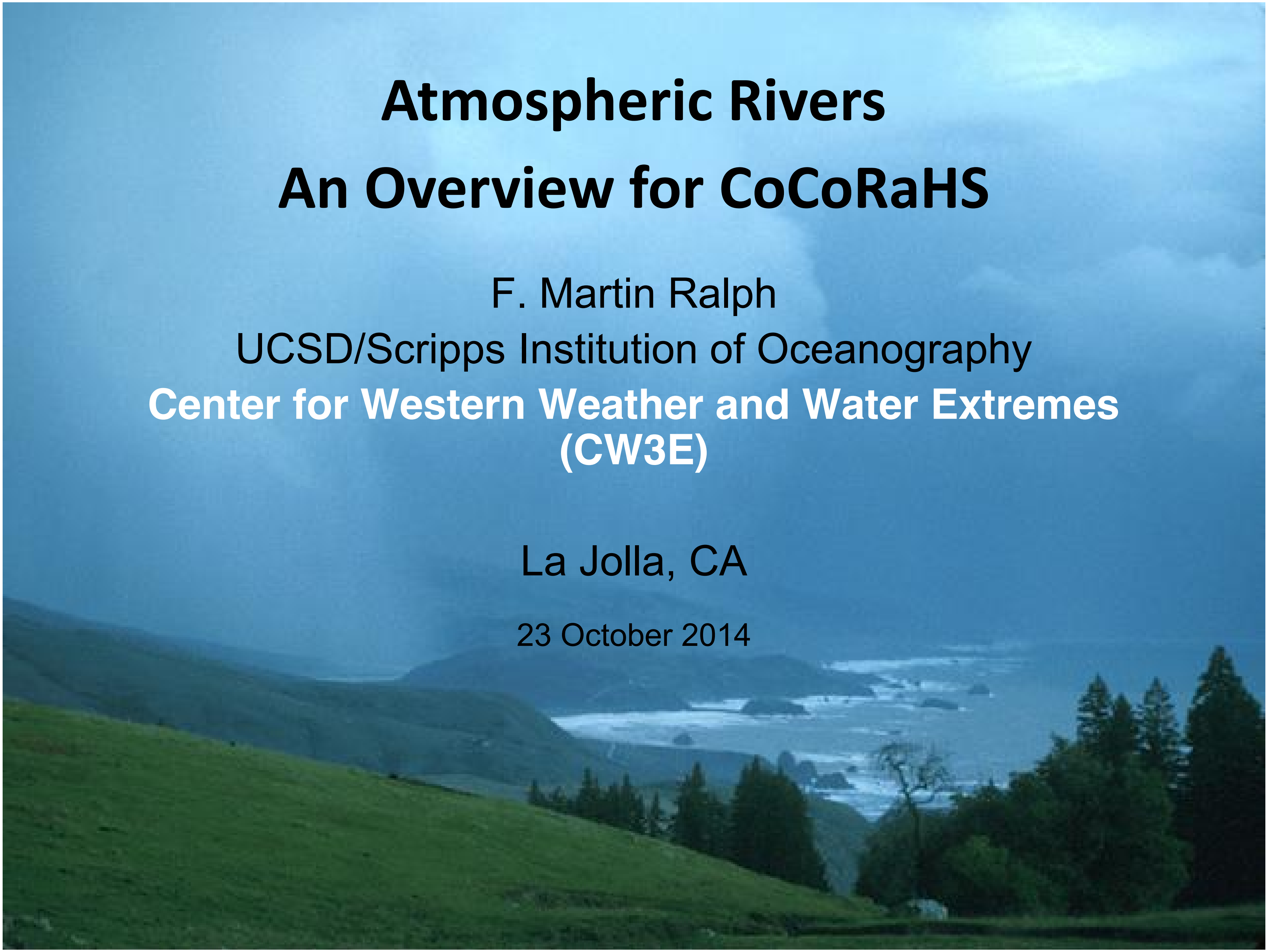


Atmospheric Rivers
An Overview for CoCoRaHS

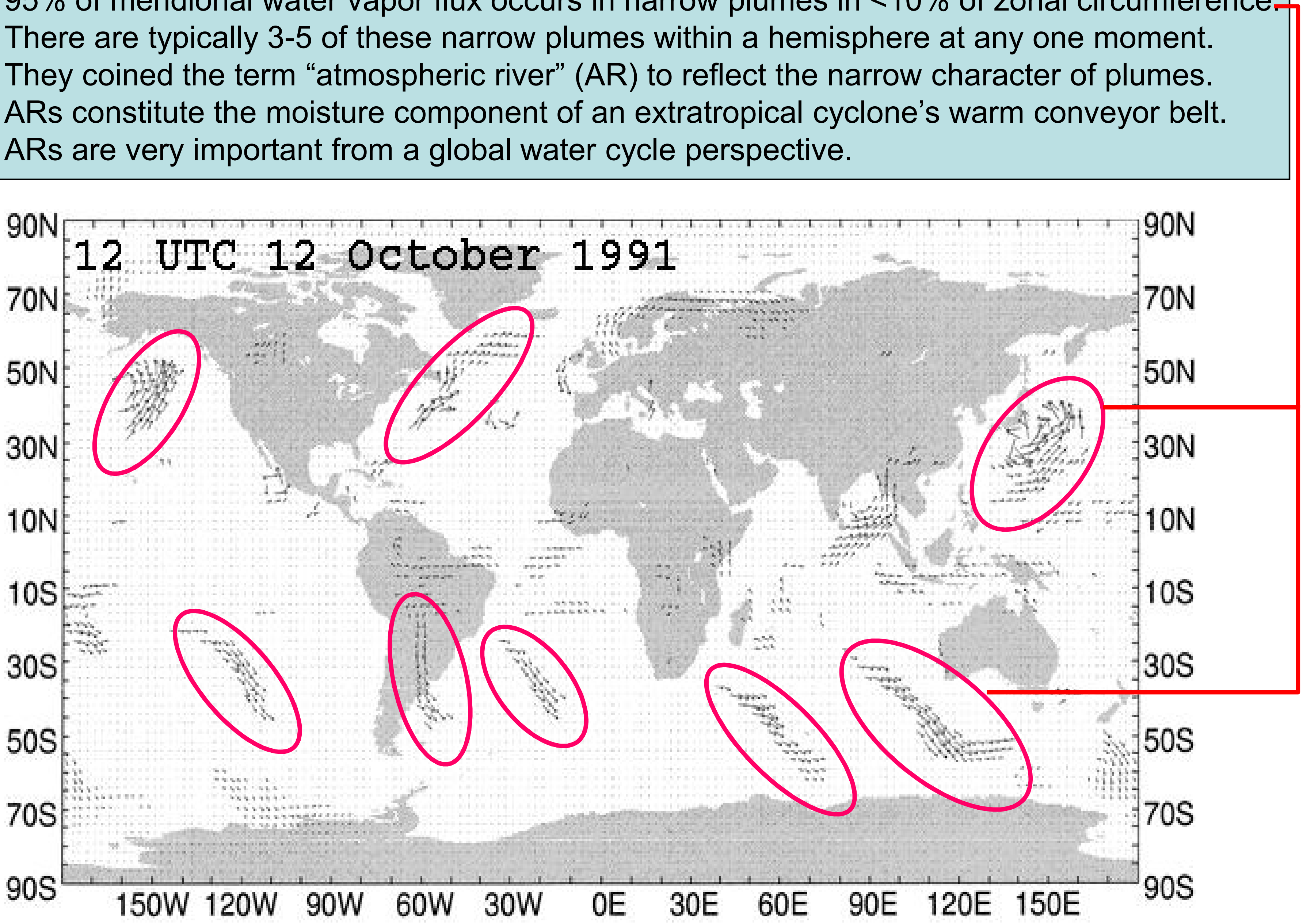
F. Martin Ralph
UCSD/Scripps Institution of Oceanography
Center for Western Weather and Water Extremes (CW3E)

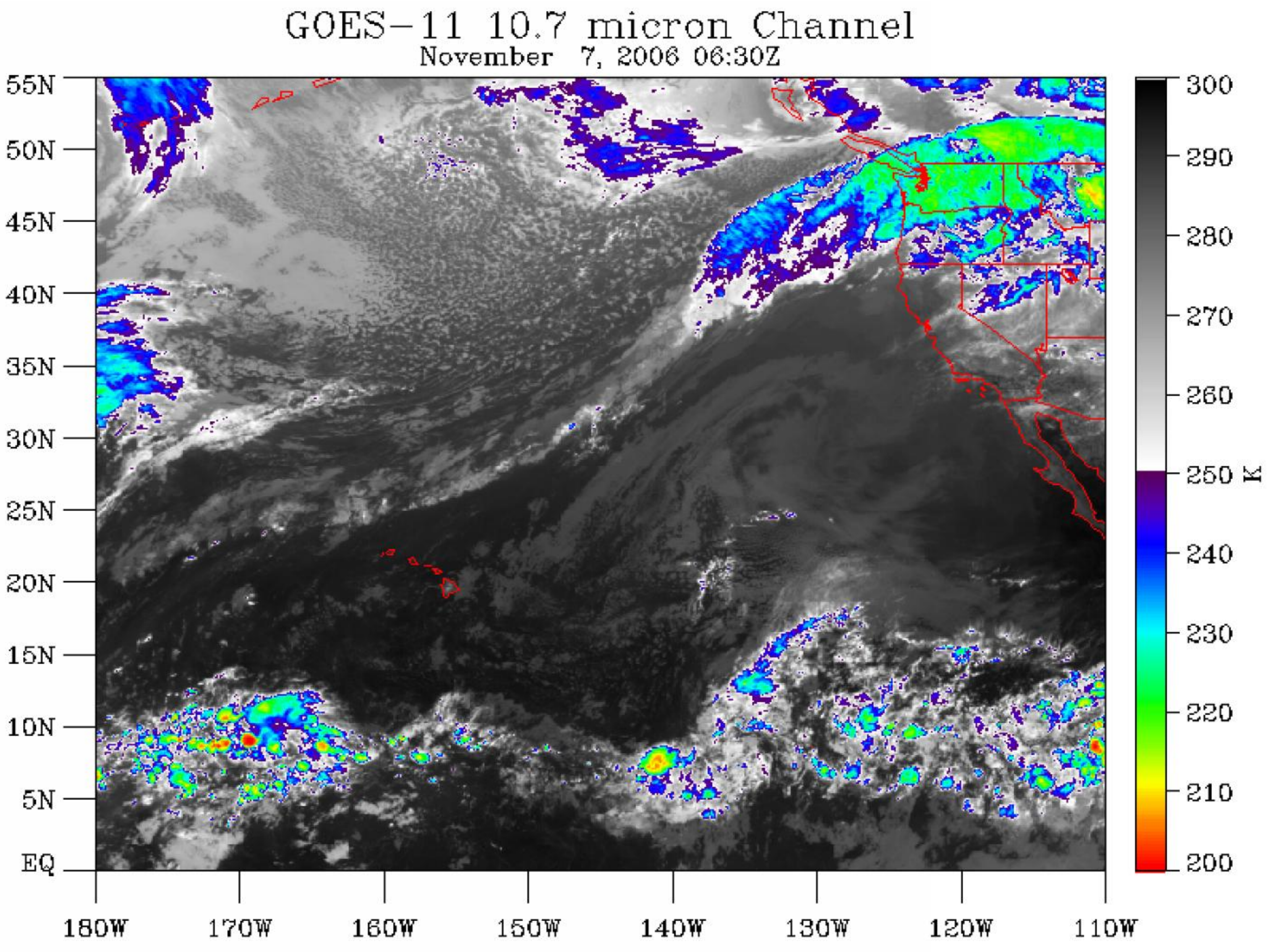
La Jolla, CA

23 October 2014

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

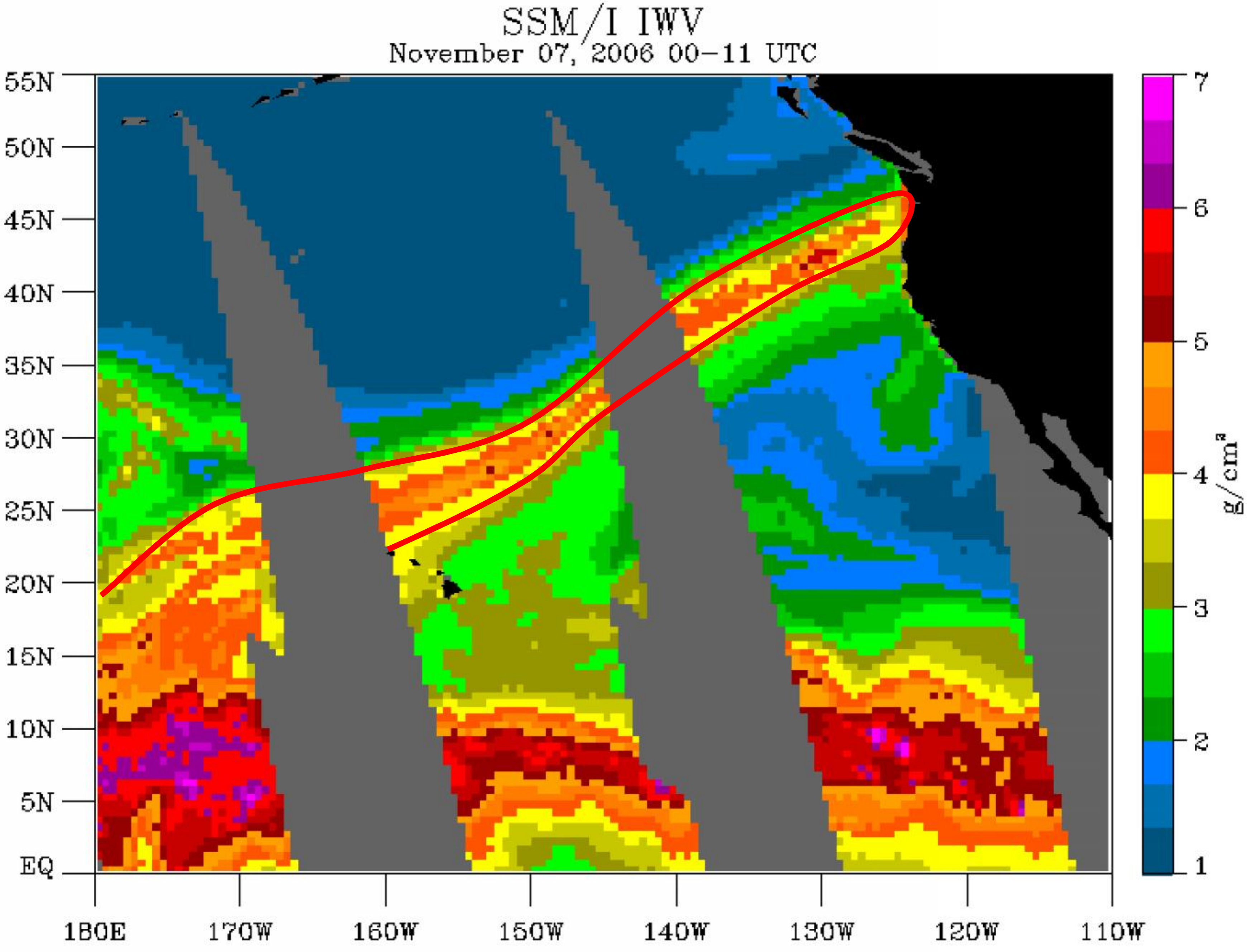
1) 95% of meridional water vapor flux occurs in narrow plumes in <10% of zonal circumference.
2) There are typically 3-5 of these narrow plumes within a hemisphere at any one moment.
3) They coined the term "atmospheric river" (AR) to reflect the narrow character of plumes.
4) ARs constitute the moisture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



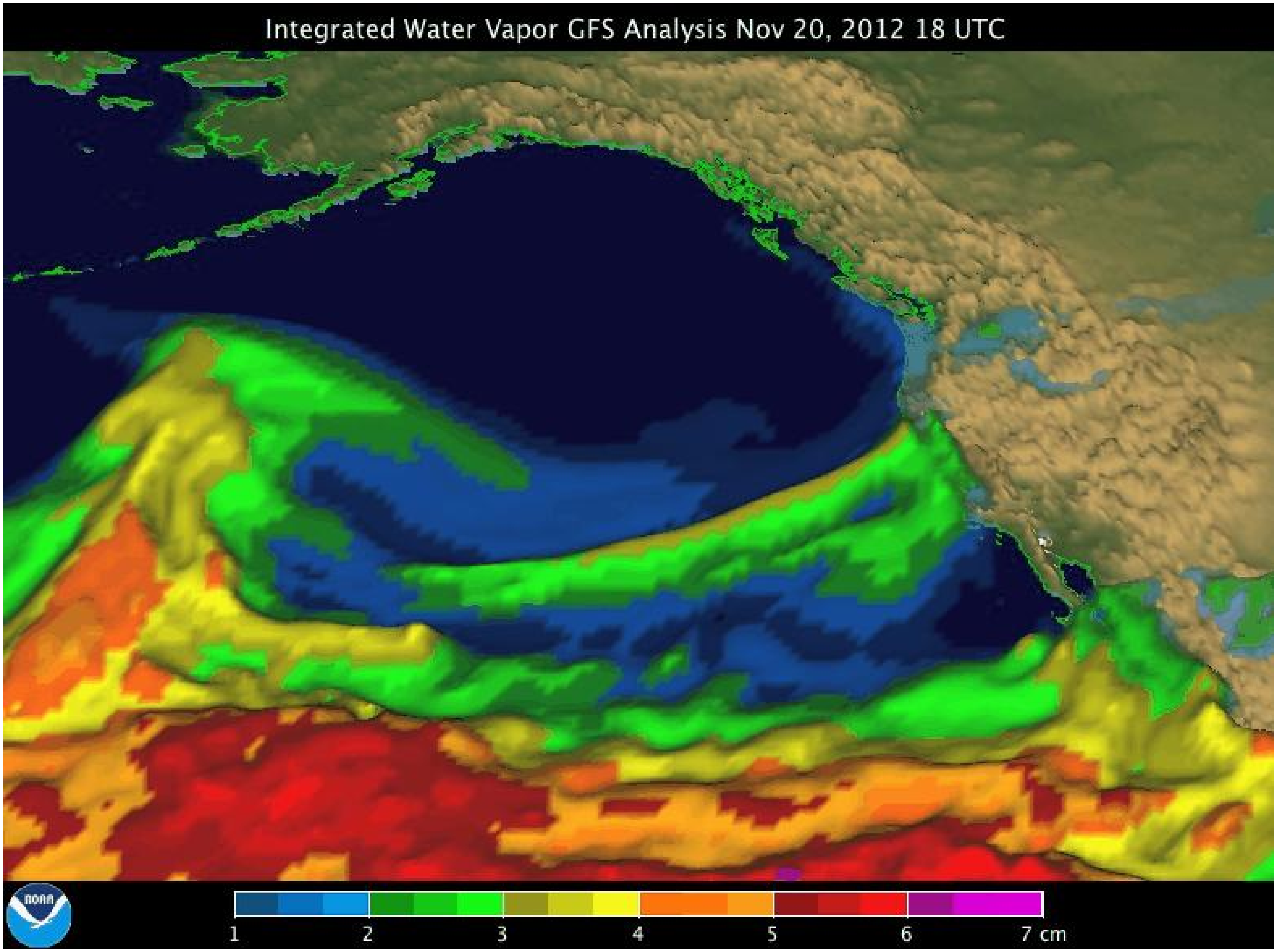


GOES-11 10.7 micron Channel

November 7, 2006 06:30Z

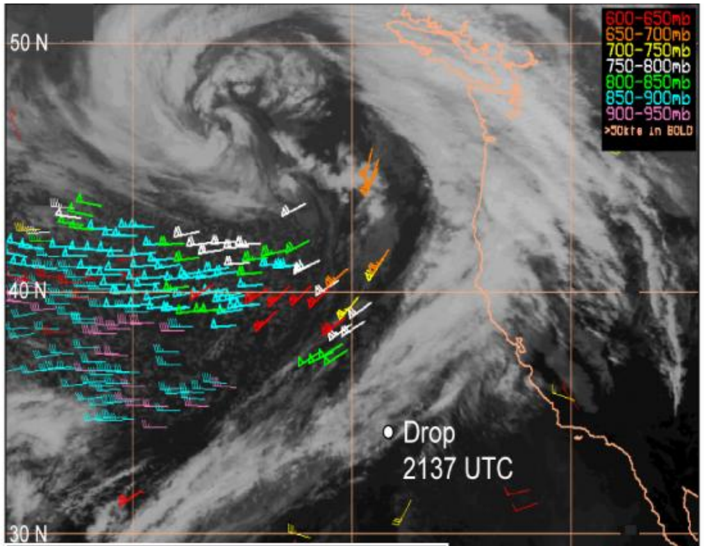

SSM/I IWV
November 07, 2006 00-11 UTC
55N
50N
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
180E
170W
160W
150W
140W
130W
120W
110W
7
6
5
4
3
2
1
g/cm³

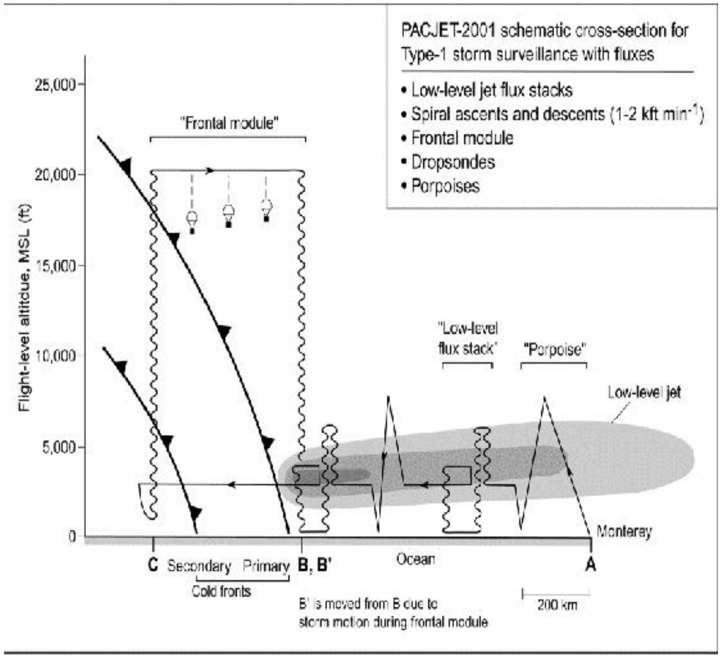
Atmospheric River Events 20 Nov-3 Dec 2012



Animation courtesy of Don Murray (NOAA/ESRL/PSD)

Offshore Structure Diagnosed with Aircraft and Satellite Observations

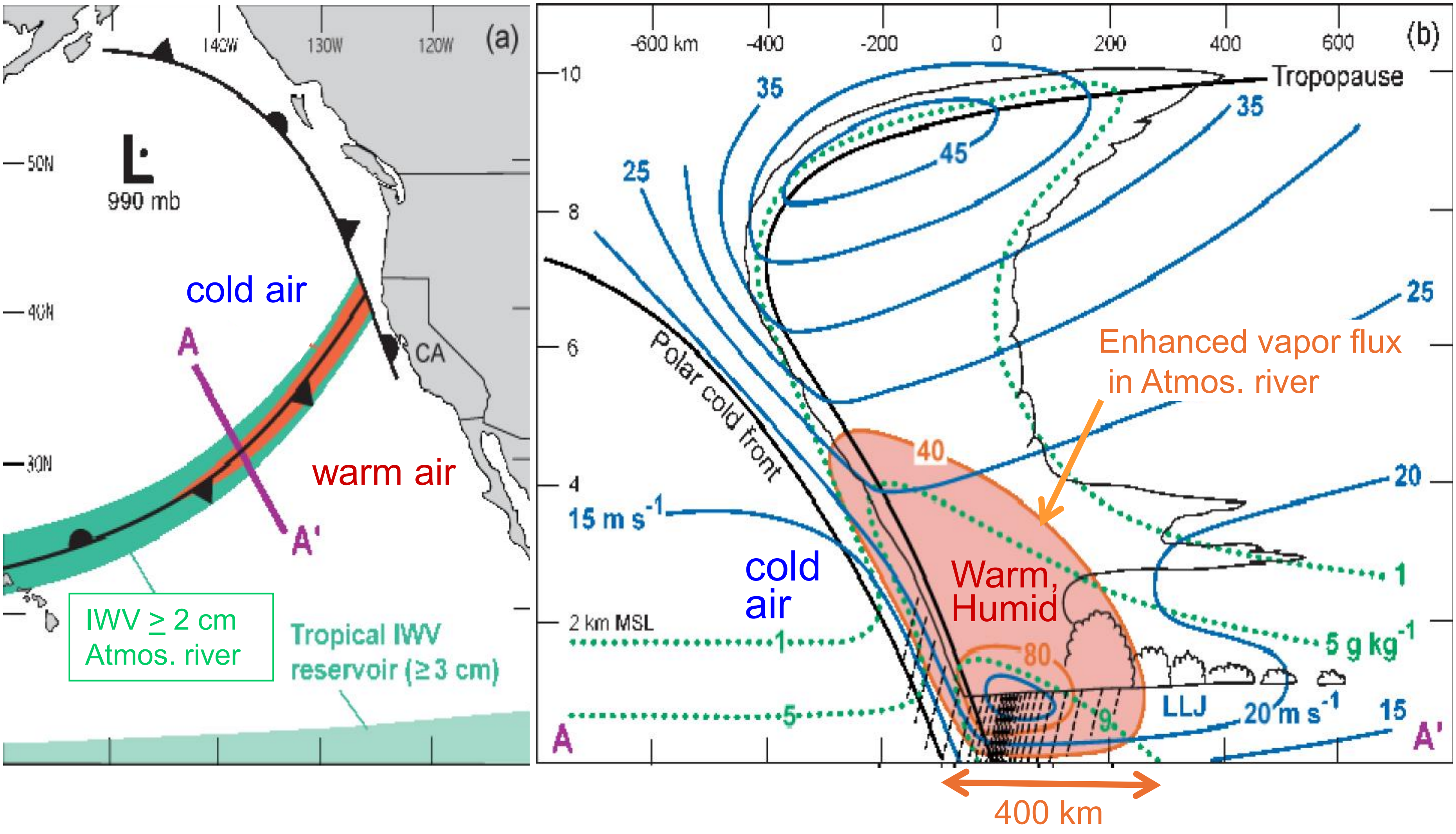




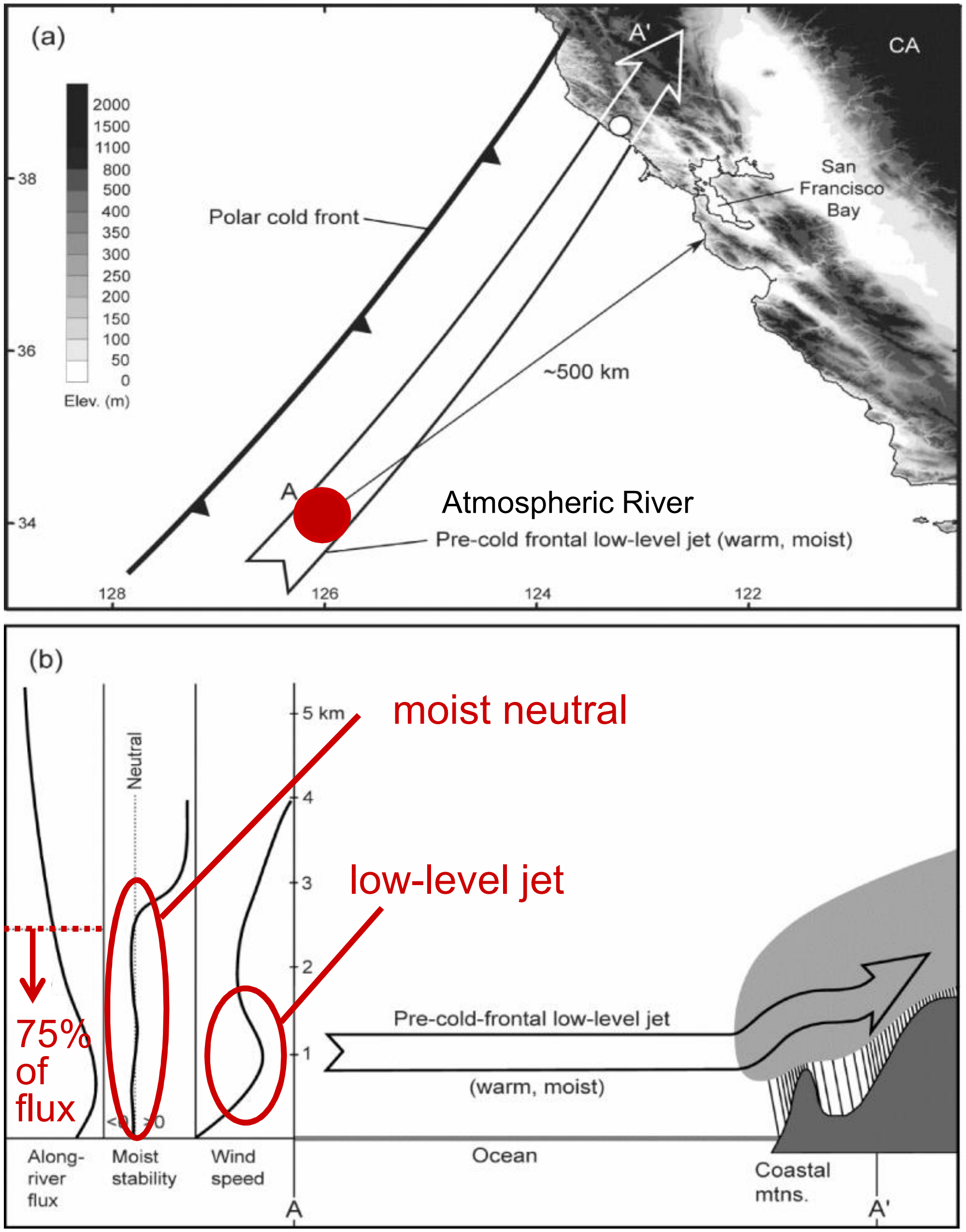
Low-level jet (LLJ) airborne P-3 observing strategy used in CALJET (1998) and PACJET (2001)

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?



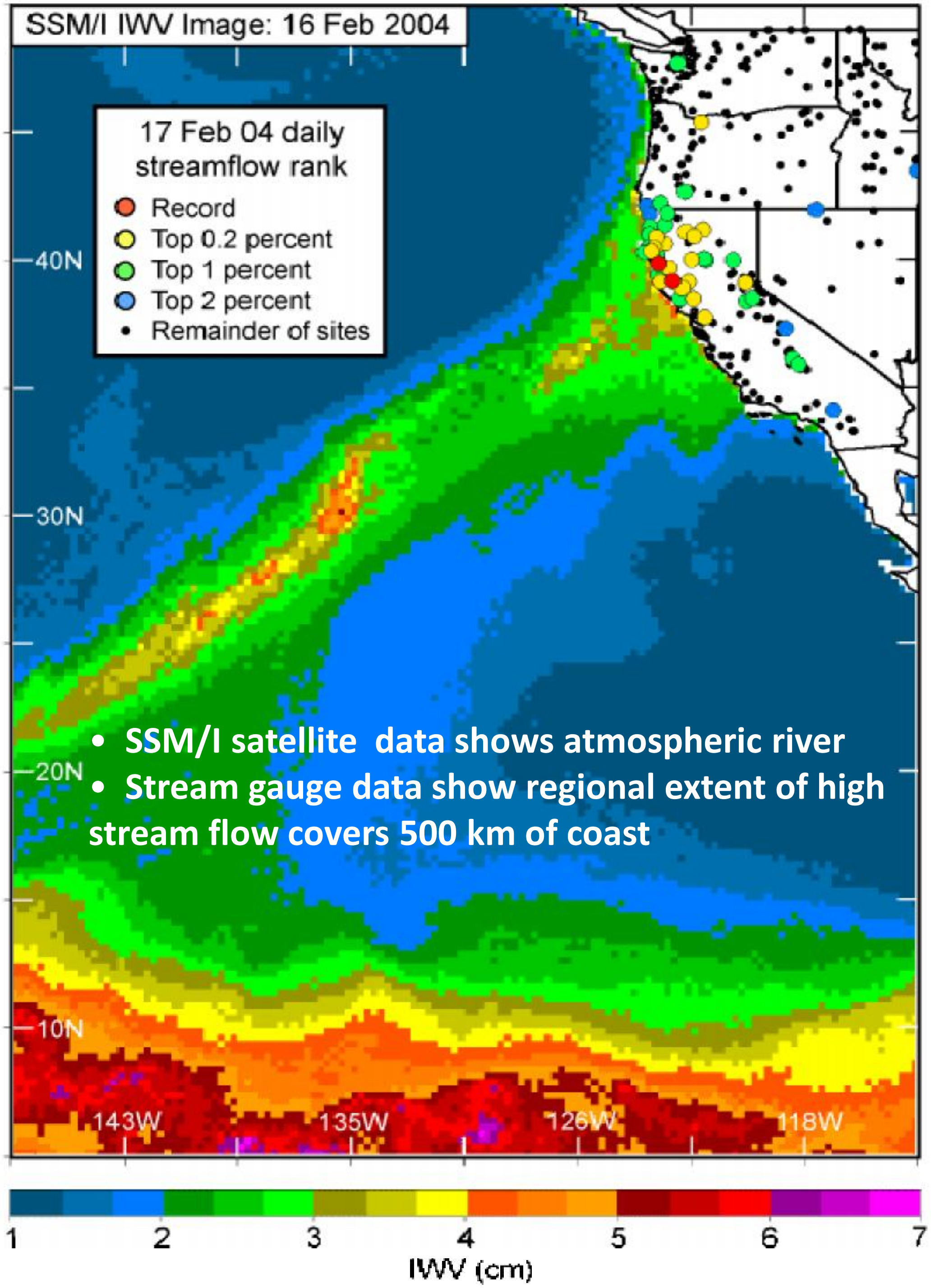
- CALJET and PACJET field experiments used the NOAA P-3 aircraft to profile ARs
- Composite sounding located 500 km off CA coast in atmos. river & pre-cold-frontal LLJ
- LLJ directed toward coast and situated at 1 km MSL
- Most (75%) of pre-cold-frontal along-river moisture flux is below 2.5 km MSL
- 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*

Flooding on California's Russian River: Role of atmospheric rivers

Ralph, F.M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, A. White

Geophys. Res. Lett., 2006



- **SSM/I satellite data shows atmospheric river**
- **Stream gauge data show regional extent of high stream flow covers 500 km of coast**

Russian River floods are associated with atmospheric rivers
- all 7 floods over 8 years.

Flooding in Western Washington: The Connection to Atmospheric Rivers

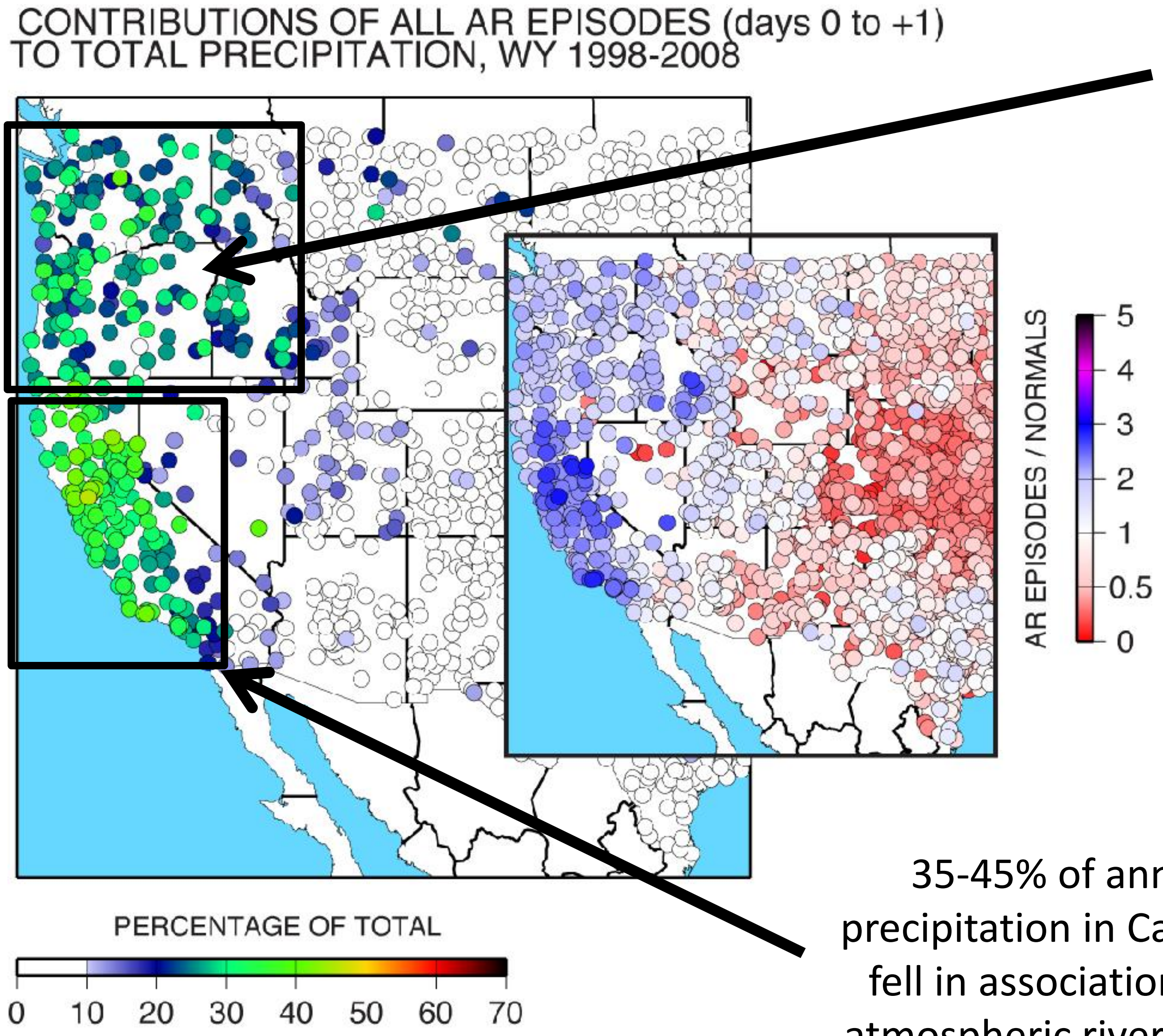
Paul J. Neiman, Lawrence J. Schick, F. Martin Ralph, Mimi Hughes, and Gary A. Wick
J. Hydrometeorology (2011)

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

Atmospheric Rivers, Floods and the Water Resources of California

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

Water, 2011 (in Press)



CONTRIBUTIONS OF ALL AR EPISODES (days 0 to +1)
TO TOTAL PRECIPITATION, WY 1998-2008

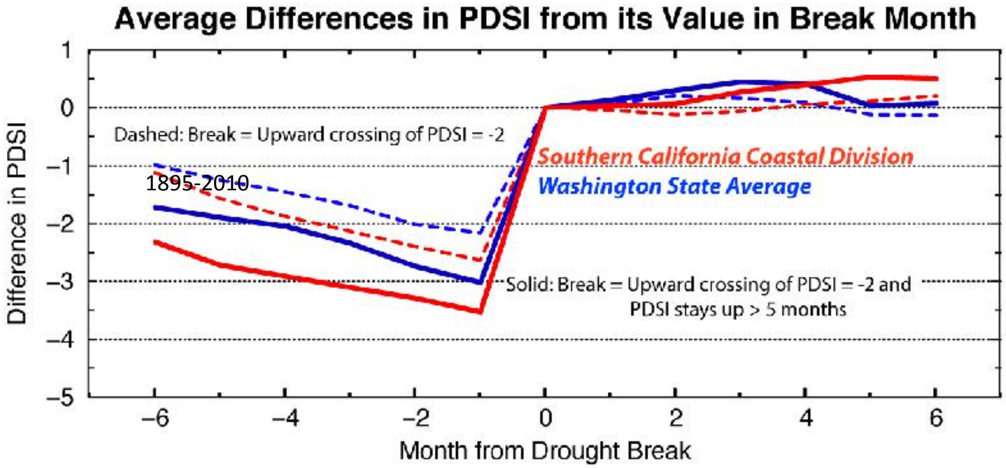
25-35% of annual precipitation in the Pacific Northwest fell in association with atmospheric river events

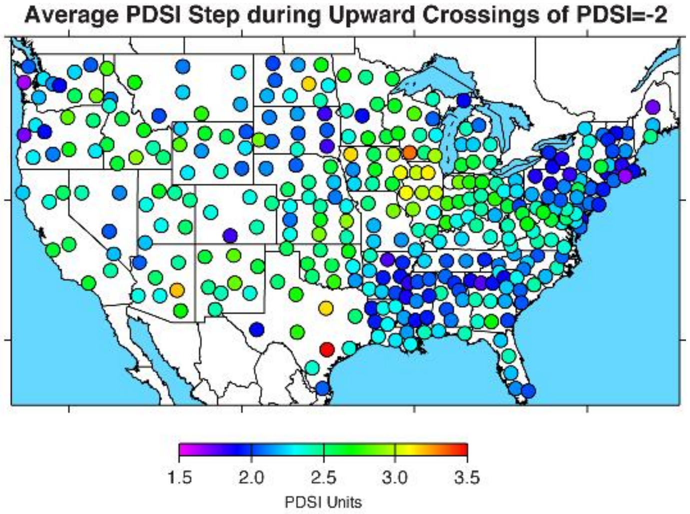
An average AR transports the equivalent of 7.5 times the average discharge of the Mississippi River, or ~10 M acre feet/day

35-45% of annual precipitation in California fell in association with atmospheric river events

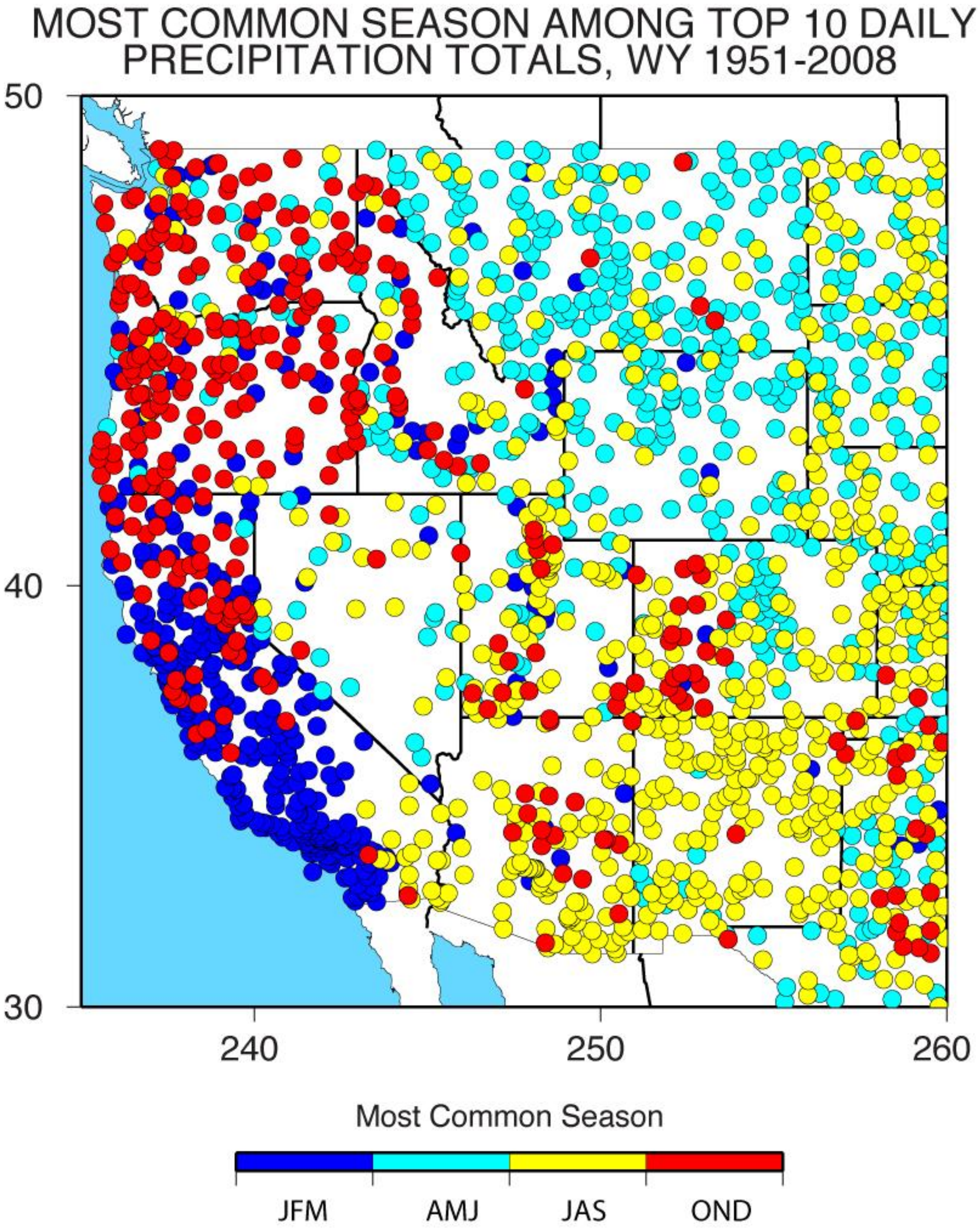
Droughts, on average, end with a bang (and begin with a whimper) all over the U.S.

- **Atmospheric rivers provide the bang** in a large fraction of the west coast drought breaks, especially in winters





Dettinger, Michael D., 2013: Atmospheric Rivers as Drought Busters on the U.S. West Coast. *J. Hydrometeor*, **14**, 1721–1732.



MOST COMMON SEASON AMONG TOP 10 DAILY PRECIPITATION TOTALS, WY 1951-2008

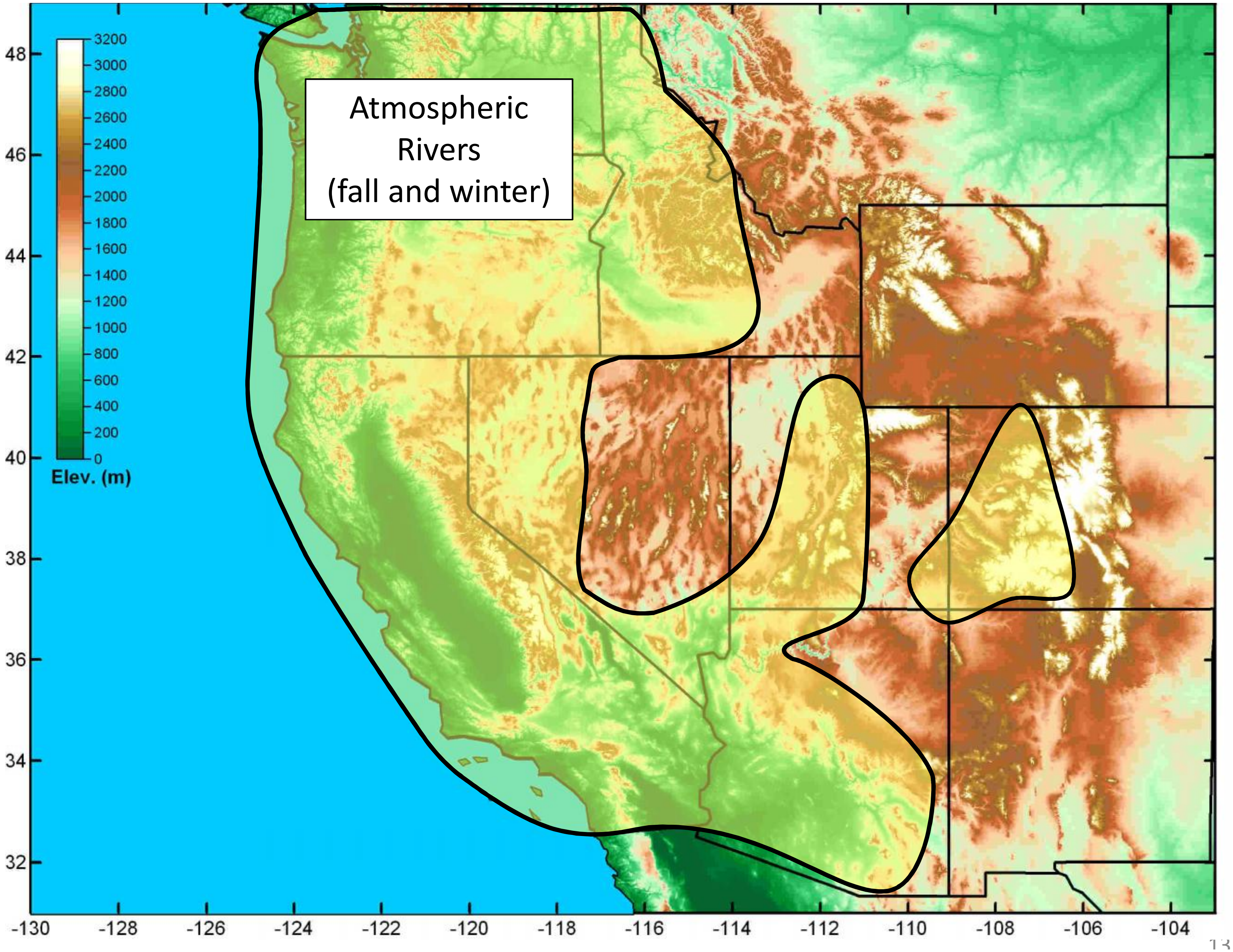
Ralph et al, 2014

Analysis from COOP daily precipitation observations.

- -Each site uses at least 30 years of data
- -The top 10 daily precip dates are found
- -The season for which most of these top-10 dates occurred at that site is color coded.

- -The affect of the southwest Monsoon is seen in yellow dots in AZ, CA, UT, NM, and CO (yellow sites in the Great Plains are not monsoon dominated)
- -The affect of atmospheric rivers is highlighted by blue and red dots, including almost all of each coastal state, plus inland penetration of AR impacts into AZ, Western CO, SW and Central UT, and ID.
- -Great Plains convective events focus in spring (light blue dots) and summer (yellow).
- -Colorado front range is mostly spring.
- -Nevada is a mixture.

Schematic illustration of regional variations in the primary weather phenomena that lead to extreme precipitation, flooding and contribute to water supply in the Western U.S.



Atmospheric
Rivers
(fall and winter)

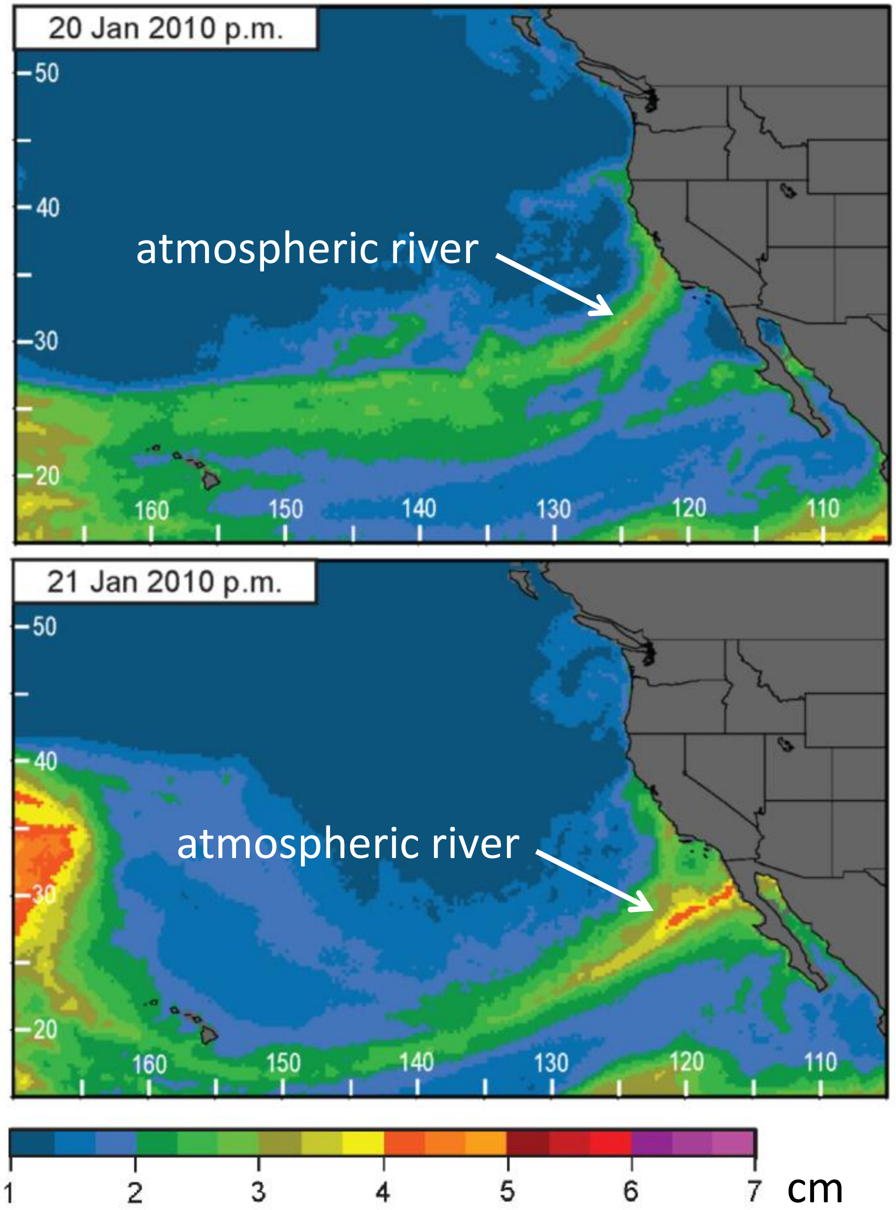
The Landfall & Inland Penetration of a Flood-Producing Atmospheric River in Arizona: Part 1: Observed Synoptic-scale, Orographic, & Hydrometeorological Characteristics

Paul J. Neiman[1], F.M. Ralph[1], B. Moore[2], M. Hughes[2], K. Mahoney[2], J. Cordeira[2], M. Dettinger[3]

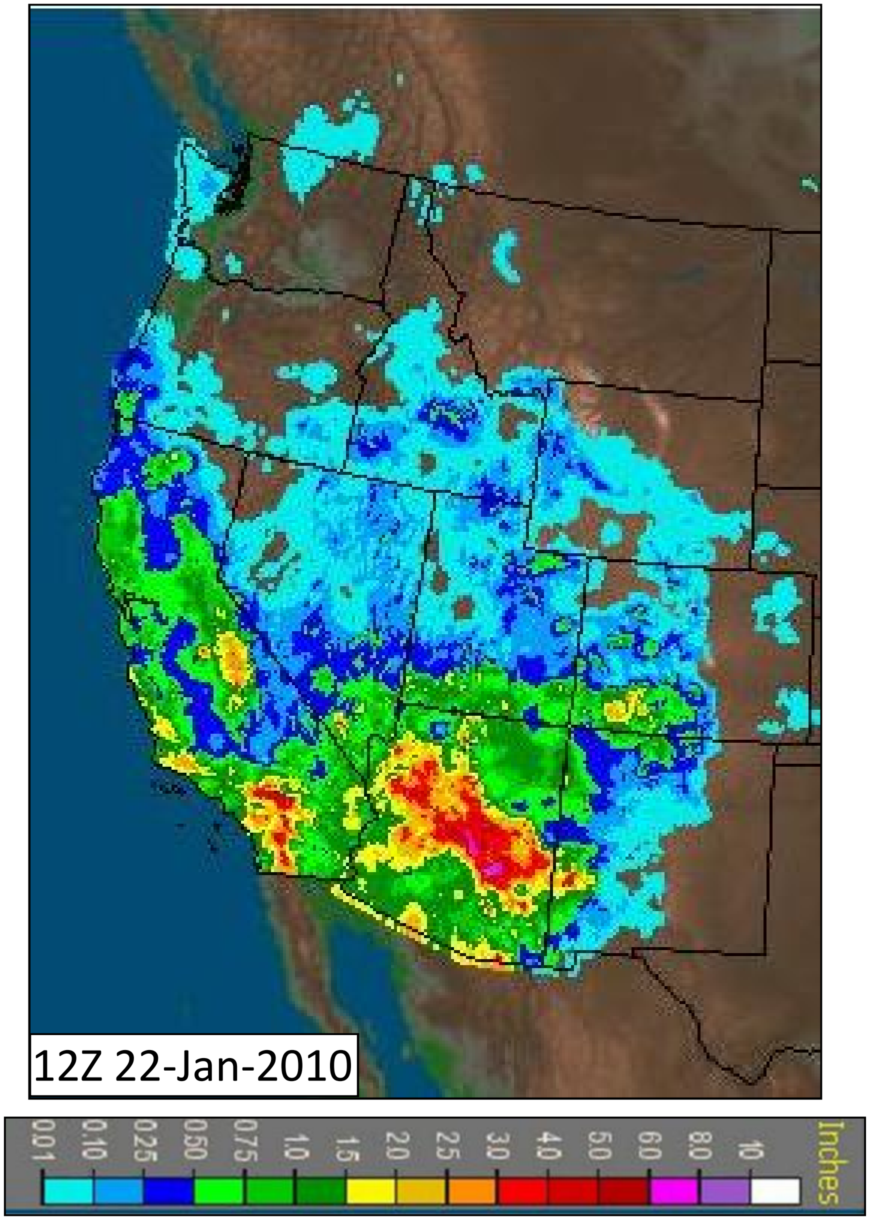
[1]NOAA/Physical Sciences Div., Boulder, CO; [2]CIRES/NOAA, Boulder, CO; [3]Scripps, La Jolla, CA

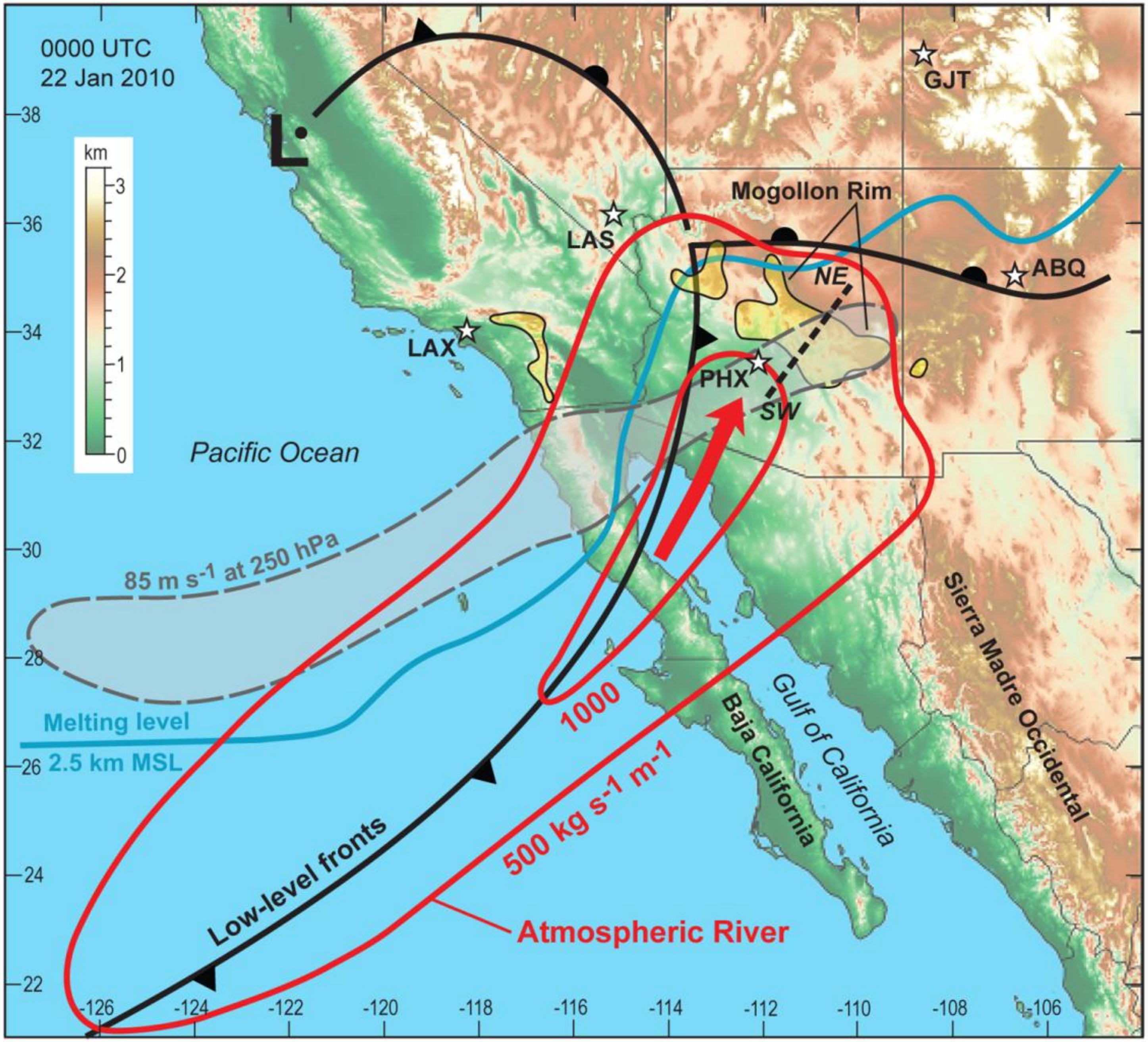
J. Hydrometeor., **14**, 460-484 (April 2013)

SSM/I IWV satellite imagery 20-21 Jan. 2010 depicts a strengthening AR making landfall



24-h precip ending 12Z 22 Jan. 2010: Advanced Hydrological Prediction Services

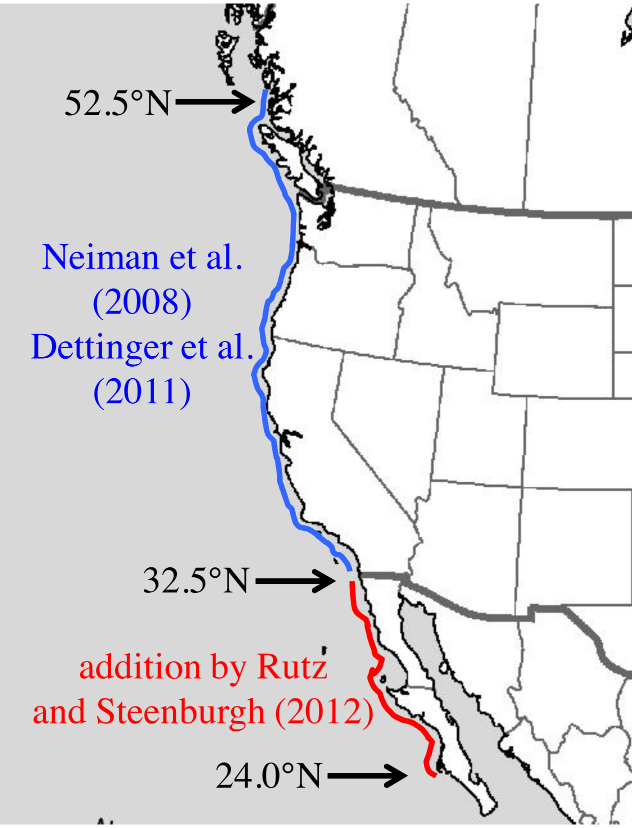



0000 UTC
22 Jan 2010
km
3
2
1
0
L
LAS
LAX
PHX
GJT
ABQ
Mogollon Rim
NE
SW
Pacific Ocean
85 m s-1 at 250 hPa
Melting level
2.5 km MSL
1000
500 kg s-1 m-1
Atmospheric River
Low-level fronts
Baja California
Gulf of California
Sierra Madre Occidental
38
36
34
32
30
28
26
24
22
-126
-124
-122
-120
-118
-116
-114
-112
-110
-108
-106

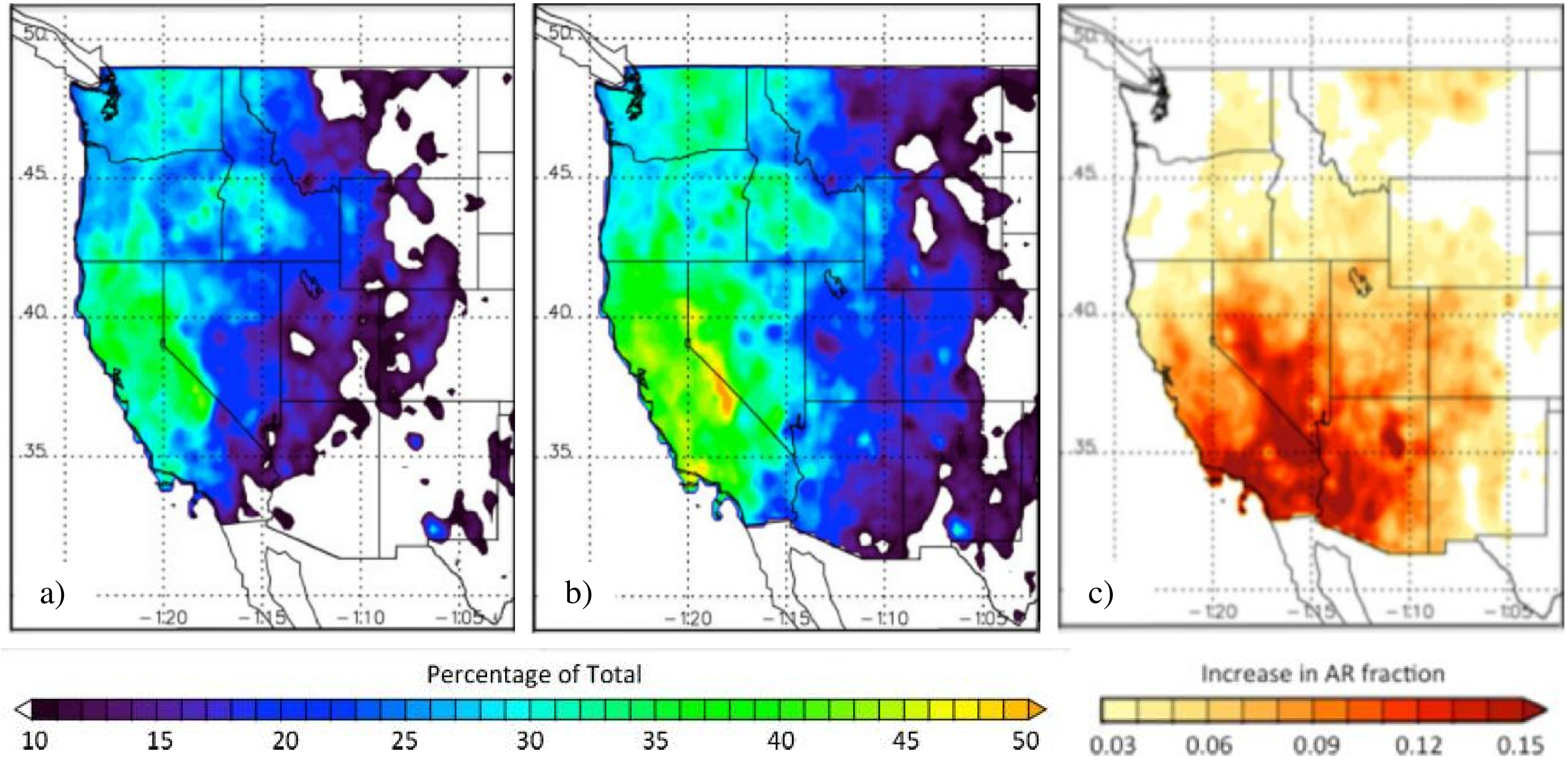
ARs crossing the Baja Peninsula

Rutz, J. J. and Steenburgh, W. J. (2012), Quantifying the role of atmospheric rivers in the interior western United States. Atmos. Sci. Lett., 13: 257–261. doi: 10.1002/asl.392

- Motivation
  - Provide a follow-up to the work of Dettinger et al. (2011), which assessed the influence of ARs on western U.S. precipitation, but did not consider ARs crossing the Baja Peninsula
- Method
  - If an AR is present for ~24 h along the North American west coast from 24–52.5°N, precipitation on that day and the next are attributed to the AR.
  - The "AR fraction" is the fraction of total cool-season (Nov – Apr) precipitation attributed to ARs
  - Includes Baja Peninsula



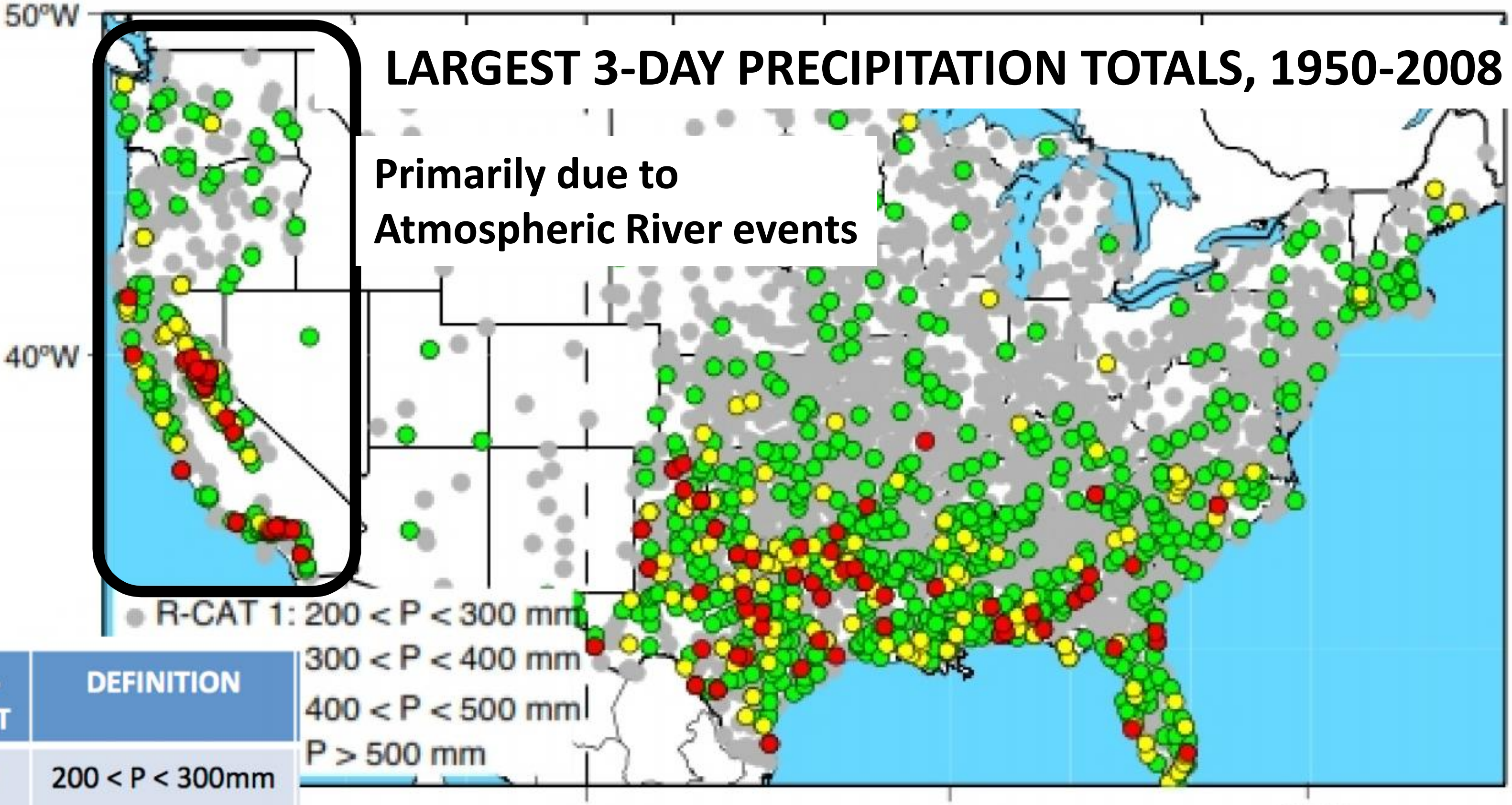
ARs crossing the Baja Peninsula



Cool-season “AR fraction” (a) without and (b) with ARs crossing the Baja Peninsula in the CPC gridded precipitation analysis during water years 1998–2008. (c) (b) - (a).

LARGEST 3-DAY PRECIPITATION TOTALS, 1950-2008

Primarily due to Atmospheric River events

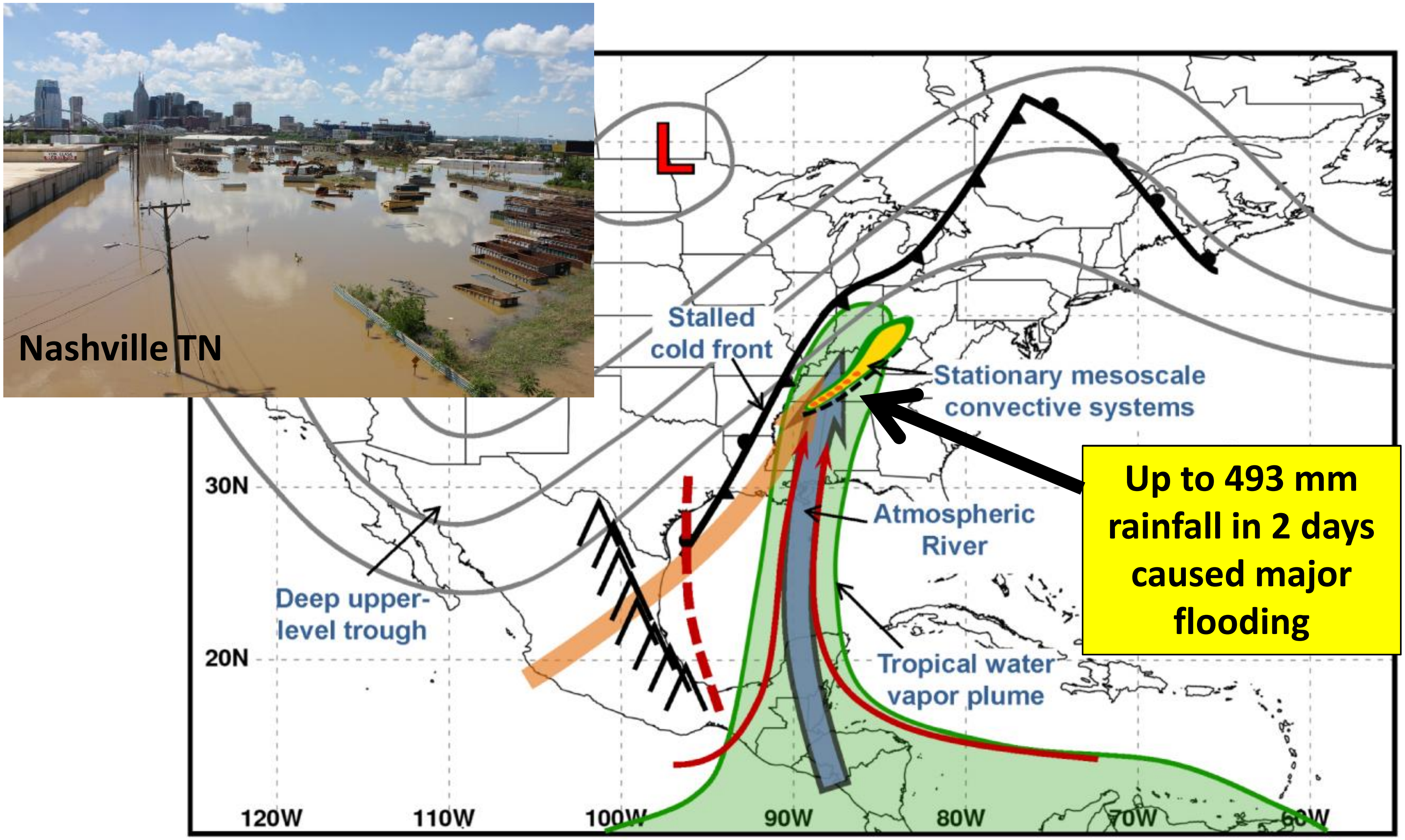


R-CAT	DEFINITION
1	200 < P < 300mm
2	300 < P < 400mm
3	400 < P < 500mm
4	P > 500mm

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

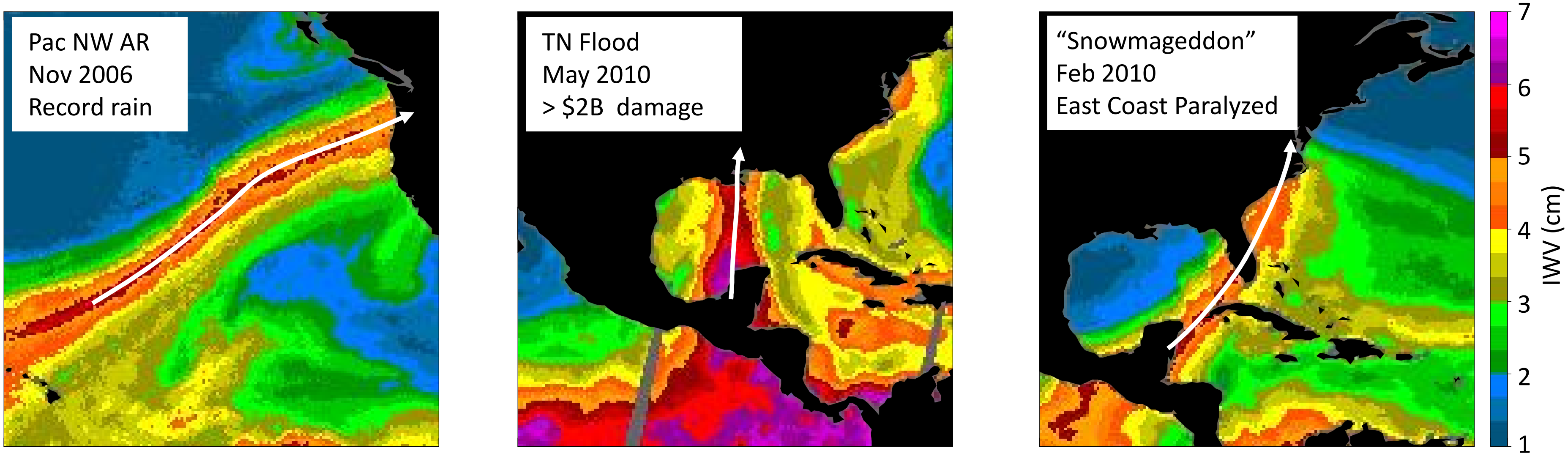
Physical Processes Associated with Heavy Flooding Rainfall in Nashville, Tennessee, and Vicinity during 1–2 May 2010: The Role of an Atmospheric River and Mesoscale Convective Systems

Ben Moore, Paul Neiman, Marty Ralph, Faye Barthold
Monthly Weather Review (2012)

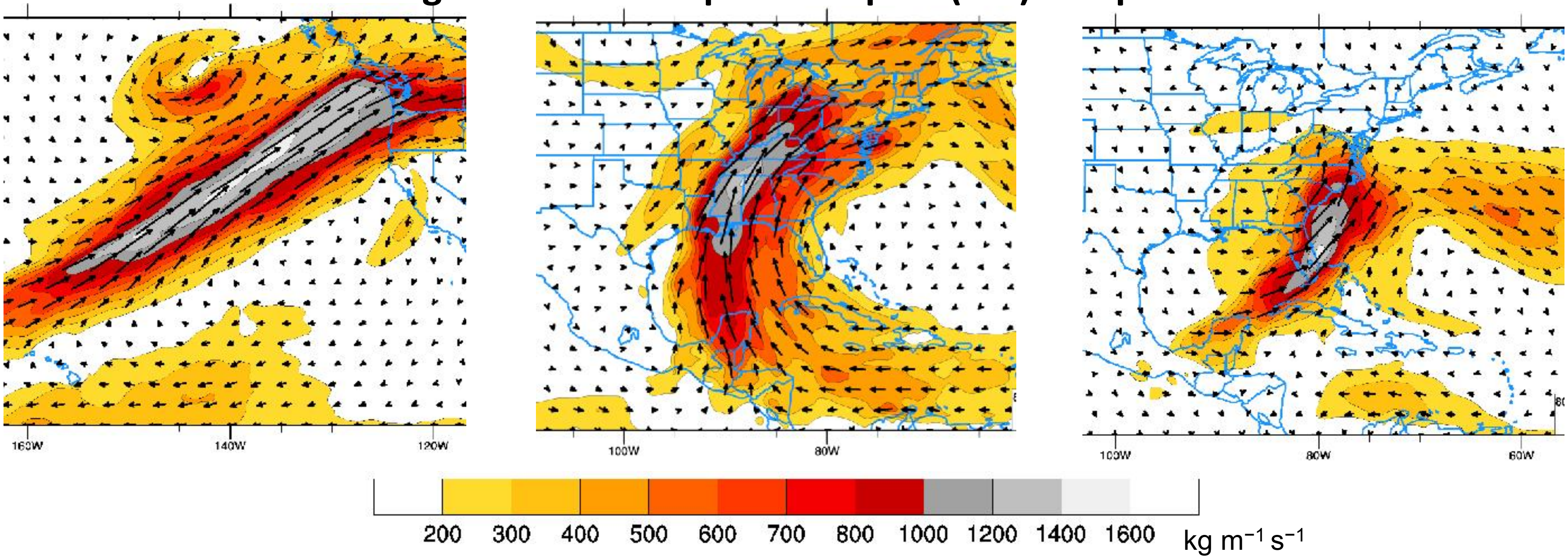


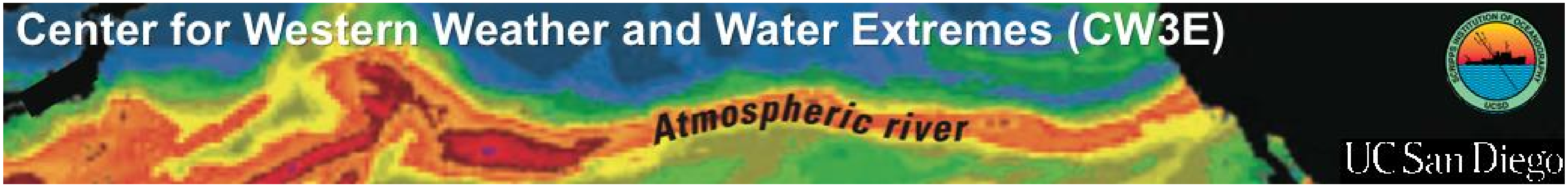
Up to 493 mm rainfall in 2 days caused major flooding

Integrated Water Vapor (IWV) Perspective



Integrated Water Vapor Transport (IVT) Perspective

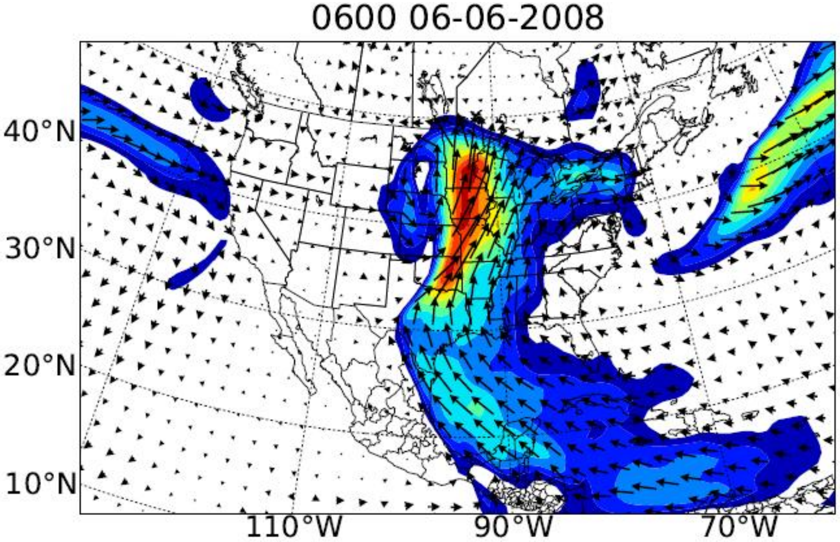




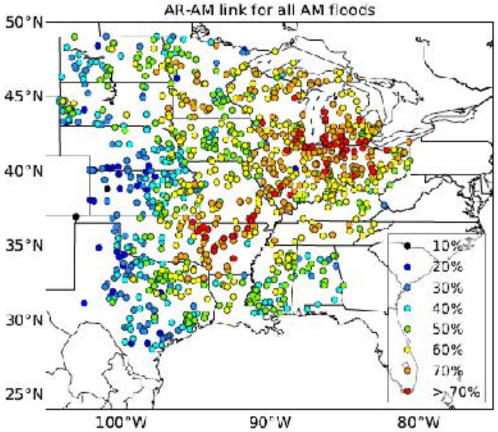
Atmospheric Rivers and Flooding over the Central United States

D.A. Lavers and G. Villarini. Journal of Climate (2013)

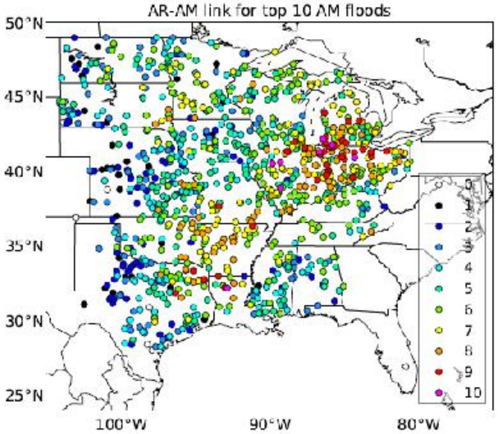
Intense AR behind June 2008 Midwest floods.



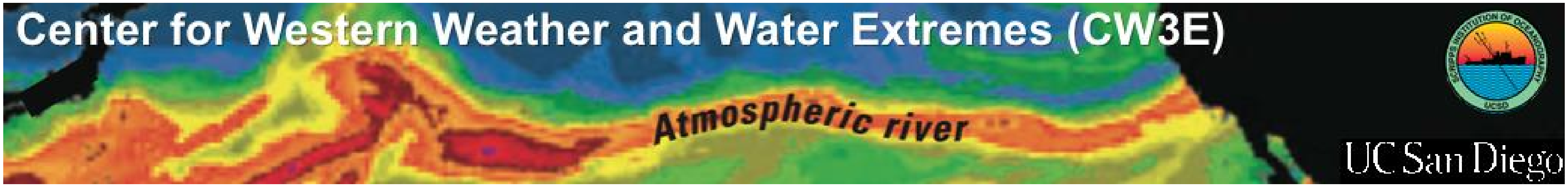
Integrated Water Vapor Transport (kg m^{-1} s^{-1}).



Percentage of all Annual Maxima (floods) related to identified ARs.



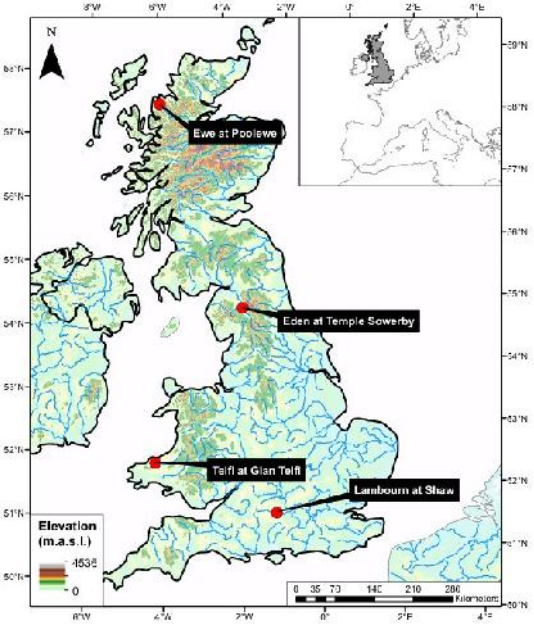
Number of Top 10 Annual Maxima (floods) related to identified ARs.



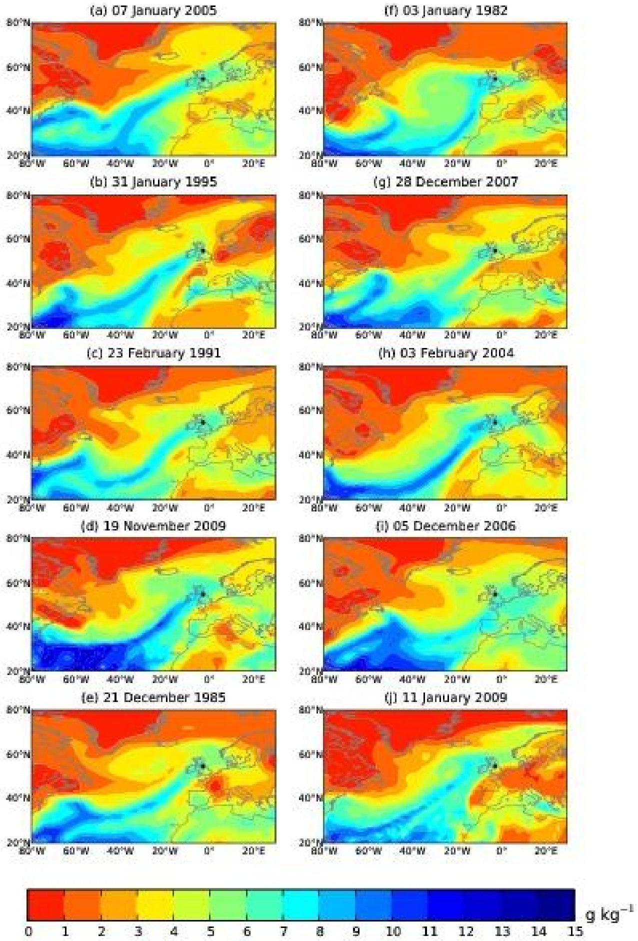
Winter floods in Britain are connected to atmospheric rivers

D.A. Lavers, R.P. Allan, E.F. Wood, G. Villarini, D.J. Brayshaw, and A.J. Wade

Geophysical Research Letters (2011)



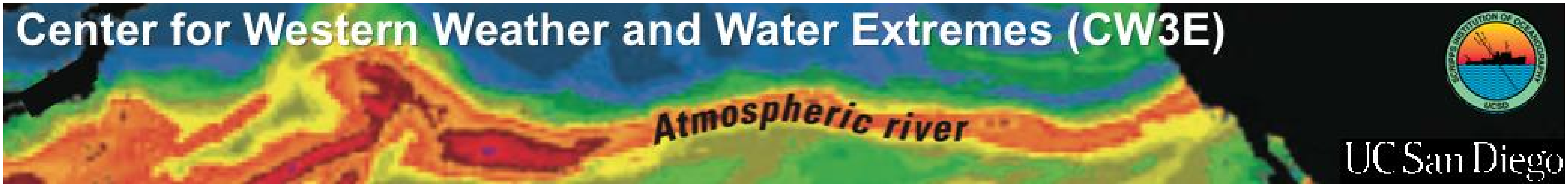
- Four basins studied.
- Floods identified using a winter maximum series over 1970-2010.



ARs before the top 10 floods in Eden basin.

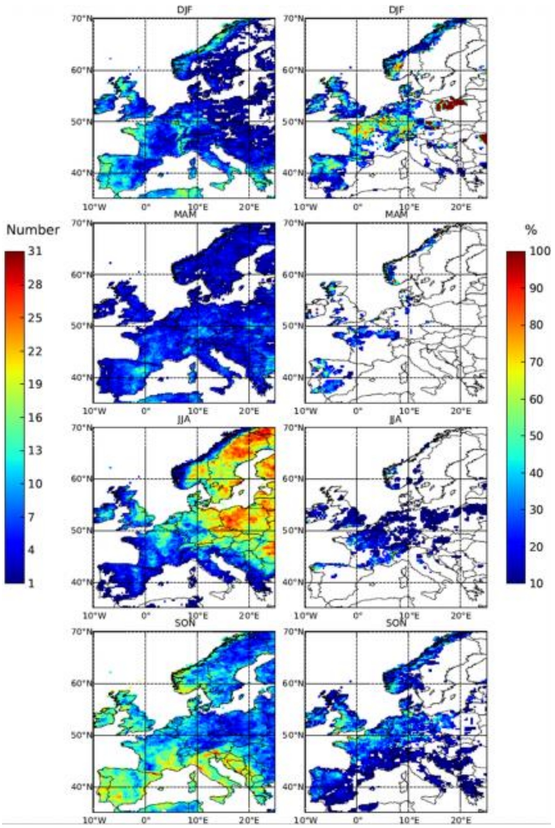
Main conclusions

1. **ARs are responsible for most winter floods, especially in fast-responding basins.**
2. **Long-lasting ARs cause the largest rain/flood events.**



The nexus between atmospheric rivers and extreme precipitation across Europe

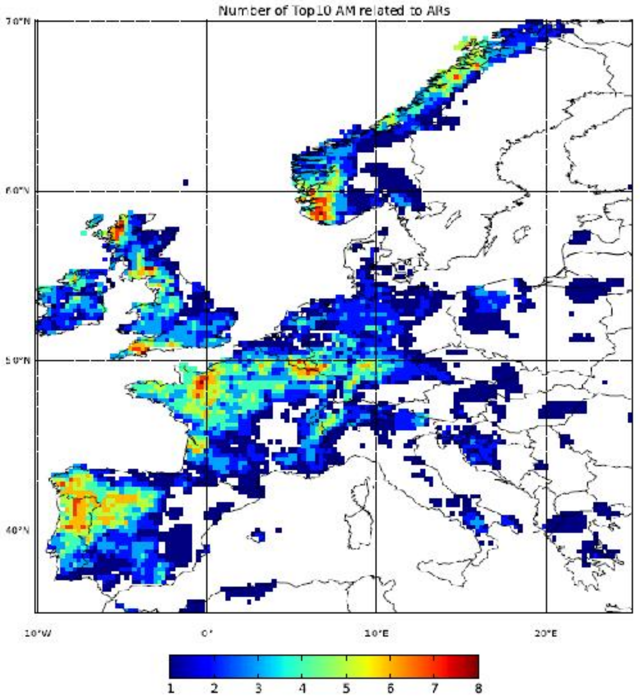
D.A. Lavers and G. Villarini. Geophysical Research Letters (2013)

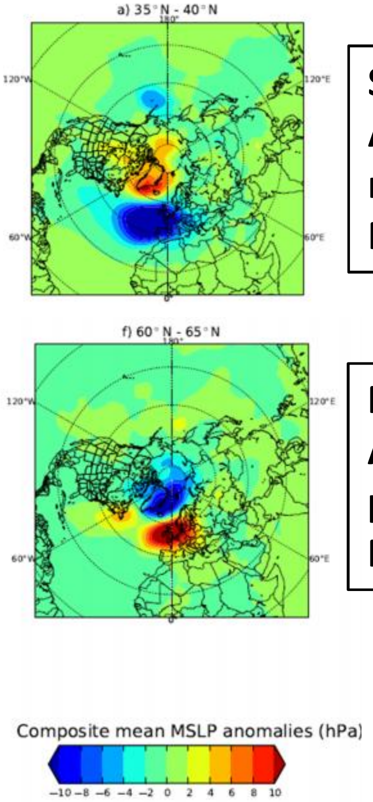


Annual Maxima in each season.

Annual Maxima related to ARs.

Number of Top 10 Annual Maxima (daily precipitation) related to ARs

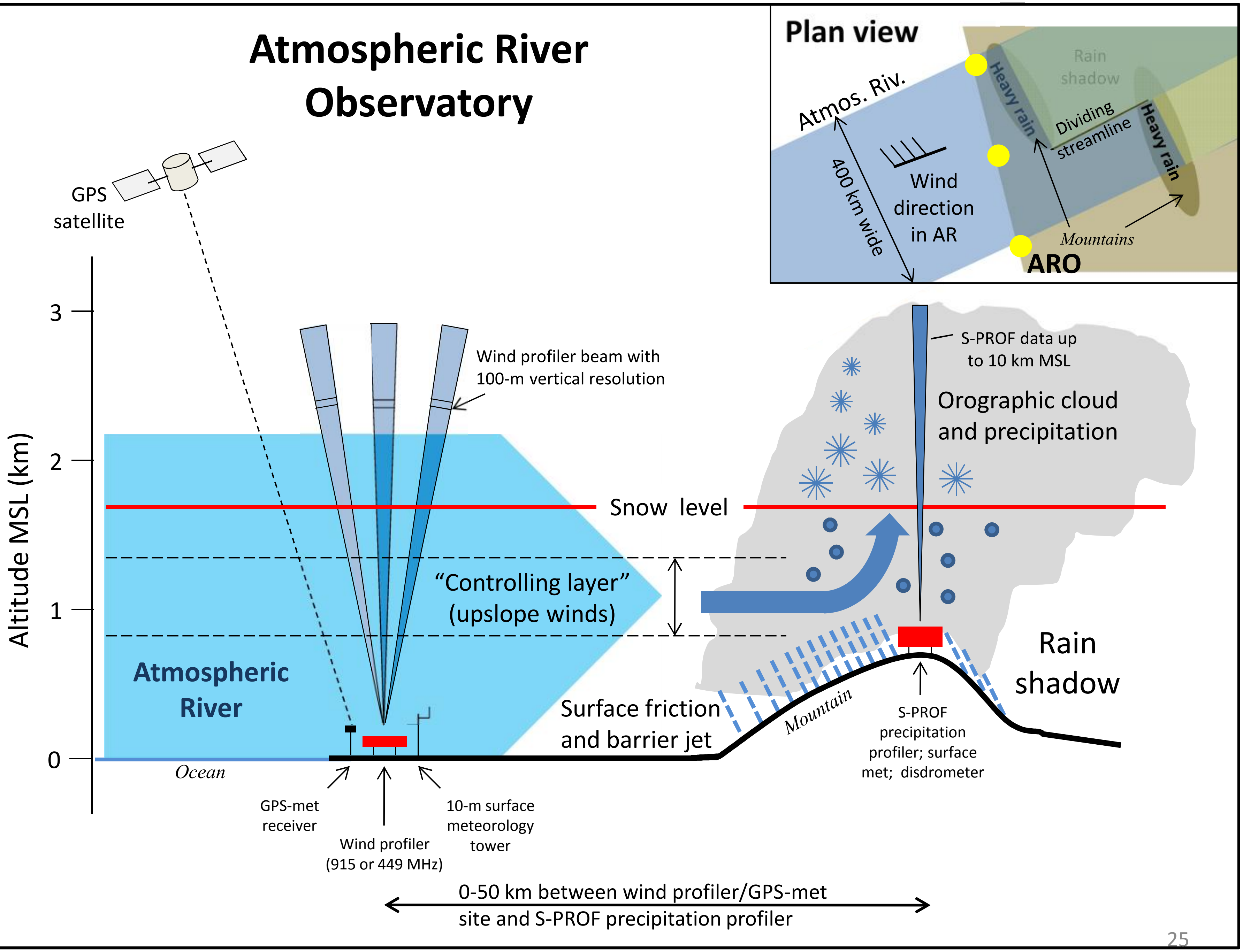




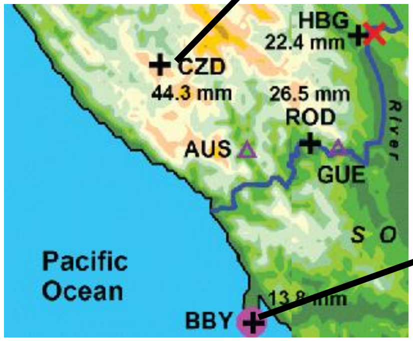
S. Eur. ARs - negative NAO.

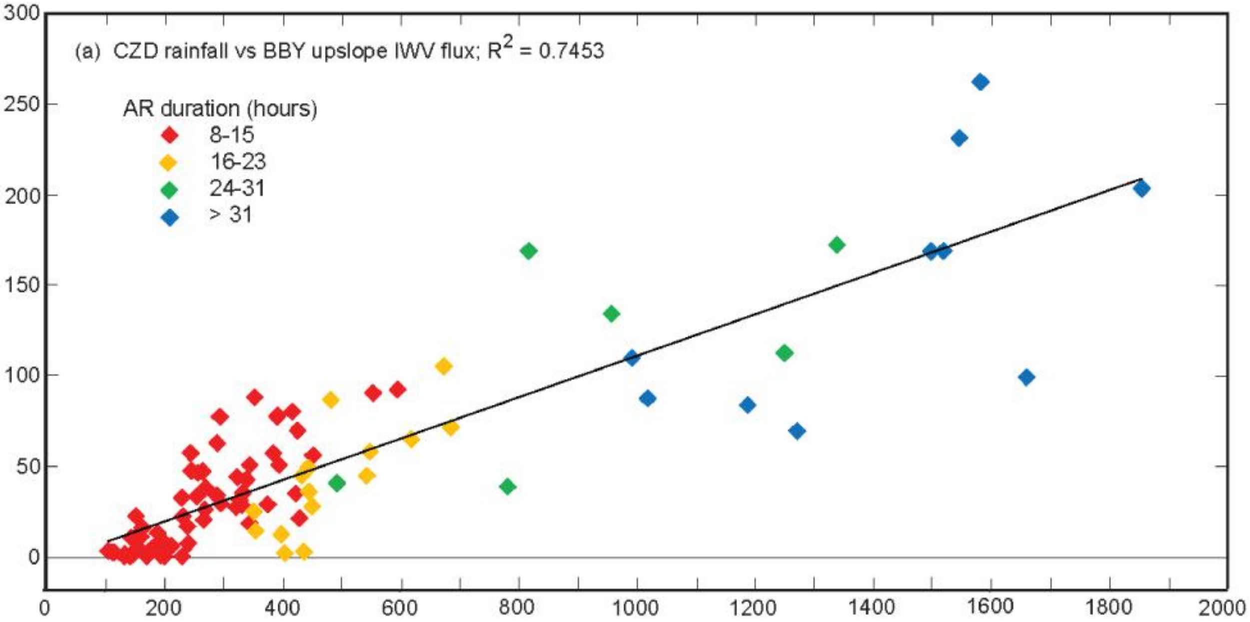
N. Eur. ARs - positive NAO.

Atmospheric River Observatory



91 AR events observed over 6 years

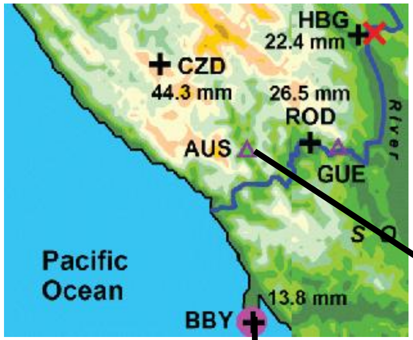


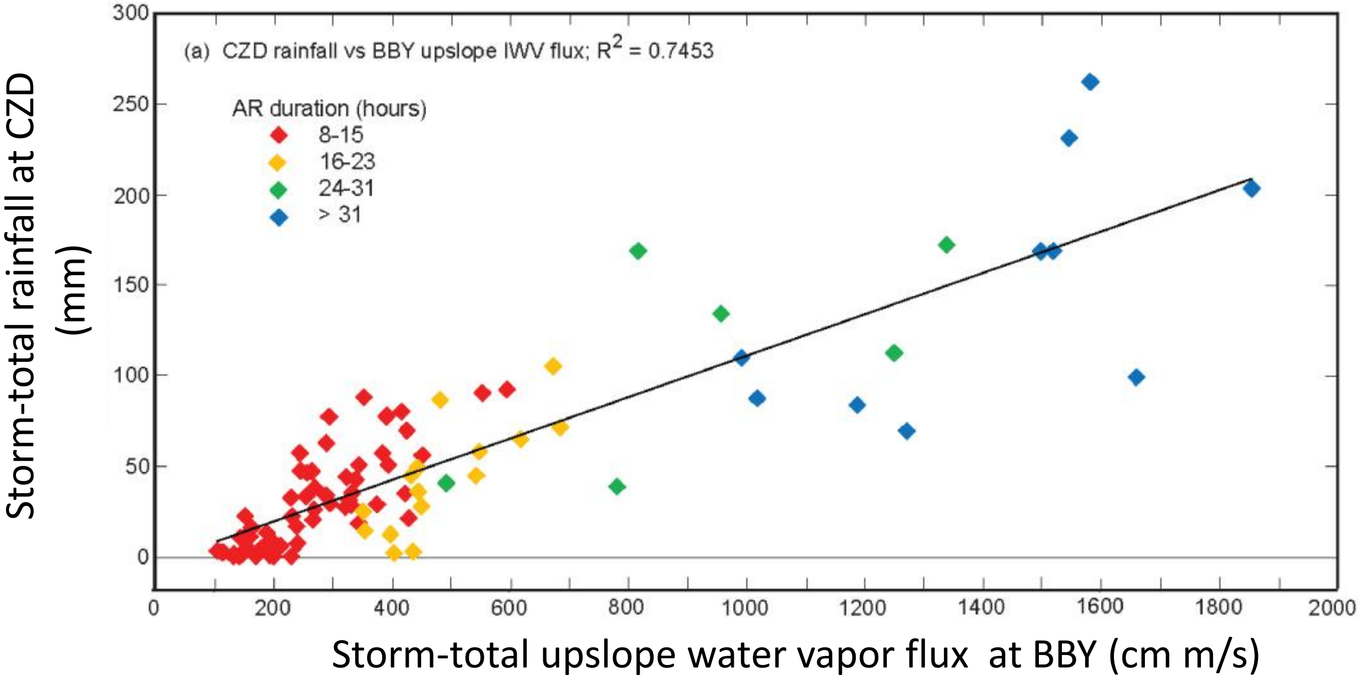


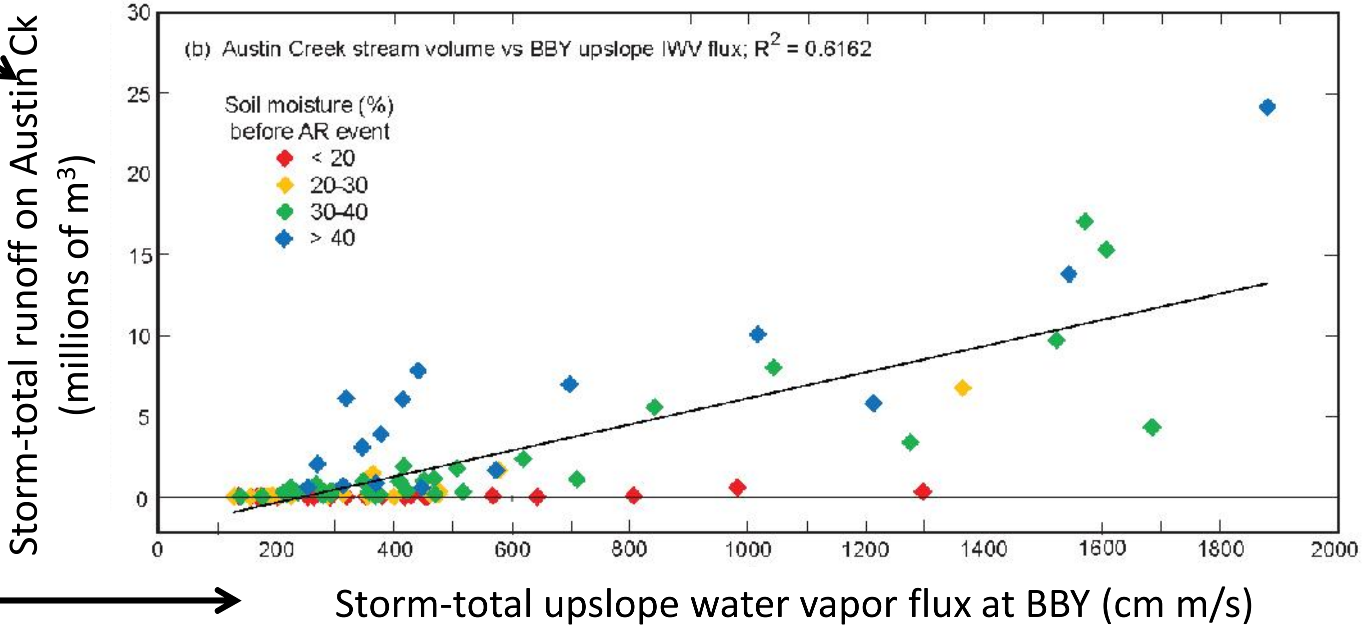
Storm-total rainfall at CZD (mm)

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

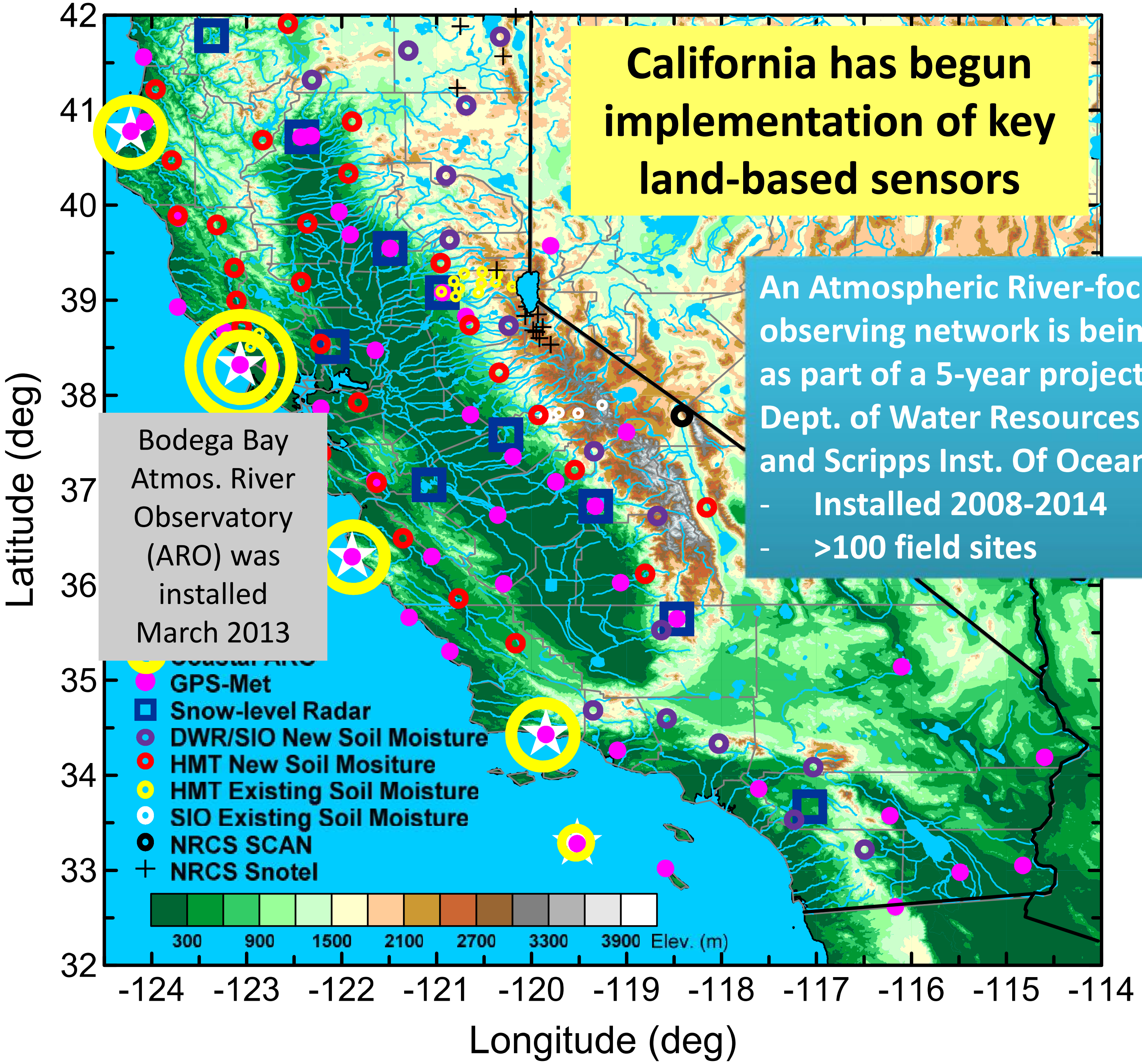
91 AR events observed over 6 years







California has begun implementation of key land-based sensors

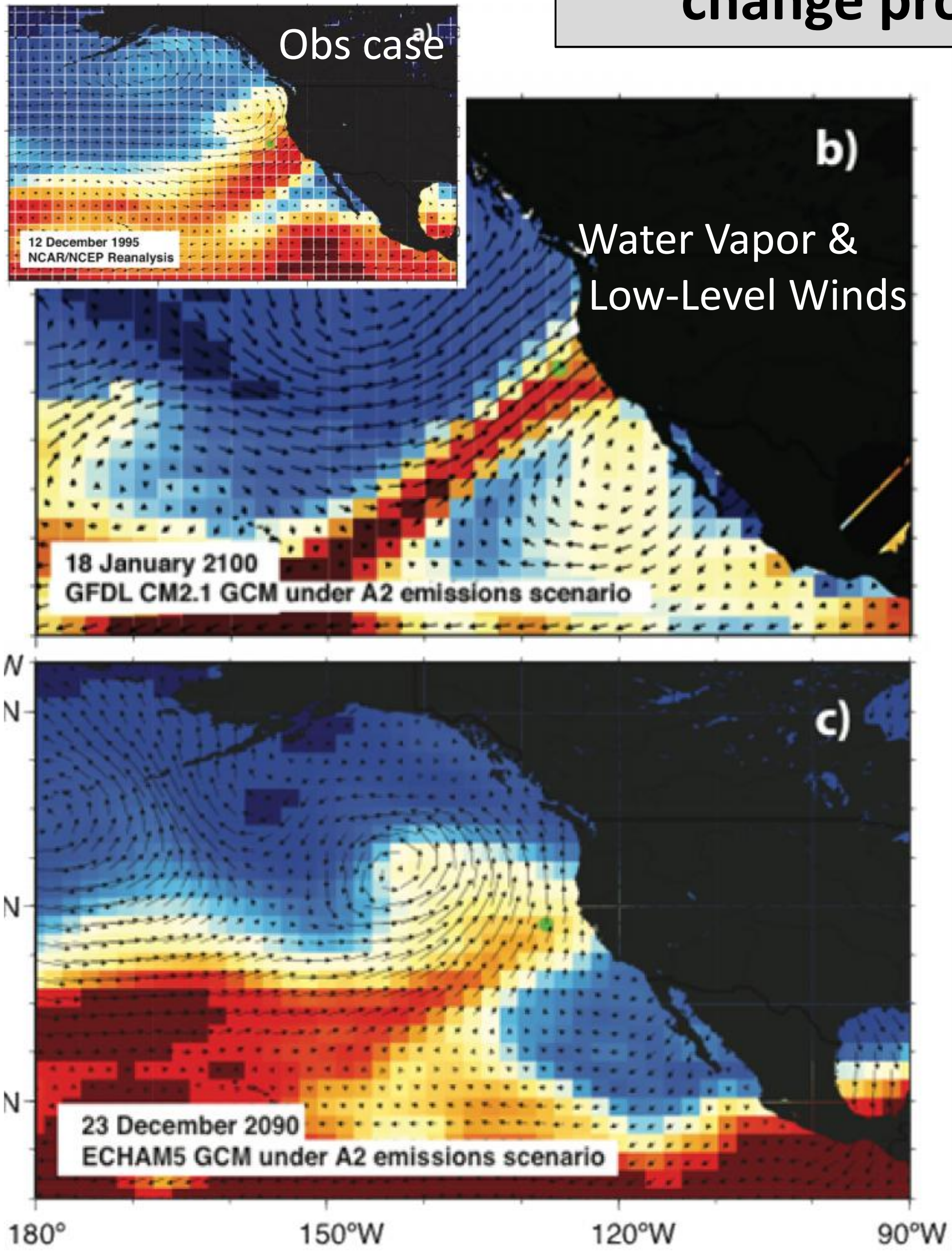


Bodega Bay Atmos. River Observatory (ARO) was installed March 2013

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

Atmospheric Rivers in IPCC-AR4 climate-change projections by 7 modern GCMs



By end of 21st Century, most GCMs yield:

- **More atmospheric vapor content, but weakening westerly winds**

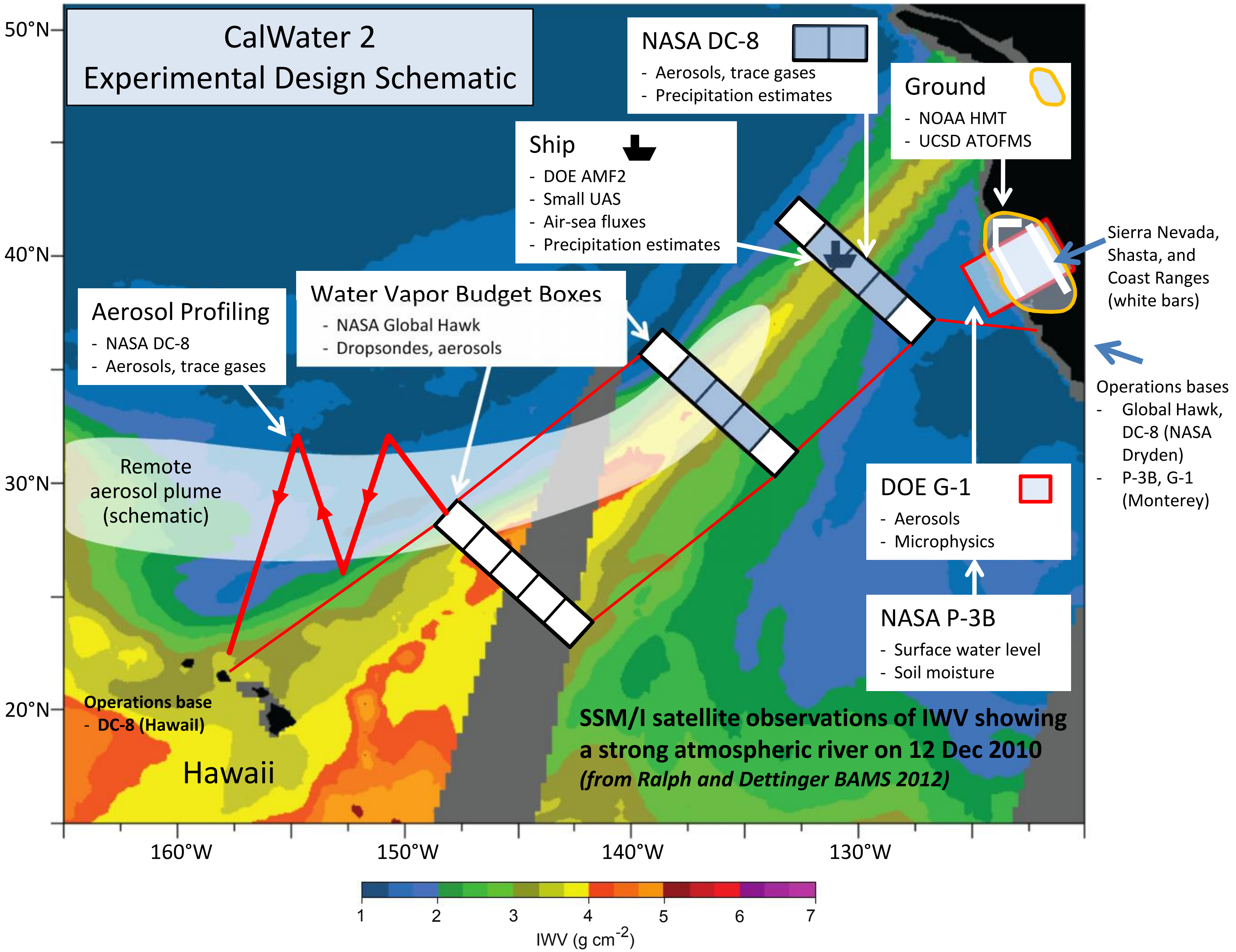
→Net increase in "intensity" of extreme AR storms

- **Warmer ARs (+1.8 C) → snowline raised by about 1000 feet on average**

- **Lengthening of AR seasons (maybe?)**

Dettinger, M.D., 2011, Climate change, atmospheric rivers and floods in California—A multimodel analysis of storm frequency and magnitude changes: Journal of American Water Resources Association, 47, 514-523.

CalWater 2
Experimental Design Schematic



NASA DC-8 ▭▭
- Aerosols, trace gases
- Precipitation estimates

Ground
- NOAA HMT
- UCSD ATOFMS

Ship
- DOE AMF2
- Small UAS
- Air-sea fluxes
- Precipitation estimates

Sierra Nevada, Shasta, and Coast Ranges (white bars)

Aerosol Profiling
- NASA DC-8
- Aerosols, trace gases

Water Vapor Budget Boxes
- NASA Global Hawk
- Dropsondes, aerosols

Operations bases
- Global Hawk, DC-8 (NASA Dryden)
- P-3B, G-1 (Monterey)

Remote aerosol plume (schematic)

DOE G-1 □
- Aerosols
- Microphysics

NASA P-3B
- Surface water level
- Soil moisture

Operations base
- **DC-8 (Hawaii)**

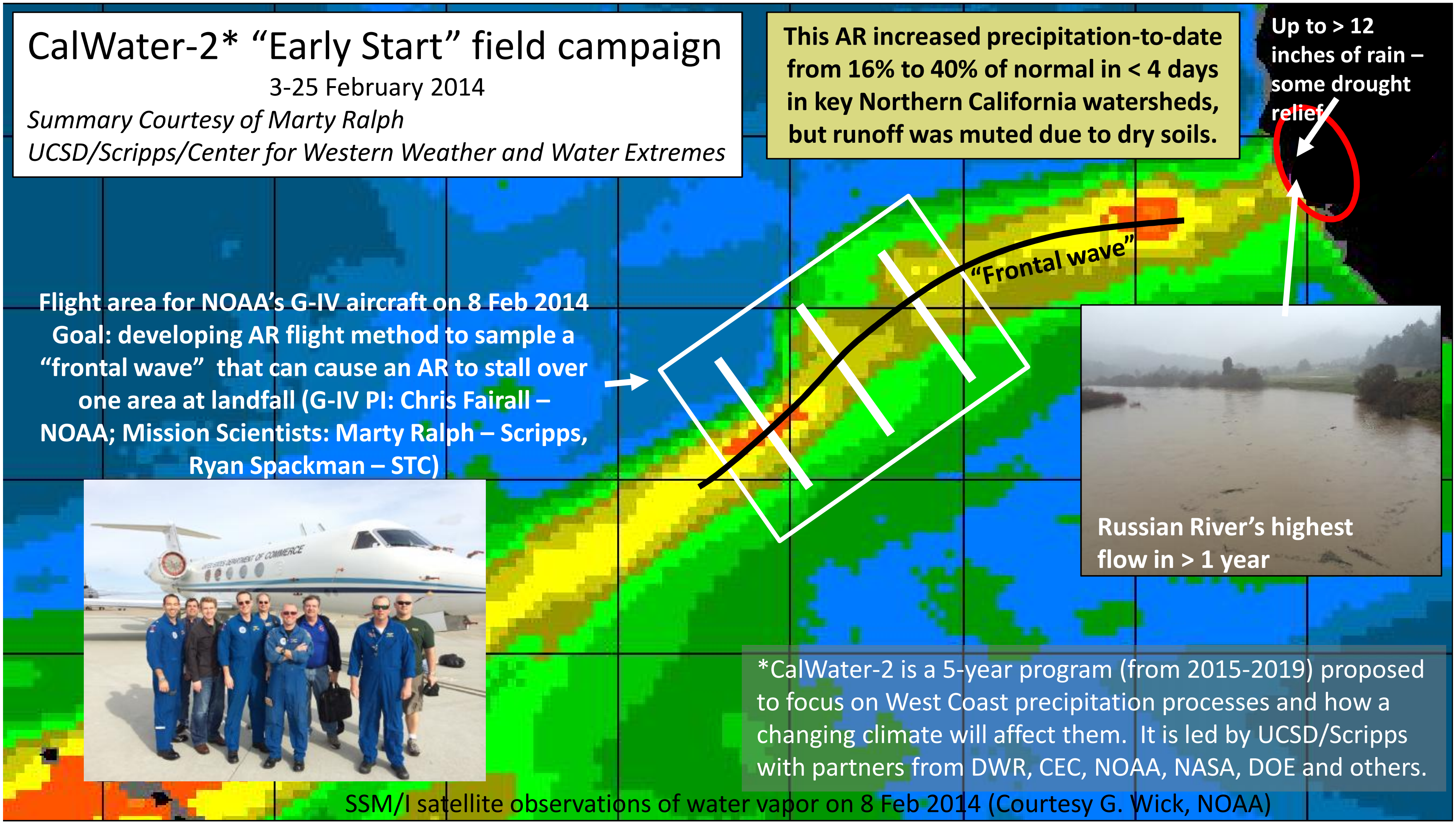
SSM/I satellite observations of IWV showing a strong atmospheric river on 12 Dec 2010
(from Ralph and Dettinger BAMS 2012)

Courtesy of F. M. Ralph, NOAA Earth System Research Laboratory

CalWater-2* “Early Start” field campaign

3-25 February 2014

Summary Courtesy of Marty Ralph
UCSD/Scripps/Center for Western Weather and Water Extremes



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

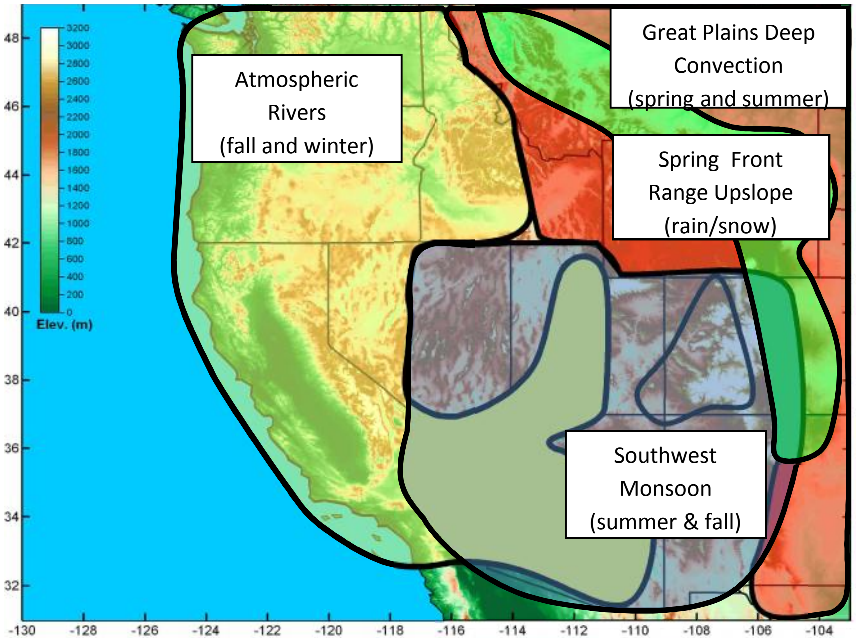
Up to > 12 inches of rain – some drought relief

Flight area for NOAA’s G-IV aircraft on 8 Feb 2014 Goal: developing AR flight method to sample a “frontal wave” that can cause an AR to stall over one area at landfall (G-IV PI: Chris Fairall – NOAA; Mission Scientists: Marty Ralph – Scripps, Ryan Spackman – STC)

Russian River’s highest flow in > 1 year

*CalWater-2 is a 5-year program (from 2015-2019) proposed to focus on West Coast precipitation processes and how a changing climate will affect them. It is led by UCSD/Scripps with partners from DWR, CEC, NOAA, NASA, DOE and others.

SSM/I satellite observations of water vapor on 8 Feb 2014 (Courtesy G. Wick, NOAA)



Center for Western Weather & Water Extremes

Where:	UC San Diego/Scripps Inst. Oceanography La Jolla, California
When:	Start - 2013
Who:	Dr. F. M. Ralph (Director) Dr. Dan Cayan Dr. Mike Dettinger 10 other staff or affiliates

SONOMA
COUNTY
WATER
AGENCY

Mission

Provide 21st 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

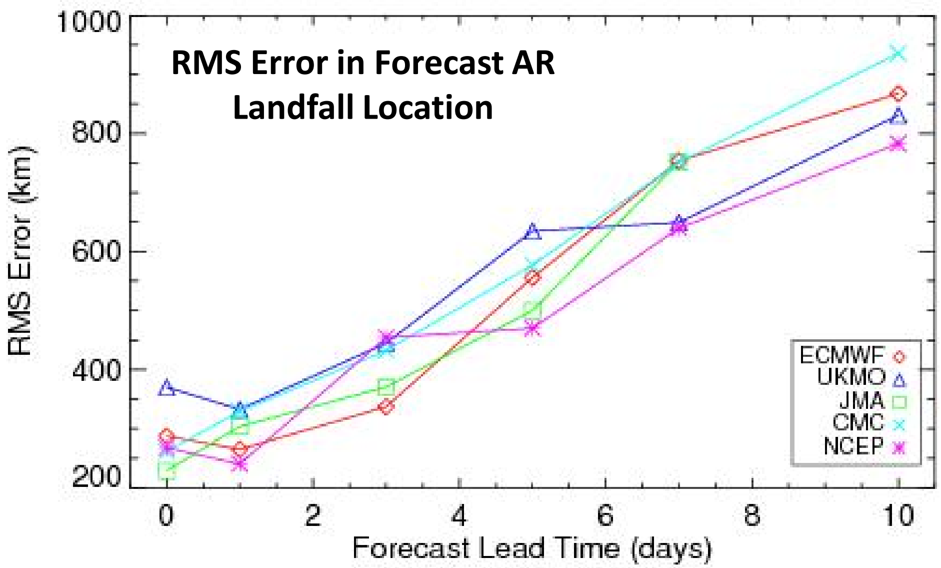
Revolutionize the physical understanding, observations, weather predictions and climate projections of extreme events in Western North America, including atmospheric rivers and the North American summer monsoon as well as their impacts on floods, droughts, hydropower, ecosystems and the economy

Thank you!

Backup slides

Validation of AR Forecasts – Results/Implications

While overall occurrence well forecast out to 10 days, landfall is less well predicted and the location is subject to significant errors, especially at longer leads



- Errors in location increase to over 800 km at 10-day lead
- Errors in 3-5 day forecasts comparable with current hurricane track errors
- Model resolution a key factor

From Wick et al., 2013
(Wea. and Forecasting)

- **Models provide useful heads-up for AR impact and IWV content, but location highly uncertain**
- **Location uncertainty highlights limitations in ability to predict extreme precipitation and flooding**
- **Improvements in predictions clearly desirable**

Overview of Scientific Findings from a Decade of Research

$50 M invested over 10 years (Federal, State, Local)

Table 1. Overview of findings from 10 years of atmospheric river research

ARs can…	Quantitative results	Formal reference
Cause heavy rain	90% of California's heaviest 1-3 day rain events are from ARs	Ralph et al. 2010
Fill reservoirs	40-50% of northern California rain and snow	Dettinger et al. 2011
Bust droughts	40% of droughts in northern California ended with an AR	Dettinger 2013
Help fish	77% of Yolo Bypass inundations of fisheries/eco. significance	Florsheim & Dett.2013
Cause floods	100% for key coastal watersheds (and many in Central Valley)	Ralph et al. 2006
Break levees	81% of Central Valley levee breaks were AR related	Florsheim & Dett.2013
Catastrophes	"ARkStorm" flood scenario found >$500 Billion impact in CA	Porter et al. 2011
Can be monitored	Simple & complex tools can help, e.g., radar, aircraft, satellite	White et al. 2013
Partly predictable	Can be seen >5 days ahead; landfall position error is large	Wick et al. 2013
Partly predictable	Of 16 AR storms that caused 5 in of rain, 2 were predicted	Ralph et al. 2010

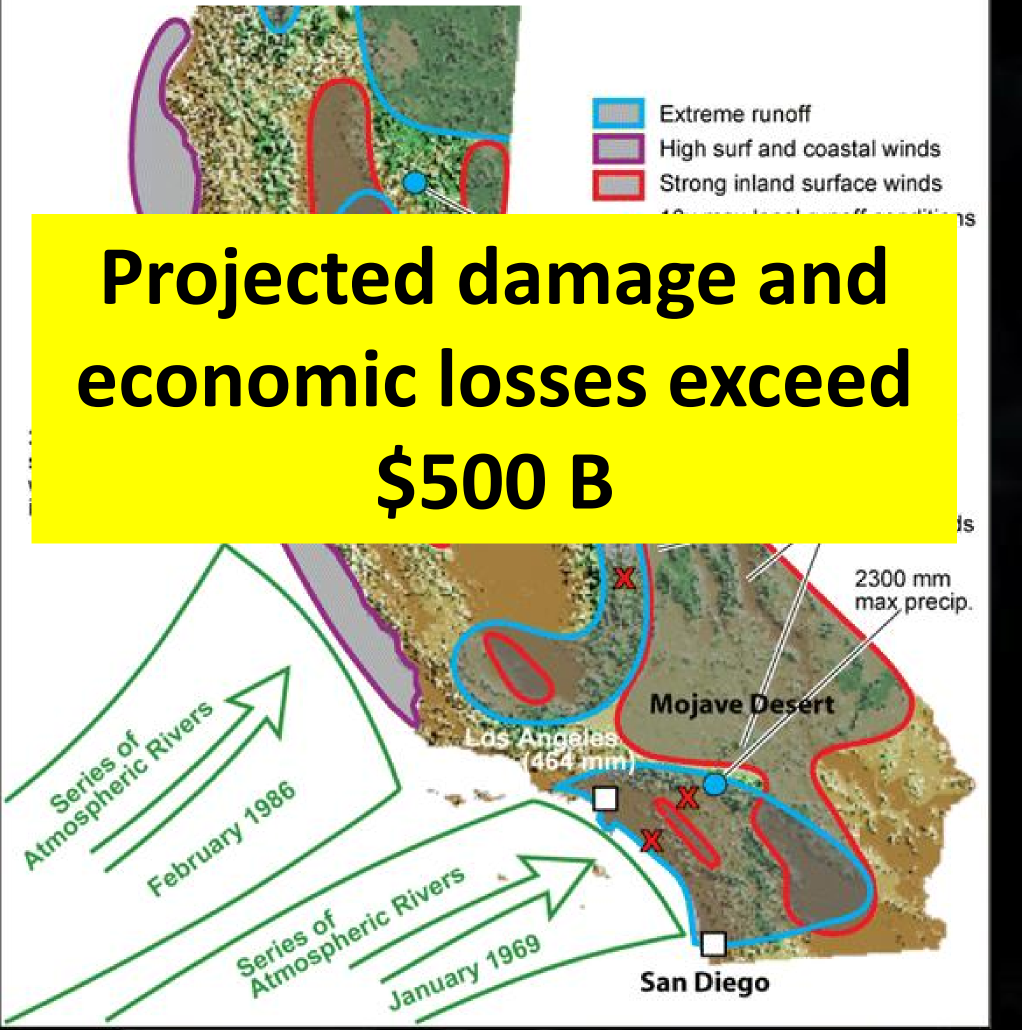
ARkStorm: An emergency preparedness scenario for California

USGS organized a large team of experts.

A meteorology team was formed and built a plausible physical scenario. Back-to-back extreme AR events (mostly based on actual 1969 and 1986 storms) struck over about 3 weeks . Considers the 1861/82 floods as an example.

The meteorological scenario was then given to follow-on groups of experts in damage assessment and economic disruption estimation and has become the basis for emergency preparedness exercises.

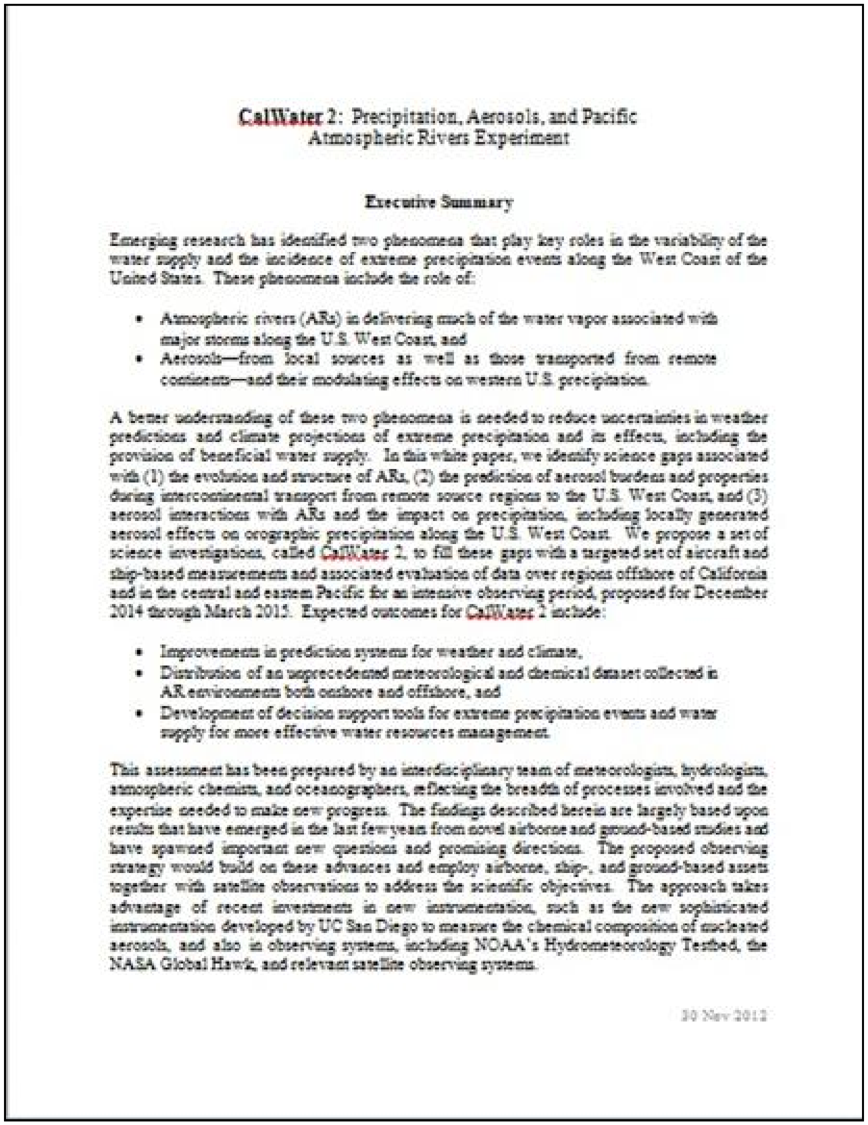
Dettinger et al. 2011 (Natural Hazards)



Projected damage and economic losses exceed $500 B

CalWater 2 Science White Paper

(22 contributors; 30 Nov 2012; 22 pp)



CalWater 2: Precipitation, Aerosols, and Pacific
Atmospheric Rivers Experiment

Executive Summary

Emerging research has identified two phenomena that play key roles in the variability of the water supply and the incidence of extreme precipitation events along the West Coast of the United States. These phenomena include the role of:

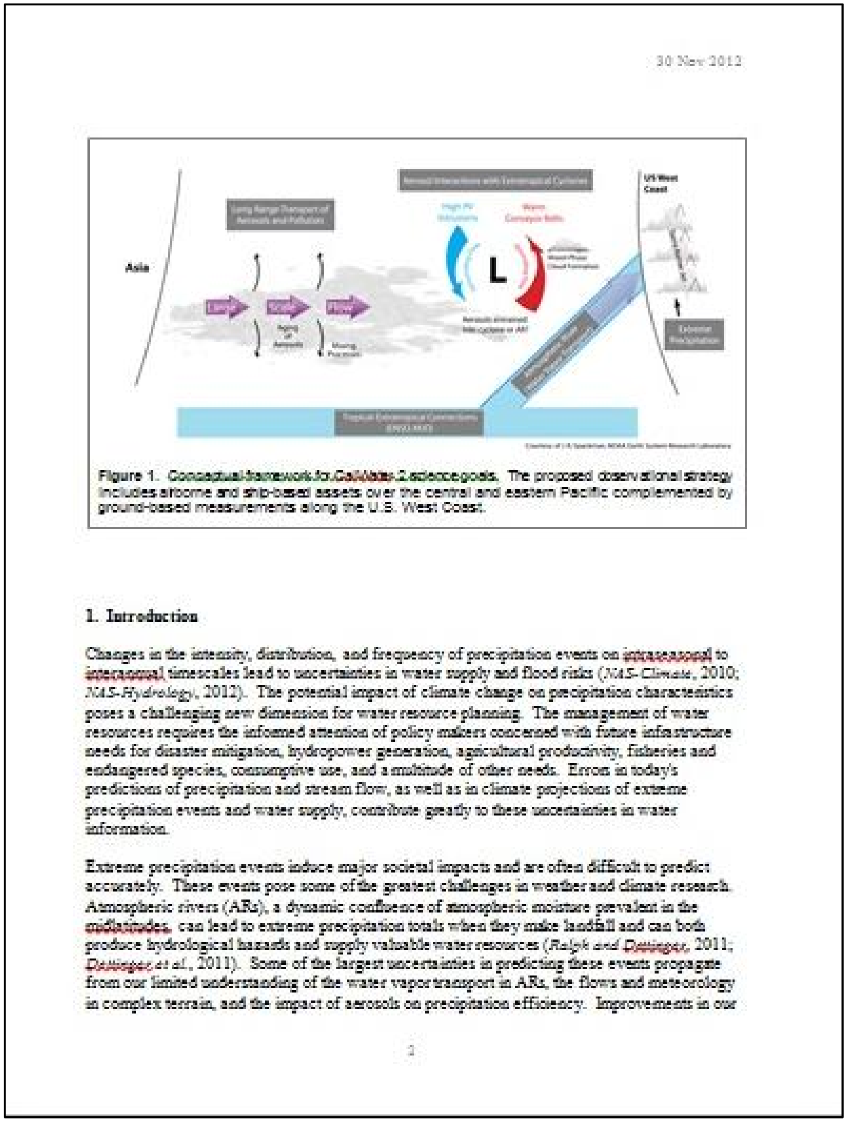
- Atmospheric rivers (ARs) in delivering much of the water vapor associated with major storms along the U.S. West Coast, and
- Aerosols—from local sources as well as those transported from remote continents—and their modulating effects on western U.S. precipitation.

A better understanding of these two phenomena is needed to reduce uncertainties in weather predictions and climate projections of extreme precipitation and its effects, including the provision of beneficial water supply. In this white paper, we identify science gaps associated with (1) the evolution and structure of ARs, (2) the prediction of aerosol burdens and properties during intercontinental transport from remote source regions to the U.S. West Coast, and (3) aerosol interactions with ARs and the impact on precipitation, including locally generated aerosol effects on orographic precipitation along the U.S. West Coast. We propose a set of science investigations, called CalWater 2, to fill these gaps with a targeted set of aircraft and ship-based measurements and associated evaluation of data over regions offshore of California and in the central and eastern Pacific for an intensive observing period, proposed for December 2014 through March 2015. Expected outcomes for CalWater 2 include:

- Improvements in prediction systems for weather and climate,
- Distribution of an unprecedented meteorological and chemical dataset collected in AR environments both onshore and offshore, and
- Development of decision support tools for extreme precipitation events and water supply for more effective water resources management.

This assessment has been prepared by an interdisciplinary team of meteorologists, hydrologists, atmospheric chemists, and oceanographers, reflecting the breadth of processes involved and the expertise needed to make new progress. The findings described herein are largely based upon results that have emerged in the last few years from novel airborne and ground-based studies and have spawned important new questions and promising directions. The proposed observing strategy would build on these advances and employ airborne, ship-, and ground-based assets together with satellite observations to address the scientific objectives. The approach takes advantage of recent investments in new instrumentation, such as the new sophisticated instrumentation developed by UC San Diego to measure the chemical composition of nucleated aerosols, and also in observing systems, including NOAA's Hydrometeorology Testbed, the NASA Global Hawk, and relevant satellite observing systems.

30 Nov 2012



30 Nov 2012

Figure 1. Conceptual framework for CalWater 2 science goals. The proposed observational strategy includes airborne and ship-based assets over the central and eastern Pacific complemented by ground-based measurements along the U.S. West Coast.

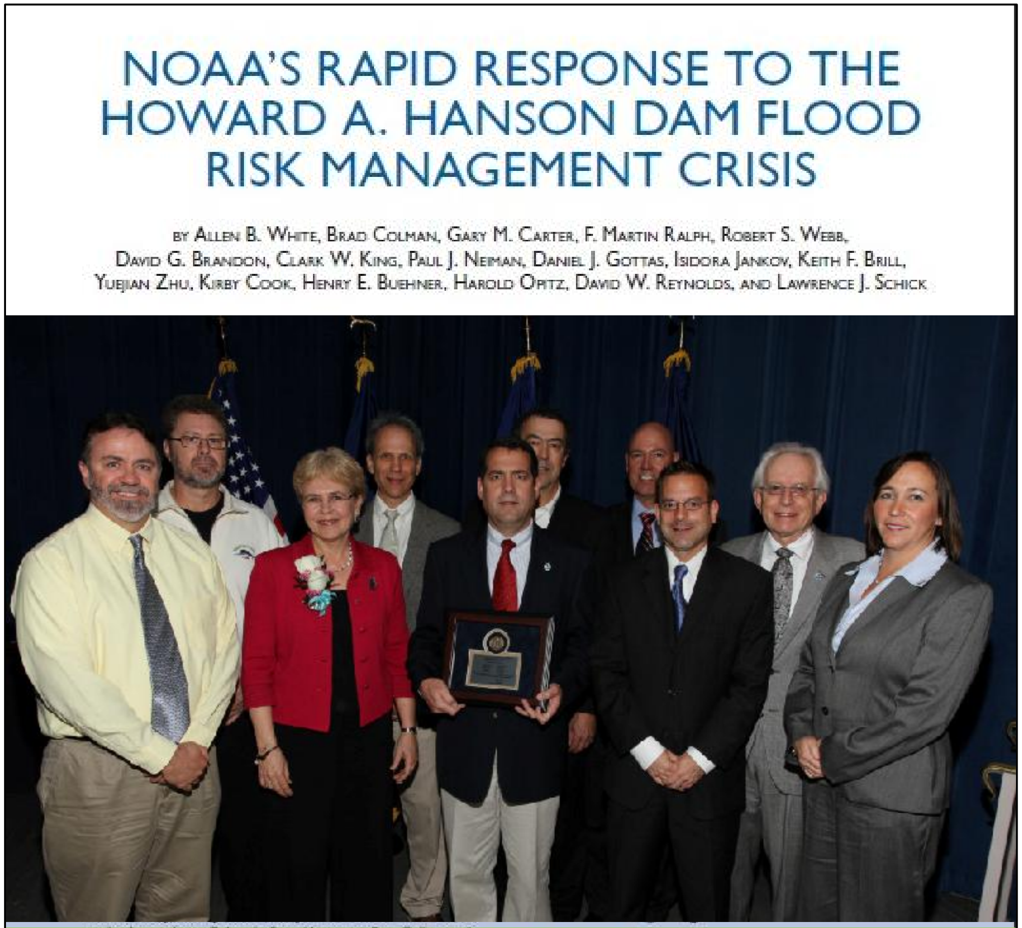
1. Introduction

Changes in the intensity, distribution, and frequency of precipitation events on intraseasonal to interannual timescales lead to uncertainties in water supply and flood risks (*NAS-Climate*, 2010; *NAS-Hydrology*, 2012). The potential impact of climate change on precipitation characteristics poses a challenging new dimension for water resource planning. The management of water resources requires the informed attention of policy makers concerned with future infrastructure needs for disaster mitigation, hydropower generation, agricultural productivity, fisheries and endangered species, consumptive use, and a multitude of other needs. Errors in today's predictions of precipitation and stream flow, as well as in climate projections of extreme precipitation events and water supply, contribute greatly to these uncertainties in water information.

Extreme precipitation events induce major societal impacts and are often difficult to predict accurately. These events pose some of the greatest challenges in weather and climate research. Atmospheric rivers (ARs), a dynamic confluence of atmospheric moisture prevalent in the midlatitudes, can lead to extreme precipitation totals when they make landfall and can both produce hydrological hazards and supply valuable water resources (*Ralph and Dettinger*, 2011; *Dettinger et al.*, 2011). Some of the largest uncertainties in predicting these events propagate from our limited understanding of the water vapor transport in ARs, the flows and meteorology in complex terrain, and the impact of aerosols on precipitation efficiency. Improvements in our

2

HMT-West innovations were key elements in NOAA’s rapid response to a flood risk crisis



NOAA’S RAPID RESPONSE TO THE HOWARD A. HANSON DAM FLOOD RISK MANAGEMENT CRISIS

BY ALLEN B. WHITE, BRAD COLMAN, GARY M. CARTER, F. MARTIN RALPH, ROBERT S. WEBB, DAVID G. BRANDON, CLARK W. KING, PAUL J. NEIMAN, DANIEL J. GOTTAS, ISIDORA JANKOV, KEITH F. BRILL, YUEJIAN ZHU, KIRBY COOK, HENRY E. BUEHNER, HAROLD OPITZ, DAVID W. REYNOLDS, AND LAWRENCE J. SCHICK

Dept. of Commerce
Bronze Medal 2012

- USACE was considering taking over operation of a dam in Washington State during a recent storm.
- Using the HMT ARO at the coast and NWS forecasts, USACE saw the back edge of the AR was coming ashore and thus heavy rain was about to end, so they did not take over operation from the local water agency.
- See recent journal article by White et al. (February 2012; Bulletin of the American Meteorological Society).