# The role of atmospheric rivers in generating extreme precipitation via orographic processes

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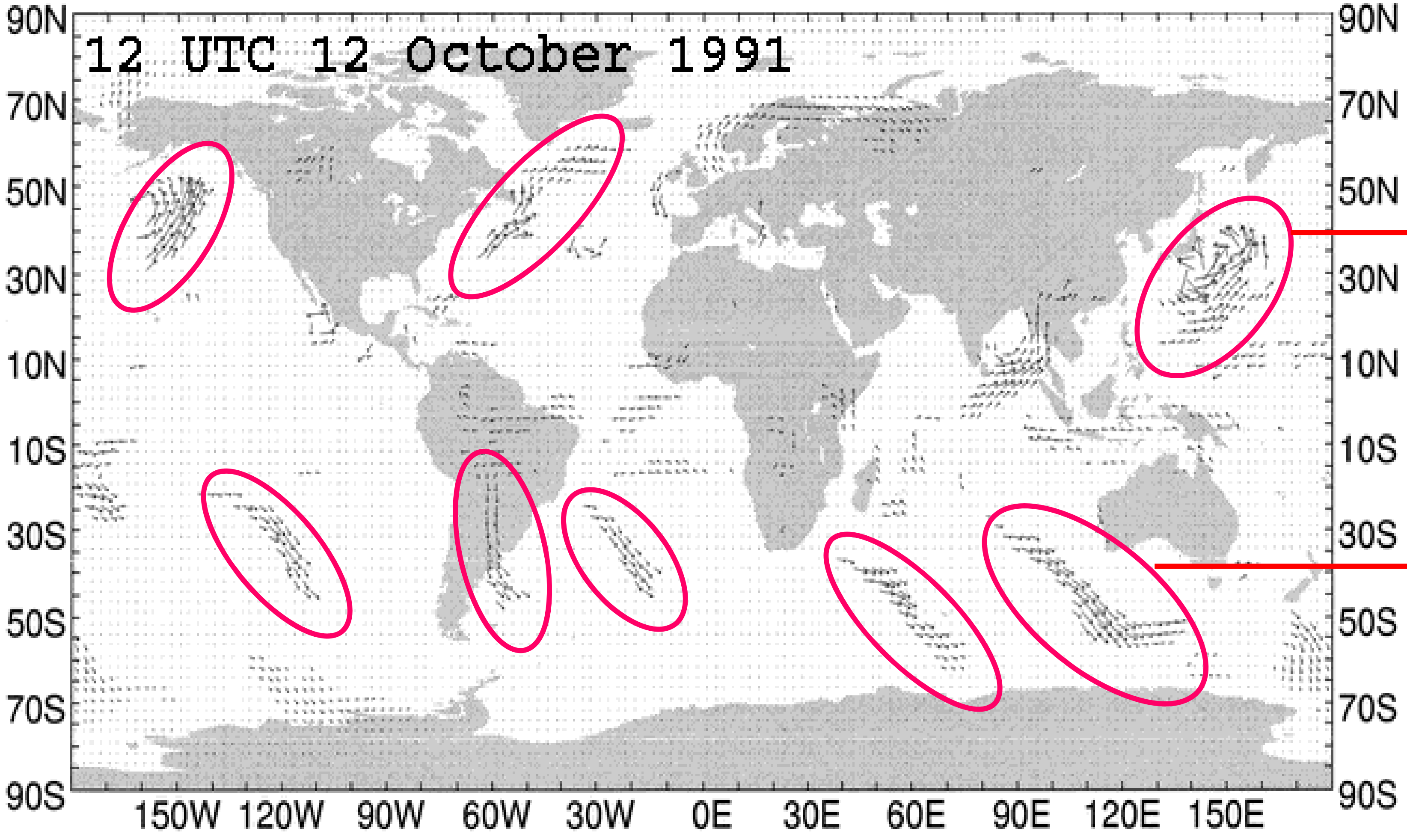
# Building Blocks

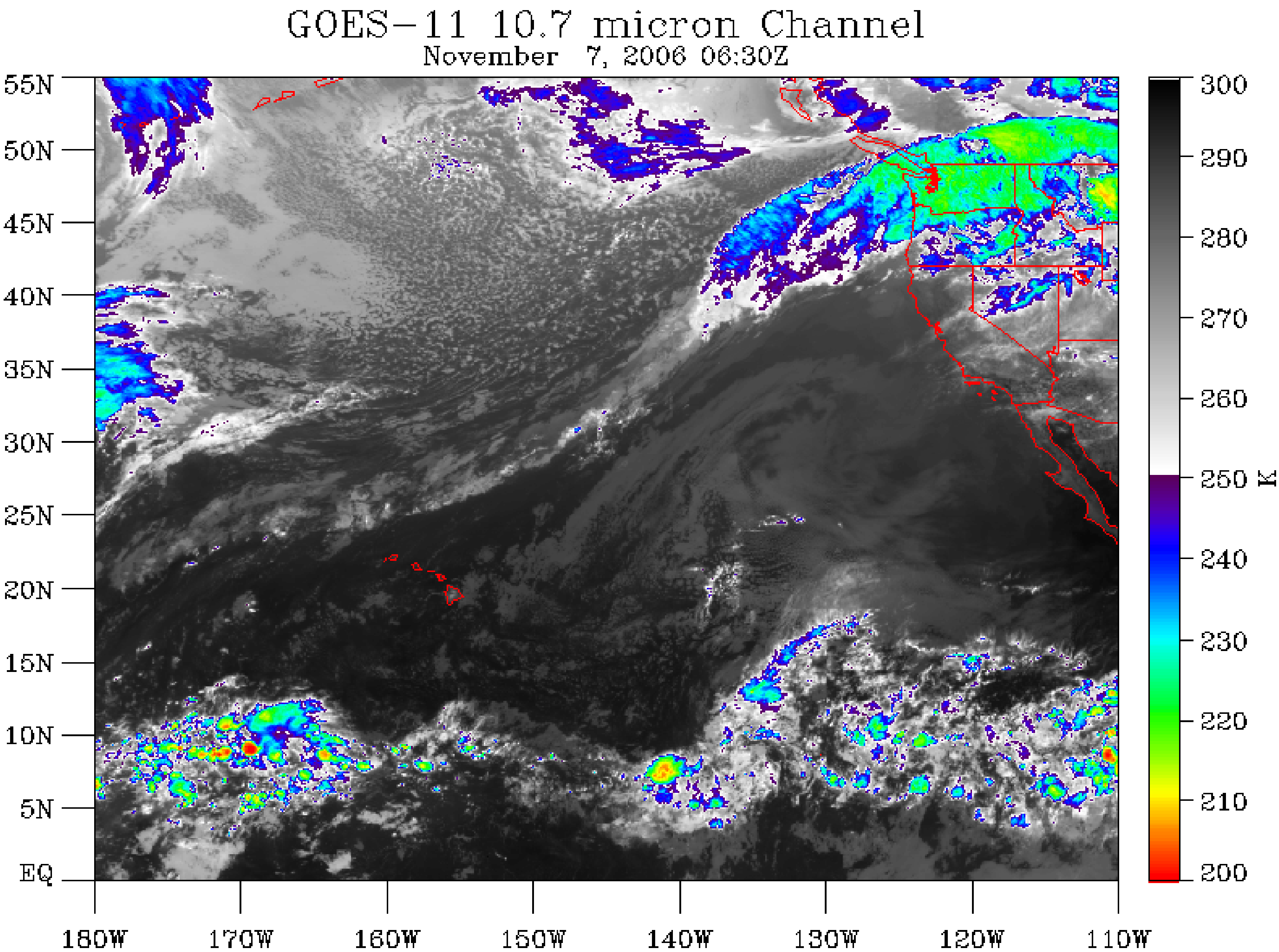
<u>Key developments that made possible the findings presented here:</u>

- Zhu and Newell defined “atmospheric rivers” (publ. 1998)
- Expanded SSM/I satellite data readily available (1998)
- CALJET/PACJET field experiments conducted (1998, 2001)
- NCEP/NCAR reanalysis data available on line (2000)
- Atmospheric River Observatory created (2001)
- NOAA’s Hydrometeorology Testbed pilot study near Russian River (2003, 2004)
- Offshore structure diagnosed using aircraft & satellite data (publ 2004, 2005)
- Neiman et al. catalogue of atmospheric river events from 1997-2005 (publ 2008)

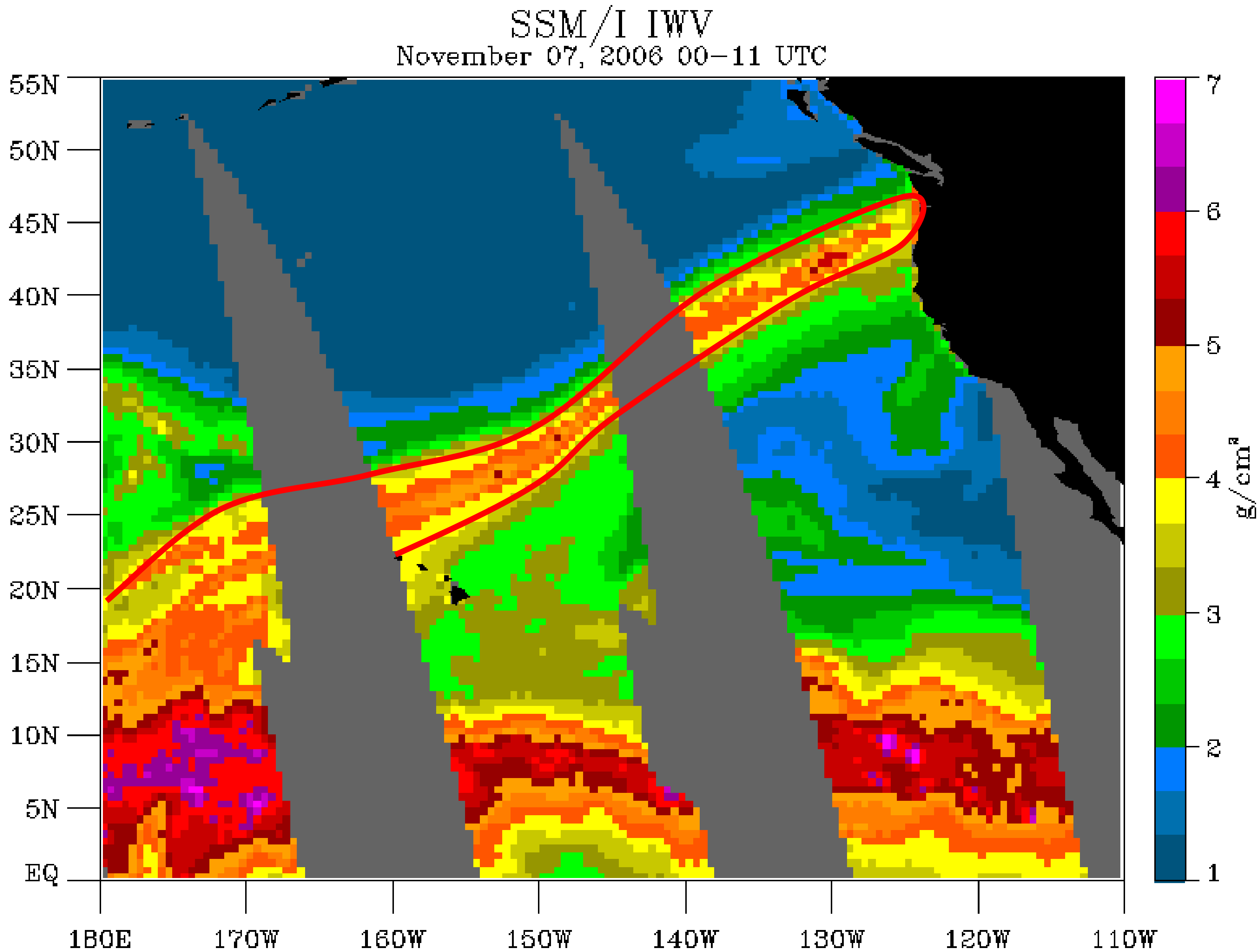
Zhu & Newell (1998) concluded in a 3-year ECMWF model diagnostic study:

1) 95% of meridional water vapor flux occurs in narrow plumes in <10% of zonal circumference.
2) There are typically 3-5 of these narrow plumes within a hemisphere at any one moment.
3) They coined the term "atmospheric river" (AR) to reflect the narrow character of plumes.
4) ARs constitute the moisture component of an extratropical cyclone's warm conveyor belt.
5) ARs are very important from a global water cycle perspective.





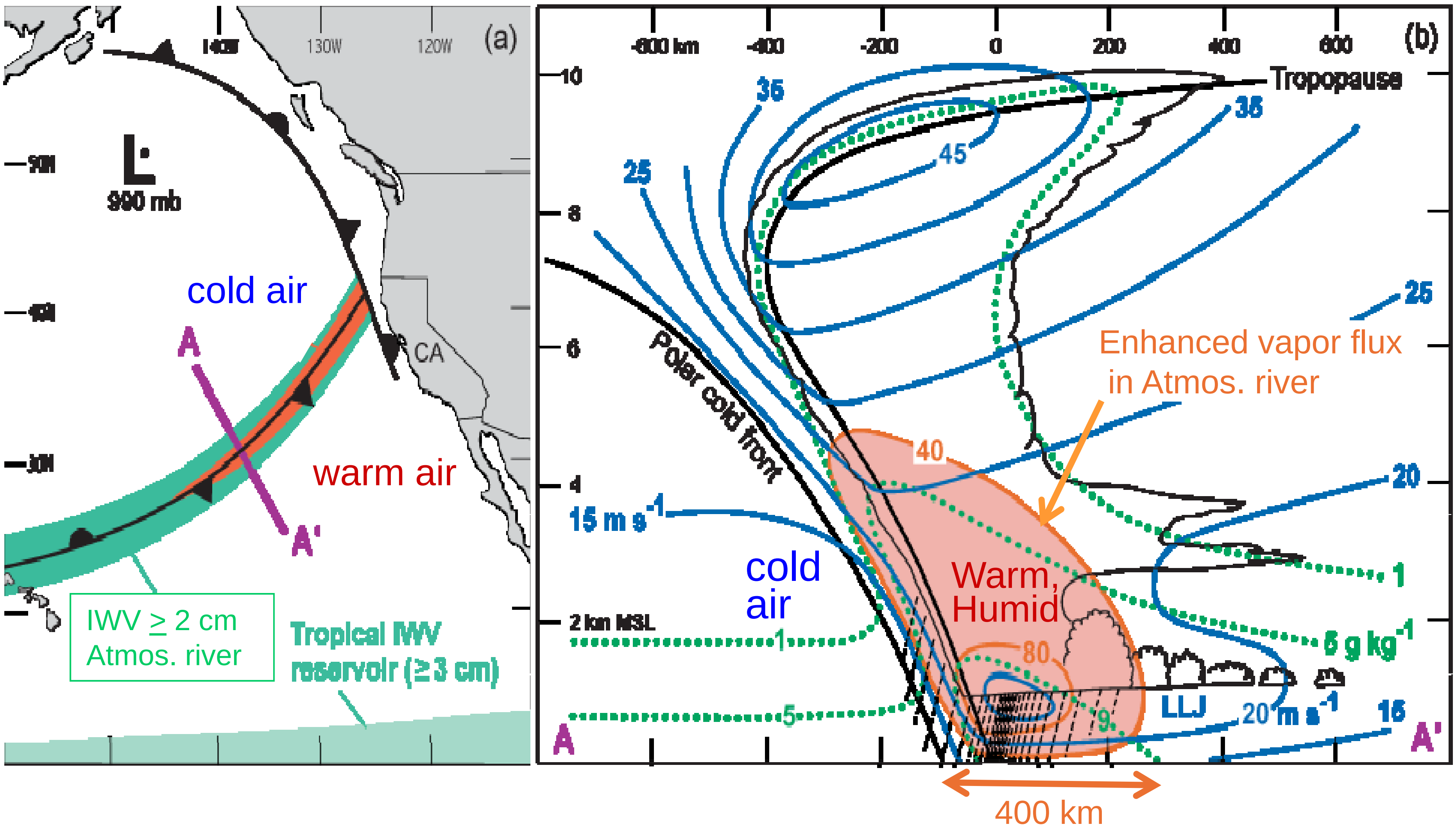
GOES-11 10.7 micron Channel
November 7, 2006 06:30Z
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
180W
170W
160W
150W
140W
130W
120W
110W
300
290
280
270
260
250
240
230
220
210
200
K



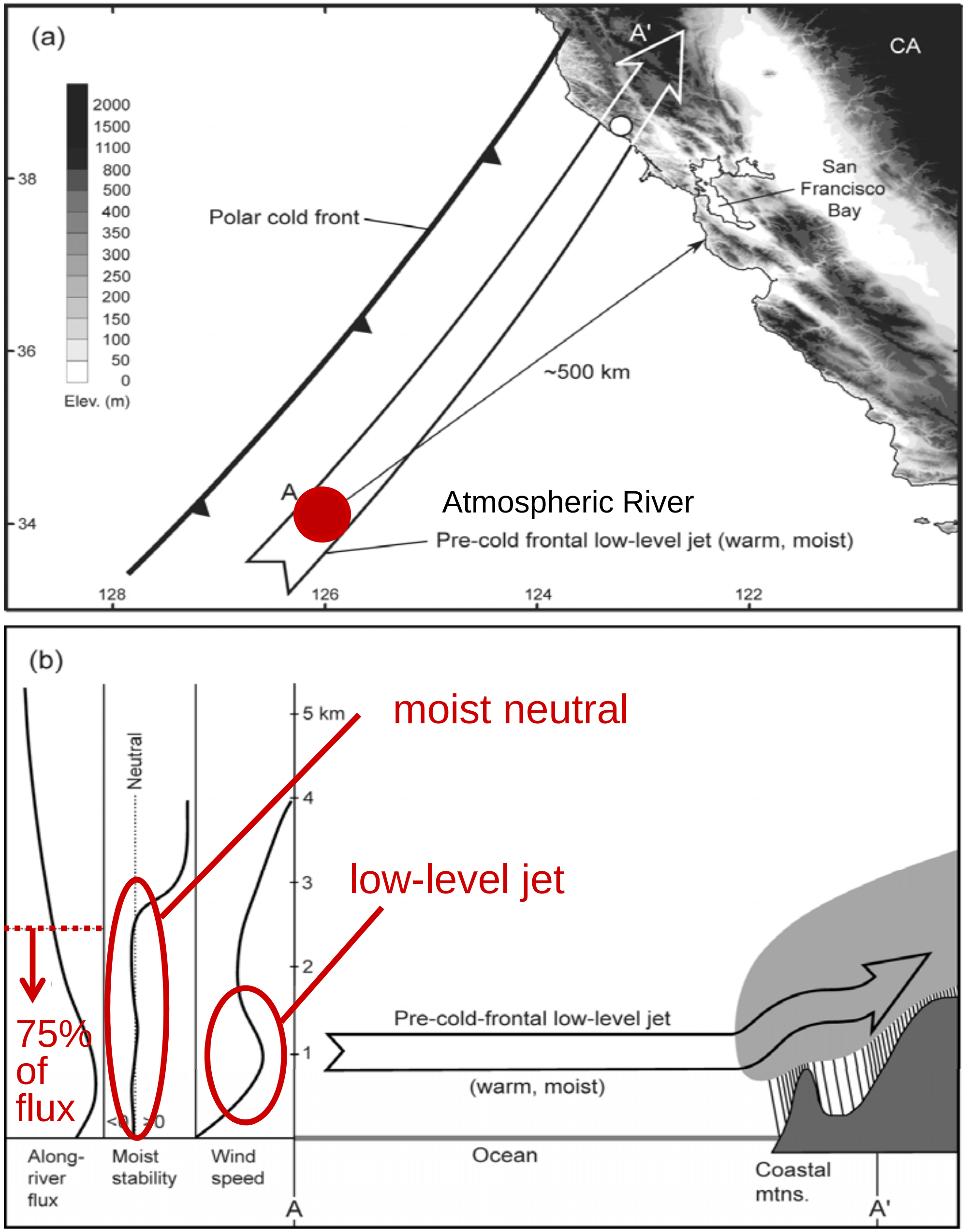
SSM/I IWV
November 07, 2006 00-11 UTC
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
180E
170W
160W
150W
140W
130W
120W
110W
7
6
5
4
3
2
1
g/cm²

## 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.



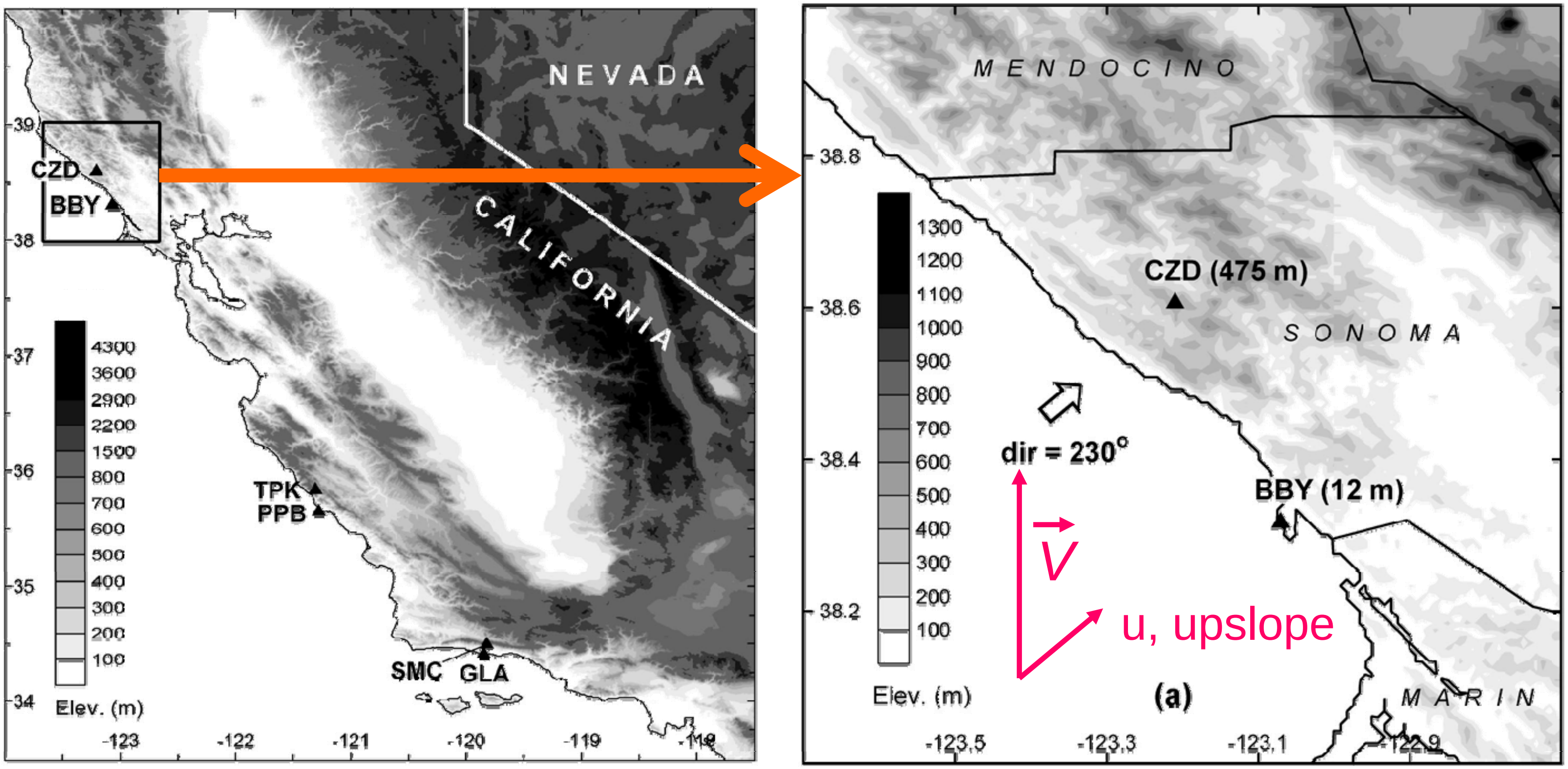
# Why do landfalling ARs create heavy rain?




- 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

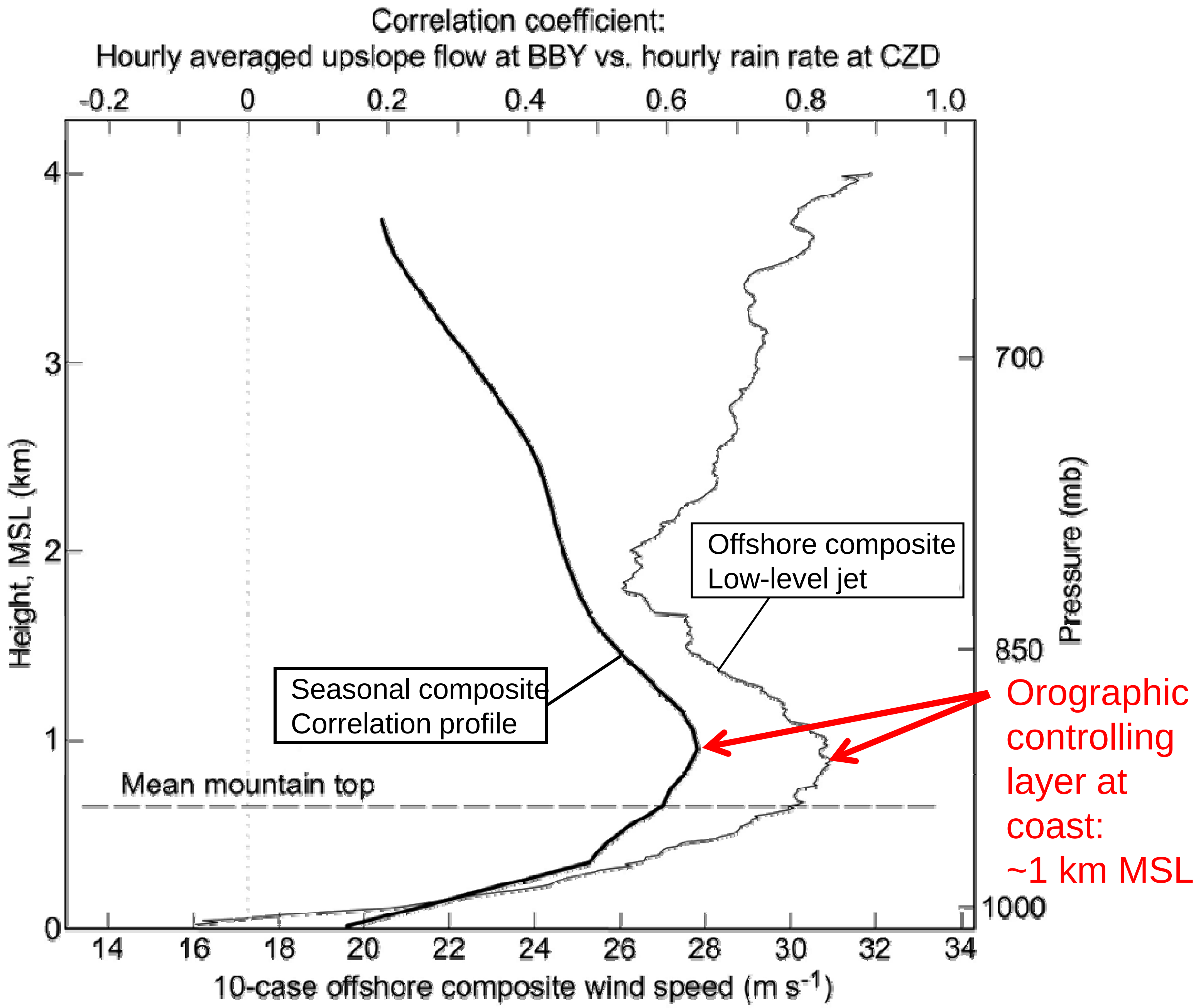
Ralph et al. (2005), *MWR*

# Orographic precipitation and the controlling layer

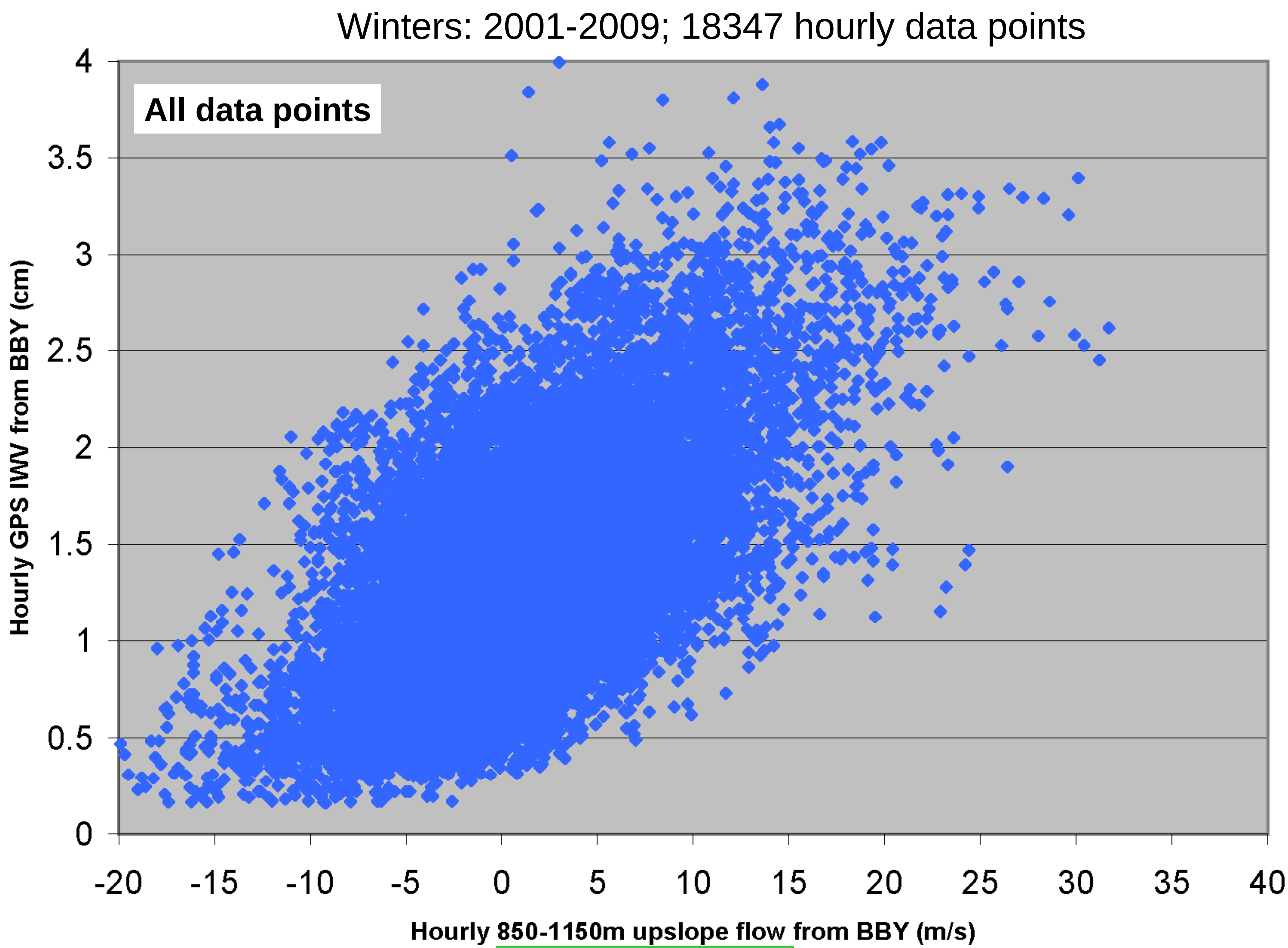



$$R \approx \overline{q\rho}(\vec{V} \bullet \nabla Z_s)$$

$$R \propto u(\partial h / \partial s)$$

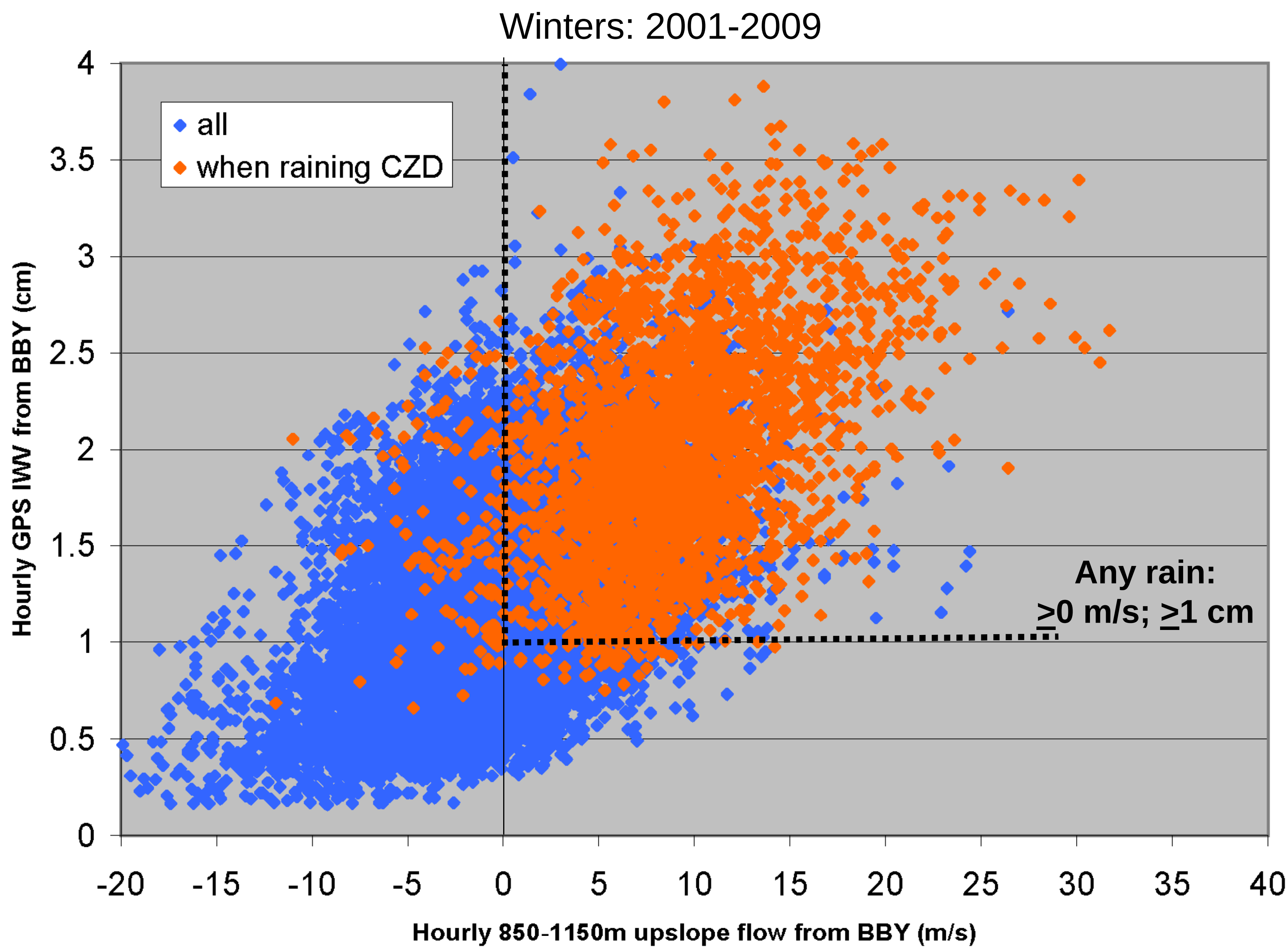



Neiman et al. (2002)

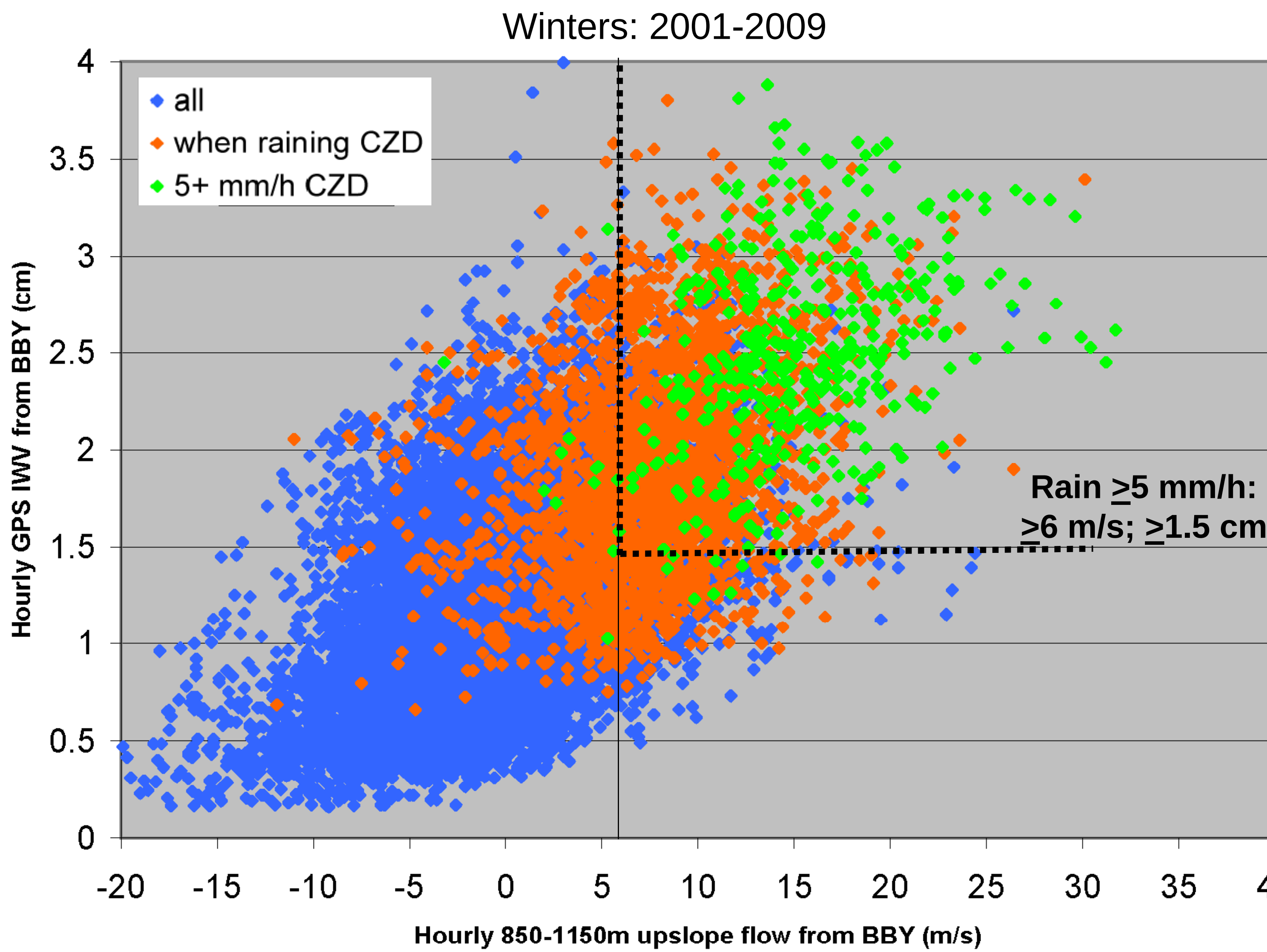



**Component of the flow in the orographic controlling layer directed from 230°, i.e., orthogonal to the axis of the coastal mtns**

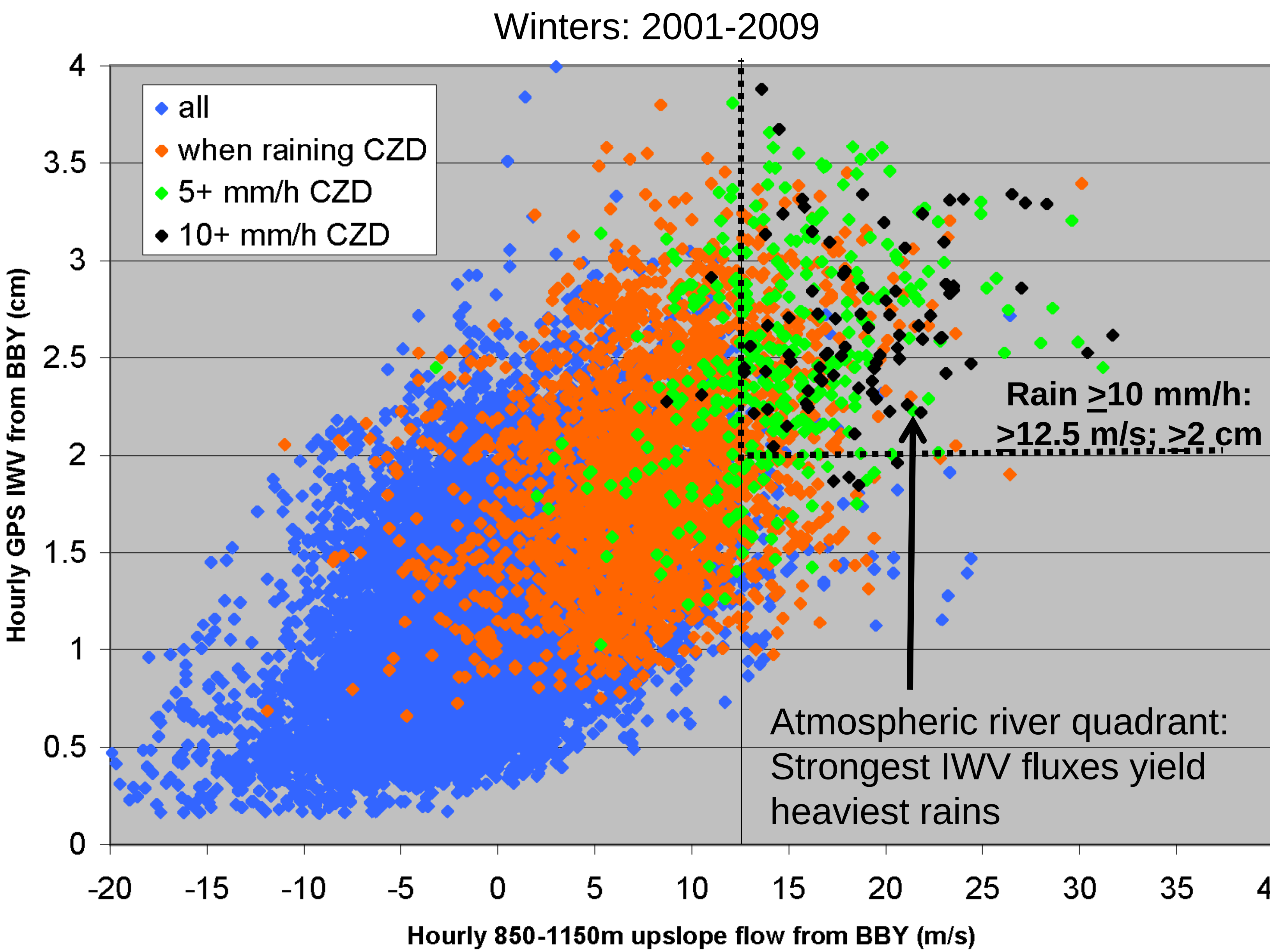
Neiman et al. (2008), *Water Management*



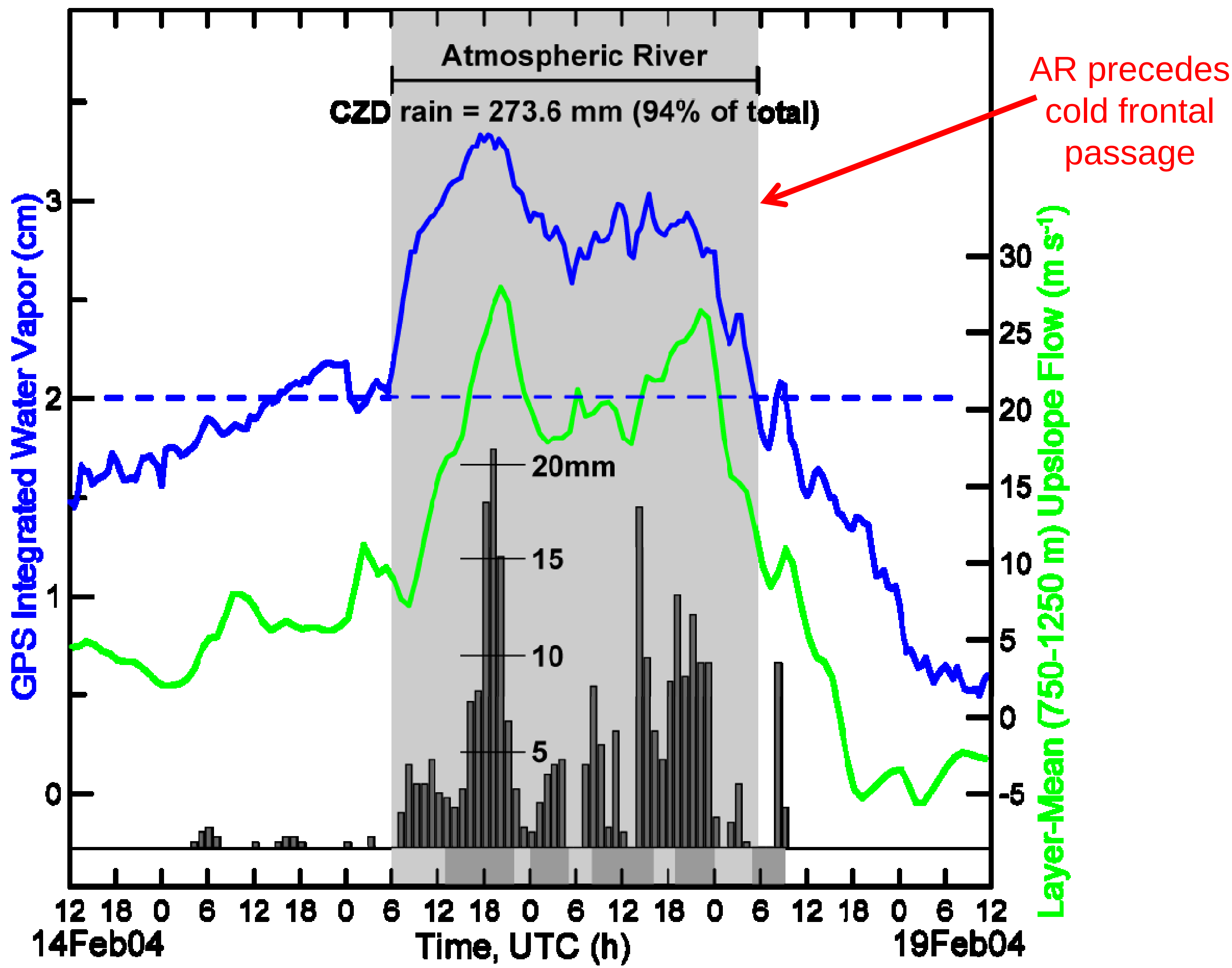
Winters: 2001-2009
all
when raining CZD
Any rain:
≥0 m/s; ≥1 cm
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)
0
0.5
1
1.5
2
2.5
3
3.5
4
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40



Winters: 2001-2009
all
when raining CZD
5+ mm/h CZD
Rain >5 mm/h:
>6 m/s; >1.5 cm
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)
0
0.5
1
1.5
2
2.5
3
3.5
4
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40



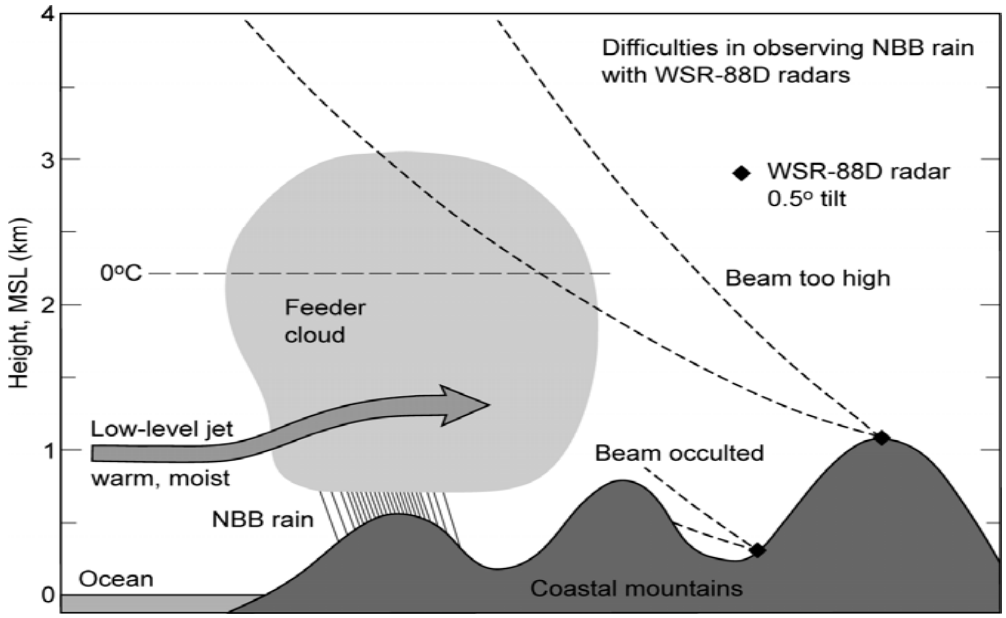

*Nearly 2/3 of tropospheric water vapor is in the lowest 2 km MSL.
Hence, to first order, the IWV flux provides a close estimate
of the low-level water-vapor transport into the coastal mountains.

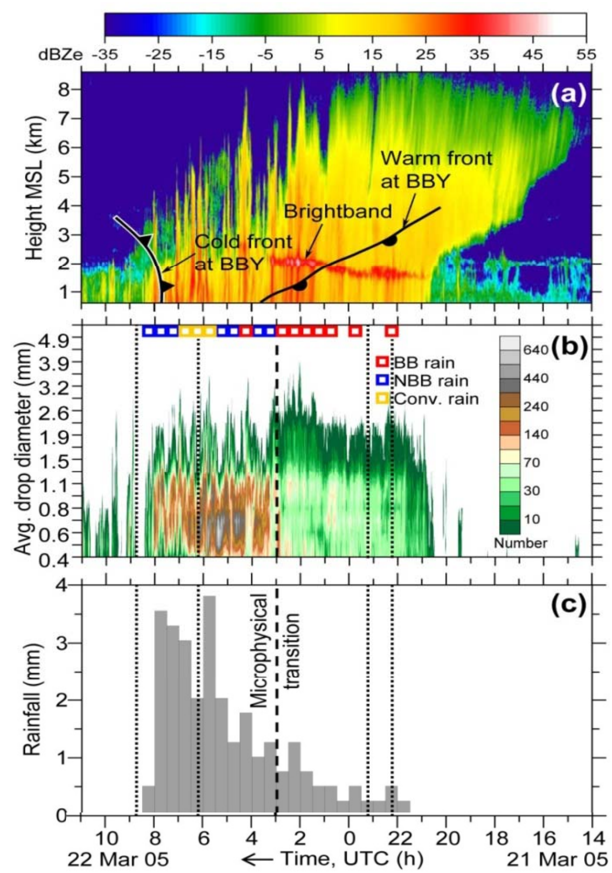


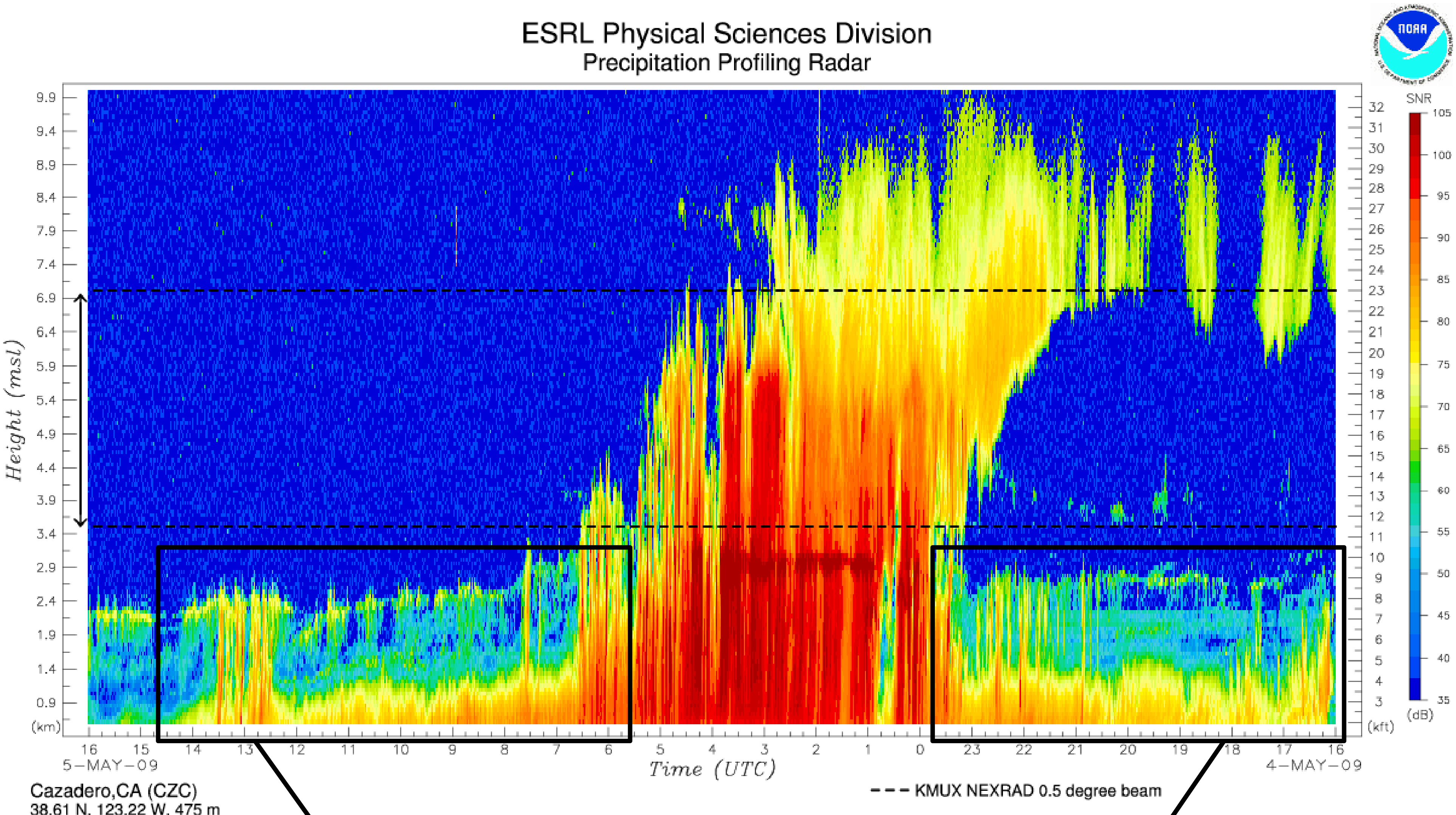
Atmospheric River
CZD rain = 273.6 mm (94% of total)
AR precedes cold frontal passage
20mm
15
10
5
GPS Integrated Water Vapor (cm)
Layer-Mean (750-1250 m) Upslope Flow (m s-1)
12 18 0 6 12 18 0 6 12 18 0 6 12 18 0 6 12 18 0 6 12
14Feb04
Time, UTC (h)
19Feb04

# SIDEBAR: Research has identified an efficient, shallow orographic precipitation process, i.e., "Non-Bright-Band" (NBB) rain (White et al. 2003, Neiman et al. 2005, Martner et al. 2008)

- Using S-Prof vertically pointing radars, periods of shallow rain without a bright band have been documented.
- This NBB rain consists of large numbers of small rain drops, like drizzle, with an absence of large drops, but can produce significant rain rates.
- Often the echoes will occur below standard NEXRAD radar scans.
- 25%-35% of annual cool-season precip in west coast states falls as NBB rain.





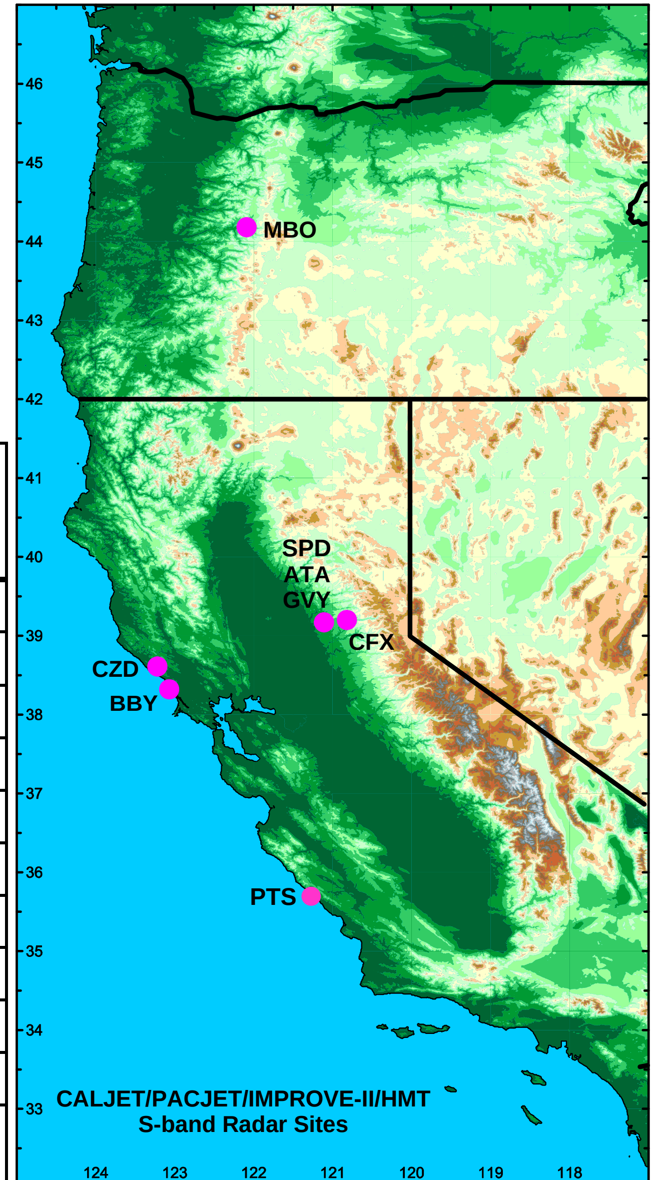

Non bright-band rain: 50% of total rain in this 3 inch event

# NBB rain accounts for a significant fraction of seasonal rainfall total

## ESRL S-band Radar Operating Sites

Coastal Mountains — Coast — Inland Mountains

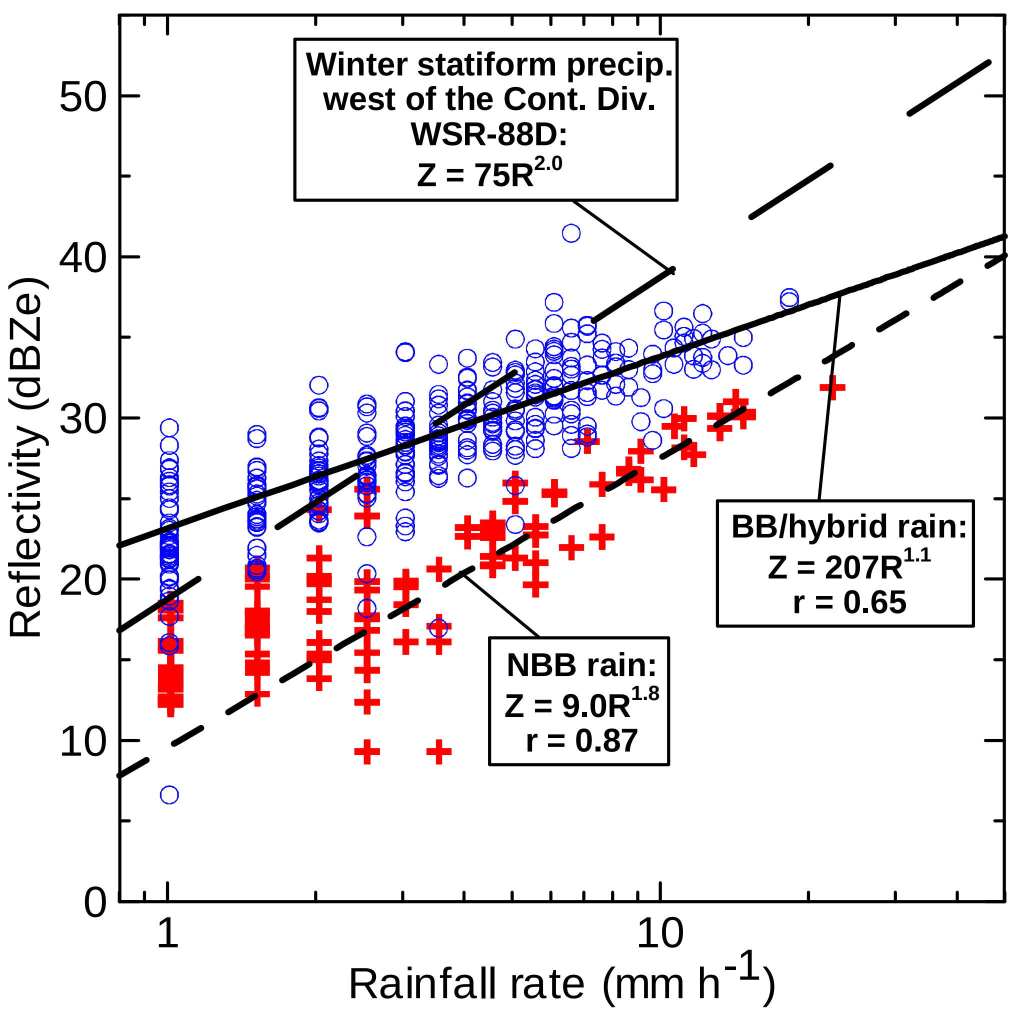
| Year | CZD | BBY | PTS | GVY | MBO | ATA | SPD | CFX |
|---|---|---|---|---|---|---|---|---|
| 1998 | 29.4 | | | | | | | |
| 2001 | 18.2 | 24.5 | | | | | | |
| 2001/02 | 50.0 | | | 35.3 | 17.8 | | | |
| 2002/03 | 41.5 | | | | | | | |
| 2003/04 | 42.2 | 31.4 | | | | | | |
| 2004/05 | 29.3 | | | | | | | |
| 2005/06 | 37.3 | | | | | 21.2 | | |
| 2006/07 | 38.0 | | | | | 29.4 | | |
| 2007/08 | 29.0 | | | | | 17.2 | | 14.9 |
| 2008/09 | 31.6 | | 26.3 | | | 31.8 | 38.8 | |
| **AVG.** | **35%** | **27%** | | **26%** | | | | |



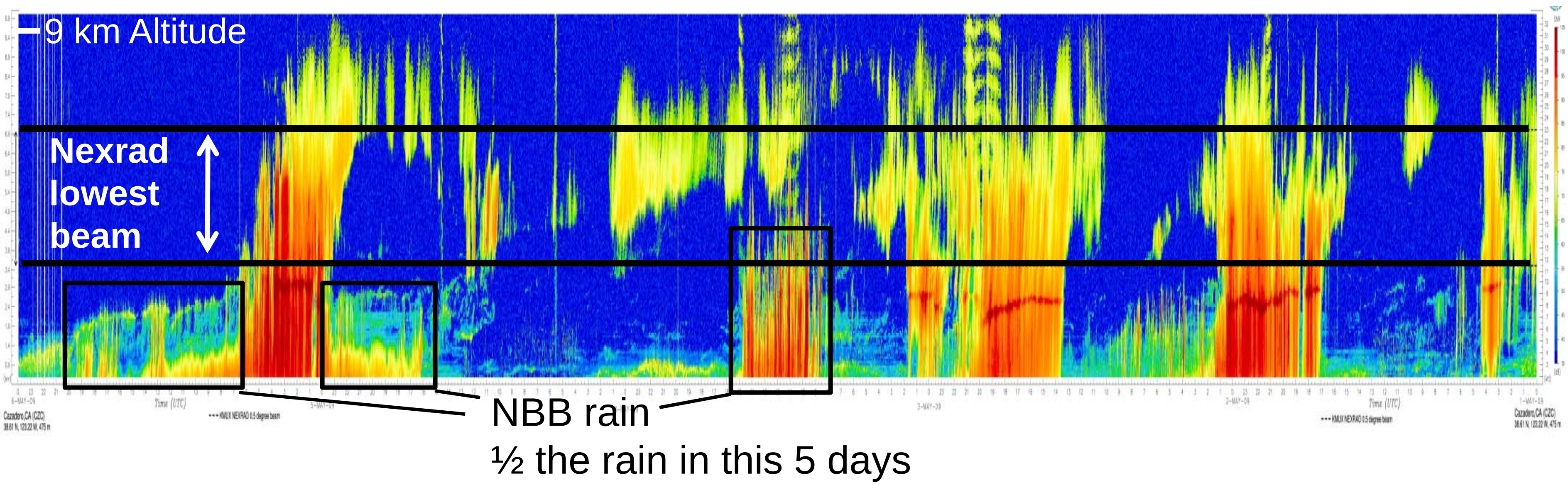
# Assuming WSR-88D network could detect shallow NBB rain, operational algorithm would greatly underestimate NBB rain rate

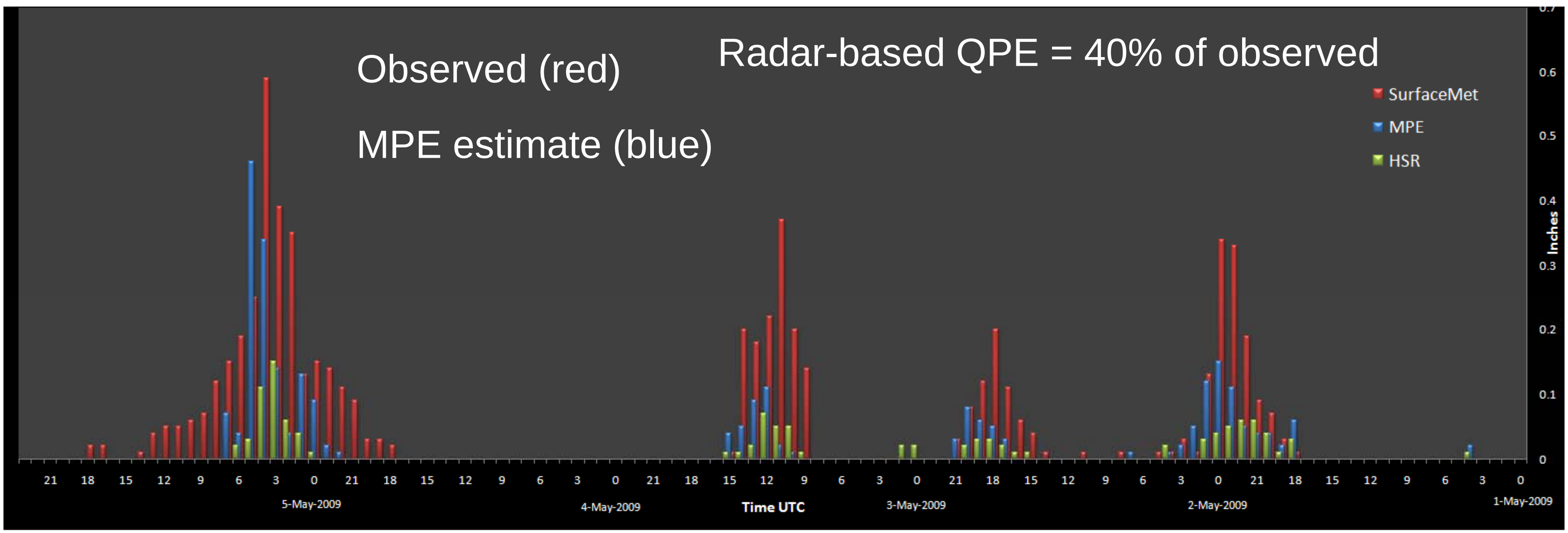
For the radar reflectivity associated with a NBB rain rate of 10 mm $hr^{-1}$, the “west coast” operational algorithm would underestimate the rain rate by a factor of 3.6, i.e., 10 mm $hr^{-1}$ vs. 2.75 mm $hr^{-1}$.

For the same radar reflectivity, the “tropical” Z-R relationship, $Z = 250R^{1.2}$, would underestimate the NBB rain rate by a factor of 5, i.e., 10 mm $hr^{-1}$ vs. 2.0 mm $hr^{-1}$.

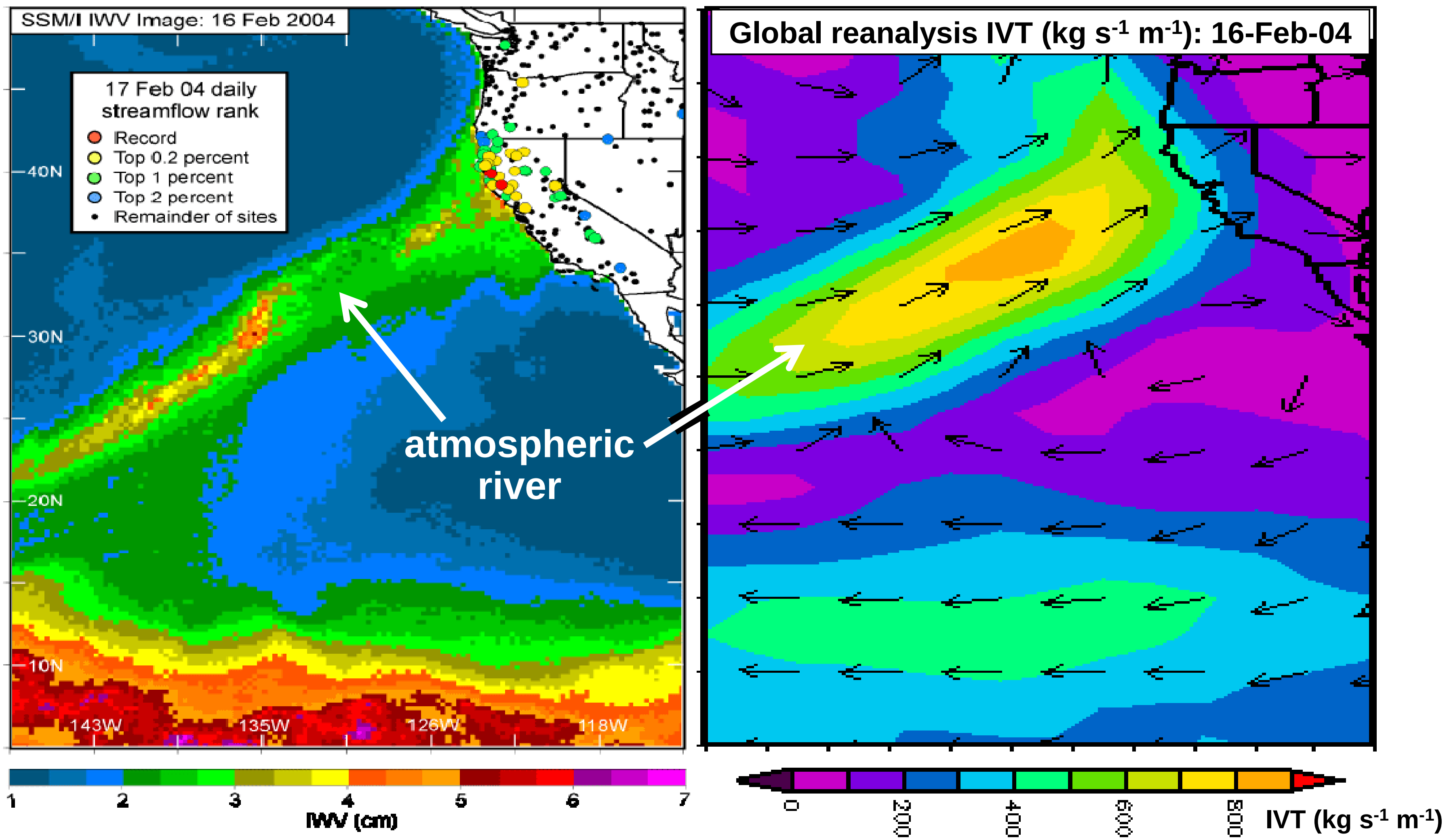


# S-Prof Radar reflectivity vertical profiles over 5 days (6.3 inches of rain)



- Heavy cool-season rain & flood events along the U.S. West Coast are orographically driven and occur most often when narrow warm-sector corridors of strong water-vapor transport (i.e., atmospheric rivers – ARs) intersect the coastal mountains (e.g., Ralph et al. 2006 in *GRL*; Neiman et al. 2008 in *JHM*).

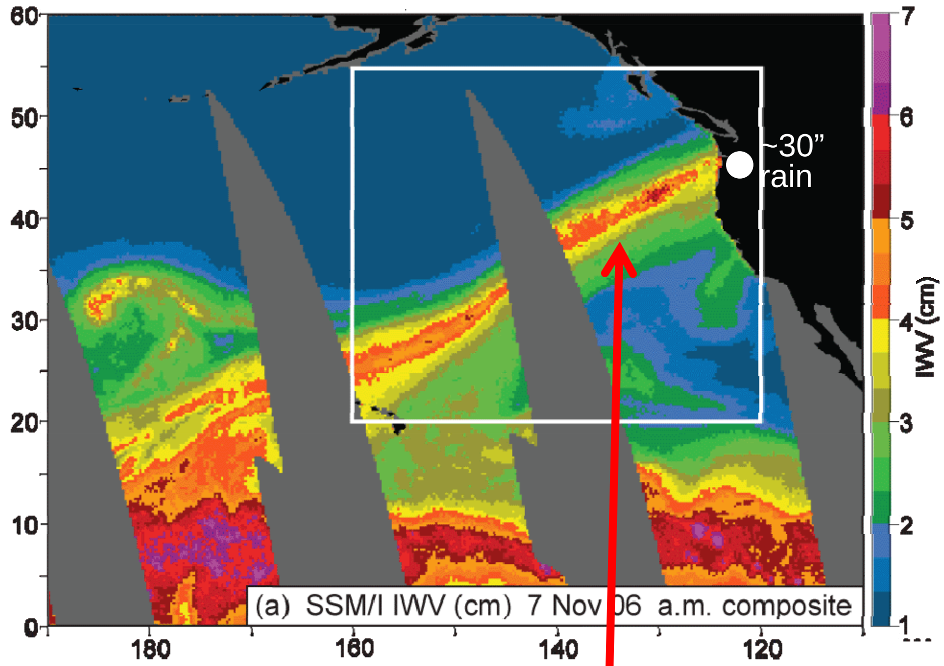


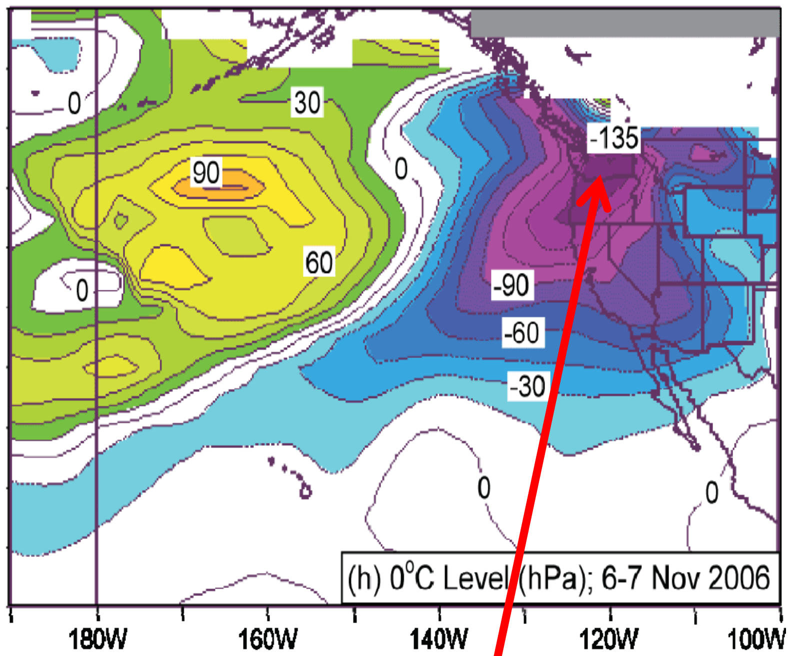
# Pacific Northwest Landfalling AR of early November 2006

Neiman et al. (2008a)

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

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



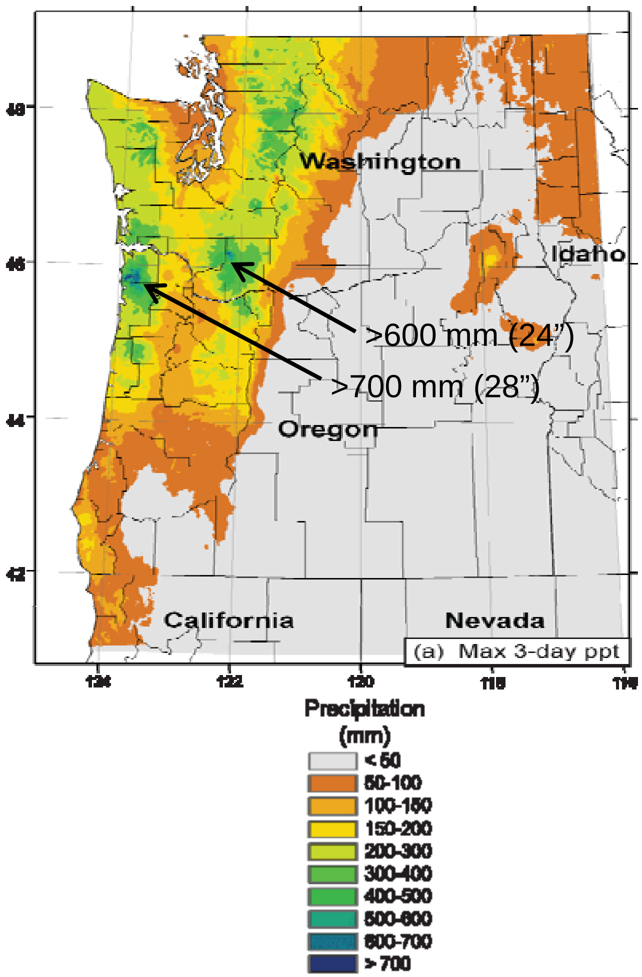




This AR is also located near the leading edge of a cold front, with strong vapor fluxes (as per reanalysis diagnostics)

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

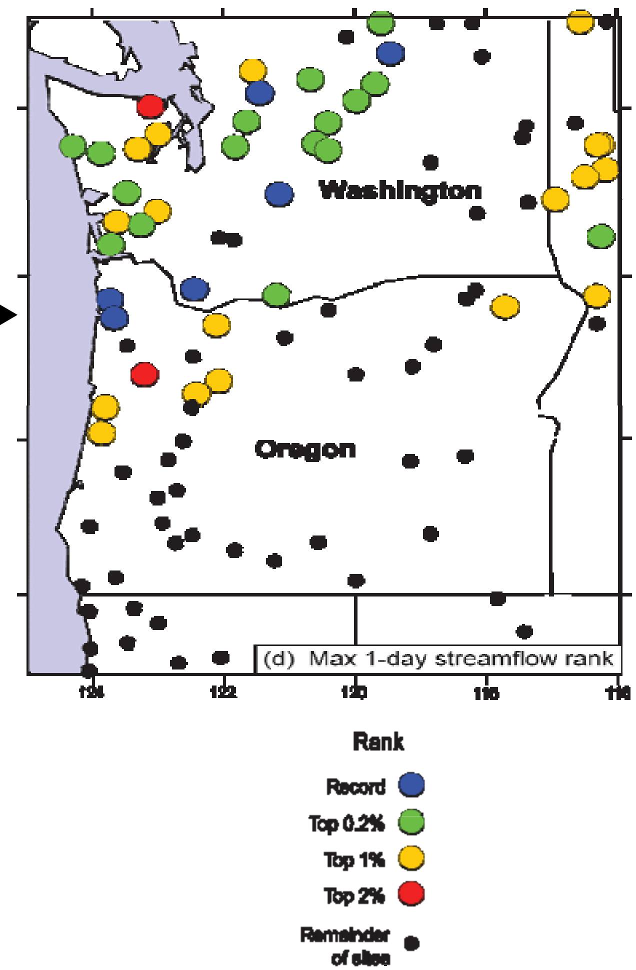
# Hydroclimatic analysis for the AR of 5-9 November 2006

Greatest 3-day precip. totals during the period between 5-9 Nov. 2006



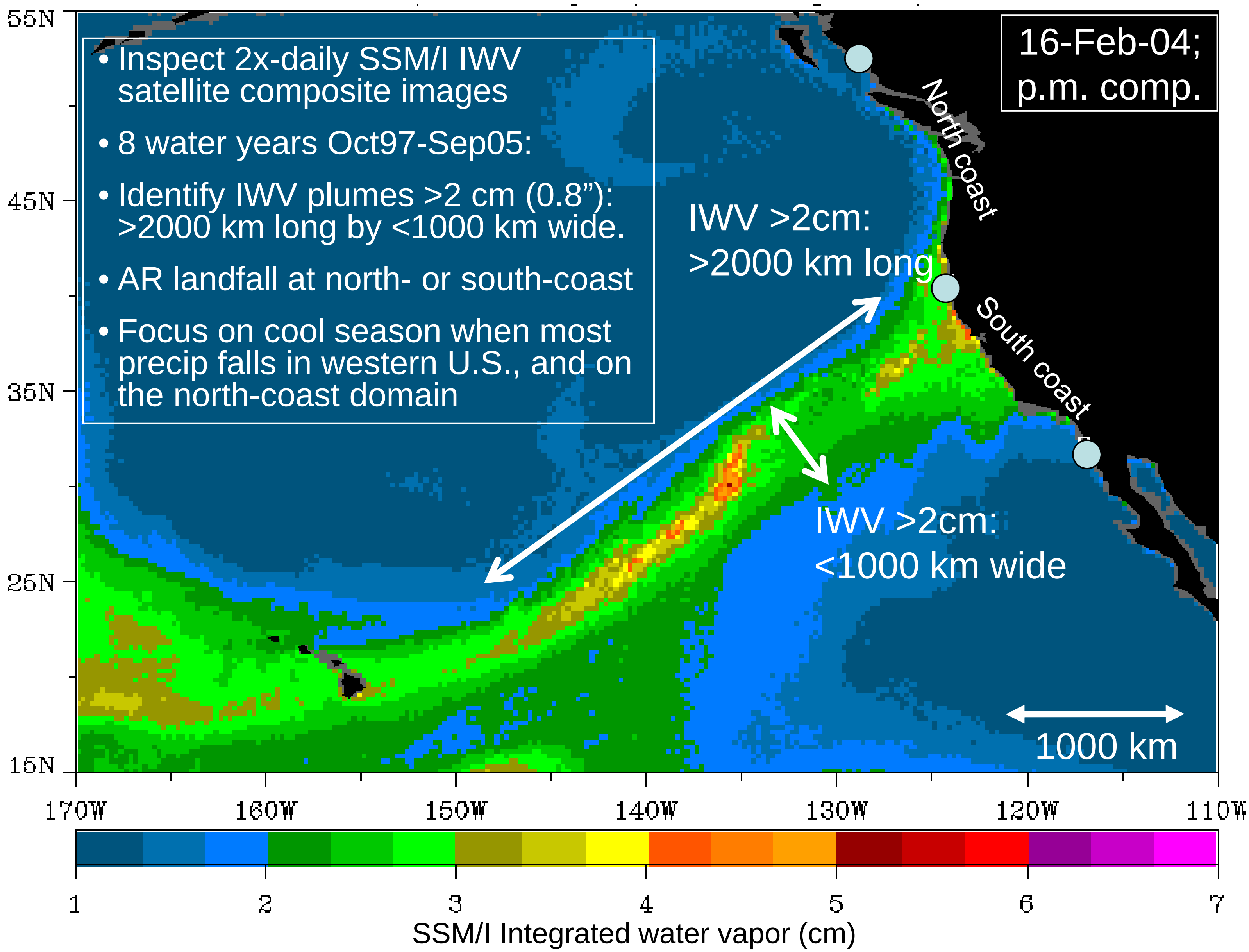

plus high melting level equals

Historical Nov. ranking for the max. daily streamflow between 5-9 Nov. 2006

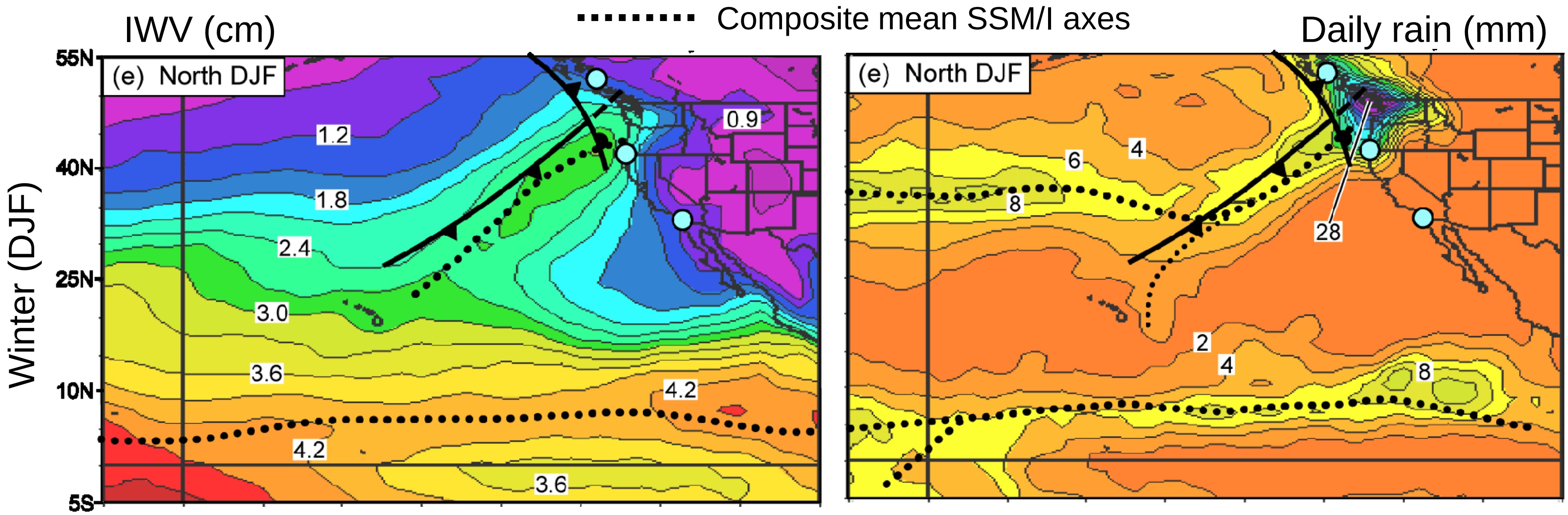


What are the long-term hydrometeorological impacts of landfalling ARs in western North America? Neiman et al. (2008b)

Approach: Developed a methodology for creating a multi-year AR inventory.

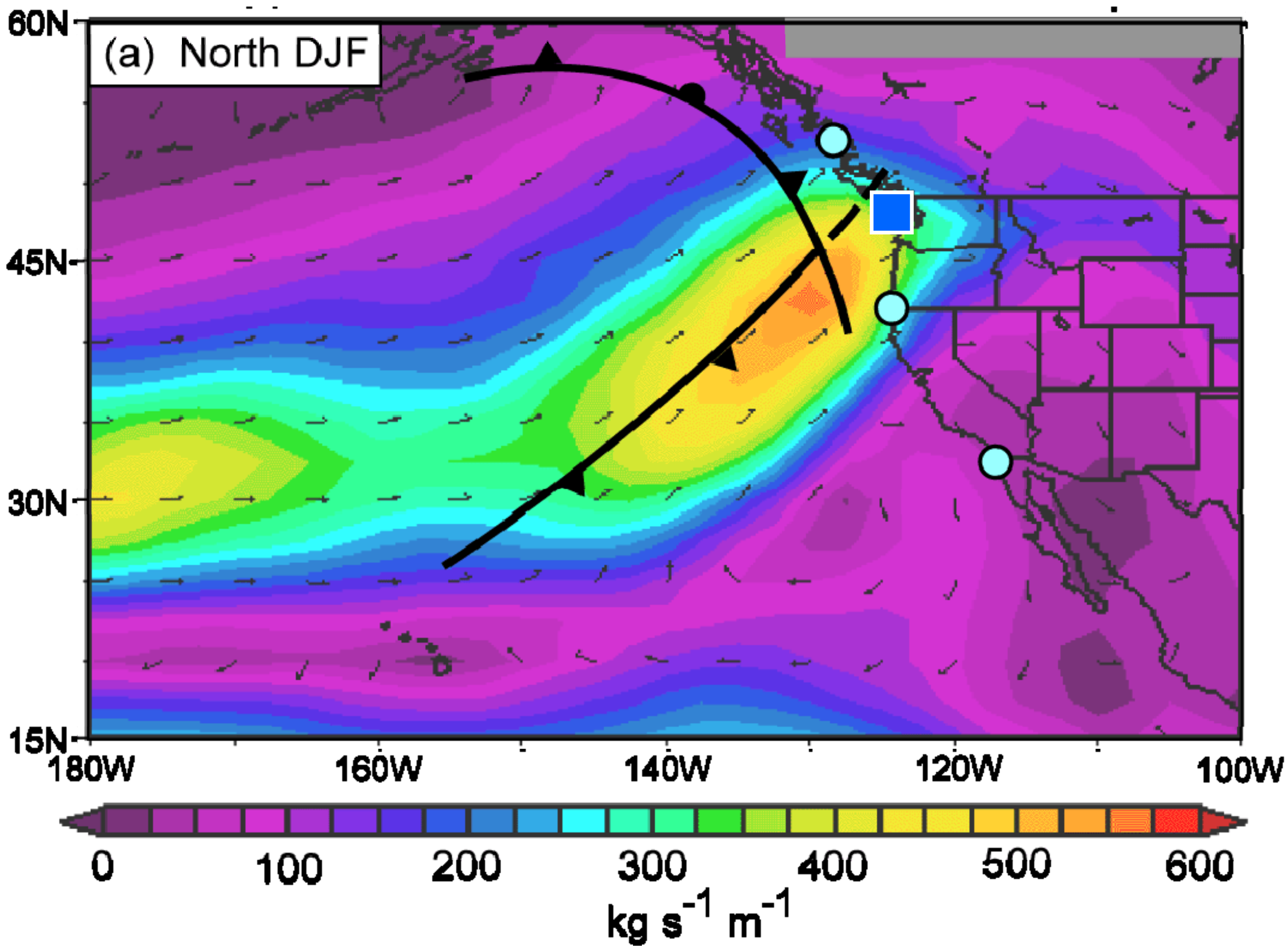


# Composite Mean Reanalyses – focus on North Coast Winter

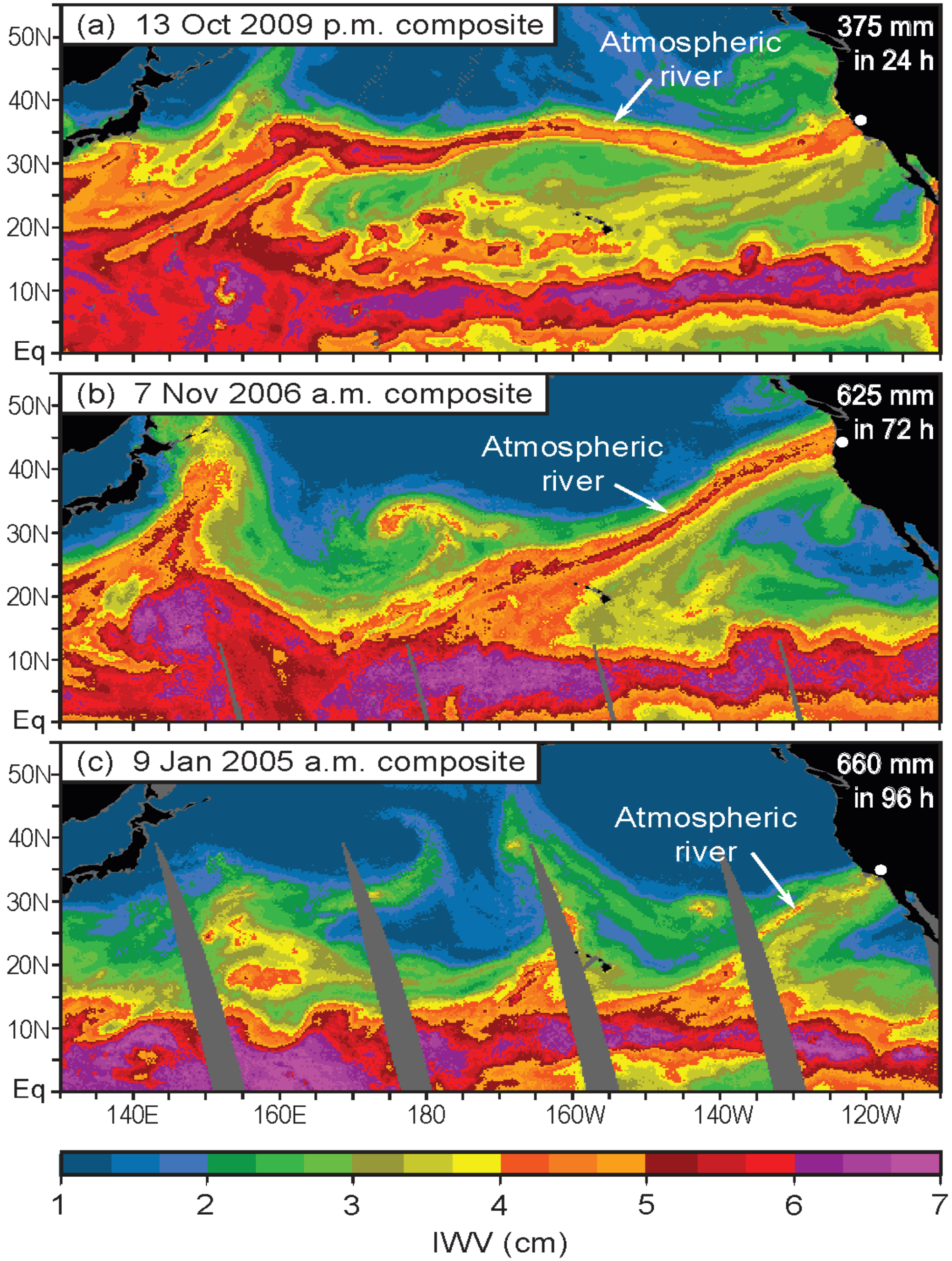



- The daily gridded NCEP–NCAR reanalysis dataset (2.5° x 2.5°; Kalnay et al. 1996) was used to create composite analyses during AR conditions – 29 dates.
- Composite reanalysis IWV plume oriented SW-NE from the tropical eastern Pacific to the coast.
- Composite plume situated ahead of the polar cold front.
- Wintertime ARs produce copious precip along coast, & frontal precip offshore.
- Reanalysis composites accurately depict the positions of the IWV plume and precip. bands observed by the SSM/I composites... denoted by dotted lines.

# Composite Mean Reanalysis IVT (kg $s^{-1}$ $m^{-1}$) – North Coast winter



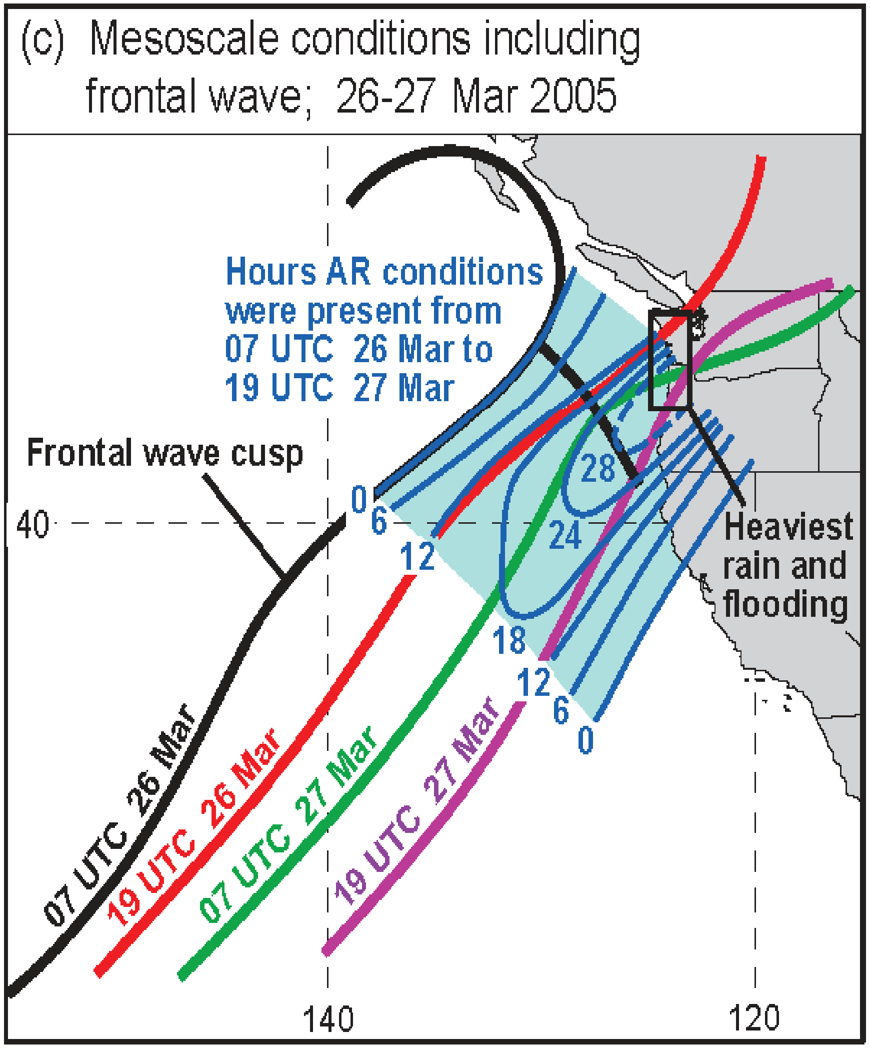

- Strong vapor transport intersects coastline during winter, with maximum on the warm side of the cold front.
- Transport originating from low latitudes



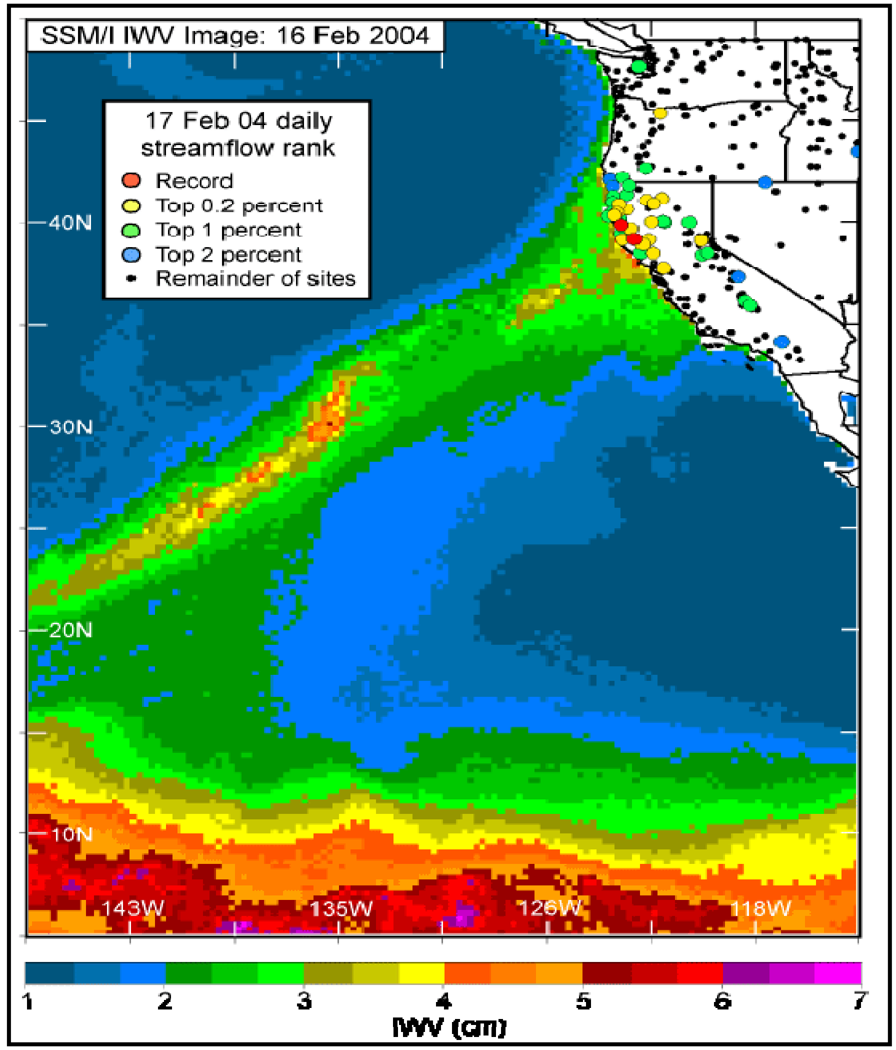

# Situational awareness: Three examples suggestive of entrainment of tropical water vapor, i.e., a TROPICAL TAP

**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.**

# Fine tuning: A mesoscale frontal wave can increase the duration of AR conditions, leading to a localized region of extreme precipitation



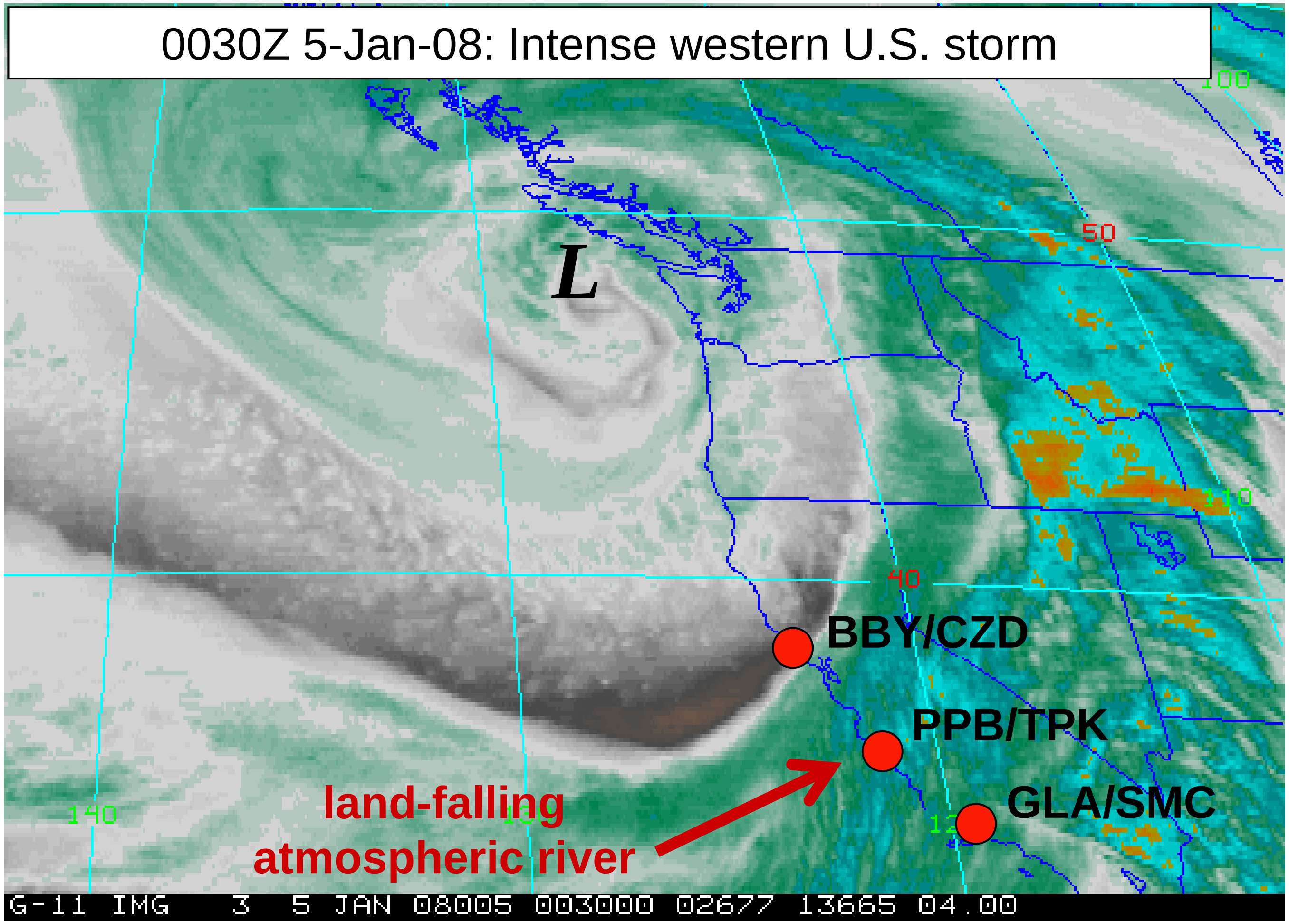

Ralph et al., *Mon. Wea. Rev.* (2011; in press)



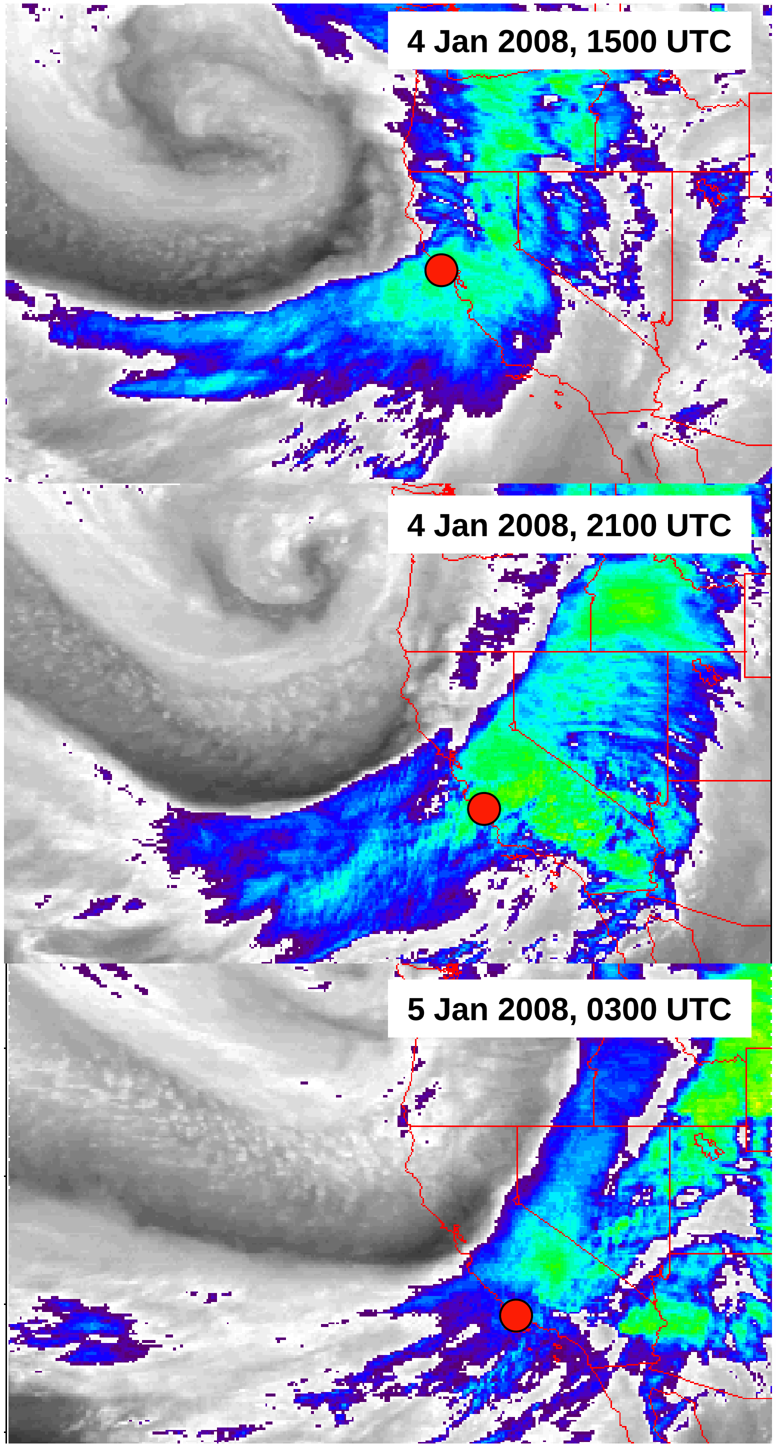

Ralph et al., *Geophys. Res. Lett.* (2006)

See also case shown in Neiman et al., *Mon. Wea. Rev.* (2004)

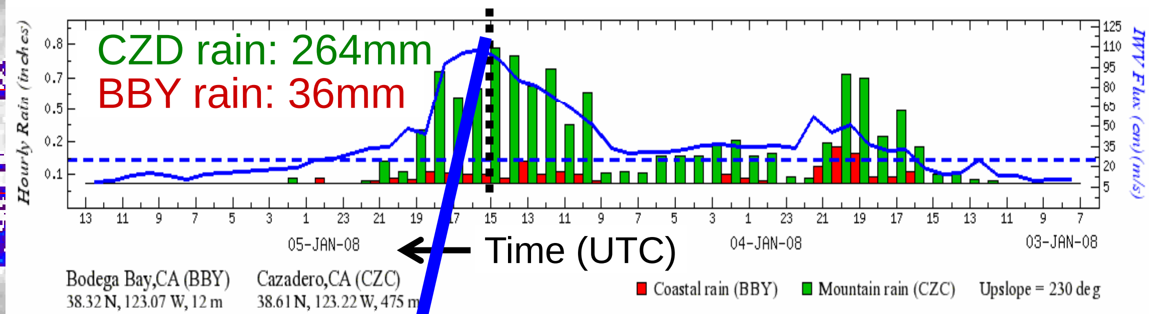
# Prototype forecast tool tested at 3 CA couplets during NOAA's HMTs




| 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) |

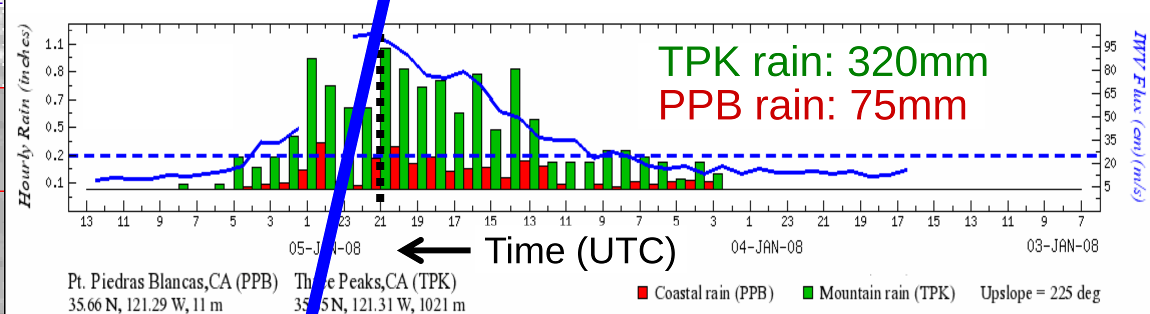



**Time of max. IWV flux at BBY: 1500 UTC 4-Jan-08**




**Max. IWV flux in AR highly correlated with max. mountain rainfall at each site**

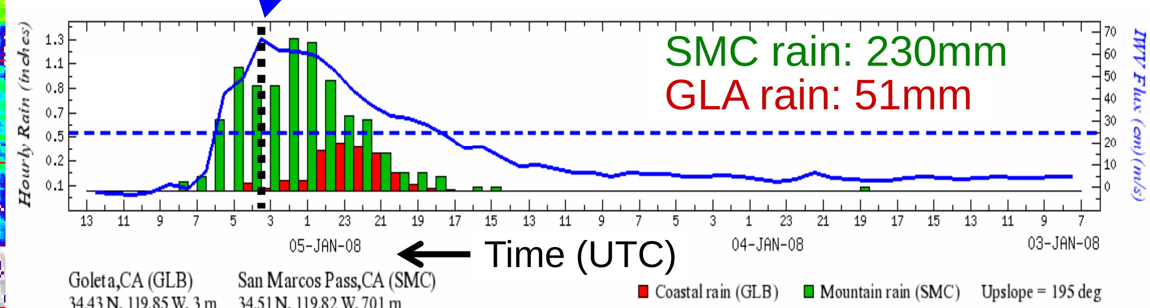
**Time of max. IWV flux at PPB: 2100 UTC 4-Jan-08**



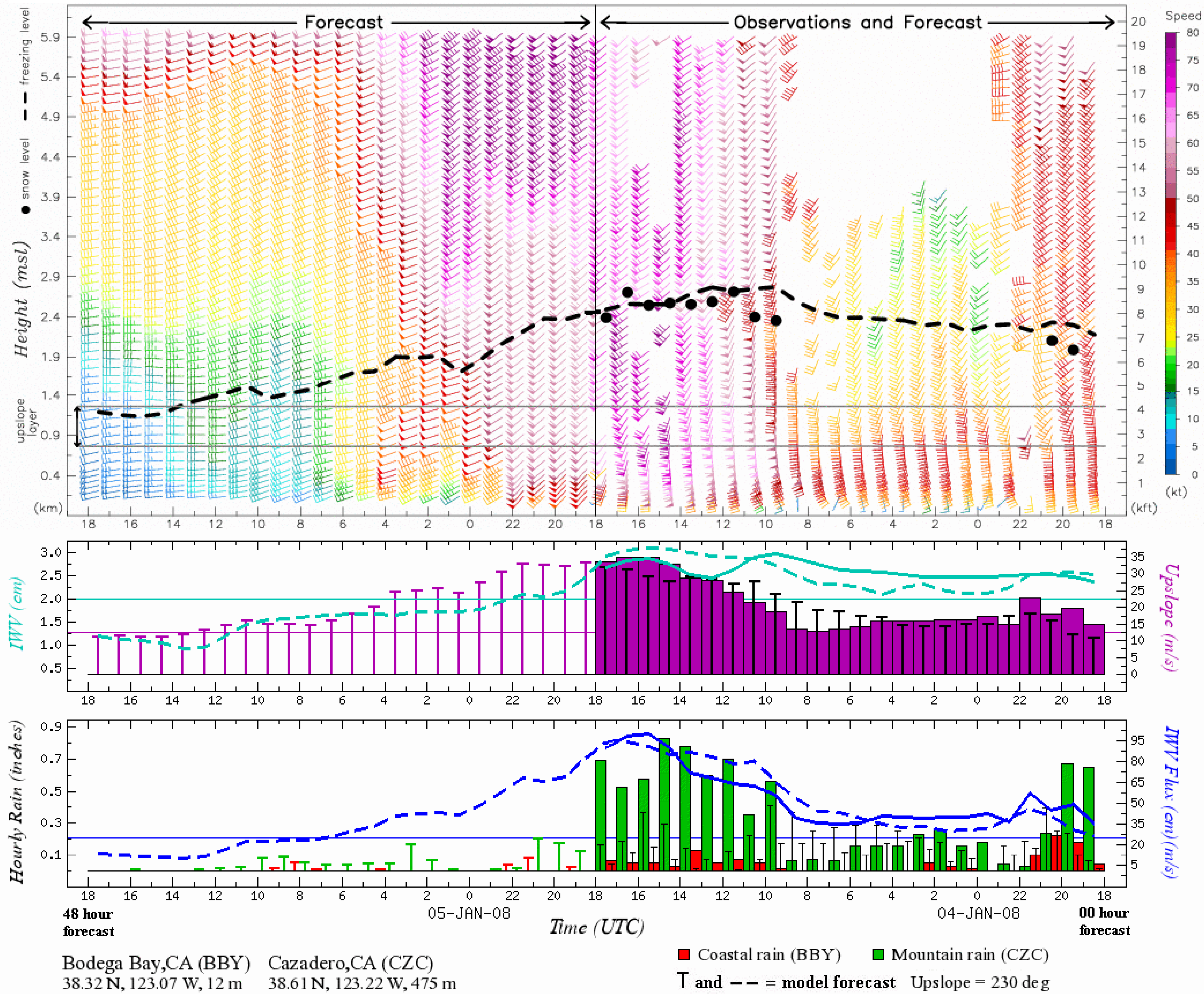

**AR Propagation: ~12 m $s^{-1}$.**

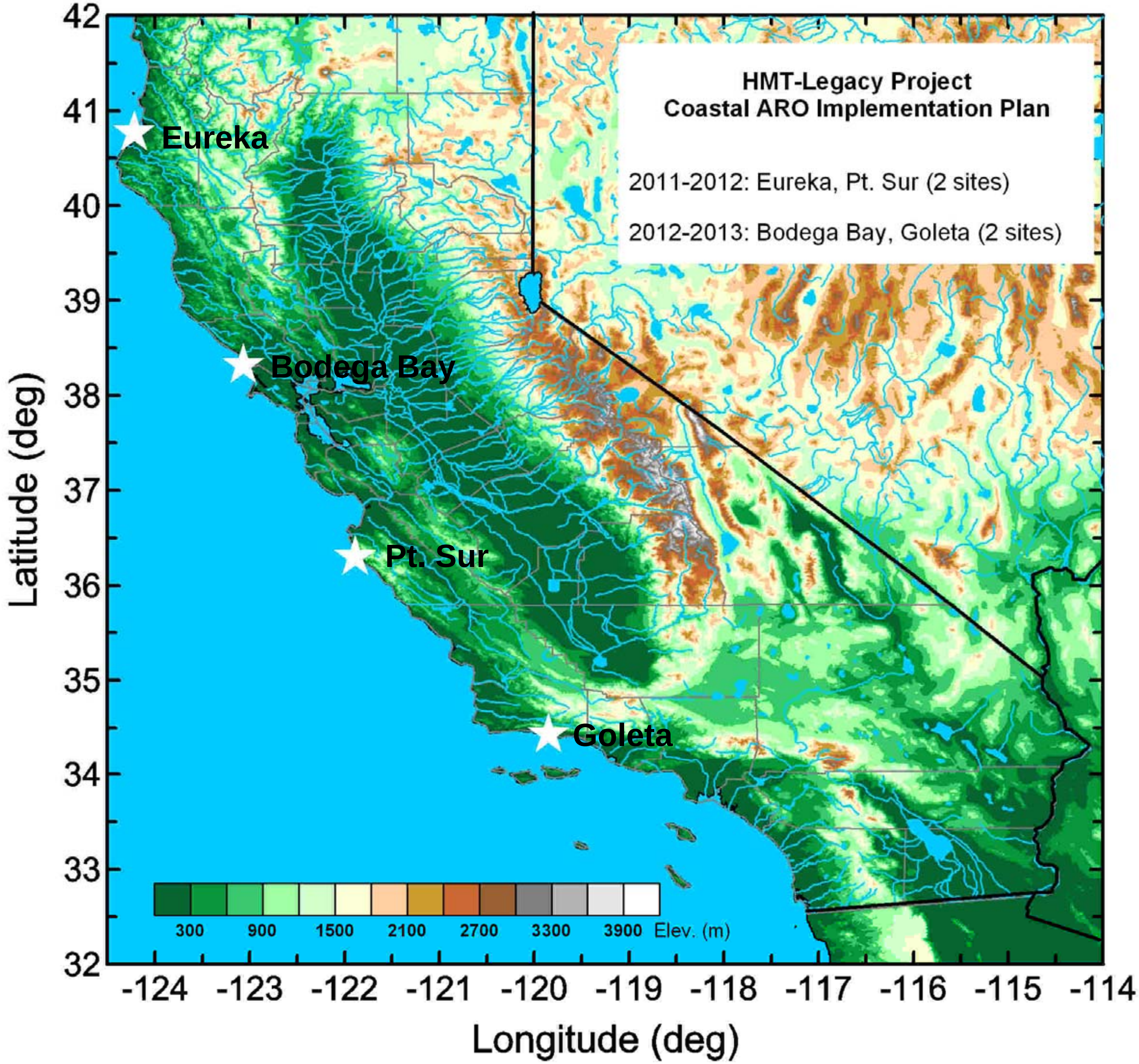
**½-day lead time for SoCal**

**Time of max. IWV flux at GLA: 0300 UTC 5-Jan-08**



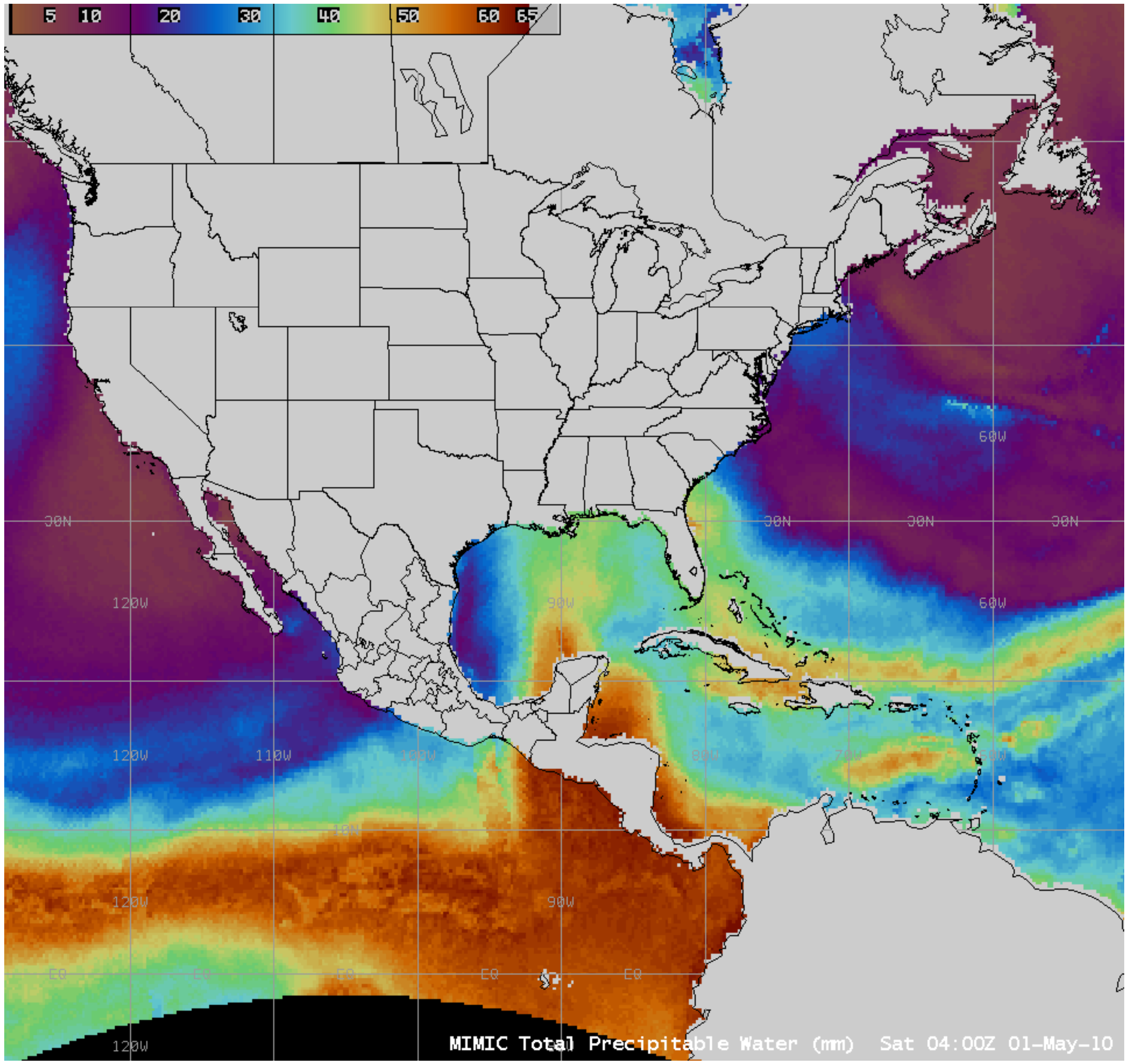
**Atmospheric River Observatory**: Combines scientifically based thresholds with observations and model forecasts



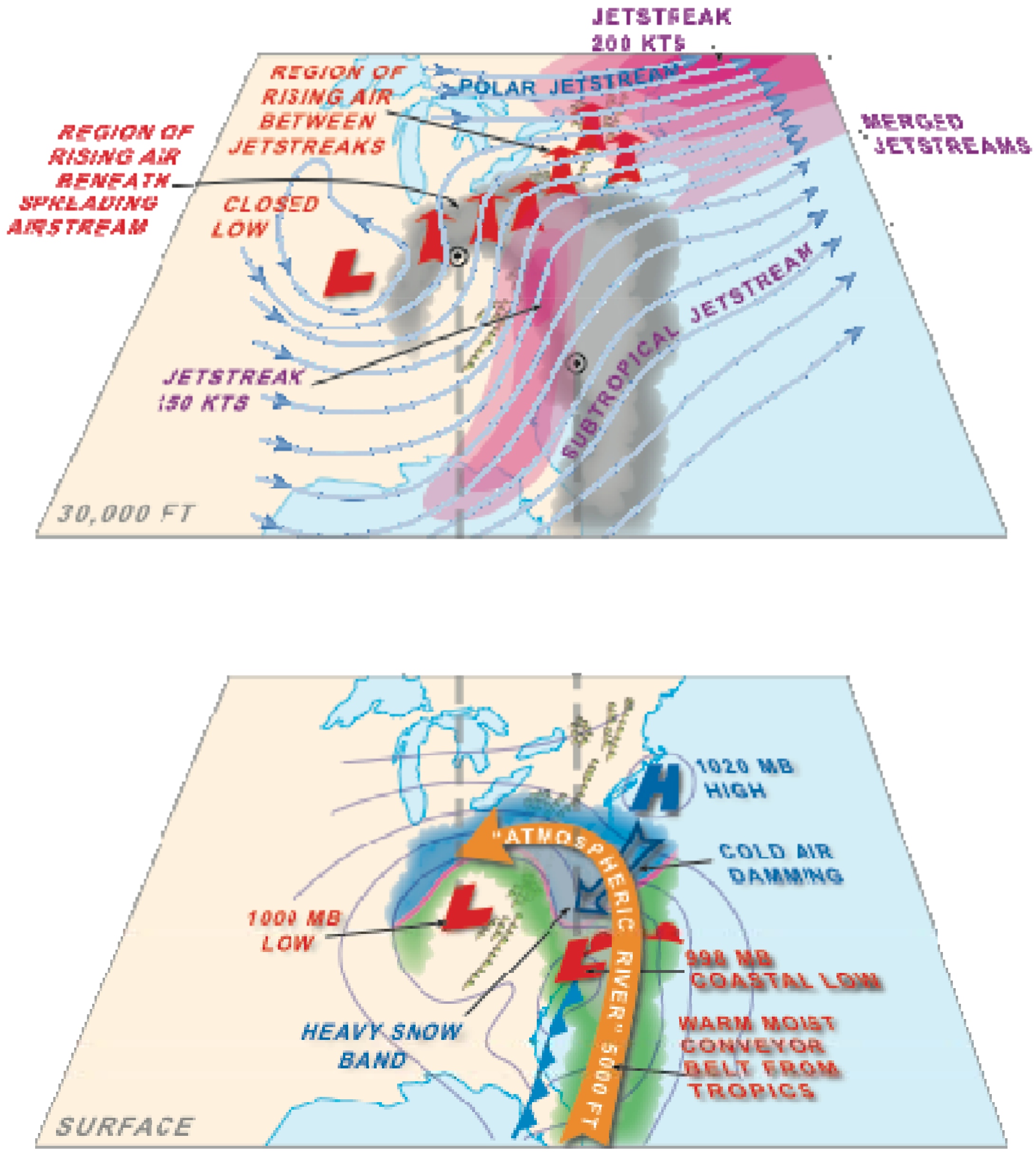

HMT-Legacy Project
Coastal ARO Implementation Plan
2011-2012: Eureka, Pt. Sur (2 sites)
2012-2013: Bodega Bay, Goleta (2 sites)
Eureka
Bodega Bay
Pt. Sur
Goleta
300
900
1500
2100
2700
3300
3900
Elev. (m)
Latitude (deg)
42
41
40
39
38
37
36
35
34
33
32
Longitude (deg)
-124
-123
-122
-121
-120
-119
-118
-117
-116
-115
-114

IWV loop of AR for Tennessee flood: 04Z 1 May – 23Z 2 May 2010

- Eastern U.S. AR springtime event generating dominated by deep convection
- Widespread 48-h rainfall 1- 2 May 2010 across TN and KY: 8 – 20 in. were common
- 26 fatalities throughout affected region (11 just in the Nashville area), $2 billion in damages



3D Connections Between Jet Stream Structures and Coastal Low Intensification – Feb 5, 6 2010




- Eastern U.S. AR winter storm tied to wrap-around AR from Atlantic
- Big snows mid-Atlantic States:
  i. Washington D.C. – 18 in. (117% of annual average)
  ii. Baltimore, MD – 25 in. (136% of annual average)
  iii. Philadelphia, PA – 29 in. (139% of annual average)

From Halverson and Rabenhorst, Weatherwise, Jul/Aug 2010

# Conclusions

- Atmospheric rivers are responsible for 90% of meridional water vapor transport.
- An AR represents the region of strong horizontal water vapor transport in the warm conveyor belt within an extratropical cyclone, ahead of surface cold front.
- AR conditions are highly favorable for creating orographic precipitation.
- Most flooding events in along the US West Coast occur in association with AR conditions.
- Not all ARs produce extreme precipitation.
- Conditions that favor an AR producing extreme rainfall and possibly flooding:
  - *Large IWV contents*
  - *Strong winds in the low-level jet*
  - *Favorable wind direction orientation relative to terrain orientation*
  - *Synoptic scale upward motion*
  - *Slow propagation of the AR across a region, possibly due to mesoscale frontal wave*
- Tools are being developed to better detect, monitor and predict AR conditions.


Thank You!

# Atmospheric Rivers Bibliography (red font denote studies presented here)

**Atmospheric River focused journal articles**

Criteria for inclusion: the term "Atmospheric river" is used in the title.


Jankov, I., J.-W. Bao, P. J. Neiman, P. J. Schultz, Y. Huiling, and A. B. White, 2009. Evaluation and comparison of microphysical algorithms in ARW-WRF model simulations of atmospheric river events affecting the California coast. *J. Hydrometeor.*, **10**, 847-870.

Kaplan, M. L., C. S. Adaniya, P. J. Marzette, K. C. King, S. J. Underwood, and J. M. Lewis, 2009. The Role of Upstream Midtropospheric Circulations in the Sierra Nevada Enabling Leeside (Spillover) Precipitation. Part II: A Secondary Atmospheric River Accompanying a Midlevel Jet. *J. Hydrometeor.*, **10**, 1327-1354.

Leung L. R, and Y. Qian, 2009. Atmospheric rivers induced heavy precipitation and flooding in the Western U.S. simulated by the WRF regional climate model. *Geophys. Res. Lett.* **36**, L03820, doi:10.1029/2008GL036445

Ma, Z., W. Y.-H. Kuo, F. M. Ralph, P. J. Neiman, G. A. Wick, E. Sukovich, and B. Wang, 2010: Assimilation of GPS radio occultation data for an intense atmospheric river with the NCEP Regional GSI system. *Mon. Wea. Rev.*, (submitted Jan, 2010).

Neiman, P. J., F.M. Ralph, G.A. Wick, J. Lundquist, and M.D. Dettinger, 2008a: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations. *J. Hydrometeor*., **9**, 22-47.

Neiman, P. J., F.M. Ralph, G.A. Wick, Y.-H. Kuo, T.-K. Wee, Z. Ma, G.H. Taylor, and M.D. Dettinger, 2008b: Diagnosis of an intense atmospheric river impacting the Pacific Northwest: Storm summary and offshore vertical structure observed with COSMIC satellite retrievals. *Mon. Wea. Rev.*, **136**, 4398-4420.

Ralph, F. M., P. J. Neiman, and G.A. Wick, 2004: Satellite and CALJET aircraft observations of atmospheric rivers over the eastern North-Pacific Ocean during the winter of 1997/98. *Mon. Wea. Rev.*, **132**, 1721-1745.

Ralph, F. M., P. J. Neiman, and R. Rotunno, 2005: Dropsonde Observations in Low-Level Jets Over the Northeastern Pacific Ocean from CALJET-1998 and PACJET-2001: Mean Vertical-Profile and Atmospheric-River Characteristics. *Mon. Wea. Rev.*, **133**, 889-910.

Ralph, F. M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, and A. B. White, 2006: Flooding on California's Russian River: Role of atmospheric rivers. *Geophys. Res. Lett.*, **33**, L13801, doi:10.1029/2006GL026689.

Ralph, F. M., P. J. Neiman, G. N. Kiladis, K. Weickman, and D. W. Reynolds, 2010: A multi-scale observational case study of a Pacific atmospheric river exhibiting tropical-extratropical connections and a mesoscale frontal wave. *Mon. Wea. Rev.*, (accepted October 2010).

Smith, B.L., S.E. Yuter, P.J. Neiman, and D.E. Kingsmill, 2010: Water vapor fluxes and orographic precipitation over northern California associated with a land-falling atmospheric river. *Mon. Wea. Rev.*, **138**, 74-100.

Stohl, A., C. Forster, and H. Sodemann, 2008: Remote sources of water vapor forming precipitation on the Norwegian west coast at 60º N - a tale of hurricanes and an atmospheric river. *J. Geophys. Res.***113**, D05102, doi:10.1029/2007JD009006.

Zhu, Y, and R. E. Newell, 1998: A proposed algorithm for moisture fluxes from atmospheric rivers. *Mon. Wea. Rev.*, **126**, 725-735.

# Atmospheric Rivers Bibliography (red font denote studies presented here)

**Journal articles on atmospheric river related topics**

Criteria for inclusion: the term "Atmospheric river" is used in the abstract or text, or the study focuses on horizontal water vapor transport closely related to atmospheric rivers, but different jargon is used.


Bao, J.-W., S. A. Michelson, P.J. Neiman, F. M. Ralph and J. M. Wilczak, 2006: Interpretation of enhanced integrated water vapor bands associated with extratropical cyclones: Their formation and connection to tropical moisture. *Mon. Wea. Rev.*, **134**, 1063-1080.

Brimelow, J. C., and G. W. Rueter, 2005: Transport of atmospheric moisture during three extreme rainfall events over the Mackenzie river basin. *J. Hydrometeor.*, **6**, 423-440.

Dettinger, M.D., H. Hidalgo, T. Das, D. Cayan, and N. Knowles, 2009, Projections of potential flood regime changes in California: California Energy Commission Report CEC-500-2009-050-D, 68 p.

Falvey, M., and R. Garreaud, 2007: Wintertime precipitation episodes in Central Chile: Associated meteorological conditions and orographic influences. *J. Hydrometeor.*, **8**, 171-193.

Jankov, I., P. J. Schultz, C. J. Anderson, and S. E. Koch, 2007: The impact of different physical parameterizations and their interactuions on cold-season QPF in the American River basin. *J. Hydrometeor.*, **8**, 1141-1151.

Junker, N. W., R. H. Grumm, R. Hart, L. F. Bosart, K. M. Bell, F. J. Pereira, 2008: Use of normalized anomaly fields to anticipate extreme rainfall in the mountains of northern California. *Wea. Forecasting*, **23**, 336-356.

Knippertz, P., and J. E. Martin, 2007: A Pacific moisture conveyor belt and its relationship to a significant precipitation event in the semiarid Southwestern United States. *Wea. Forecasting*, **22**, 125–144

Knippertz, P., and H. Wernli, 2010: A Lagrangian climatology of tropical moisture exports to the Northern Hemispheric extratropics. *J. Climate*, **23**, 987-1003.

Lackmann, G. M., J. R. Gyakum, and R. Benoit, 1998: Moisture transport diagnosis of a wintertime precipitation event in the Mackenzie River basin. *Mon. Wea. Rev.*, **126**, 668–692.

Morss, R. E., and F. M. Ralph, 2007: Use of information by National Weather Service Forecasters and emergency managers during the CALJET and PACJET-2001. *Wea. Forecast.*, **22**, 539-555.

Neiman, P. J., F.M. Ralph, A.B. White, D.E. Kingsmill, and P.O.G. Persson, 2002: The statistical relationship between upslope flow and rainfall in California's coastal mountains: Observations during CALJET. *Mon. Wea. Rev.*, **130**, 1468-1492.

Neiman, P. J., P.O.G. Persson, F.M. Ralph, D.P. Jorgensen, A.B. White, and D.A. Kingsmill, 2004: Modification of fronts and precipitation by coastal blocking during an intense landfalling winter storm in Southern California: Observations during CALJET. *Mon. Wea. Rev.*, **132**, 242-273.

Neiman, P.J., A.B. White, F.M. Ralph, D.J. Gottas, and S.I. Gutman, 2009: A Water Vapor Flux Tool for Precipitation Forecasting. U.K. */Journal of Water Management/*, **162**, 83-94.

# Atmospheric Rivers Bibliography (red font denote studies presented here)

**Journal articles on atmospheric river related topics (continued)**

Criteria for inclusion: the term "Atmospheric river" is used in the abstract or text, or the study focuses on horizontal water vapor transport closely related to atmospheric rivers, but different jargon is used.


Neiman, P.J., E.M. Sukovich, F.M. Ralph, and M. Hughes, 2010: A seven-year wind profiler-based climatology of the windward barrier jet along California's northern Sierra Nevada. *Mon. Wea. Rev.*, **138**, 1206-1233.

Persson, P.O.G., P.J. Neiman, B. Walter, J.-W. Bao and F.M. Ralph, 2005: Contributions from California coastal-zone surface fluxes to heavy coastal precipitation: A CALJET case study During the Strong El Niño of 1998. *Mon. Wea. Rev.*, **133**, 1175-1198.

Ralph, F. M., P. J. Neiman, D. E. Kingsmill, P. O. G. Persson, A. B. White, E. T. Strem, E. D. Andrews, and R. C. Antweiler, 2003: The impact of a prominent rain shadow on flooding in California's Santa Cruz mountains: A CALJET case study and sensitivity to the ENSO cycle. *J. Hydrometeor.*, **4**, 1243-1264.

Ralph, F. M., R. M. Rauber, B. F. Jewett, D. E. Kingsmill, P. Pisano, P. Pugner, R. M. Rassmussen, D. W. Reynolds, T. W. Schlatter, R. E. Stewart and J. S. Waldstreicher, 2005b: Improving short-term (0-48 hour) Cool-season quantitative precipitation forecasting: Recommendations from a USWRP Workshop. *Bull. Amer. Meteor. Soc.*, **86**, 1619-1632.

Ralph, F. M., E. Sukovich, D. Reynolds, M. Dettinger, S. Weagle, W. Clark, P.J. Neiman, 2010: Assessment of extreme quantitative precipitation forecasts and development of regional extreme event thresholds using data from HMT-2006 and COOP observers. *J. Hydrometeor*., (in press April 2010).

Smirnov, V. V., and G. W. K. Moore, 1999: Spatial and temporal structure of atmospheric water vapor transport in the Mackenzie River basin. *J. Clim.*, **12**, 681–696.

Smirnov, V. V., and G. W. K. Moore, 2001: Short-term and seasonal variability of atmospheric water vapor transport through the Mackenzie River basin. *J. Hydrometeor.*, **2**, 441-452.

Sodemann, H., H. Wernli, and C. Schwierz 2009: Sources of water vapour contributing to the Elbe flood in August 2002-A tagging study in a mesoscale model. *Quarterly Journal of the Royal Meteorological Society* **135**:638, 205-223

Wick, G. A., Y. Kuo, F. M. Ralph, T. Wee, and P. J. Neiman, 2008: Intercomparison of integrated water vapor retrievals from SSM/I and COSMIC, *Geophys. Res. Lett*., **35**, L21805, doi:10.1029/2008GL035126.

Wratt, D. S., R.N. Ridley, M.R. Sinclair, H. Larsen, S.M. Thompson, R. Henderson, G.L. Austin, S.G. Bradley, A. Auer, A.P. Sturman, I. Owens, B. Fitzharris, B.F. Ryan, and J.-F. Gayet, 1996: The New Zealand Southern Alps Experiment. *Bull. Amer. Meteor. Soc.*. **77**, 683–692.

Yuan, H. J., J. A. McGinley, P. J. Schultz, C. J. Anderson, and C. Lu, 2008: Short-range precipitation forecasts from time-lagged multimodel ensembles during HMT-West 2006 field campaign. *J. Hydrometeor.*, **9**, 477-491.

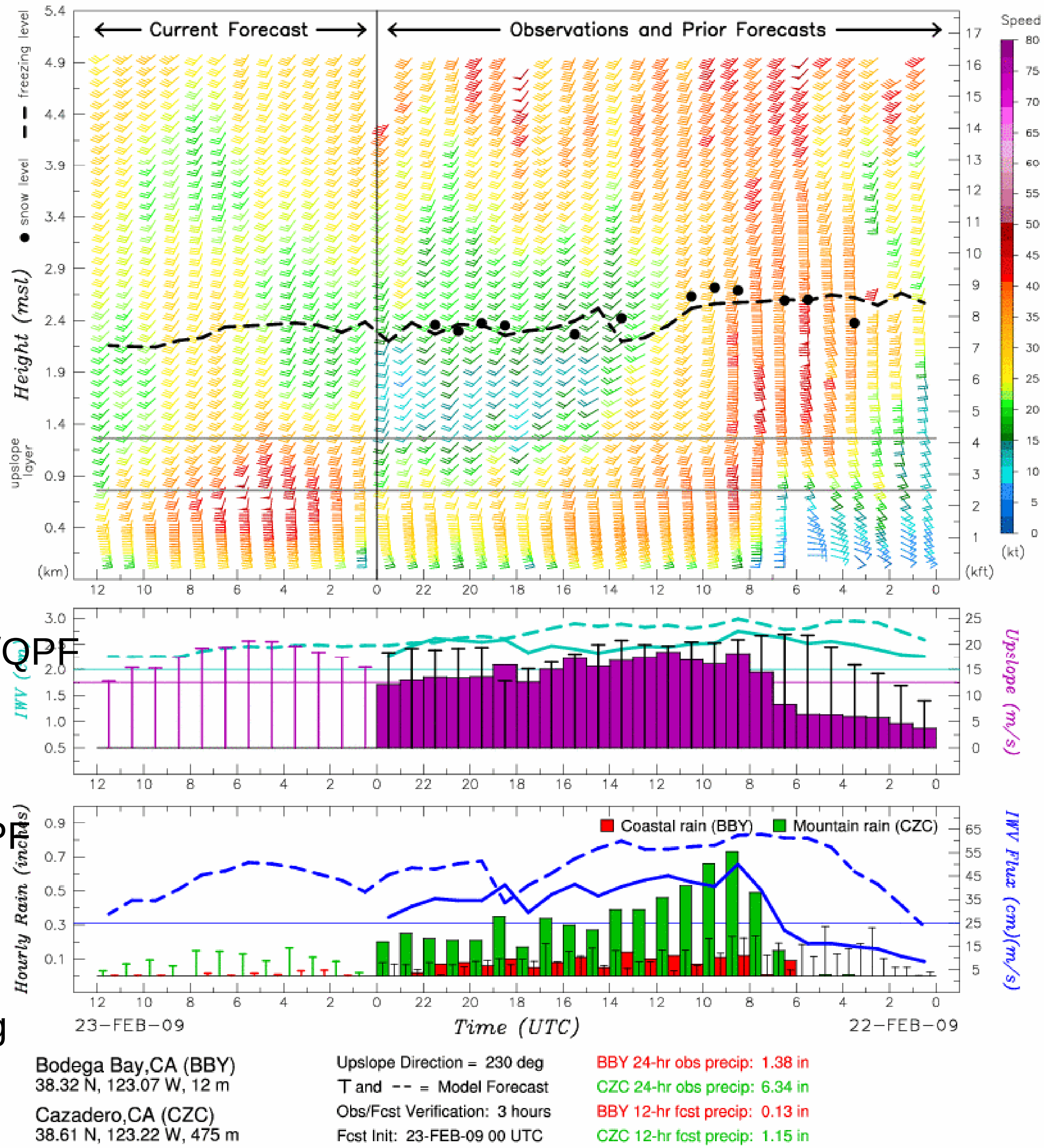
# Backup slides on ARO display

## 2nd generation flux tool: Observations & model

ARW Model: NOAA/GSD:
-5 km resolution; 51 levels
-LAPS initial conditions
-GFS for lateral BCs (NAM)
-Schultz microphysics
-model reinitialized hourly
-generates 12-h forecast
-available 0.9-1.8 h later

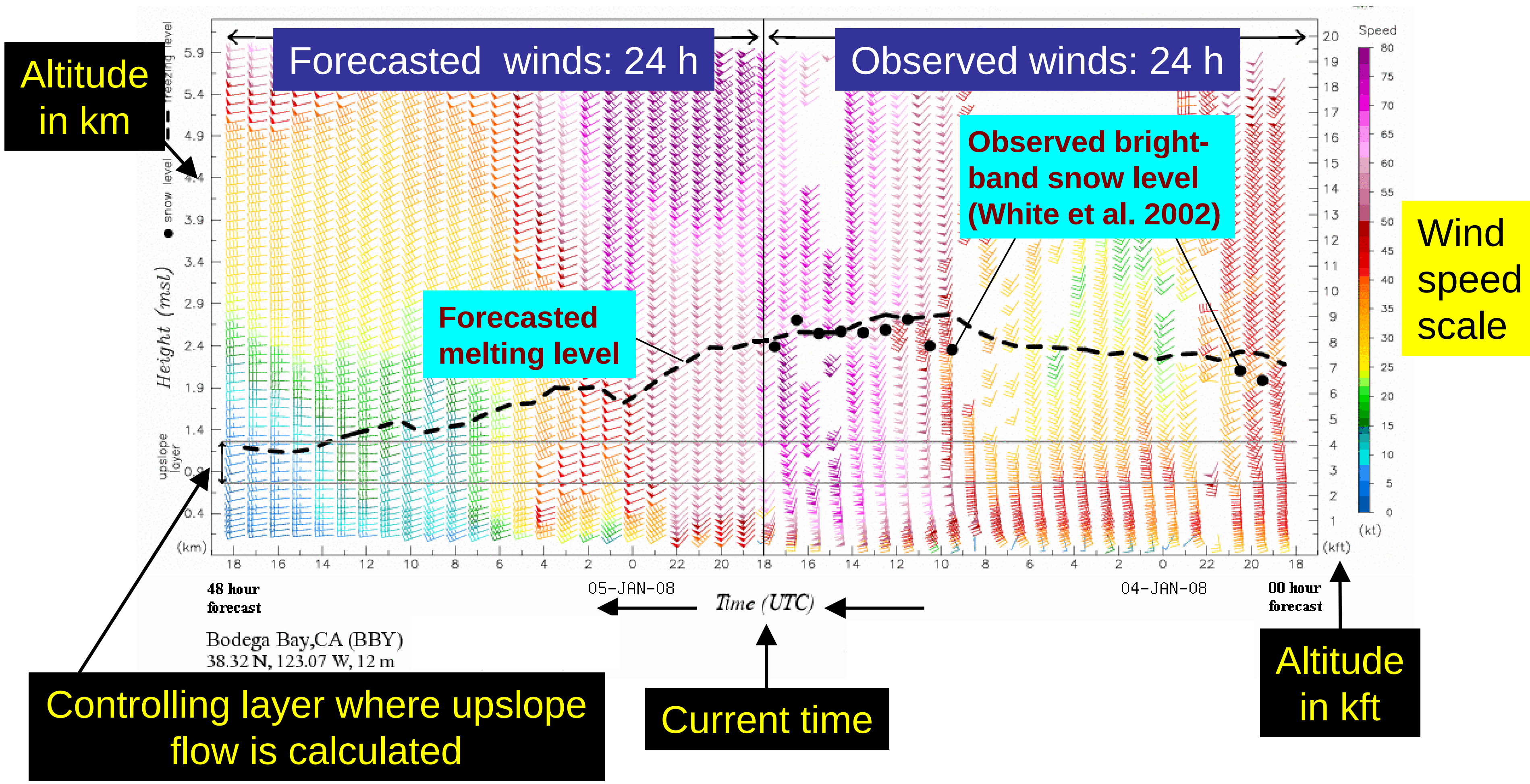
Model tendencies:
-no gap flow; too much flux/QPF
-overestimate upslope flow
-closer on IWV
-overestimate IWV flux
-way underestimate mtn QPF

Comparison of obs and model serves to calibrate predicted orographic forcing and resulting QPF in the short range.

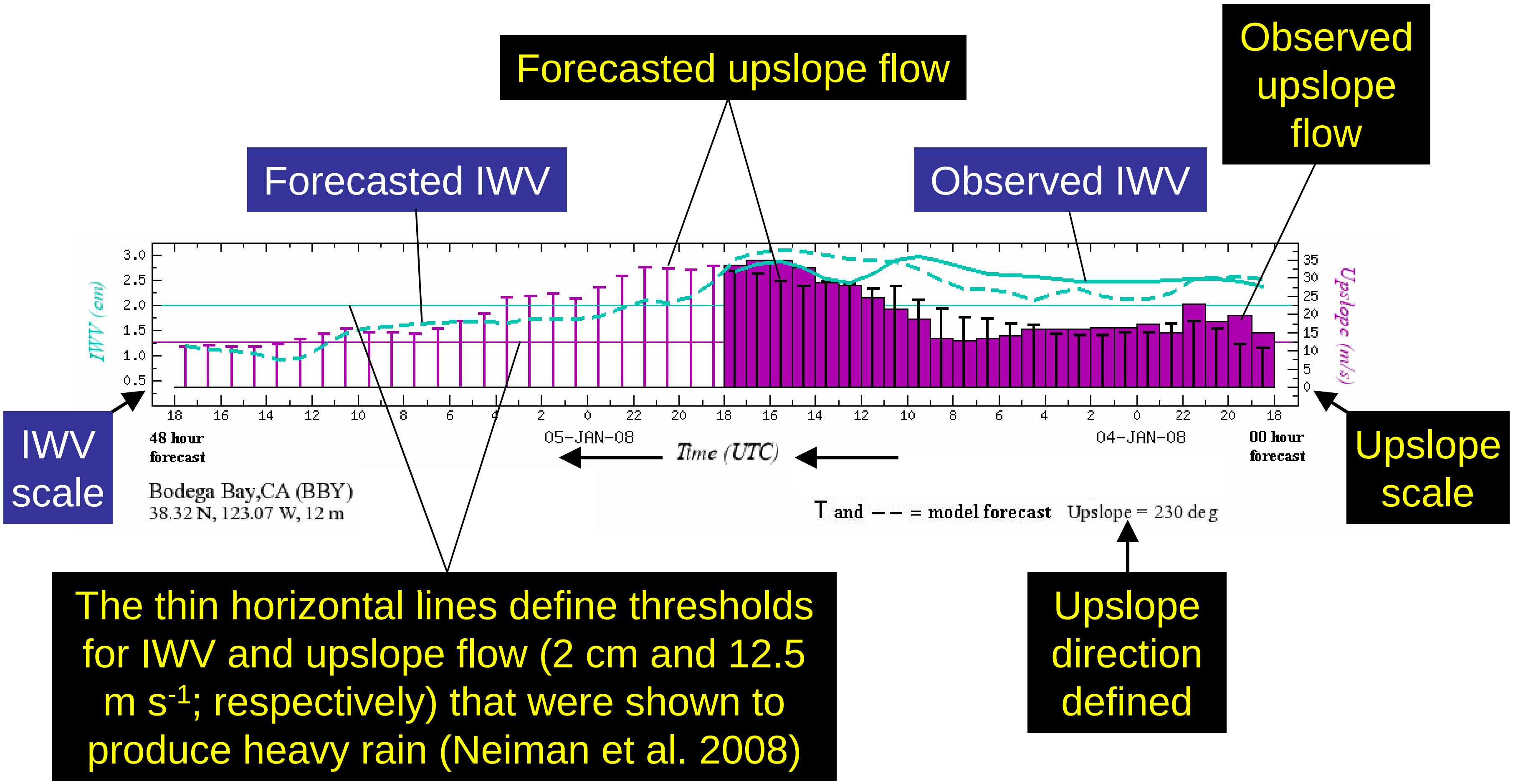


# The top of three panels of the forecast tool displays hourly wind profiles and snow levels

Model: Advanced Research WRF (ARW), 48-h duration
Grid configuration: 3 km horizontal, 30 vertical levels



# The middle panel displays the upslope component of the flow and the IWV



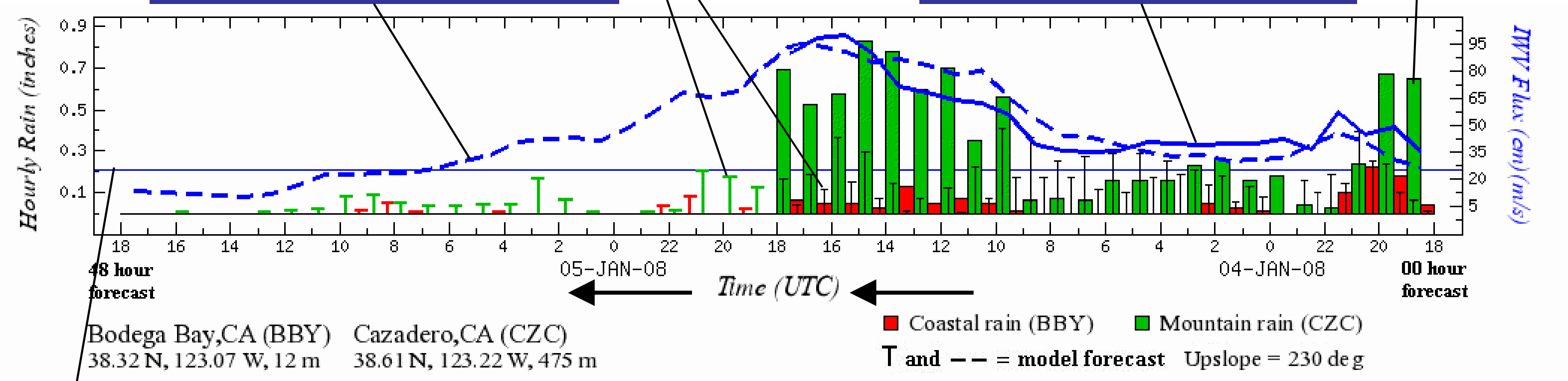
# The IWV and upslope flow from the middle panel are combined to produce a bulk IWV flux, which is displayed in the bottom panel along with the coastal and mountain hourly rainfall

Forecasted rainfall (T posts):
Red = coastal site
Green = mountain site

Observed rainfall (bars):
Red = coastal site
Green = mountain site

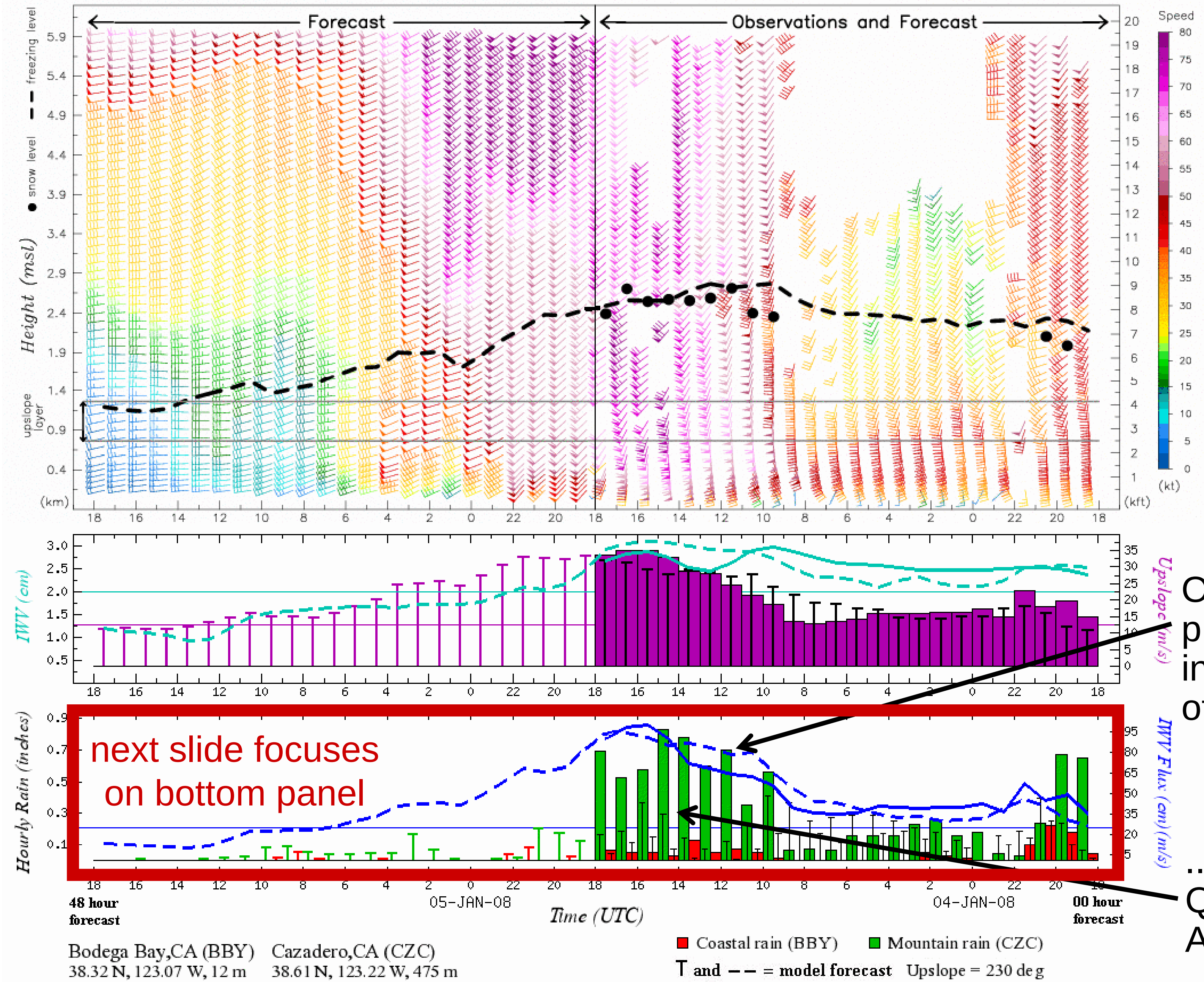
Forecasted IWV flux

Observed IWV flux




The thin blue horizontal line gives the IWV flux threshold (25 cm x m $s^{-1}$) determined by multiplying the IWV and upslope flow thresholds defined in the middle panel

# Northern couplet: BBY & CZD



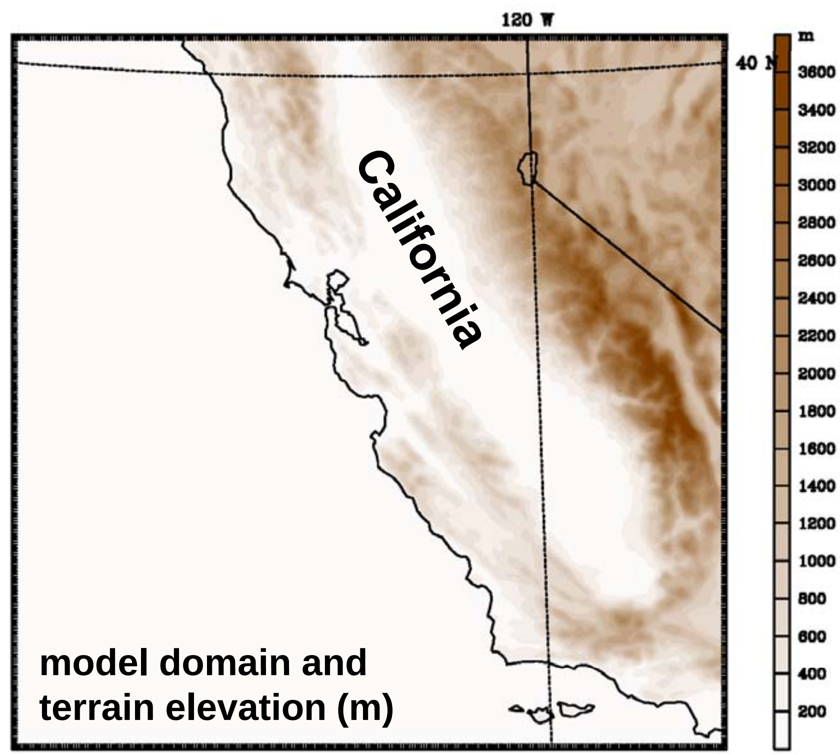

Orogr. forcing predicted well in this portion of the AR...

...but not the QPF, esp. in AR conditions.

**Compare observations with numerical model results to gauge how well the model is performing with respect to the orographic forcing and associated QPF.**

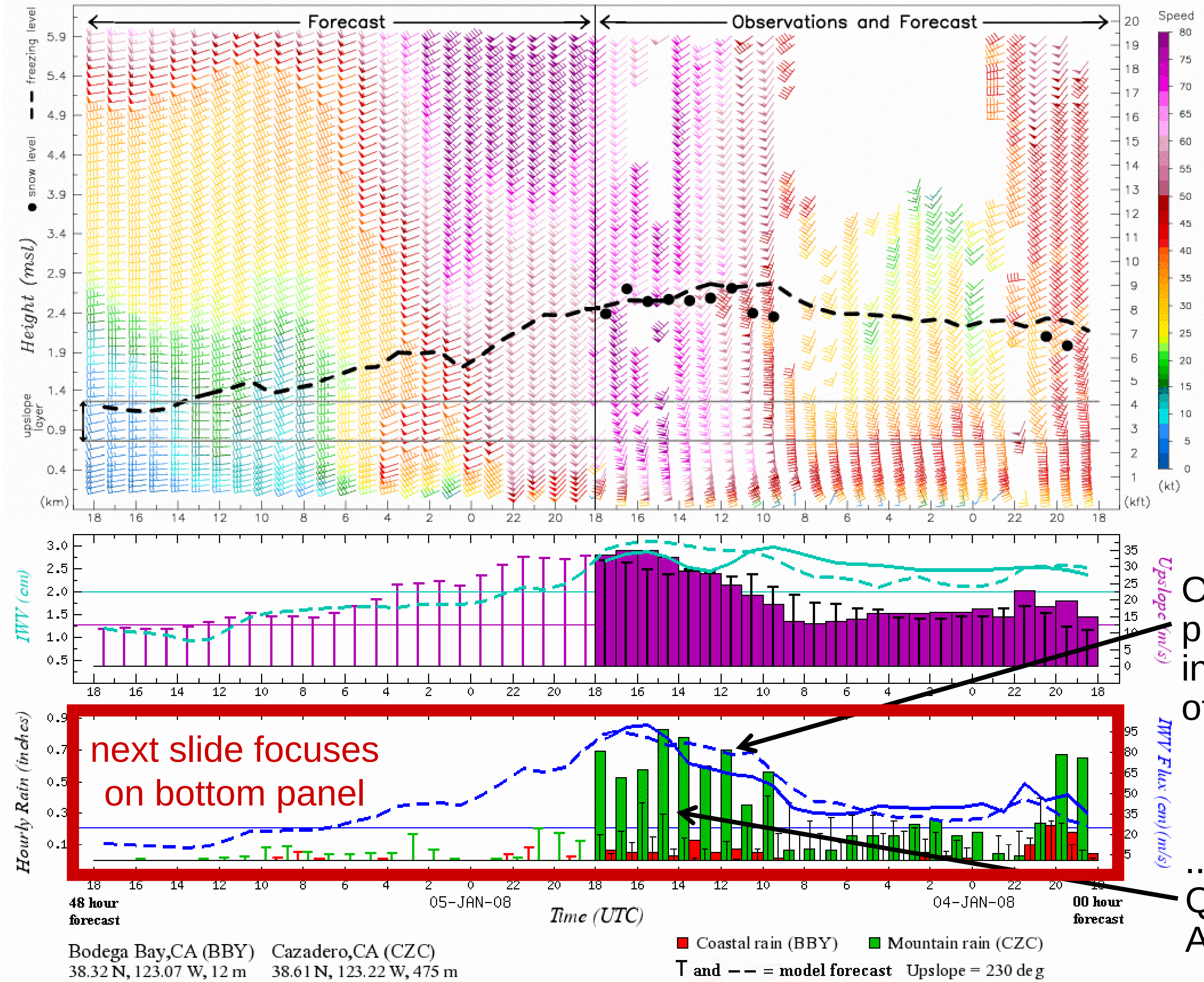
## Forecast Model Configuration

- **Model type: Advanced Research WRF (ARW)**
- **Grid Configuration:**
  - **- 3 km horizontal grid spacing**
  - **- 30 vertical layers**
- **Forecast duration: 48 hour forecast**
- **Model Physics:**
  - **- Ferrier microphysics**
  - **- RRTM long-wave radiation**
  - **- Dudhia short-wave scheme**
  - **- MRF surface layer scheme**
  - **- thermal diffusion land-surface scheme**
  - **- YSU boundary layer scheme**
- **Initial and boundary conditions:**
  - **- NAM forecast**



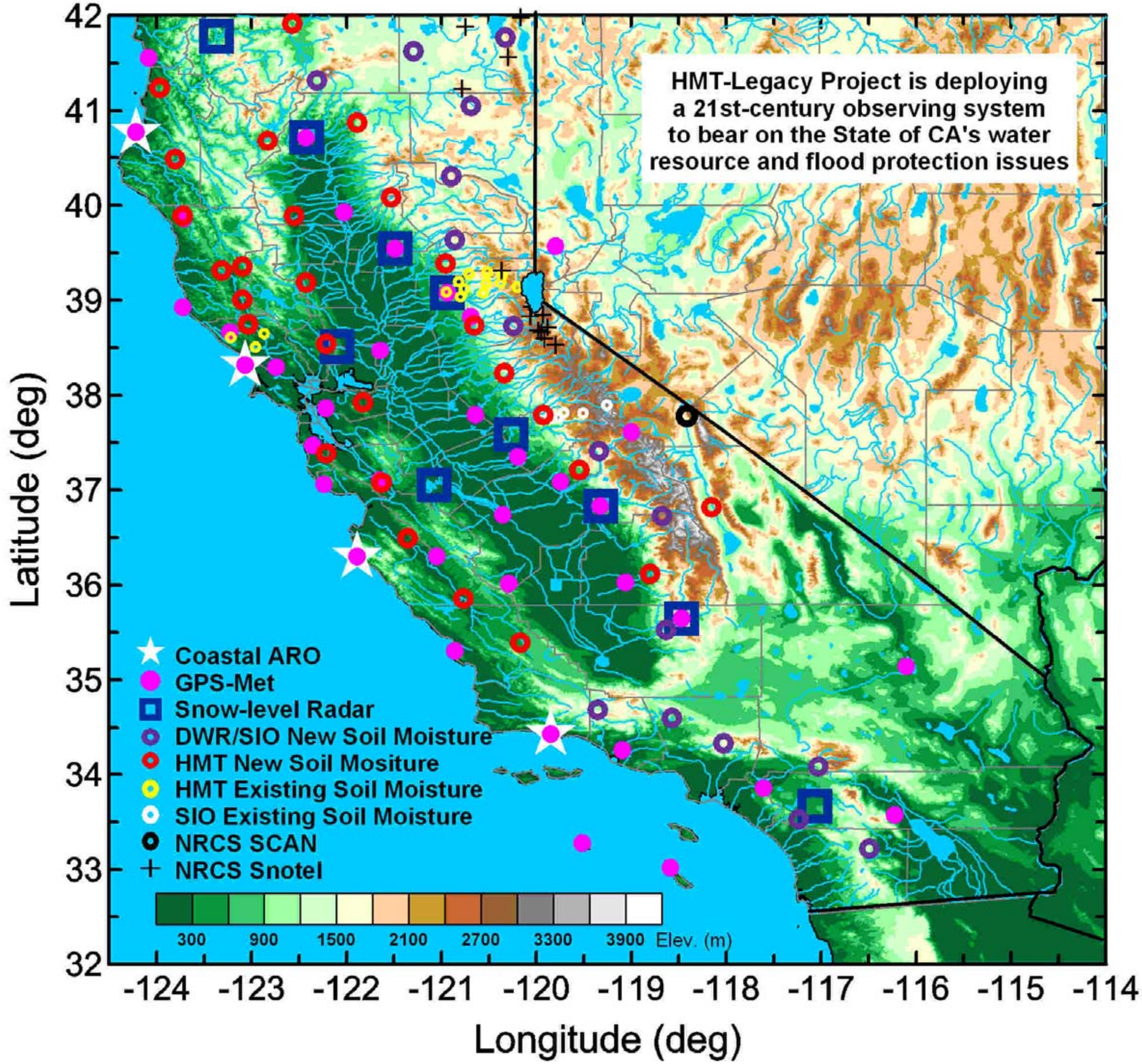

**model domain and terrain elevation (m)**

# Northern couplet: BBY & CZD




Orogr. forcing predicted well in this portion of the AR...

...but not the QPF, esp. in AR conditions.



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)
42 41 40 39 38 37 36 35 34 33 32
Longitude (deg)
-124 -123 -122 -121 -120 -119 -118 -117 -116 -115 -114