Emergence of the Concept of Atmospheric Rivers

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International Atmospheric Rivers Conference (IARC)
Keynote Presentation
8 August 2016, La Jolla, CA

Center for Western Weather and Water Extremes

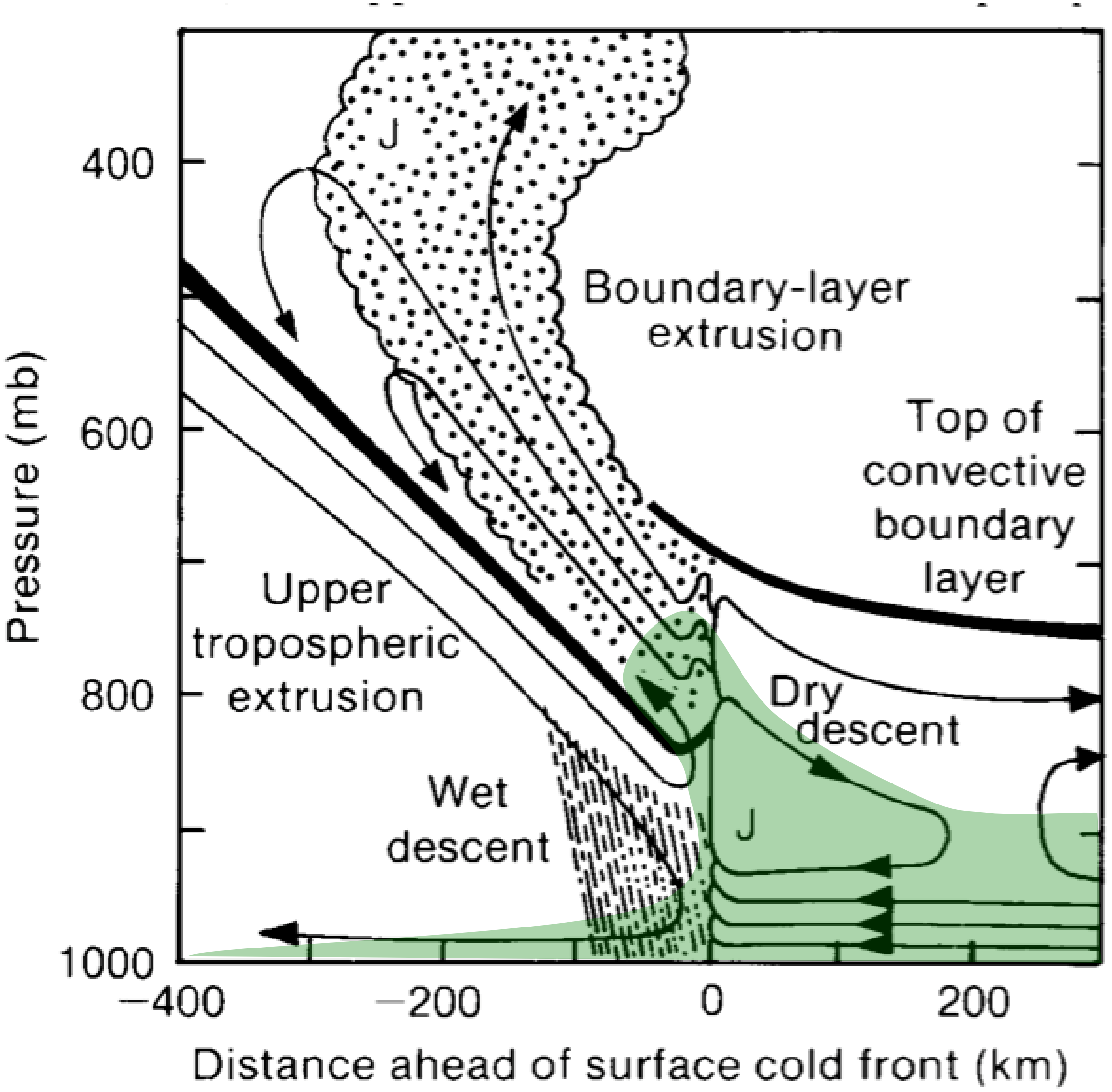
SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

Outline

Purpose: Describe major milestones in development of the AR concept

- 1970s and 1980s: Underlying concepts established
- 1990s: Global perspectives lead to the term “atmospheric river” (AR)
- 2000s: U.S. West Coast experiments, forecasts and practical goals focus on ARs
- 2010-2015: The concept matures, science and practical applications grow
- 2016 and beyond: A diverse community exists and is pursuing a range of promising science and application directions

The low-level jet



Browning described the LLJ in the region of the polar cold front as a cork-screw like motion that can advance warm moist air both poleward and upward

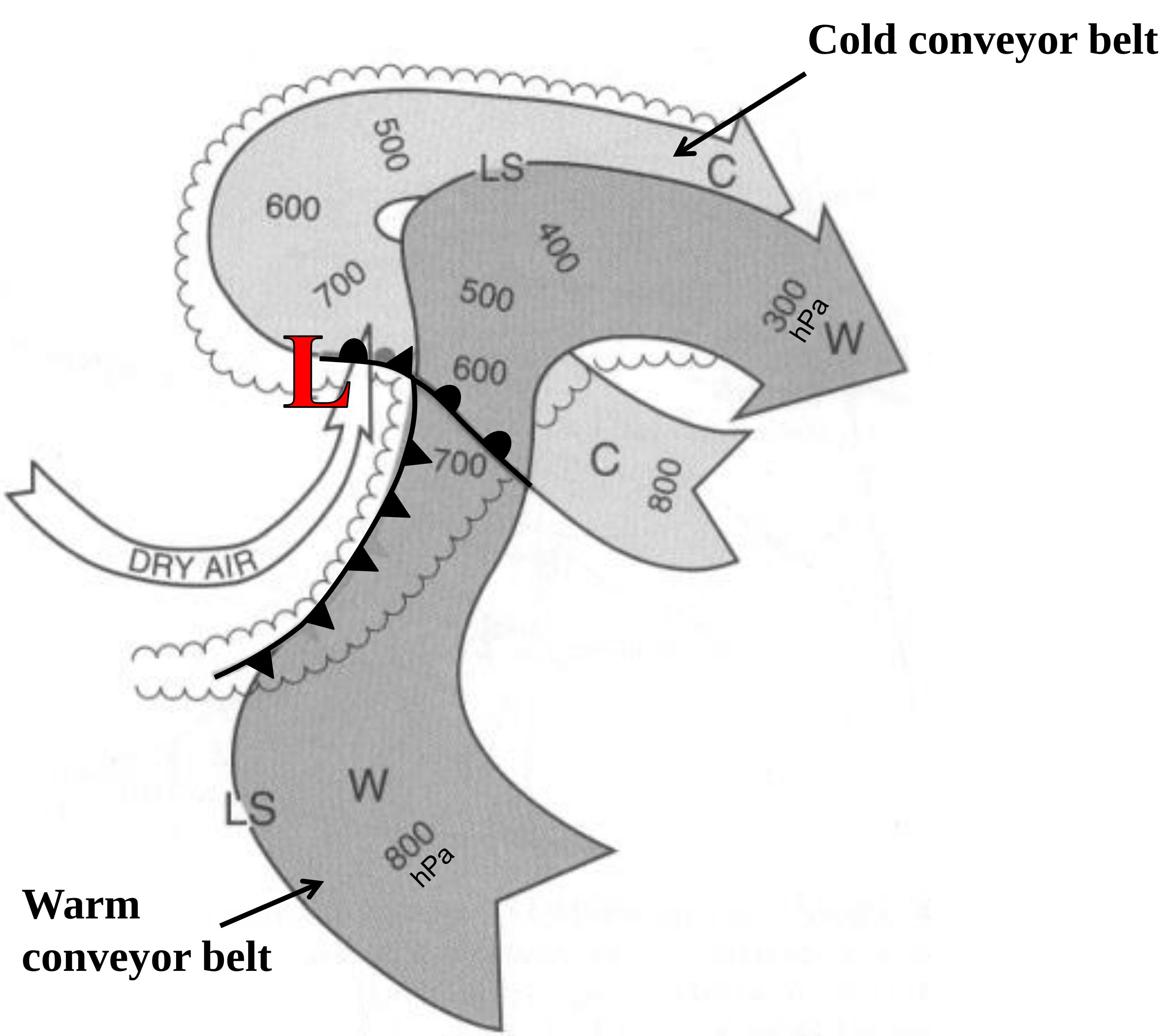
Browning and Pardoe (1973-QJRMS)

Slide courtesy of J. Cordeira

Warm and Cold Conveyor Belt Concepts

- 3D kinematic and thermodynamic schematic
- Warm conveyor belt
  - Ahead of cold front
  - Ascends over warm front
  - Represents sensible and latent heat

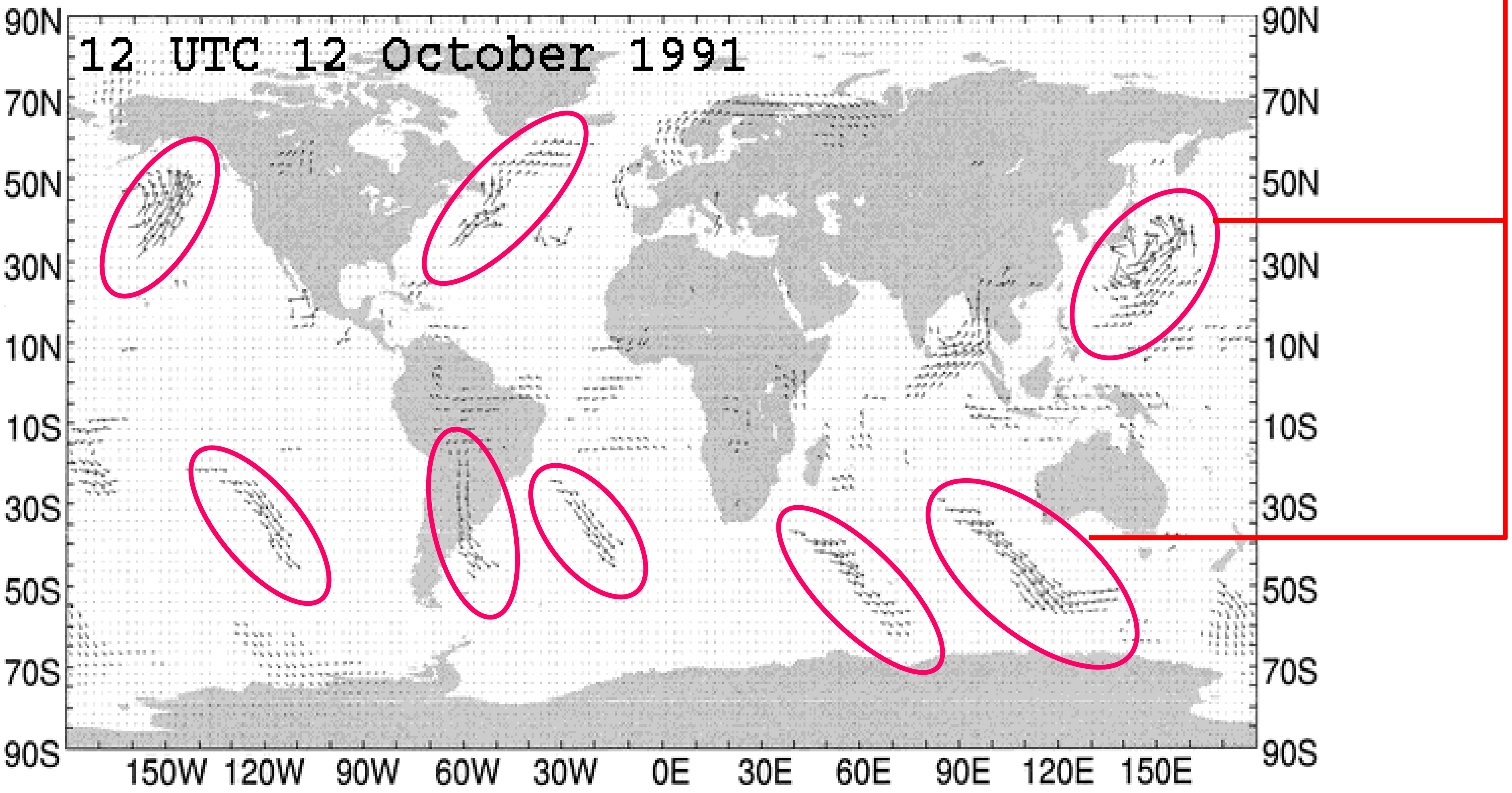
Image adapted from Carlson (1980)



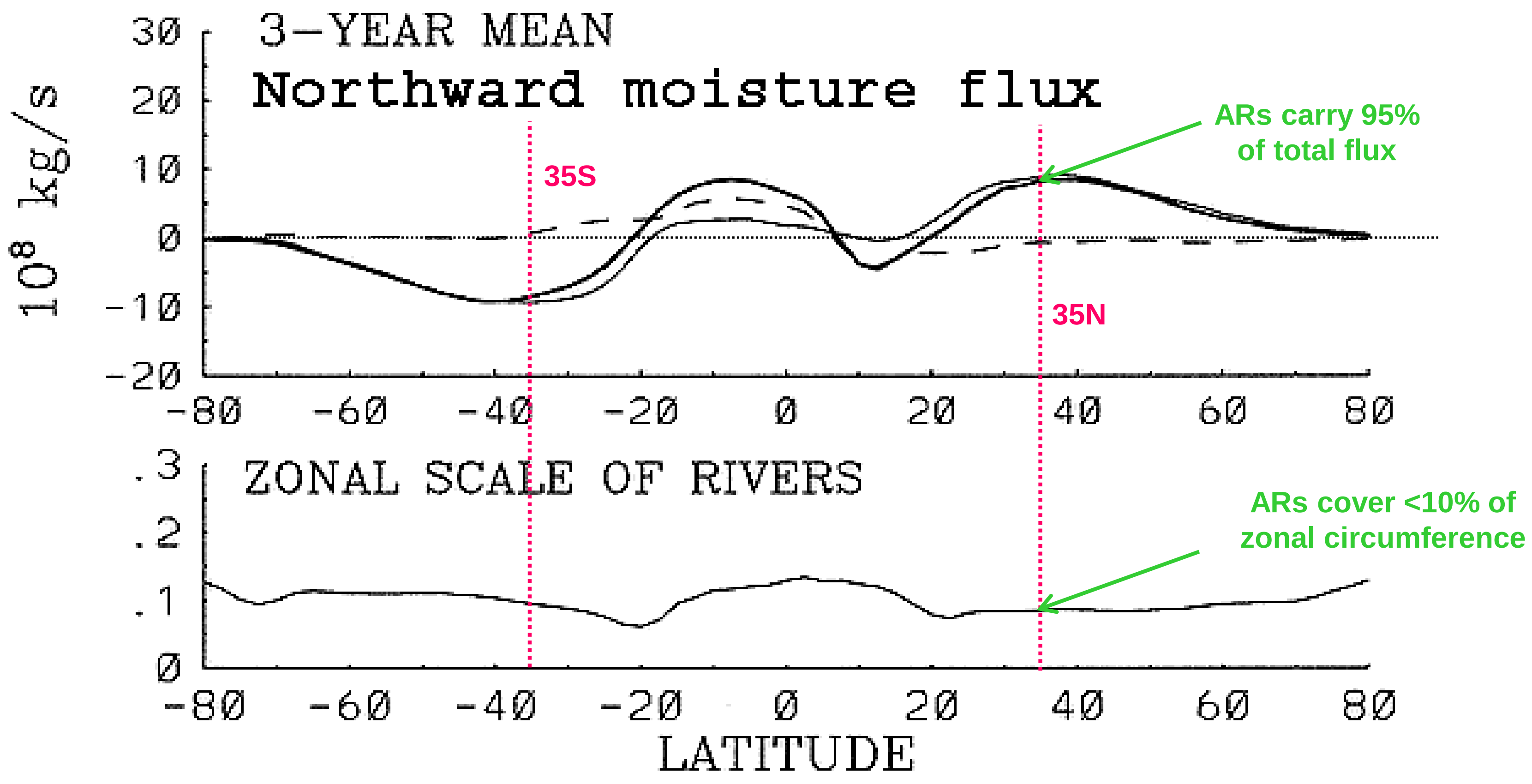
Slide courtesy of J. Cordeira

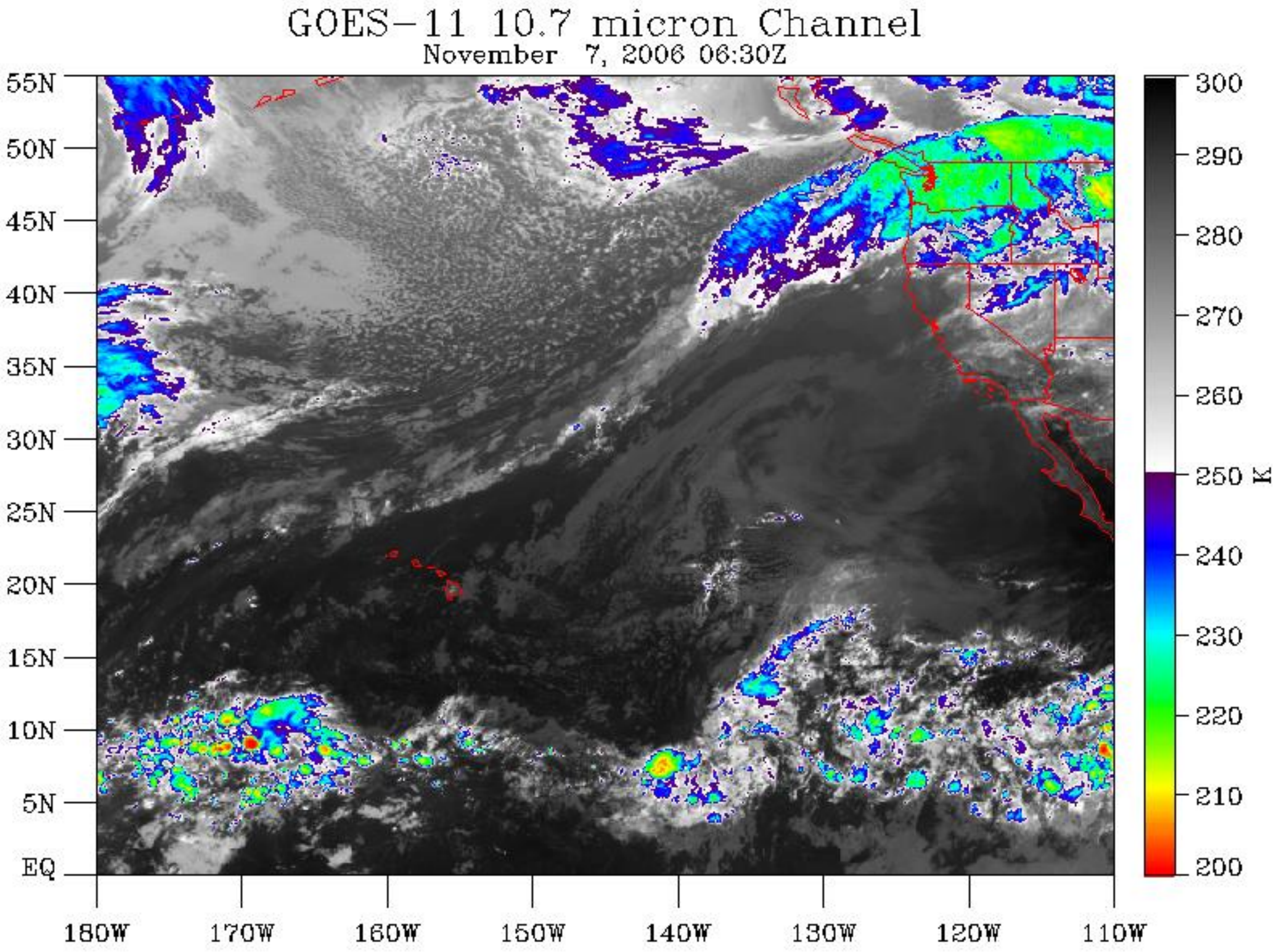
Zhu & Newell (1998) concluded in a 3-year ECMWF model diagnostic study:

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 are very important from a global water cycle perspective.



Atmospheric Rivers are responsible for 90 - 95% of the total global meridional water vapor transport at midlatitudes, and yet constitute <10% of the Earth's circumference at those latitudes. (Zhu and Newell 1998)




GOES-11 10.7 micron Channel
November 7, 2006 06:30Z
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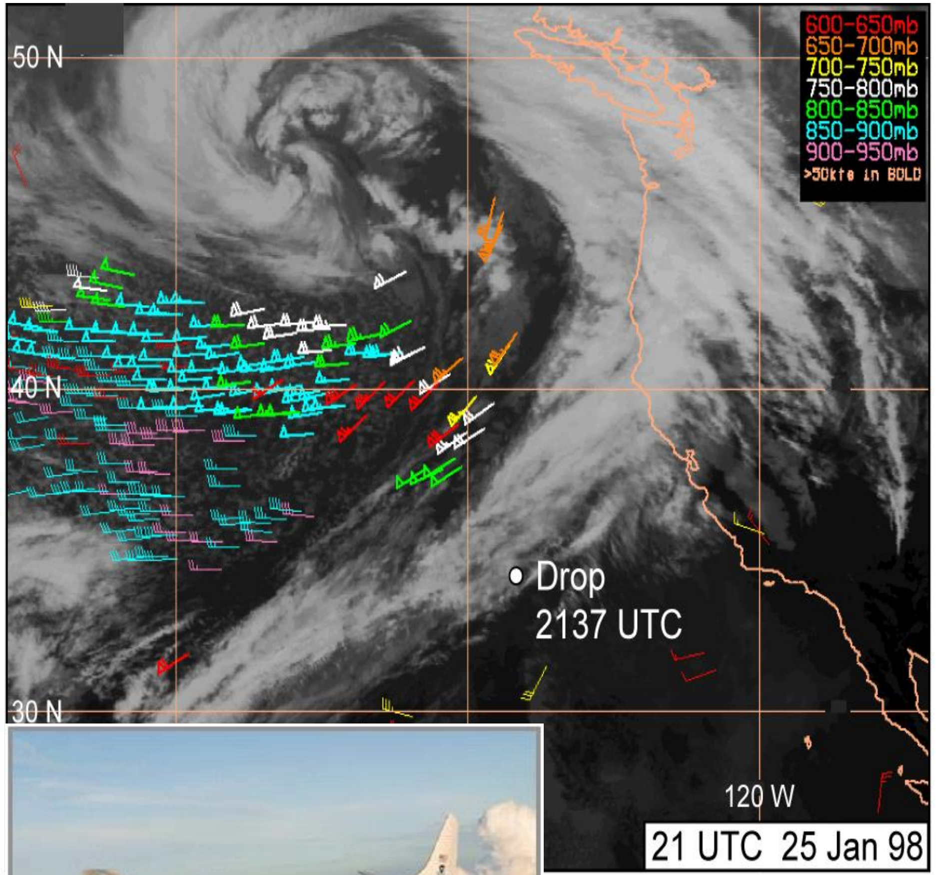
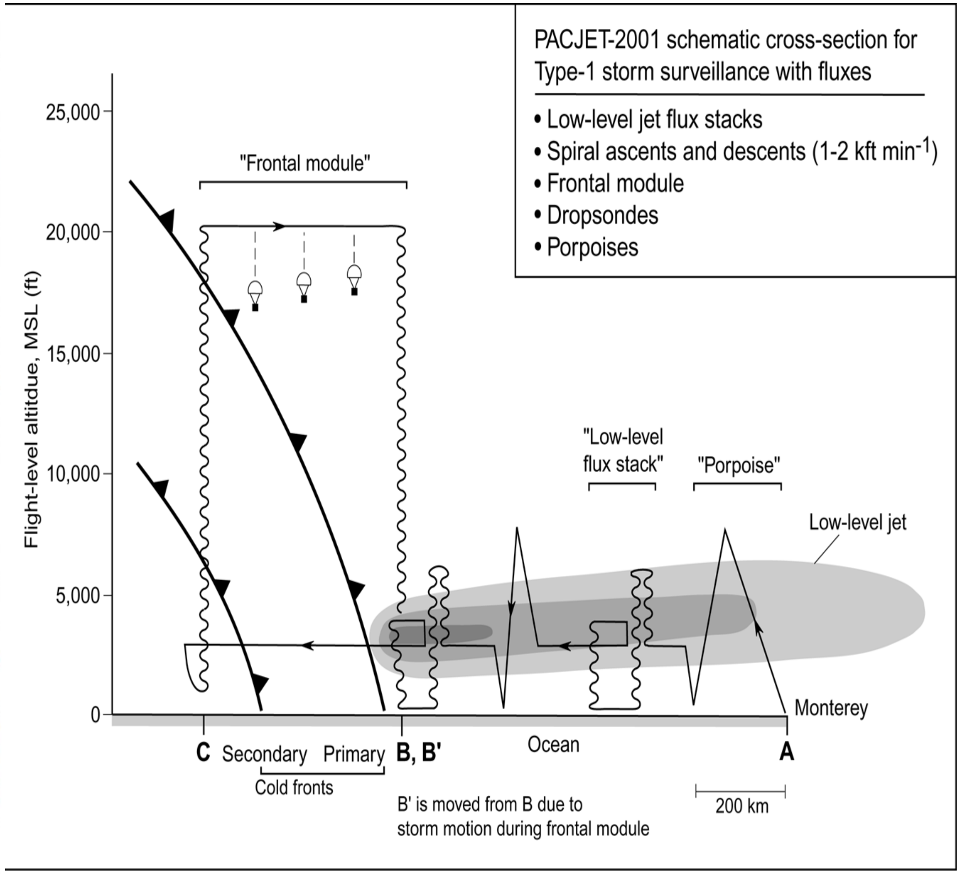
Offshore Structure Diagnosed with Aircraft and Satellite Observations

Ralph et al. 2004, 2005 (MWR)

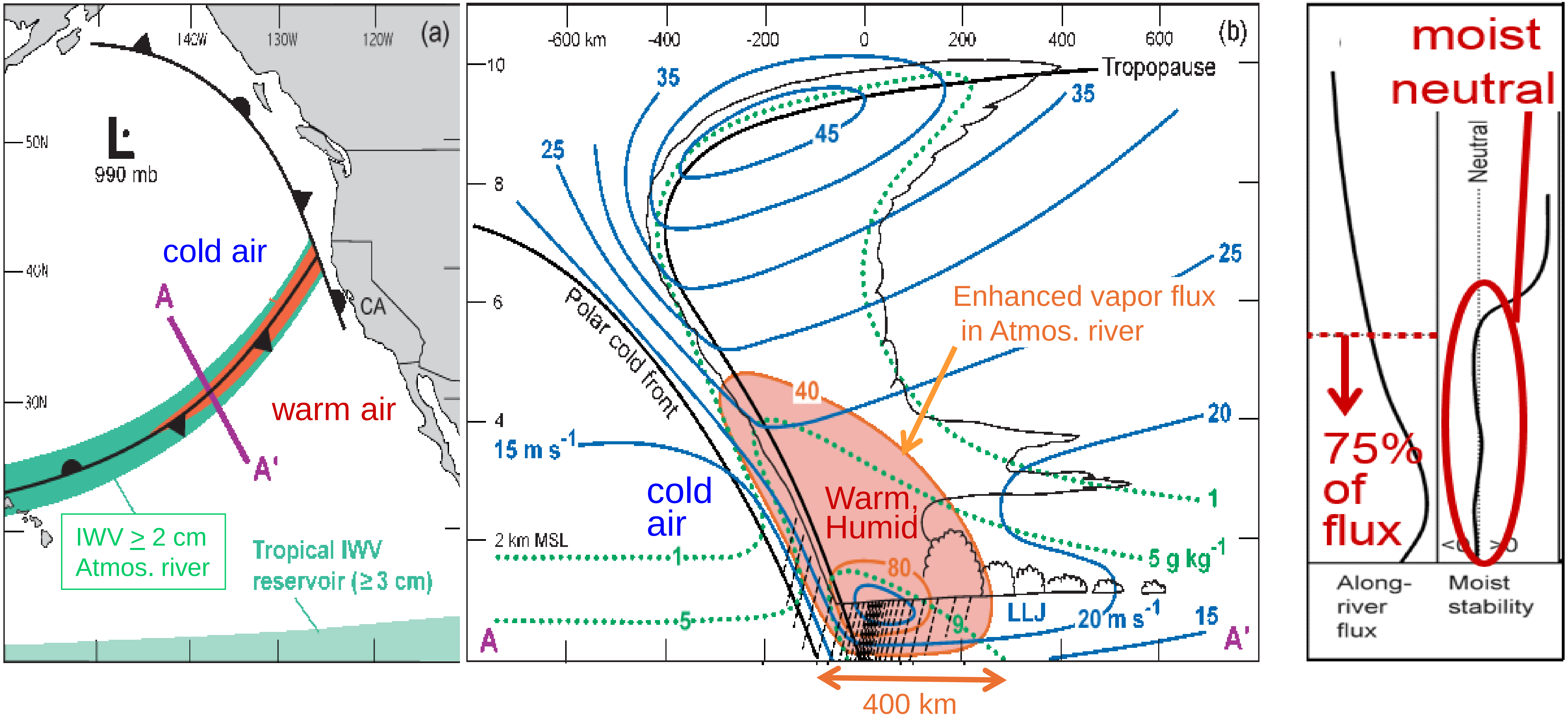


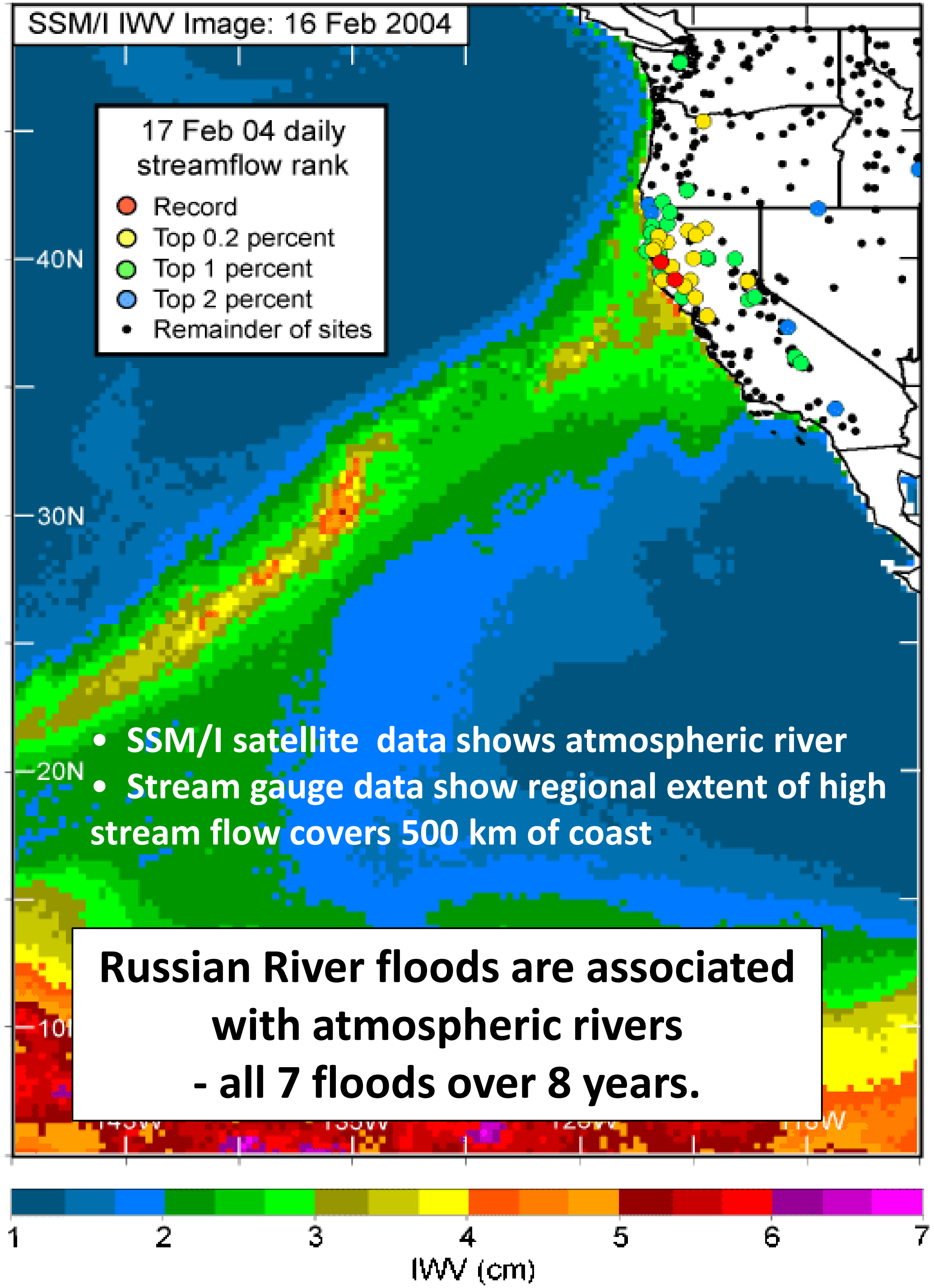


Low-level jet (LLJ) airborne P-3 observing strategy used in CALJET (1998) and PACJET (2001)

Airborne observational studies extended model results:

1) Ralph, Neiman, Wick 2004 (RNW-2004) created first obs'-based AR detection method: used IWV >2 cm from satellite.
2) These plumes, had to be >2000 km long and <1000 km wide, are 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) 17 airborne cases showed 75% of the vapor flux was below 2.5 km MSL in vicinity of LLJ (Ralph Neiman Rotunno 2005).





- 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.

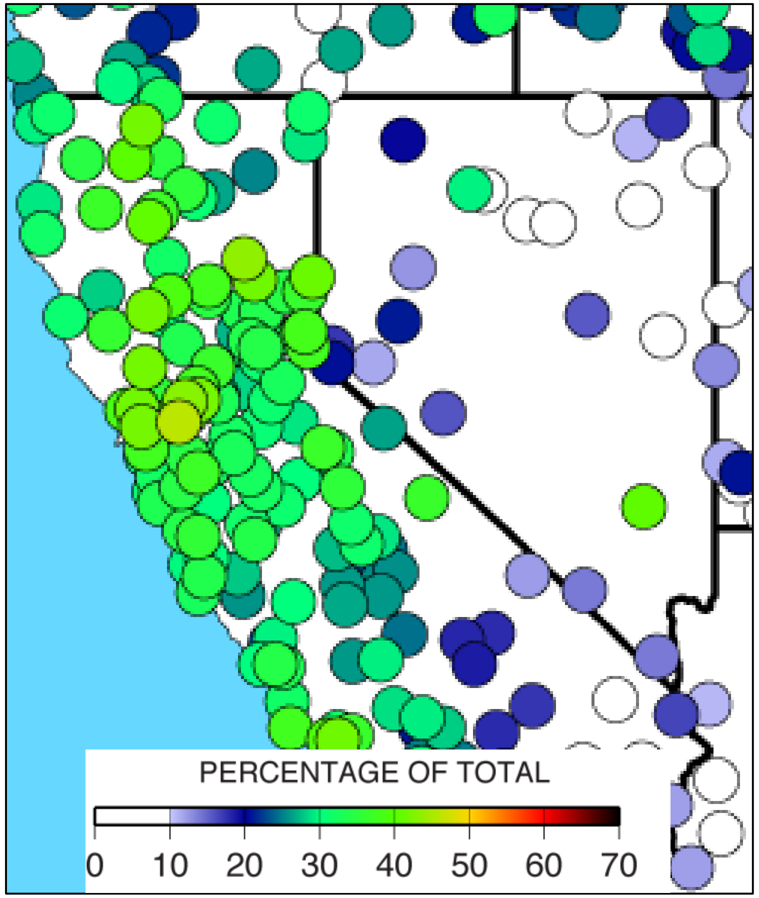
Flooding on California's Russian River: Role of atmospheric rivers

Ralph, F.M., P. J. Neiman, G. A. Wick, S. I. Gutman, M. D. Dettinger, D. R. Cayan, A. White (*Geophys. Res. Lett., 2006)*

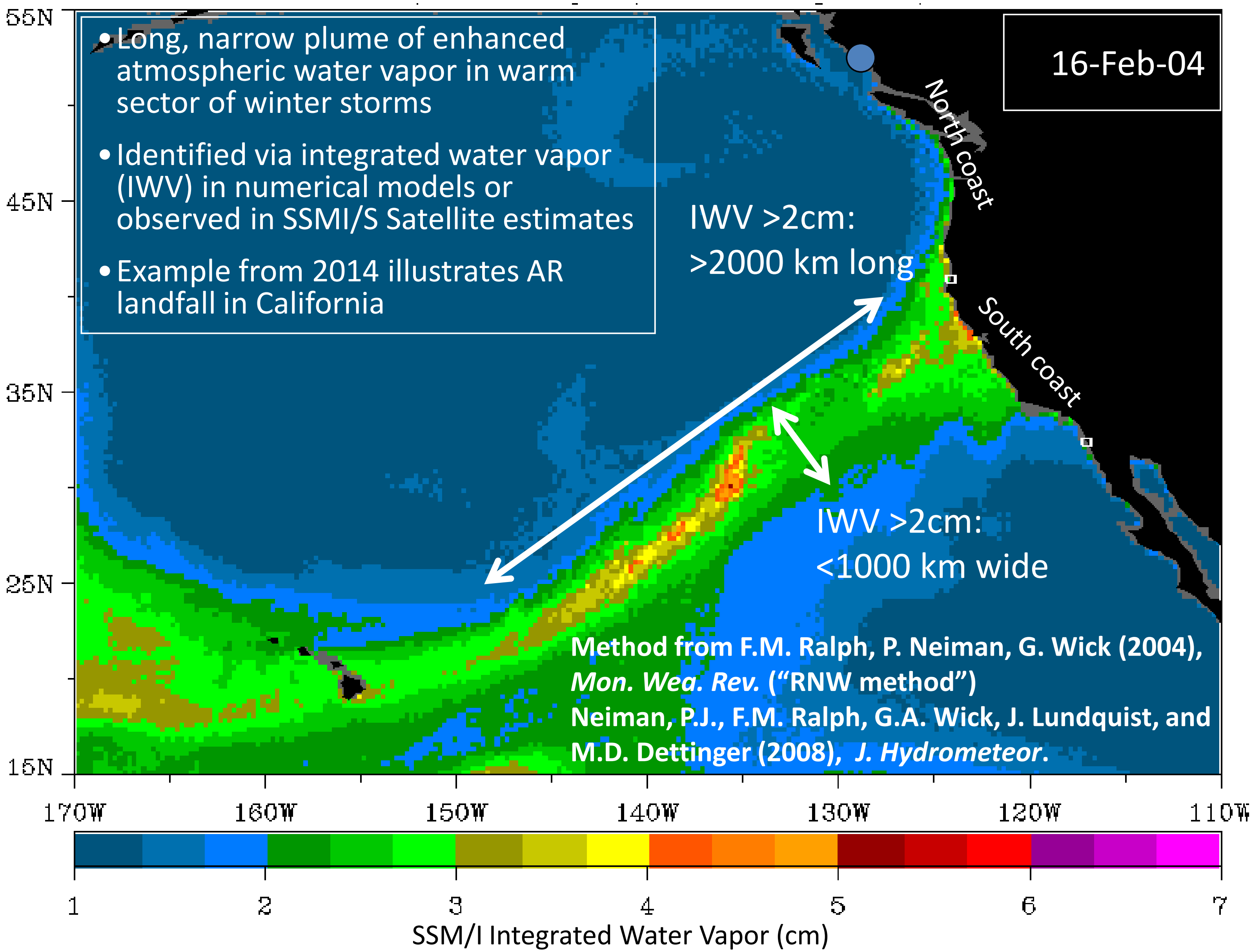
ARs can CAUSE FLOODS and PROVIDE WATER SUPPLY

Atmospheric Rivers, Floods and the Water Resources of California

Mike Dettinger, M. Ralph, , T. Das, P. Neiman, D. Cayan *(Water, 2011*)



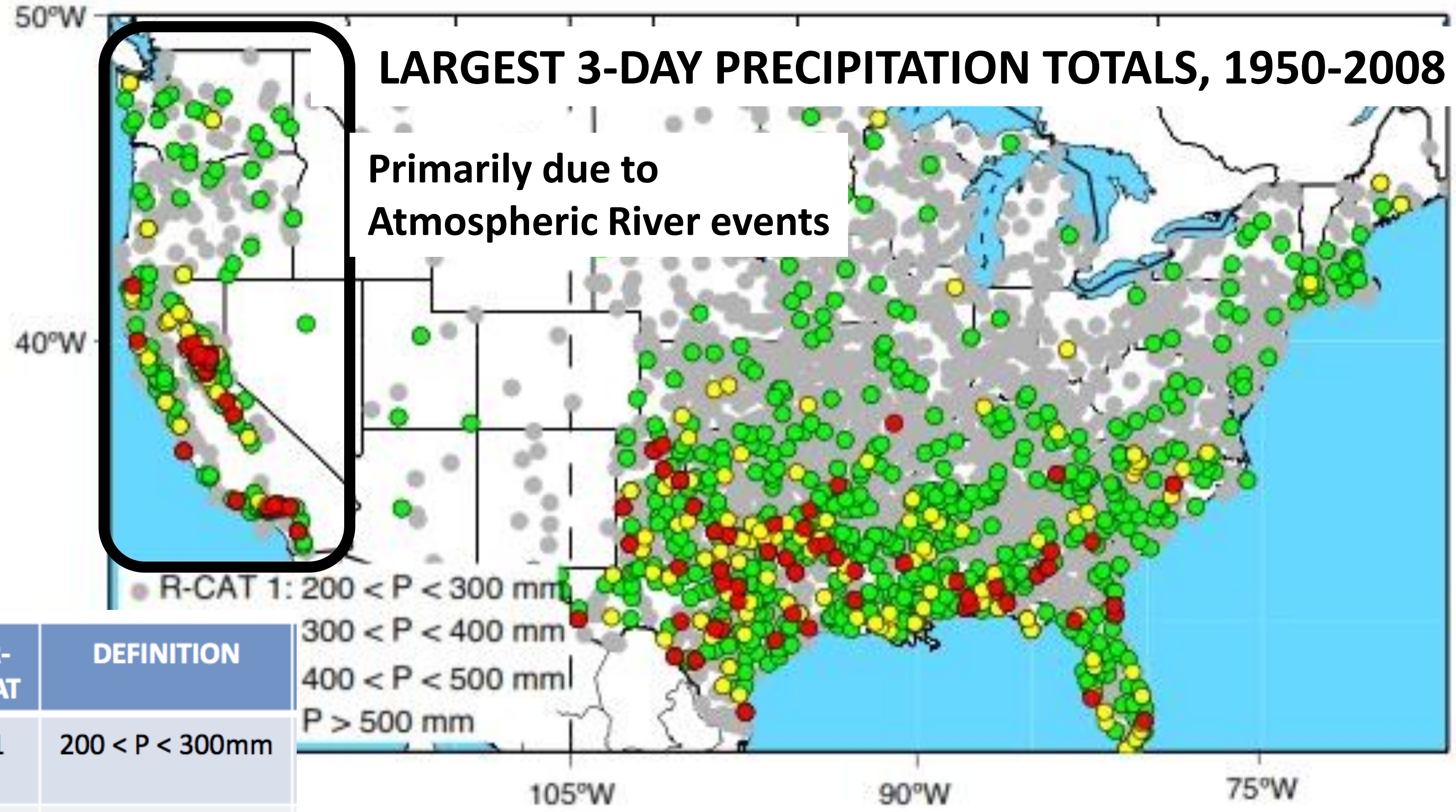
First Multi-year Catalog of AR Events Created: Used RNW 2004 Method & Satellite IWV Data



- Long, narrow plume of enhanced atmospheric water vapor in warm sector of winter storms
- Identified via integrated water vapor (IWV) in numerical models or observed in SSMI/S Satellite estimates
- Example from 2014 illustrates AR landfall in California

Method from F.M. Ralph, P. Neiman, G. Wick (2004), ***Mon. Wea. Rev.*** **("RNW method")**
Neiman, P.J., F.M. Ralph, G.A. Wick, J. Lundquist, and M.D. Dettinger (2008), ***J. Hydrometeor.***

LARGEST 3-DAY PRECIPITATION TOTALS, 1950-2008



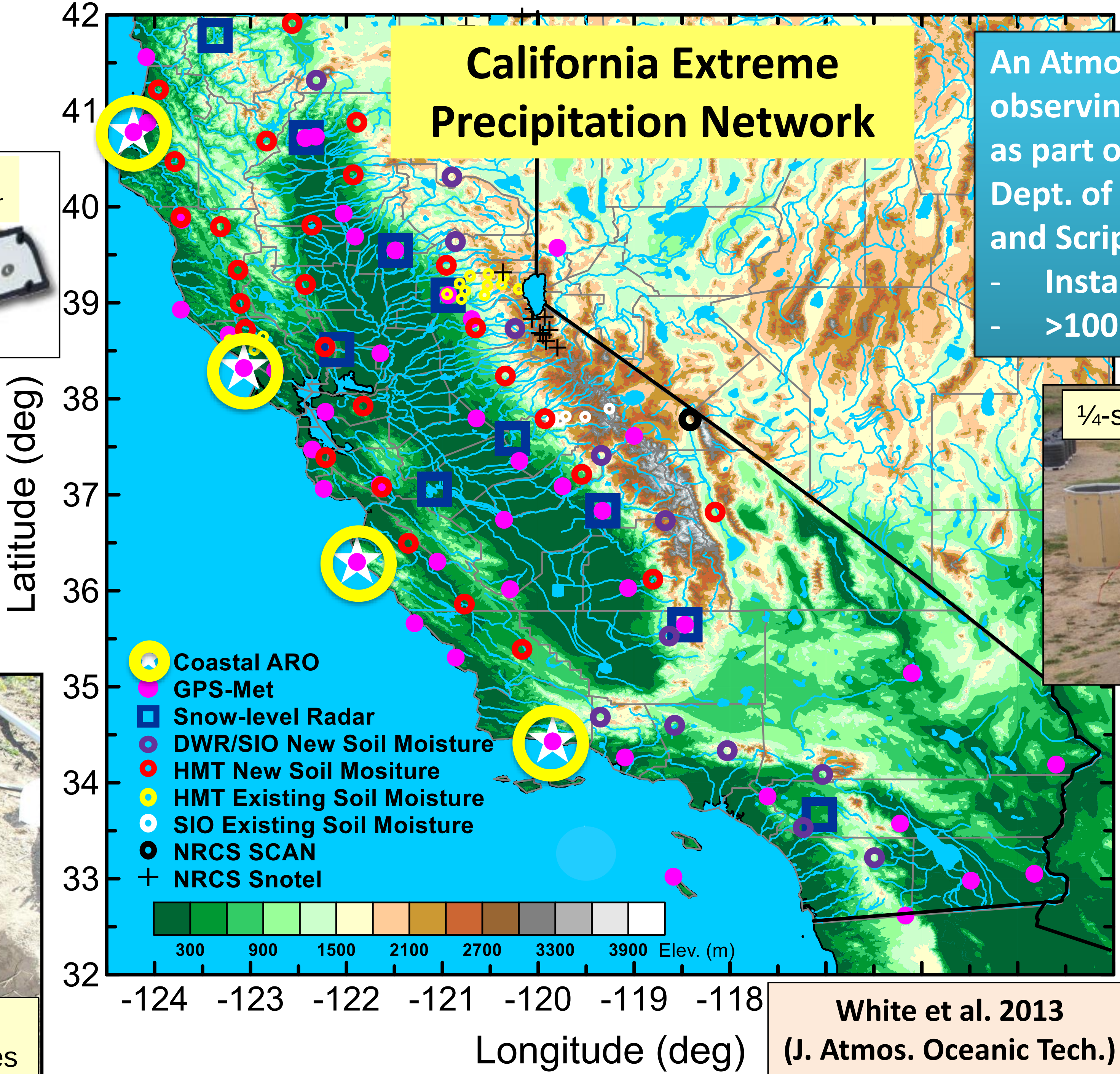
R-CAT	DEFINITION
1	200 < P < 300mm
2	300 < P < 400mm
3	400 < P < 500mm
4	P > 500mm

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)

California Extreme Precipitation 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 2008-2015**
- **>100 field sites**

GPS receiver for integrated water vapor



White et al. 2013
(J. Atmos. Oceanic Tech.)

Soil Moisture and Temperature Probes

¼-scale 449-MHz wind profiler with RASS

FM-CW snow-level radar

ARkStorm: An emergency preparedness scenario for California

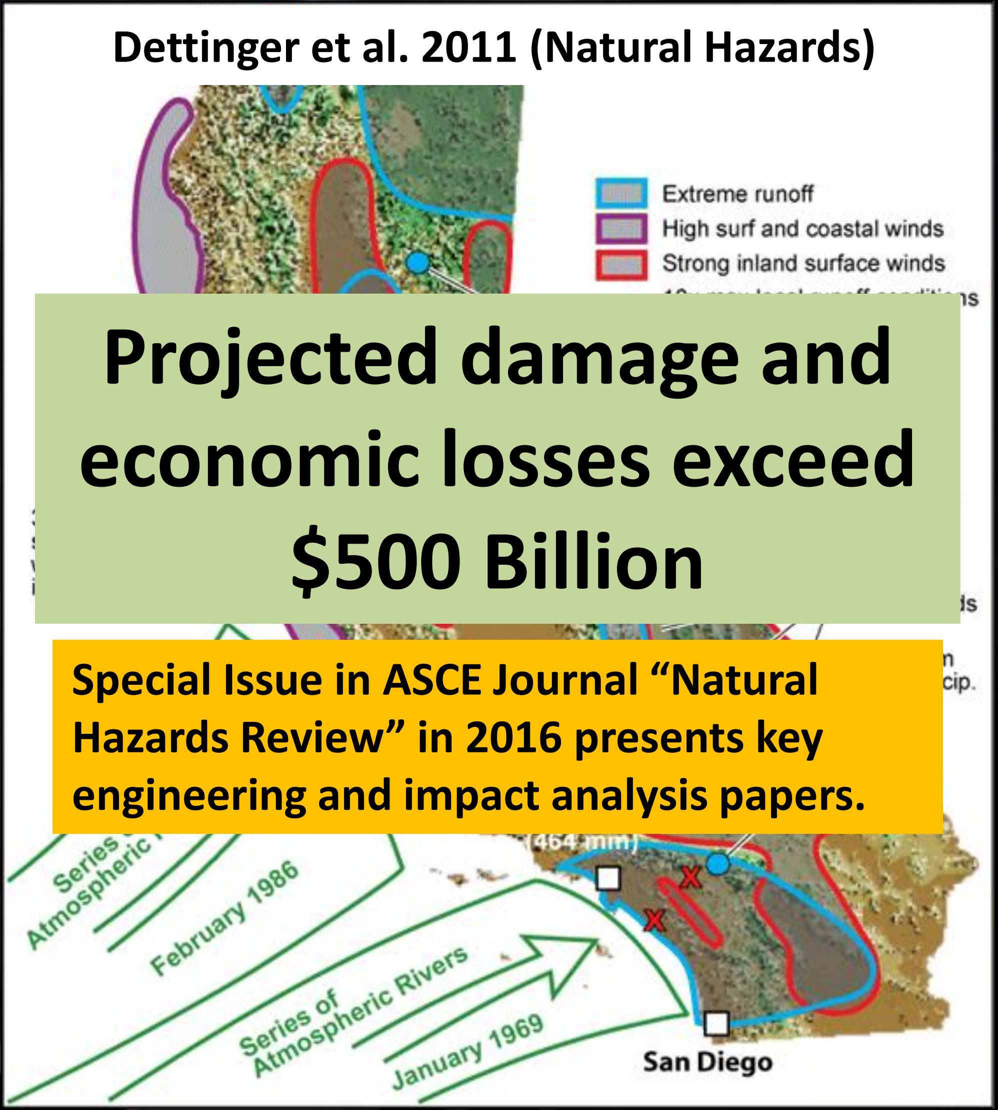
USGS organized a large team of experts.

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.

Dale Cox (USGS) – ARkStorm lead

Dettinger et al. 2011 (Natural Hazards)

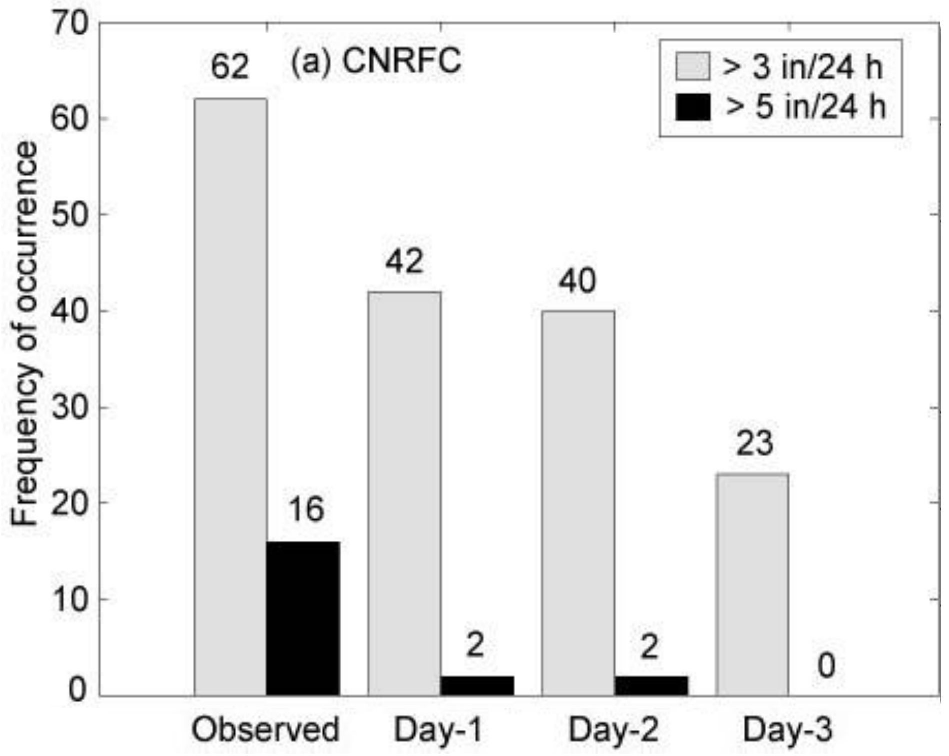


Projected damage and economic losses exceed $500 Billion

Special Issue in ASCE Journal "Natural Hazards Review" in 2016 presents key engineering and impact analysis papers.

The Forecasting Challenge

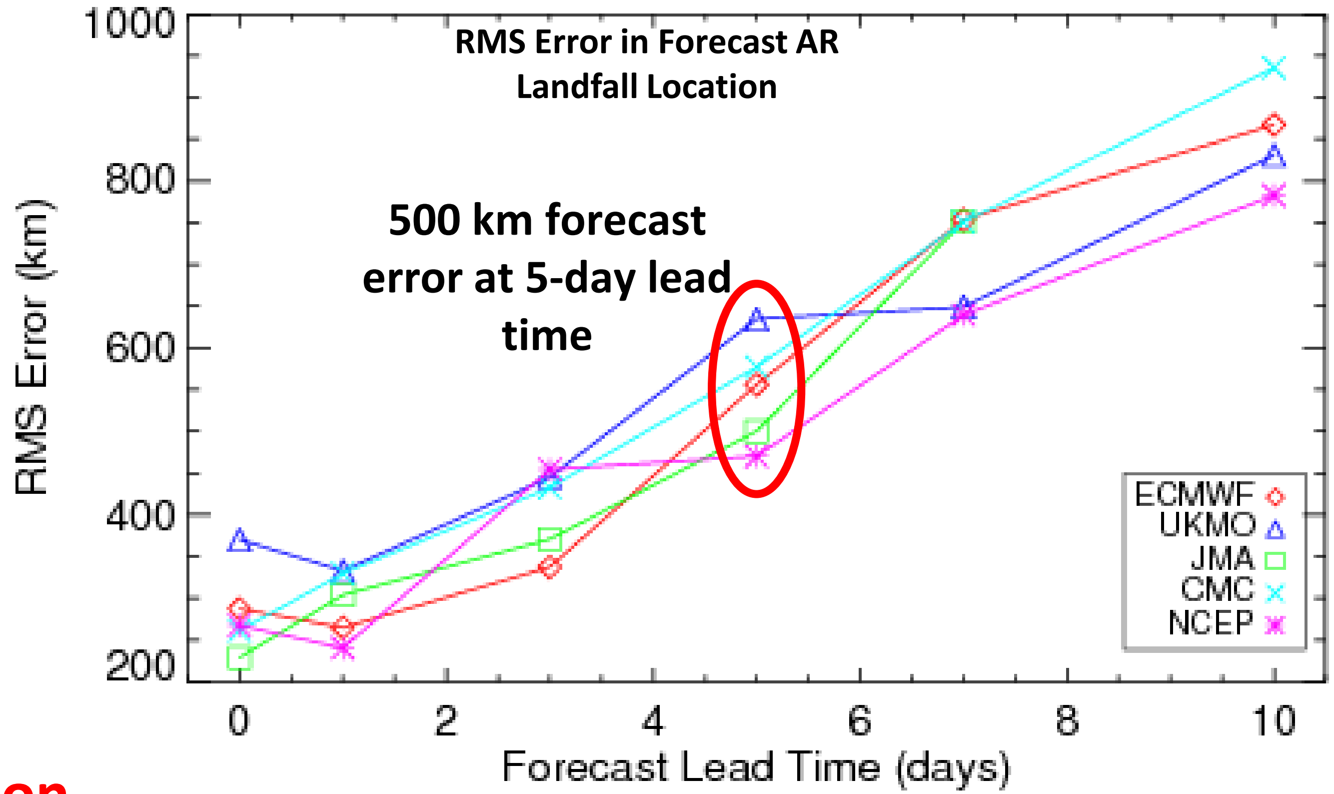
Forecasting large precipitation amounts is difficult



Of the 20 dates with >3 inches of precipitation in 1 day, 18 were associated with ARs.

Ralph et al. 2010

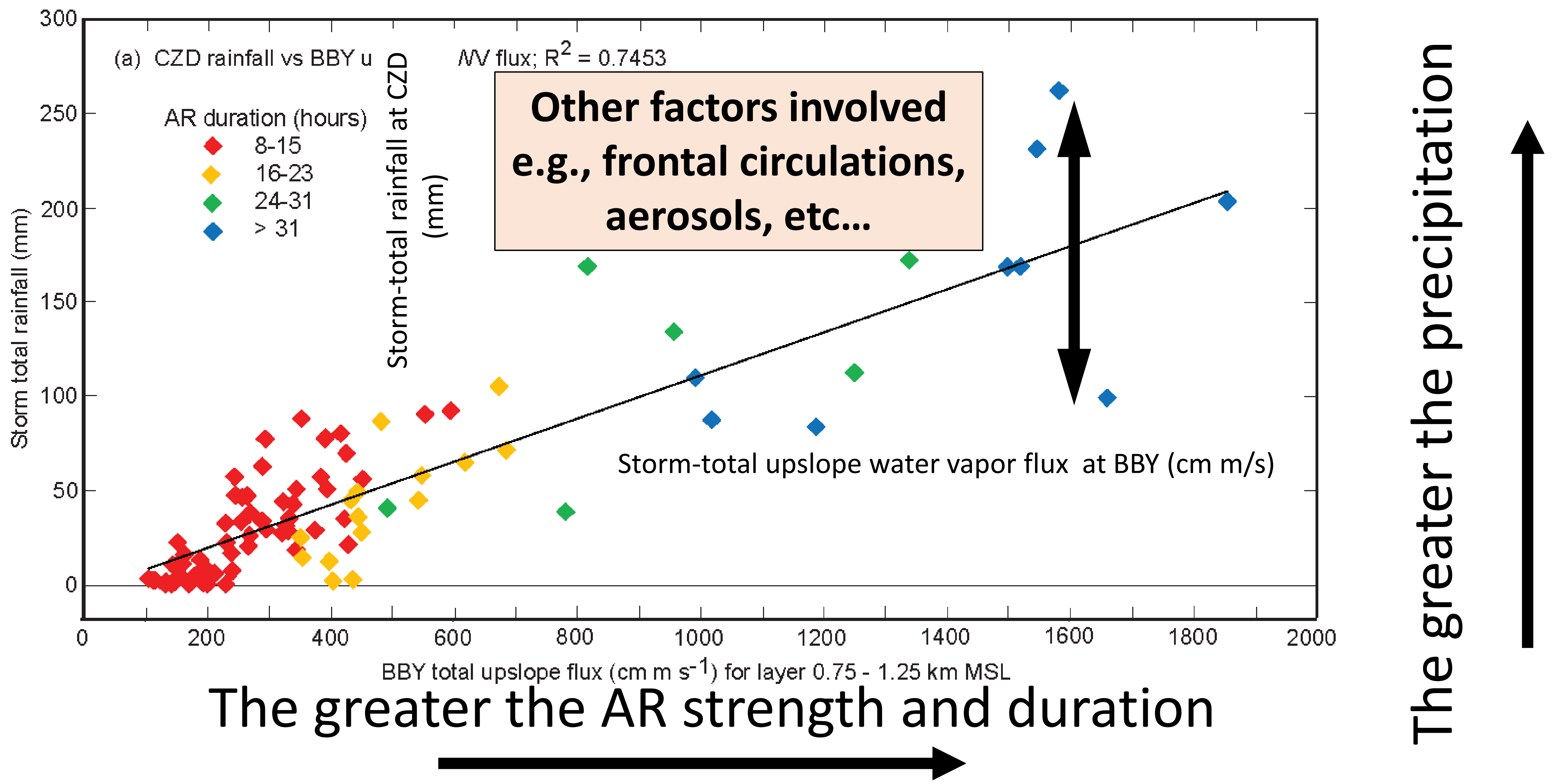
Forecasting AR landfall includes position errors larger than watersheds



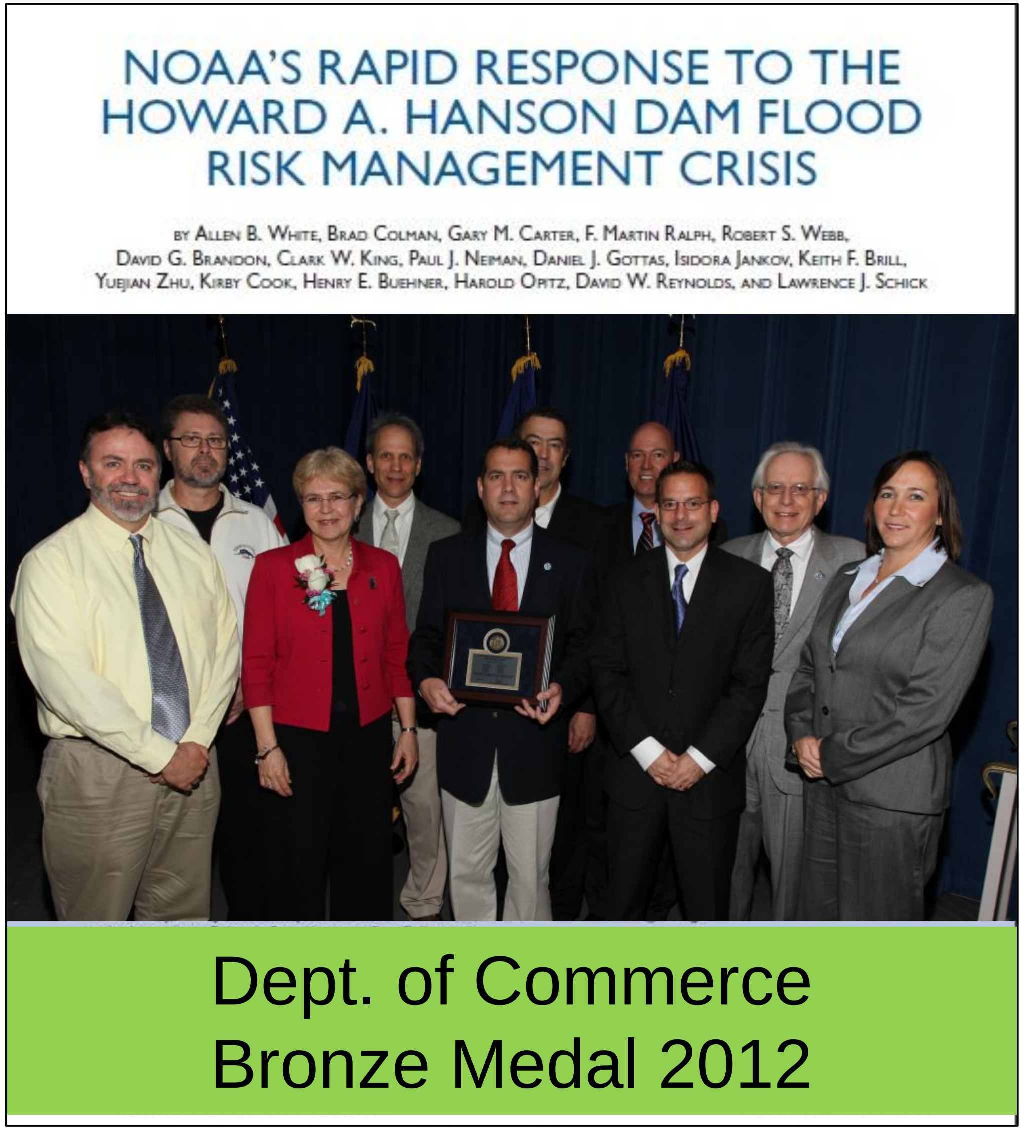
Wick et al. 2013

Observed impacts of duration and seasonality of atmospheric-river landfalls on soil moisture and runoff in coastal northern California

Ralph, F. M., T. Coleman, P.J. Neiman, R. Zamora, and M.D. Dettinger, J. Hydrometeorology, 2013

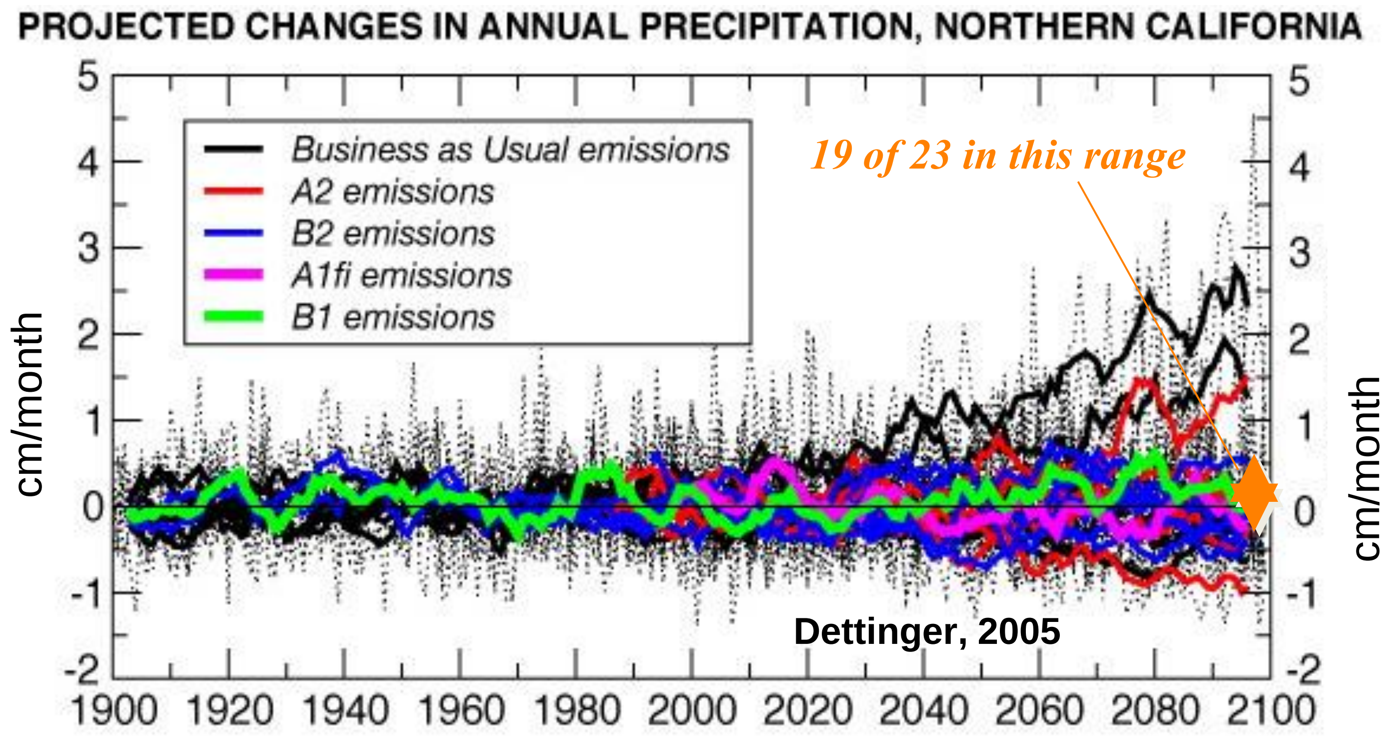


Atmospheric River concepts and tools developed in California were key components of NOAA's rapid response to the Howard Hanson Dam flood risk crisis that affected the Seattle area from 2009-2012



- As research showed predictability in the medium range lead times, NWS' Hydromet Prediction Center extended the lead time of their QPF an additional 2 days, i.e., added days 6 and 7 for the first time. This started in the West, and then became national.
- 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.
- Case study and statistics on forecaster use of AR data are presented in White et al. 2012 (Bulletin of the American Meteorological Society).

A Key Challenge: Changing Climate



Annual precipitation projections vary mostly due to how extreme precipitation events are handled (in CA this means ARs).

Pierce et al 2013 (J. Clim.): Model disagreements in the projected change in occurrence of the heaviest precipitation days (>60 mm day^{-1}) account for the majority of disagreement in the projected change in annual precipitation, and occur preferentially over the Sierra Nevada and Northern California.

CalWater Field Studies Designed to Quantify the Roles of Atmospheric Rivers and Aerosols in Modulating U.S. West Coast Precipitation in a Changing Climate

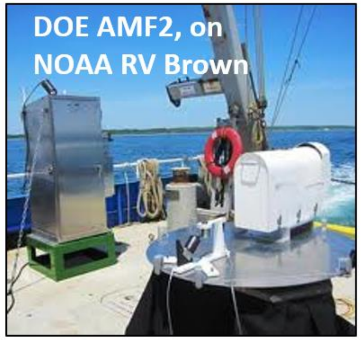
Ralph F.M., K. A. Prather, D. Cayan, J.R. Spackman, P. DeMott, M. Dettinger, C. Fairall, R. Leung, D. Rosenfeld, S. Rutledge, D. Waliser, A. B. White, J. Cordeira, A. Martin, J. Helly, and J. Intrieri, 2016, ***Bull. Amer. Meteor. Soc.***

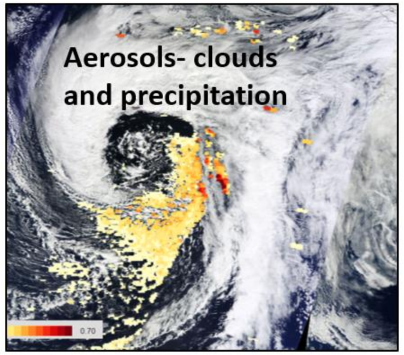
"CalWater – 2015" Field Experiment on Atmospheric Rivers & Aerosols

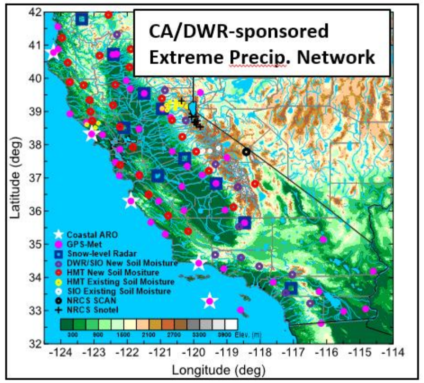
Steering Committee
Co-Chairs: F.M. Ralph
K. Prather, D. Cayan of USCD
+ NOAA, DOE, USGS, NASA
and other Univ. members

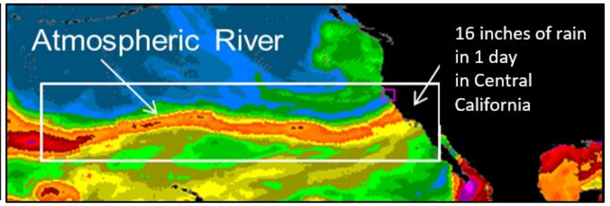
Atmospheric Sci., Chemistry, Hydrology, Oceanography

Ralph et al. 2016
Bull. Amer. Meteor. Soc.









Field seasons

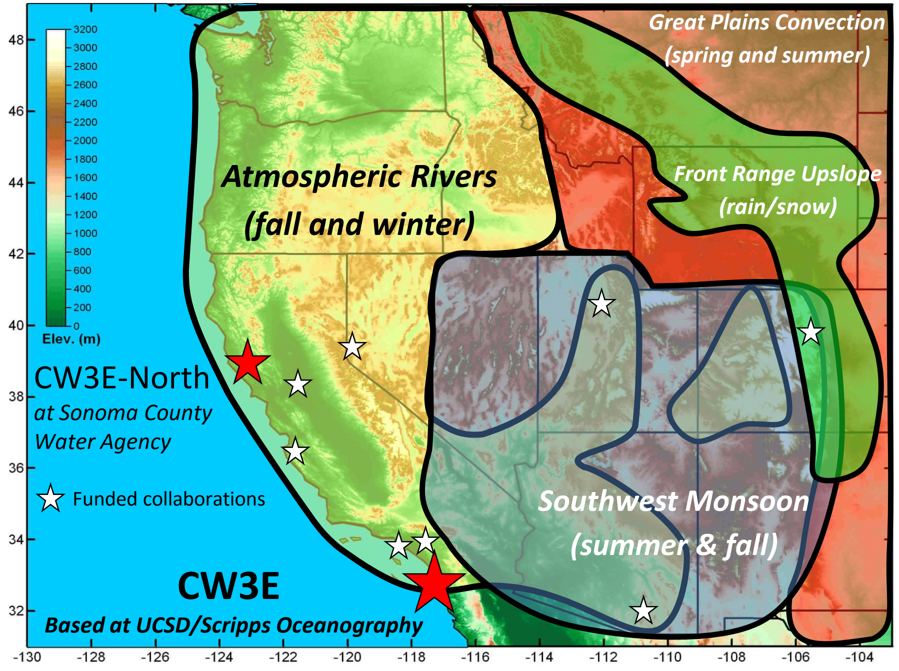
CalWater-1: 2009-2011
CalWater-2: 2014-2016

Locations

California
Eastern Pacific Ocean

Sponsors

DOE, NOAA
California Energy Commission
California Dept. of Water Resources
NSF, NASA, ONR



Key Phenomena Causing Extreme Precipitation in the Western U.S. (Ralph et al. 2014)

Center for Western Weather and Water Extremes

SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

Director: F. Martin Ralph, Ph.D. **Website: cw3e.ucsd.edu**

Strategies: Observations, physical processes, modeling, decision support

Scope: A group of roughly 25 people with 10 major projects

Partners: California DWR, Sonoma County Water Agency, CNAP, USGS San Diego Supercomputing Center

Sponsors: CA DWR, USACE/ERDC, NOAA, SCWA, NASA, USBR

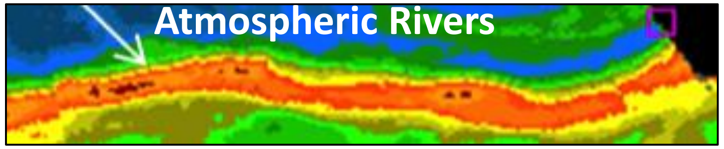
Mission

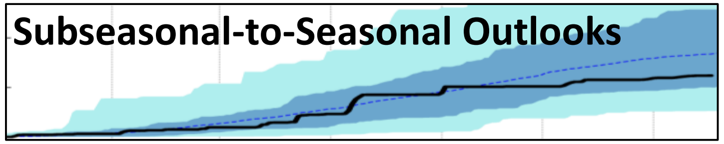
Provide 21st Century water cycle science, technology and outreach to support effective policies and practices that address the impacts of extreme weather and water events on the environment, people and the economy of Western North America

Goal

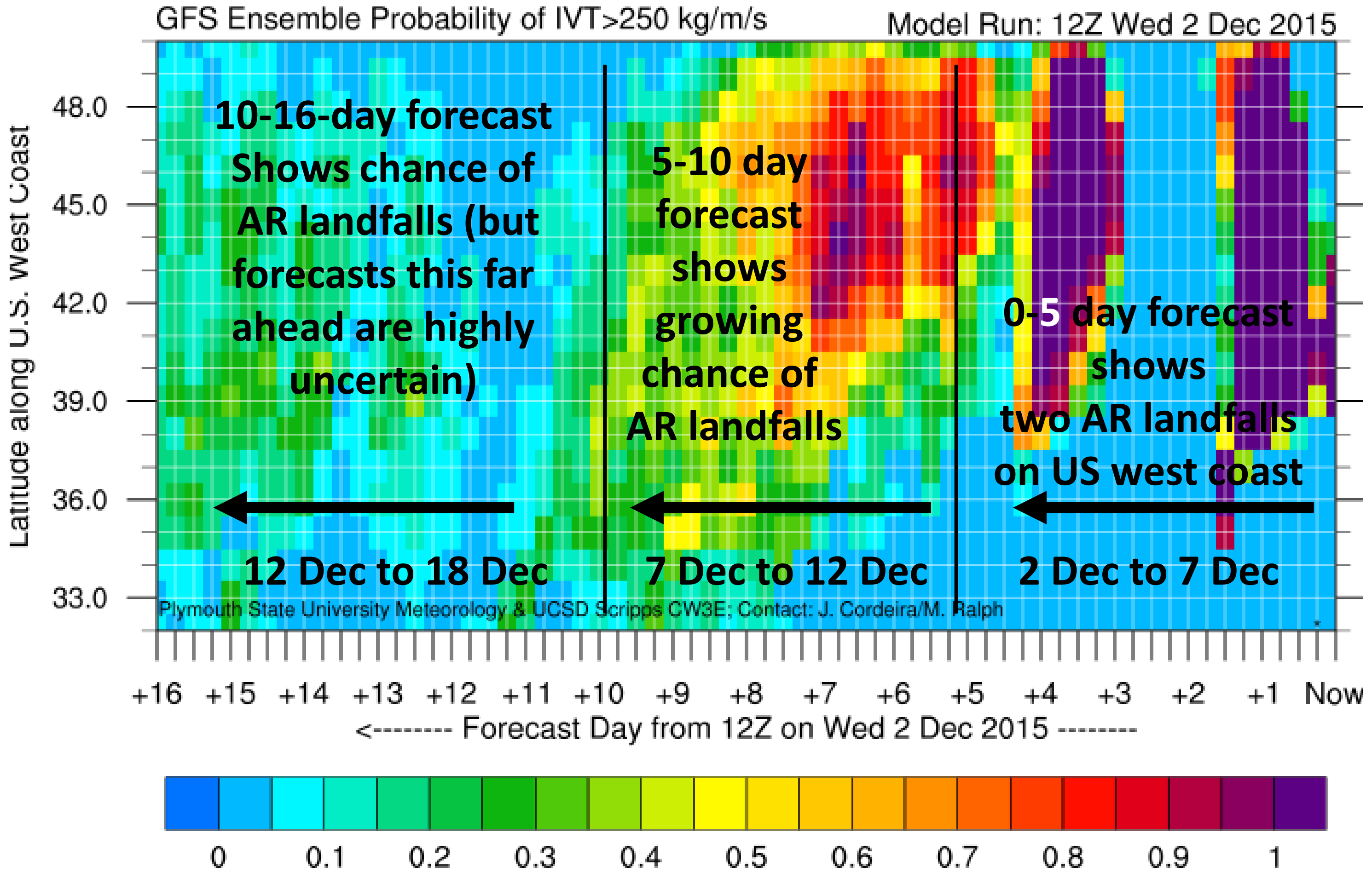
Revolutionize the physical understanding, observations, weather predictions and climate projections of extreme events in Western North America, including atmospheric rivers and the North American summer monsoon as well as their impacts on floods, droughts, hydropower, ecosystems and the economy

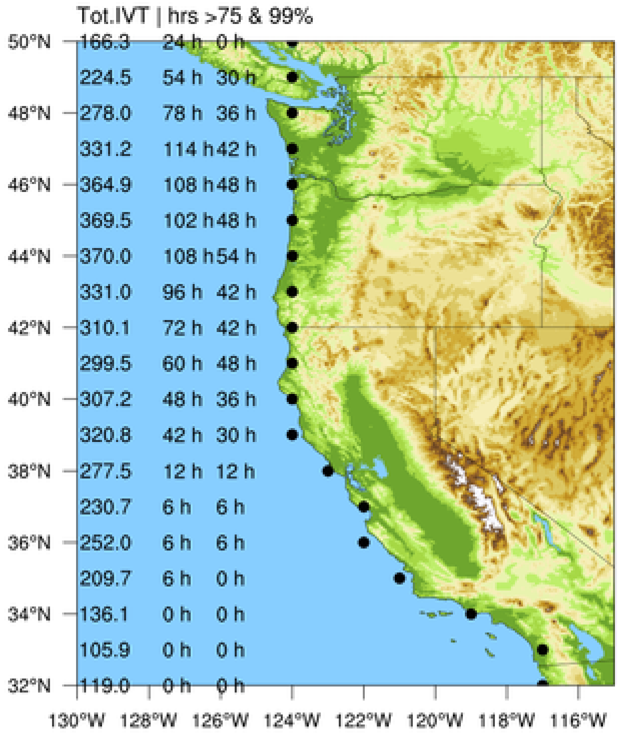
CW3E's Core Efforts





Forecast chances of landfall of at least WEAK Atmospheric River conditions on the U.S. West Coast from 2-18 Dec 2015 - updates available at cw3e.ucsd.edu *(Cordeira et al. BAMS 2016, in press)*





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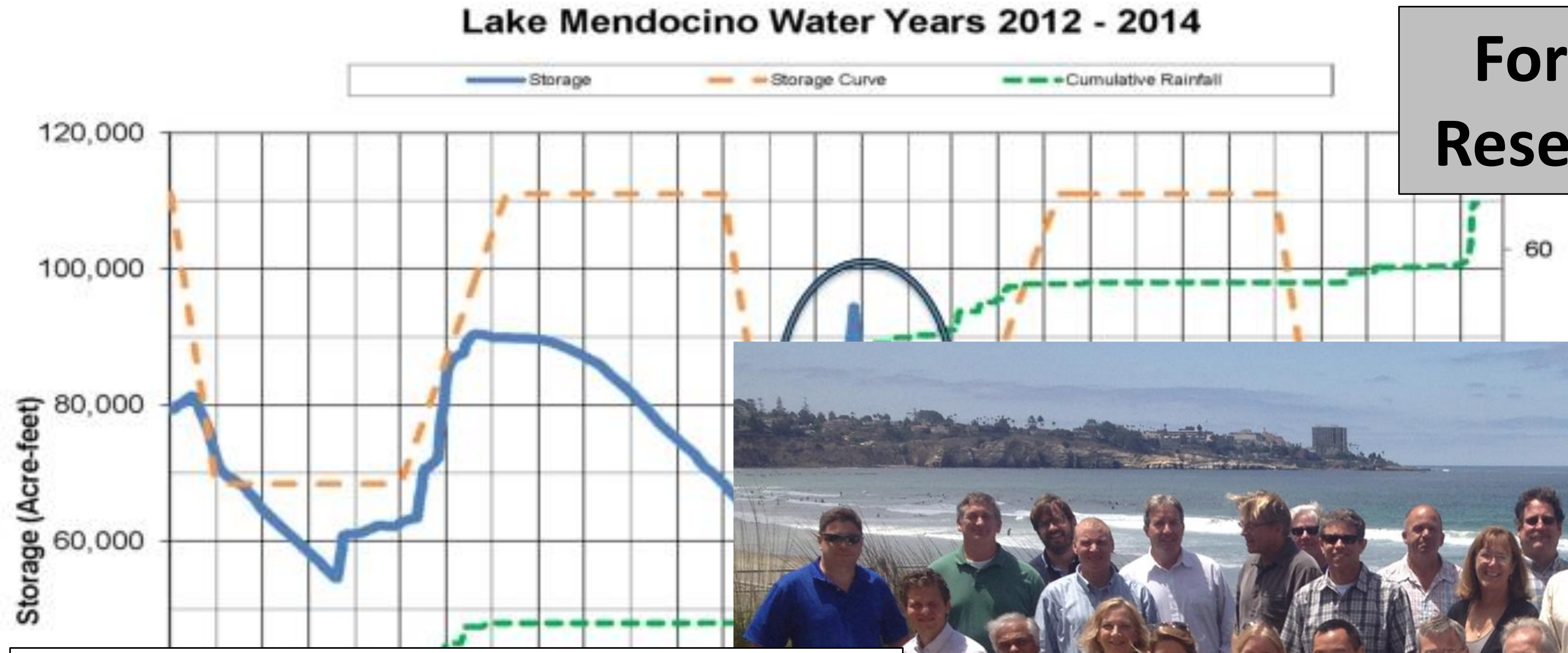
PLYMOUTH STATE METEOROLOGY

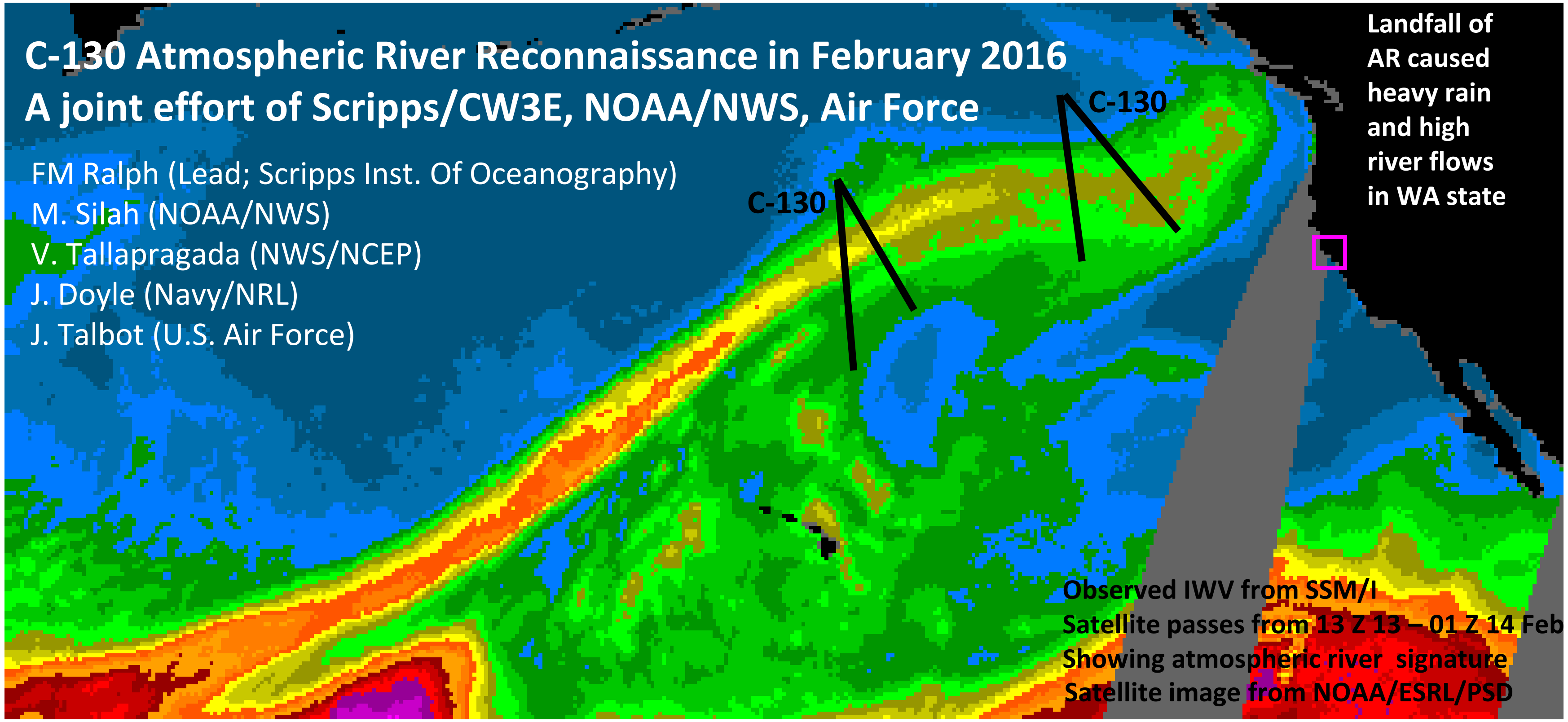
What does this diagram show? The main diagram (left display) is read from *right* to *left* at a given latitude in order to indicate how many days from today AR conditions are likely at the coast. By plotting the display from *right* to *left*, the display shows you "what is in the pipeline" as storm systems generally move from west to east. This diagram shows the chances (i.e., probability) of having at least weak "atmospheric river" conditions (i.e., strong horizontal water vapor transport, called "IVT" exceeding 250 kg/m/s) at different latitudes along the U.S. West Coast from "today" through the next 16 days at 6-hour increments. It uses a threshold of IVT>250 kg/m/s as the threshold for AR conditions based on years of study. The landfall locations are the black dots in the right-most panel. The probability is based on 21 different forecasts run simultaneously with slightly different starting conditions (which simulates the "butterfly effect"). The forecasts are from the NOAA/NWS' "GFS" global weather forecast model. The probability is shaded on a scale from 0% (blue) to 100% (purple). The landfall locations are the black dots in the right-most panel. The right map-panel shows the total 16-day time-integrated IVT (Tot.IVT) for that location in millions of kg/m (left column of numbers). The diagram also shows the number of hours a location along the coast may expect to see AR conditions along with uncertainty. These hours are drawn in the region next to the U.S. West Coast in the right-most panel. These numbers represent the number of hours (over the next 16 days) a location has a 75% chance of AR conditions (middle column of numbers) or a 99% chance of AR conditions (right column of numbers). The higher this number, the longer AR conditions are likely and the more precipitation may be expected!

Forecast-Informed Reservoir Operations



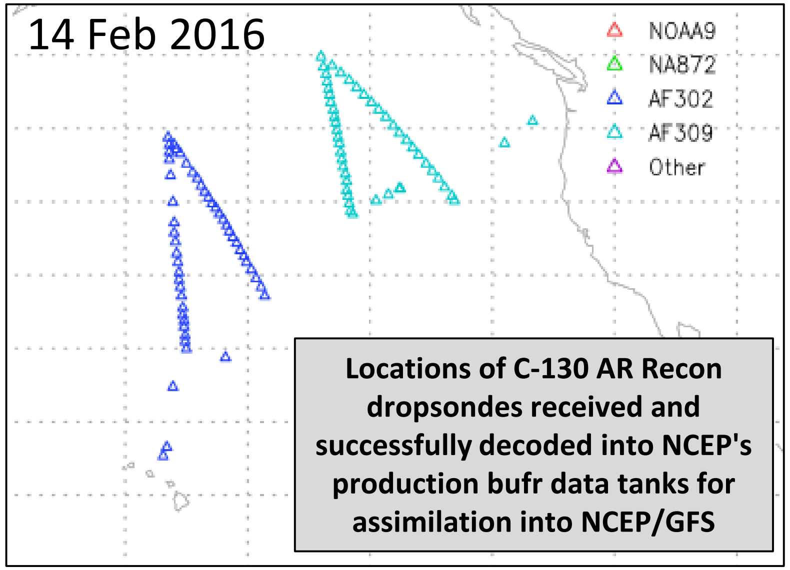
<u>FIRO Steering Committee</u>

Sonoma County Water Agency
Scripps CW3E
U.S. Army Corps of Engineers
CA Dept. of Water Resources
NOAA, USGS, US BurRec
Meteorologists, climatologists, hydrologists
Civil Engineers, biologists, economists



1st C-130 AR Recon Mission 13-14 Feb 2016

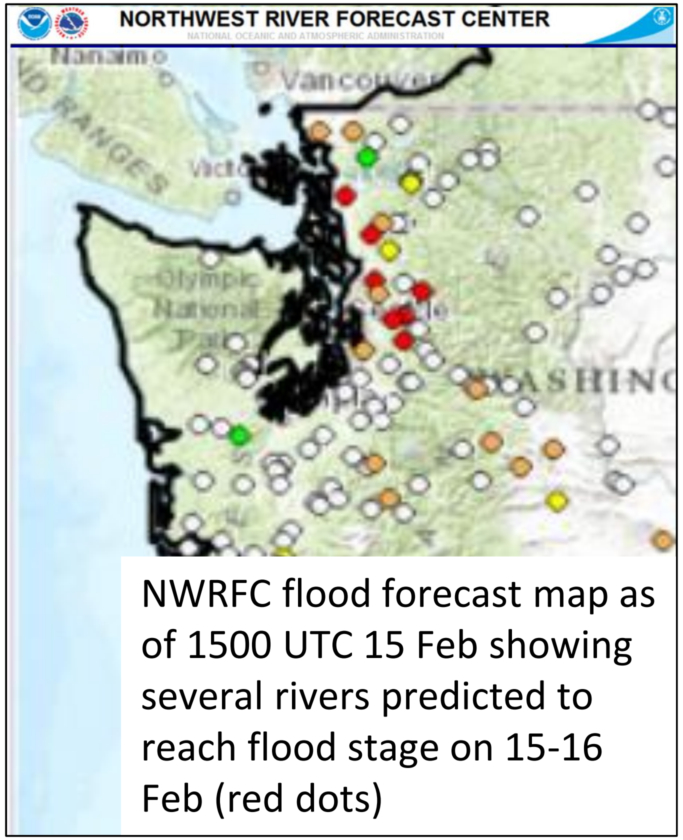
Dropsondes released for the 0000 UTC 14 Feb 2016 GFS data assimilation window



Locations of C-130 AR Recon dropsondes received and successfully decoded into NCEP's production bufr data tanks for assimilation into NCEP/GFS

Air Force C-130 Aircraft – Weather Recon' Squadron

Center for Western Weather and Water Extremes



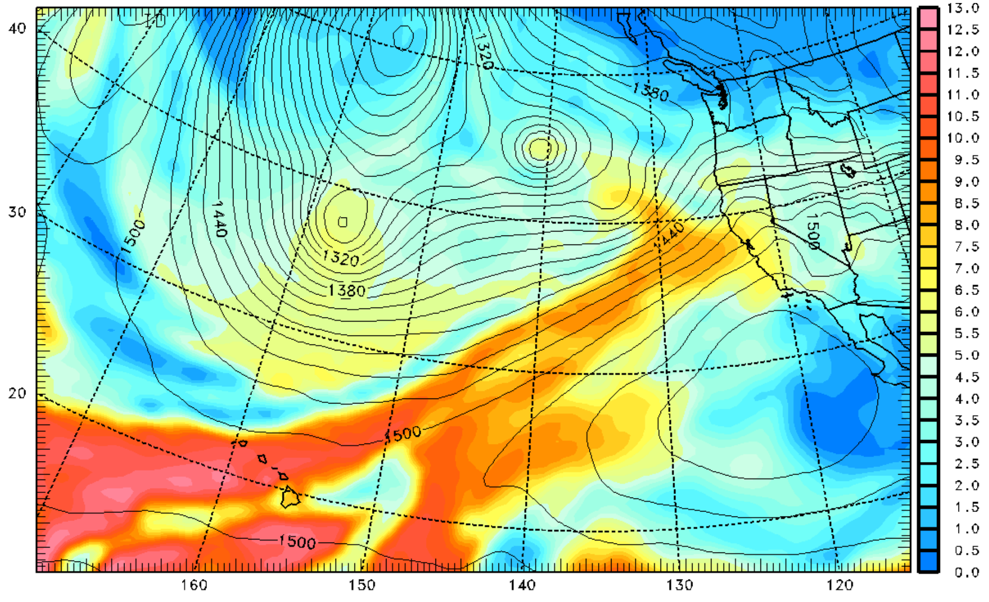
NWRFC flood forecast map as of 1500 UTC 15 Feb showing several rivers predicted to reach flood stage on 15-16 Feb (red dots)

Nested Adjoint Sensitivity

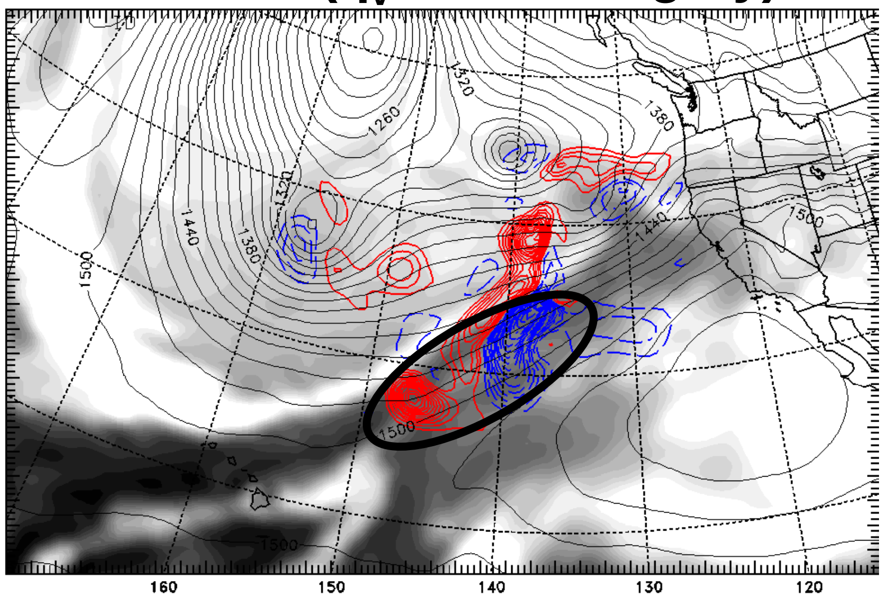
Jim Doyle - NRL

36-h Sensitivity (Analysis)
12Z 8 February 2014 (Final Time 00Z 10 February)

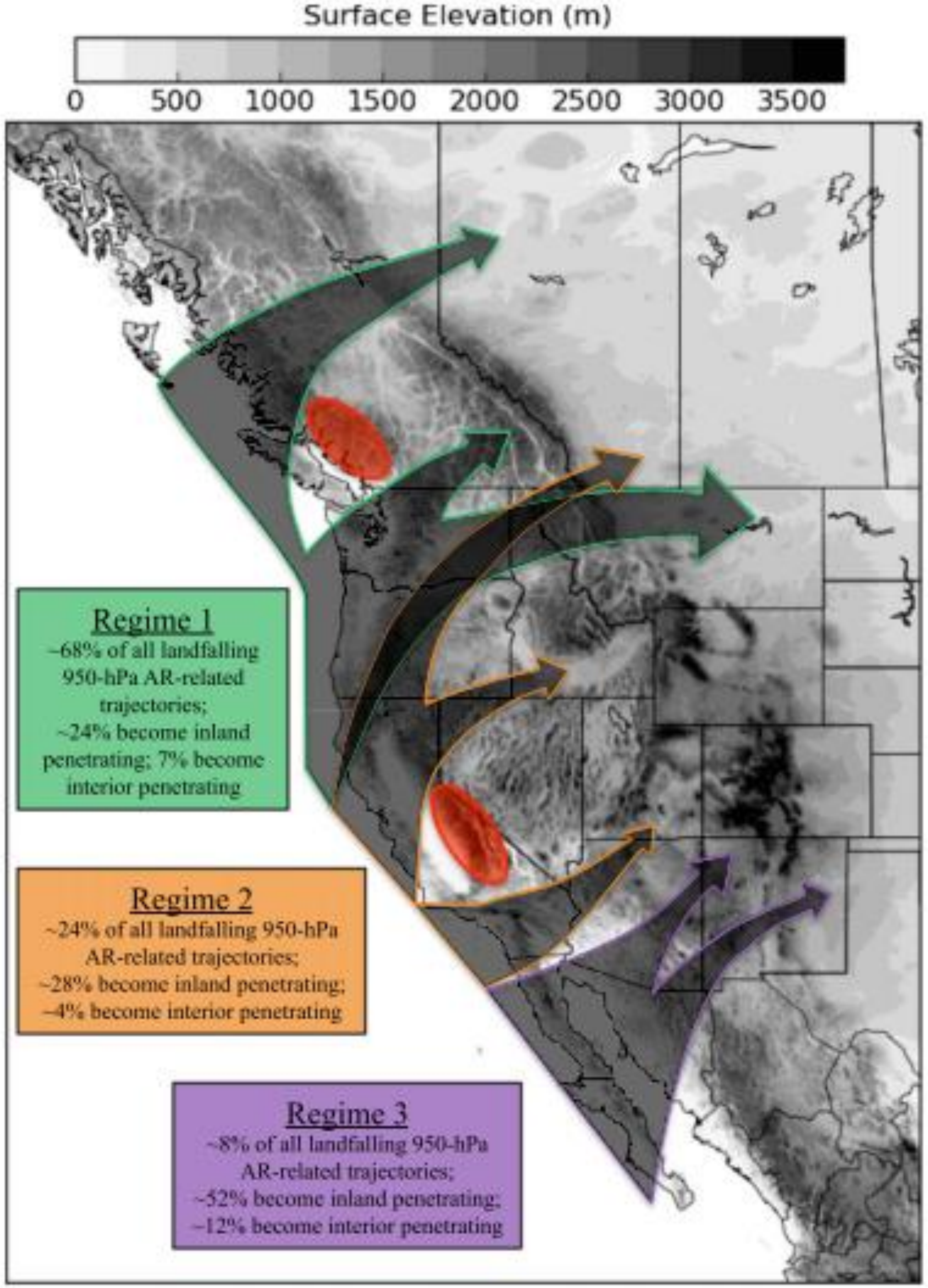
Geopotential Heights and Water Vapor 850 hPa



36-h Water Vapor Sensitivity 850 hPa (q_v shown in gray)



- 36-h forecast sensitivity calculations for 12Z 8 February 2014 case
- Moisture sensitivity is a maximum along the atmospheric river and just to the north of the AR.
- Moisture sensitivity is 2X larger than the temperature and 3X larger than the wind component sensitivity (assume analysis errors are ~1 K, 1 m/s, 1 g/kg)

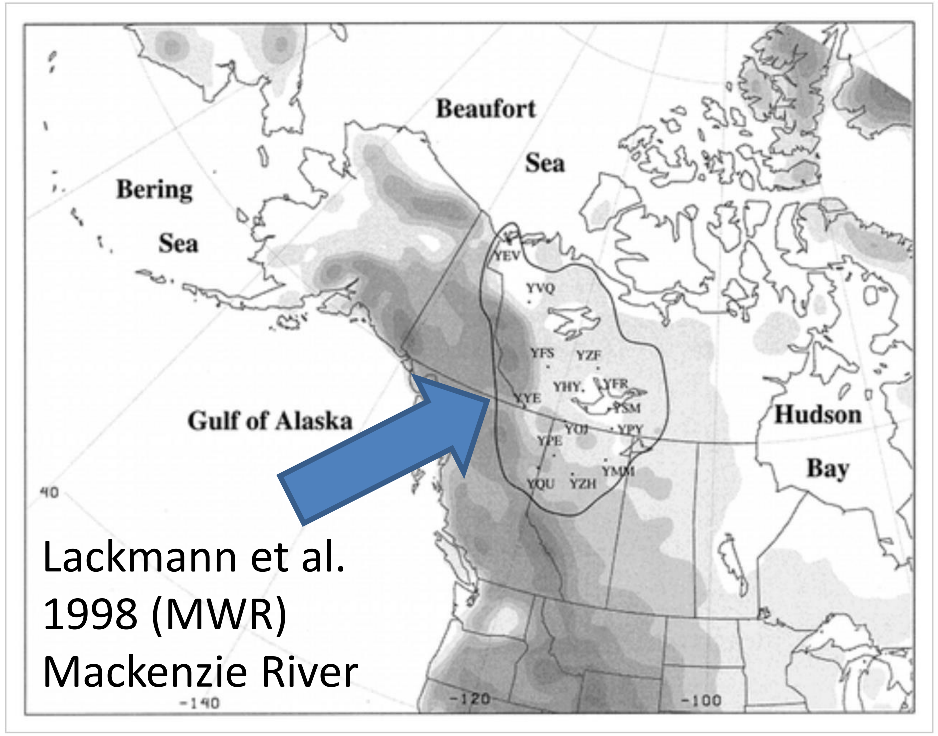


The Inland Penetration of Atmospheric Rivers over Western North America: A Lagrangian Analysis

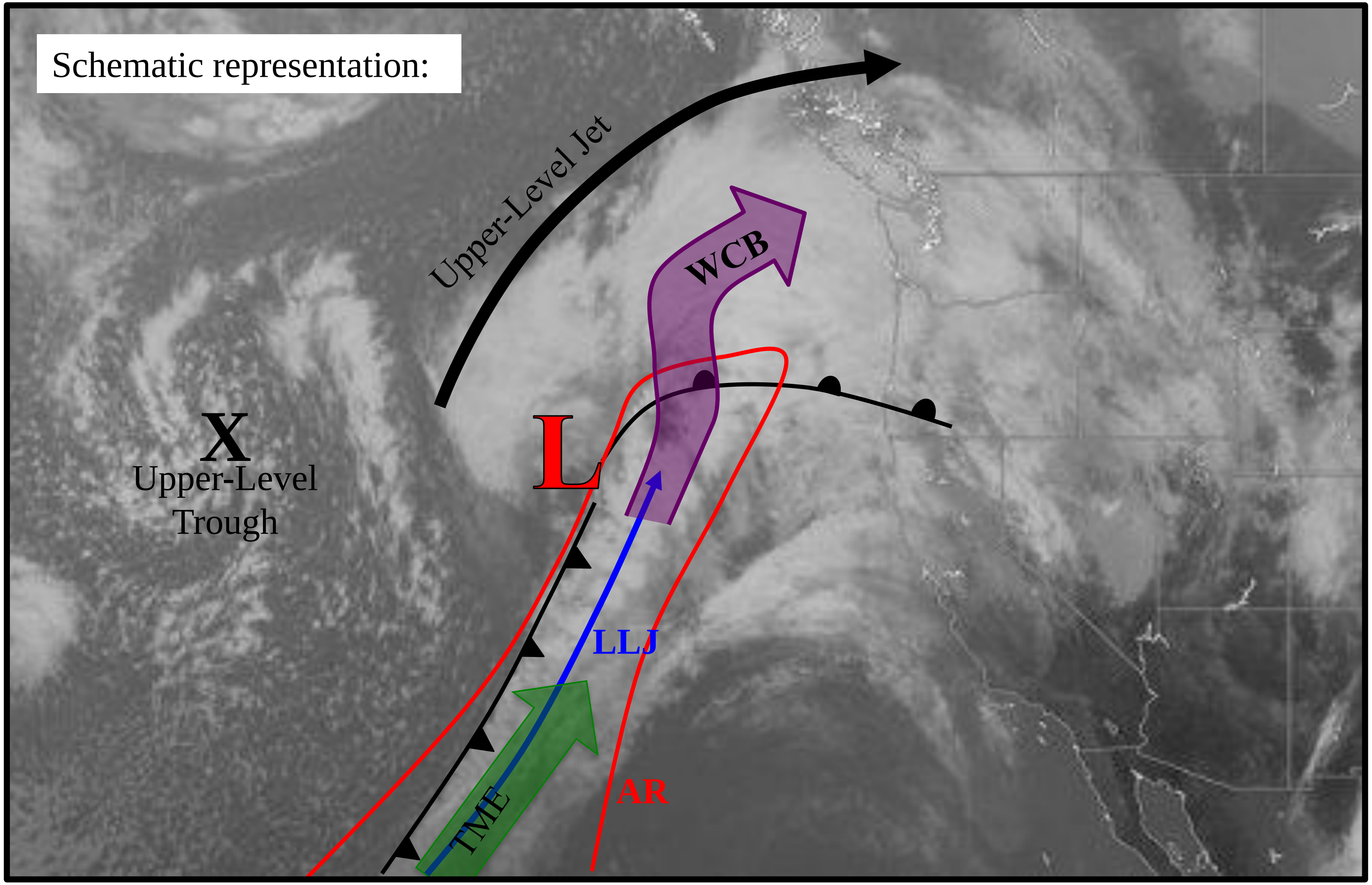
J.J. Rutz, J. W. Steenburgh and F.M. Ralph

Mon. Wea. Rev., 2015

FIG. 16. Schematic showing the primary pathways for the penetration of 950-hPa AR-related trajectories into the interior of western North America. Pathways associated with regimes 1–3 are represented by green, orange, and purple arrows, respectively. Regions associated with frequent AR decay are shaded in red. Topography is shaded in grayscale. Note that while this schematic highlights common regimes and pathways, individual trajectories follow many different paths.



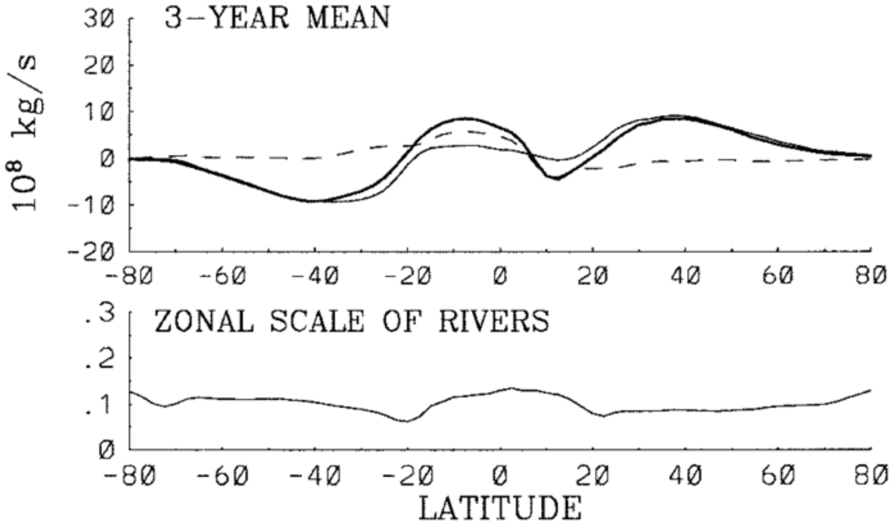
AR Workshop June 2015: Compared TMEs, ARs, the LLJ, and WCBs



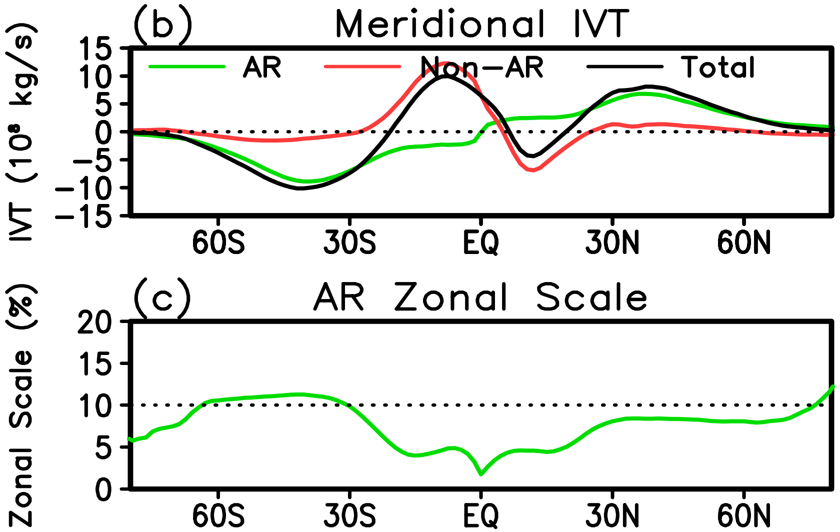
Slide courtesy of J. Cordeira, derived from AR (Cordeira), WCB (Wernli), TME (Sodemann) presentations at the AR Workshop in June 2015

Poleward Water Vapor Transport: Modern tool and global landfall map

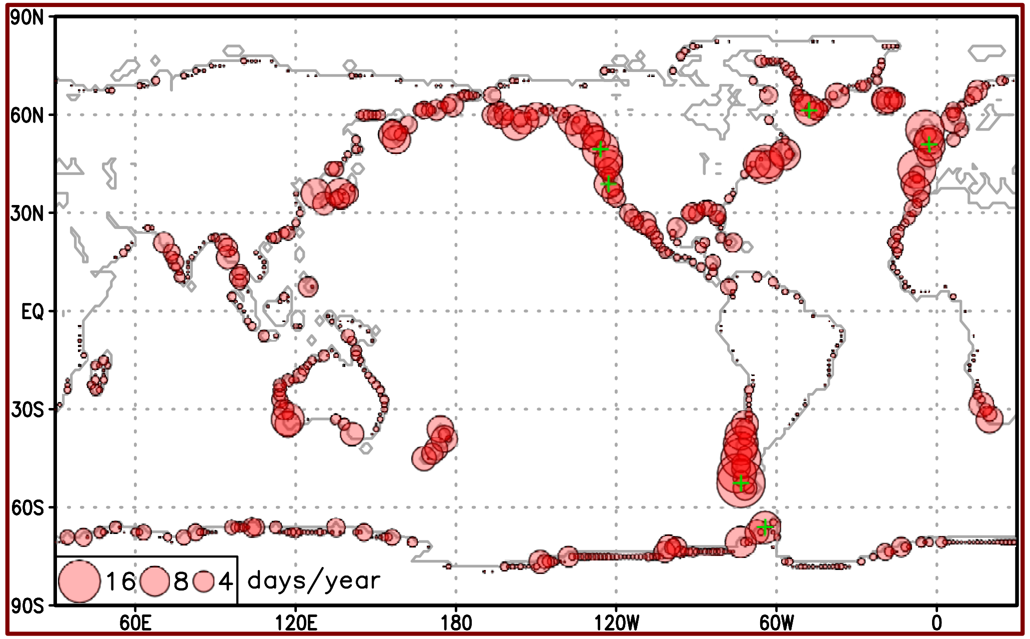
Zhu and Newell (1998)



Guan and Waliser (2015)



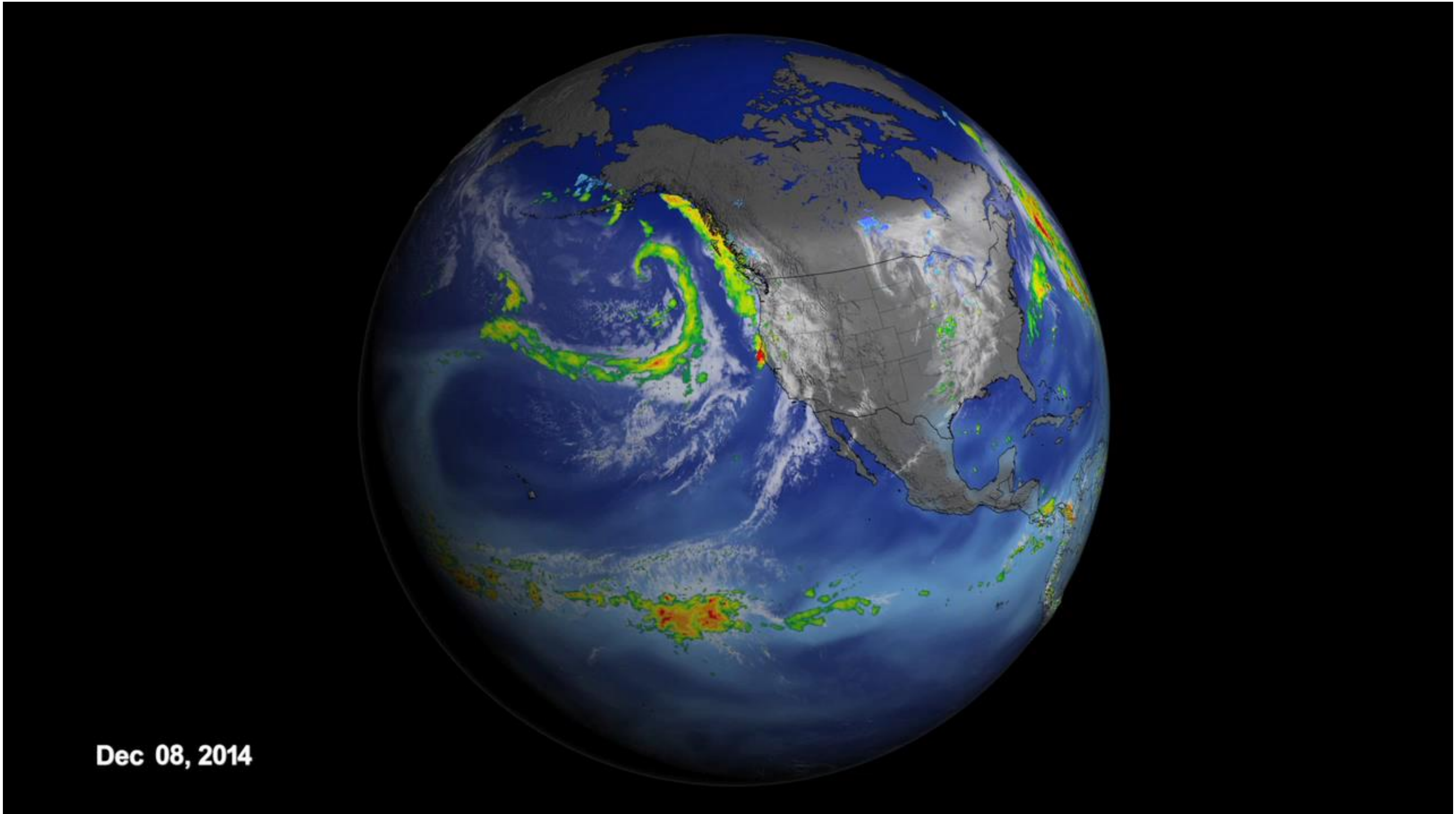
AR fractional poleward IVT and integrated zonal scale using Guan and Waliser (2015) AR detection algorithm applied globally largely consistent with original estimate by Zhu and Newell (1998)



Summary

The emergence of the atmospheric river concept represents an example of the complex and often circuitous route that major new research directions take before maturing and having impact through applications.

The path provides a telling example of the importance of sustained basic research, and of connecting researchers with people in operational or application-oriented roles.


Dec 08, 2014

2016 International Atmospheric Rivers Conference

Scripps Institution of Oceanography - La Jolla, California

8^{th} – 11^{th} August 2016

http://cw3e.ucsd.edu/ARconf2016

Many regions face either drought or flood, or are challenged by regional water management issues. Recent advances in atmospheric sciences and hydrology have identified the key role of atmospheric rivers (AR) in determining the distribution of strong precipitation events in midlatitudes. Combined with related phenomena, warm conveyor belts (WCB) and tropical moisture exports (TME) (Fig. 1), the frequency, position and strength of ARs determines the occurrence of many water extremes. This conference brings together experts across atmospheric, hydrologic, oceanic and polar science, water management and civil engineering to advance the science and explore needs for new information.

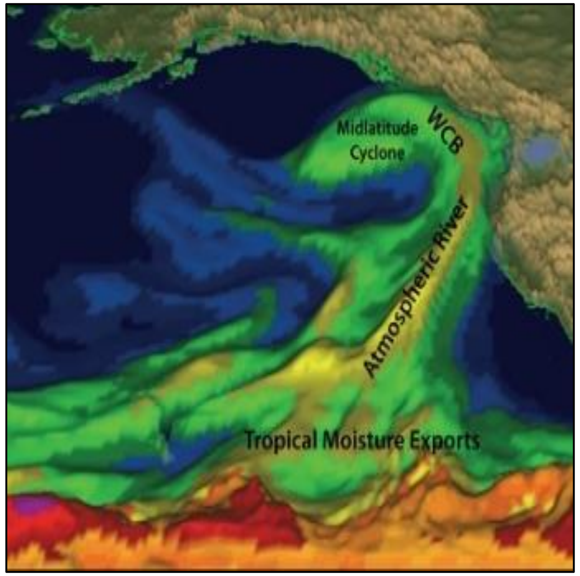


Fig. 1. Depiction of an atmospheric river, interacting with West Coast mountains. Credit: Adapted from NOAA/ESRL Physical Sciences Div. Source: EOS Meeting Report

Center for Western Weather and Water Extremes

Conference Goals

- Evaluate the current state and applications of the science of the mid-latitude atmospheric water cycle, with particular emphasis on ARs and associated processes (e.g., WCB and TME)
- Discuss differing regional perspectives
- Assess current forecasting capabilities
- Plan for future scientific and practical challenges

International organizing committee

Allen White (*NOAA ESRL/PSD; Co-Chair*)
Irina Gorodetskaya (*K.U. Leuven, Belgium; Co-Chair*)
Andrew Martin (*CW3E, Scripps; Co-Chair*)
Maximiliano Viale (*Universidad de Chile; Co-Chair*)
Mike Dettinger (*USGS, CW3E*)
David Lavers (*ECMWF*)
Nina Oakley (*Desert Research Institute*)
F. Martin Ralph (*Scripps Inst. Oceanography/CW3E*)
Jonathan Rutz (*U. S. National Weather Service*)
Ryan Spackman (*Science and Technology Corporation*)
Heini Wernli (*ETH Zurich*)

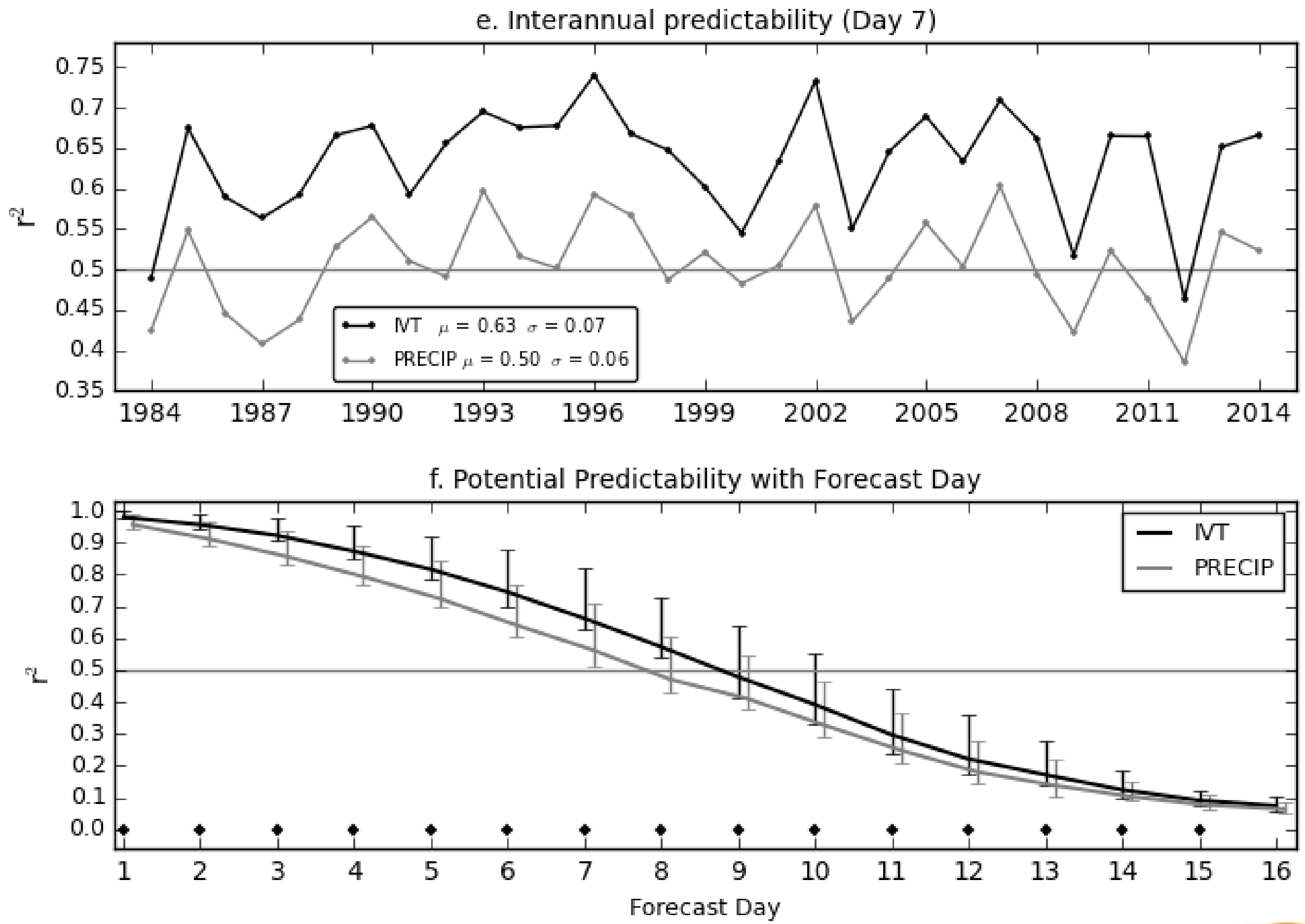
The conference will be held at the beautiful oceanfront venue of the Robert Paine Scripps Forum for Science, Society and the Environment located at the Scripps Inst. of Oceanography, Univ. of CA – San Diego.

Contributions for the 2016 Conference are now invited

For further information or to submit an abstract, please contact:
Mike Dettinger (mddettin@usgs.gov) or
Mary Tyree (mtyree@ucsd.edu)

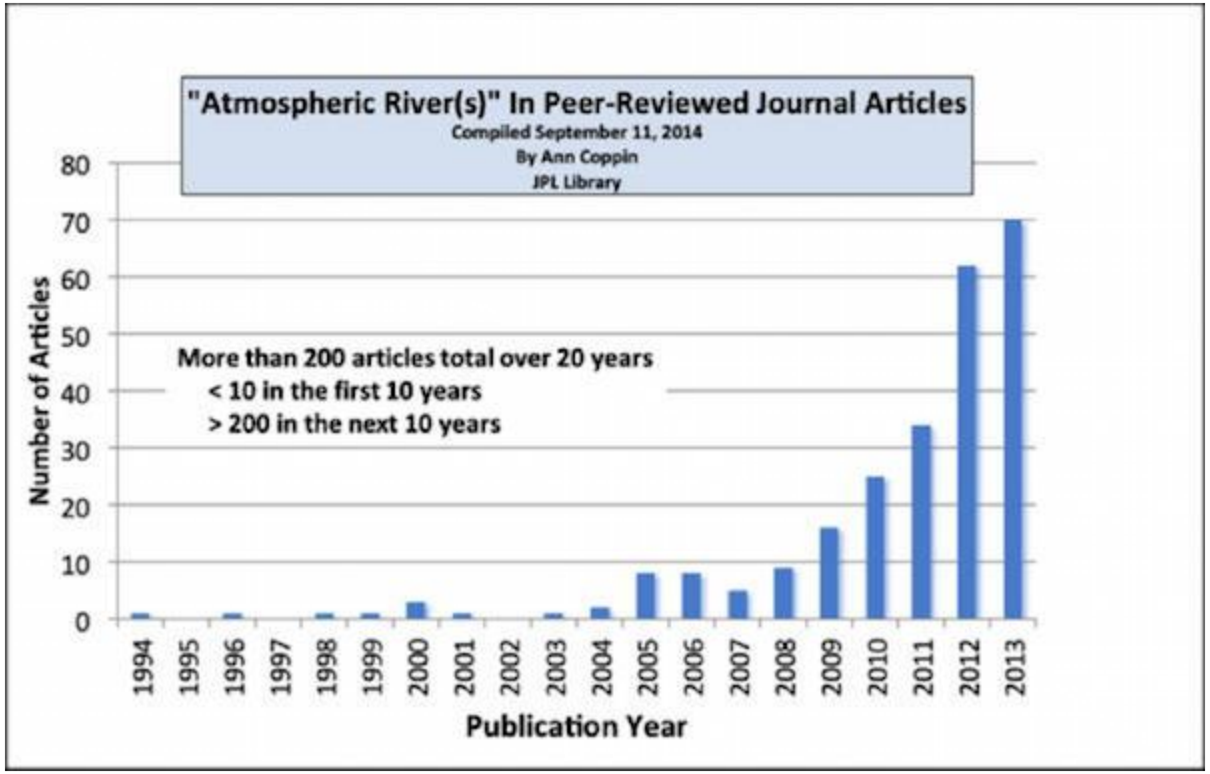
Predictability of horizontal water vapor transport relative to precipitation

Applying the potential predictability concept to the NCEP global ensemble reforecasts, across 31 winters, IVT is found to be more predictable than precipitation.



Courtesy of Lavers, Waliser, Ralph, Dettinger
In preparation Dec. 2015

Center for Western Weather and Water Extremes


"Atmospheric River(s)" In Peer-Reviewed Journal Articles
Compiled September 11, 2014
By Ann Coppin
JPL Library
More than 200 articles total over 20 years
< 10 in the first 10 years
> 200 in the next 10 years
Number of Articles
Publication Year
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10
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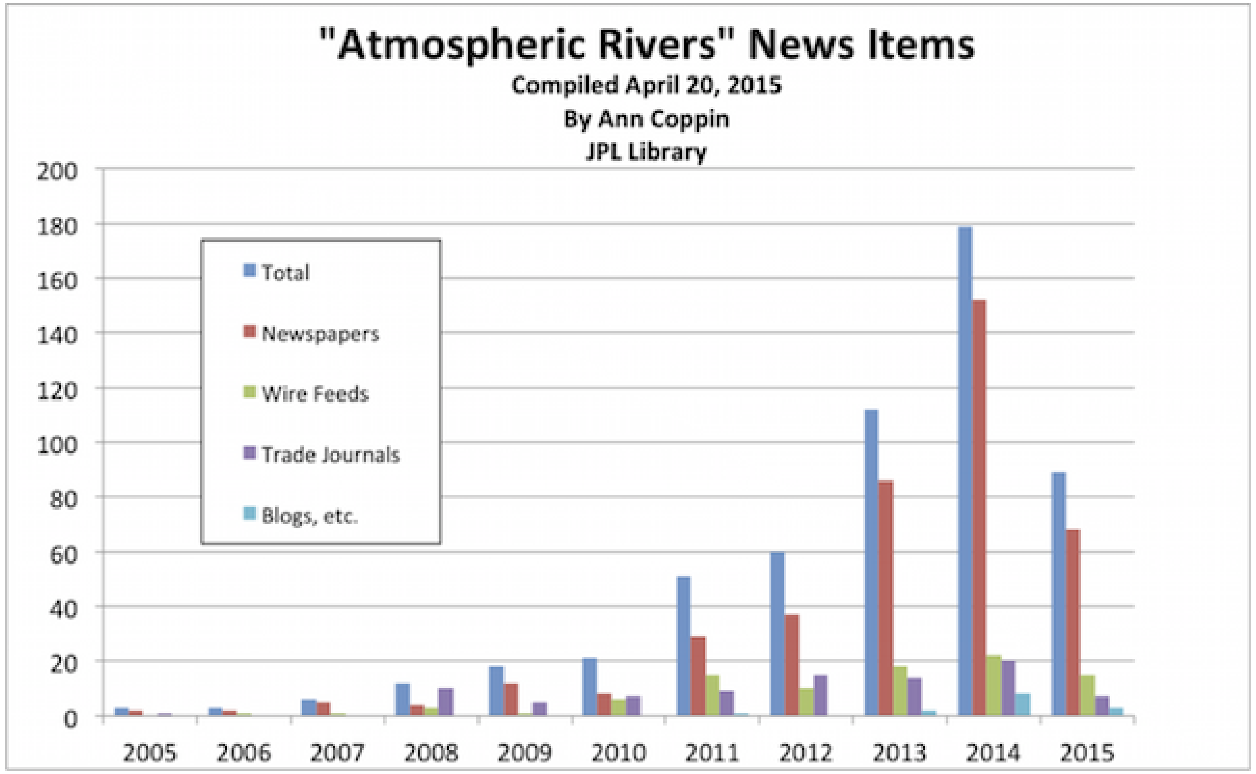
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Compiled April 20, 2015
By Ann Coppin
JPL Library
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Wire Feeds
Trade Journals
Blogs, etc.
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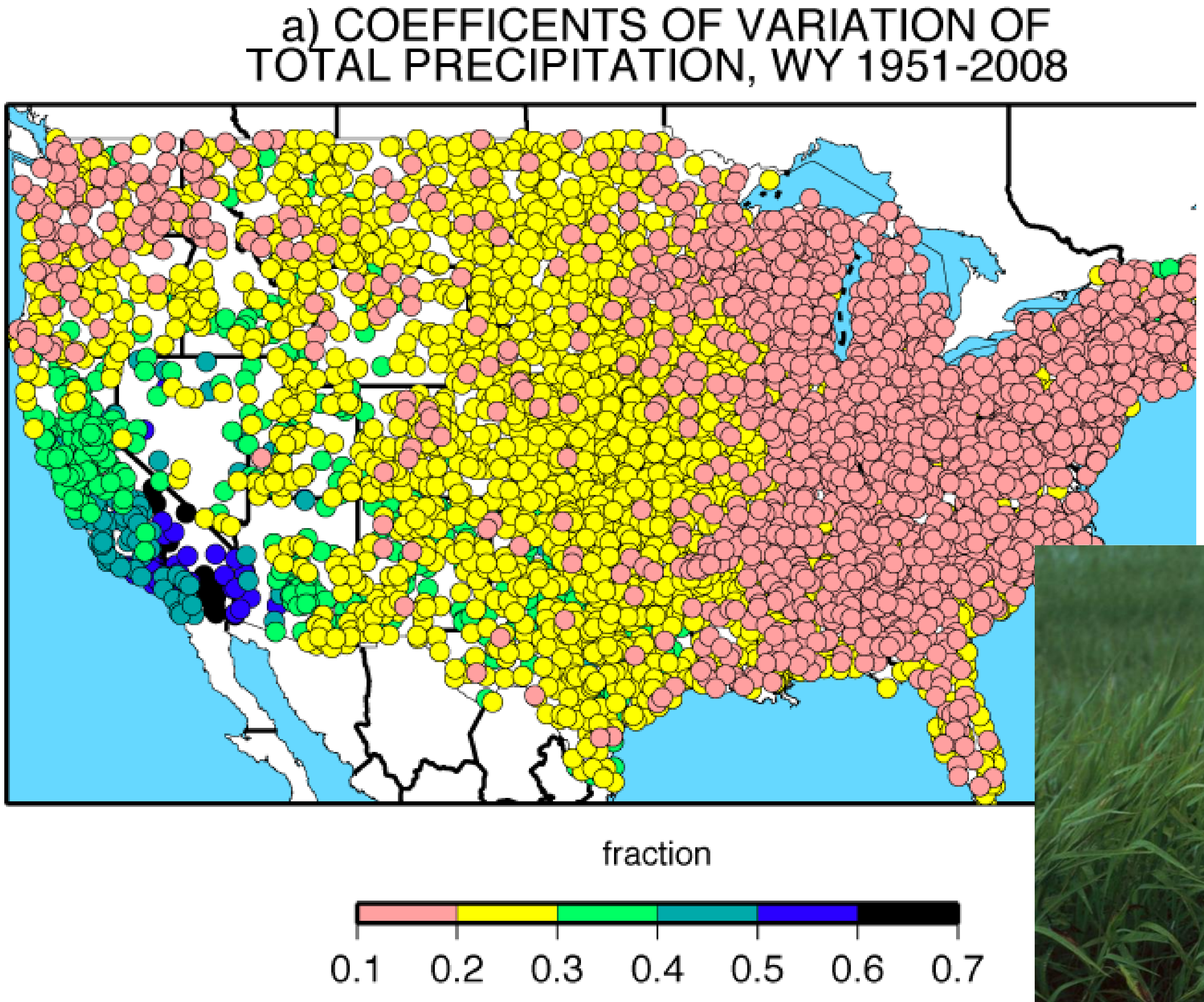
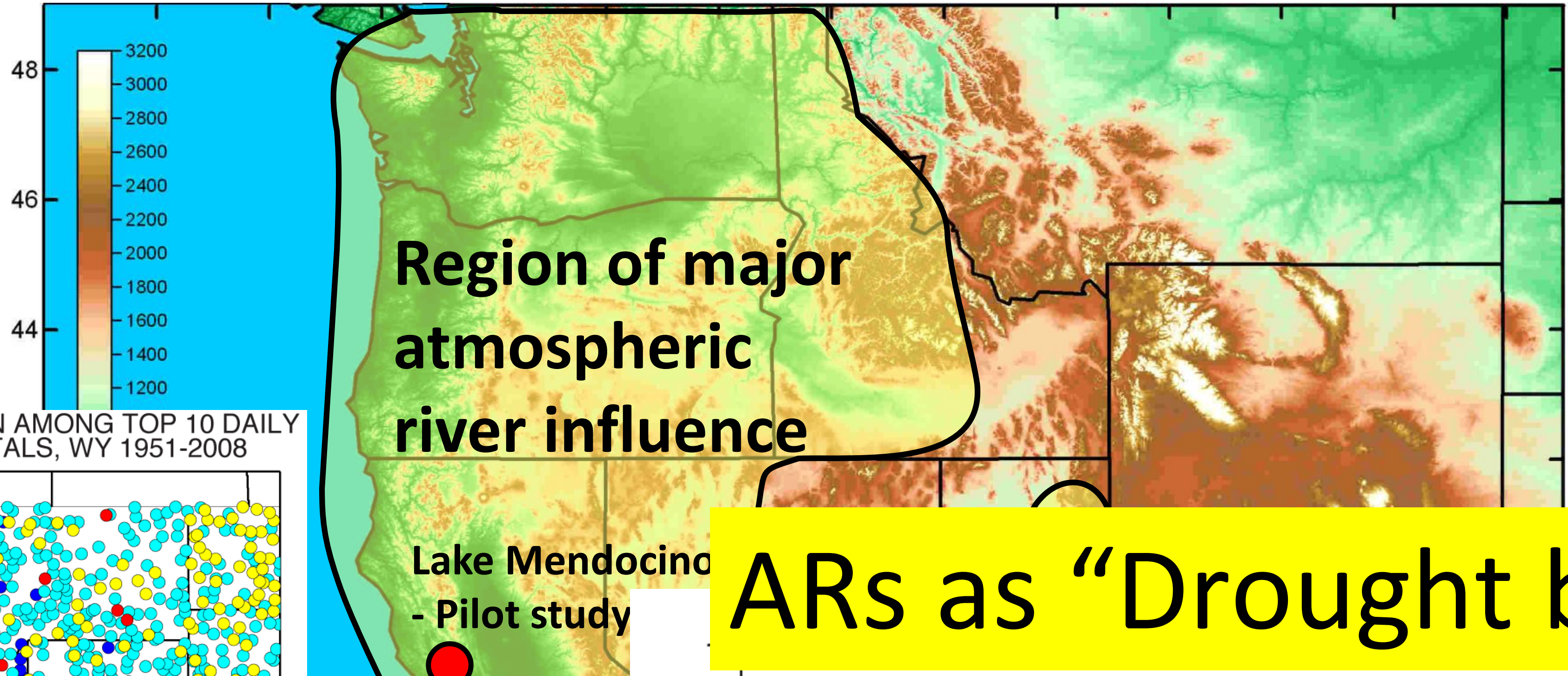
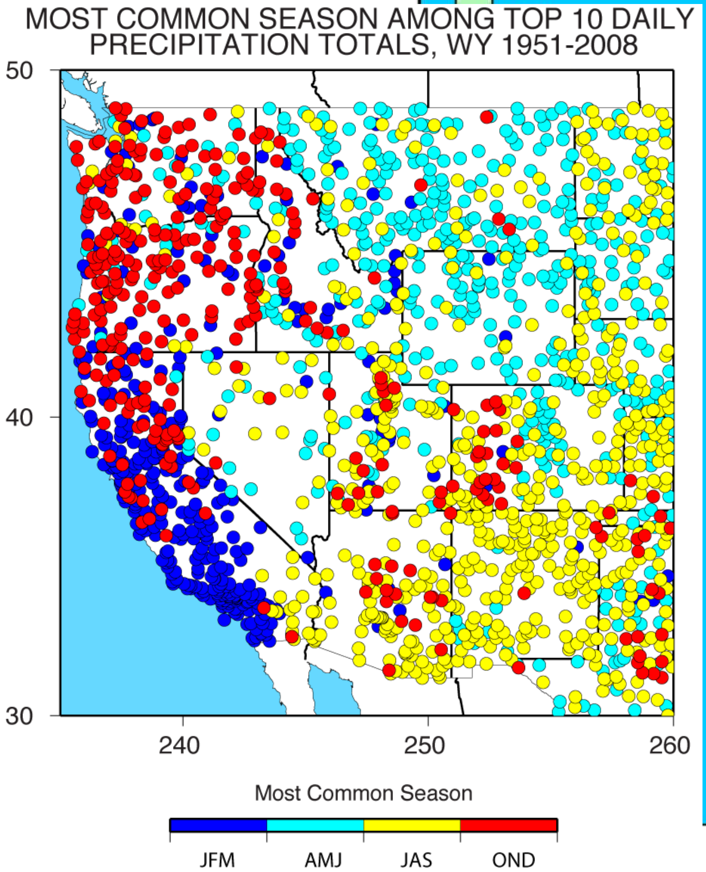


SOUTHWEST U.S. PRECIPITATION IS UNIQUELY VARIABLE

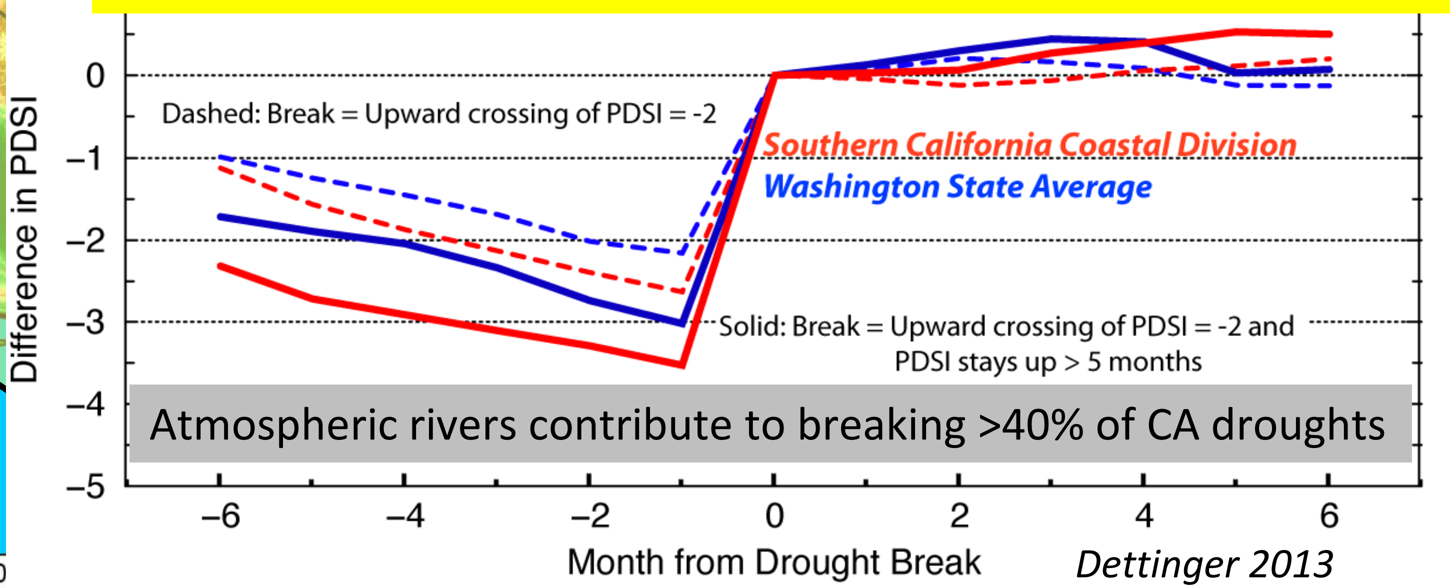
Dettinger et al. 2011, *Water*

Region for which atmospheric river events are a dominant cause of extreme precipitation, flooding and contribute to water supply in the Western U.S. (Ralph et al. 2014)





ARs as "Drought busters"



Dettinger 2013

Overview of Scientific Findings from a Decade of Research

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

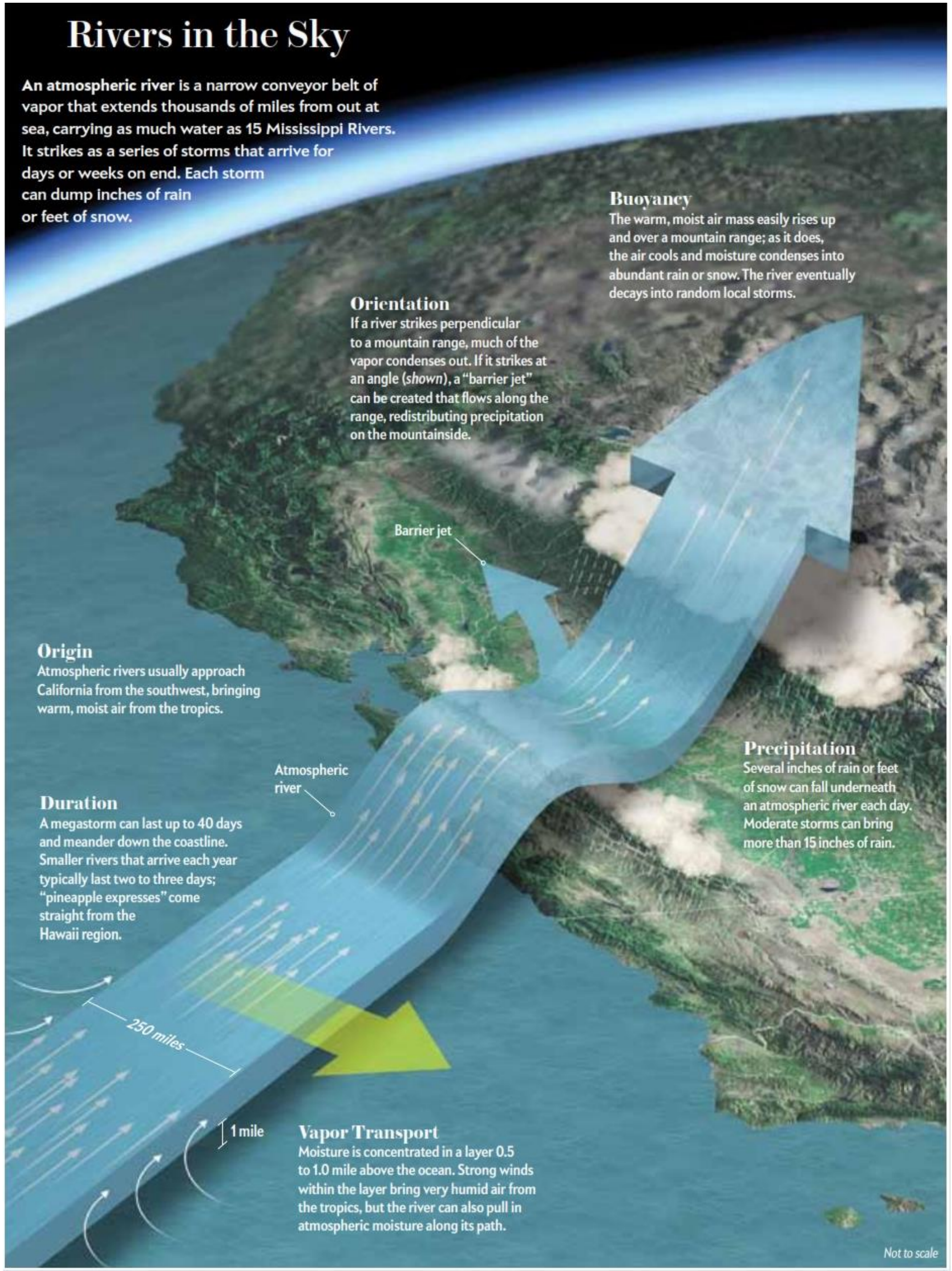
Table 1. Overview of findings from 10 years of atmospheric river research		
ARs can…	**Quantitative results**	**Formal reference**
Cause heavy rain	90% of California's heaviest 1-3 day rain events are from ARs	Ralph et al. 2010
Fill reservoirs	40-50% of northern California rain and snow	Dettinger et 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

Winter Storms and Pacific Atmospheric Rivers (WISPAR)

J. R. Spackman[1,2], G. A. Wick[1], M. L. Black[3], F. M. Ralph[1], Y. Song[4], Y. Zhu[4], P. J. Neiman[1], J. Intrieri[1], T. Hock[5], B. H. Lambrigtsen[6], R. E. Hood[7]

[1]NOAA Earth System Research Laboratory
[2]Science and Technology Corporation
[3]NOAA AOML Hurricane Research Division
[4]NCEP Environmental Modeling Center
[5]National Center for Atmospheric Research
[6]NASA Jet Propulsion Laboratory
[7]NOAA Unmanned Aircraft Systems Program

Photo Credit: NASA

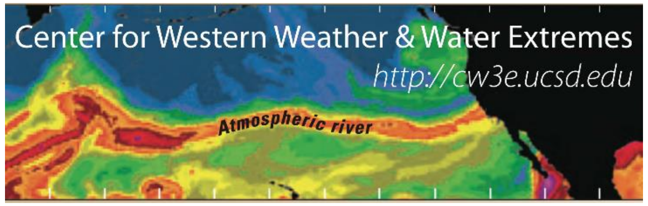


A Major Result from 10-years of Research

Atmospheric rivers – what they are, how they work, and their crucial role in both water supply and flooding across much of the the U.S. West Coast

Figure from an article in Scientific American

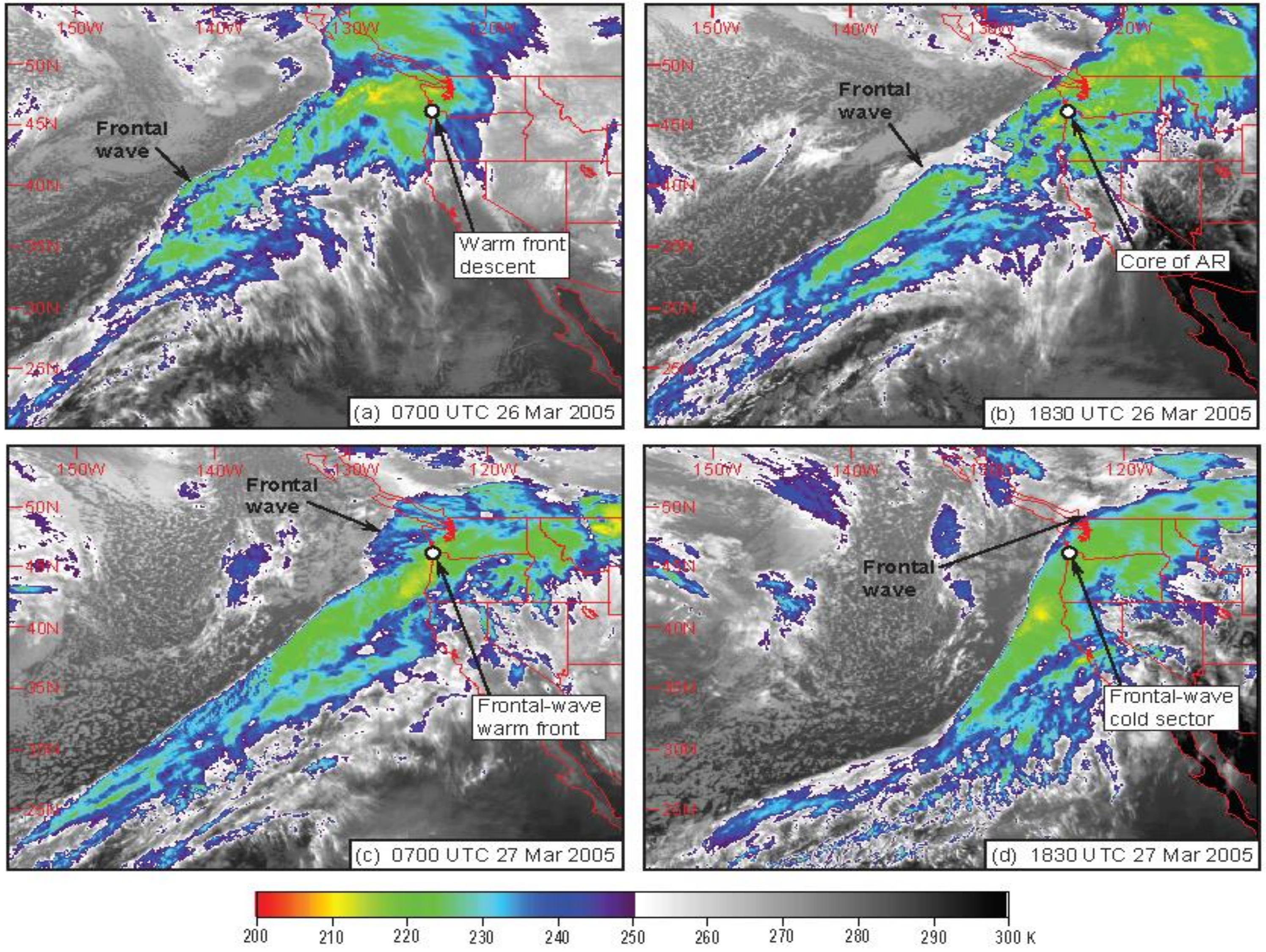
by Dettinger and Ingram (January 2013)



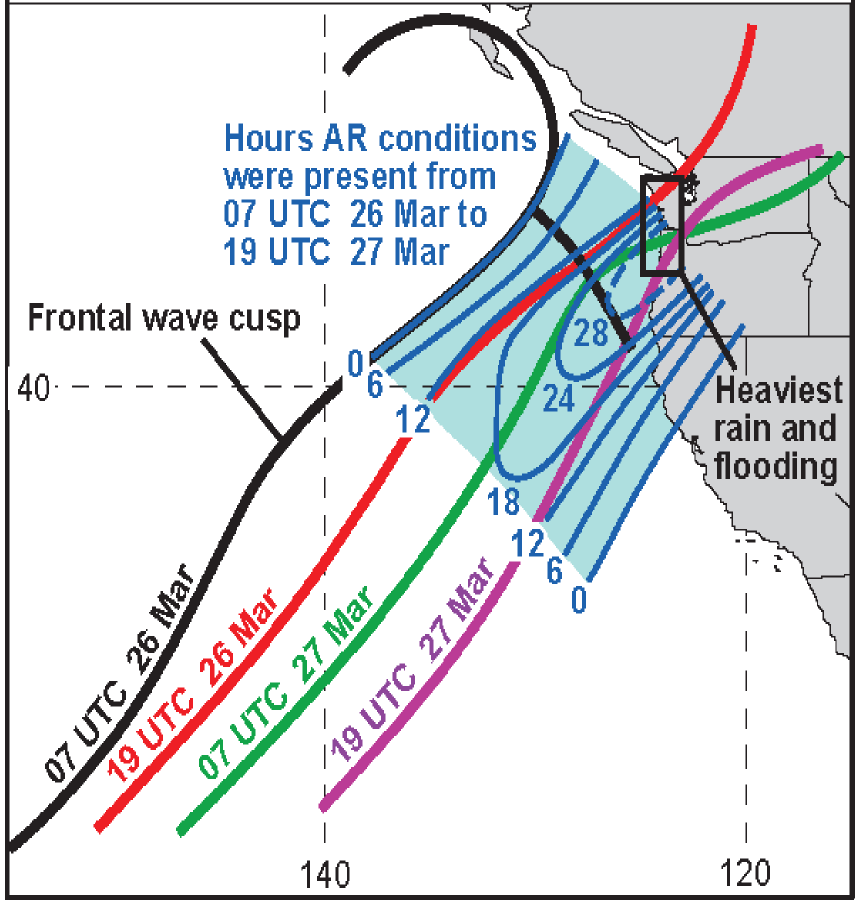
A multi-scale observational case study of a Pacific atmospheric river exhibiting tropical-extratropical connections and a mesoscale frontal wave

Ralph, F. M., P. J. Neiman, G. N. Kiladis, K. Weickman, and D. W. Reynolds, Mon. Wea. Rev., 2011,

GOES IR Imagery



The frontal wave increased the duration of AR conditions and determined where the heaviest precipitation occurred



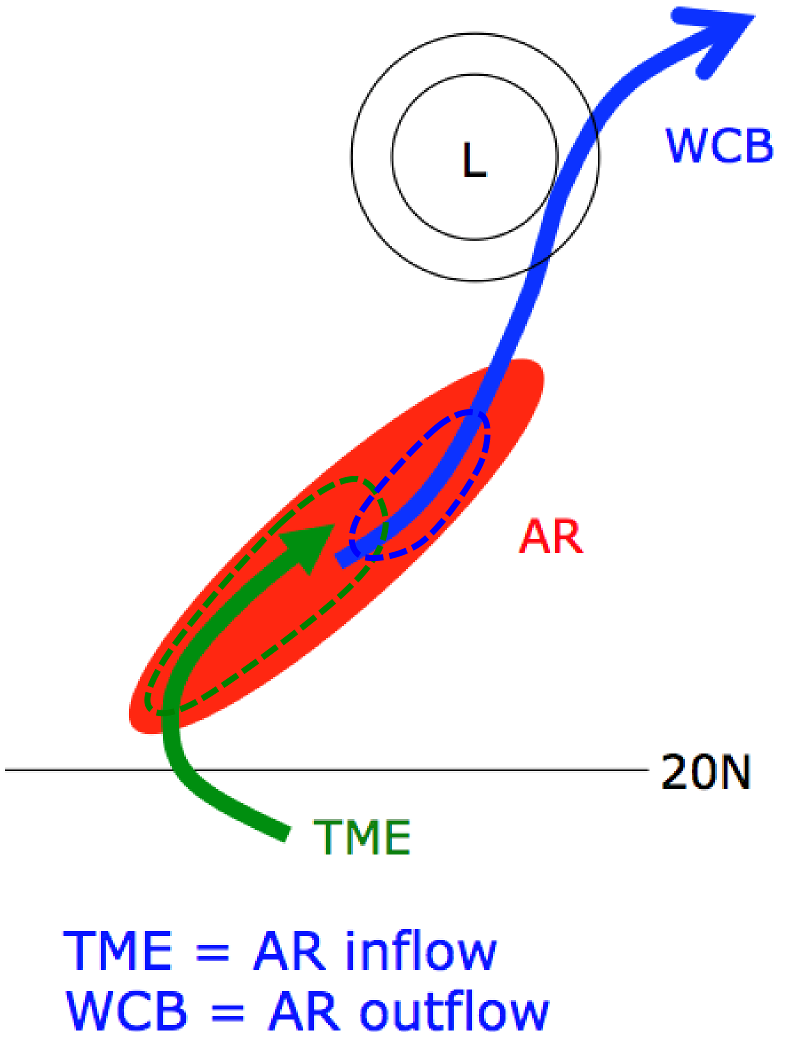
Contact: F. Martin Ralph, Ph.D.
Director, CW3E at Scripps Inst. Of Oceanography at UCSD
mralph@ucsd.edu
858-822-1809

The CW3E website has up-to-date information on atmospheric rivers.

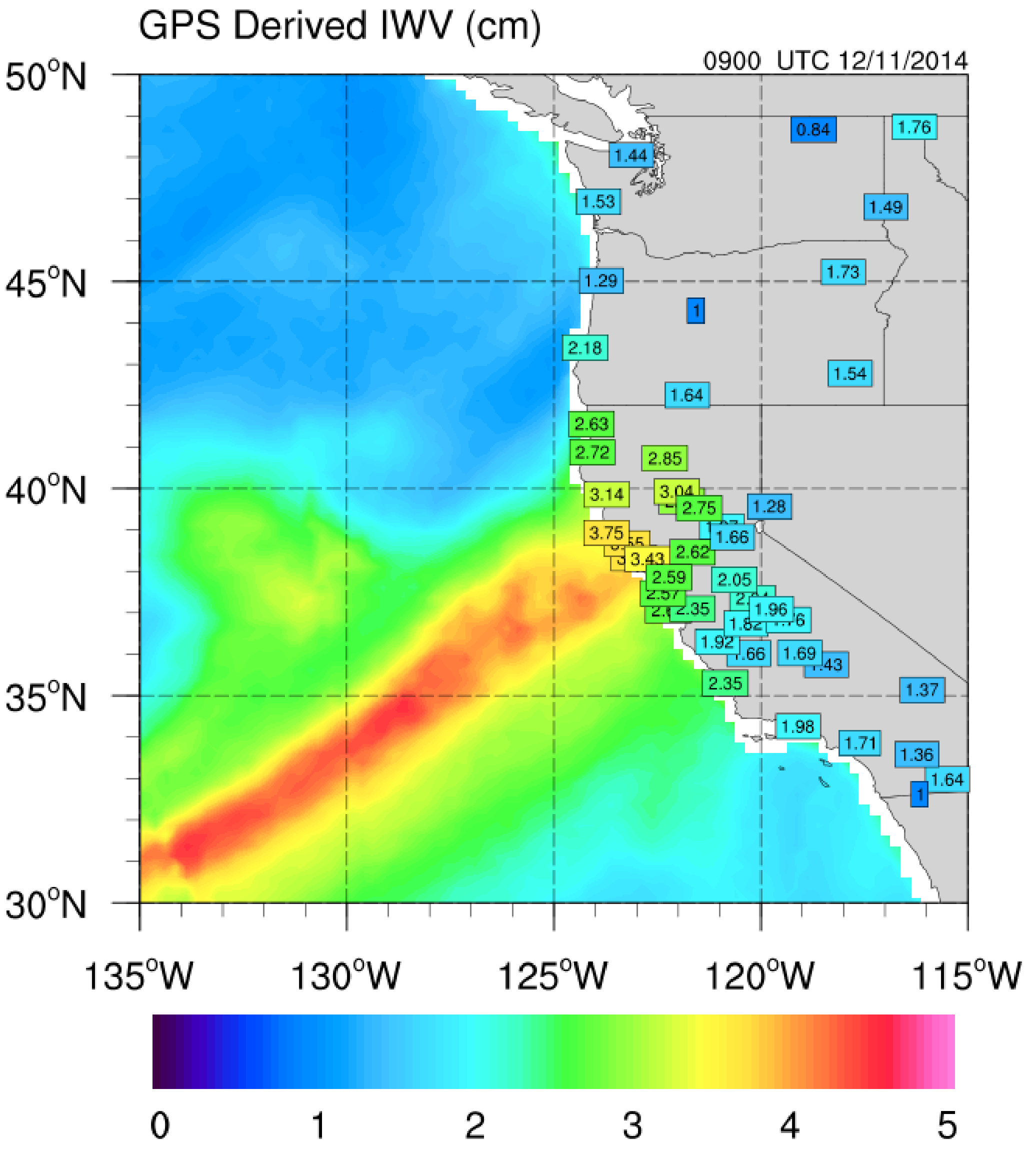
CW3E.UCSD.EDU

AR Workshop June 2015 (at Scripps): ARs, TMEs, and WCBs

- ARs are relatively "small" spatial features on a global scale (~6%)
- ~50% of spatial area defined as an AR also TME
- ~25% of spatial area defined as AR also part of WCB
- Note that using thresholds of IVT=250 kg m^{-1} s^{-1} and IWV=20 mm resulted in a null overlap of 40%



Slide courtesy of J. Cordeira, derived from AR (Cordeira), WCB (Wernli), TME (Sodemann) presentations at the AR Workshop in June 2015


GPS Derived IWV (cm)
0900 UTC 12/11/2014
50°N
45°N
40°N
35°N
30°N
135°W
130°W
125°W
120°W
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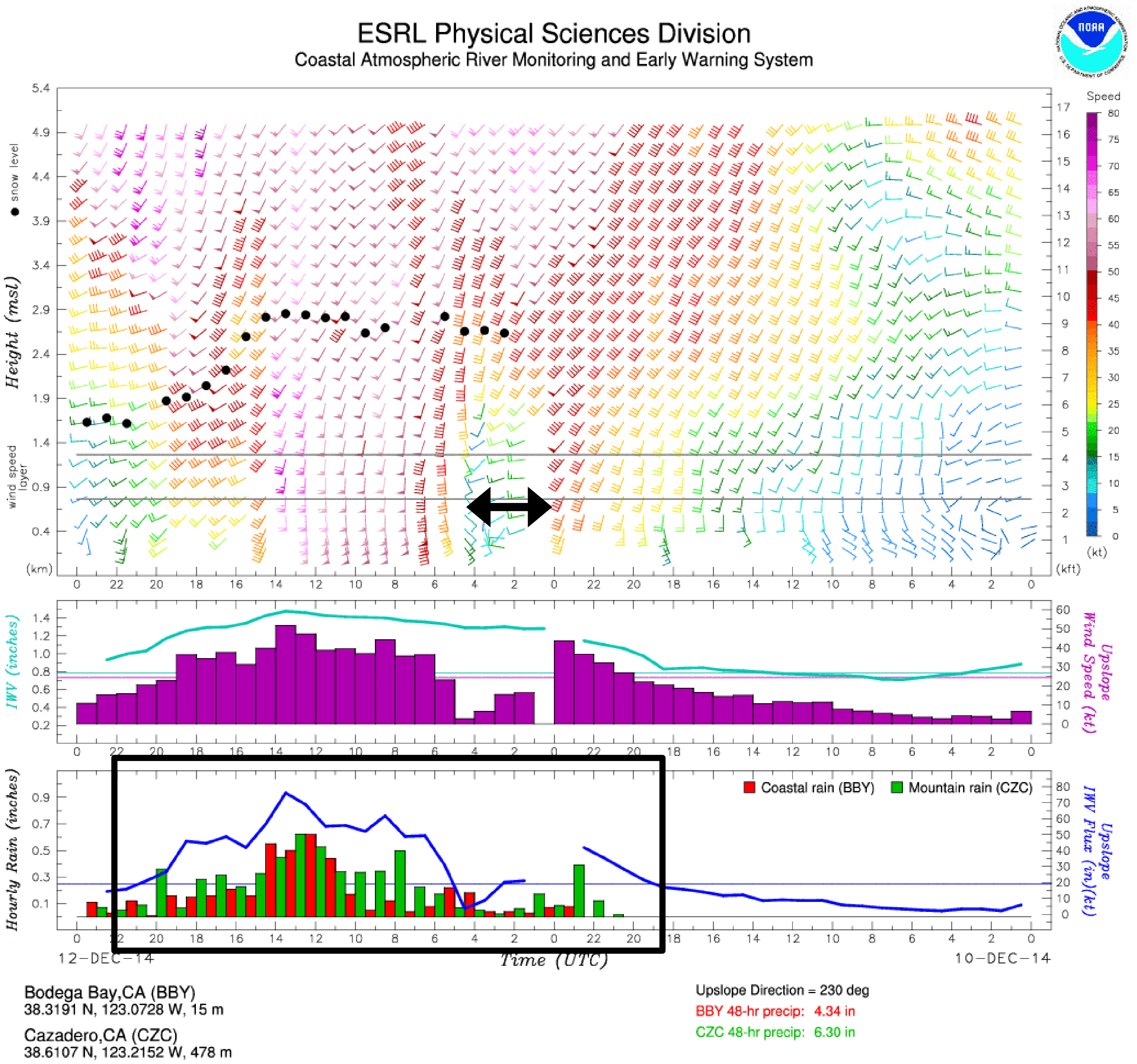
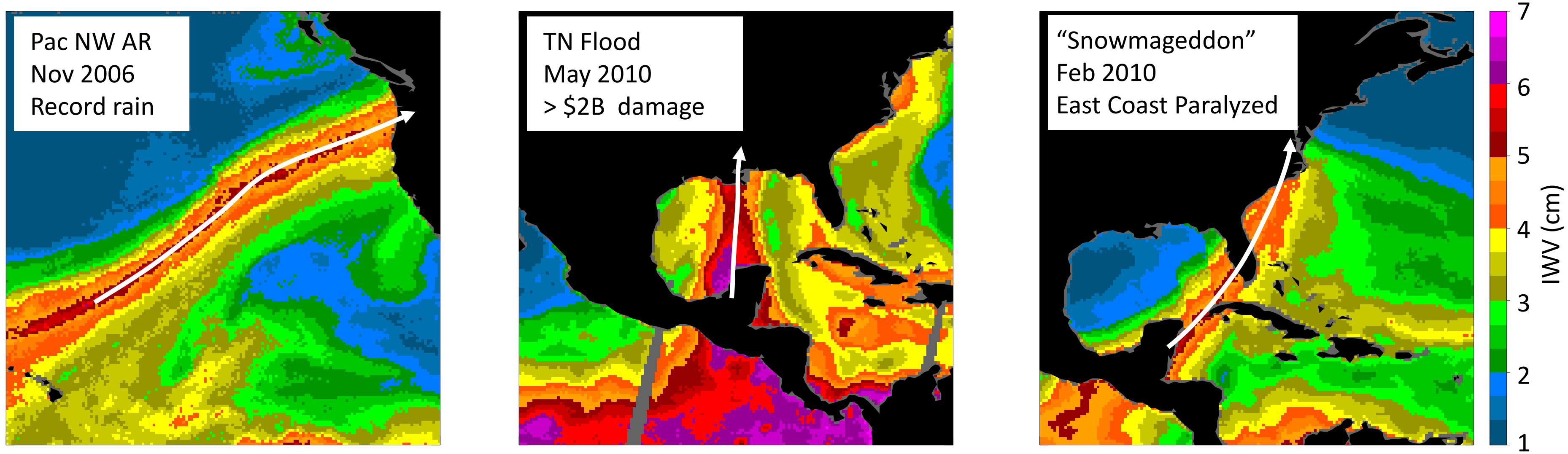
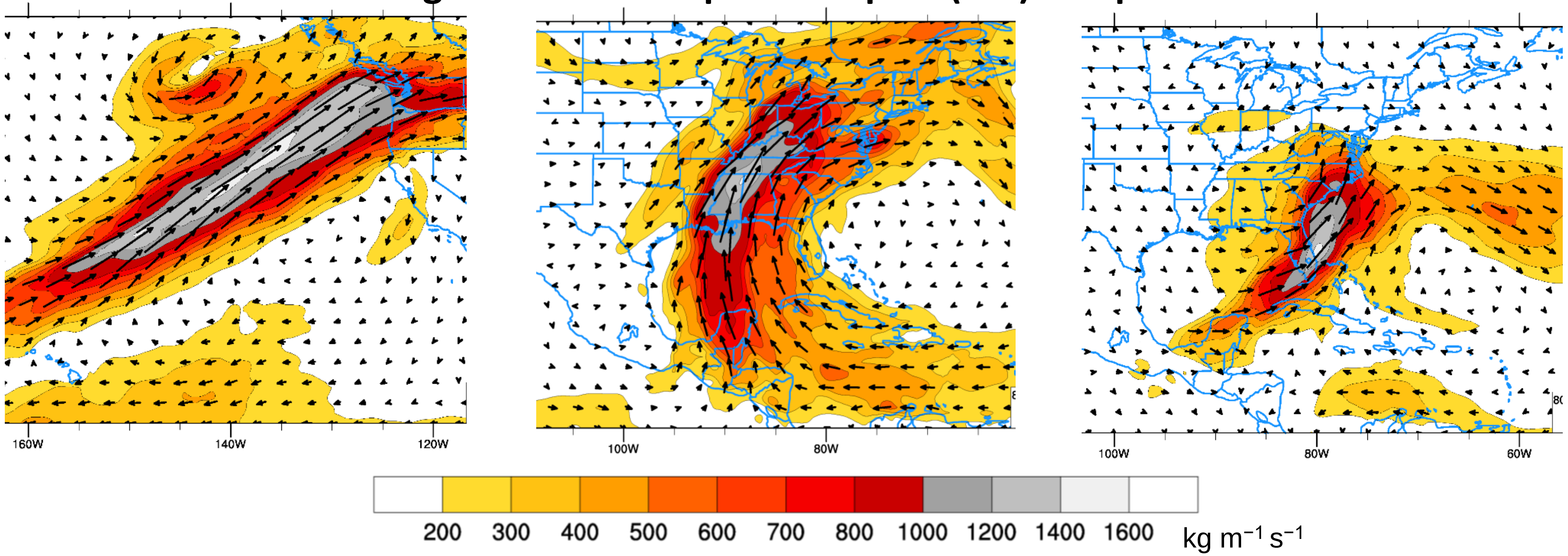
1
2
3
4
5


ESRL Physical Sciences Division
Coastal Atmospheric River Monitoring and Early Warning System
Height (msl)
snow level
wind speed layer
(km)
(kft)
Speed
(kt)
IWV (inches)
Upslope Wind Speed (kt)
Hourly Rain (inches)
Coastal rain (BBY)
Mountain rain (CZC)
Upslope IWV Flux (in)(kt)
12-DEC-14
Time (UTC)
10-DEC-14
Bodega Bay,CA (BBY)
38.3191 N, 123.0728 W, 15 m
Cazadero,CA (CZC)
38.6107 N, 123.2152 W, 478 m
Upslope Direction = 230 deg
BBY 48-hr precip: 4.34 in
CZC 48-hr precip: 6.30 in

Integrated Water Vapor (IWV) Perspective

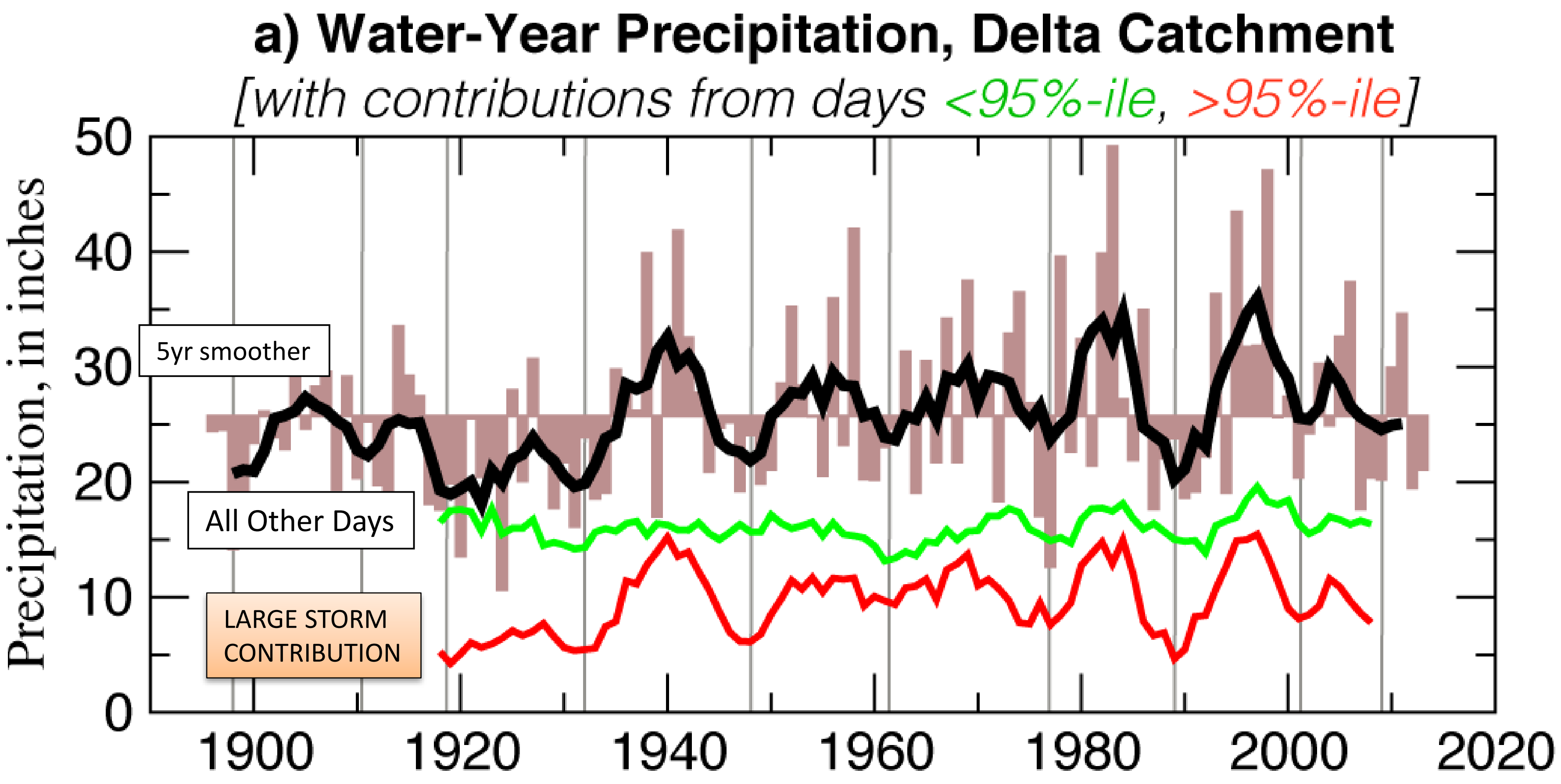


Integrated Water Vapor Transport (IVT) Perspective



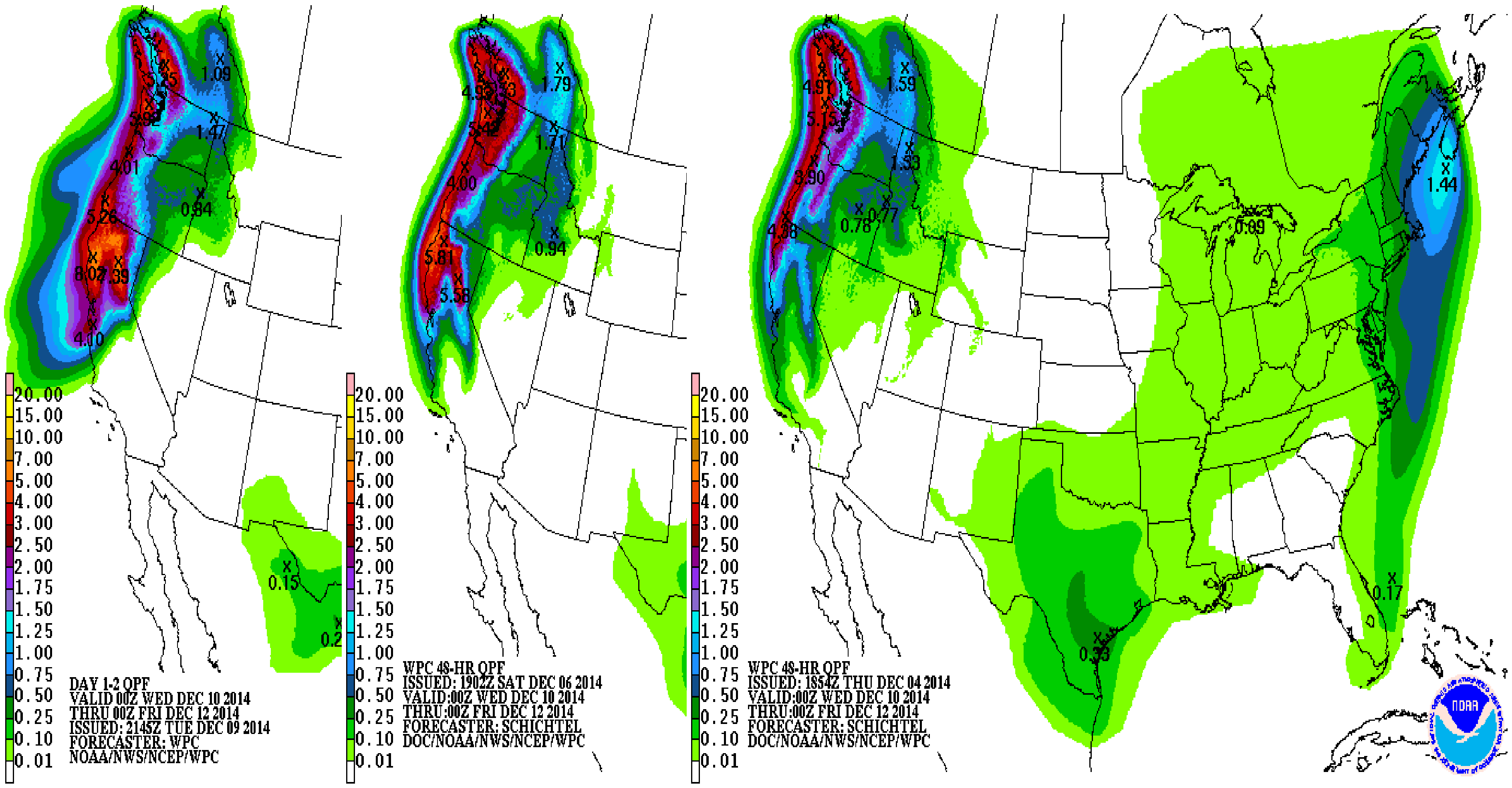
A few large storms (or their absence)

account for a disproportionate amount of California's precipitation variability



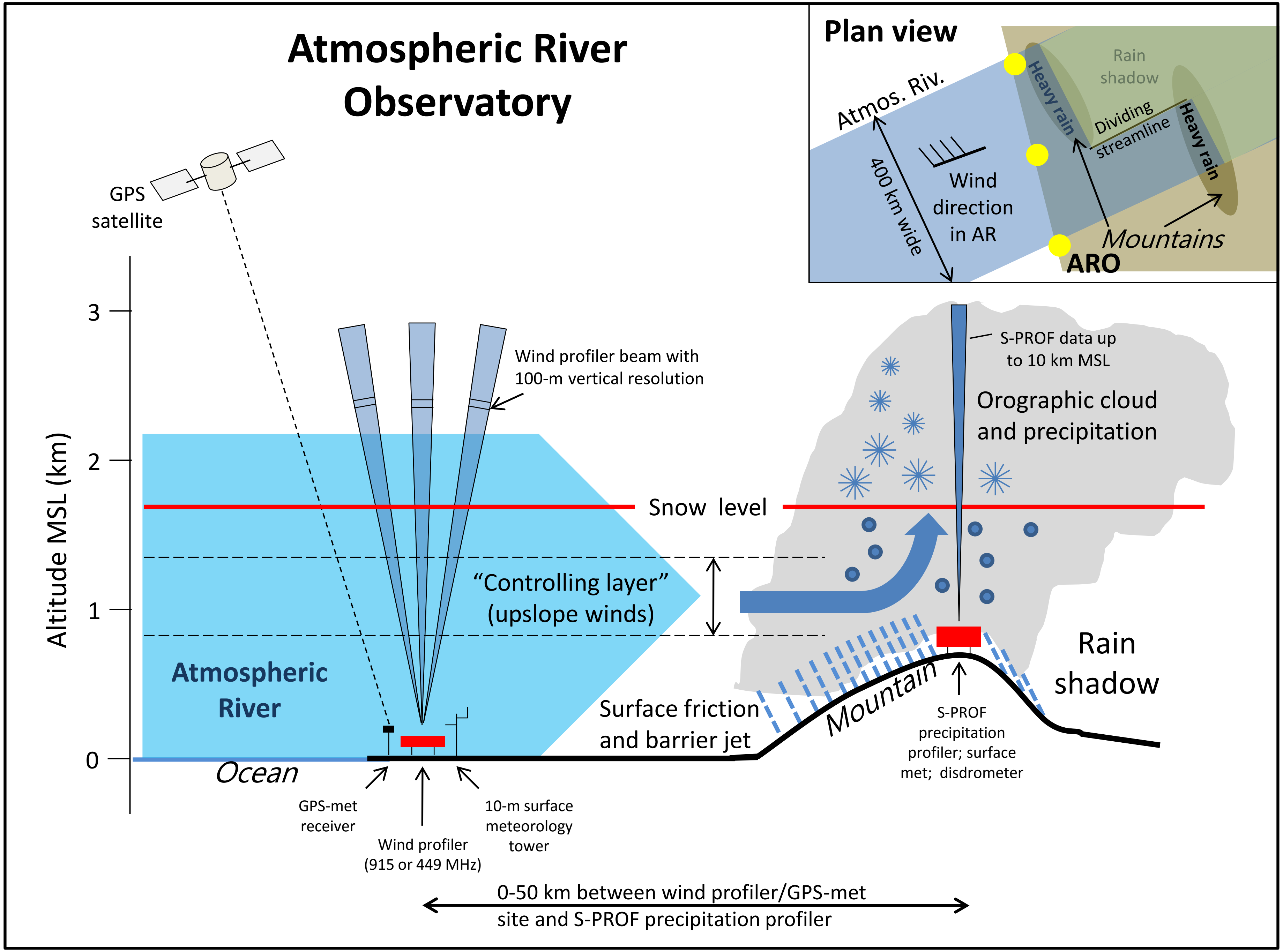
Dettinger and Cayan **Drought and the Delta—A Matter of Extremes**
accepted, San Francisco Estuary and Watershed Science, April 2014

48-h QPF Dprog-Dt out to 7 days lead time ending 0000 UTC 12 Dec 2014



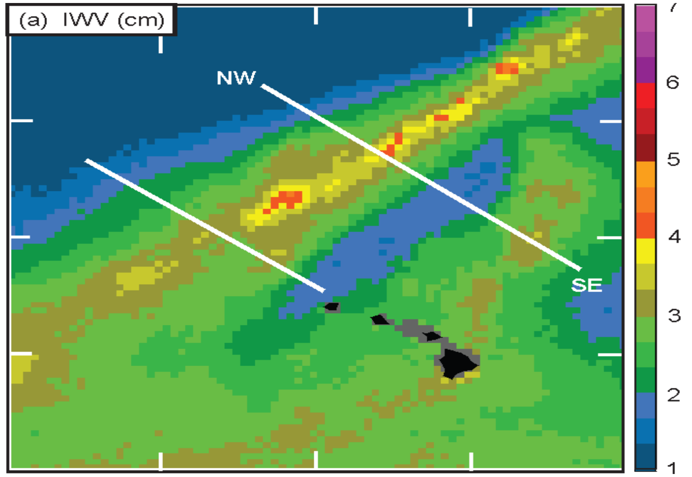
Outline

- Purpose: Set the stage for the first International Atmospheric Rivers Conference by describing major milestones in the development of the AR concept.
- 1970s and 1980s: Underlying concepts established
- 1990s: A global perspective introduces the term “atmospheric river” (AR)
- 2000s: U.S. West Coast experiments and practical goals focus on ARs
- 2010-2015: The concept matures, science and practical applications grow
- 2016 and beyond: A diverse community exists and is pursuing a range of promising science and application directions
- The term AR started appearing in the 1990s and spawned concern about the jargon and its relationship to topics studied earlier. After falling relatively out of favor by the early 2000s, the availability of satellite images showing long filaments of large IWV, confirmed by research aircraft measurements to correspond to strong horizontal water vapor transport, the concept reemerged in scientific papers. By 2005, a series of experiments and programs began pursuing the topic in a focused manner. The HMT program in particular, which focused on US West Coast heavy precipitation, identified ARs as a primary cause of heavy precipitation and flooding in the region. This was followed by the creation of the CalWater program of field studies that emerged from a community planning workshop in 2008 that identified climate change science gaps around ARs and aerosol-precipitation topics as the top priorities. Impacts on drought and water supply then became apparent in the Western US, while European and South American scientists began studying their impacts on the west coasts of those continents. The first AR session at a conference was held at AGU in 2010 - right as a major AR struck California.
- During this period some in the research community continued to have concerns about the appropriateness or need for the term. One manifestation of this was the perception by some that the concept was duplicative of the warm conveyor belt (WCB) concept. To help resolve this a workshop was held at Scripps Institution of Oceanography bringing together experts on ARs, WCBs and the related tropical moisture exports (TME). This workshop brought closure to the subject by identifying the unique attributes of each and how they relate to one another.
- While the science community debated and advanced the understanding of the phenomenon, the water management and flood control communities became aware of the topic and quickly recognized its value. So too did climate change researchers. As of 2016 many studies are underway to advance the science, field programs are being planned, tailored forecast tools are operating, applications tools are under development, policy makers briefed, and programs formed - key examples being this International AR Conference and the creation of it host organization, CW3E. From the 10 or so peer-reviewed scientific articles published in the 1990s, to the over 400 published since then, the topic has helped bring greater attention to the structure, behavior, predictions and importance of the horizontal water vapor transport part of the global water budget. A topic that had long been considered simple and secondary to the topics of vertical transport by convection and air-sea-land fluxes.
- The emergence of the atmospheric river concept represents an example of the complex and often circuitous route that major new research directions take before maturing and having impact through applications. The path provides a telling example of the importance of sustained basic research, and of connecting researchers with people in operational or application-oriented roles.



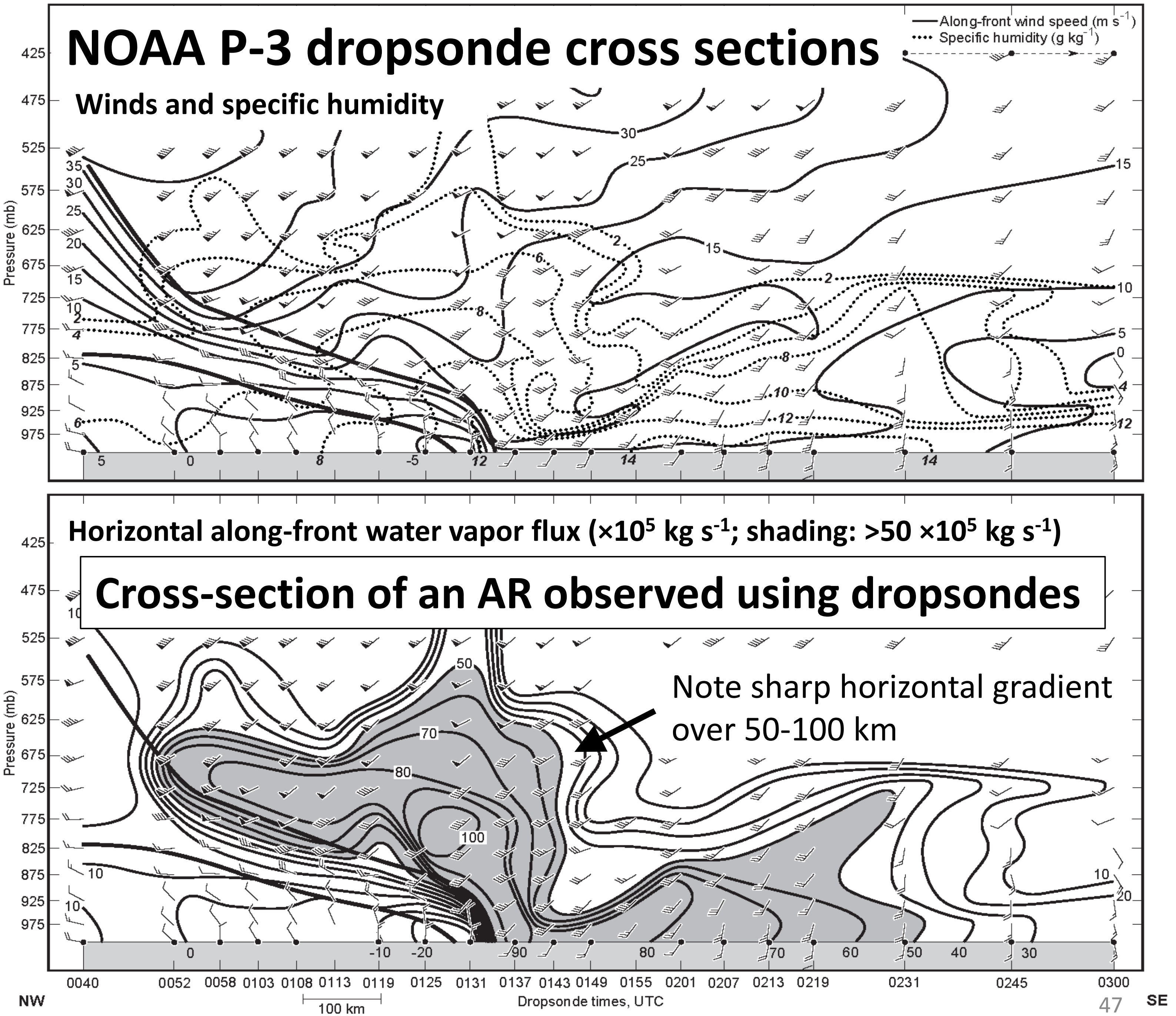
Atmospheric River Observatory
Plan view
Atmos. Riv.
400 km wide
Wind direction in AR
Heavy rain
Rain shadow
Dividing streamline
Heavy rain
Mountains
ARO
GPS satellite
Altitude MSL (km)
3
2
1
0
Wind profiler beam with 100-m vertical resolution
S-PROF data up to 10 km MSL
Orographic cloud and precipitation
Snow level
"Controlling layer" (upslope winds)
Atmospheric River
Surface friction and barrier jet
Mountain
Rain shadow
Ocean
GPS-met receiver
Wind profiler (915 or 449 MHz)
10-m surface meteorology tower
S-PROF precipitation profiler; surface met; disdrometer
0-50 km between wind profiler/GPS-met site and S-PROF precipitation profiler

Dropsonde measurements can improve AR position and characteristics offshore for numerical weather prediction



The atmospheric river as seen in SSM/I integrated water vapor (IWV). The upper white line marks the cross-section baseline.

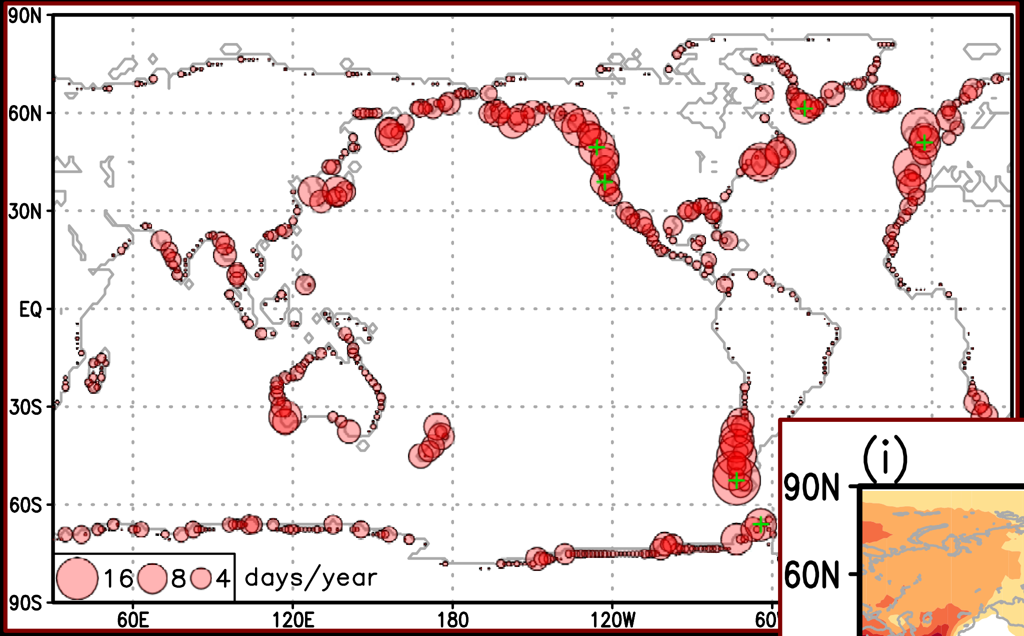
Ralph, F. M., P. J. Neiman, G. N. Kiladis, K. Weickman, and D. W. Reynolds, 2011: A multi-scale observational case study of a Pacific atmospheric river exhibiting tropical-extratropical connections and a mesoscale frontal wave. *Mon. Wea. Rev.*, **139**, pp. 1169-1189, doi: 10.1175/2010MWR3596.1.

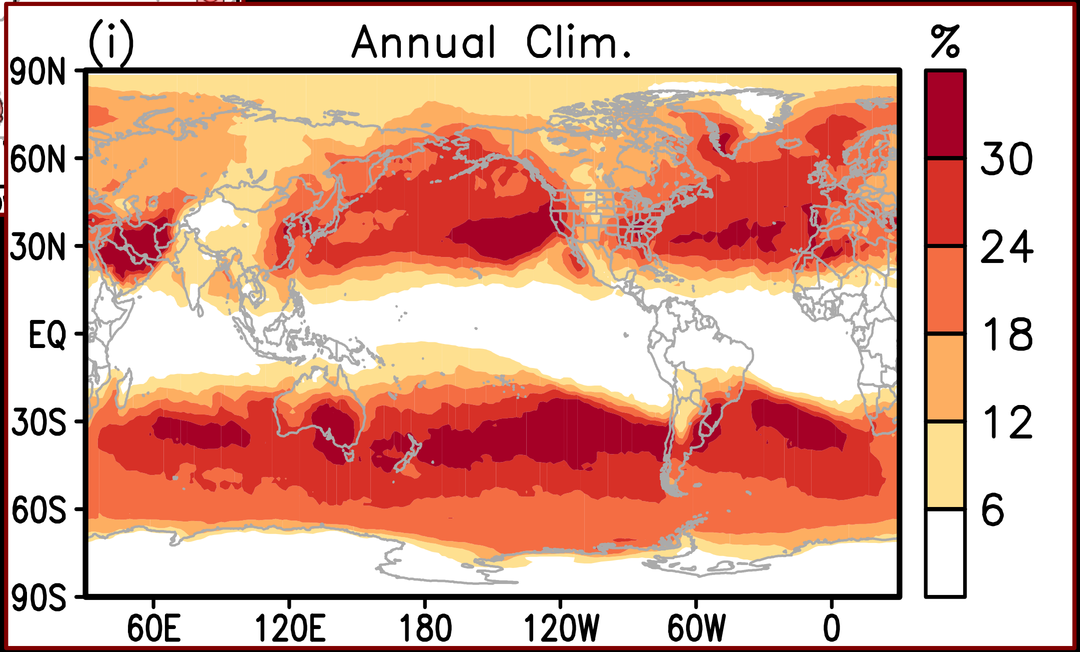


Grey shaded area is the core area of water vapor transport in the AR

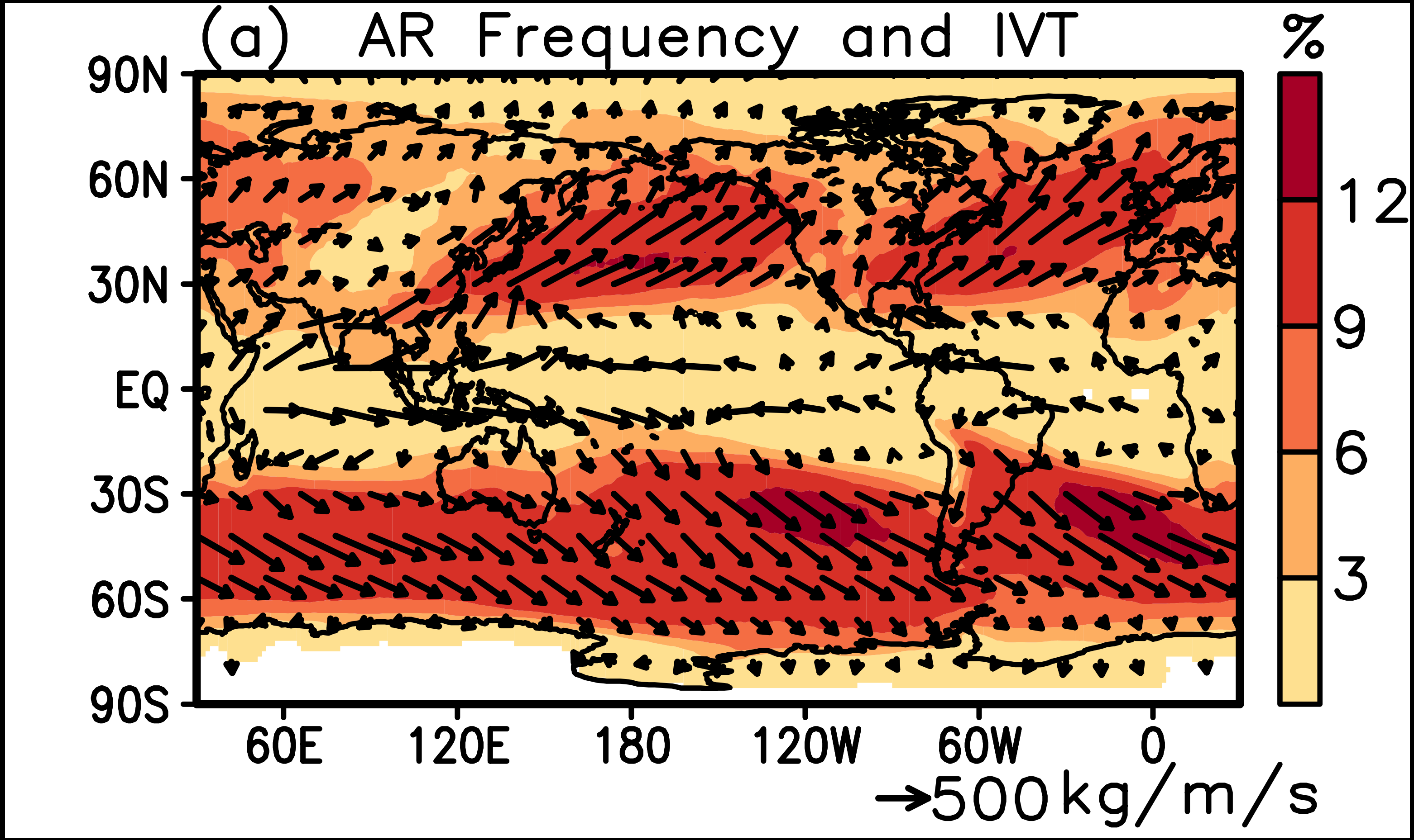
AR Landfalls & Fraction of Annual Precipitation

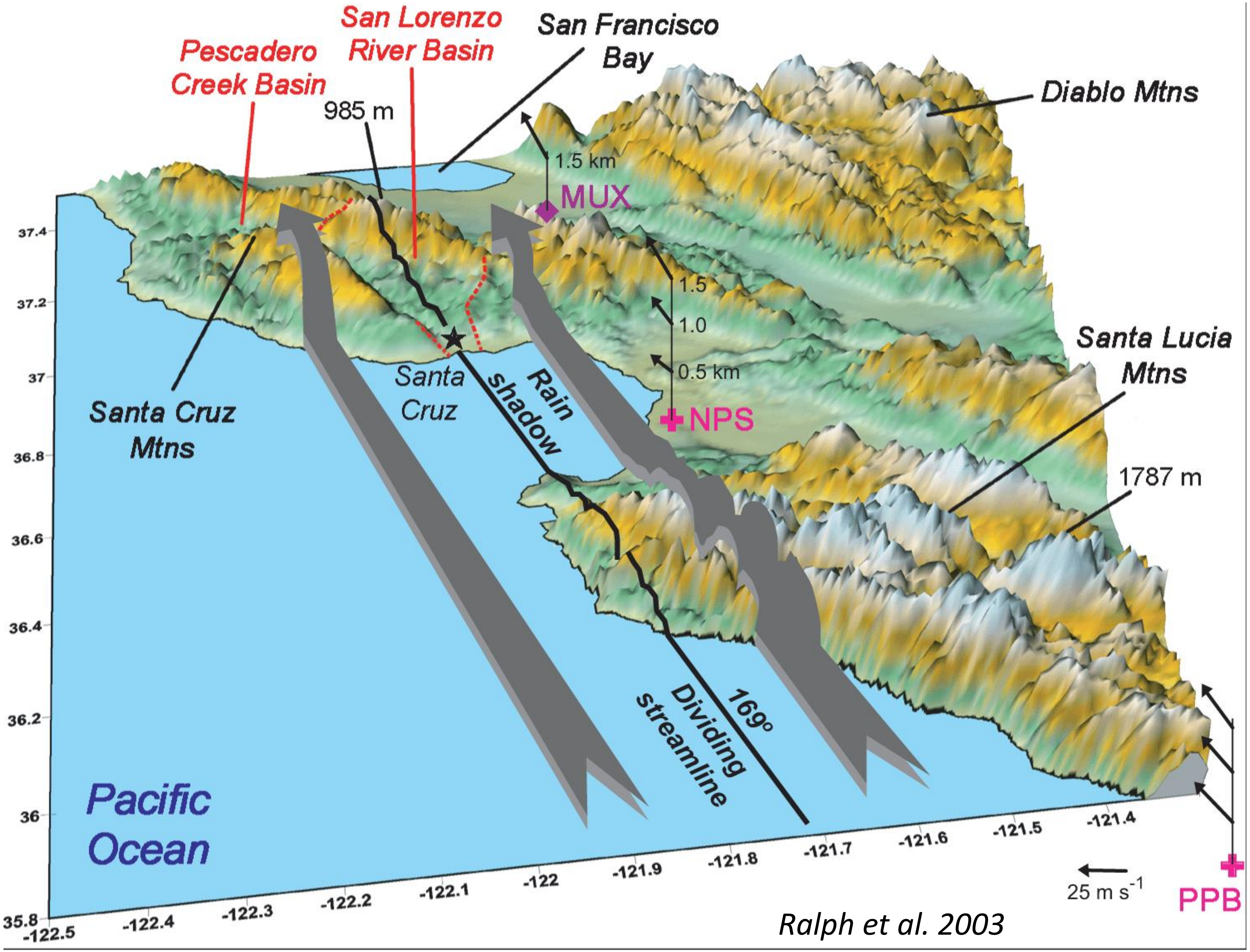
A Global Perspective





Global Map of AR Frequency and IVT





Ralph et al. 2003

AR "Angle of Attack" can determine flooding in mountainous areas

CALIFORNIA PRECIPITATION

CNAP CW3E Southwest Climate Science Center

CALIFORNIA PRECIPITATION

Seasonality of Precipitation

Precipitation in California is highly variable year-to-year and understanding this variability is critical to water resource management and policy. California has a Mediterranean climate – cool, wet winters and warm, dry summers. This means that the bulk of California's precipitation falls in the cool season months from October through April. It is highly variable across the state with the southeast deserts receiving less than 5 inches in a year to the north coast which can get over 100 inches per year. One way to visualize the temporal distribution of California precipitation is using the Northern California 8-station precipitation index from the California Department of Water Resources. The index, which averages 50 inches per year, gives a sense of how much precipitation the Sacramento River watershed – a key area for the state's water supply - has received. A map of the location of the stations is shown in Figure 1 along with the average monthly distribution of precipitation. As can be seen in Figure 1, about half the annual precipitation total arrives in the three-month period from December through February and 90% of the annual precipitation falls between October 1 and April 30.

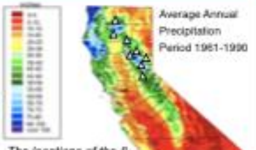
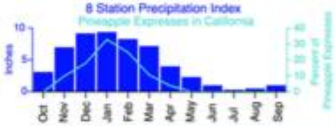


Figure 1. The locations of the 8 stations incorporated into the index is plotted on top of the average annual precipitation for CA (PRISM data set). The monthly distribution of the Northern Sierra 8-Station Index and Pineapple Express storms (strong atmospheric rivers) are graphed below.



During this time period, winter storms come off the Pacific Ocean delivering rain and snow to California. Some of these storms include moisture from atmospheric rivers – narrow bands of high concentration water vapor that extend from the tropics – and deliver heavy precipitation to the state which can lead to flooding (Ralph et al., 2006; Fig. 2). On average 5-7 larger storms contribute most of the precipitation that falls during the wet months (Dettinger et al., 2011). When more storms arrive, conditions are wetter; when fewer storms arrive, conditions are drier.

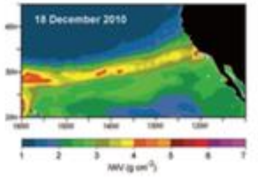


Figure 2. Image of an atmospheric river making landfall in California (Ralph and Dettinger, 2012)

Ralph, F. M., et al., 2006, Geophys. Res. Lett., 33, L13801.
Ralph F. M. and Dettinger, M.D., 2012, Bull. Amer. Meteor. Soc., 93, 783–790.
Dettinger, M. D., et al., 2011, Water, 3, 455-478.
Dettinger, M.D. and Cayan, D.R., 2014, San Francisco Estuary and Watershed Science, 12(2).

Climate Change

Research to date provides no clear signal of how precipitation may change in California as climate changes. Although precipitation changes are uncertain, climate models agree that California will become warmer. The increased temperatures will mean more of the precipitation will fall as rain instead of snow which will change the timing of river flows in the state. Efforts are underway to develop a metric to track the rain versus snow percentages and identify regions that are vulnerable to this transition that is already beginning.

Large Storms Control California's Annual Precipitation Variability

Variability in precipitation is tied to the number of large storms, also known as atmospheric river events (Dettinger and Cayan, 2014). A depiction of the variability is shown in Figure 3.The top figure in Figure 3 shows the annual precipitation accumulations with a five-year averaged time series illustrated by the heavy black line. The red line shows the contribution to the annual precipitation made by the top 5% of rainy days while the green line shows the contribution from the other 95%. Note the red line follows the five-year line quite closely. This implies that the decadal scale variability is tied to the number of extreme events. This conclusion is further illustrated in the bottom figure which shows a count of the number of strongest atmospheric river events, often called pineapple express storms, that hit California.

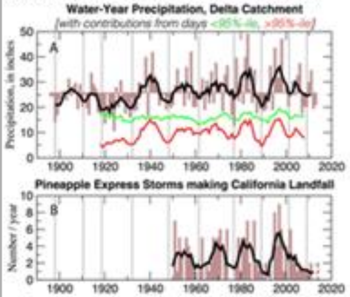


Figure 3. Water-year precipitation and associated contributions from the top 5% of wet days versus the other 95% and association with pineapple express storms.

In addition to the decadal scale fluctuations in precipitation associated with the number of large events, there is year-to-year variability in precipitation accumulation. Figure 4 shows an estimate of the year-to-year variability in precipitation for the Continental United States (Dettinger et al., 2011). Note that California has the largest year-to-year variability depicted by the green and blue circles indicating yearly variability on the order of half the annual average. It is also a unique

Figure 4. Coefficient of variation (the standard deviation divided by the average) of total precipitation based on water year data from 1951-2008 (Dettinger et al. 2011).

phenomenon to California as shown in Figure 5, which shows the percent of year to year variance in total precipitation due to the wettest 0.2% of days based on data from 1950-1999 (Dettinger and Cayan, 2014). As floods, drought and water availability are all related to a few large storms every year that occur in a limited time frame, understanding and forecasting these extreme precipitation events are critical to improving California's water management resilience now and in the future with warmer temperatures and declining snowpacks.

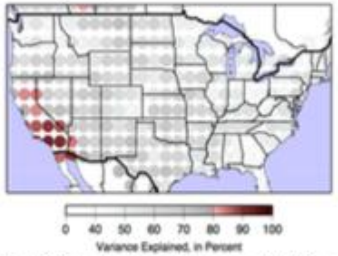


Figure 5. Percent variance of water-year precipitation from wettest 0.2% of days using water year data from 1951-1999.

The **CA State Climatologist** is supported by California Department of Water Resources to collaborate with NOAA programs to provide climate information and interpretation for California.
CNAP, the California Nevada Applications Program, is a NOAA RISA team conducting applied climate research that is inspired by and useful to decision makers in the region (http://cnap.ucsd.edu).
CW3E, Center for Western Weather and Water Extremes, provides science to support effective policy on extreme weather and water events (http://cw3e.ucsd.edu).
The **SWCSC**, Southwest Climate Science Center, sponsored by the US Depart. of the Interior, provides scientific information, tools, and techniques to anticipate, monitor, and adapt to climate change.

This 1-page summary is available as a 1-page handout. See CW3E.UCSD.EDU.

A brief history of ARs as a US West Coast Focus

- 1990s AR papers + SSM/I IWV images + CalJet/PacJet (1998 to 2002)
- HMT West begins first specific programmatic focus on ARs (2003 start)
- IWV pattern recognition method created using SSM/I obs (2004)
- ARs key in California's Russian River floods (2006) [and in WA (2011), in AZ (2013)]
- AR Catalog created using SSM/I obs (2008)
- DWR-NOAA-Scripps launched EFREP Mesonetwork (2008 start)
- CalWater-1 (2008 workshop, 2009-2011 field studies)
- Howard Hanson Dam (near Seattle) flood risk crisis (damaged by an AR storm in 2009)
- QPF skill quantified (2010) and NWS adds QPF at 6-7 day lead time in PacNW
- Water Supply studies, incl snowpack, and ARs as western drought busters (2011-2013)
- ARk-Storm emergency preparedness scenario identifies series of big ARs as threat (2010)
- WISPAR (Winter Storms and Pacific Atmospheric Rivers) experiment uses the Global Hawk UAS with dropsondes to measure "10 Mississippis" (2011)
- 3-day extreme precipitation from ARs on west coast is as extreme as any storms in US (2011)

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- ARs tracked in climate change models and show increased extreme ARs (2011-current)
- Sonoma County Water Agency identifies ARs as a key phenomenon to flood and water supply and fish (2011)
- NOAA's Habitat Blueprint program (e.g., salmon) identifies Russian River as first regional focus area and selects ARs as a key subject (2012)
- Western Obs Vision (2012)
- Inland penetration of ARs (2012-current)
- Role of Sierra Barrier Jet (2013 – current)
- CalWater-2 (2012 planning start, 2014-2018 campaigns)
- ARDT and landfall skill, plus key role of AR duration (2013 publications)
- CW3E (2013 launched at UC San Diego/Scripps)
- Legislation proposed that focuses on ARs and their impacts (Federal 2013; State 2015)
- FIRO (2014 steering committee formed for Lake Mendocino)
- AR Portal and West-WRF (2015 launch)
- **AR Workshop , Monograph and International Conference (2015-2016)**