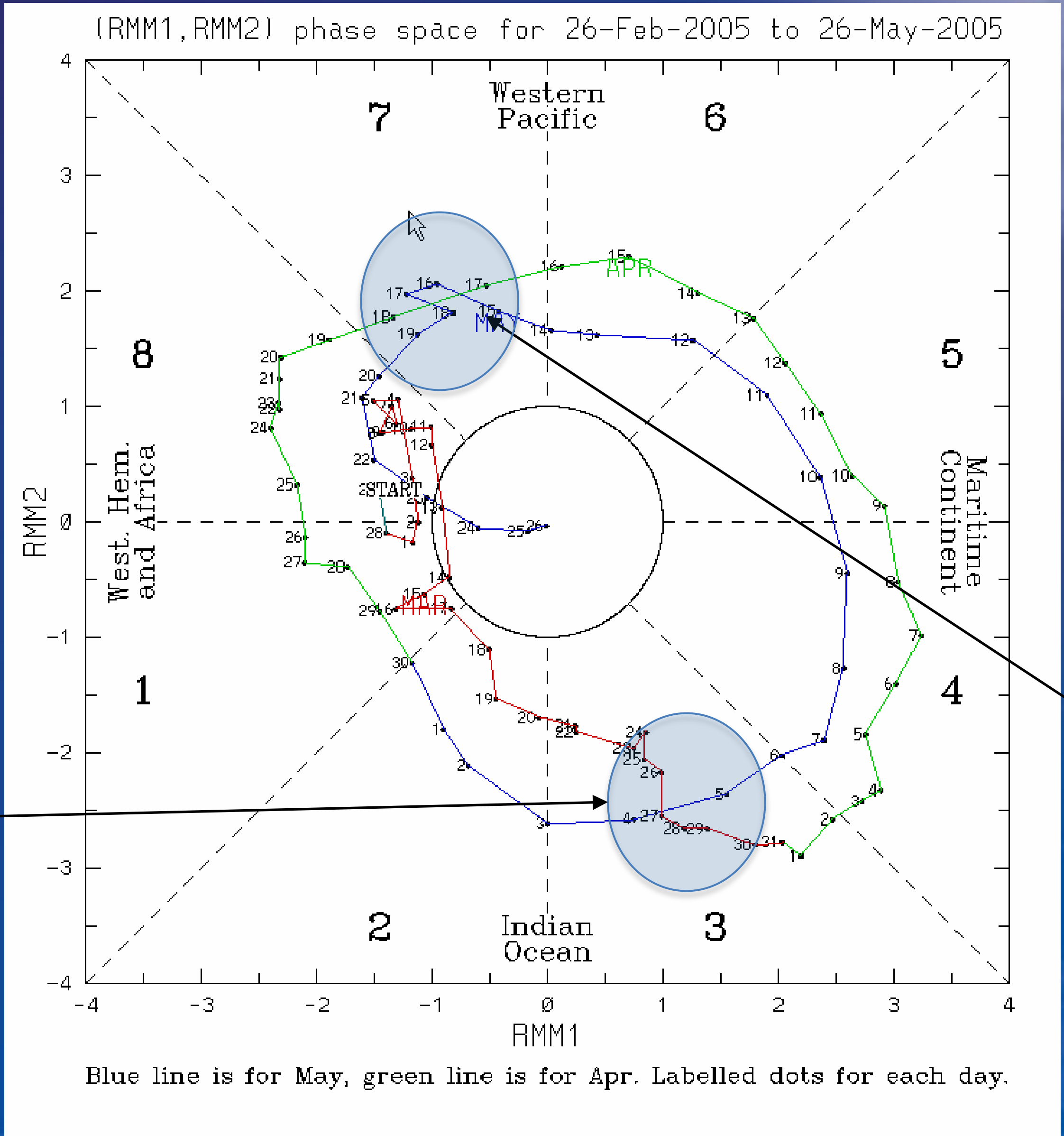
Flooding North Bay


16 Feb 2004 Daily IWV composite
CZD
IWV >2 cm
35N
15N
160W
130W

Flooding North Bay



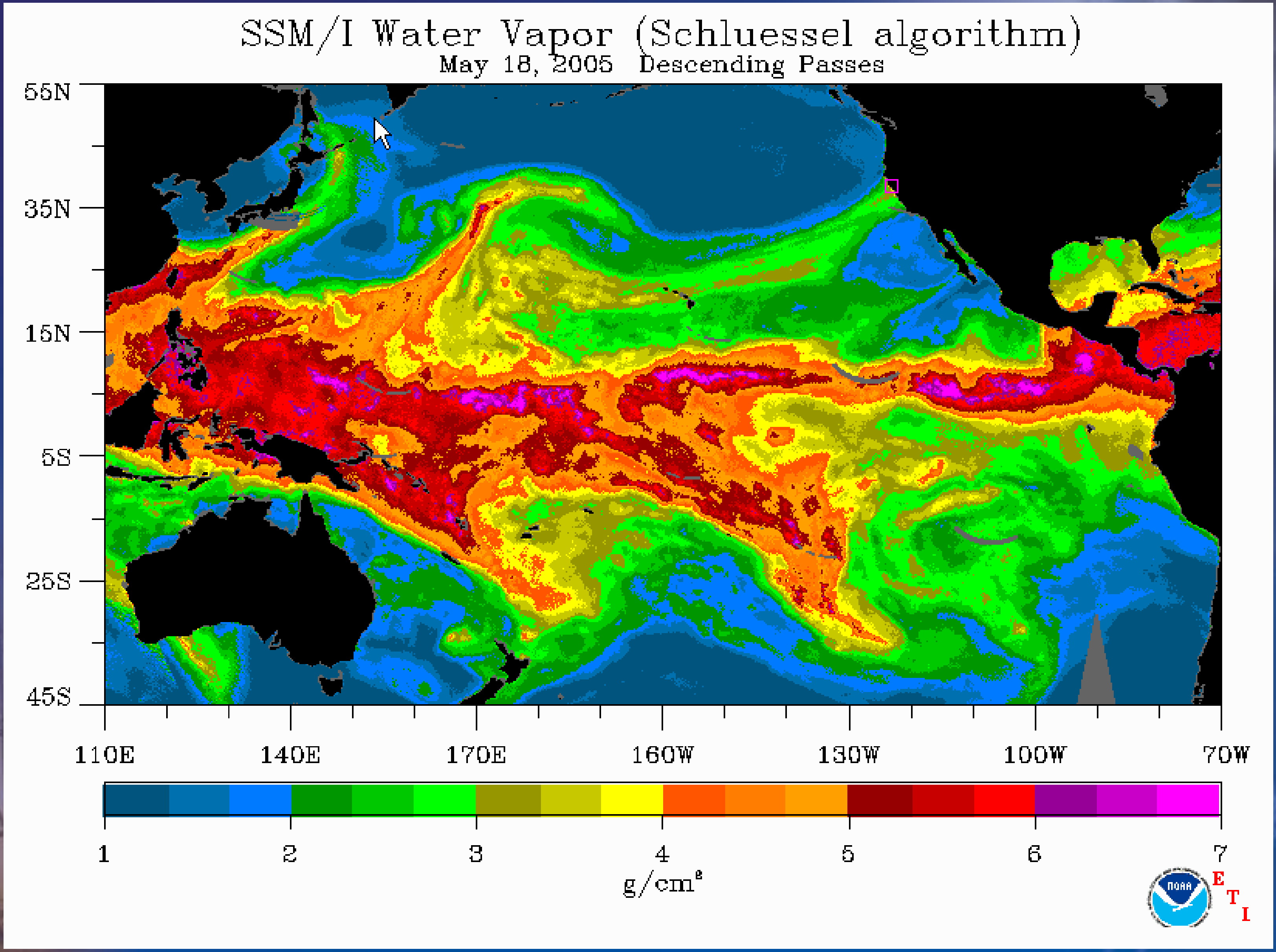
May Floods Yosemite Valley



Mar 2005 OR AR event

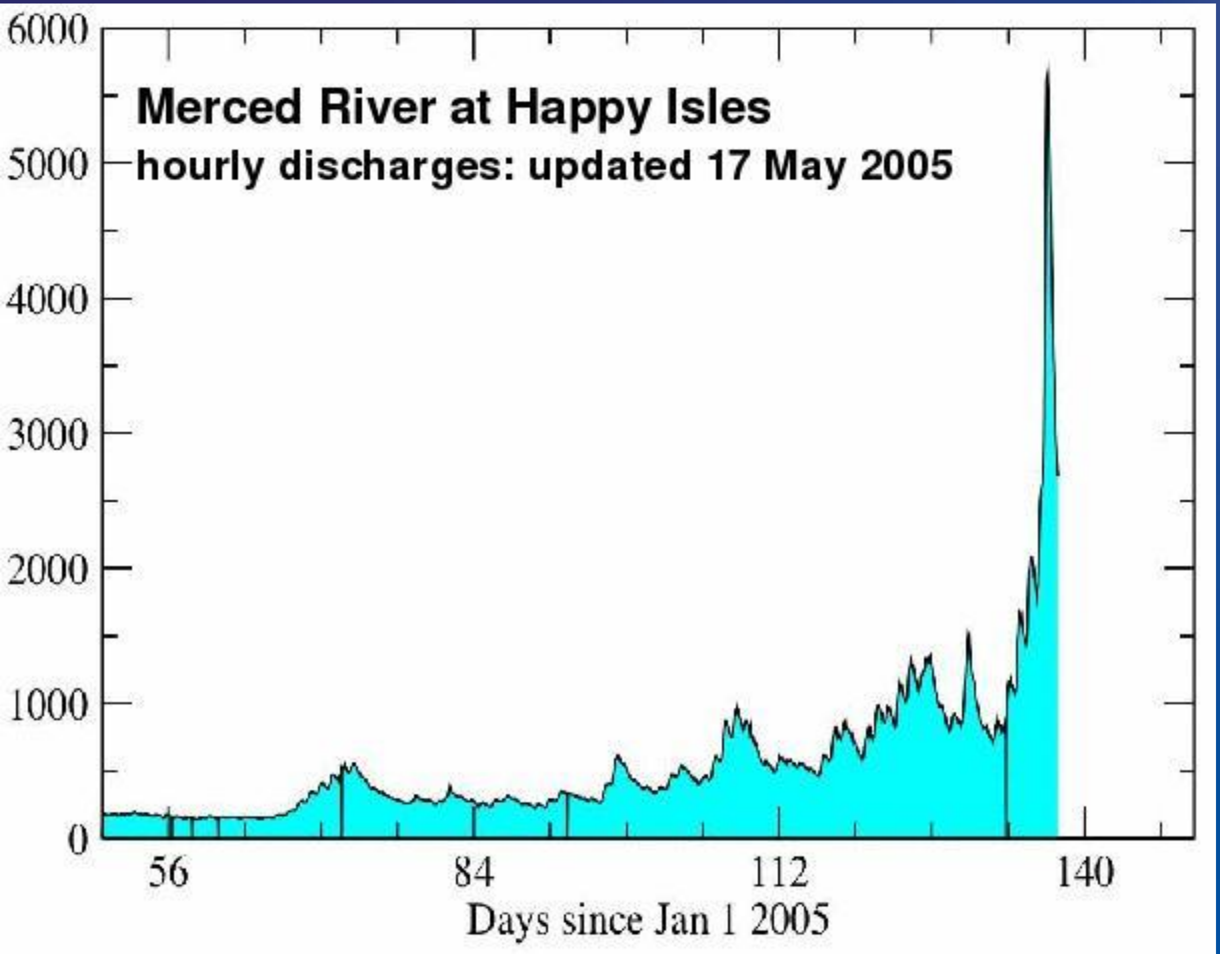
May 2005 event

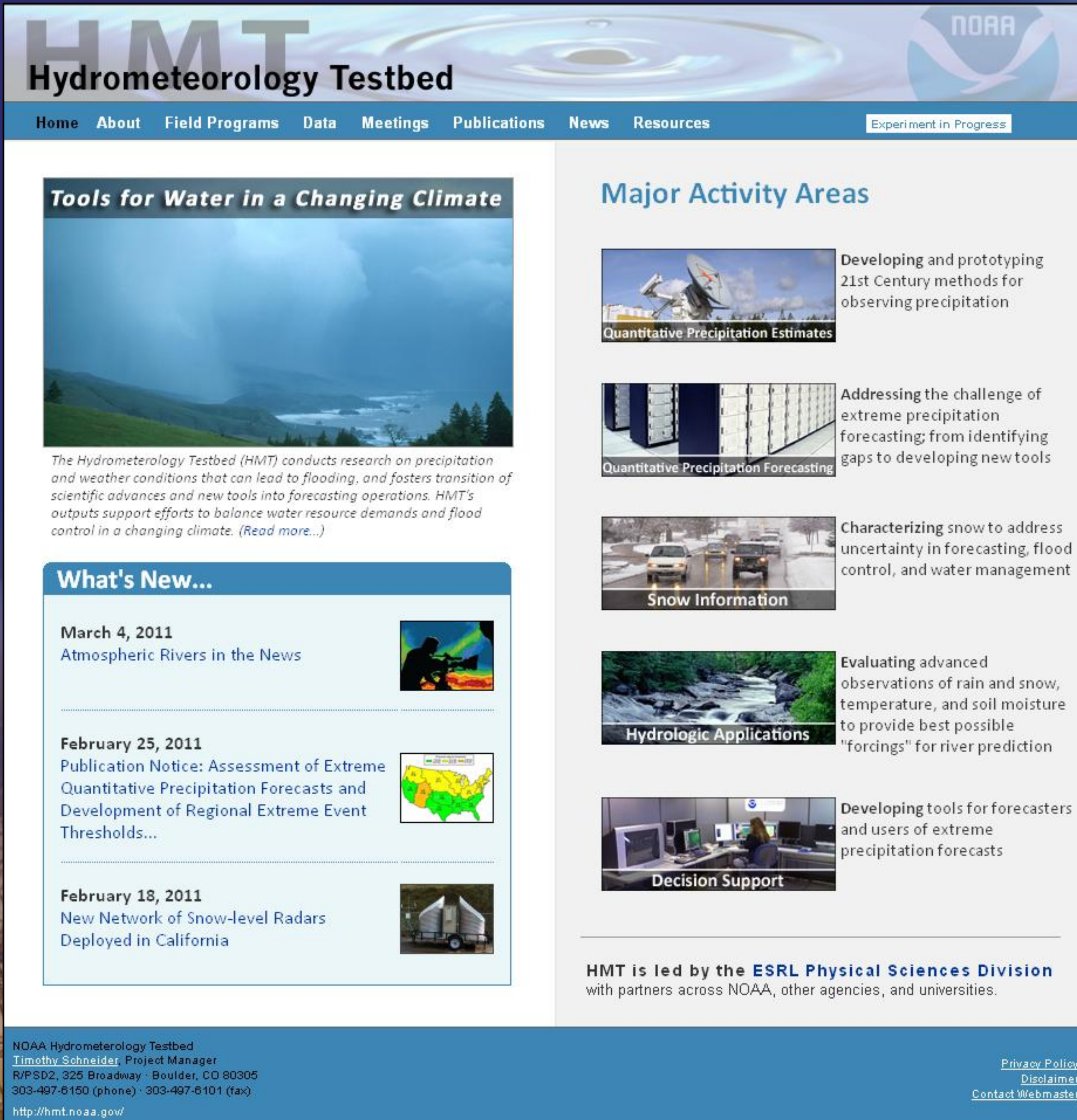
AR May 2005



SSM/I Water Vapor (Schluessel algorithm)
May 18, 2005 Descending Passes
55N
35N
15N
5S
25S
45S
110E
140E
170E
160W
130W
100W
70W
1
2
3
4
5
6
7
g/cm²
NOAA
E T I

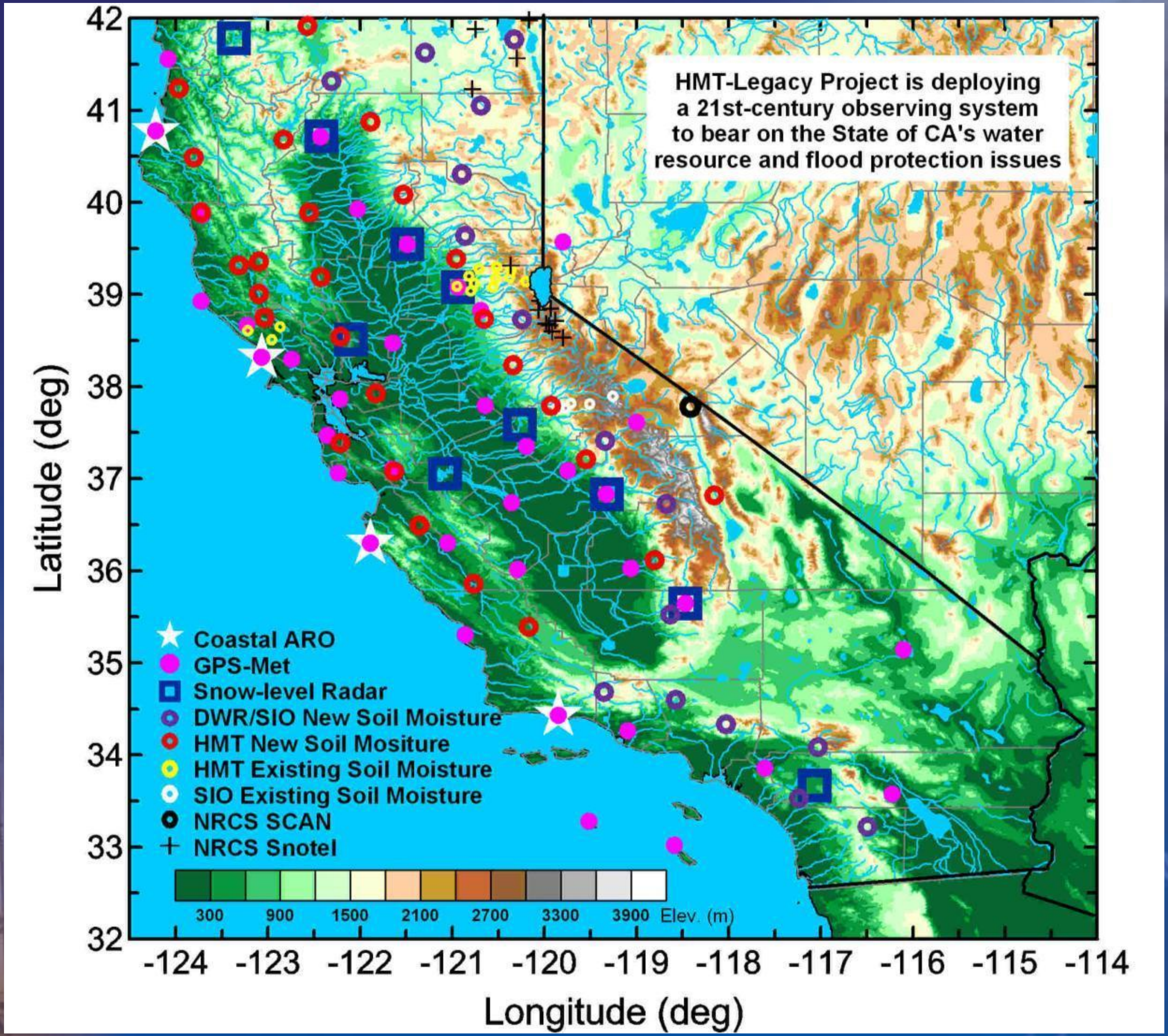
Yosemite Flooding



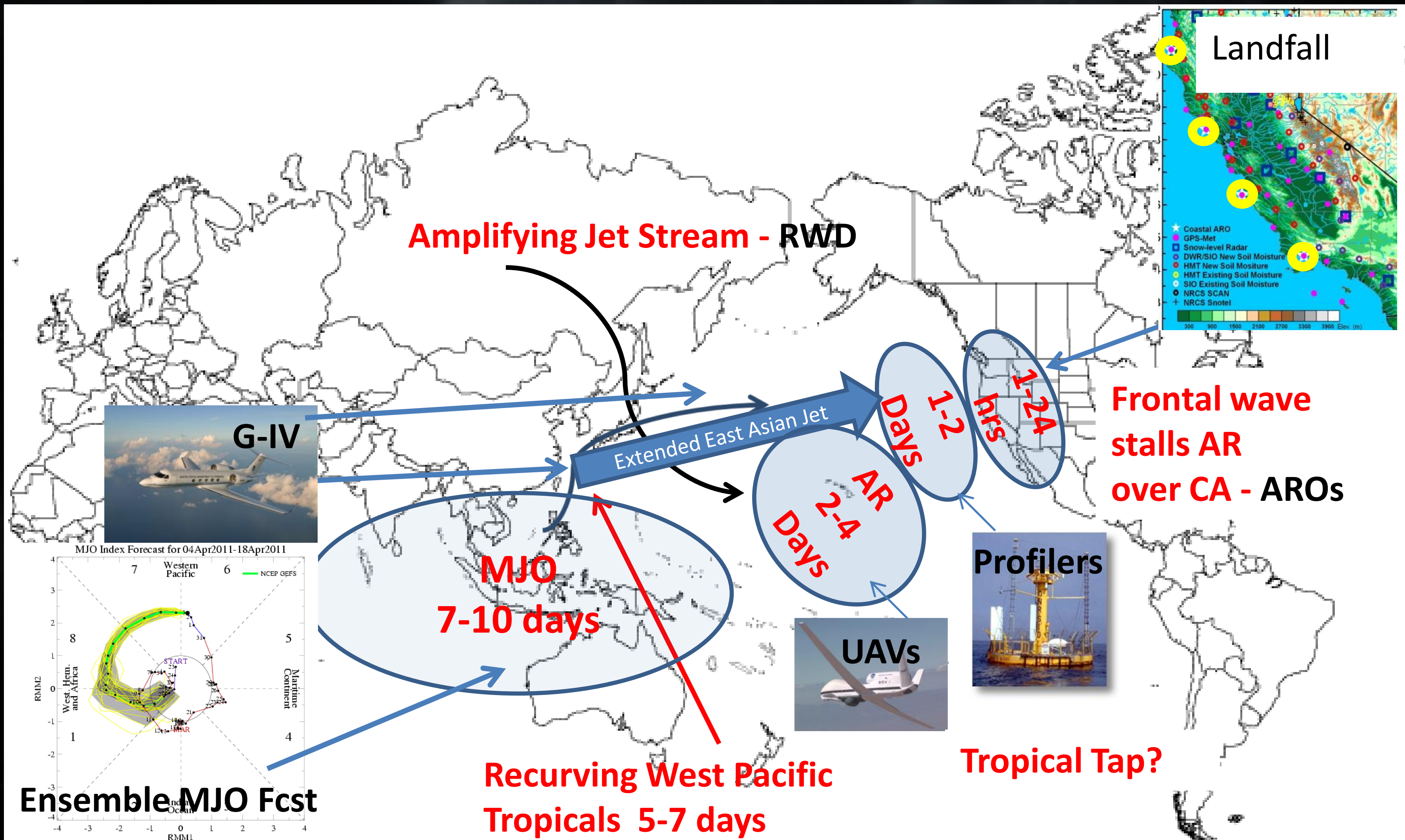


New Website launched

- ***Additional features***
- ***News items updated weekly***
- ***http://hmt.noaa.gov/***


HMT-Legacy Project is deploying
a 21st-century observing system
to bear on the State of CA's water
resource and flood protection issues
Coastal ARO
GPS-Met
Snow-level Radar
DWR/SIO New Soil Moisture
HMT New Soil Mositure
HMT Existing Soil Moisture
SIO Existing Soil Moisture
NRCS SCAN
NRCS Snotel
300 900 1500 2100 2700 3300 3900 Elev. (m)
Latitude (deg)
Longitude (deg)
42 41 40 39 38 37 36 35 34 33 32
-124 -123 -122 -121 -120 -119 -118 -117 -116 -115 -114

Conceptual Observation Network and Forecast Lead Time of AR Development/Impacts



NASA Global Hawk during Test flight for NOAA-led Winter Storm and Pacific Atmospheric River "WISPAR"

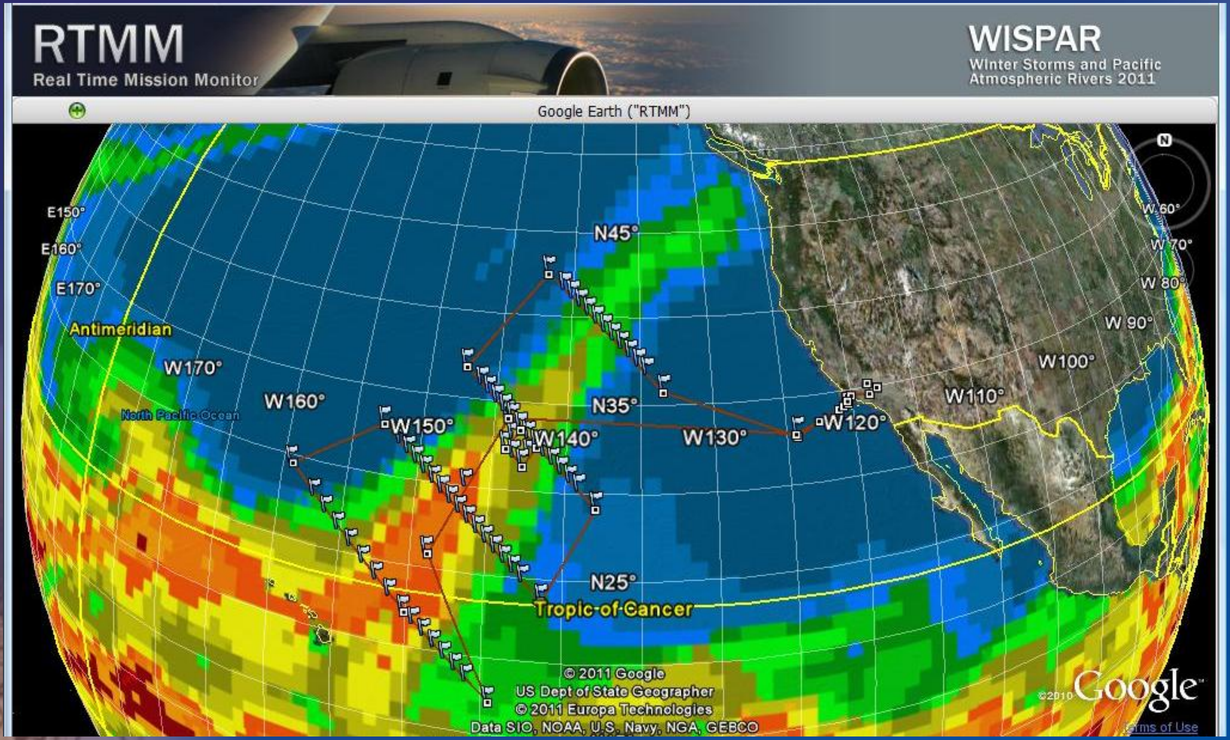
dropsonde demonstration project

January 2011

*Courtesy Dr. Gary Wick (WISPAR Mission Scientist)

Winter Storm and Pacific Atmospheric Rivers experiment “WISPAR”

Courtesy of Dr. Gary Wick (WISPAR Mission Scientist) and CMDR Phil Hall (NOAA/OMAO)



NOAA UAS Project conducted a technology demo using the NASA Global Hawk operated out of California and flown over the Pacific to sample atmospheric rivers using a new dropsonde system for the first time.

- GH can fly up to 28 hours
- Released up to 70 sondes in one mission
- 3 Flights were conducted between 11Feb – 12 Mar 2011

Figure. Global Hawk flight plan highlighting dropsonde locations over an atmospheric river during a 24 hour flight. The background field is simulated IWV from the NOAA GFS weather forecast model. The actual flight lasted 16 h and released 37 dropsondes prior to a computer fault. The two later WISPAR flights each completed their 24 hour missions with 70 dropsondes each, including some observation in two other atmospheric rivers.

Total moisture fluxes associated with 5 strong atmospheric rivers (ARs) calculated from the North American Regional Reanalysis (NARR)

AR Case	Flux value (kg s^{-1})	Annual Discharge Units
00 UTC 26 Jan 1998	3.67×10^{8}	18
00 UTC 17 Feb 2004	4.89×10^{8}	25
12 UTC 26 Mar 2005	5.23×10^{8}	26
12 UTC 06 Nov 2006	10.1×10^{8}	50
00 UTC 14 Oct 2009	9.62×10^{8}	48

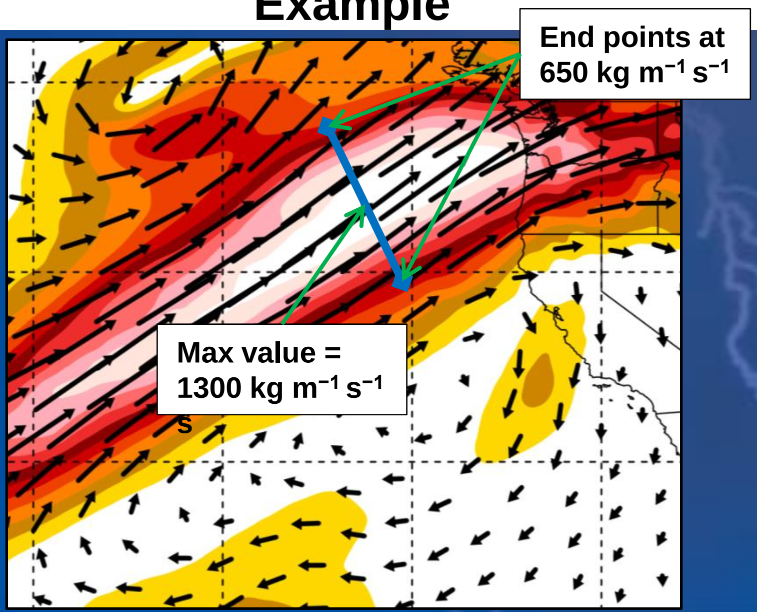
Method

- Horizontal transects taken normal to the AR through the maximum vertically integrated moisture flux (VIMF) value (i.e., core of the AR).
- Endpoints for the transects placed at 50% of the maximum VIMF value
- VIMF values taken at 100-km increments along transect
- Total moisture flux along transect computed using the formulation:

$$\sum_{i=1}^{n} (VIMF_i)\Delta L$$

where ΔL =100 km

Example



Key Forecast Challenges

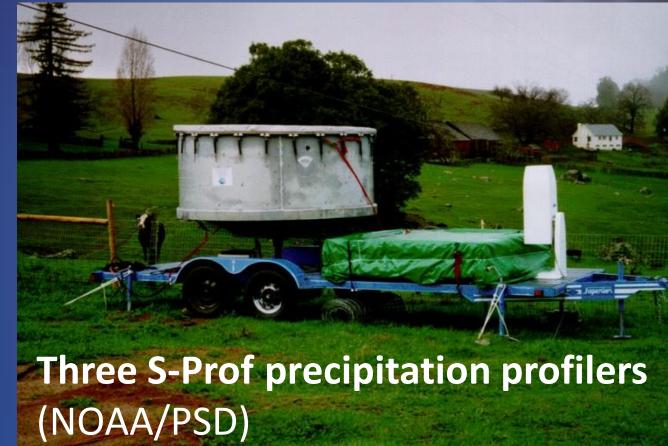
- Overarching science challenges
  - Weather Issues
    - Lead time and preparation for emergency managers key to saving lives and property
      - 7-10 day outlook desired for high impact hydrologic events
      - Forecast based reservoir operations possible outcome
    - Knowing when MJO will or will not provide forcing mechanism for AR's and how to determine impact locations.
      - Minimize false alarm rates
  - How well are ARs and the major precipitation events associated with them, represented in global and regional simulation and forecast models.
    - Timing, location and duration beyond 12-hrs poor.
  - QPF for land-falling ARs still very problematic
    - Models in short term seem to handle thermodynamics and kinematics within the AR OK but very poor in getting condensate to the ground.
    - Clouds much more efficient than models understand
      - Role of aerosols ?

Thank You

- For more information, please see:
  - http://hmt.noaa.gov/
  - http://www.esrl.noaa.gov/psd/atmrivers/
  - http://esrl.noaa.gov/psd/calwater/

Backup

CalWater & HMT-West Observing Systems Winter 2010/2011 in California

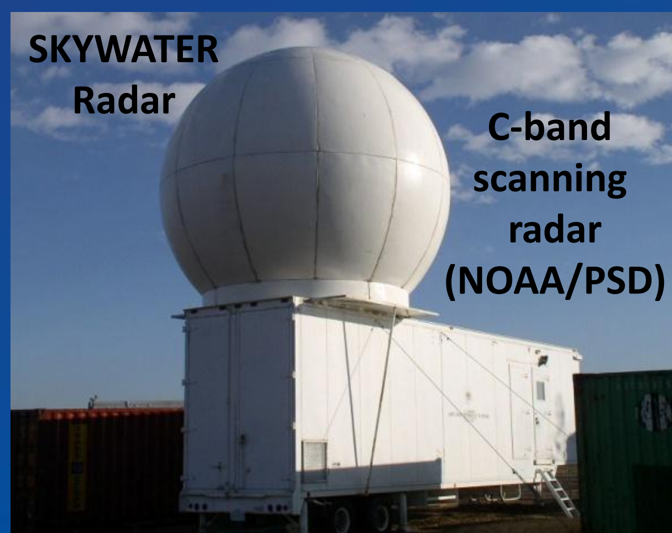


Three S-Prof precipitation profilers (NOAA/PSD)

G-1 Research aircraft for CalWater (DOE/PNNL)
1 Feb – 7 mar 2010

449 MHz wind profiler

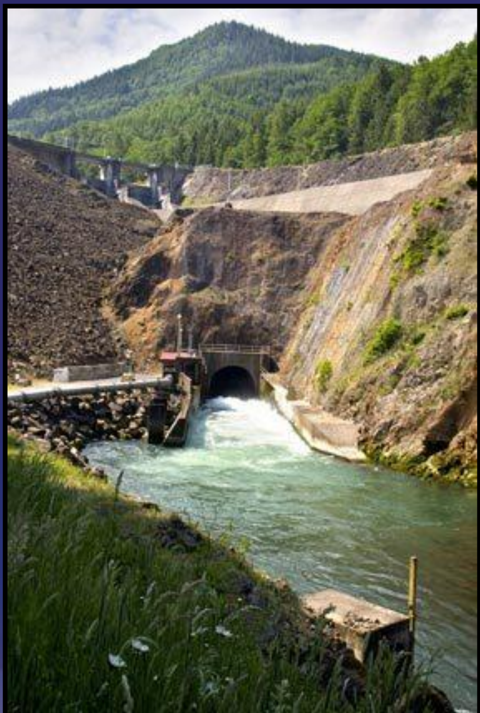
GPS IWV & balloon Sounding Systems

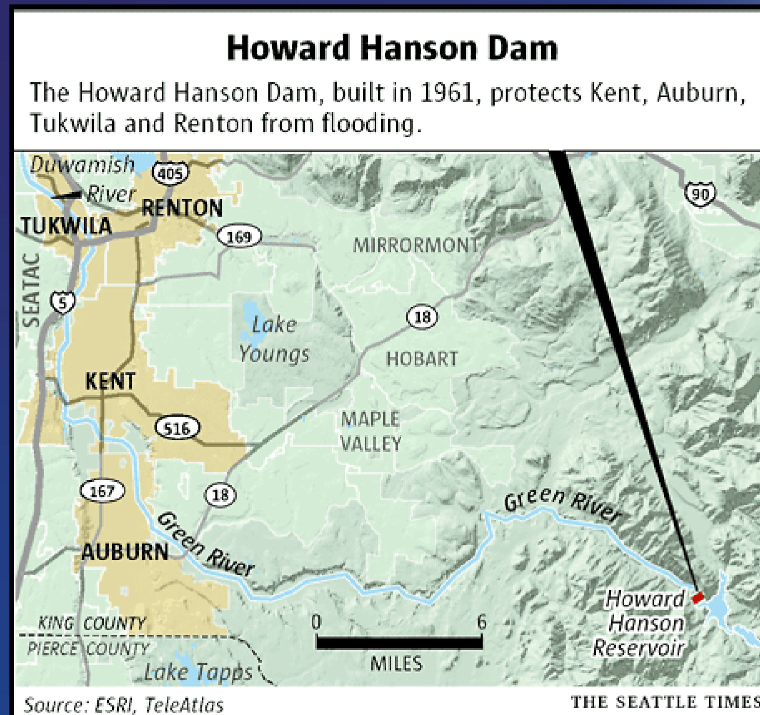


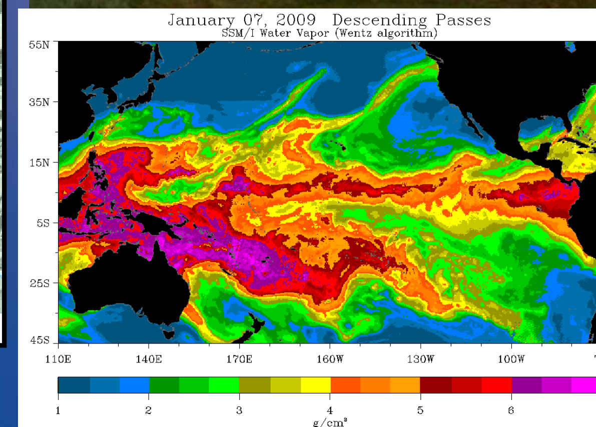
SKYWATER Radar

C-band scanning radar (NOAA/PSD)

Seven 915 MHz wind profilers (NOAA/PSD)

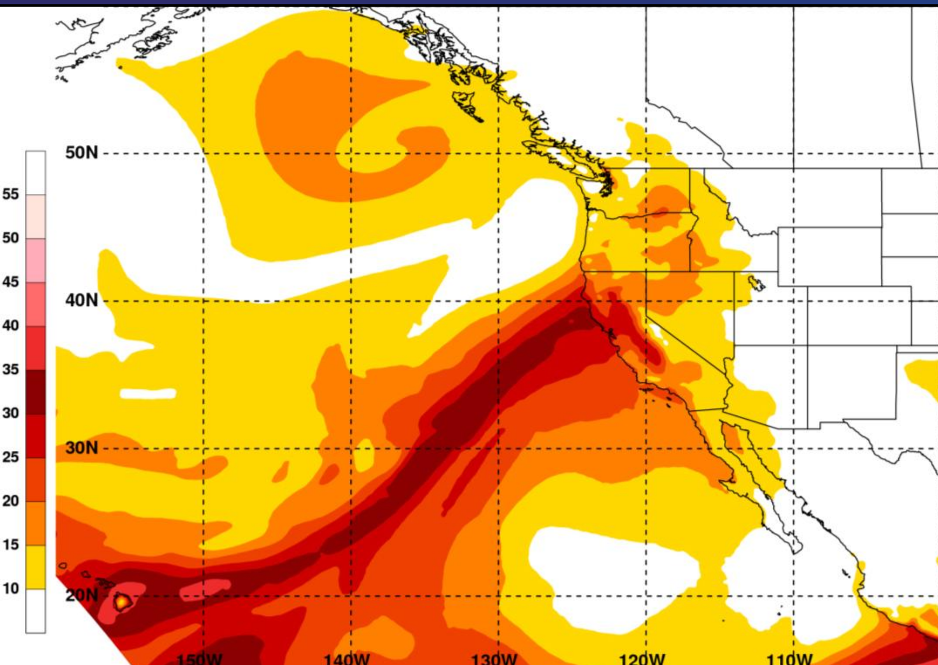




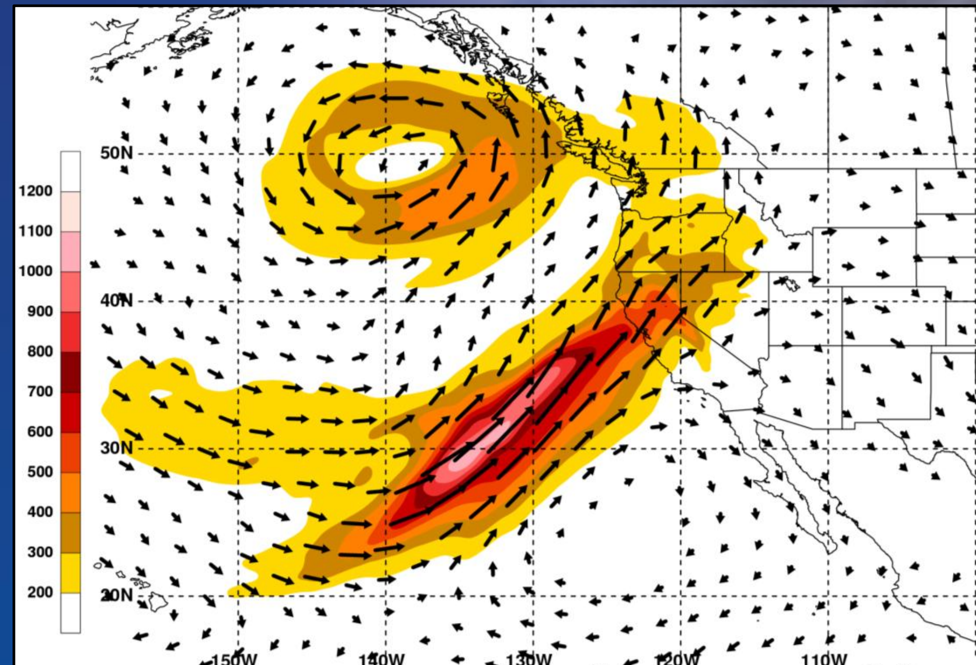


- Two NOAA Line Offices (NWS and OAR) and five NWS Office units (Western Region, NWRFC, Seattle WFO, HPC, and EMC) collaborated successfully to quickly organize, develop, and implement wide ranging and comprehensive mitigation efforts involved with managing the HHD flood control crisis
  - Also engaged US-ACE; University of Washington
- BAMS article describing these efforts has been submitted

0000 UTC 17 Feb 2004

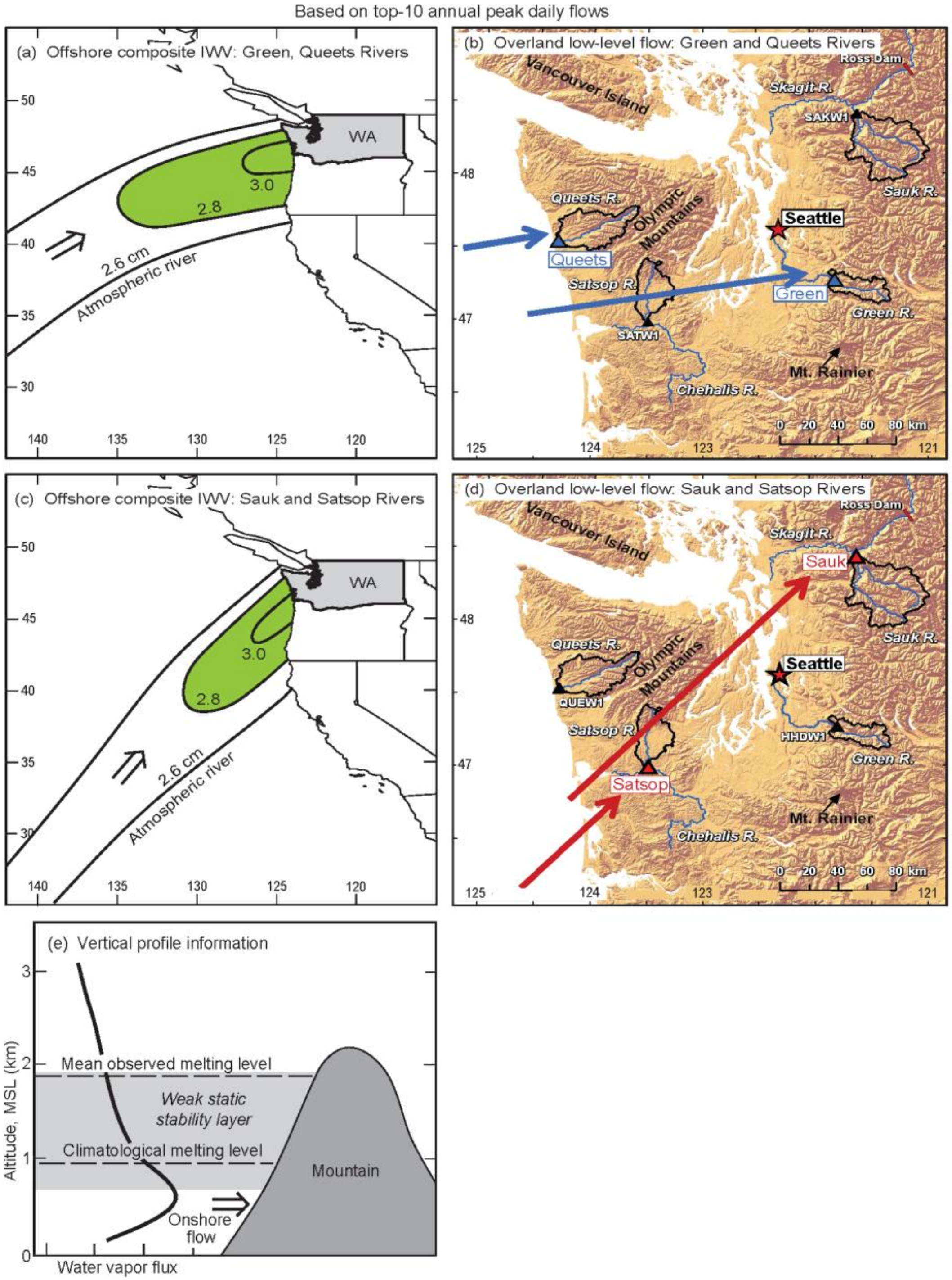


Total precipitable water (mm)



1000–200-hPa vertically integrated moisture flux (kg m^{-1} s^{-1})

Source: NARR



Flooding in Western Washington: The Connection to Atmospheric Rivers

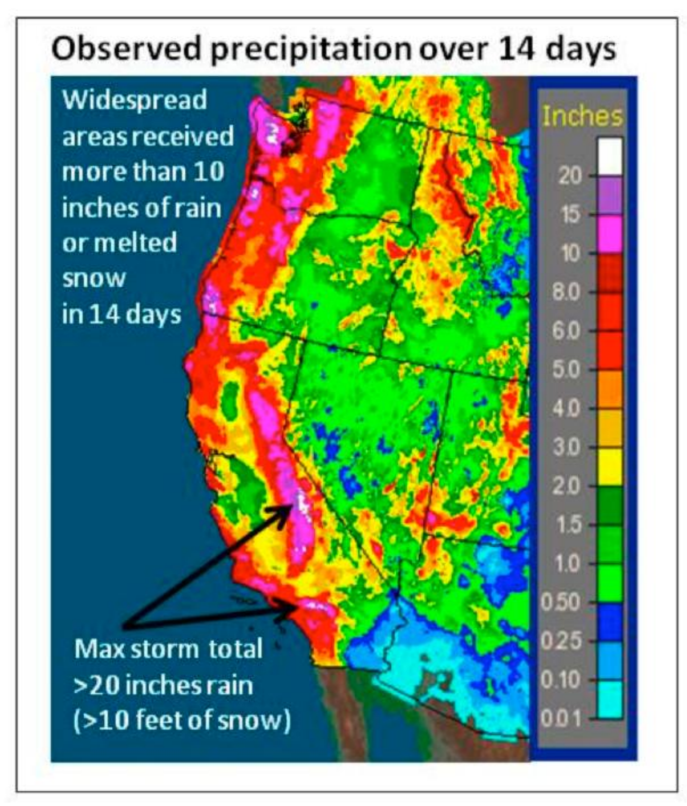
by Paul J. Neiman, Lawrence J. Schick, F. Martin Ralph, Mimi Hughes, and Gary A. Wick

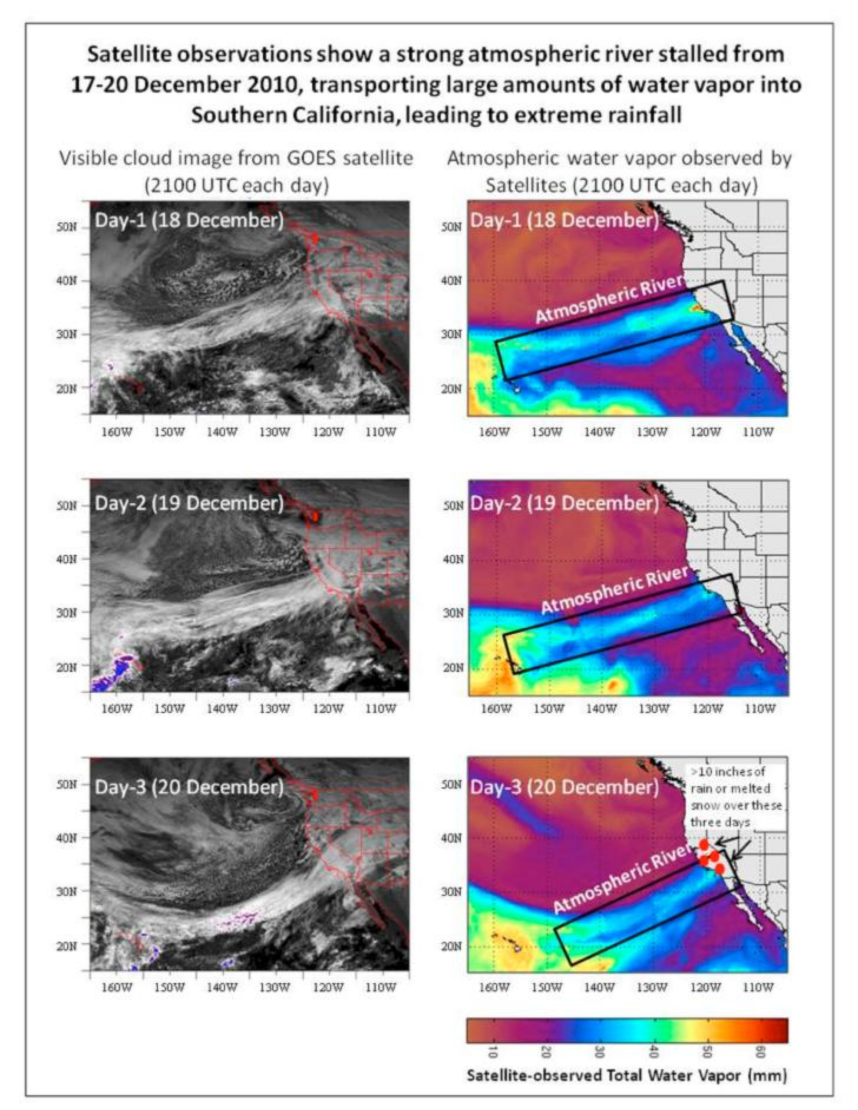
in review at *Monthly Weather Review*

Of 48 annual peak daily flows on 4 watersheds, 46 were associated with the land-fall of atmospheric river conditions.

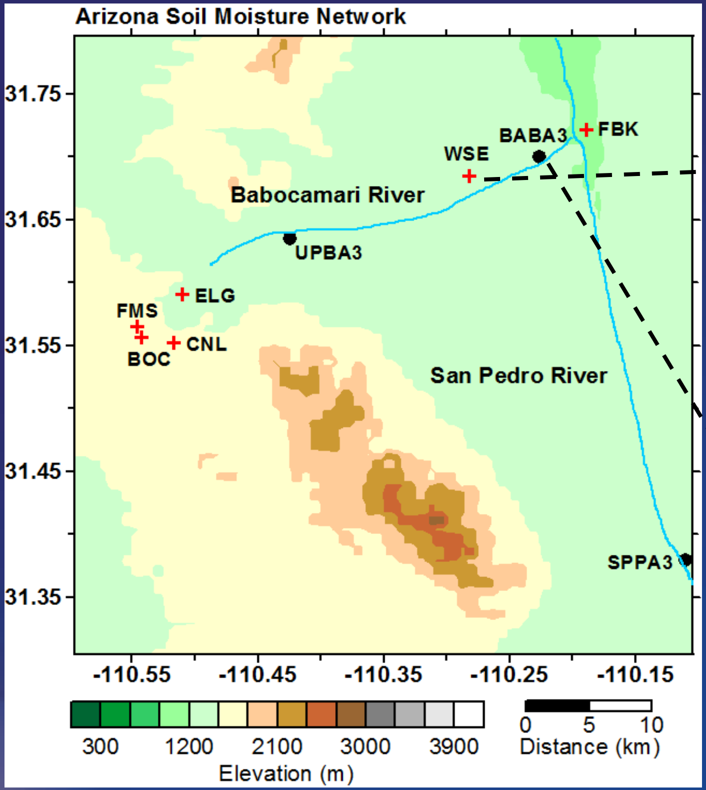
The orientation of an atmospheric river strongly influences which specific watersheds receive the most precipitation and highest stream flow.

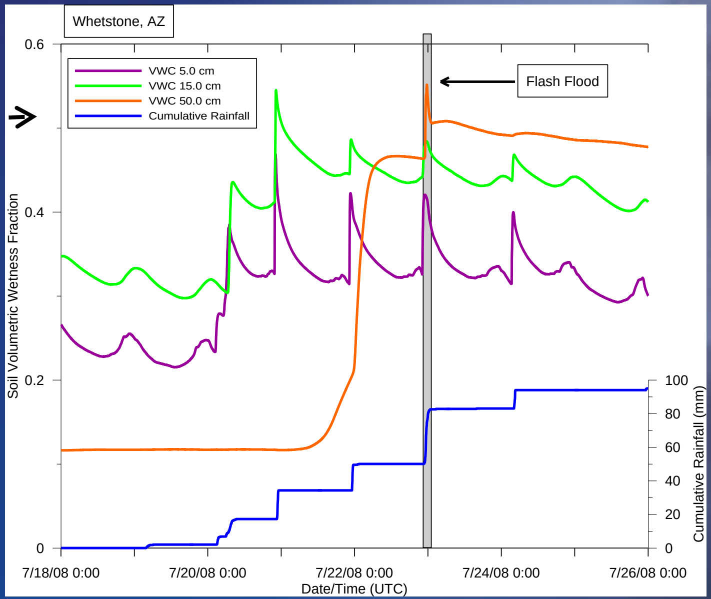
Series of strong ARs struck US West Coast in December 2010



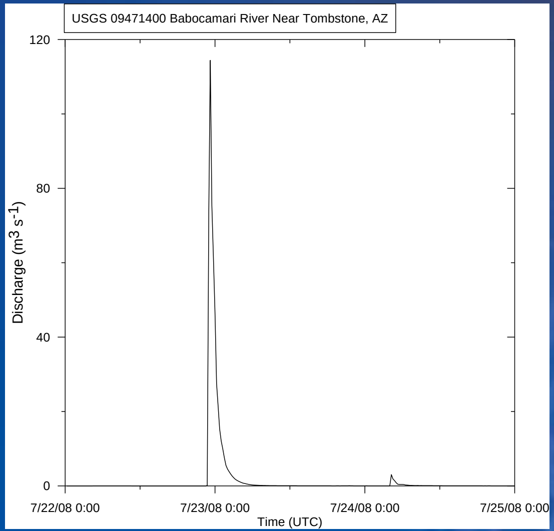


HMT techniques help forecasts after NWS training sessions: http://hmt.noaa.gov/news/2011/010711.html





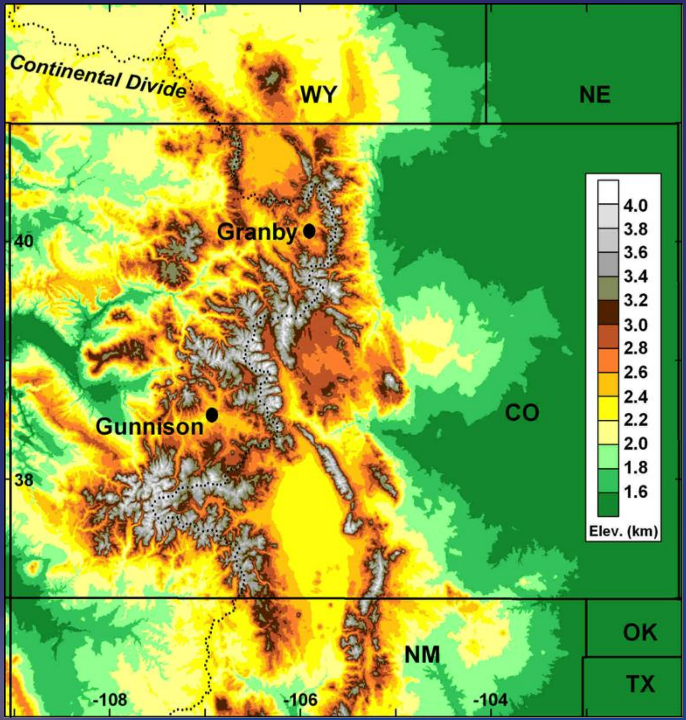
The monsoon rain event occurring on 00 UTC 22July finally brought the soil column to saturation.



Flooding coincided with a storm that dropped 30 mm of precipitation on top of saturated soil near 00 UTC 23 July.

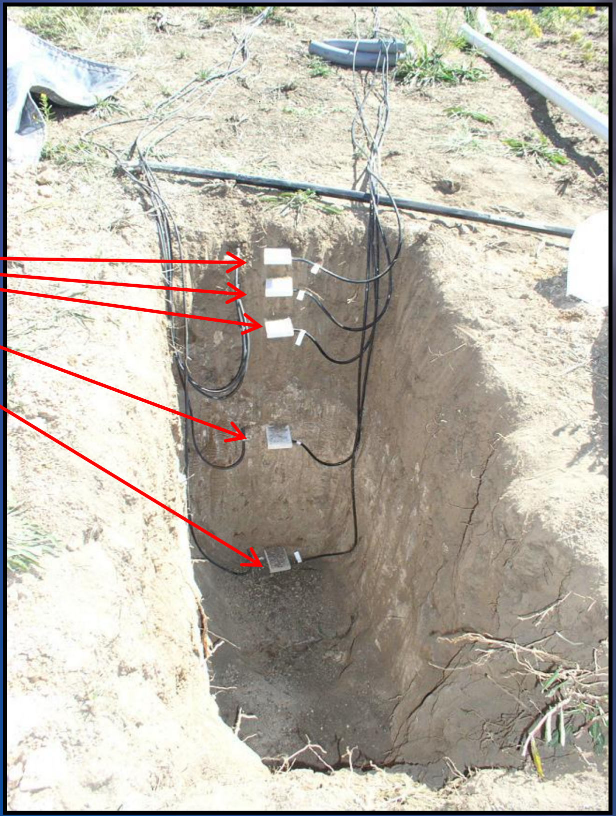
- Five stations operational since May 2008
- Fairbank (FBK) will be installed early February
- NWS Handbook 5 ID's established for all stations to allow data ingest into CBRFC
- R.J. Zamora, F.M. Ralph, E. Clark, T. Schneider, 2011: *The NOAA Hydrometeorology Testbed Soil Moisture Observing Networks Design, Instrumentation and Preliminary Results,* Journal of Atmospheric and Oceanic Technology (In Press)

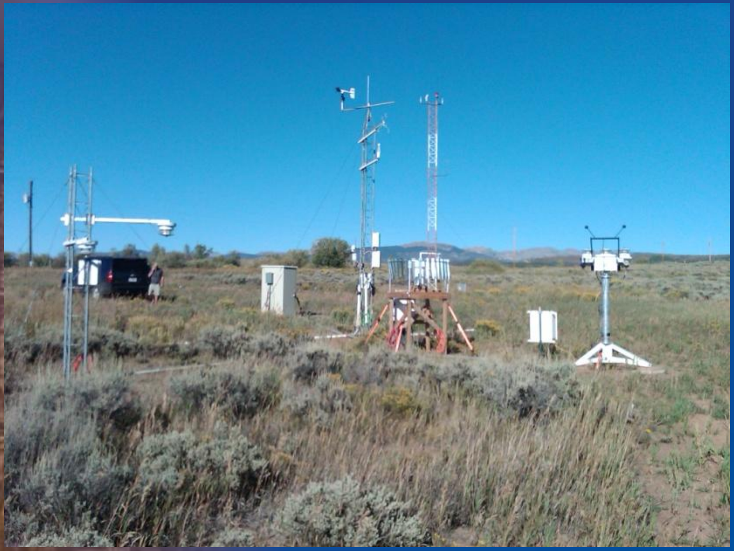
Upper Colorado River Basin: Granby, Colorado



Soil Moisture and Temperature Probes

Standard NRCS Observational Depths: 5, 10, 20, 50, 100 cm

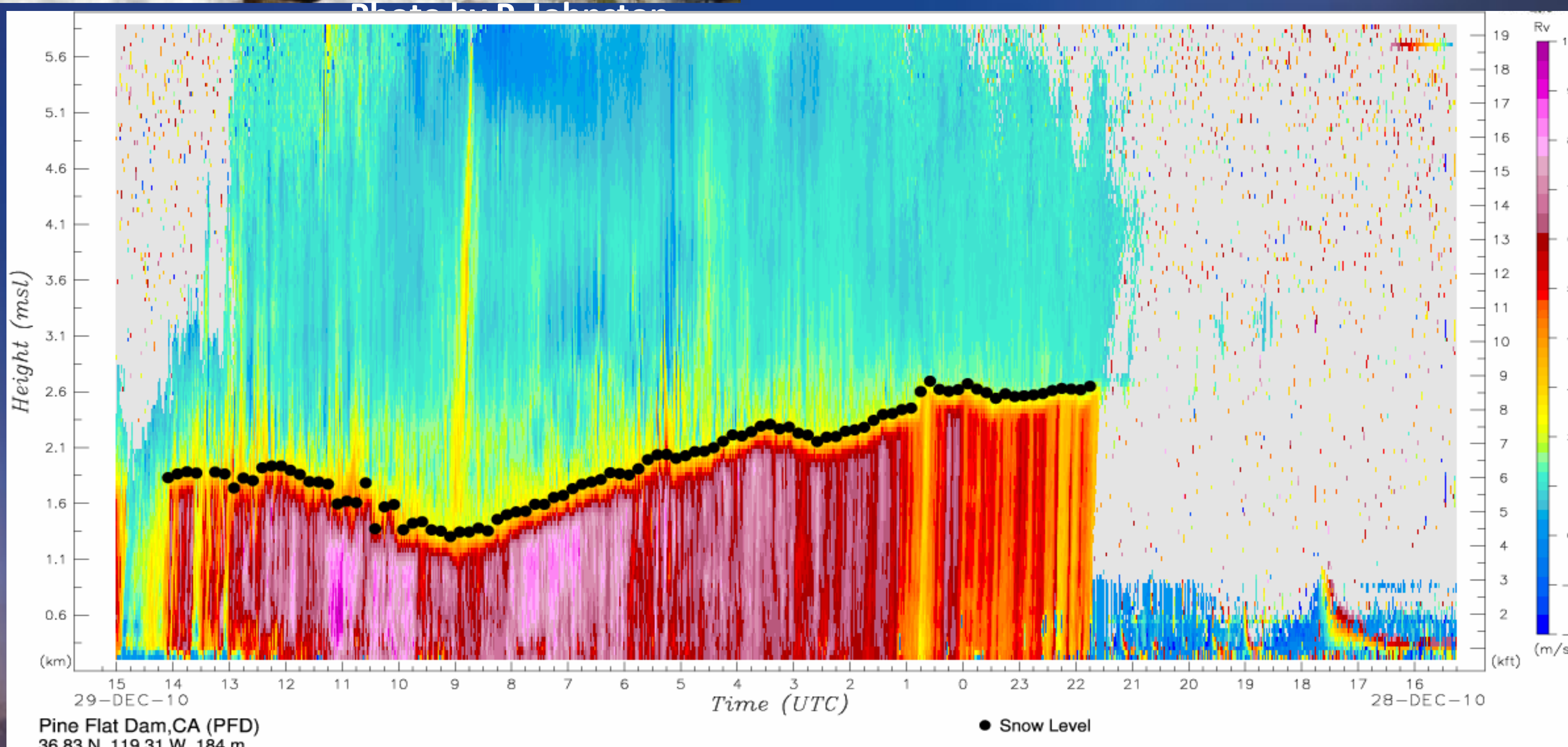




- Surface Sensible, Latent Heat and CO_2 Fluxes
- Ground Heat Flux
- Surface Temperature and RH
- Heated Rain Gage
- Snow Depth
- Diffuse and Direct Solar Irradiance (Up and Downwelling)
- Infrared Irradiance (Up and Downwelling)
- Dual 1.0 m soil pits spaced 20 m apart

New Snow-level Radars

- Provides snow-level altitude during precipitation events
- Utilizes proven FMCW technology to substantially lower cost
- **Uses the patented ESRL automated snow-level detection algorithm proven in nationwide field experiments**
- Less than 8’ diameter footprint
- Low-power ***(< 1watt!)*** requiring minimal infrastructure



Attendees of the 2010 HMT-West Workshop, held on 7-8 October 2010 at the Sonoma County Water Agency, Santa Rosa, CA

Kneeling, from left to right: Dave Reynolds (SFO/MIC), Mike Smith (NWS/OHD), Dave Kingsmill (PSD/CIRES), Paul Neiman (PSD), Art Henkel (CNRFC), Gary Estes

Standing, from left to right: Andy Edman (NWS/WRHQ), Warren Blier (SFO/SOO), Dan Kozlowski (CNRFC), Gary Carter (NWS/OHD), Mike Ekern (CNRFC), Tom Galarneau (PSD), Chengmin Hsu (PSD/CIRES), Woody Roberts (GSD), Isidora Jankov (GSD), Dave Myrick(NWS/SOO), Mel Nordquist (NWS/SOO), Brad Colman (SEA/MIC), Rob Cifelli (PSD/CIRA), Ed Tollerud (GSD), Marty Ralph (PSD), Lidia Cucurul (NCEP/EMC), Allen White (PSD), Bob Zamora (PSD), Ellen Sukovich (PSD/CIRES), Lynn Johnson (PSD), Larry Schick (ACE/SEA), Tara Jensen (NCAR/DTC), Mike Dettinger (USGS/Scripps), Jian Zhang (NSSL), Zoltan Toth (GSD), Brian Motta (NWS/COMET), Guido Franco (CEC/PIER), Tim Schneider (PSD), Rob Hartman (CNRFC/HIC), Martyn Clarke (NCAR)

Not shown: Grant Davis (SCWA), Chris Delaney (SCWA), Barb DeLuisi (PSD), Art Hinojosa (CA-DWR), Bill Neff (PSD, Director)

HMT-West Annual Meeting

Held at *Sonoma County Water Agency (SCWA)*

- Santa Rosa, CA
- October 2010

21st Century Observations, Numerical Models, Display Systems, and Decision Support Tools for Forcings of Extreme Precipitation and Flood Events in California

Part of the California Department of Water Resources Enhanced Flood Response and Emergency Preparedness (EFREP) Program

DWR, NOAA/ESRL, Scripps Institute of Oceanography

Photo by Stephan Dietrich

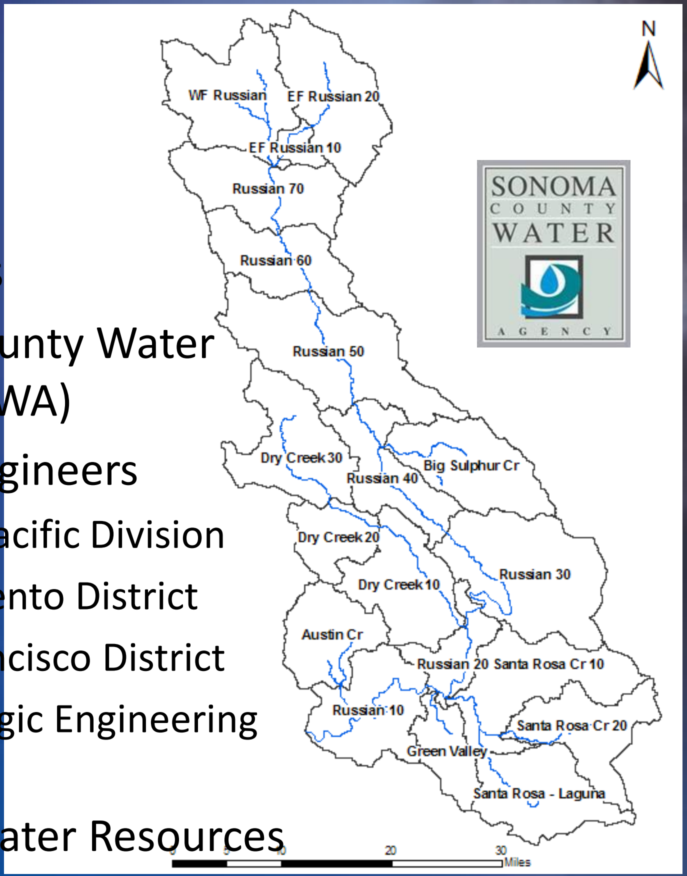
HHD Crisis: Specific Actions

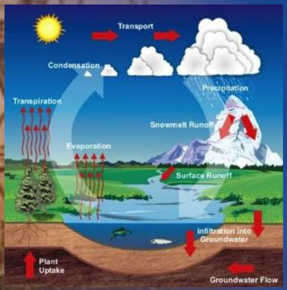
- Enhanced rain gauge network telecommunications (14 gage sites) were installed
- Atmospheric River Observatories were installed based on HMT results
- A specialized "S-PROF" precipitation profiling radar was deployed near the Dam
- A specialized workstation "ALPS" was installed at SEA WFO to view the new data
- HMT's high-resolution weather model simulations were extended north to include the region
- Forecaster training was conducted on new concepts and tools from HMT
- Critical precipitation thresholds for HHD were developed
- Alert Level Forecasts Developed
- Hydrology section in Area Forecast Discussion was implemented
- Customized precipitation guidance products were developed (10 day QPF/PQPF Forecasts)
- National Weather Service Web Site was created
- Dedicated Chat Room: to handle coordination was established
- New Web Site for HHD was developed at the NWRFC
- Instituted AHPSMobile – Hydrographs/Info on Cell Phone
- Flood Potential Outlook on NWS WAWA Page

RUSSIAN RIVER

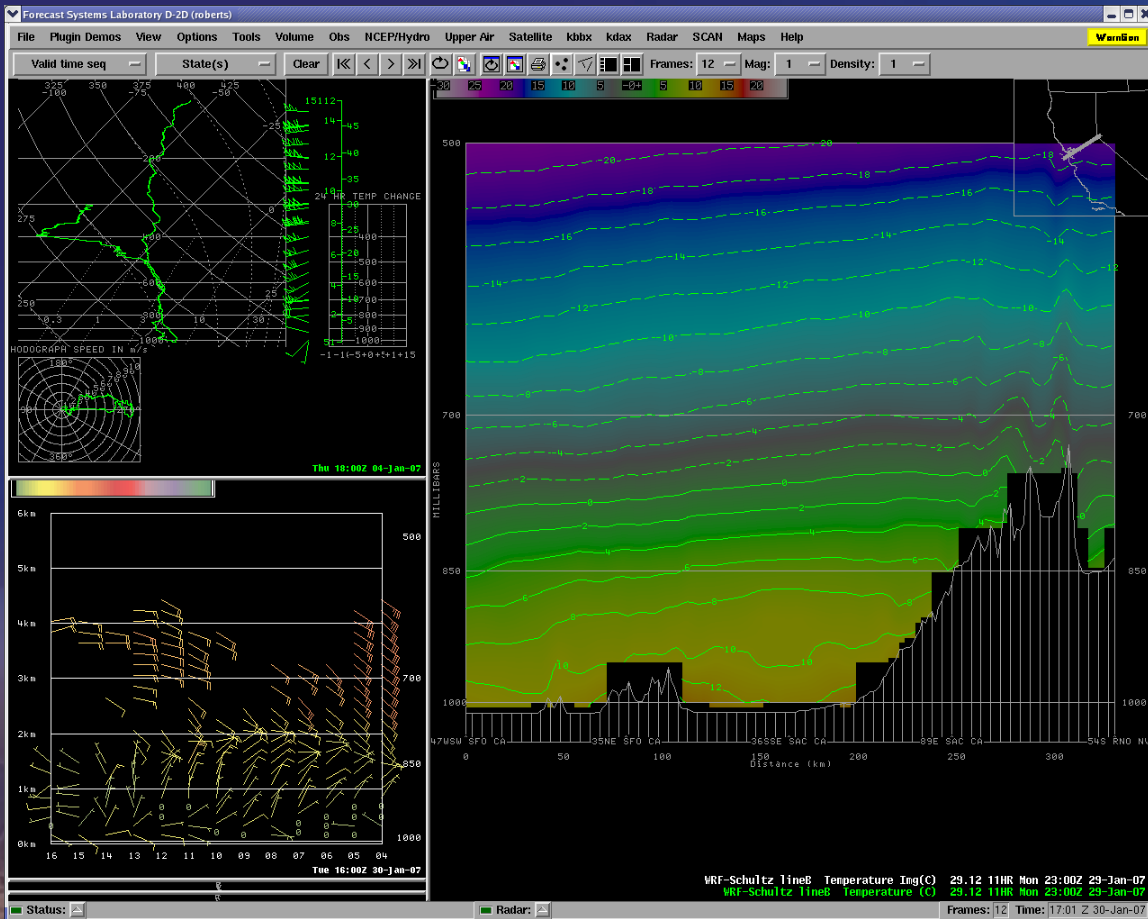
- Water Issues
  - Flooding
  - Endangered fisheries
  - Water supply
- IWRSS Pilot
  - October Workshop at Santa Rosa
  - Steering Committee
    - NOAA, USACE, USGS, SCWA
  - Goals
    - Integrate information
    - Increase accuracy and timeliness
    - Summit-to-sea info and forecasts

- Collaborations
  - Sonoma County Water Agency (SCWA)
  - Corps of Engineers
    - South Pacific Division
    - Sacramento District
    - San Francisco District
    - Hydrologic Engineering Center
  - CA Dept. Water Resources
  - USGS
  - NOAA
    - HMT
    - OHD
    - OAR
    - CNRFC
    - WFO – Monterrey
    - Nat’l Marine Fisheries





ALPS - Advanced LINUX Workstations



- Remote access to special HMT datasets in field offices along with regular product streams
  - Local HMT ensemble forecast model
  - MADIS: surface data, profilers, special RAOBs

- Workstations successfully deployed at six offices (CNRFC; Seattle, Sacramento Eureka, Monterey, and Reno WFOs) during the last two field seasons.

Observation Network and Forecast Lead Time of AR Development/Impacts