# A Wind Profiler and GPS-Based Water Vapor Flux Tool for Precipitation Forecasting in Coastal Mountains

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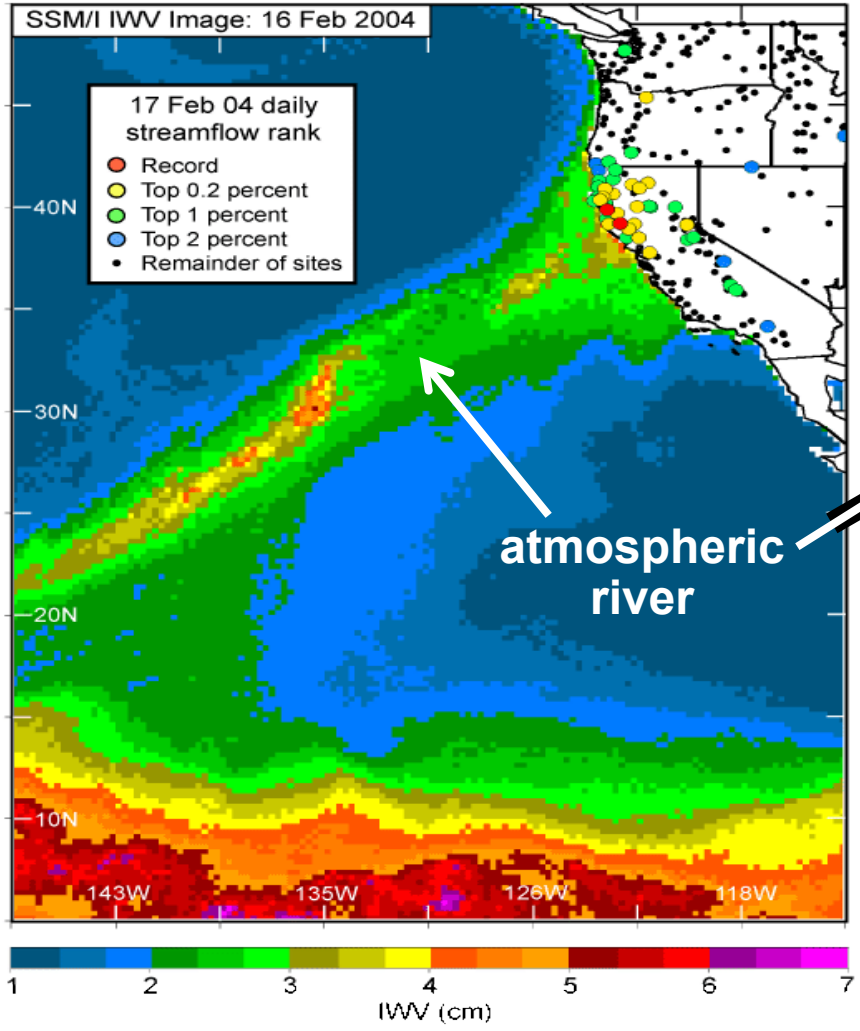
# Purpose and Outline

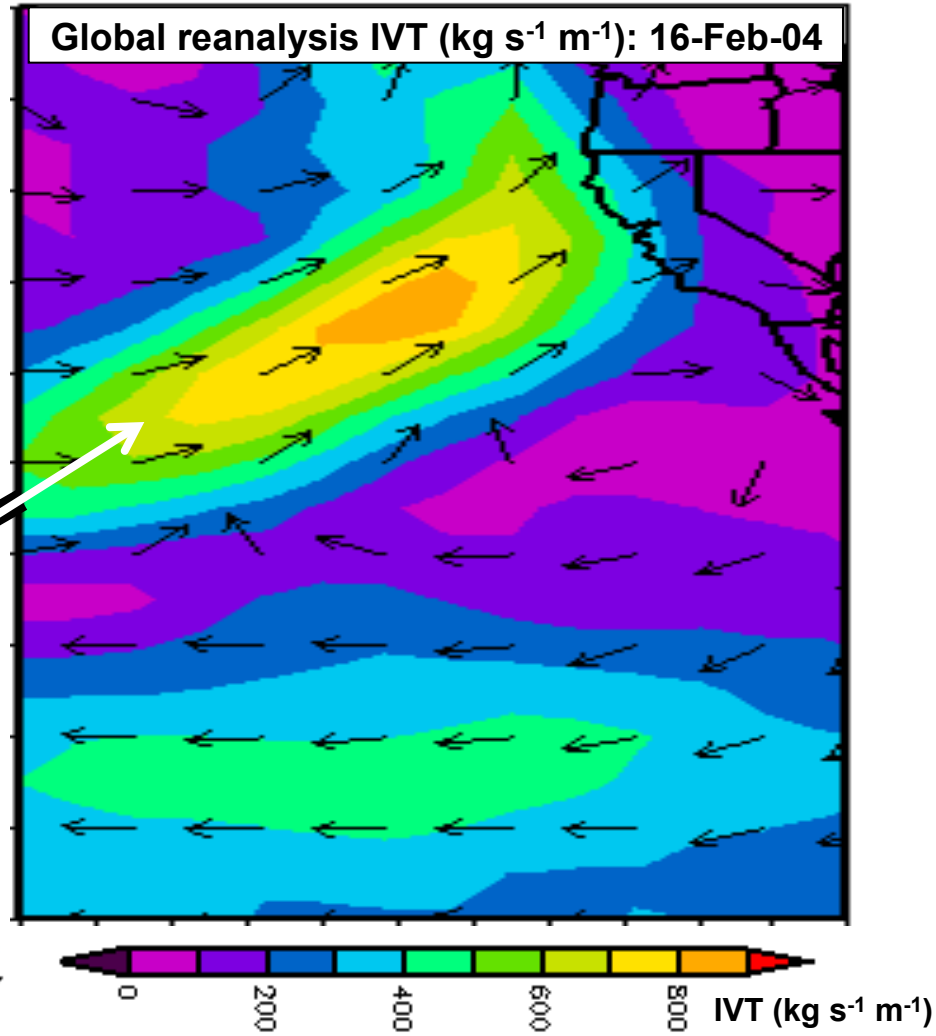
Purpose: To describe the development of a prototype real-time observation and model forecast evaluation tool of low-level water vapor flux as a key determinant of orographic precipitation in extreme events.

Outline

- Scientific background
- An integrated observing system
- Comparison with mesoscale model forecast
- Local Analysis and Prediction System (LAPS)
- Conclusions

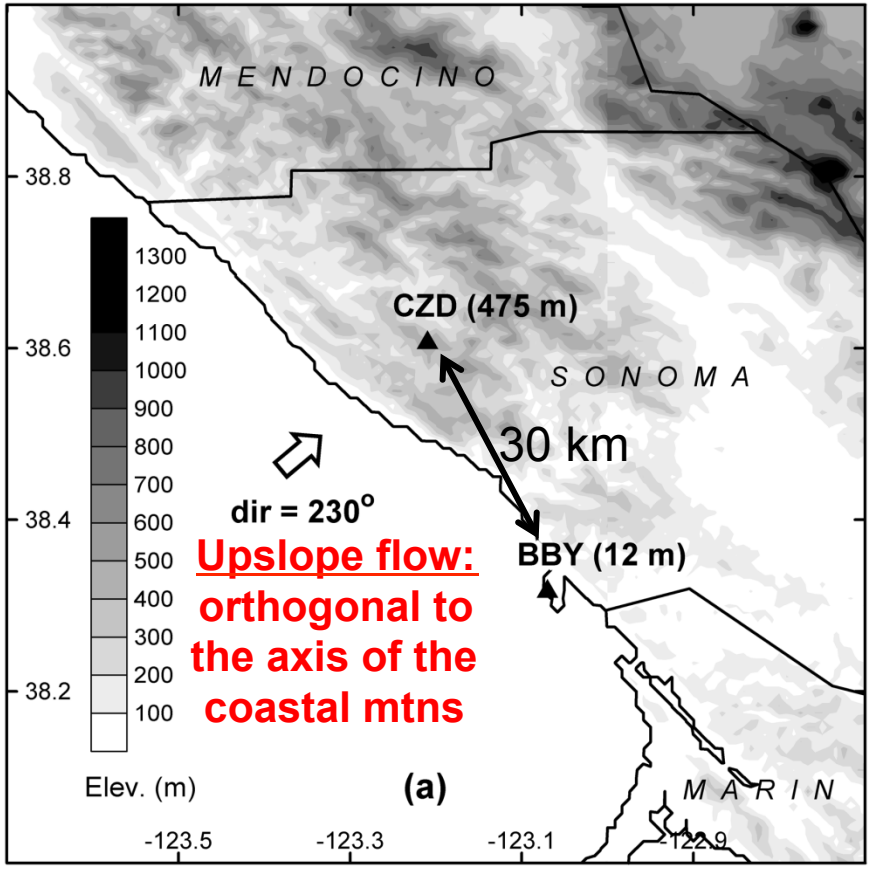
- Heavy cool-season rain & flood events along the U.S. West Coast are orographically driven and occur most often when narrow warm-sector corridors of strong water-vapor transport (i.e., atmospheric rivers – ARs) intersect the coastal mountains (e.g., Ralph et al. 2006 in *GRL*; Neiman et al. 2008 in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



# Wintertime orographic forcing climatology along northern California coast

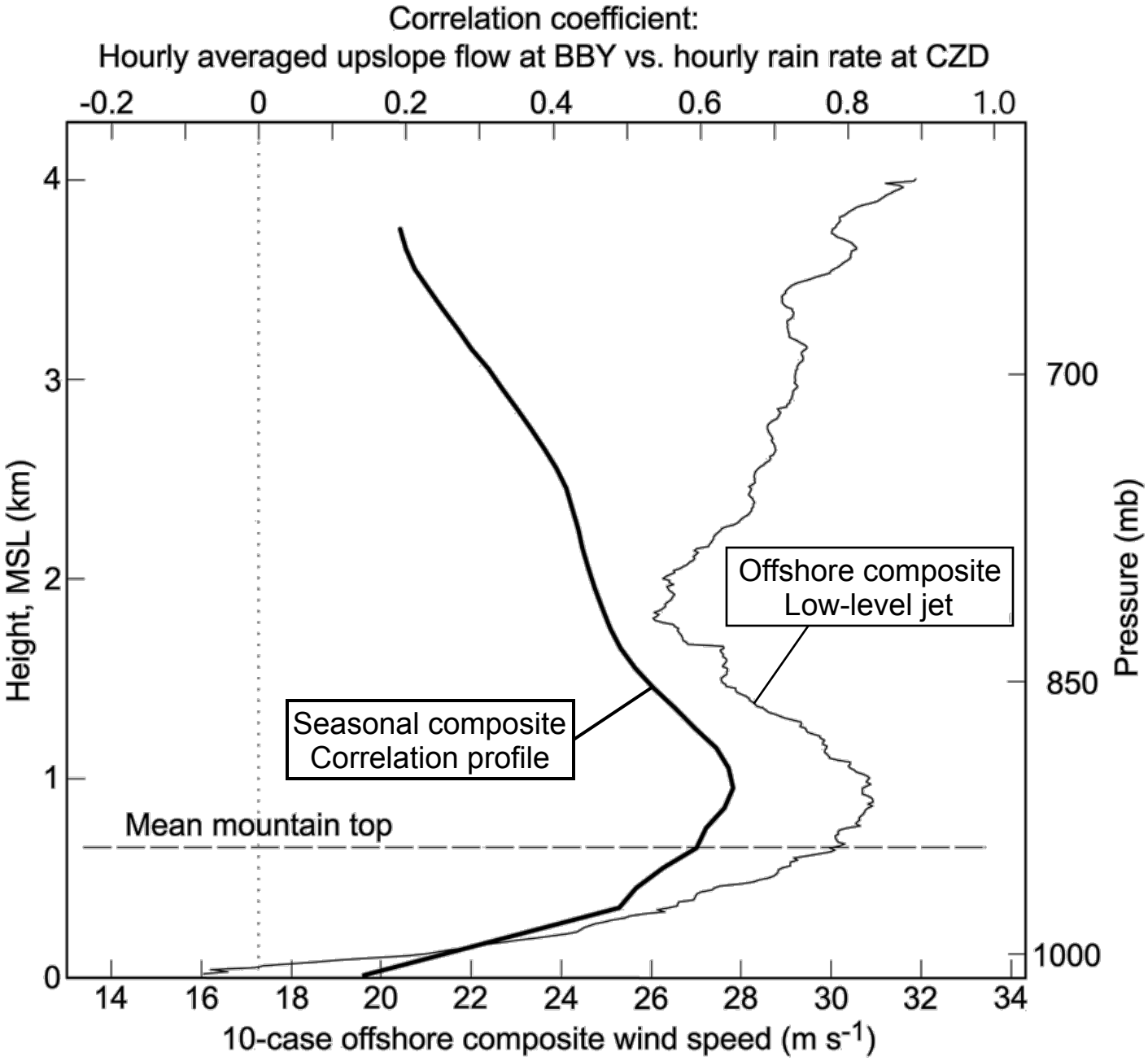
Developed real-time monitoring of vapor transports to assess the orographic forcing, based on published research using wind profilers, as well as GPS receivers that measure IWV

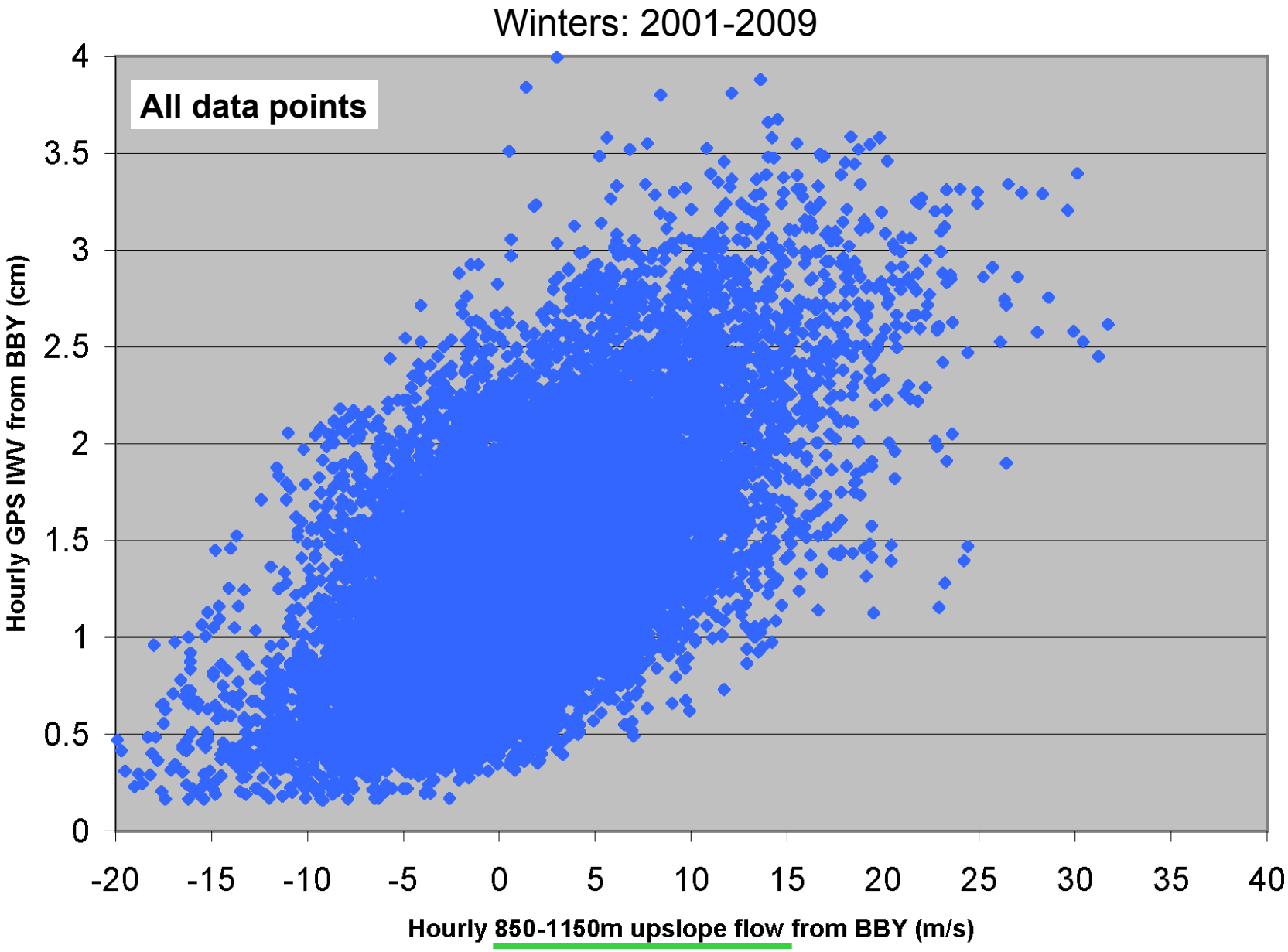



Neiman et al. (2002), *Mon. Wea. Rev.*

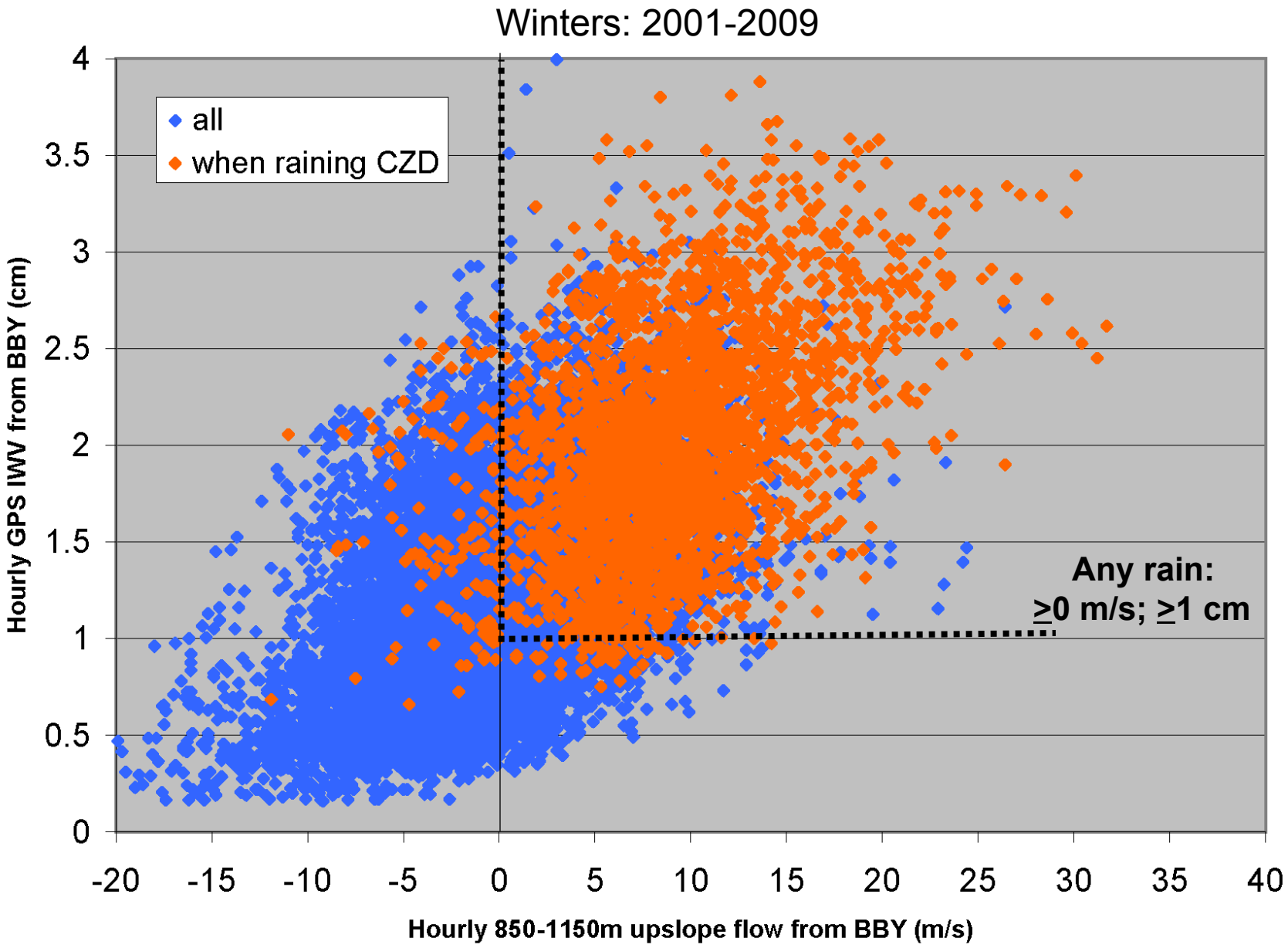
- Flood-prone Russian River Basin northwest of San Francisco: 2000/01, 2003/04, 2004/05, 2005/06, 2006/07, 2007/08, 2008/09
- Analyses for when the following observing systems were simultaneously operating – (a) Bodega Bay (BBY): GPS-IWV unit, 915-MHz wind profiler, rain gauge (b) Cazadero (CZD): rain gaugeTotal precip: CZD=6857 mm, BBY=2761 mm (ratio 2.48:1)
- 18347 hourly data points

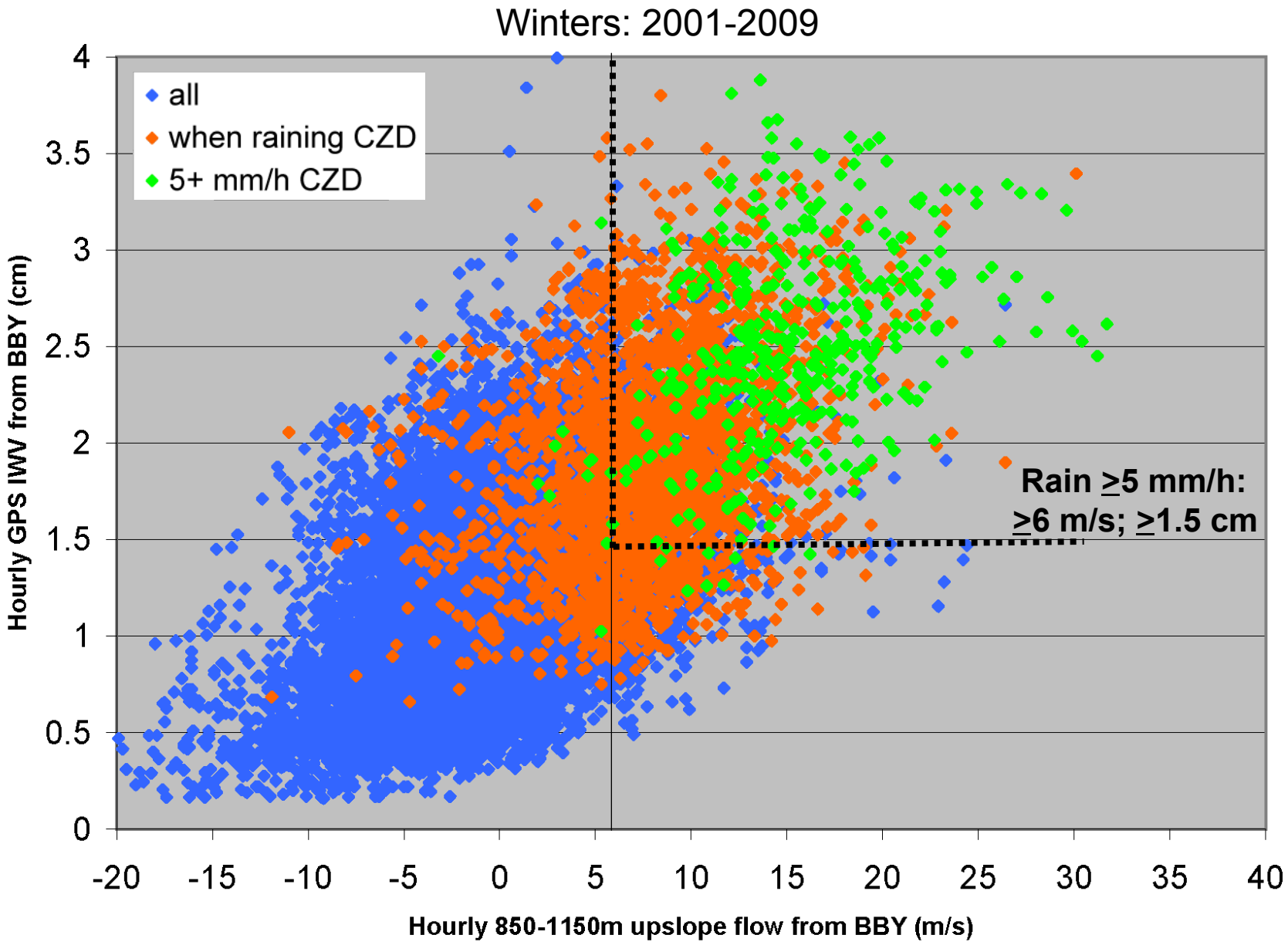
Neiman et al. (2008), *Water Management*

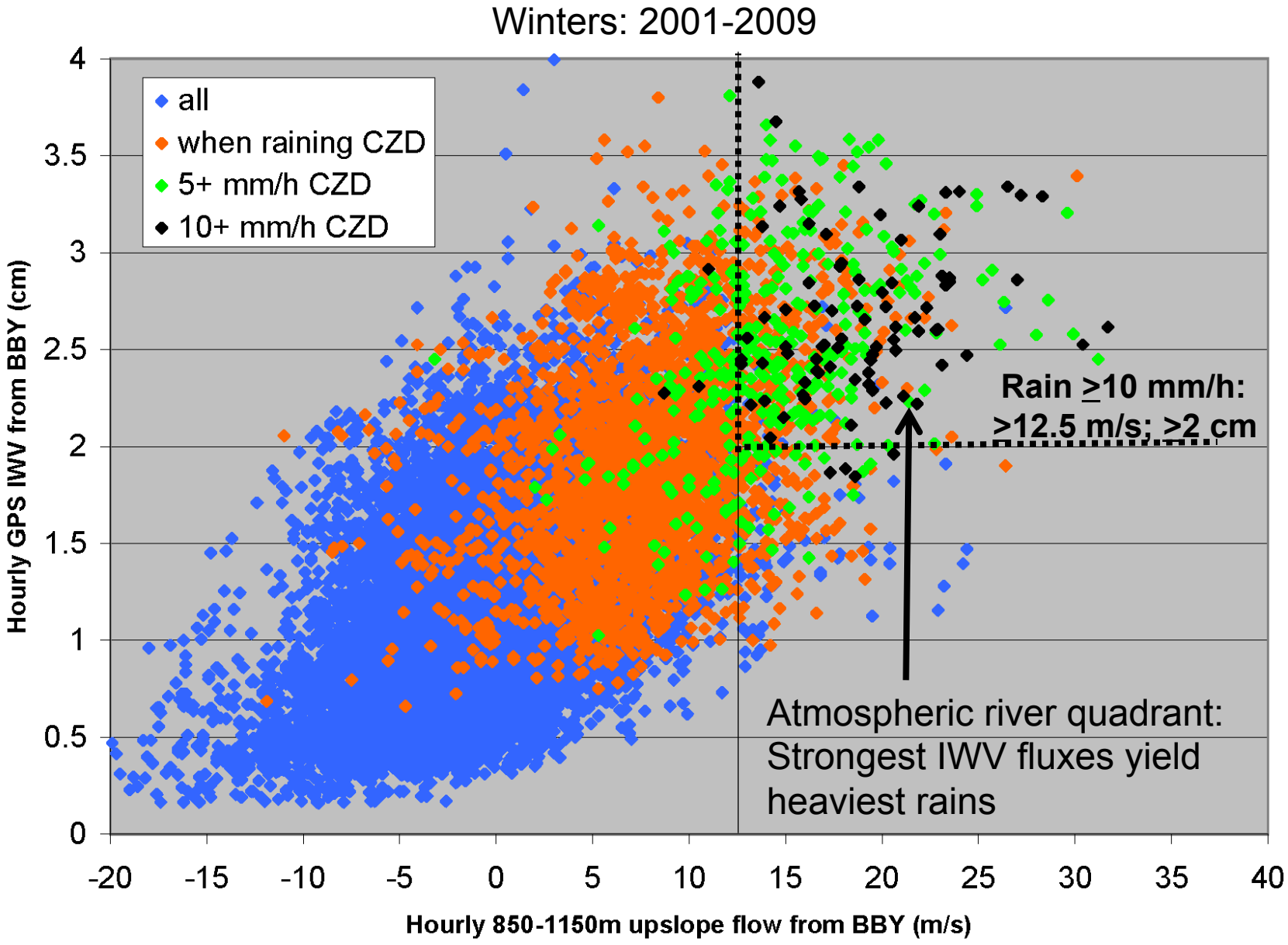

Correlation coefficient:
Hourly averaged upslope flow at BBY vs. hourly rain rate at CZD
-0.2
0
0.2
0.4
0.6
0.8
1.0
Height, MSL (km)
4
3
2
1
0
Pressure (mb)
700
850
1000
Offshore composite
Low-level jet
Seasonal composite
Correlation profile
Mean mountain top
14
16
18
20
22
24
26
28
30
32
34
10-case offshore composite wind speed (m s-1)




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

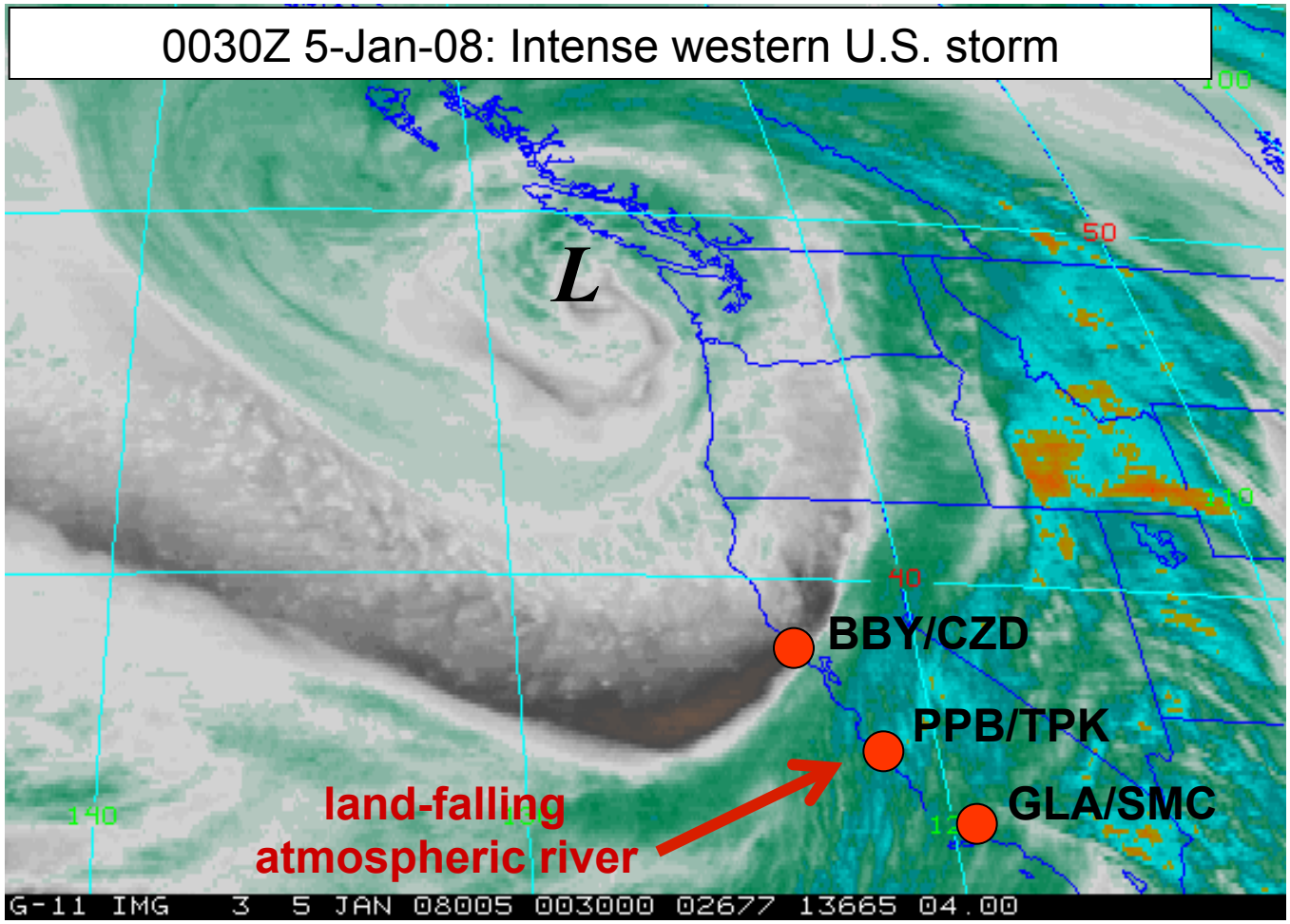

Winters: 2001-2009
all
when raining CZD
Any rain:
≥0 m/s; ≥1 cm
Hourly GPS IWV from BBY (cm)
Hourly 850-1150m upslope flow from BBY (m/s)
4
3.5
3
2.5
2
1.5
1
0.5
0
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40


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)
4
3.5
3
2.5
2
1.5
1
0.5
0
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40



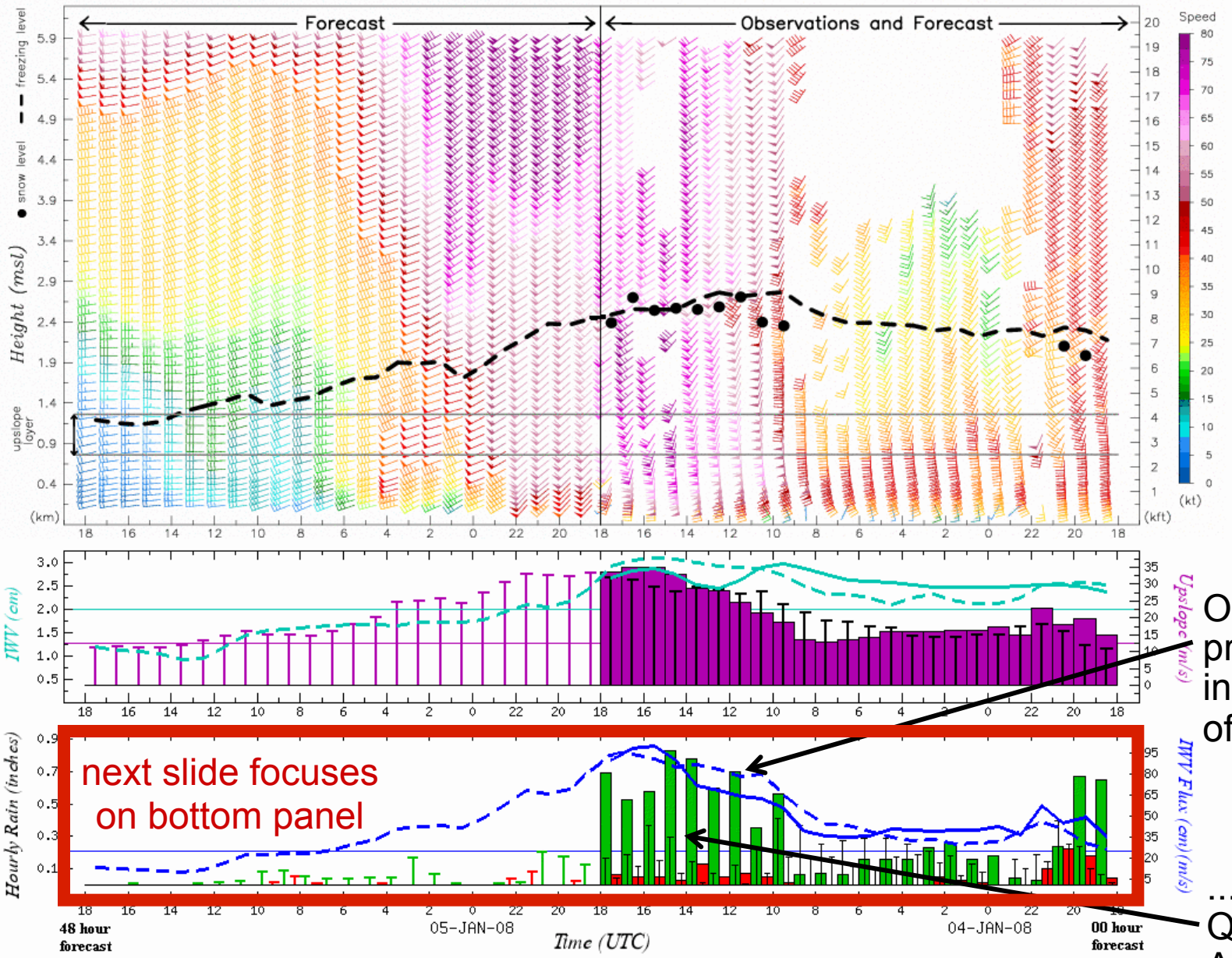

*Nearly 2/3 of tropospheric water vapor is in the lowest 2 km MSL.
Hence, to first order, the IWV flux provides a close estimate
of the low-level water-vapor transport into the coastal mountains.

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



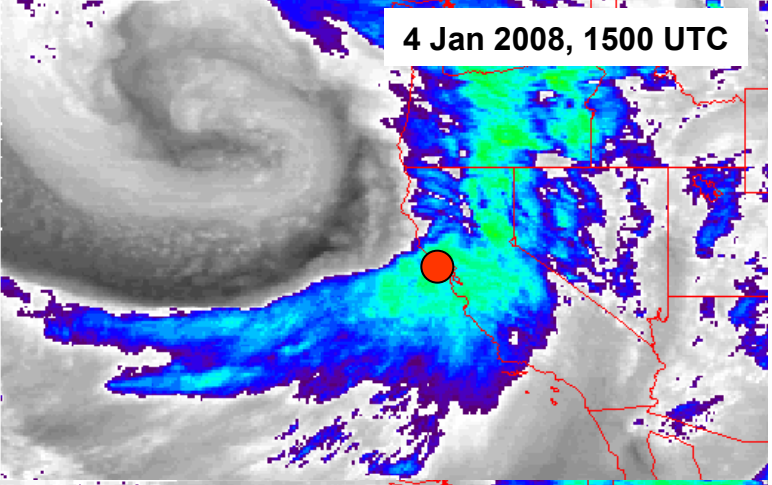

| **Couplet** | **Coast** (*profiler, GPS, rain gauge*): | **Mountains** (*rain gauge*): |
|---|---|---|
| North: | Bodega Bay (BBY; 12 m MSL) | Cazadero (CZD; 475 m MSL) |
| Central: | Piedras Blancas (PPB; 11 m MSL) | Three Peaks (TPK; 1021 m MSL) |
| South: | Goleta (GLA; 3 m MSL) | San Marcos Pass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

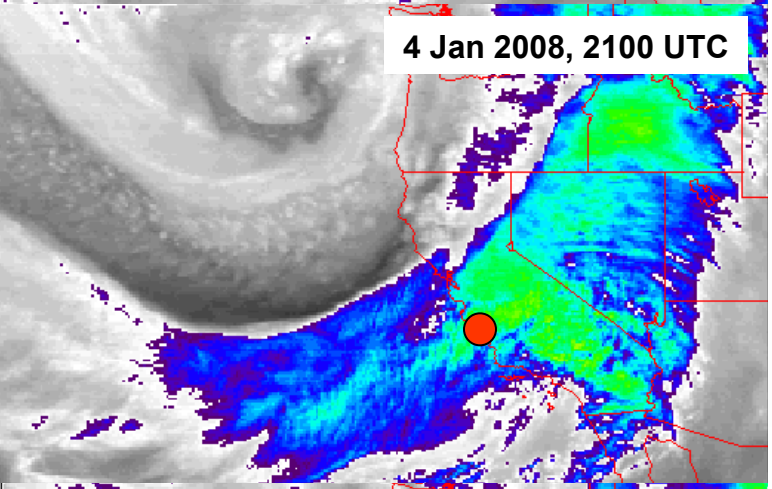
# Northern couplet: BBY & CZD

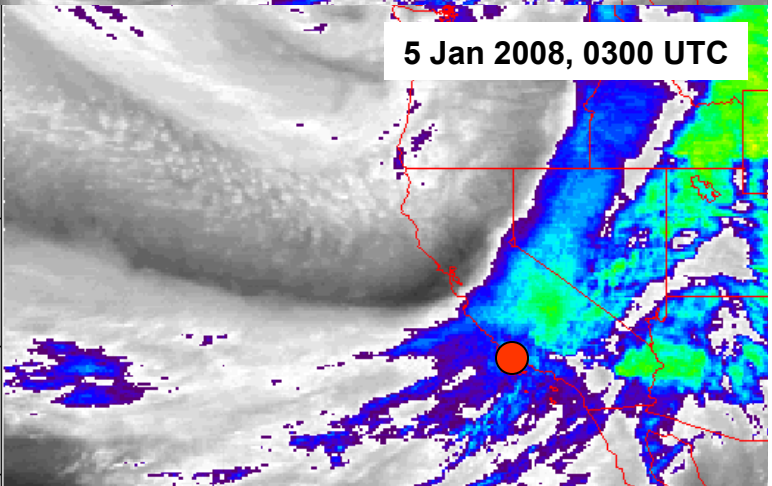



Orogr. forcing predicted well in this portion of the AR...

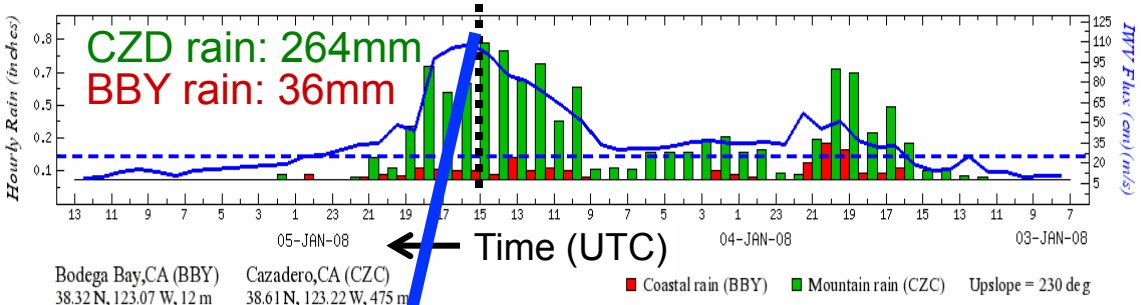
...but not the QPF, esp. in AR conditions.



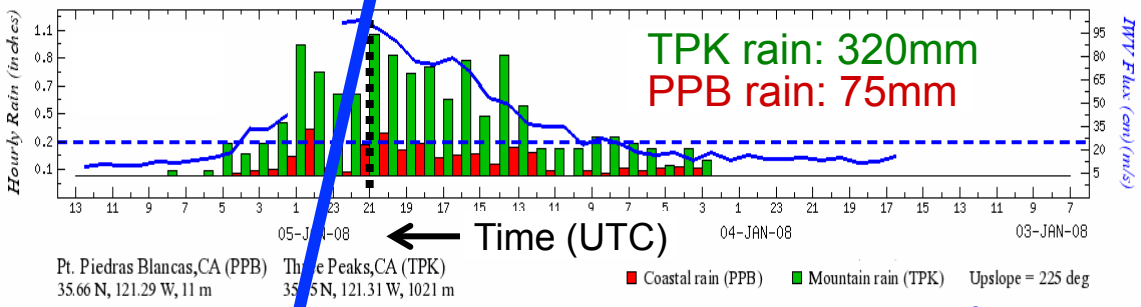




## Time of max. IWV flux at BBY: 1500 UTC 4-Jan-08



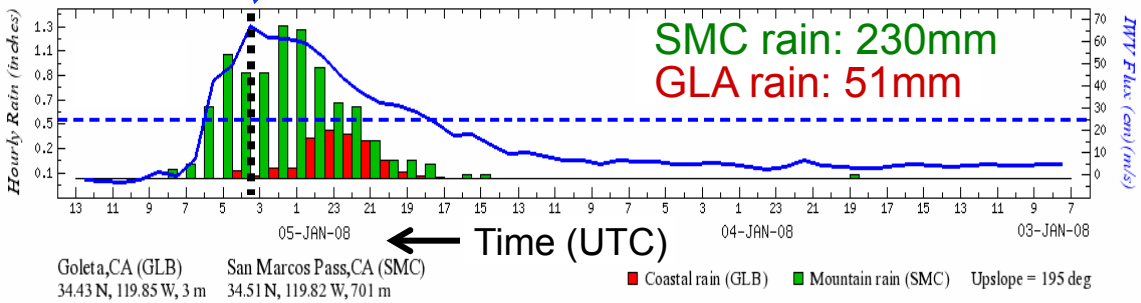

**Max. IWV flux in AR highly correlated with max. mountain rainfall at each site**

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

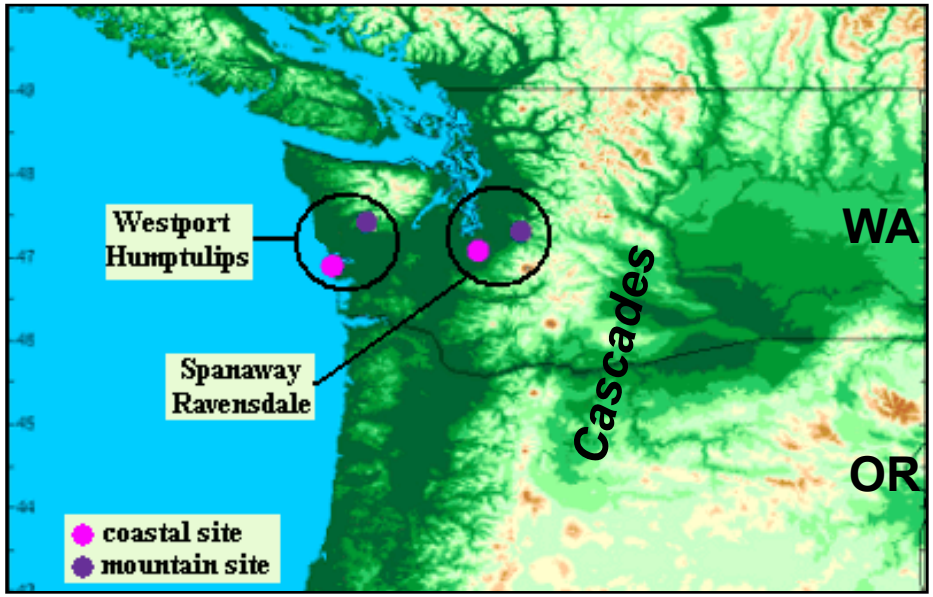



**AR Propagation: ~12 m $s^{-1}$. ½-day lead time for SoCal**

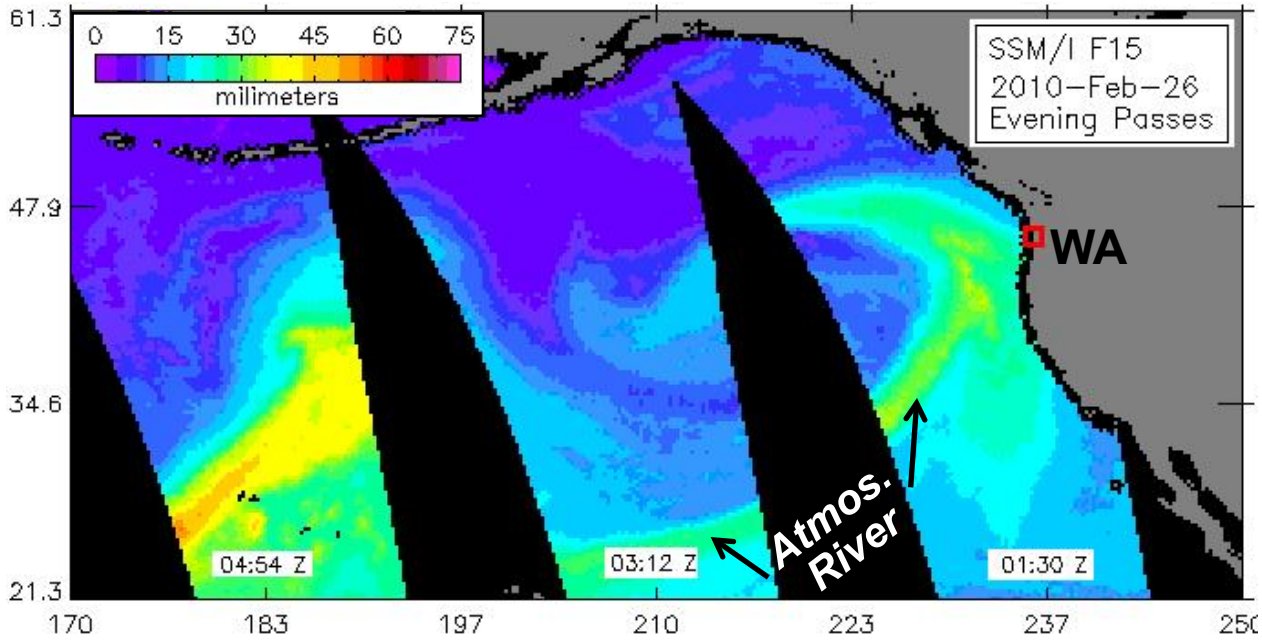
## Time of max. IWV flux at GLA: 0300 UTC 5-Jan-08



IWV flux tool expanded to the Pacific Northwest as part of the Howard Hanson Dam rapid response effort – discussed in more detail later in this meeting

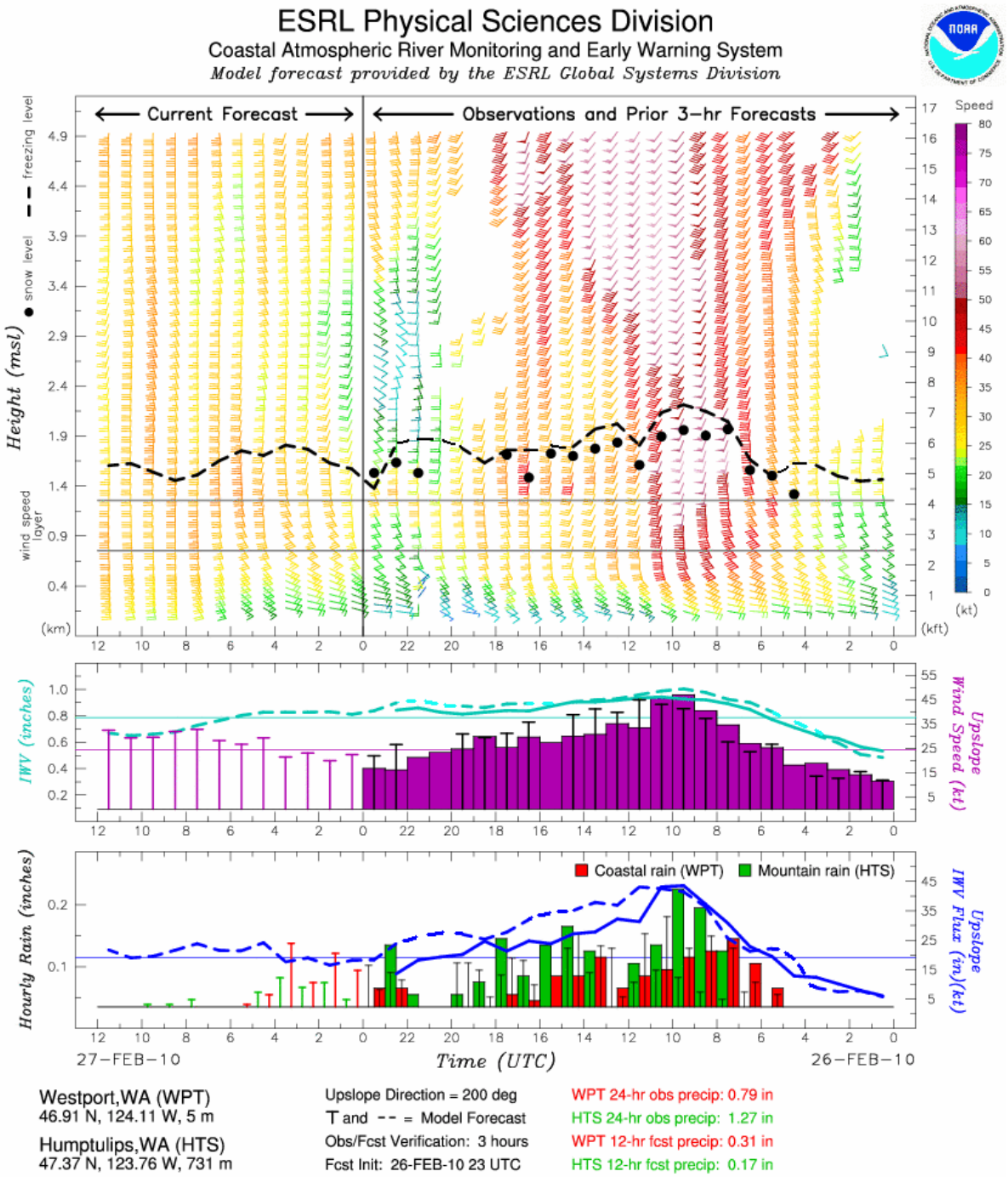



Two AROs deployed in the complex terrain of western Washington

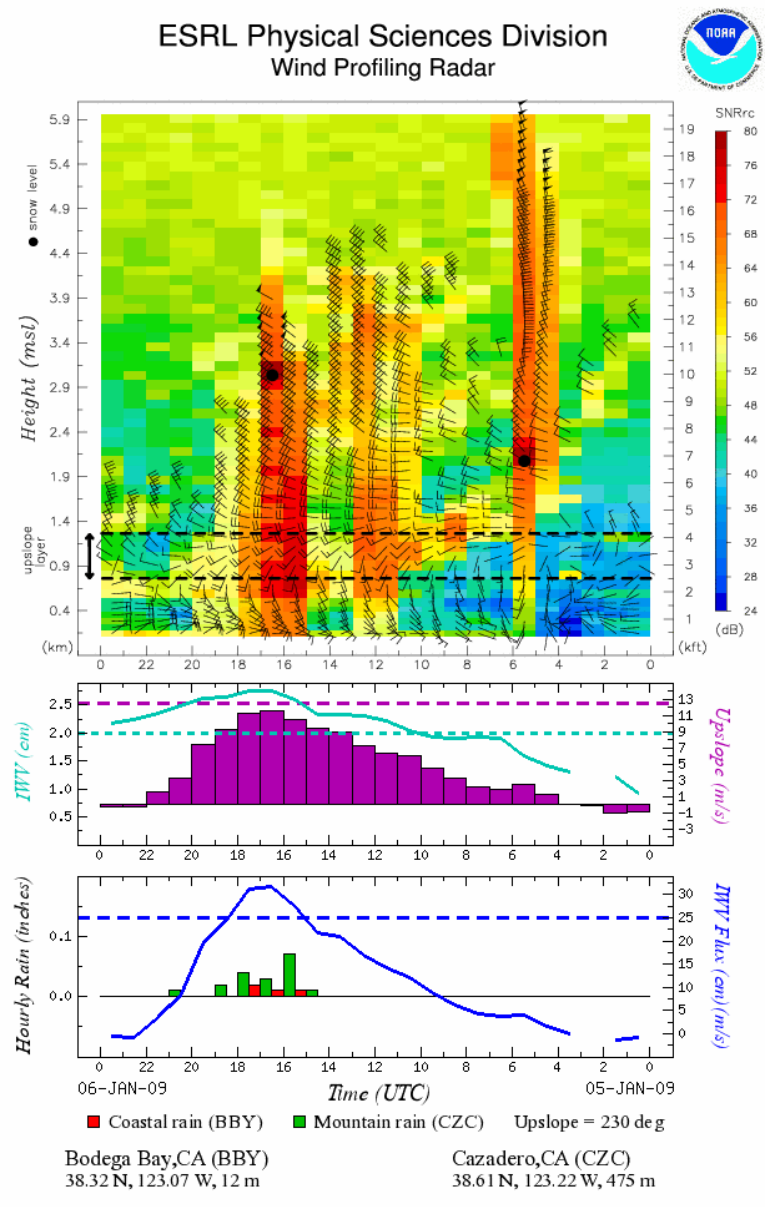


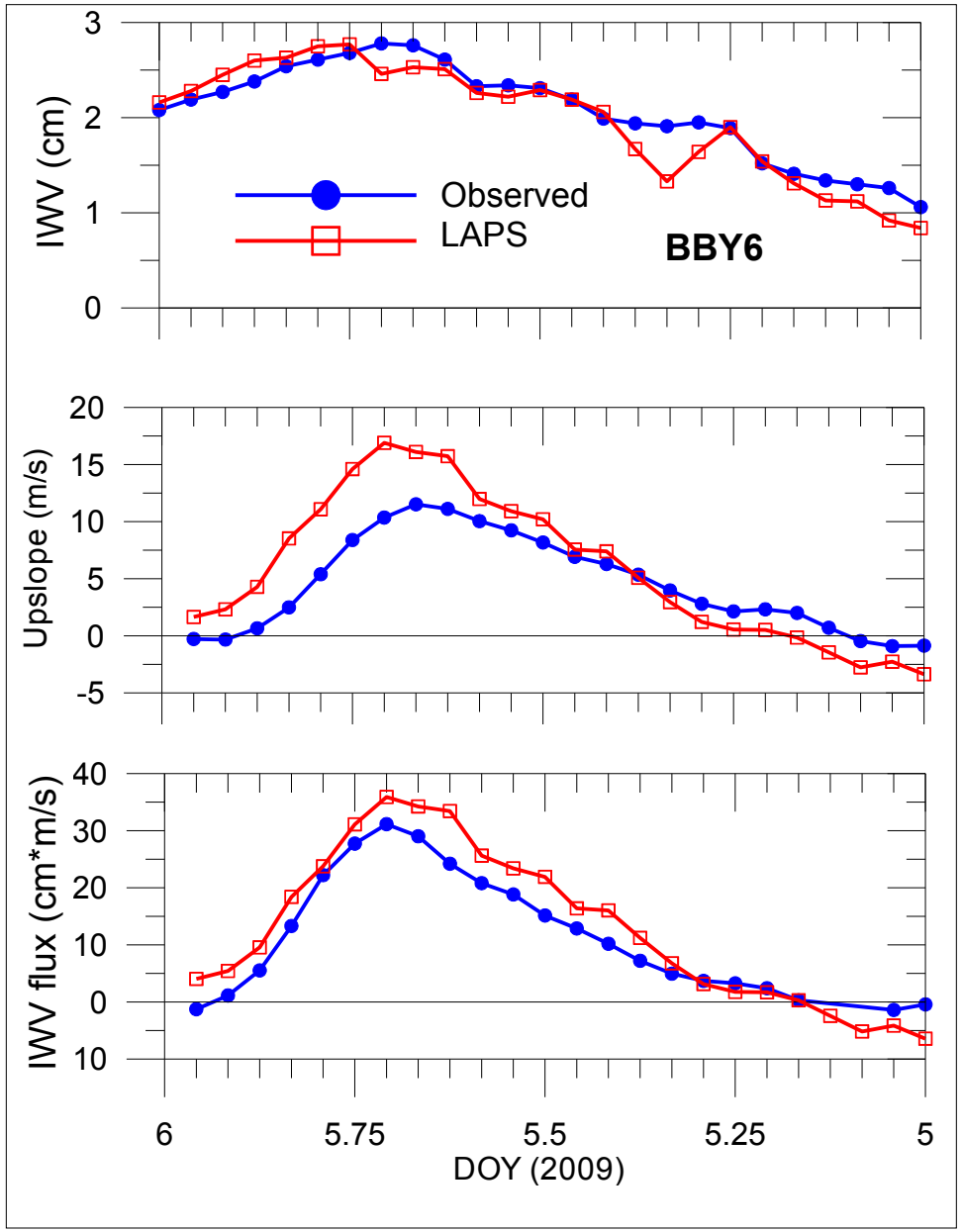

AR landfall in WA on 26 Feb 2010

IWV Flux Tool
at WPT/HTS
on 26 Feb 2010



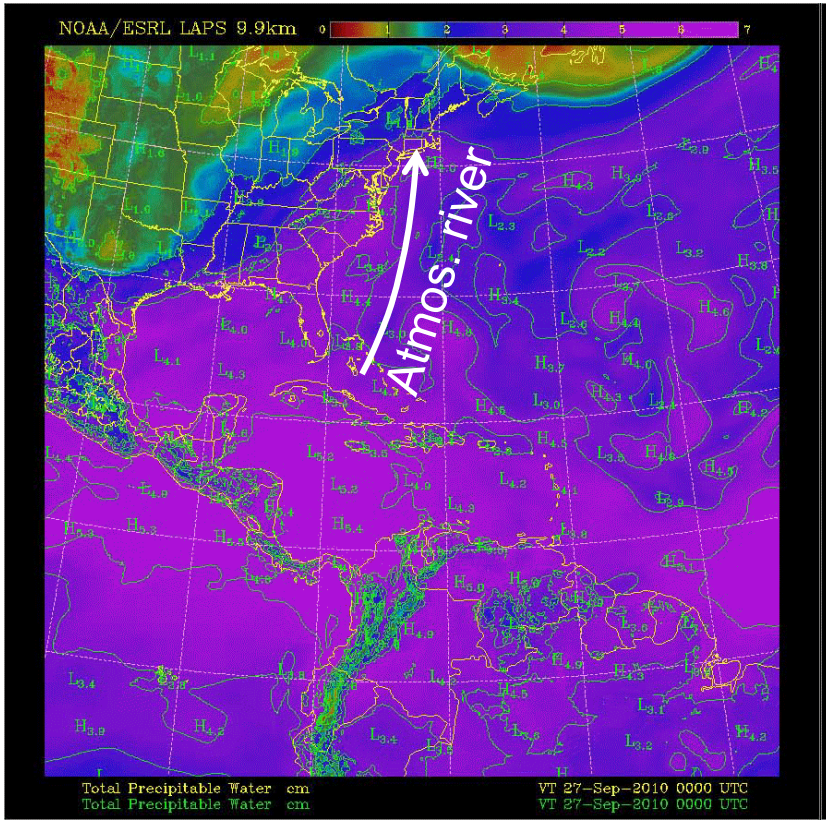
# Local Analysis and Prediction System (LAPS; ~10 km resolution): Verifying against observations at Bodega Bay, CA by Seth Gutman



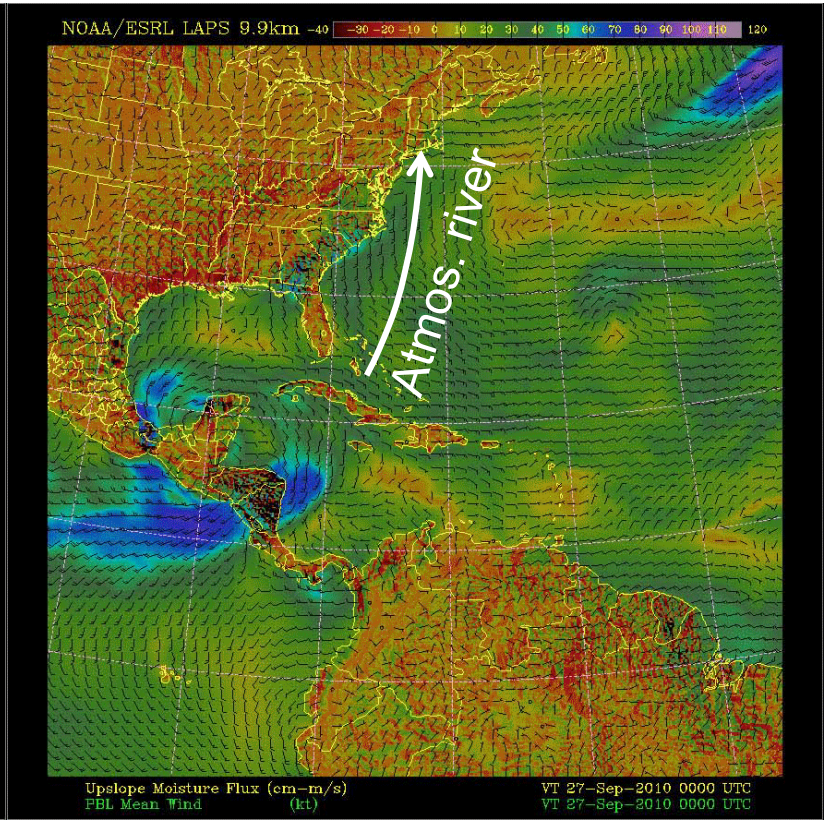



Local Analysis and Prediction System (LAPS; ~10 km resolution): East Coast rain event late Sept. 2010; provided by Seth Gutman

IWV (cm)




IWV Flux (q x v) @ 1 km MSL

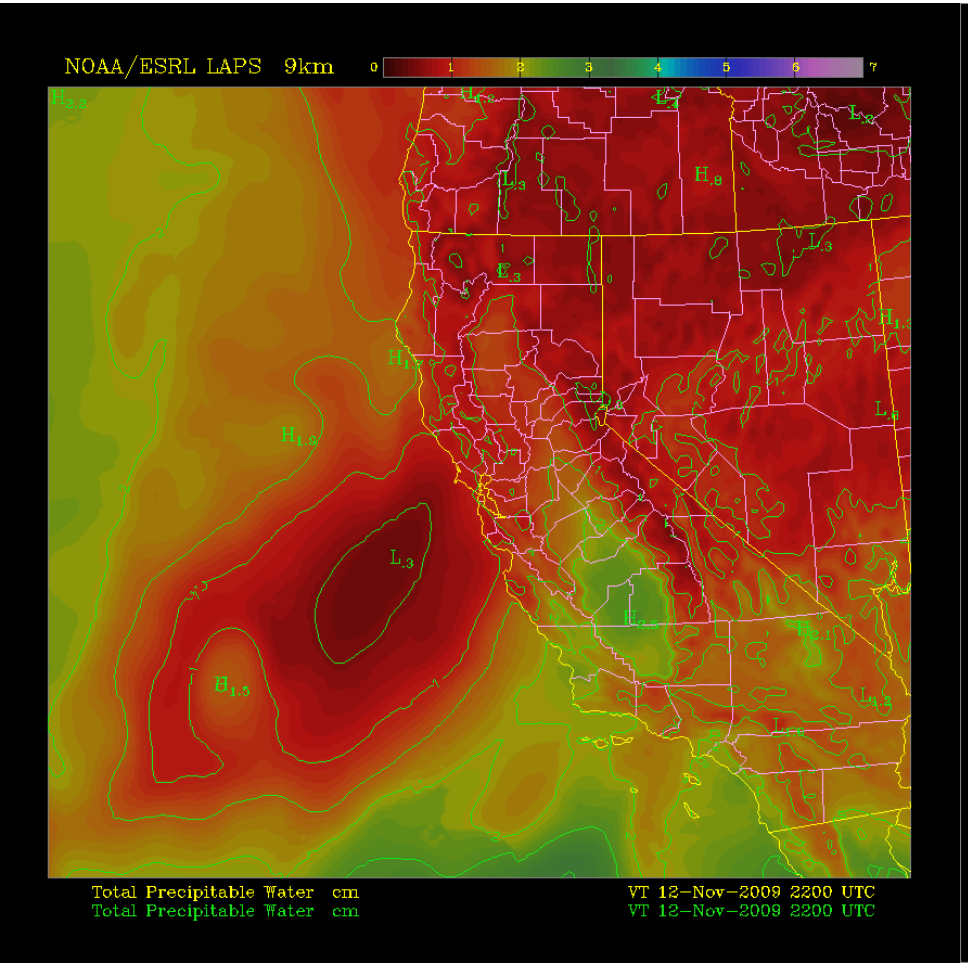


# Conclusions

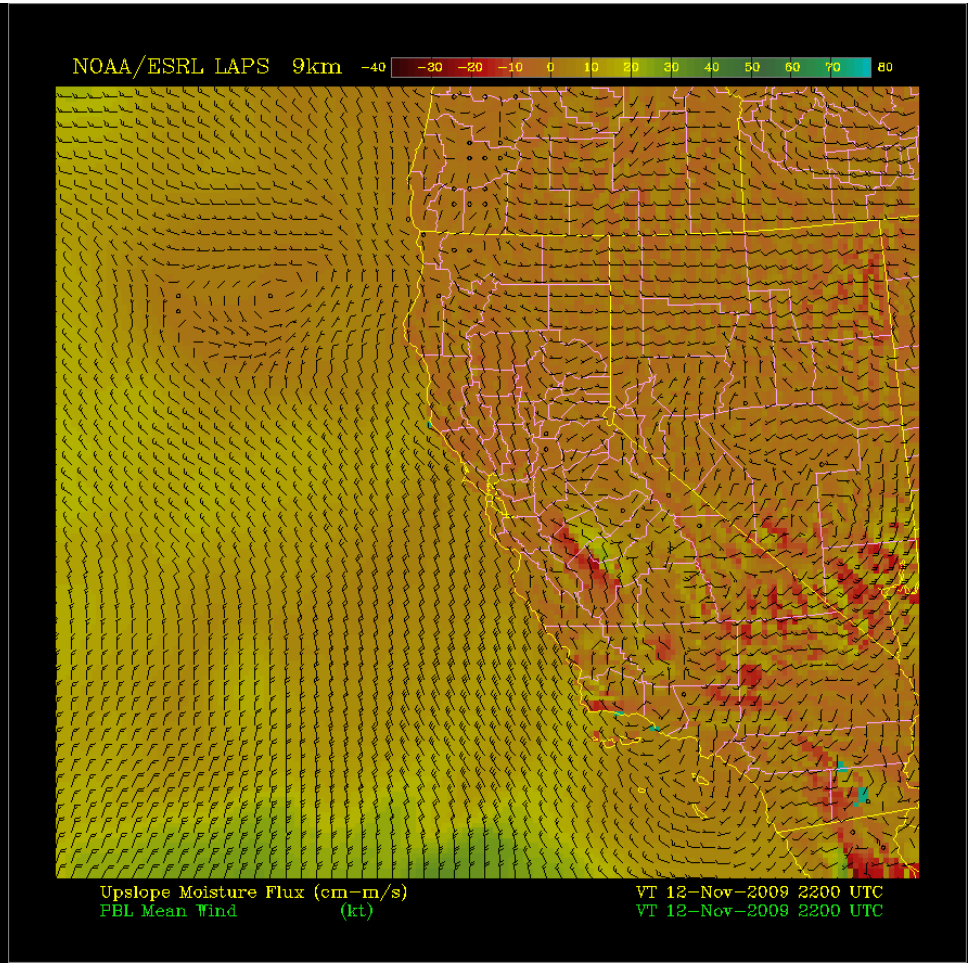
- Ongoing research has led to the creation of a real-time vapor-flux tool to monitor orographic rainfall forcing at multiple coastal sites.
- By combining observations and forecast model output, users can see how well a forecast model represents land-falling ARs and their resulting impacts on orographic rainfall enhancement.
- In the cases shown, the WRF model reasonably captured parts of the orographic forcing. However, the coastal and mountain rains were predicted poorly (*due to microphysics & terrain resolution?*).
- The three monitoring couplets deployed along the CA coast provided valuable lead time to forecasters for conditions leading to extreme rainfall. *This approach has now also been implemented in the complex orography of western WA.*
- LAPS has promise to extend this capability onto a gridded domain, although representativeness will be on ongoing issue.


Thank You!

# Local Analysis and Prediction System (LAPS):
# IWV & Upslope Moisture Flux Displays, ~9 km resolution (DWR domain)




IWV (cm)



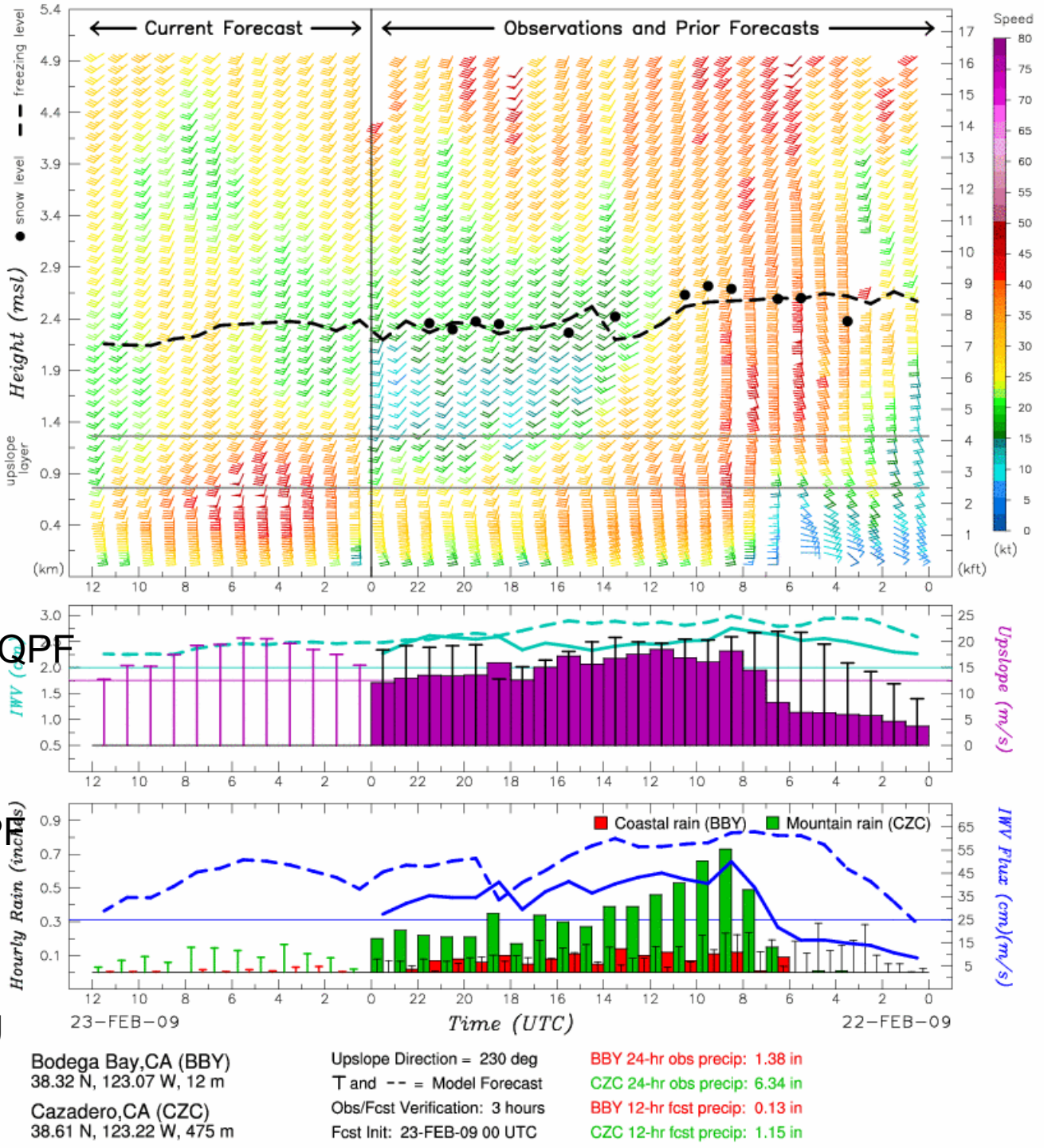

IWV Flux (q x v)

# 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

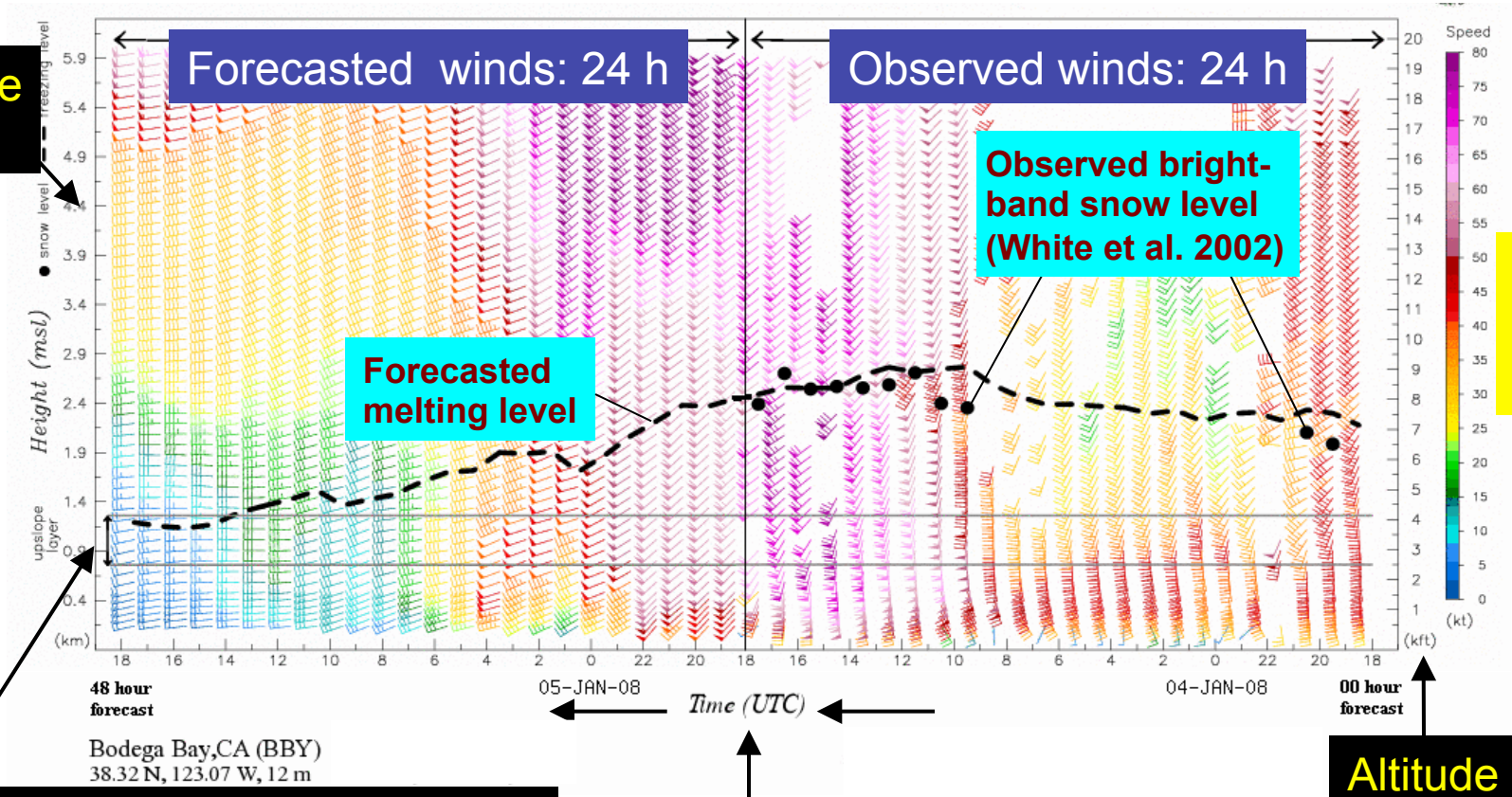
Model tendencies:
-no gap flow; too much flux/QPF
-overestimate upslope flow
-closer on IWV
-overestimate IWV flux
-way underestimate mtn QPF

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




Altitude in km

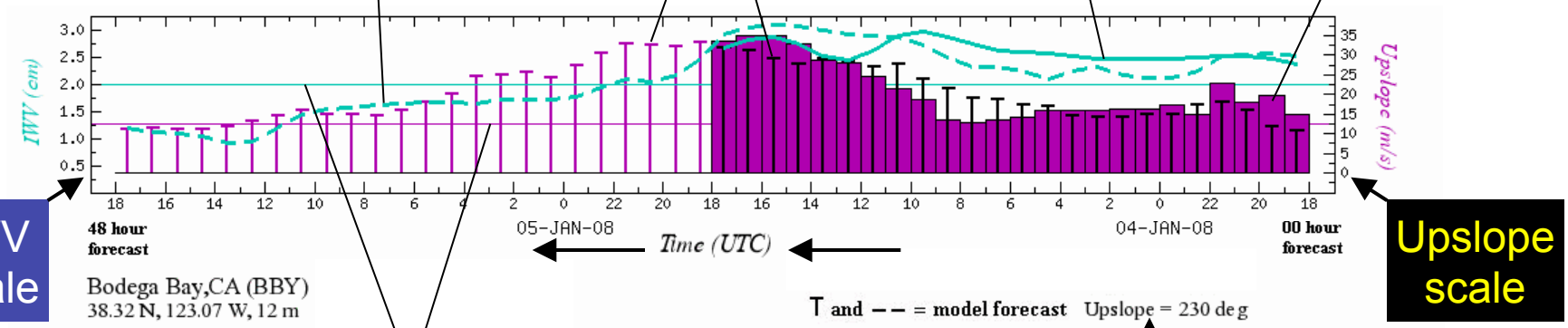
Wind speed scale

Controlling layer where upslope flow is calculated

Current time

Altitude in kft

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




Forecasted upslope flow

Observed upslope flow

Forecasted IWV

Observed IWV

IWV scale

Upslope scale

The thin horizontal lines define thresholds for IWV and upslope flow (2 cm and 12.5 m $s^{-1}$; respectively) that were shown to produce heavy rain (Neiman et al. 2008)

Upslope direction defined

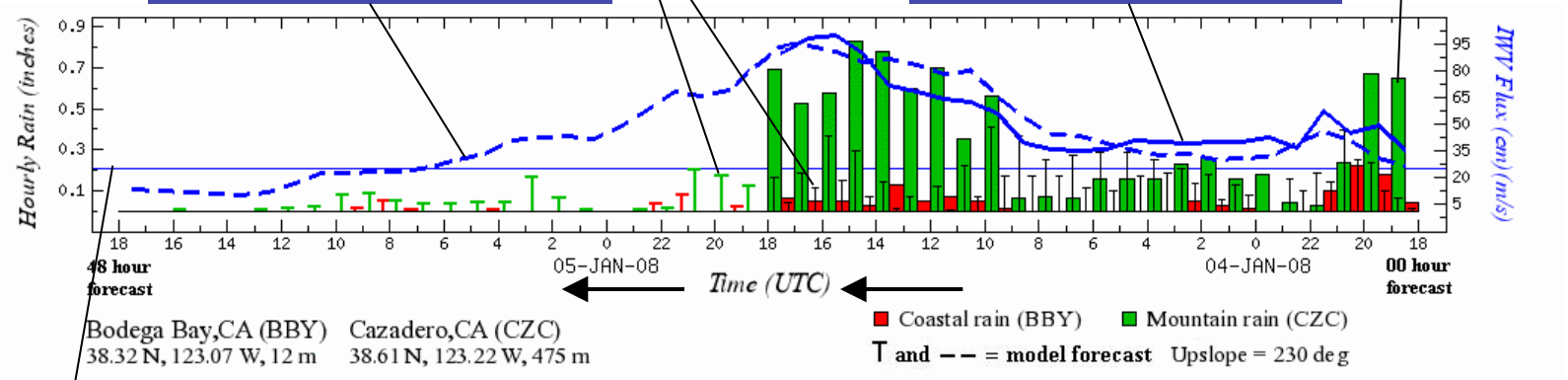
# The IWV and upslope flow from the middle panel are combined to produce a bulk IWV flux, which is displayed in the bottom panel along with the coastal and mountain hourly rainfall

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

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

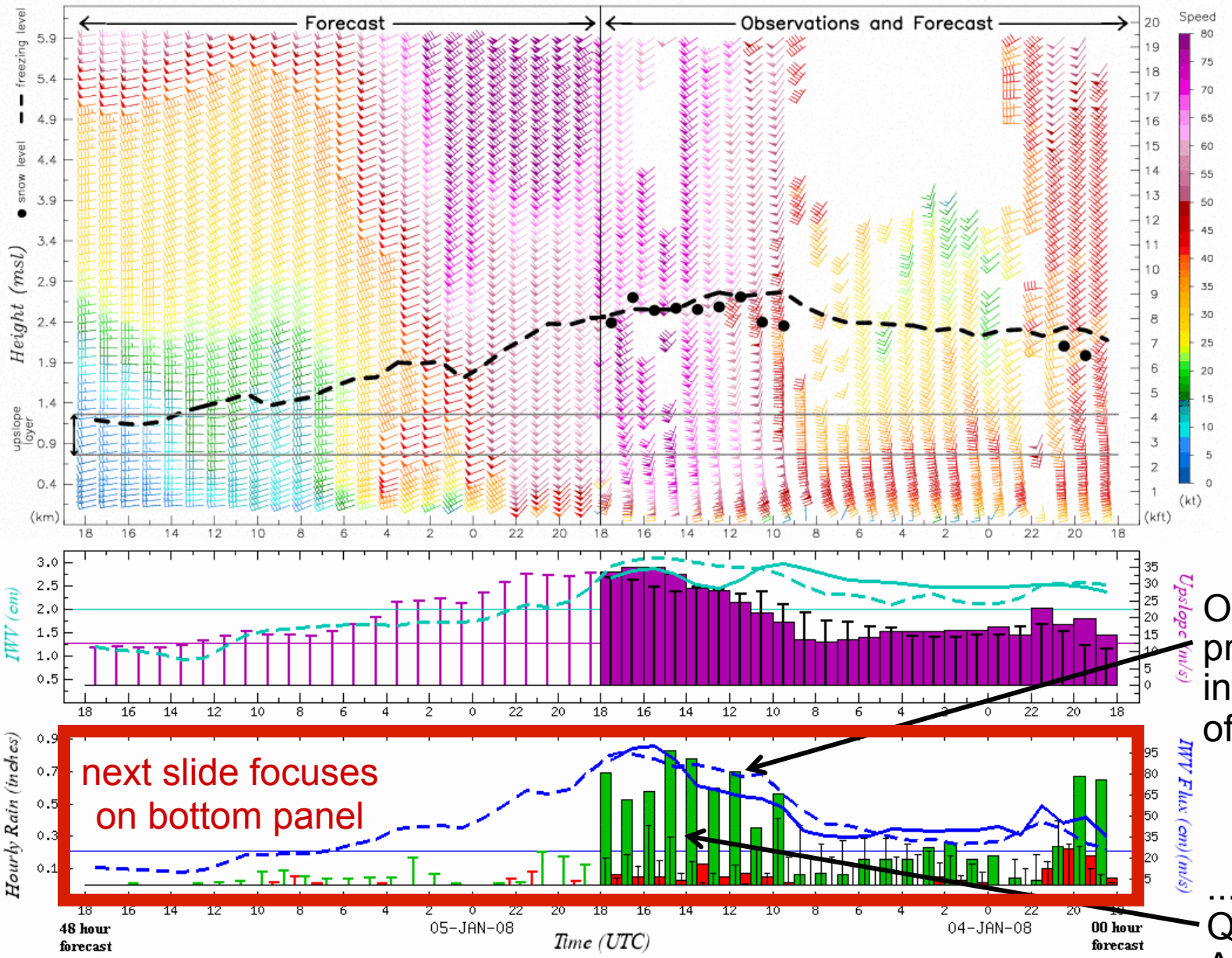
Forecasted IWV flux

Observed IWV flux



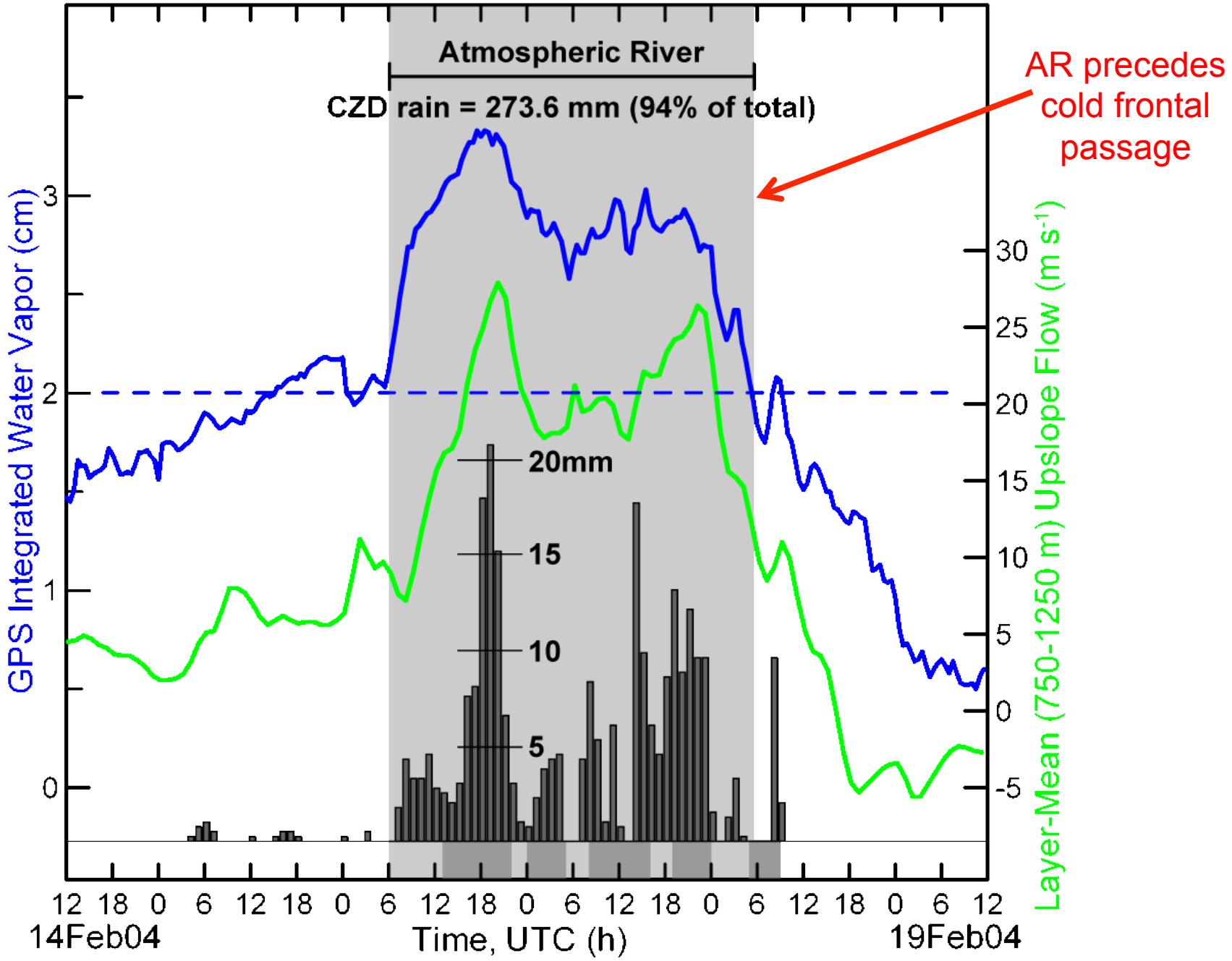

The thin blue horizontal line gives the IWV flux threshold (25 cm x m $s^{-1}$) determined by multiplying the IWV and upslope flow thresholds defined in the middle panel

# Northern couplet: BBY & CZD




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

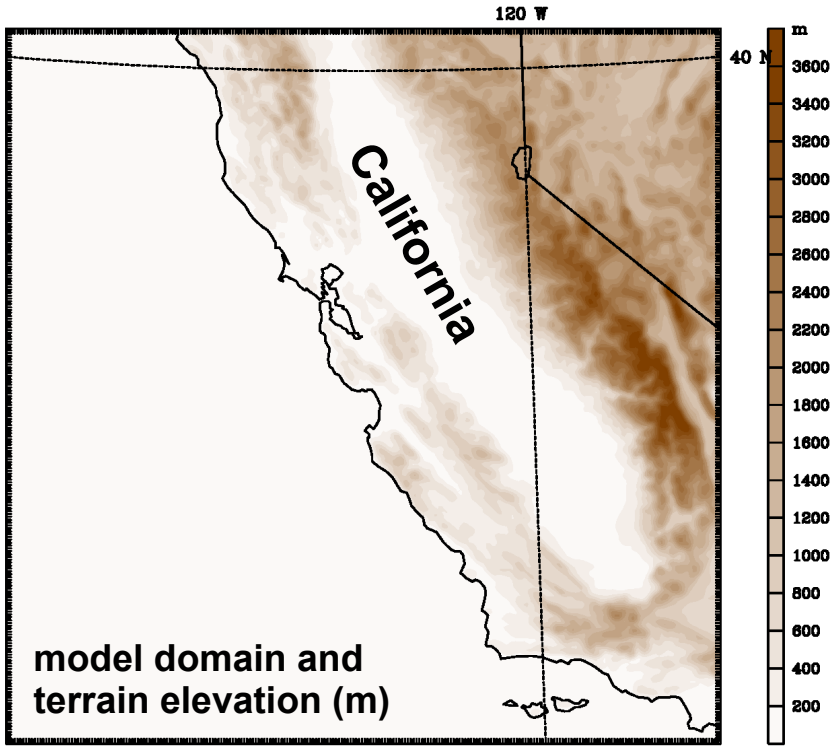
...but not the QPF, esp. in AR conditions.


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)
0
1
2
3
30
25
20
15
10
5
0
-5
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

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

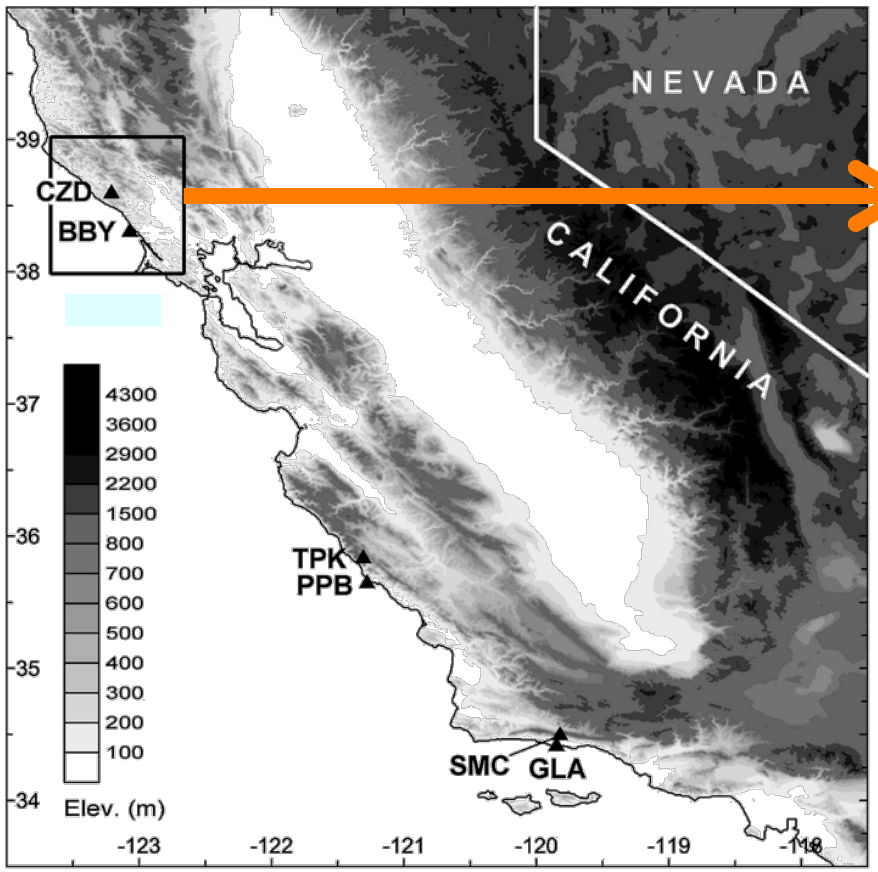
# Forecast Model Configuration

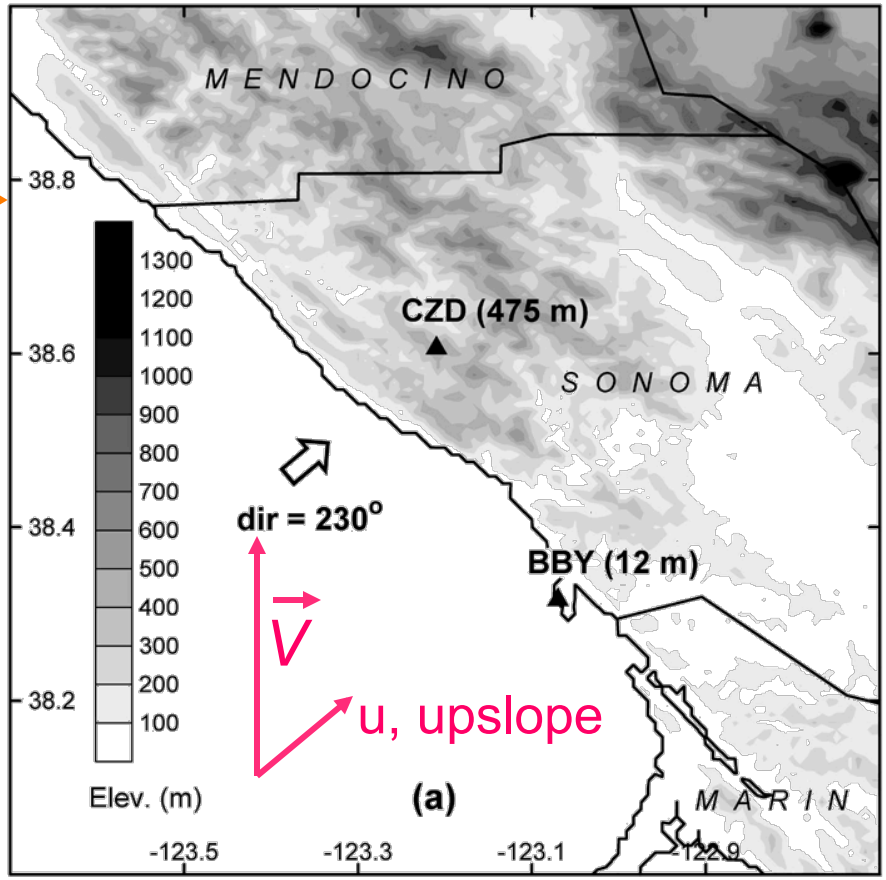
- Model type: Advanced Research WRF (ARW)
- Grid Configuration:
  - 3 km horizontal grid spacing
  - 30 vertical layers
- Forecast duration: 48 hour forecast
- Model Physics:
  - Ferrier microphysics
  - RRTM long-wave radiation
  - Dudhia short-wave scheme
  - MRF surface layer scheme
  - thermal diffusion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



model domain and terrain elevation (m)

# LLJ controls rain rate in coastal mountains – wind speed

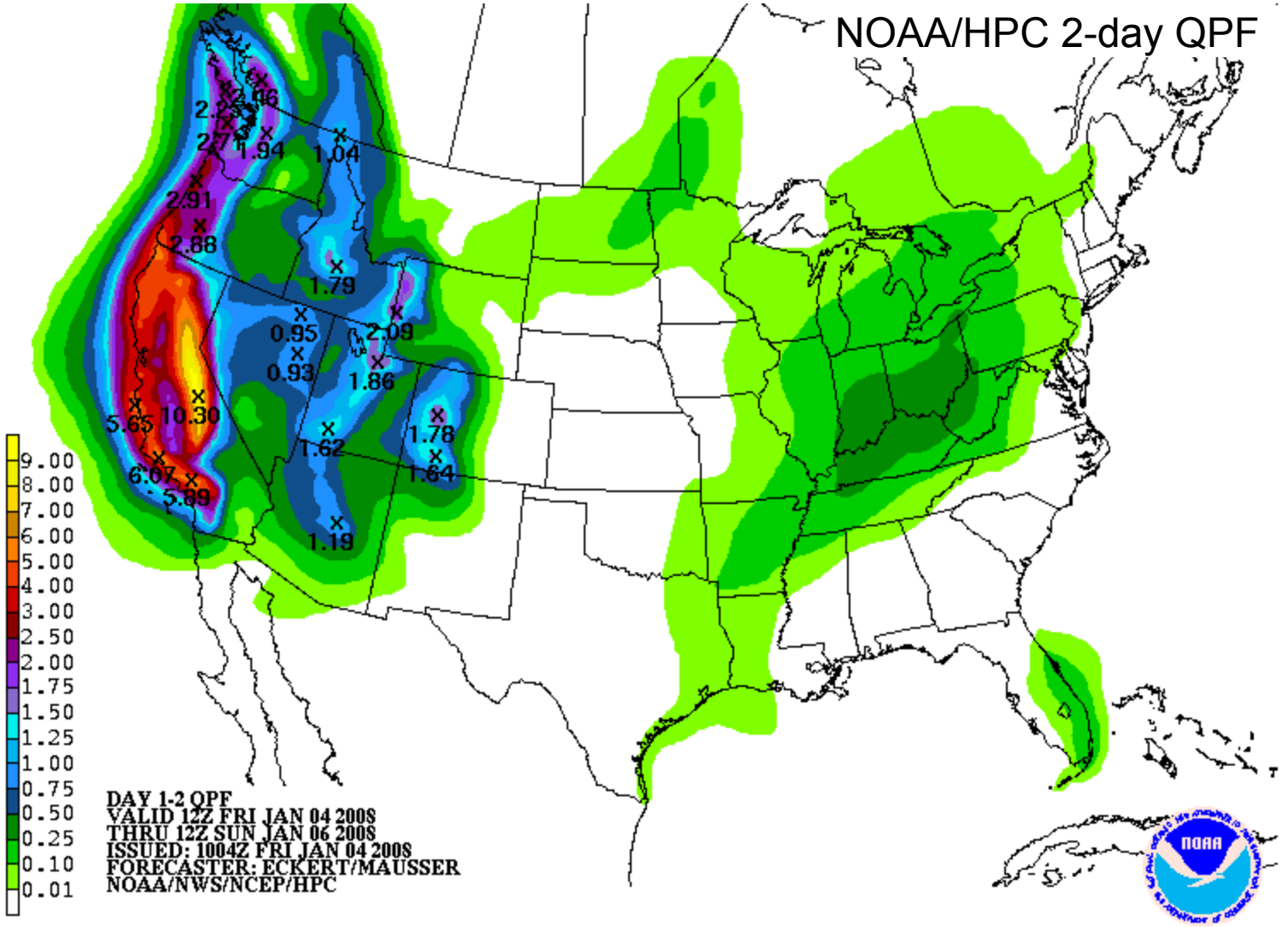


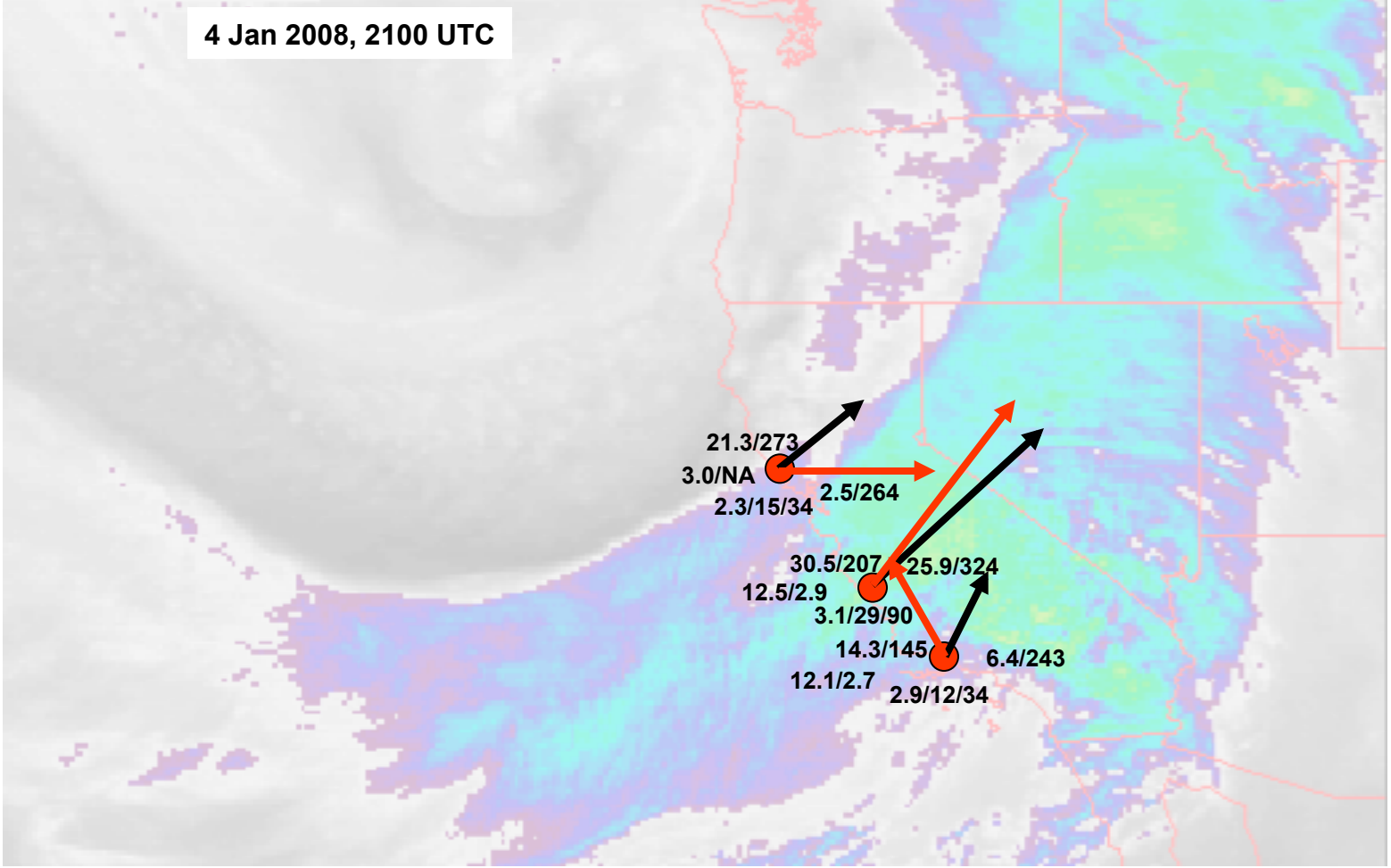




$$R \approx \overline{q\rho(\underline{\vec{V}} \bullet \nabla Z_s)}$$

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

# Major precipitation event includes forecast of >10 in. of rain/48 h (many feet of snow above 7000 ft), with many NWS warnings

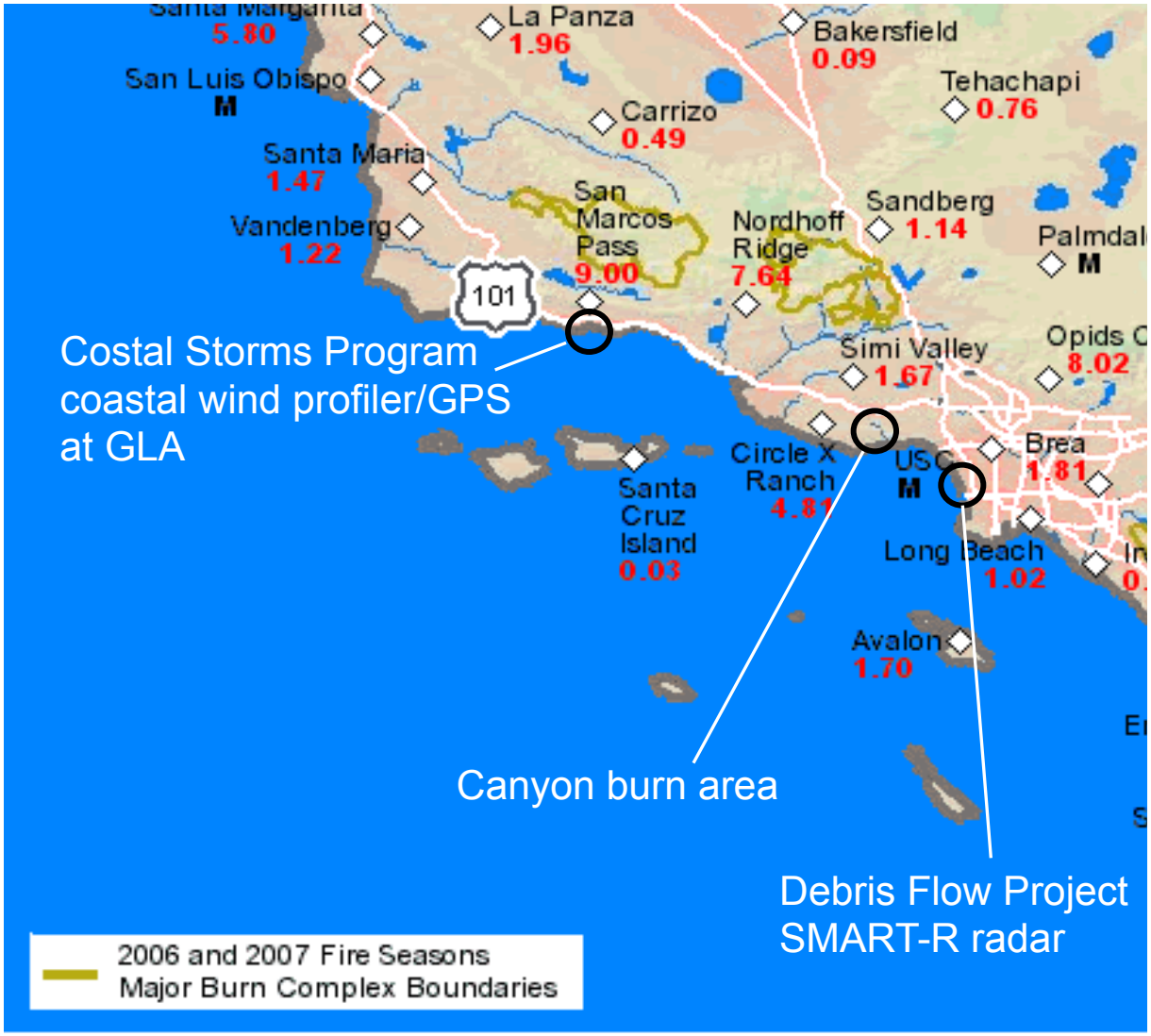




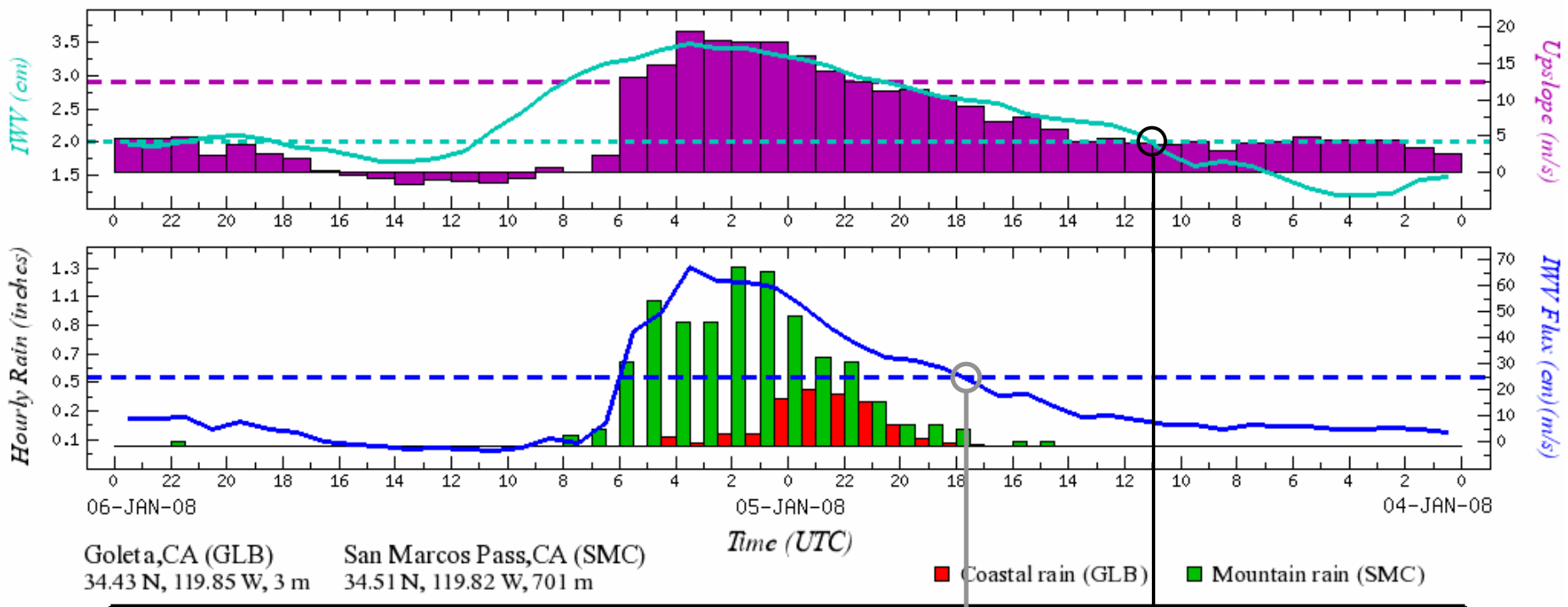

| 2100 UTC 4 Jan 2008 Atmospheric river conditions | | | | | |
|---|---|---|---|---|---|
| Site | IWV (cm) | Full wind* speed, dir. (m $s^{-1}$, deg) | Upslope flux (cm m $s^{-1)}$ | Mtn rain rate (mm $h^{-1}$) | SnL (km) |
| BBY | 2.3 | 21/273 | 34 | 3 | na |
| **PPB** | **3.1** | **31/207** | **90** | **26** | **2.9** |
| GLA | 2.9 | 14/145 | 34 | 6 | 2.7 |

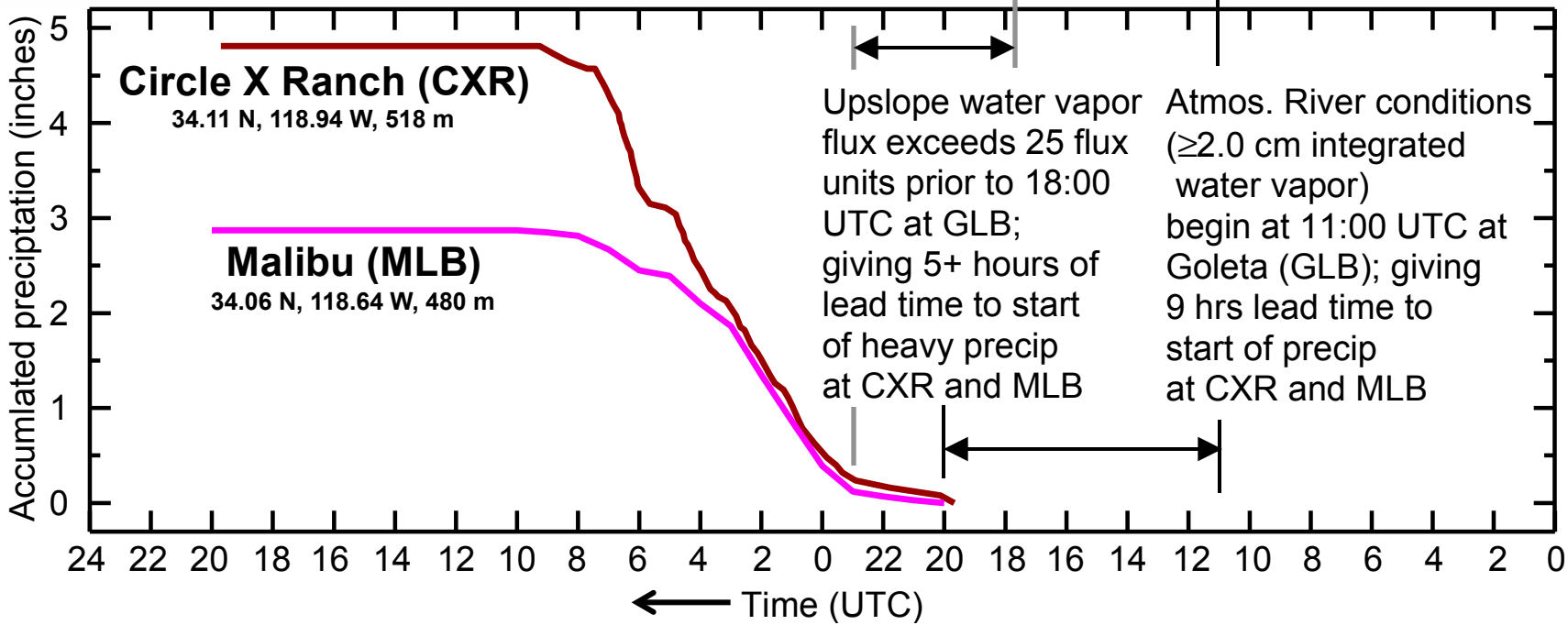
*hourly averaged over the "controlling layer" from 750-1250 m MSL

This new water vapor flux tool developed by ESRL scientists measures key precursor conditions to mountain precipitation enhancement. In this case, the tool provided valuable lead time for heavy rainfall occurring near the Canyon burn area.




**24 Hour Synoptic Precipitation (Inches) Ending Sat Jan 05 2008 at 12 UTC**
NOAA / NWS / California Nevada River Forecast Center

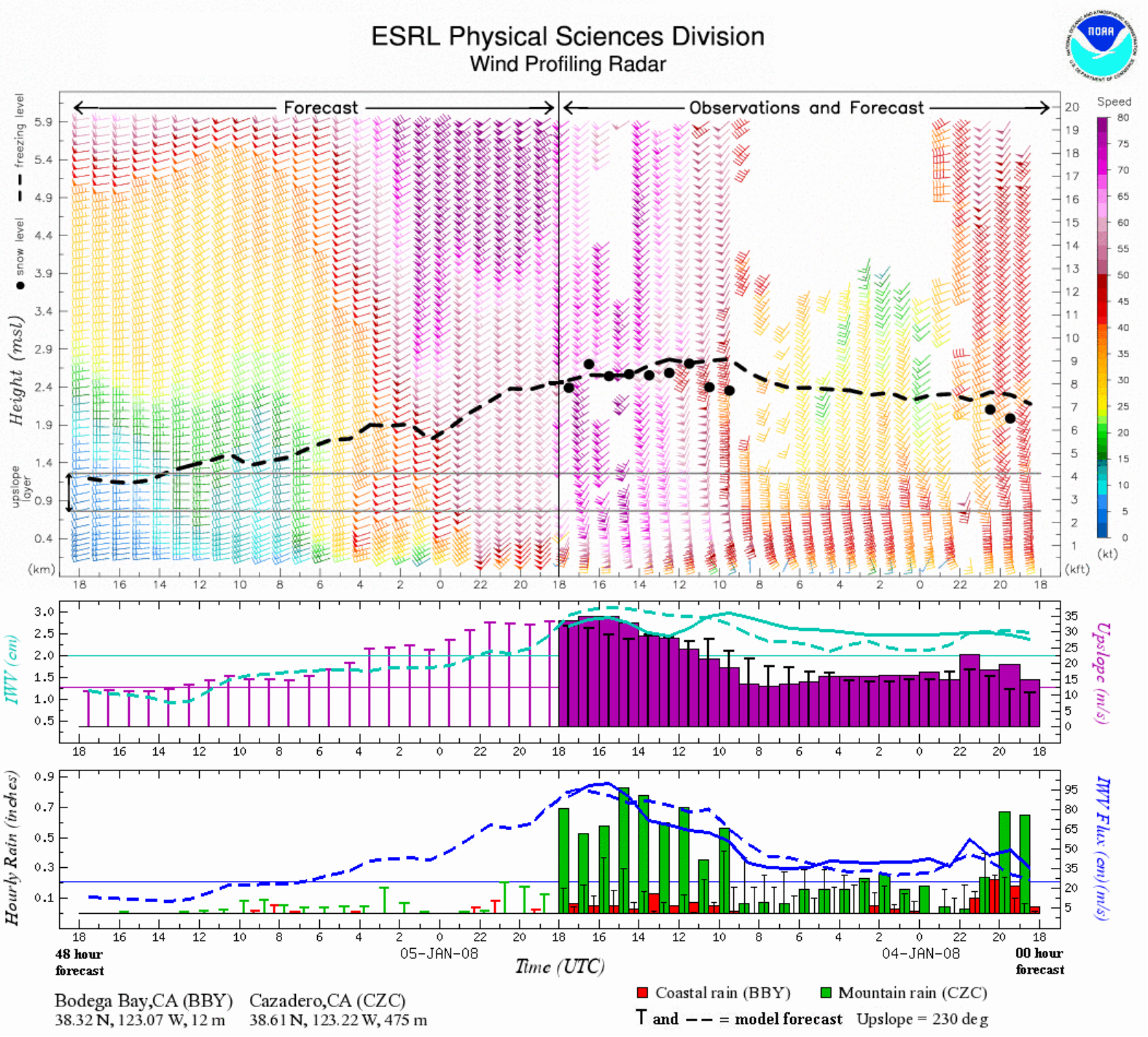

IWV (cm)
Upslope (m/s)
Hourly Rain (inches)
IWV Flux (cm)(m/s)
06-JAN-08
05-JAN-08
04-JAN-08
Time (UTC)
Goleta,CA (GLB)
34.43 N, 119.85 W, 3 m
San Marcos Pass,CA (SMC)
34.51 N, 119.82 W, 701 m
Coastal rain (GLB)
Mountain rain (SMC)


Circle X Ranch (CXR)
34.11 N, 118.94 W, 518 m
Malibu (MLB)
34.06 N, 118.64 W, 480 m
Accumlated preciptation (inches)
Upslope water vapor flux exceeds 25 flux units prior to 18:00 UTC at GLB; giving 5+ hours of lead time to start of heavy precip at CXR and MLB
Atmos. River conditions (≥2.0 cm integrated water vapor) begin at 11:00 UTC at Goleta (GLB); giving 9 hrs lead time to start of precip at CXR and MLB
Time (UTC)

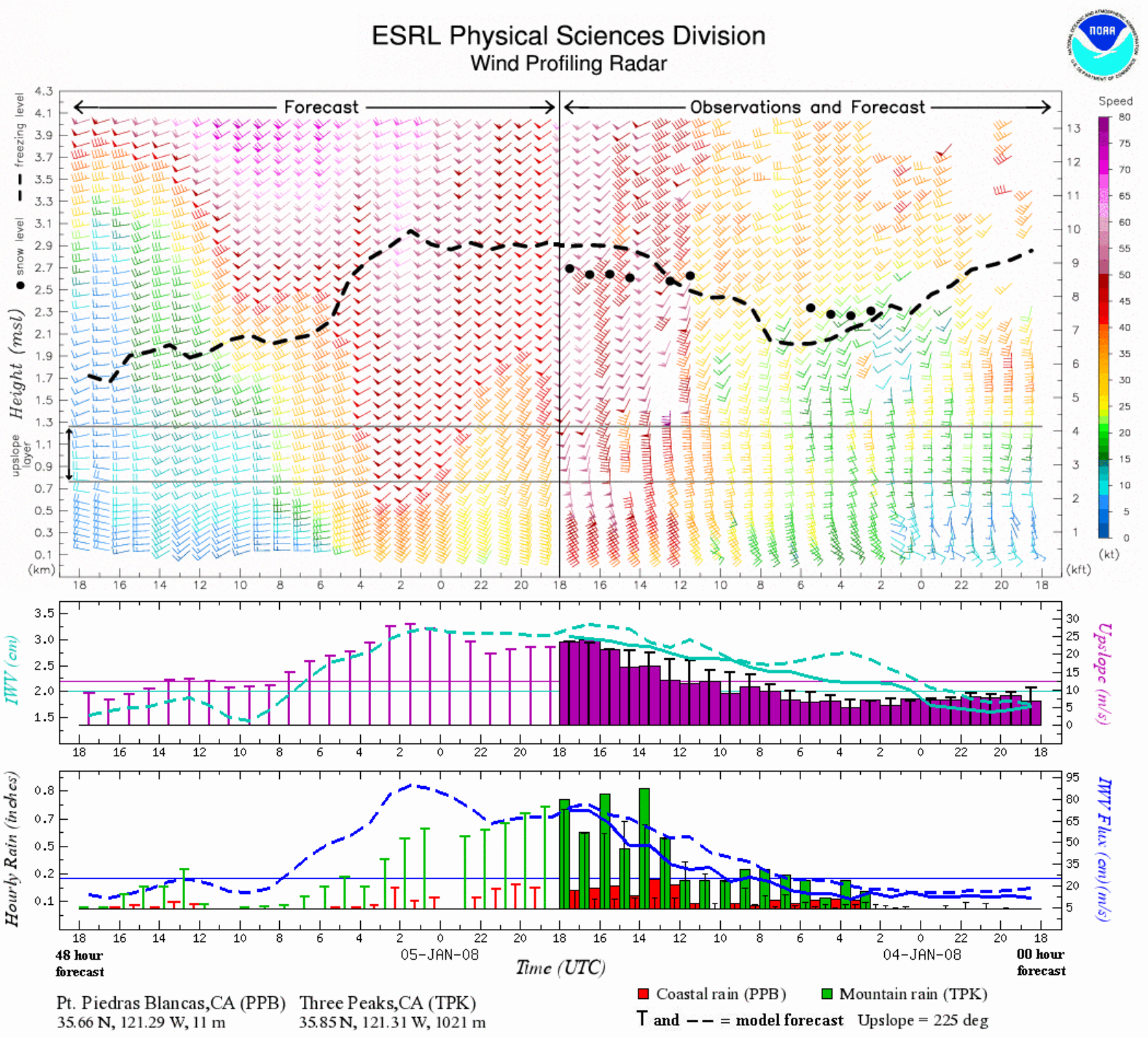
Day 1 Forecast verification: Northern couplet

Dashed lines and T posts represent model output

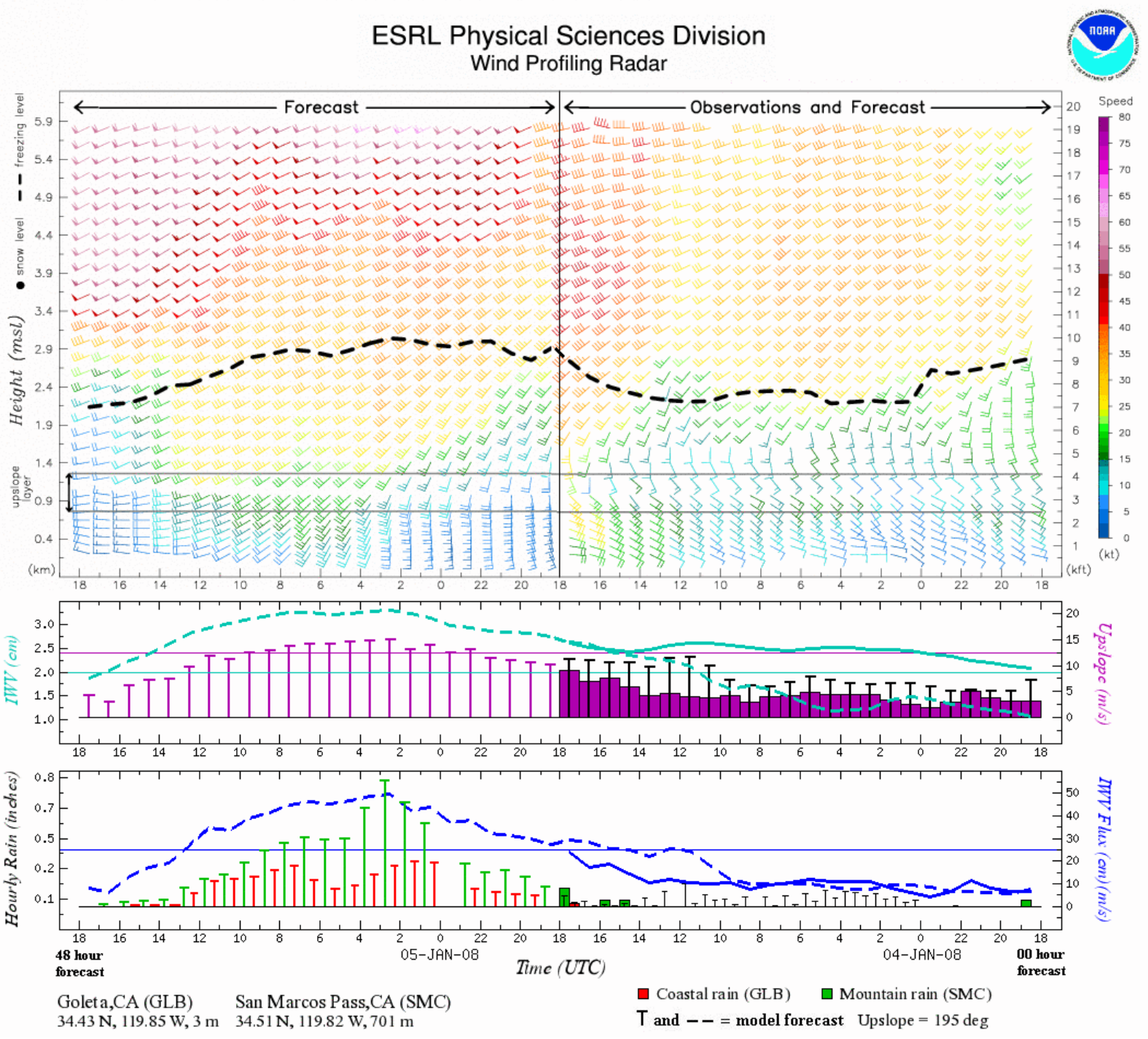
Solid lines and filled bars show observed data



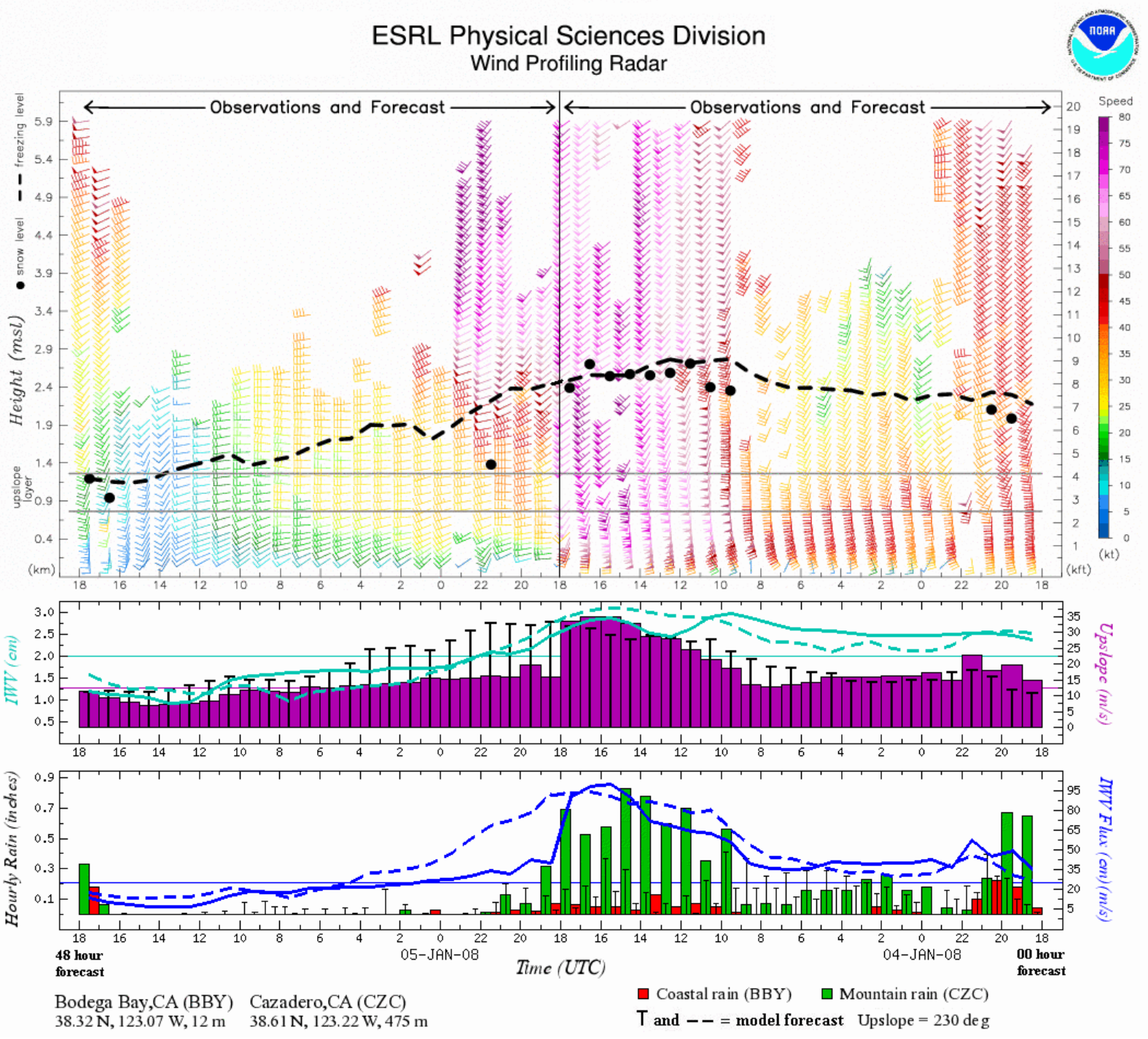
Day 1 Forecast verification: Central couplet



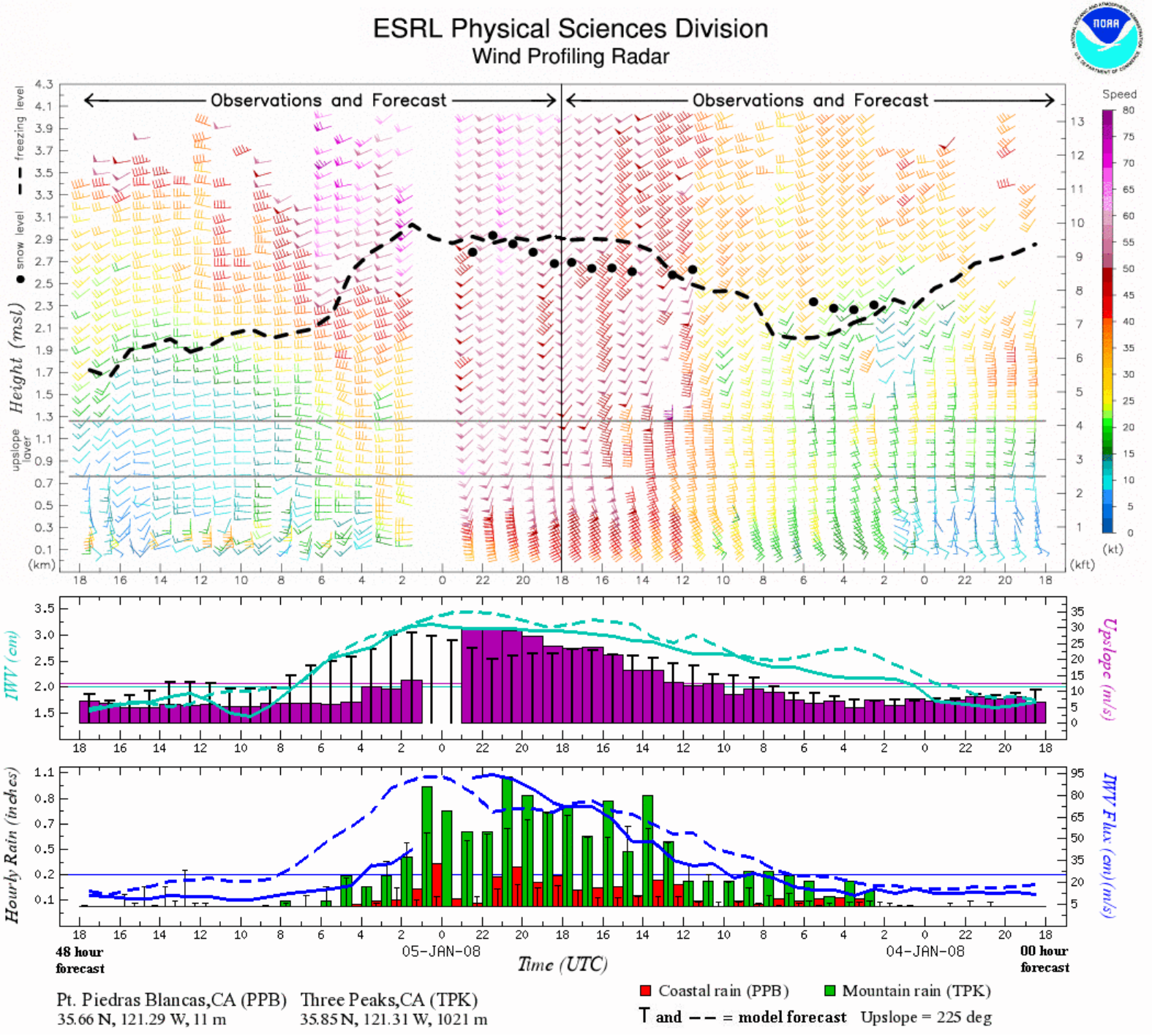
Day 1 Forecast verification: Southern couplet



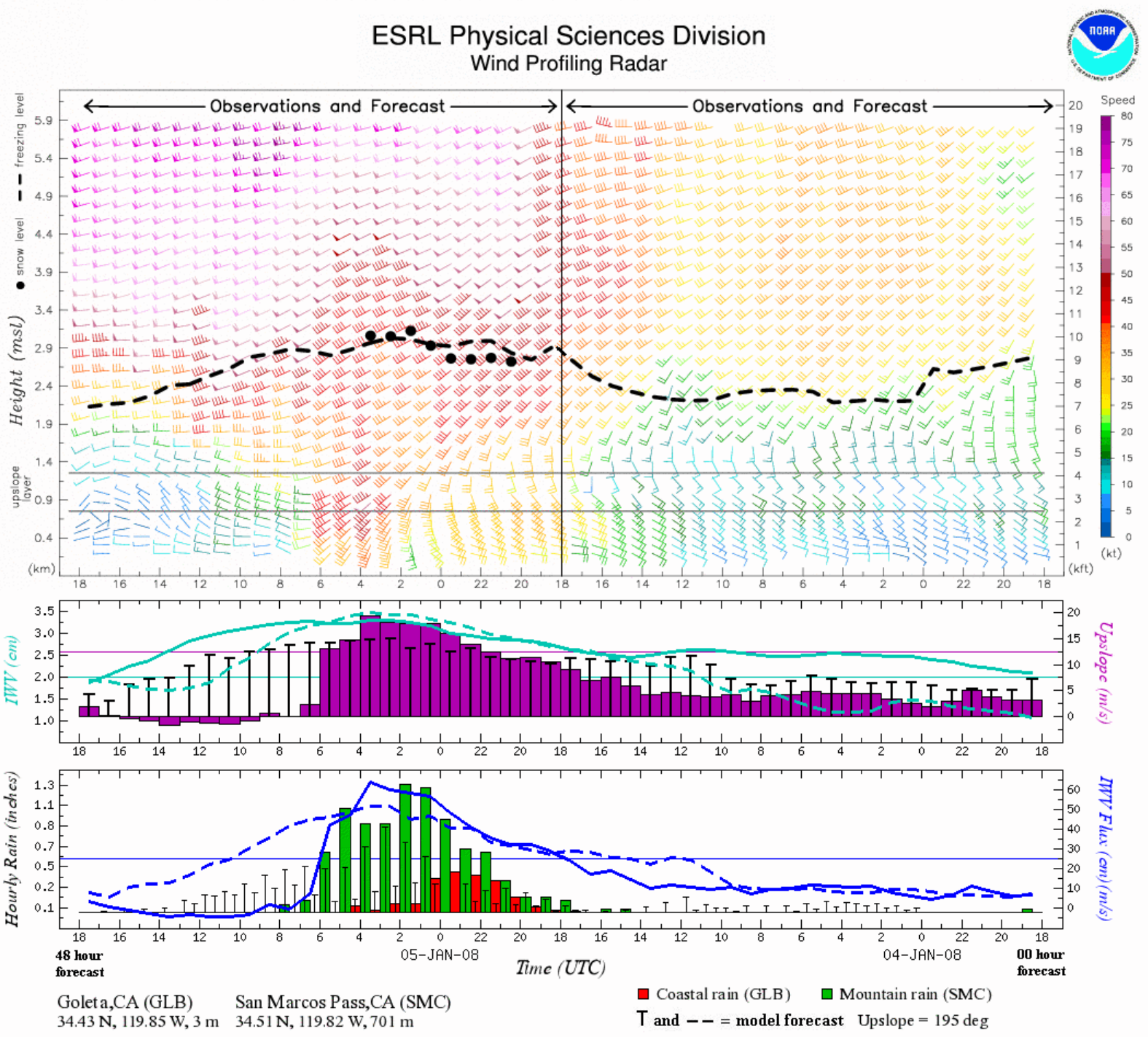
Days 1 & 2 Forecast verification: Northern couplet



Days 1 & 2 Forecast verification: Central couplet



Day 1 & 2 Forecast verification: Sothern couplet



## Northern Couplet

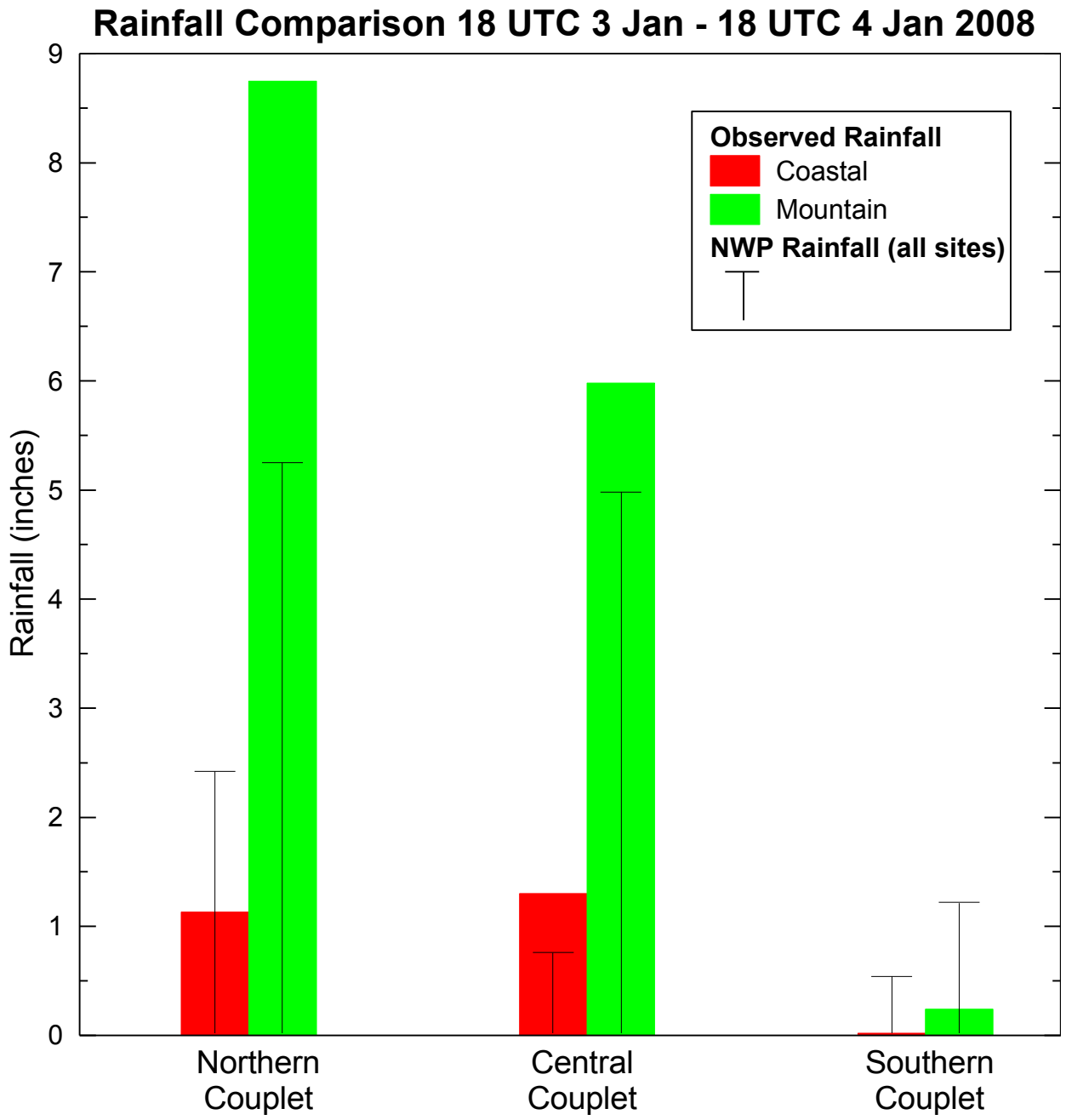
- Coastal rainfall overpredicted by more than 100%
- Mountain rainfall underpredicted by 3.5 in

## Central Couplet

- Model reasonably predicts coastal and mountain rainfall

## Southern Couplet

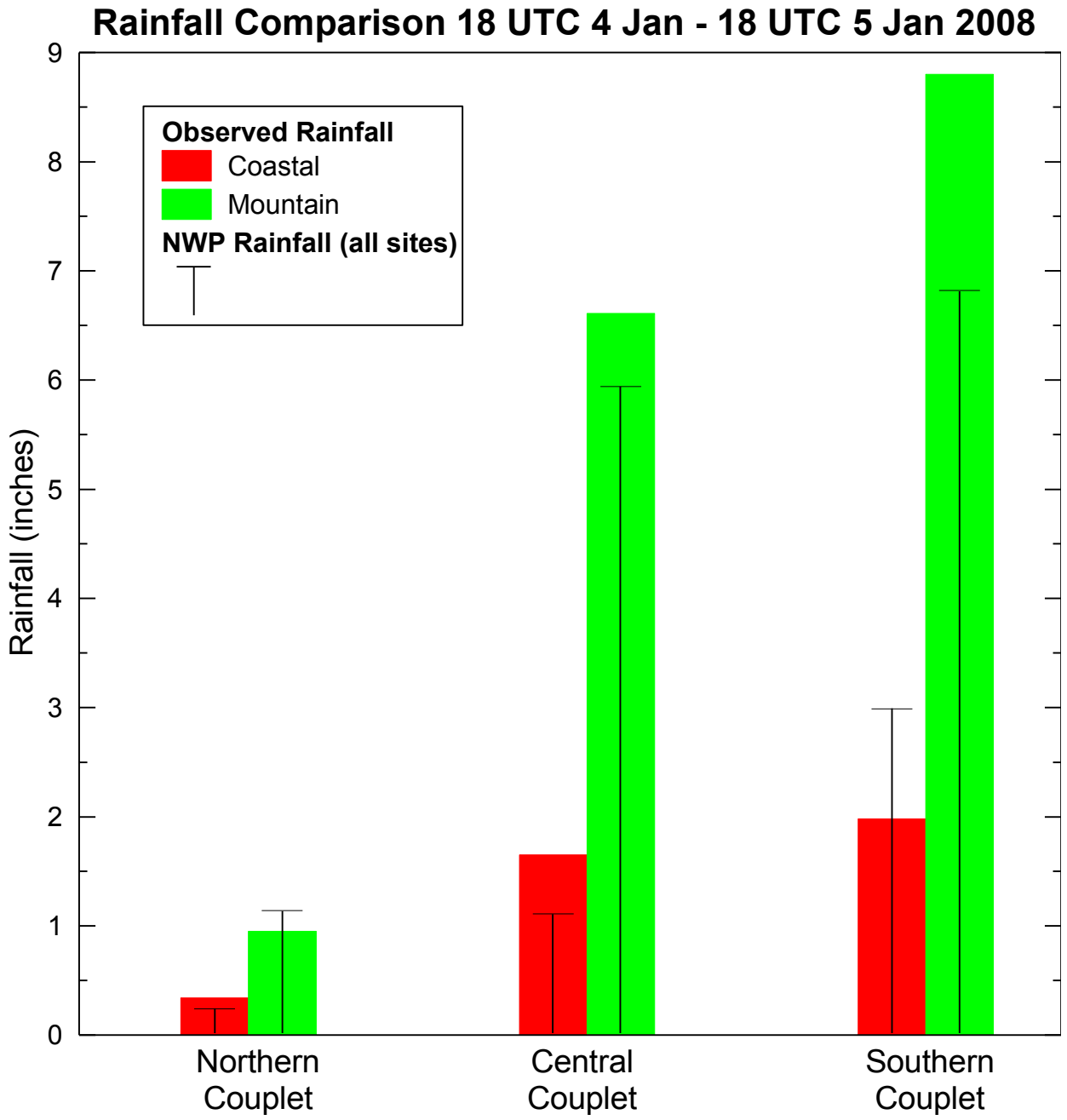
- Blocked flow delays onset of coastal and mountain rainfall
- Model misrepresents blocked flow, thereby overpredicting upslope flow and corresponding rainfall

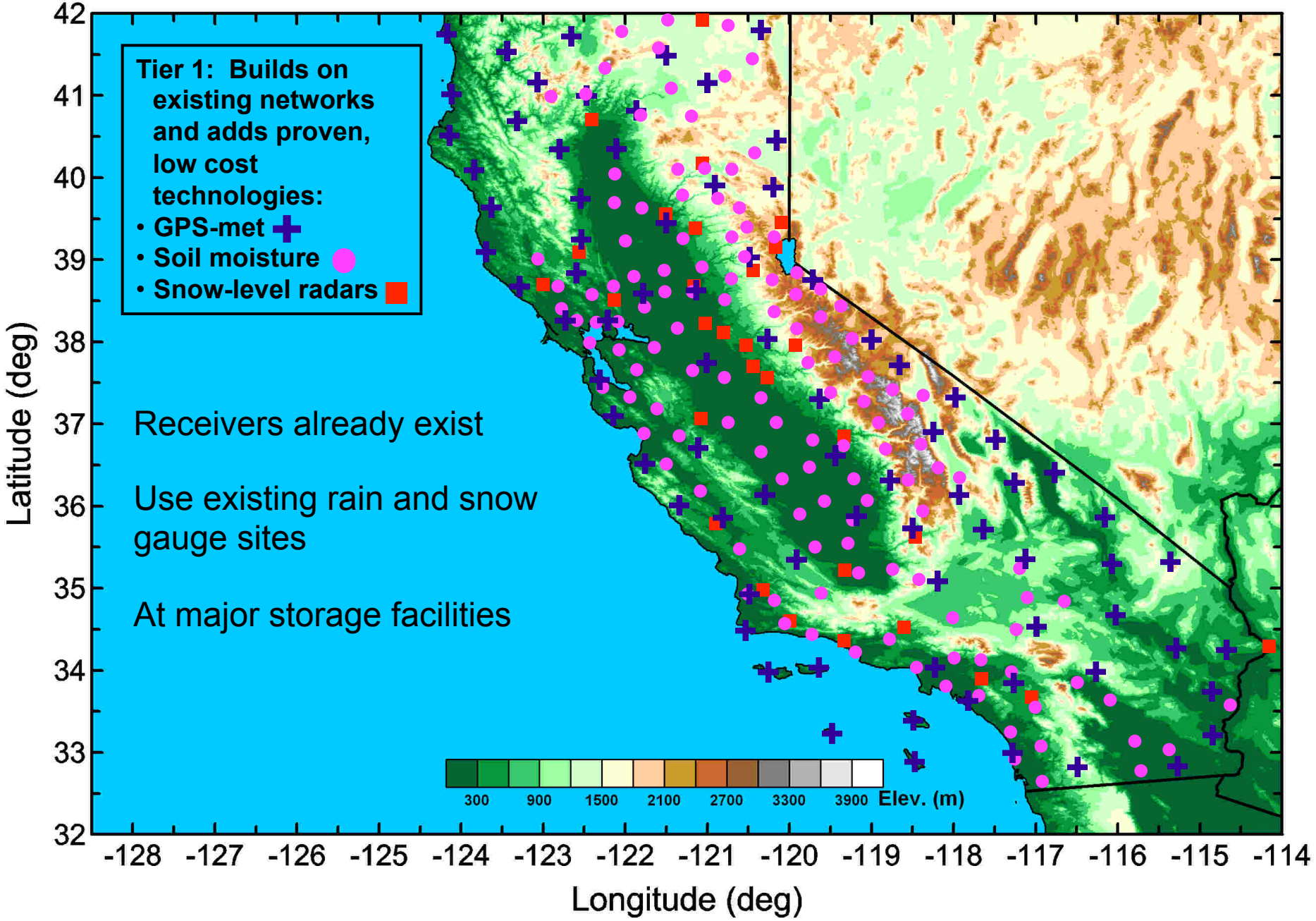


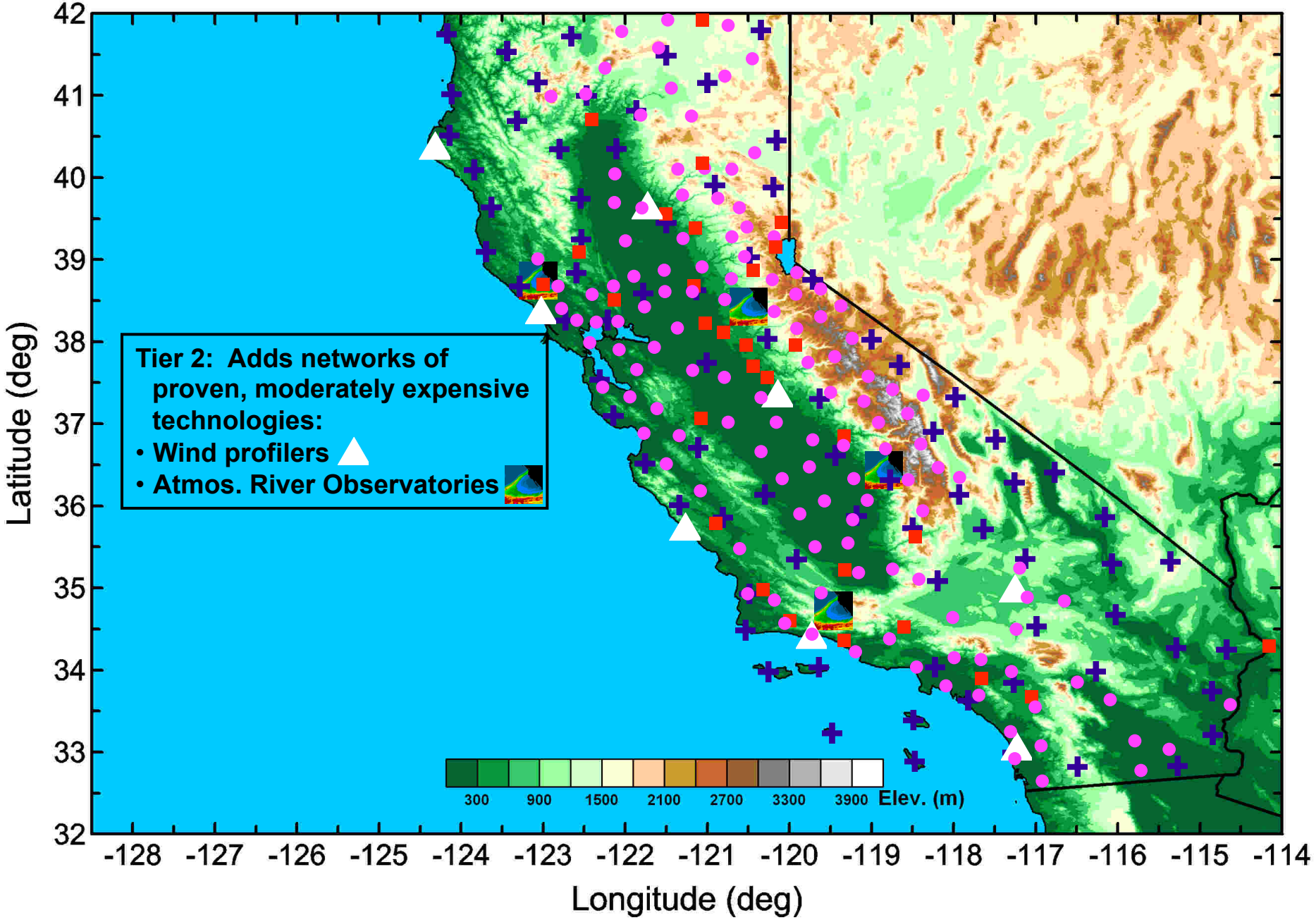
## All Couplets

- Model underpredicts rainfall during atmospheric river conditions, but then misrepresents drying and wind direction shift following passage of storm's trailing cold front resulting in rainfall overprediction. As a result, compensating errors produce forecast improvement over Day 1

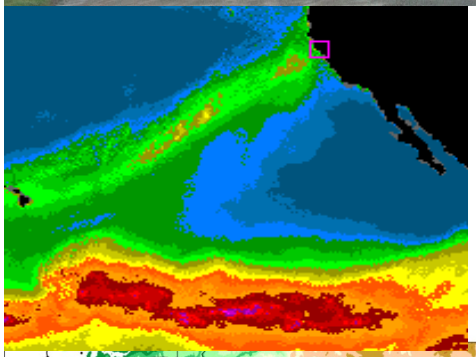
- Three Peaks gauge in central couplet records 12.6 in of rain in 48 h.

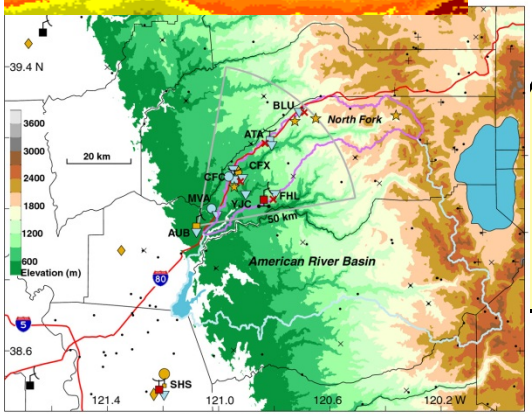



Tier 1: Builds on existing networks and adds proven, low cost technologies:
• GPS-met
• Soil moisture
• Snow-level radars
Receivers already exist
Use existing rain and snow gauge sites
At major storage facilities
300 900 1500 2100 2700 3300 3900 Elev. (m)
Latitude (deg)
42 41 40 39 38 37 36 35 34 33 32
Longitude (deg)
-128 -127 -126 -125 -124 -123 -122 -121 -120 -119 -118 -117 -116 -115 -114


Tier 2: Adds networks of proven, moderately expensive technologies:
• Wind profilers
• Atmos. River Observatories
300
900
1500
2100
2700
3300
3900
Elev. (m)
Latitude (deg)
Longitude (deg)
42
41
40
39
38
37
36
35
34
33
32
-128
-127
-126
-125
-124
-123
-122
-121
-120
-119
-118
-117
-116
-115
-114

# A tiered approach for new obs to help address CA's water resource issues






IV: Off-shore recon.

Tier III: Newer technology
Ex: Gap-filling radars, Buoy-mounted WPs

Tier II: Expand on well-defined needs with proven technology
Ex: Wind profilers, Coastal Atmospheric river observatory

Tier I: Address well-defined needs with proven technology
Ex: Soil moisture sensors at CIMIS sites, GPS receivers of opportunity, snow-level radars