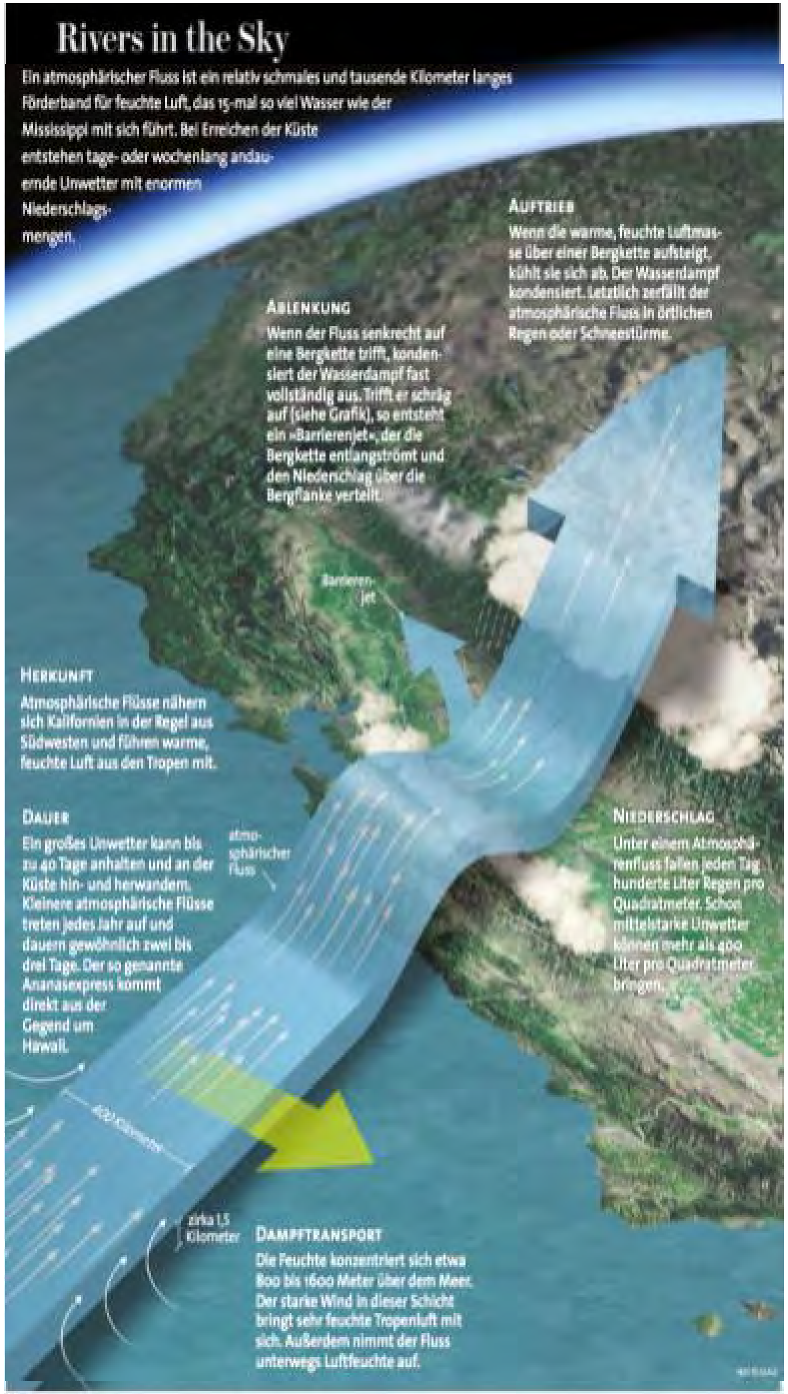


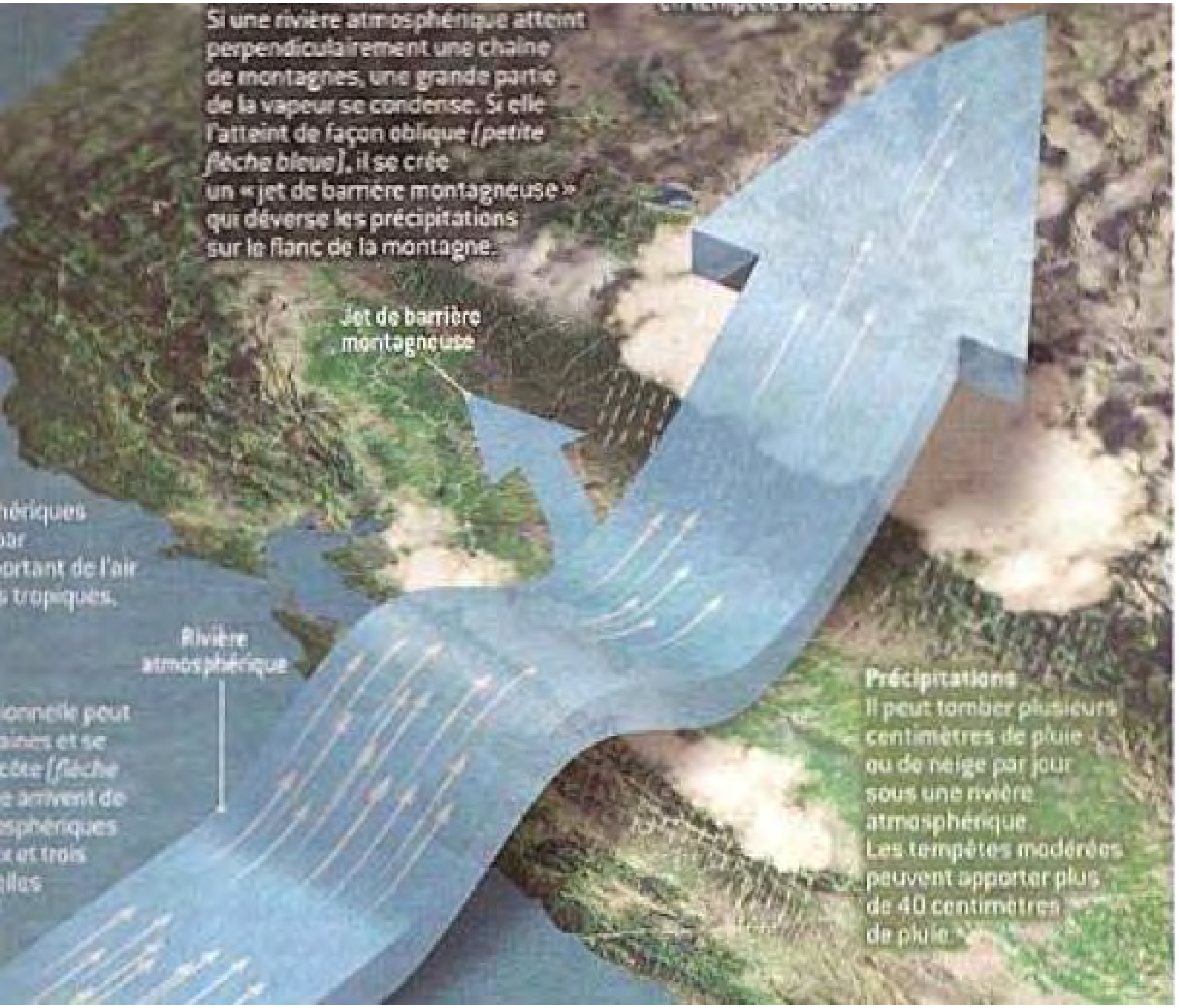

# The meteorology of extreme orographic precipitation in California—A synthesis as of 2014

Marty Ralph, CW3E, Scripps Institution of Oceanography

Mike Dettinger, USGS/SIO/CW3E

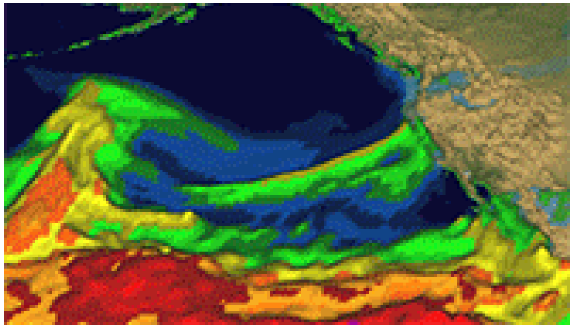
**A Major Result from 10-years of Research:**
**Atmospheric rivers** are key to understanding & forecasting extreme precipitation in the mountains along the U.S. West Coast

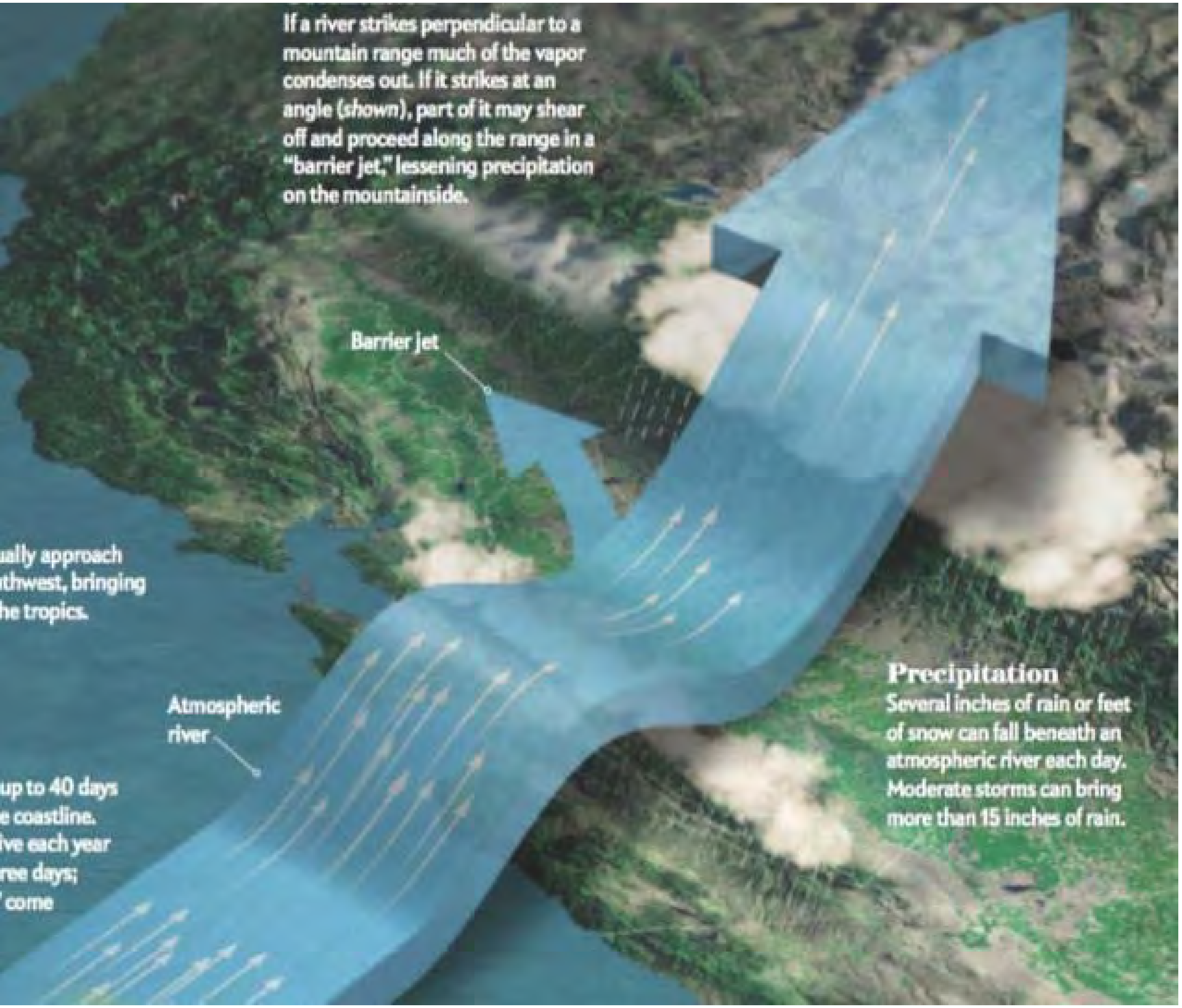
# Outline




- **What are atmospheric rivers?**
- **Why do they produce so much precipitation?**
- **What controls how much precipitation they produce?**
- **How are we building on this new information?**

# Atmospheric Rivers



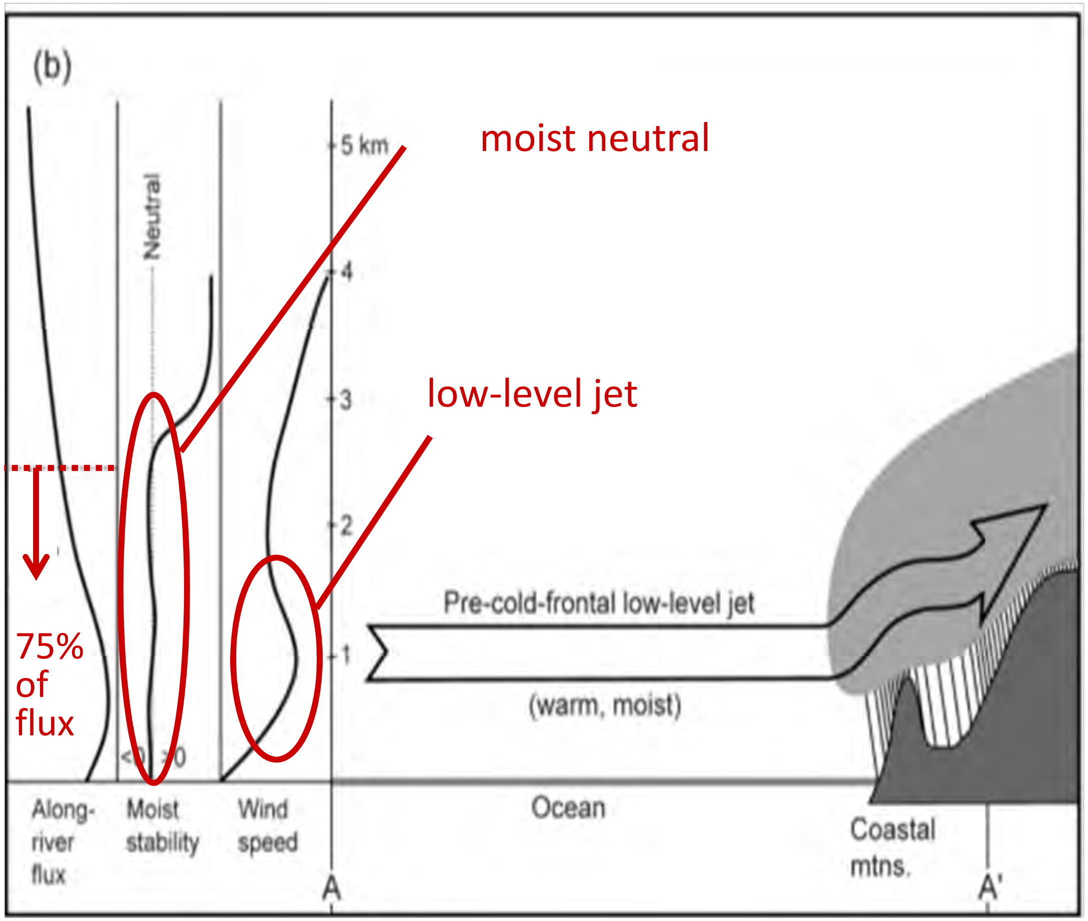



**-Vertical structure: Intense jets transporting vapor, between 0 – 2.5 km above sea level**--*from airplanes & AROs*

**-Map-view structure: ~400 km width & 2000 km long**--*from satellite data*

*Ralph et al., MWR, 2004; Ralph et al., MWR, 2005; Dettinger & Ingram, Sci Am 2013*

# Why do landfalling ARs yield heavy rain?

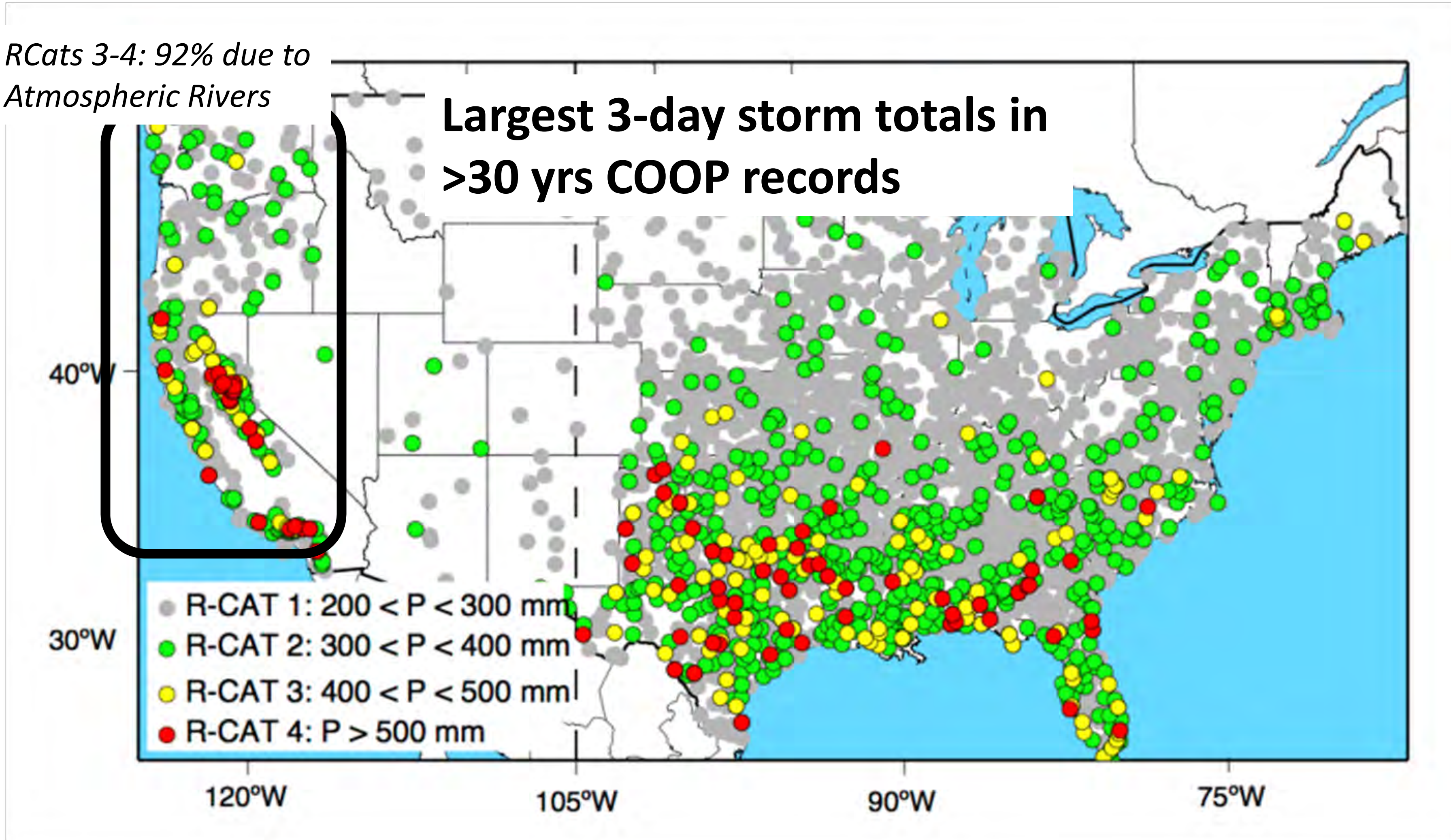



- Composite sounding located 500 km off CA coast in pre-cold-frontal LowLevel Jet (atmospheric river)
- LL Jet directed toward coast and situated at 1-2 km MSL, wind speeds 15 to 20 m/s
- Most (75%) of pre-cold-frontal along-river moisture flux is below 2.5 km MSL
- Vapor transport ~ 10-20 Mississippis
- Moist neutral stratification below 2.8 km MSL, hence no resistance to orographic lifting
- **Overlapping set of conditions very conducive to orographic rain enhancement in coastal mtns & Sierra Nevada**

*Ralph et al. (2004, 2005) MWR*

# Just how BIG are these storms?

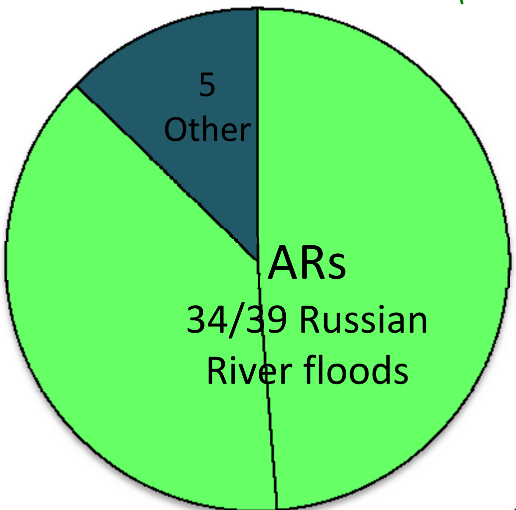
*RCats 3-4: 92% due to Atmospheric Rivers*



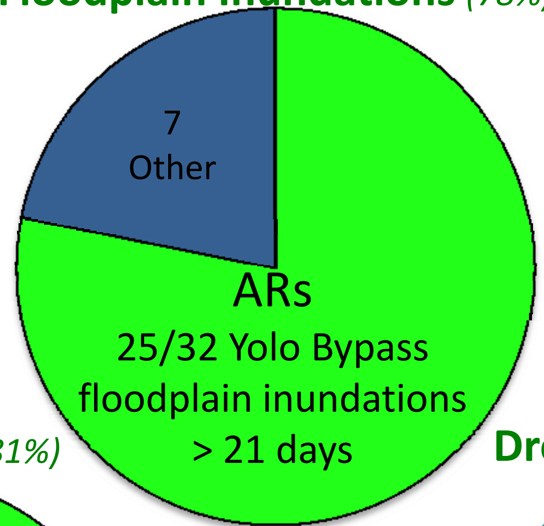

*Ralph & Dettinger, BAMS, 2012*

# California extremes since 1950

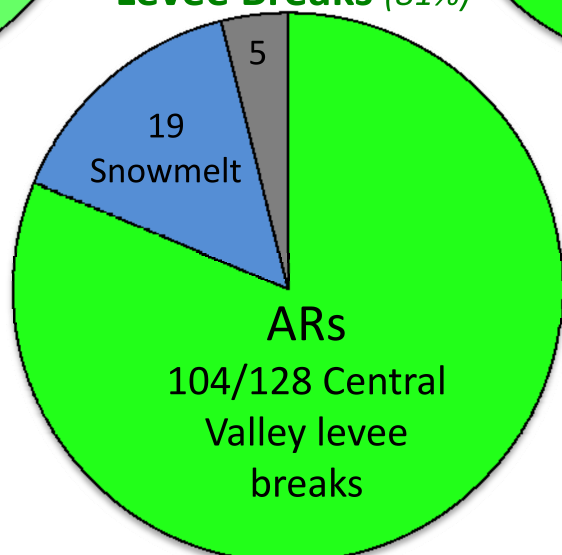
**Russian River Floods** *(87%)*



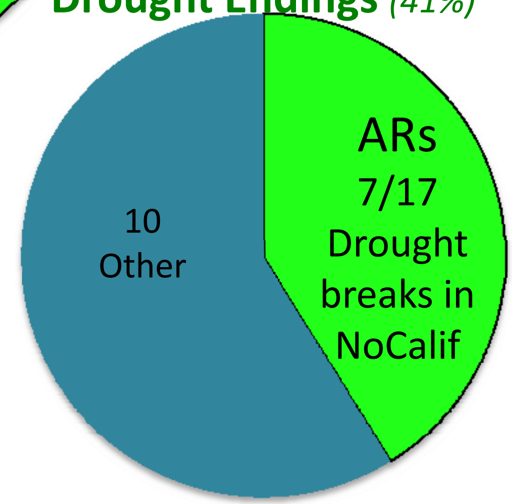

**Floodplain Inundations** *(78%)*




**Levee Breaks** *(81%)*




**Drought Endings** *(41%)*

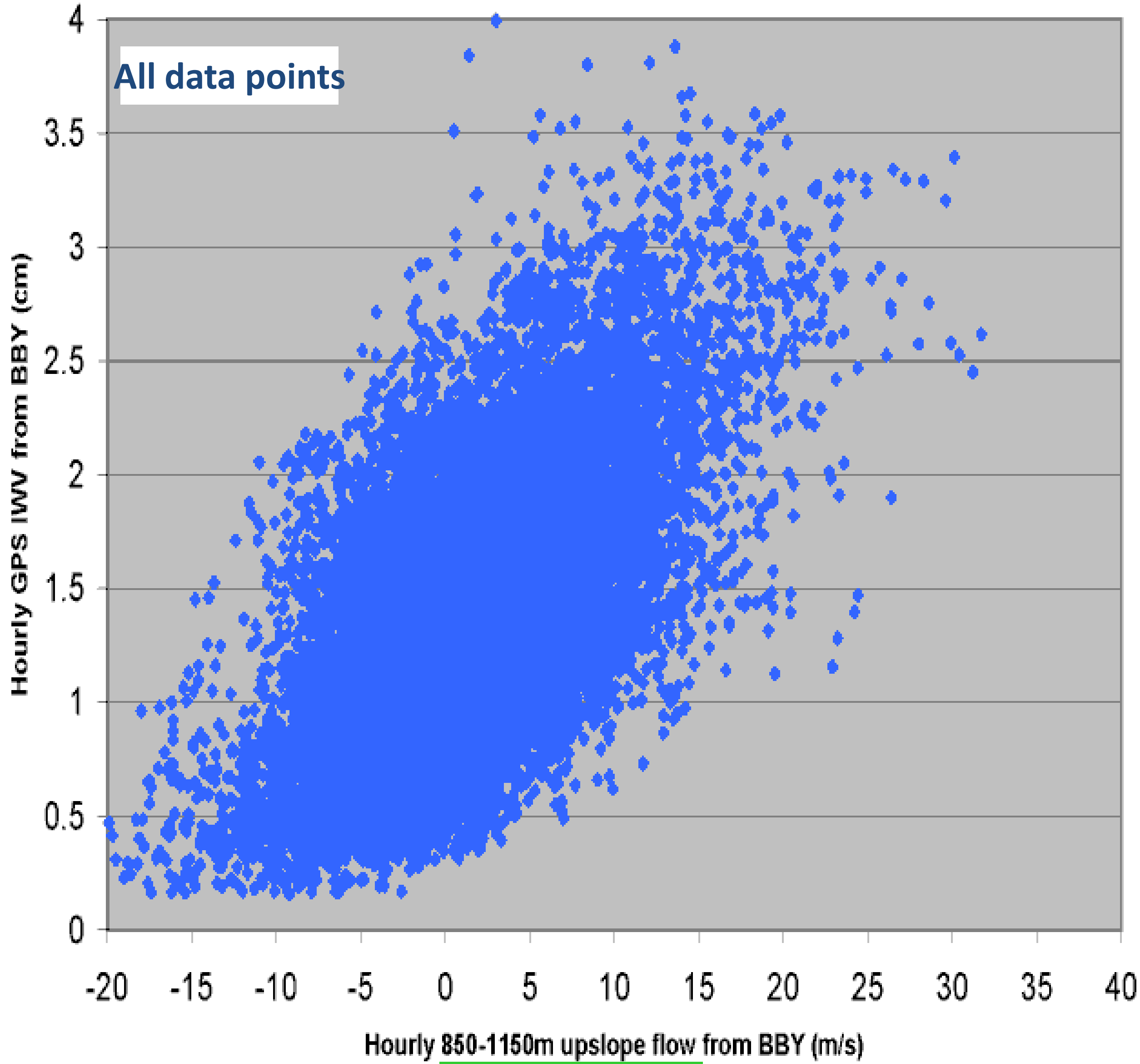



**All Calendar Days** *(4%)*

*Florsheim & Dettinger, book chapter, 2014; Dettinger, JHM, 2013*

Winters: 2001-2009; 18347 hourly data points

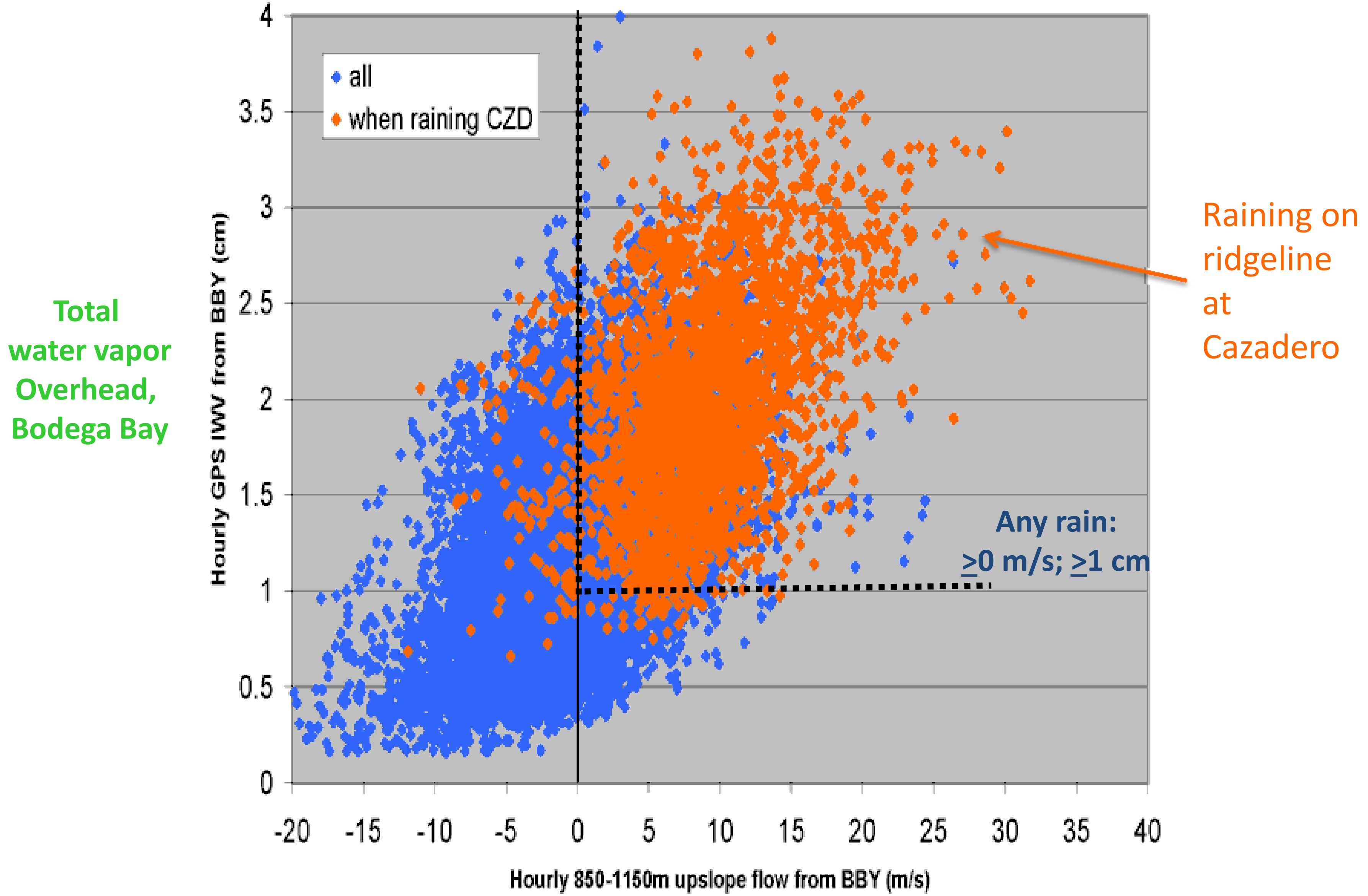
Total water vapor Overhead, Bodega Bay




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

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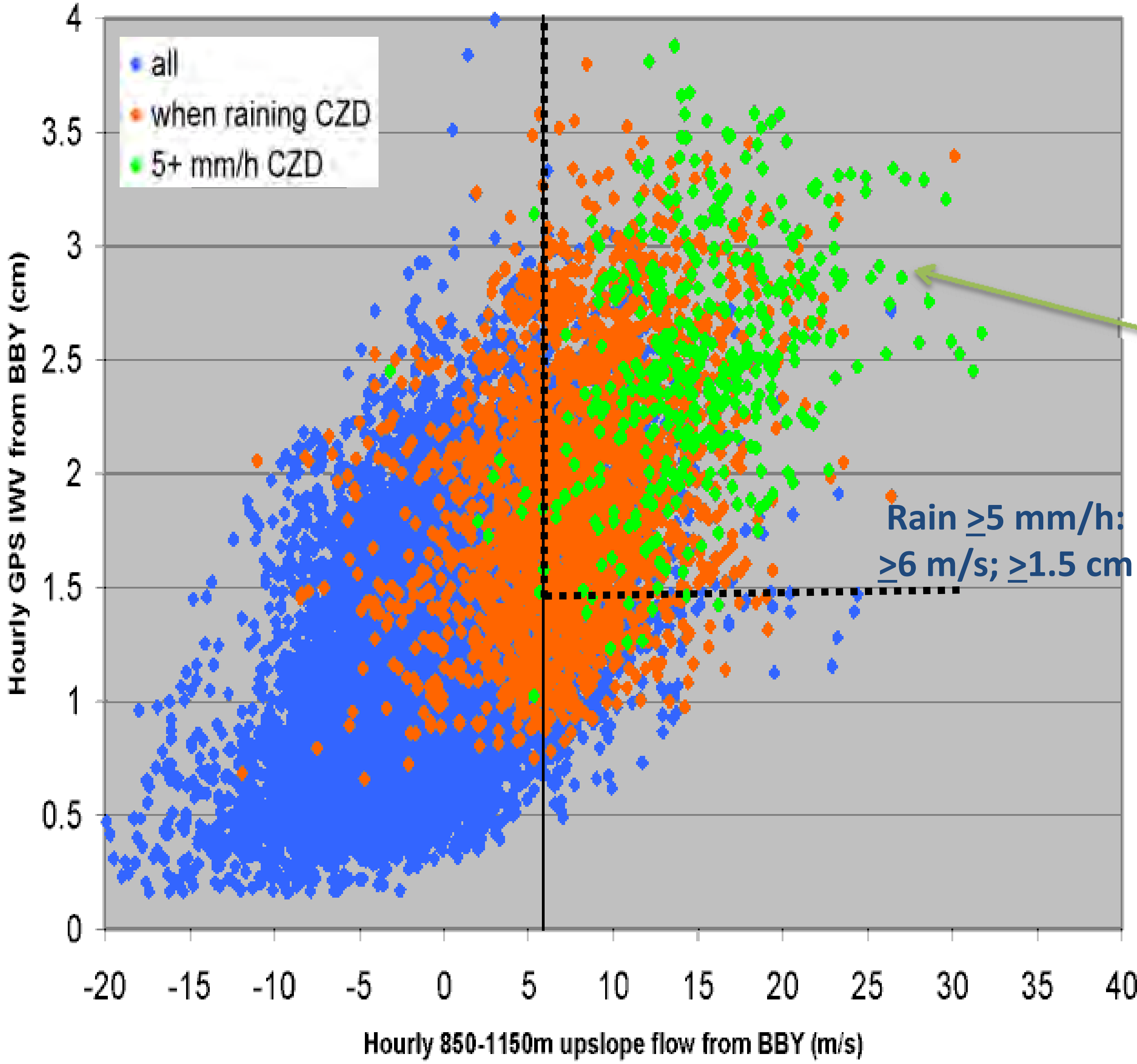
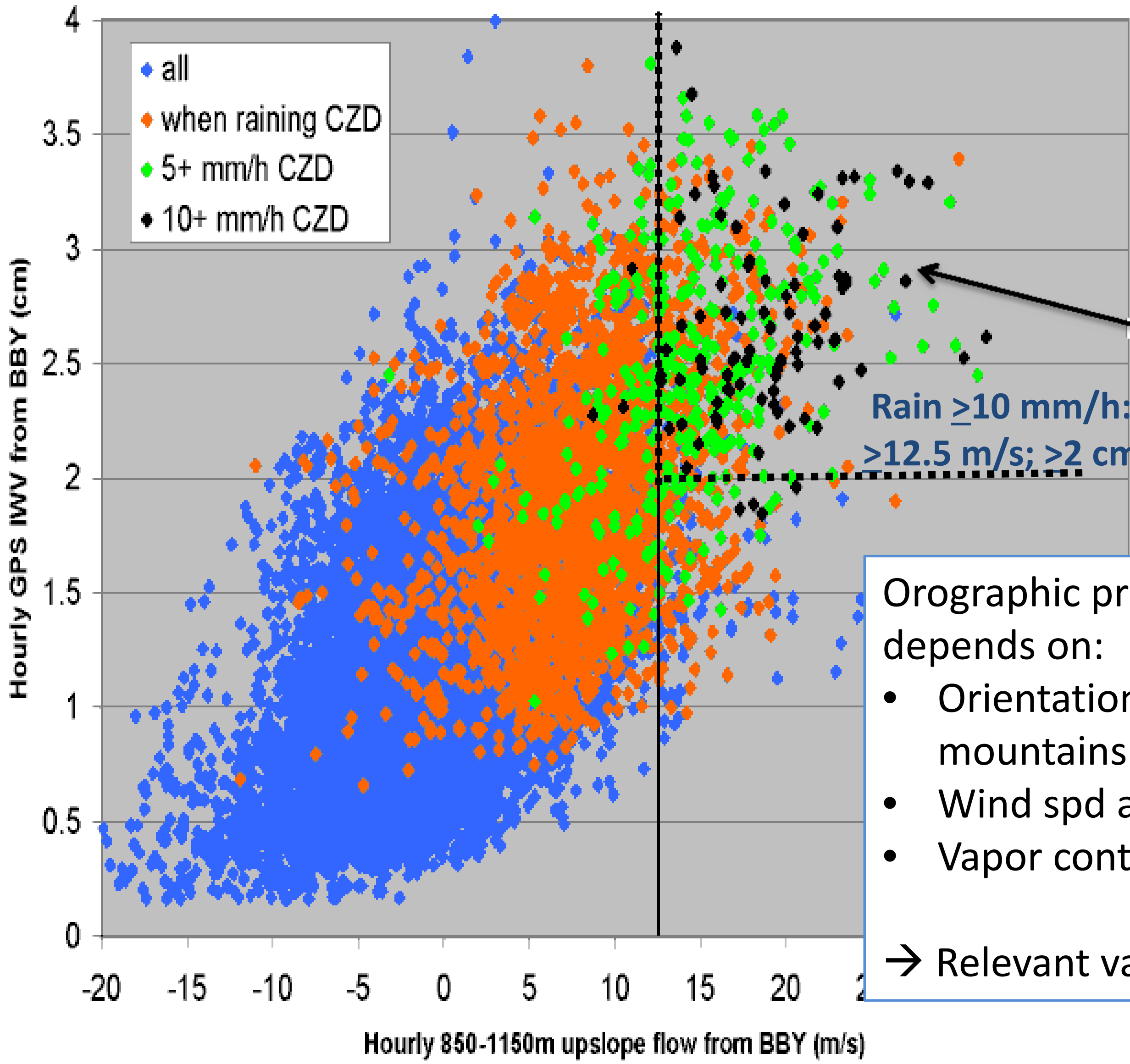



Total water vapor Overhead, Bodega Bay

Raining > 5mm/hr on ridgeline at Cazadero

**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




**Total water vapor Overhead, Bodega Bay**

Raining > 10mm/hr on ridgeline at Cazadero

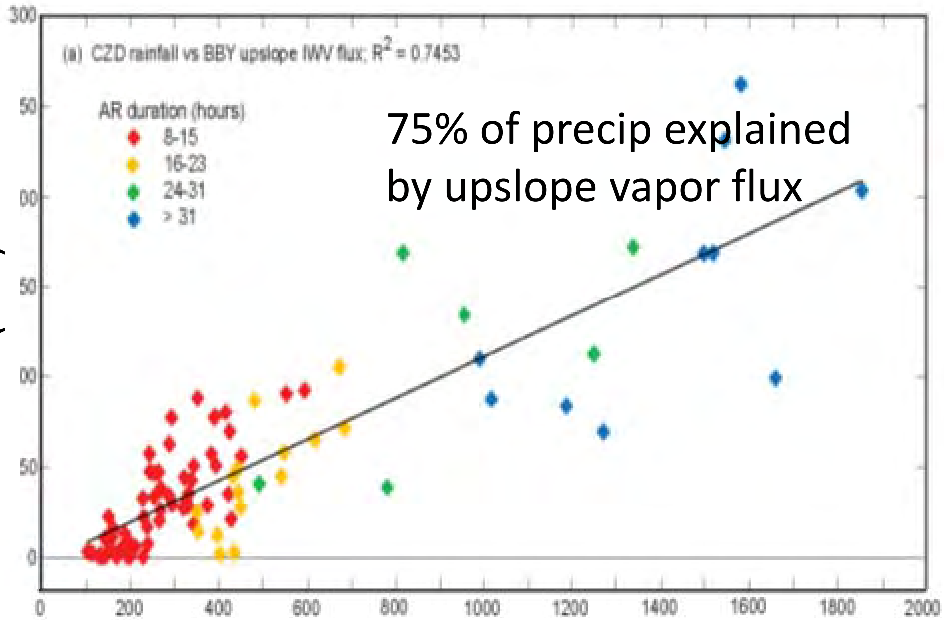
Orographic precipitation depends on:

- Orientation of AR rel to mountains
- Wind spd at about 1.5 km msl
- Vapor content

→ Relevant vapor transport

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

**91 AR events observed over 6 years**

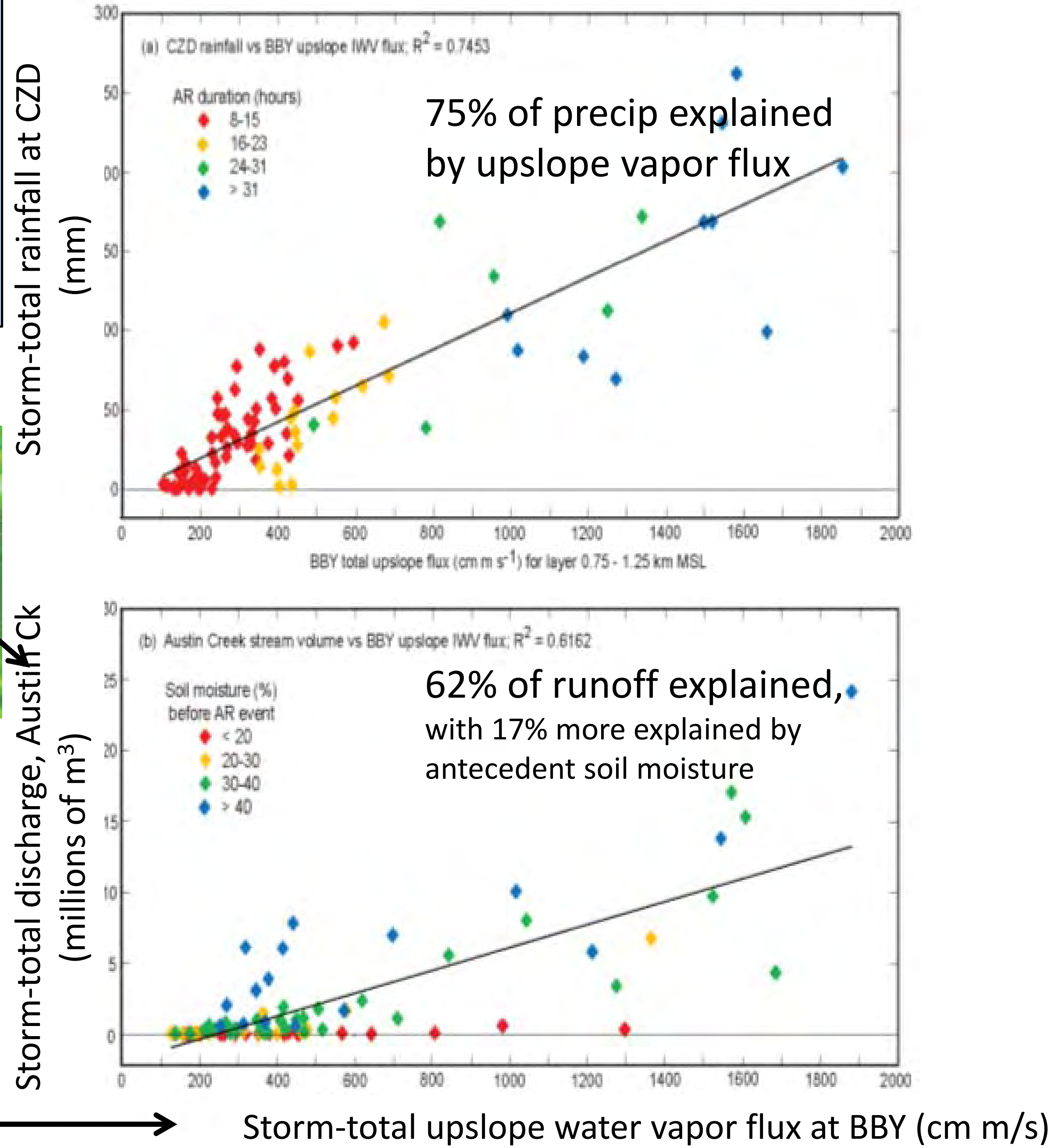

75% of precip explained by upslope vapor flux

Storm-total rainfall at CZD (mm)

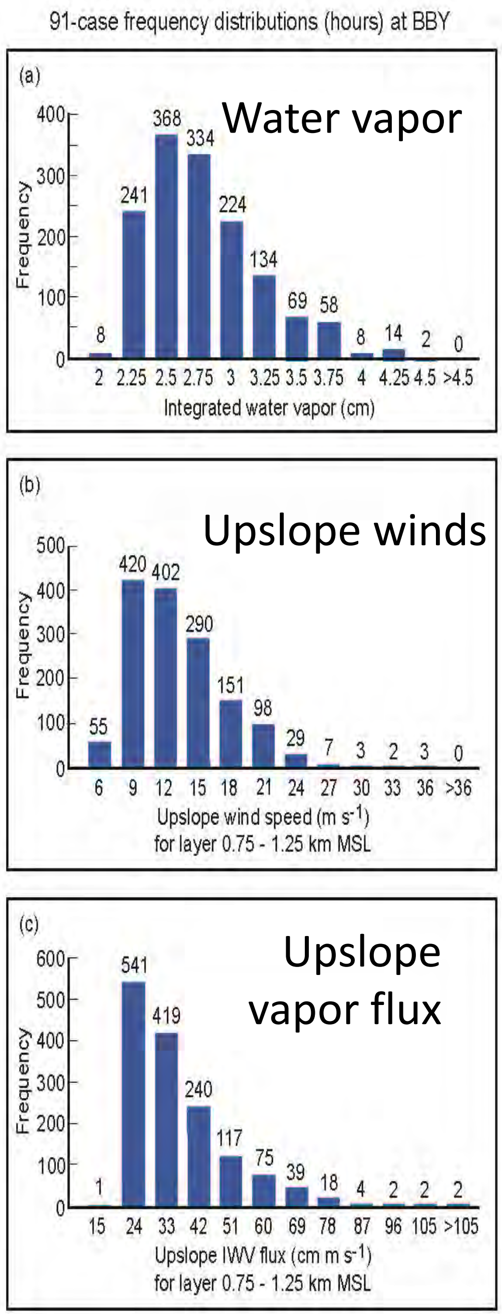
Storm-total upslope water vapor flux at BBY (cm m/s)

*Ralph et al. (2013) JHM*

**91 AR events observed over 6 years**


*Ralph et al. (2013) JHM*




Orographic precipitation depends on:

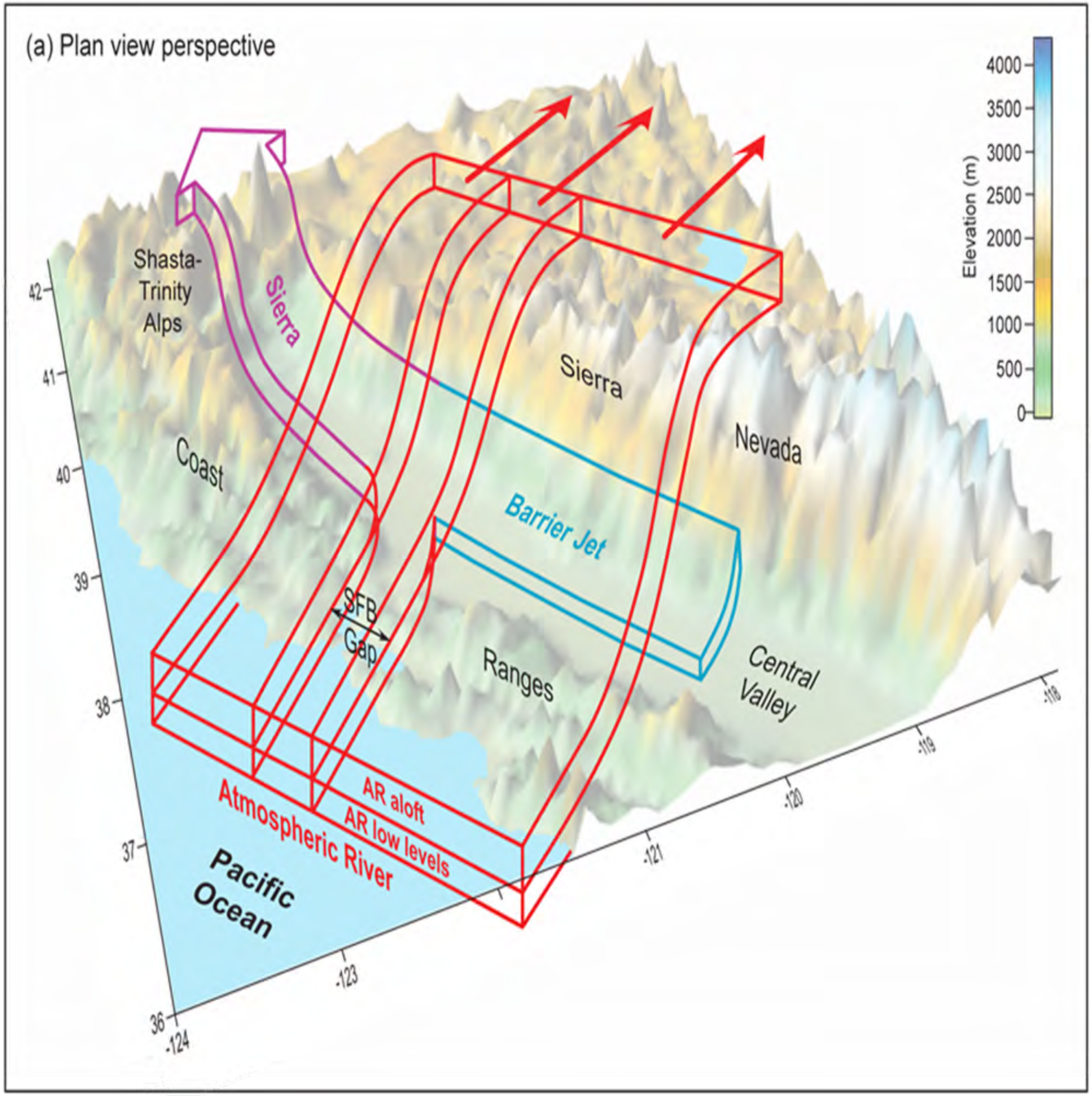
- Orientation of AR rel to mountains
- Wind speed at about 1.5 km msl
- Vapor content

→ Relevant vapor transport

With >1460 AR-hours from >91 AR landfalls in hand, we are increasingly able to intelligently compare the extremity (or not) of current or predicted events to historical extremes

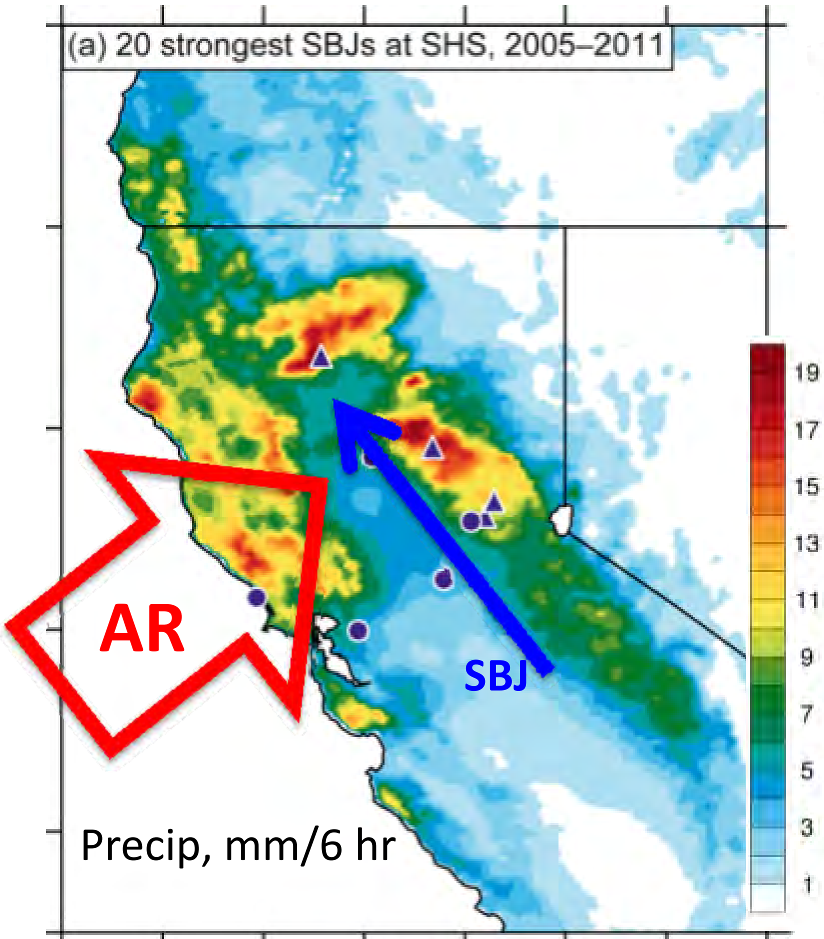
*Ralph et al. (2013) JHM*

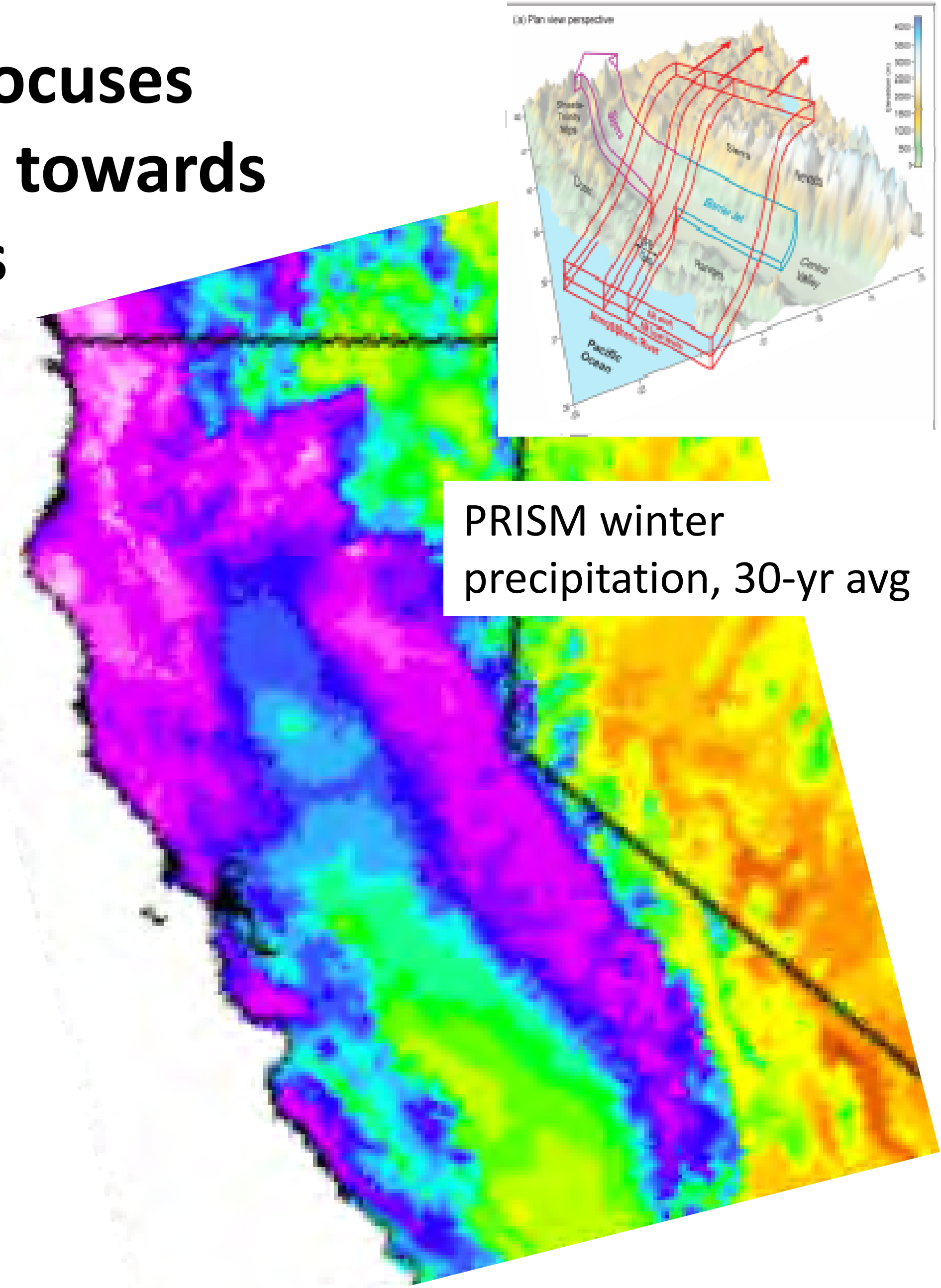
The Sierra Barrier Jet is another key to patterns of precip in California




*Neiman et al. (2013) MWR 2013*

# A strong Sierra Barrier Jet focuses orographic precipitation up towards Shasta/Oroville catchments



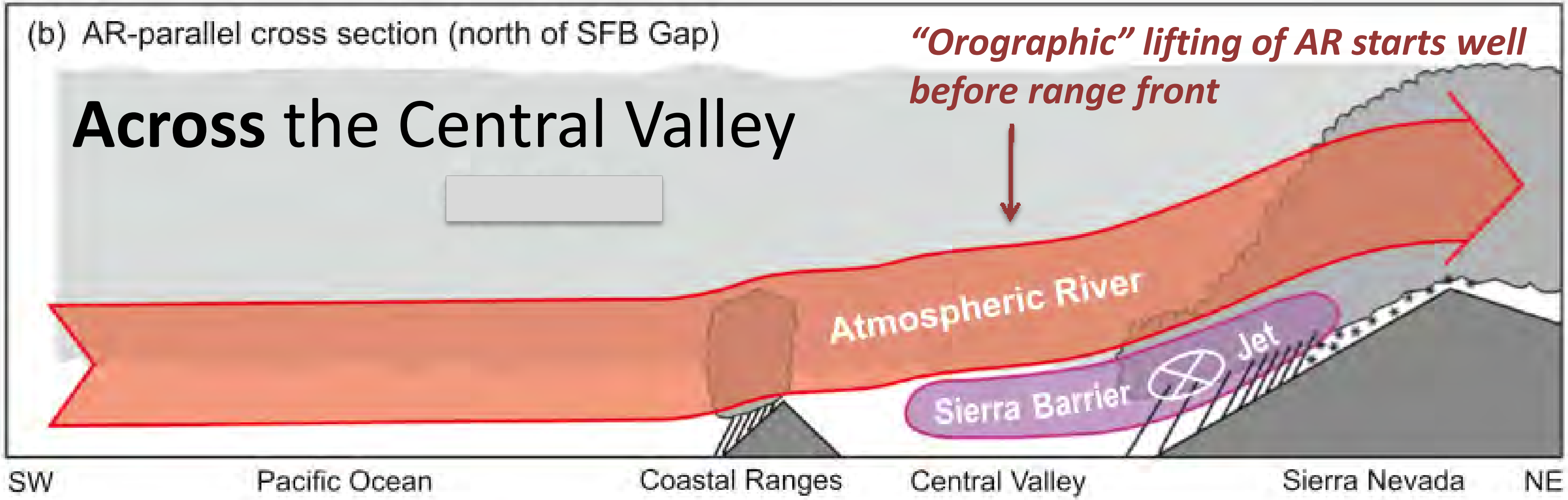



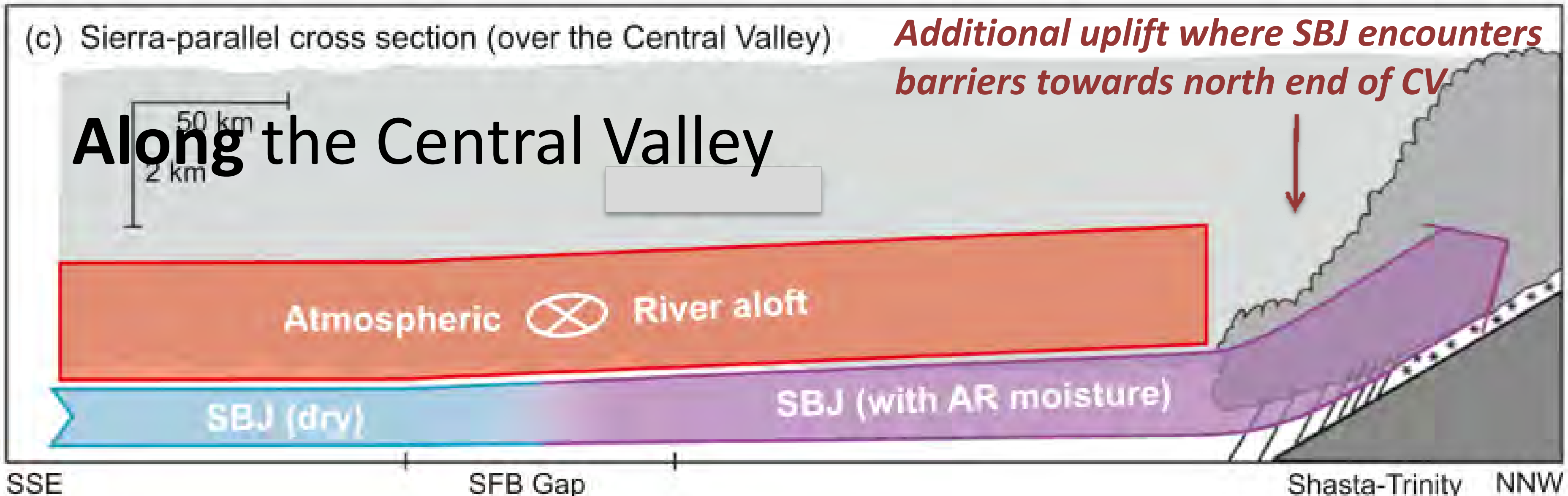

More SBJ → More focus

Average mix of storms → Less focus

*Neiman et al. (2013) MWR*

# Schematically, this looks like:

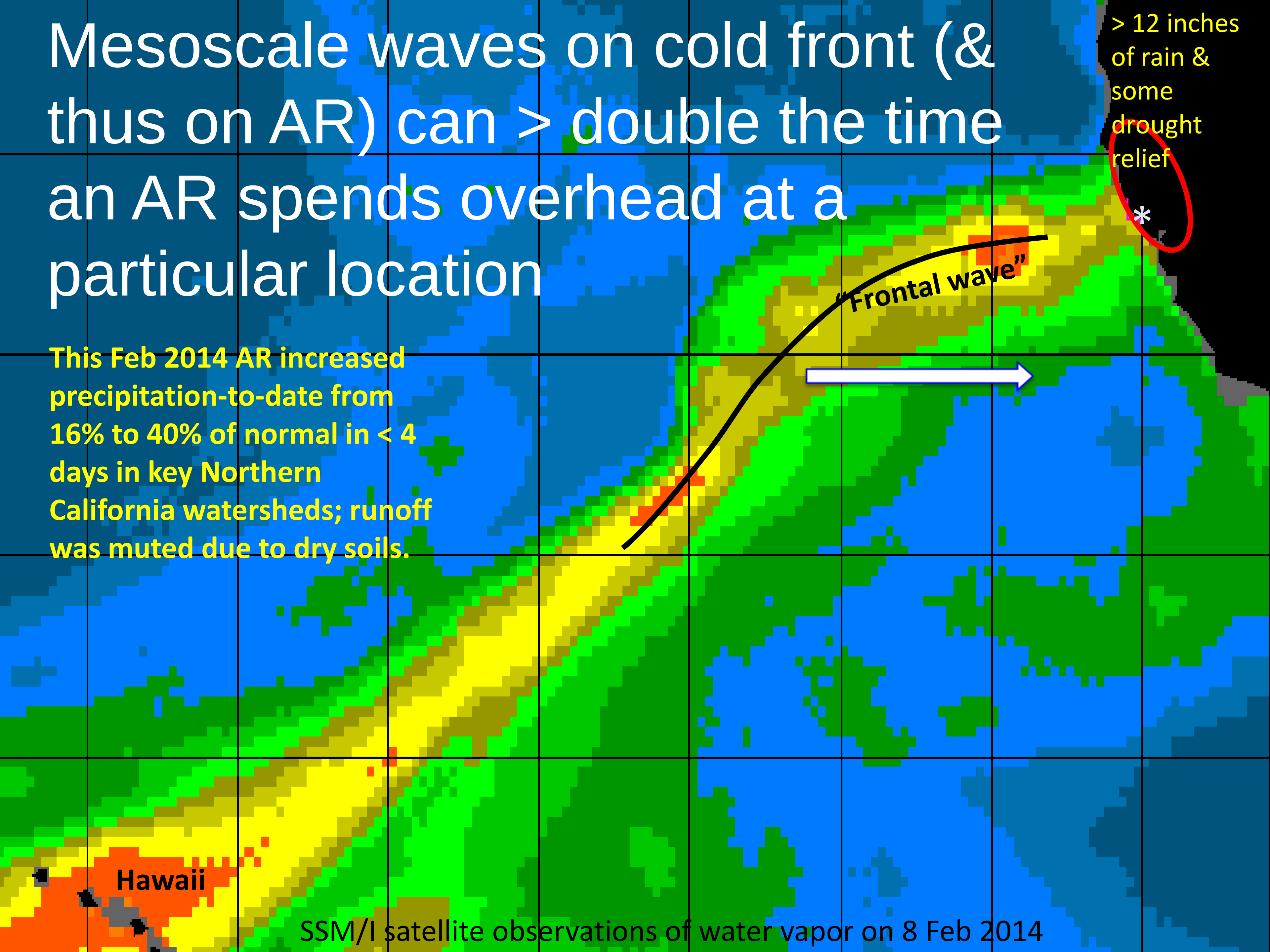



*Neiman et al. (2013) MWR*

# Mesoscale waves on cold front (& thus on AR) can > double the time an AR spends overhead at a particular location

**This Feb 2014 AR increased precipitation-to-date from 16% to 40% of normal in < 4 days in key Northern California watersheds; runoff was muted due to dry soils.**



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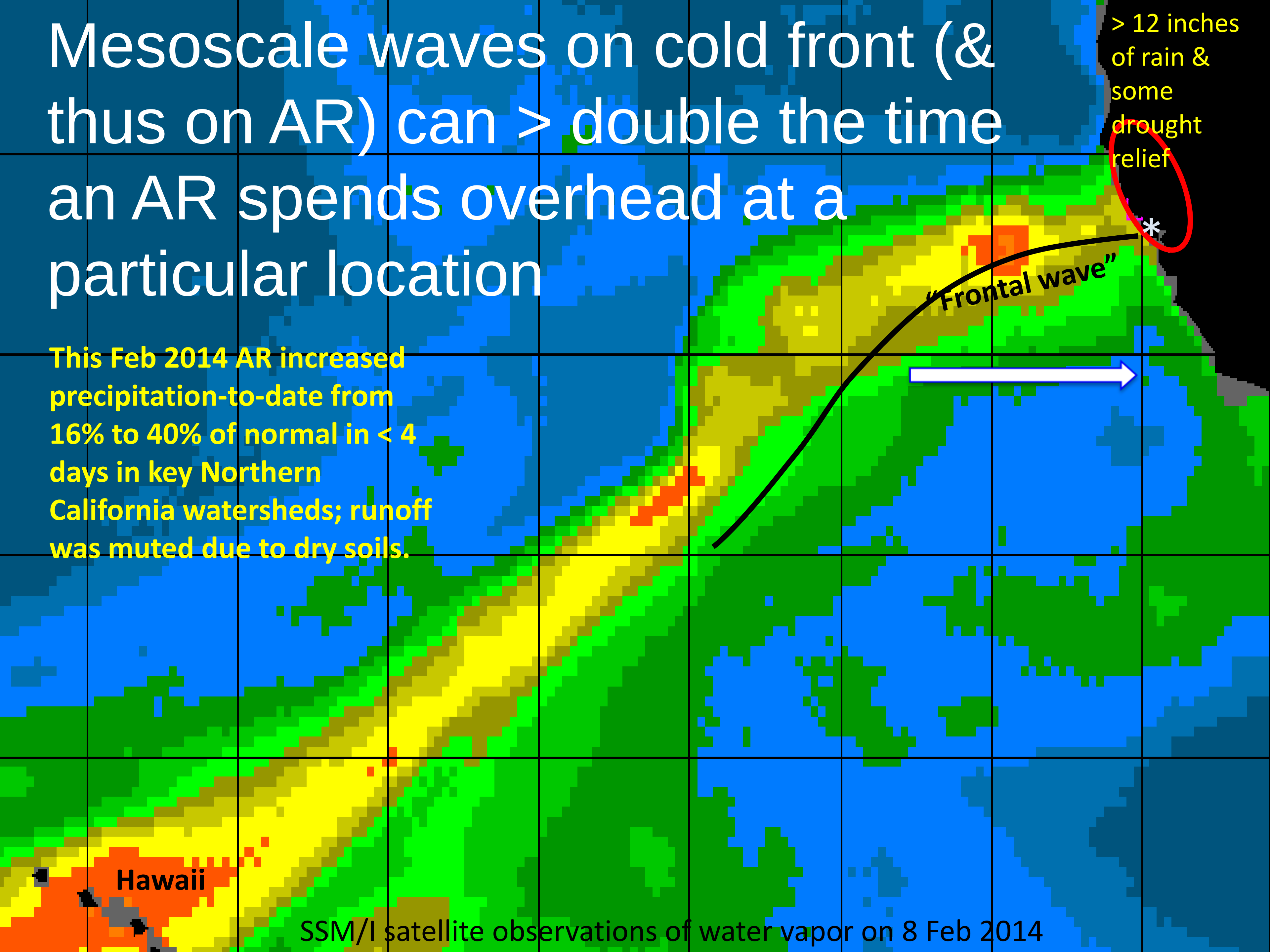


SSM/I satellite observations of water vapor on 8 Feb 2014

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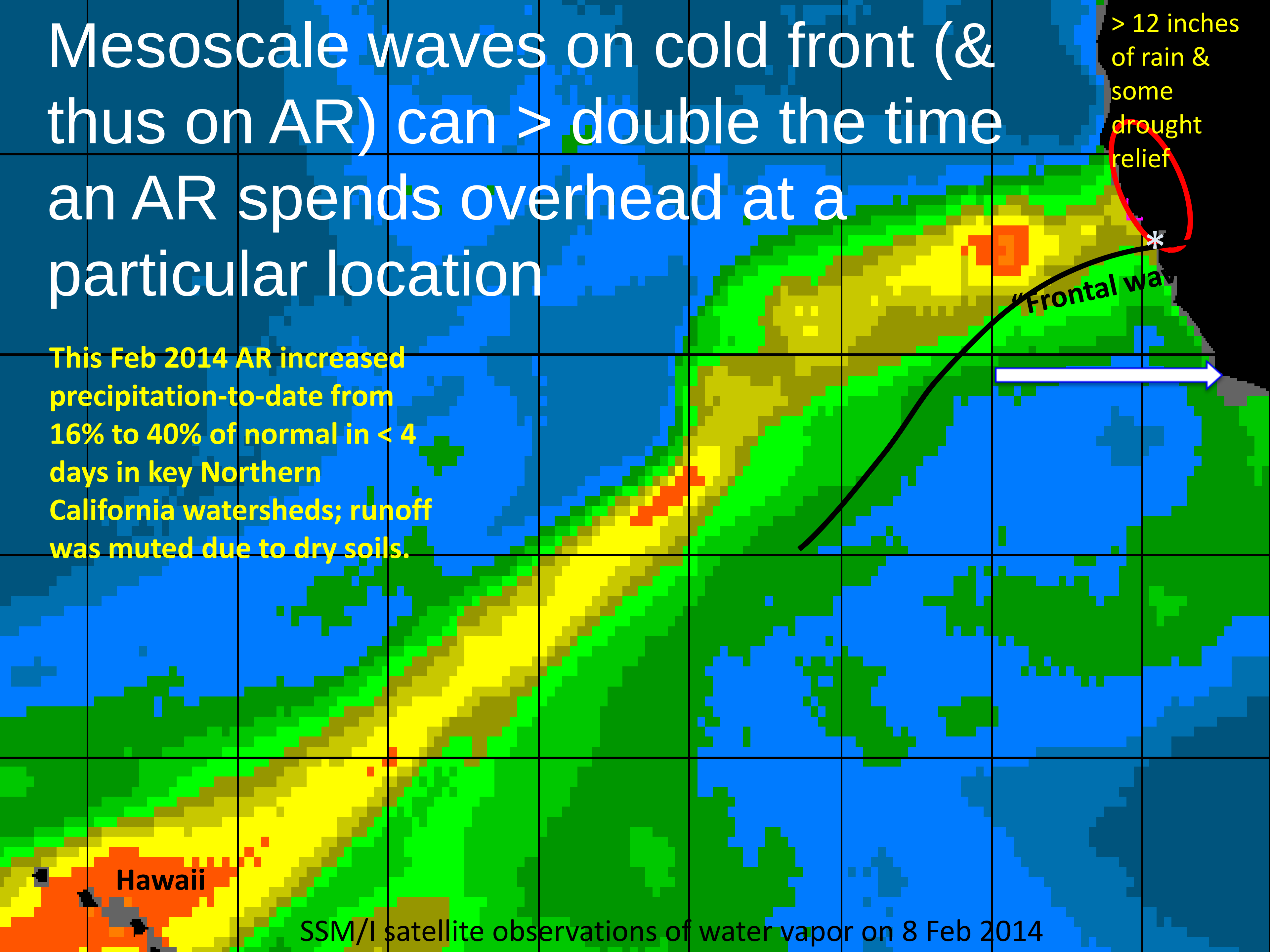


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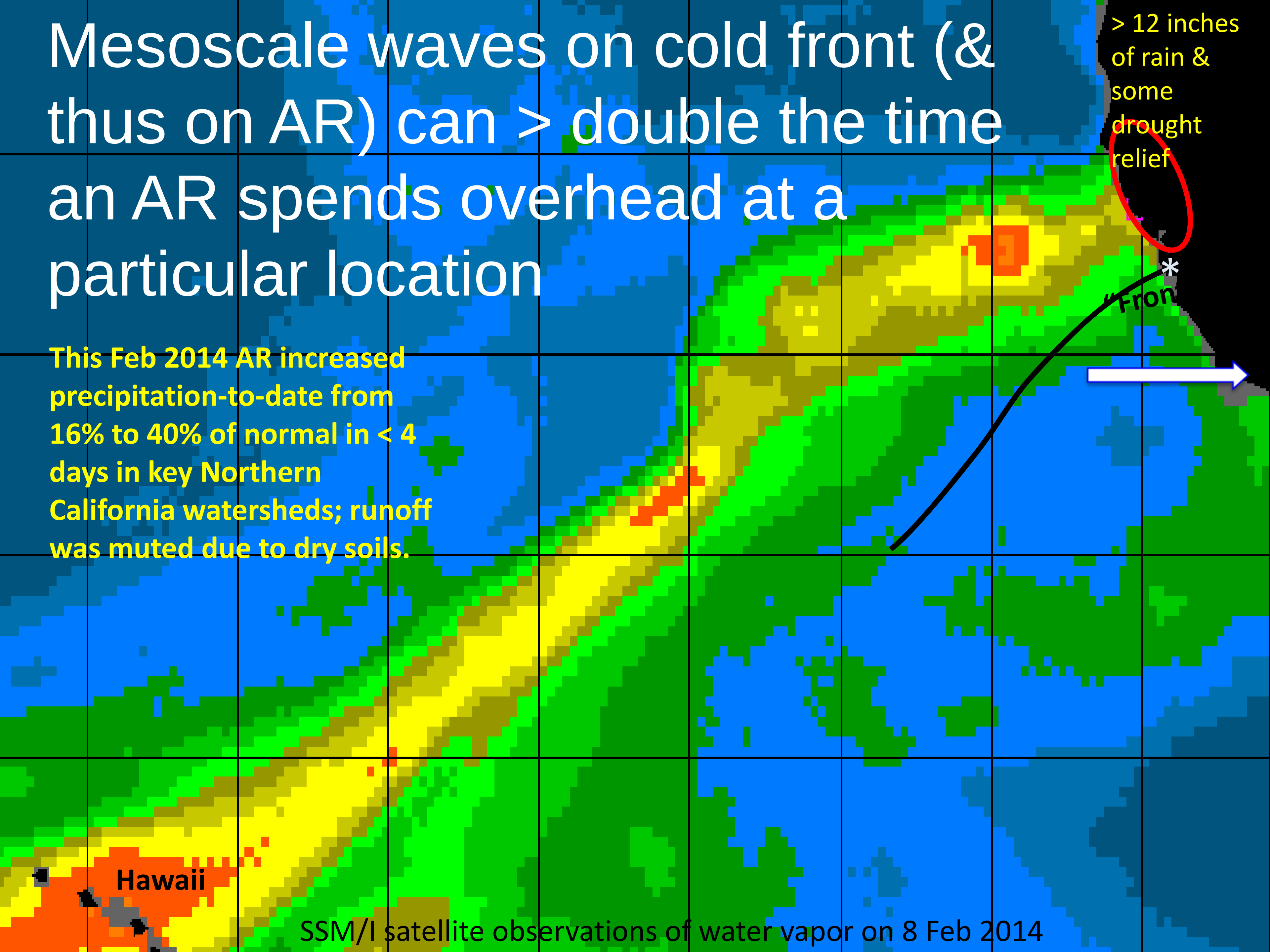


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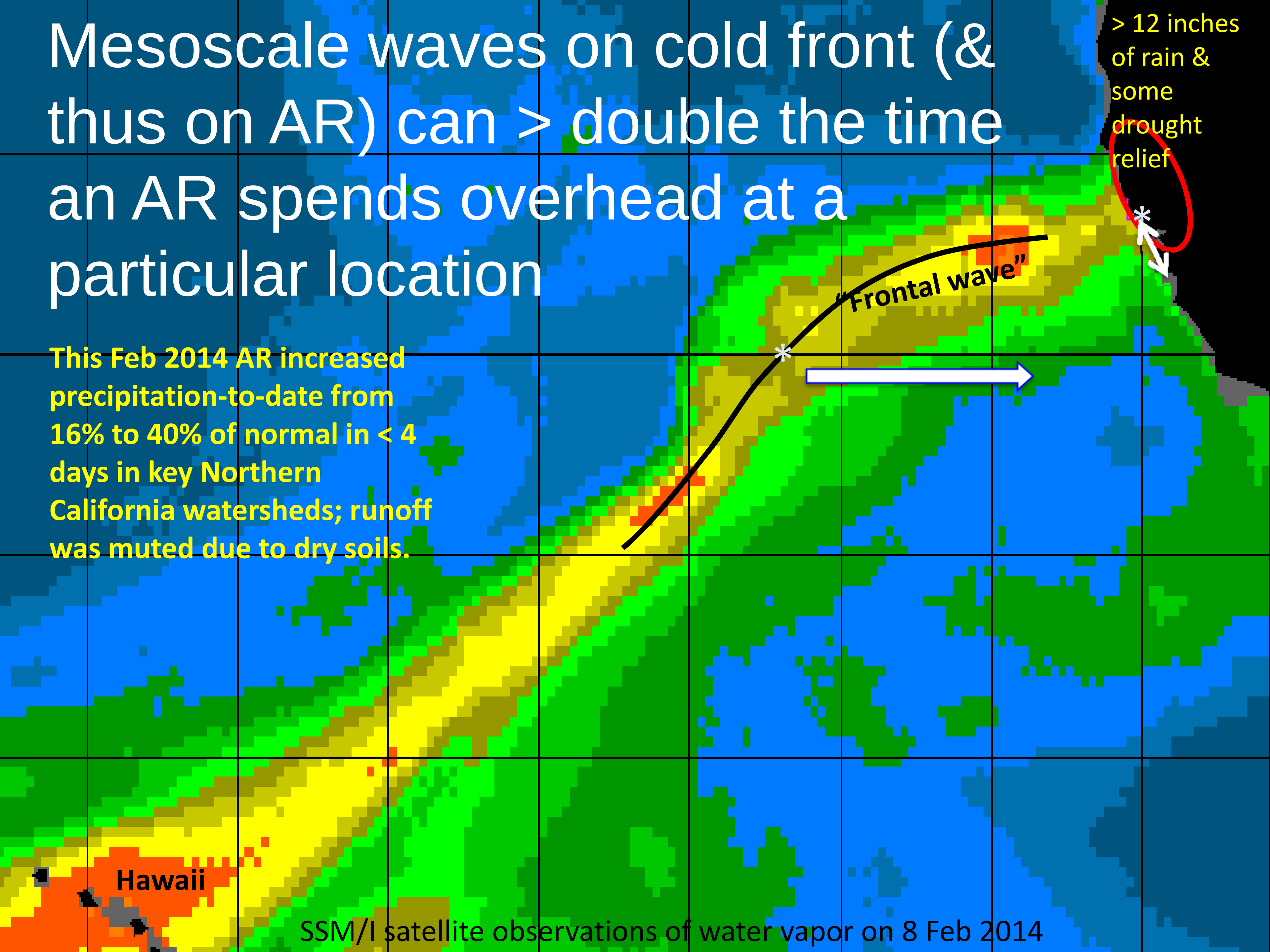


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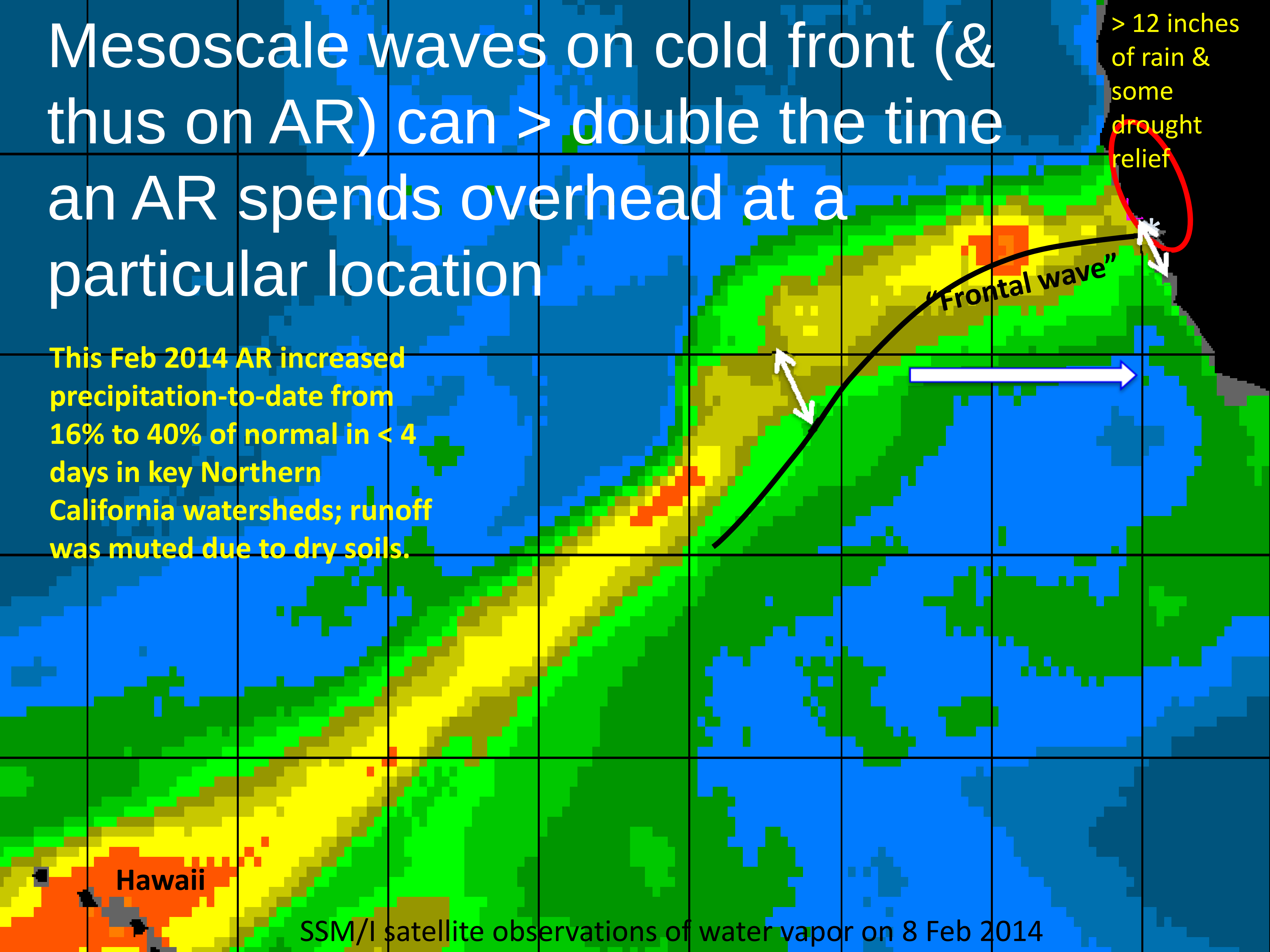
Mesoscale waves on cold front (& thus on AR) can > double the time an AR spends overhead at a particular location
This Feb 2014 AR increased precipitation-to-date from 16% to 40% of normal in < 4 days in key Northern California watersheds; runoff was muted due to dry soils.
> 12 inches of rain & some drought relief
"Frontal wave"
Hawaii
SSM/I satellite observations of water vapor on 8 Feb 2014

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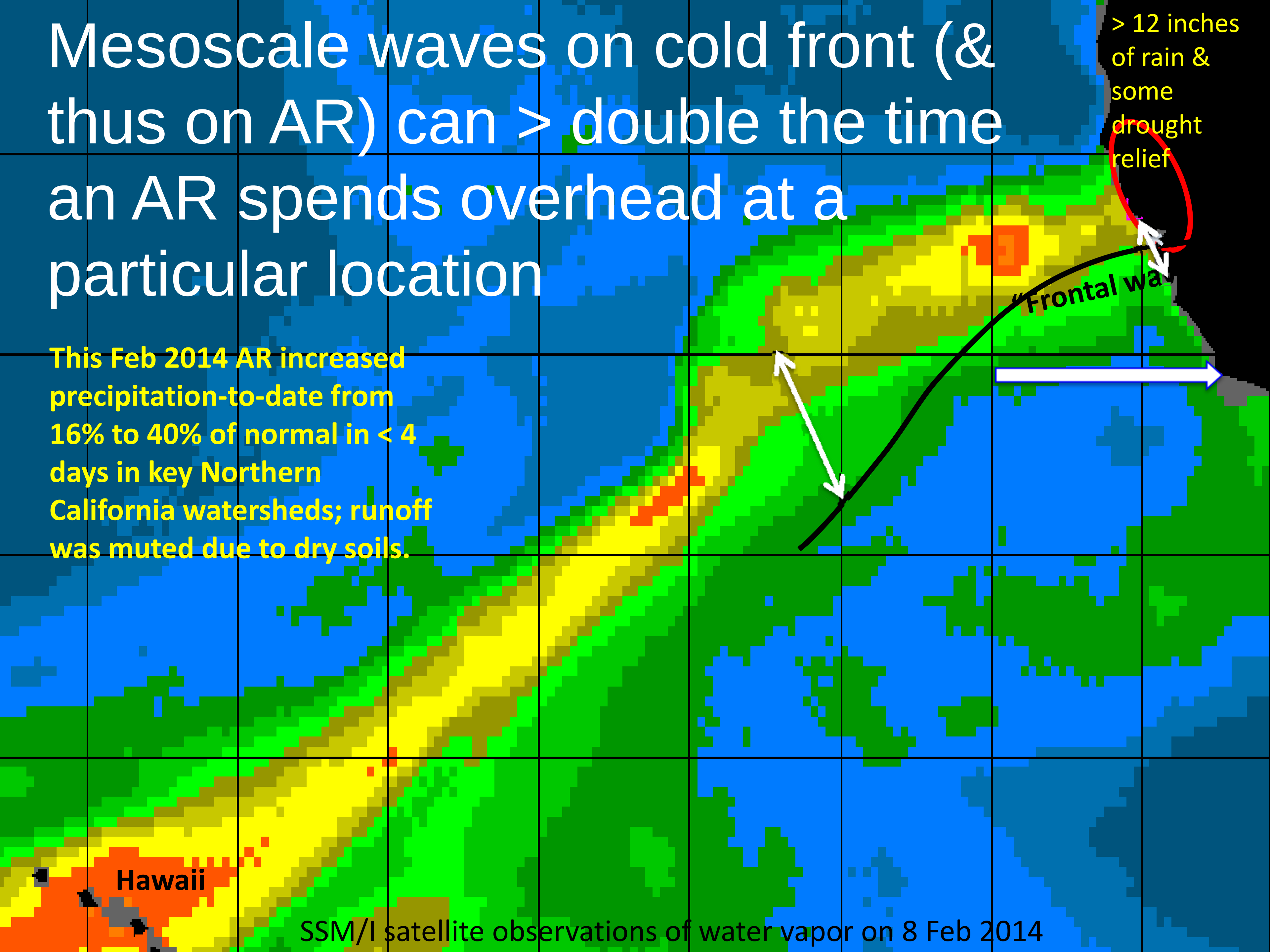


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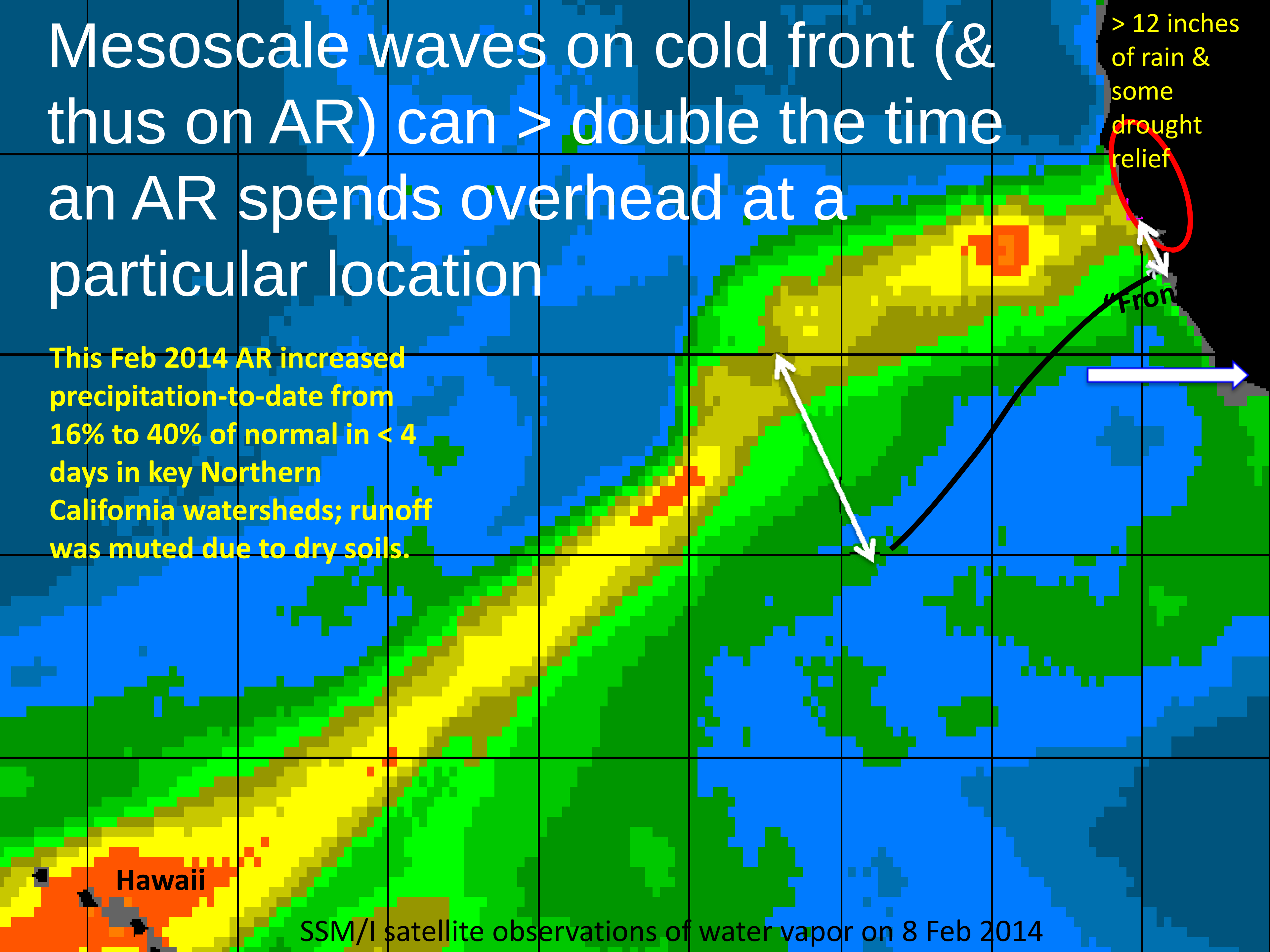
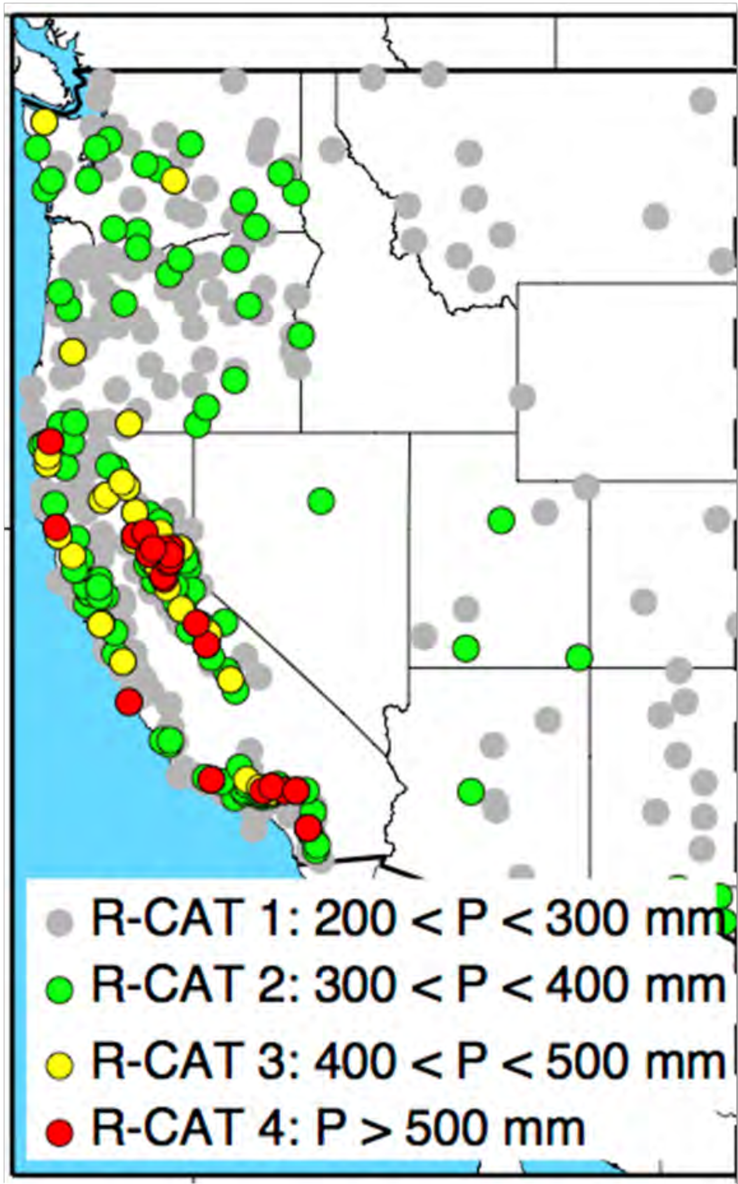



SSM/I satellite observations of water vapor on 8 Feb 2014

# What determines intensity, totals, distribution & impacts of orographic precipitation from ARs?

- **Number of landfalls per year**
- **Vapor transport onshore by ARs**
  *Wind speed in low-level jet & vapor content*
- **Orientation of transport wrt topography**
- **Duration of AR passage overhead**
  *Mesoscale frontal waves*
- **Temperature of AR**
  *Snowline altitude*
- **Closeness to saturation**
  *How much uplift before precipitation begins*
- **Stability of atmosphere**
  *How readily is AR lifted by orography*
- **Presence/absence of resulting SBJ**
- **Antecedent soil moisture**



# What are we doing with this knowledge?

**Continued research obs & NEW statewide monitoring network built upon these "AR principles"**

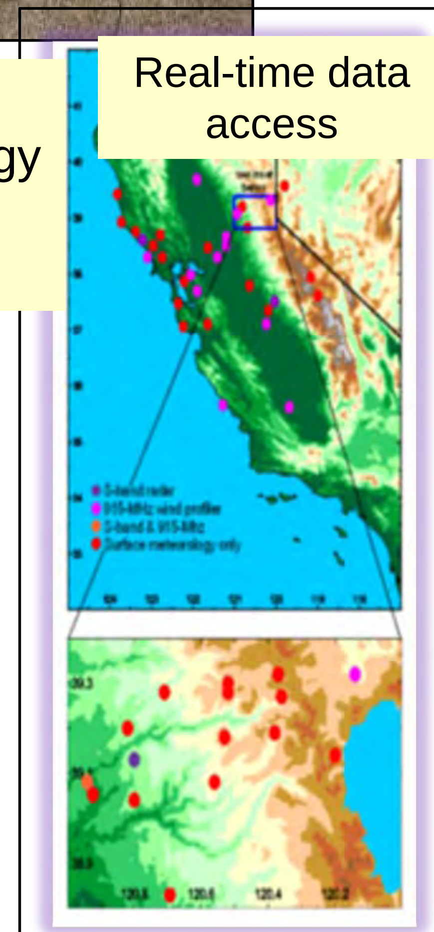
# Surface Observing Systems

Precipitation gauges

Precipitation droplet sizes/rates (disdrometers)

Surface meteorology & snow depth

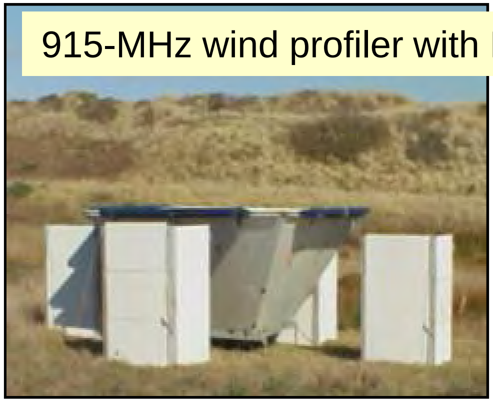
Real-time data access



Soil moisture

Stream stage/flow

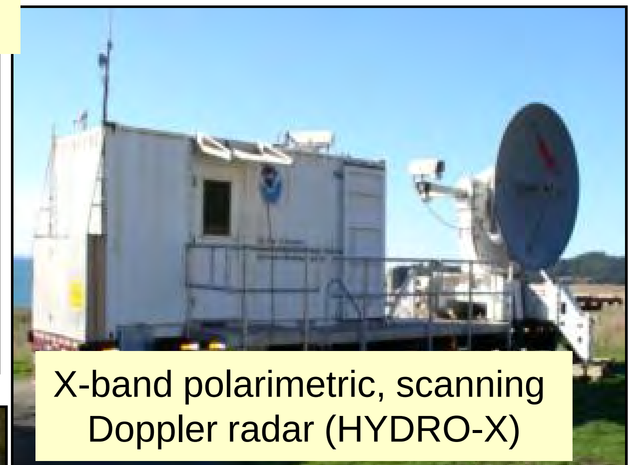
# Remote Sensing Observing Systems



915-MHz wind profiler with RASS

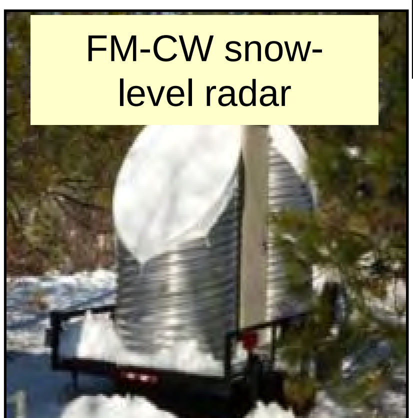
¼-scale 449-MHz wind profiler with RASS

S-band precipitation profiling radar (S-PROF)



X-band polarimetric, scanning Doppler radar (HYDRO-X)

C-band scanning Doppler radar (SKYWATER)

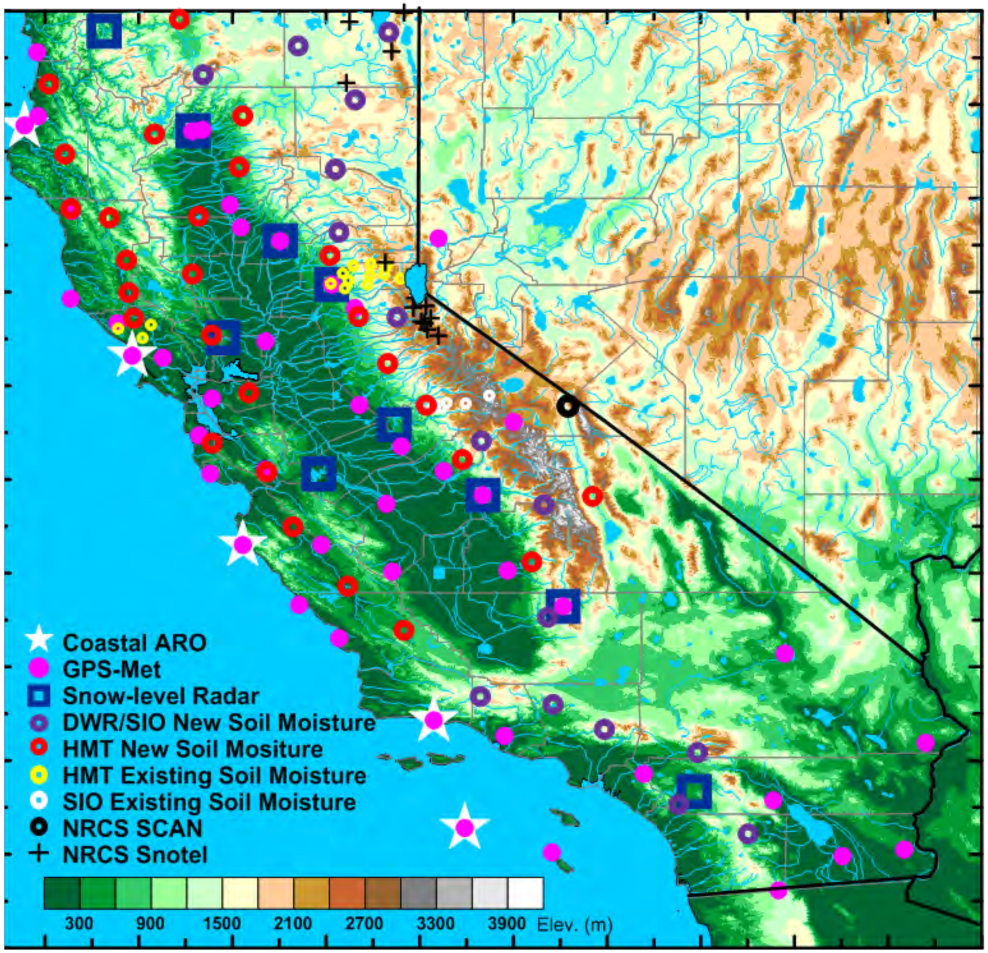


FM-CW snow-level radar


GPS receiver for integrated water vapor

# What are we doing with this knowledge?

**Continued research obs & NEW statewide monitoring network**




**An Atmospheric River-focused long-term observing network is being installed in CA as part of a 5-year project between CA Dept. of Water Resources (DWR), NOAA and Scripps Inst. Of Oceanography**

- **Installed 2008-2014**
- **>100 field sites**

*White et al. (2013) JAOT*

# What are we doing with this knowledge?

Statewide monitoring

**Preparing the way for offshore reconnaissance**

*CalWater2* **–** Field campaigns, winters 2015-2018

*SIO, DOE, NOAA, CEC, NSF, NASA, USGS, DWR …*

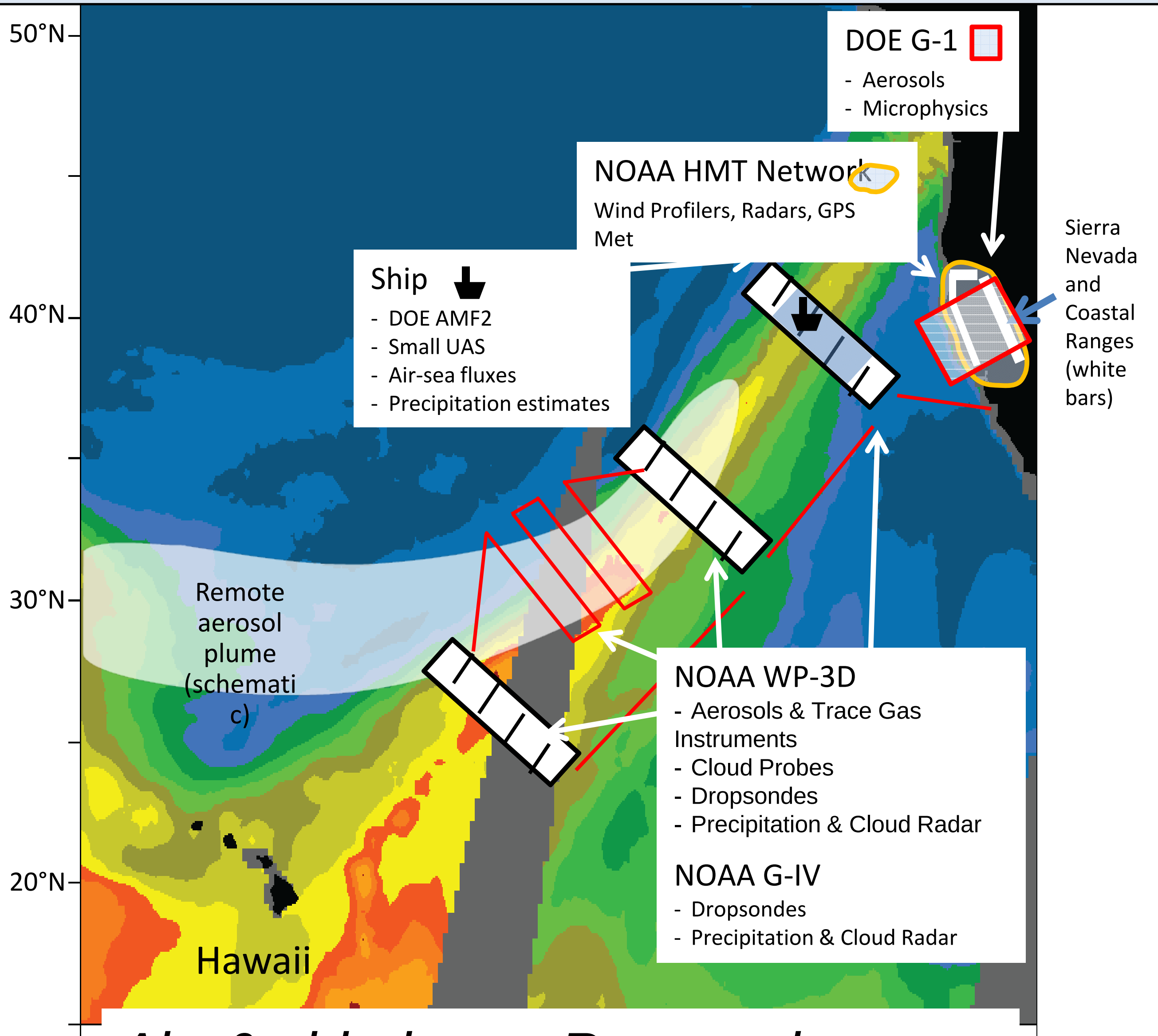
*-- AR structure/evolution onshore/offshore*

*-- Aerosols & precip, local/Asian*

*http://www.gewex.org/gewexnews/Feb2013.pdf*

# CalWater 2 / DOE ACAPEX Observational Campaign

Jan – Mar 2015



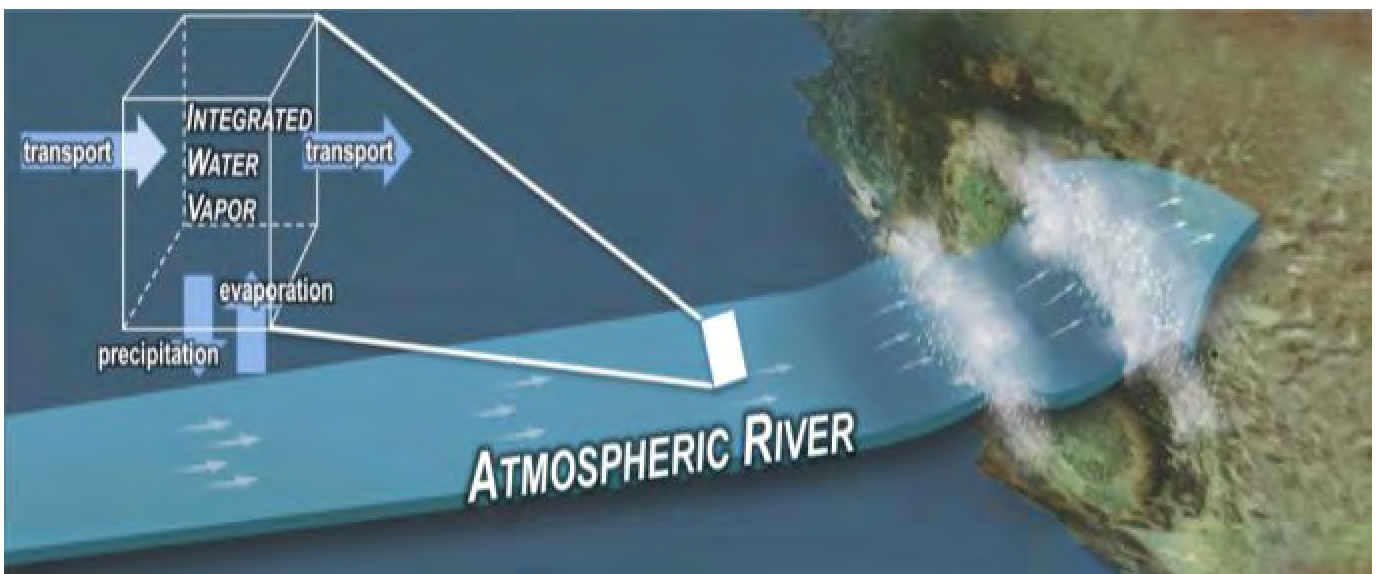

*Air- & ship-borne Reconnaissance*

# Atmospheric River Experiment (AREX)
# Proposal to NASA Earth Ventures
*Winters 2015-2018*

**Marty Ralph (PI)**
**Duane Waliser (Deputy PI)**
**Ryan Spackman (Deputy PI)**

Scripps Institution of Oceanography
NASA JPL
Science and Technology Corporation
NOAA-Earth Syst Research Lab

Water vapor budget of ARs offshore and impacts on landfall
- NASA Global Hawk (3 winters)
- NASA DC-8 (2 winters)
- AR Obs network onshore



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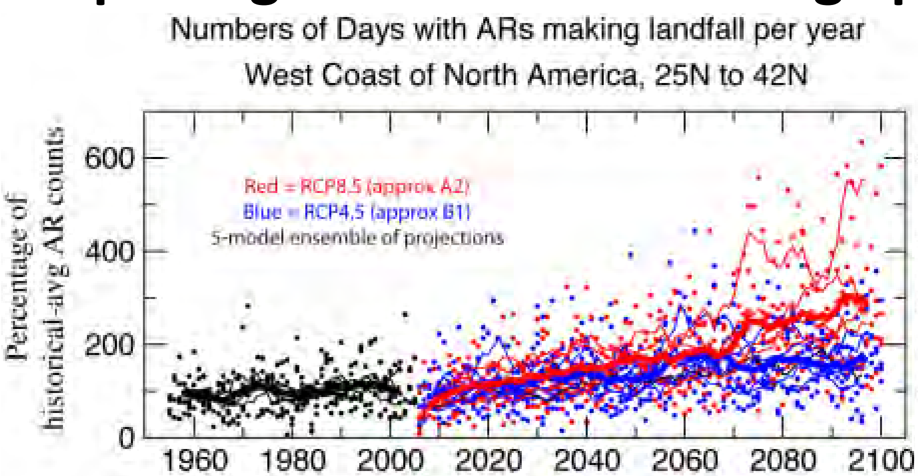
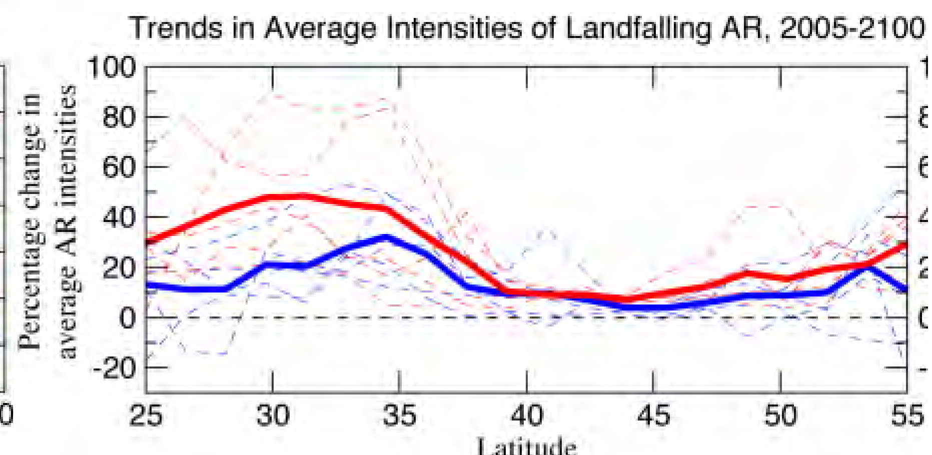
Statewide monitoring

Preparing the way for offshore reconnaissance

## Exploring ARs in climate-change projections




**Central California:**

- Stability declines ~ 20%
- Temps increase ~ 4ºC (+600 m snowline)
- Lifting-condensation levels rise ~ 200 m
- Number of persistent ARs triples !?

**West Coast:**

- Width of ARs increase a bit
- Numbers of ARs increase more in NORTH
- AR intensities increase more in SOUTH

*Updates to Dettinger, JAWRA, 2011*

# What are we doing with this knowledge?

Statewide monitoring

Preparing the way for offshore reconnaissance

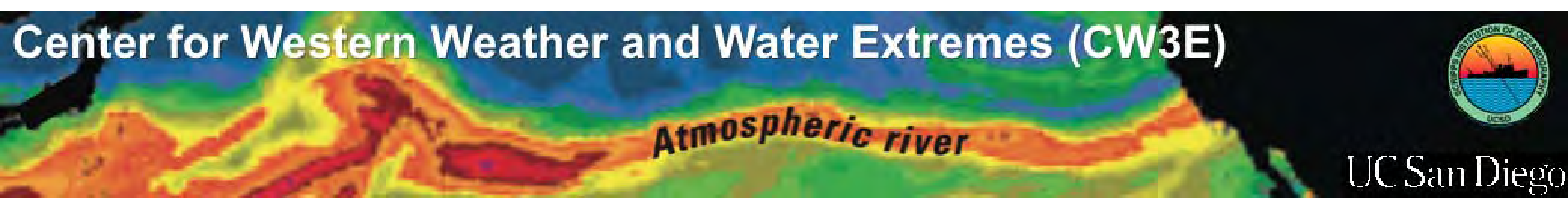
Exploring ARs in climate-change projections

**New CENTER FOR WESTERN WEATHER & WATER EXTREMES**

*(centered at Scripps and teaming w/groups across California & the West)*

- **Designing, using & serving data from new observing systems**
- **Developing regional weather model tailored for ARs & extreme precip**
- **Providing unique forecast products**
- **Conducting research to push forward even more**

***http://cw3e.ucsd.edu/***



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| Atmospheric Rivers (ARs) historically… | Quantitative Finding | *References* |
|---|---|---|
| **Cause the heaviest West Coast rains** | 92% of West Coast's heaviest 3-day rain events fed by ARs | *Ralph & Dettinger, BAMS, 2012* |
| **Fill CA reservoirs & provide supplies** | 30-50% of Sierra Nevada rain, snow & streamflow from ARs | *Guan et al., GRL, 2010; Dettinger et al. Water, 2011* |
| **Bring cycles of wet & dry years** | Account for 85% of year-to-year precipitation variance over northern California | *Dettinger & Cayan, SFEWS, 2014* |
| **End West Coast droughts** | 40% of droughts in northern California ended by an AR | *Dettinger, JHM, 2013* |
| **Cause CA floods** | 80-100% of major floods in central California rivers have been fed by ARs | *Ralph et al., GRL, 2006; Dettinger & Ingram, Sci Am, 2013* |
| **Sustain wetlands, floodplains & fisheries** | ARs initiated 77% of ecologically significant inundations of Yolo Bypass, Central Valley | *Florsheim & Dettinger, book chapter, 2014* |
| **Breach levees** | 81% of Central Valley levee breaks have happened during landfalling ARs | *Florsheim & Dettinger, book chapter, 2014* |
| **Can cause catastrophes** | "ARkStorm" California flood scenario yields estimated >$500B impacts | *Porter et al., USGS OFR 2010-1312* |
| **Sometimes penetrate far inland** | ARs have caused major storms in Arizona, Utah, and other Western states | *Neiman et al., JHM, 2013; Rutz et al., MWR, 2014* |
| **Can be forecast** | ARs can be seen >5 days ahead; landfall position error is still large | *Wick et al., WAF, 2014* |

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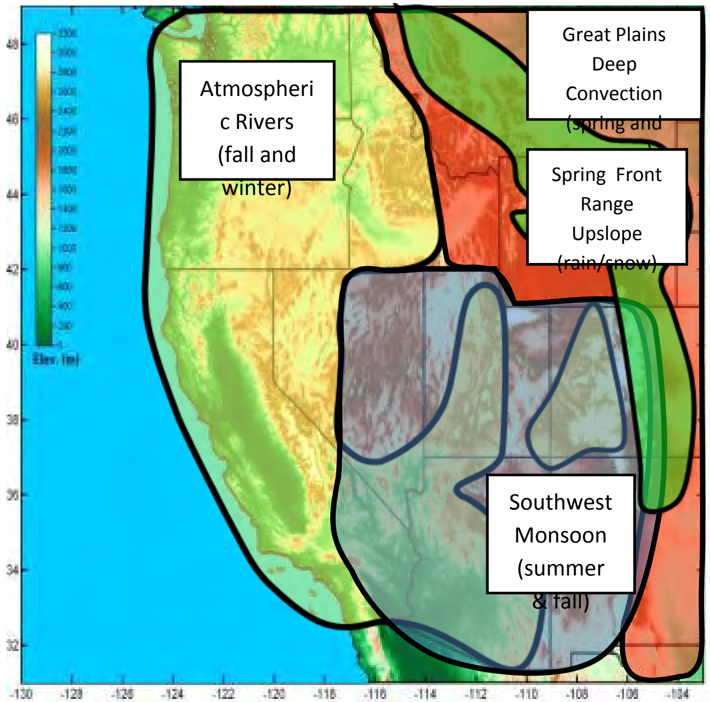



# Center for Western Weather & Water Extremes

Where: UCSD/Scripps Inst. Oceanography
La Jolla, California
When: Start - 2013
Who: Dr. F. M. Ralph (Director)
Dr. Dan Cayan
Dr. Mike Dettinger
Dr. Ryan Spackman

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## *Mission*

*Provide 21$^{st}$ Century water cycle science, technology and outreach to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people and the economy of Western North America*

## *Goal*

*Revolutionize the physical understanding, observations, weather predictions and climate projections of extreme events in Western North America, including atmospheric rivers and the North American summer monsoon as well as their impacts on floods, droughts, hydropower, ecosystems and the economy*