Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

WEST COAST FORECAST CHALLENGES AND DEVELOPMENT OF ATMOSPHERIC RIVER RECONNAISSANCE

F. Martin Ralph
Director, Center for Western Weather and Water Extremes

Warm Conveyor Belt Workshop
European Center for Medium Range Weather Forecasting
10 March 2020, Virtual Meeting

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

Glossary of Meteorology

Added May 2017. Process described in Ralph, Dettinger, Cairns, Galarneau, Eylander, 2018, *Bull. Amer. Meteor. Soc.*, ***99***, pp 837-839.

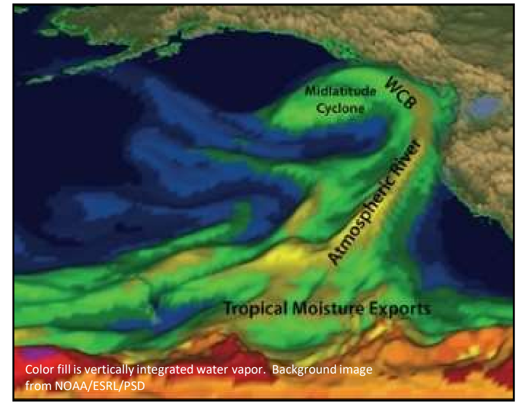
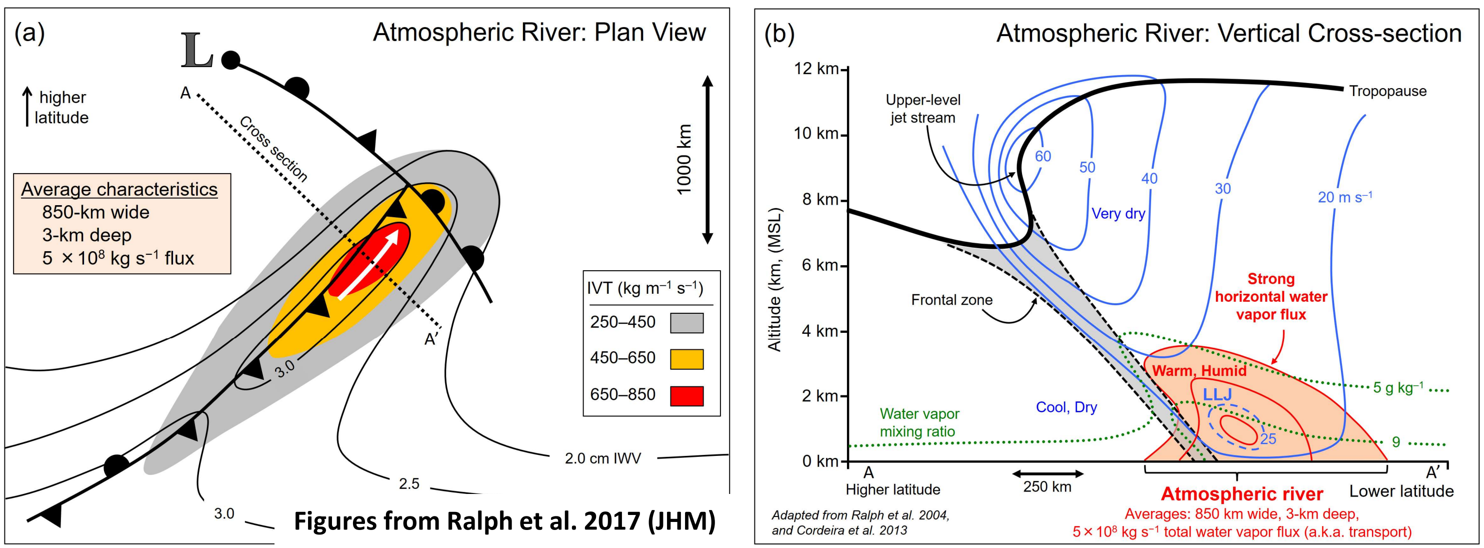


Fig. from Dettinger, Ralph, Lavers, EOS 2015

ATMOSPHERIC RIVER

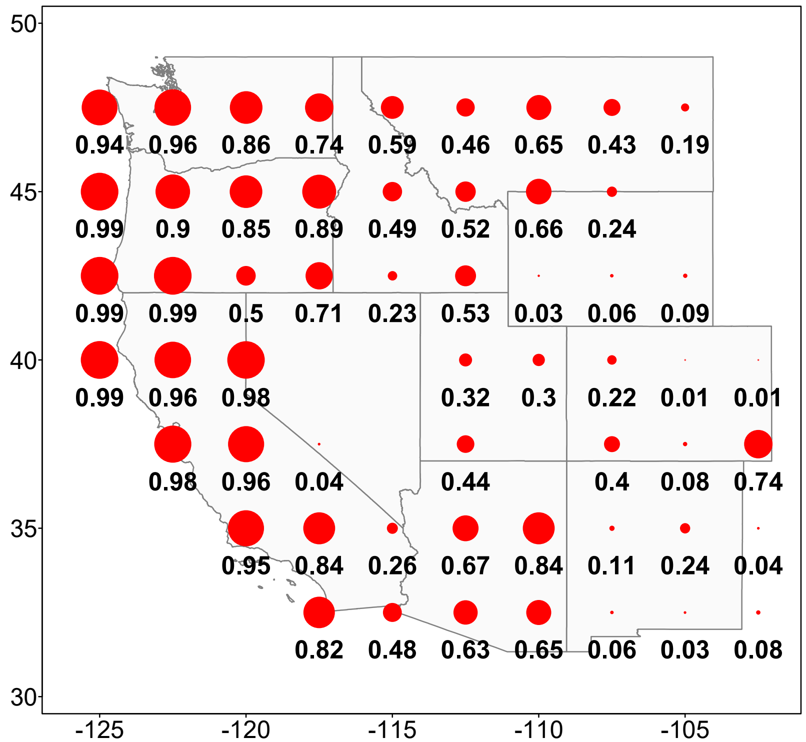
A long, narrow and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward, e.g., by mountains or by ascent in the warm-conveyor-belt. Horizontal water vapor transport in the mid-latitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.



Figures from Ralph et al. 2017 (JHM)

ARs drive economic flood losses

Proportion of Economic Losses Due to ARs



84% of insured losses in the 11 western states were caused by ARs

Post-Fire debris flows pose a serious hazard. This case killed >20 people near Montecito, CA.

T. Corringham, 2018

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A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

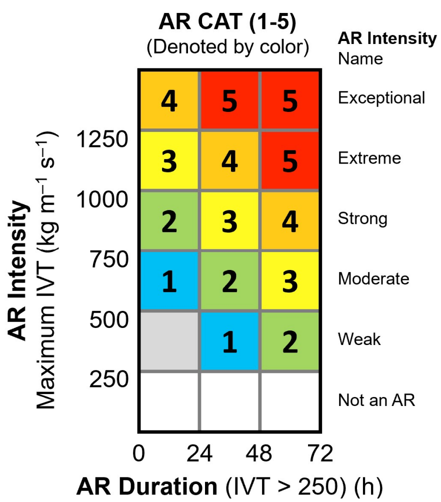
F. Martin Ralph (SIO/CW3E), J. J. Rutz (NWS), J. M. Cordeira (Plymouth State), M. Dettinger (USGS), M. Anderson (CA DWR), D. Reynolds (CIRES), L. Schick (USACE), C. Smallcomb (NWS); *Bull. Amer. Meteor. Soc. 269-289 (2019);*

The AR CAT level of an AR Event* is based on its *Duration* and max *Intensity* (IVT)*****

** An "AR Event" refers to the existence of AR conditions at a specific location for a specific period of time.*
*** How long IVT>250 at that location. If duration is <24 h, reduce AR CAT by 1, if longer than 48 h, add 1.*
**** This is the max IVT at the location of interest during the AR.*

IMPACTS

- AR Cat 5 – Primarily hazardous
- AR Cat 4 – Mostly hazardous, also beneficial
- AR Cat 3 – Balance of beneficial and hazardous
- AR Cat 2 – Mostly beneficial, also hazardous
- AR Cat 1 – Primarily beneficial



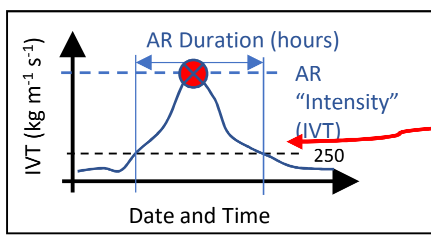
Determining AR Intensity and AR Category

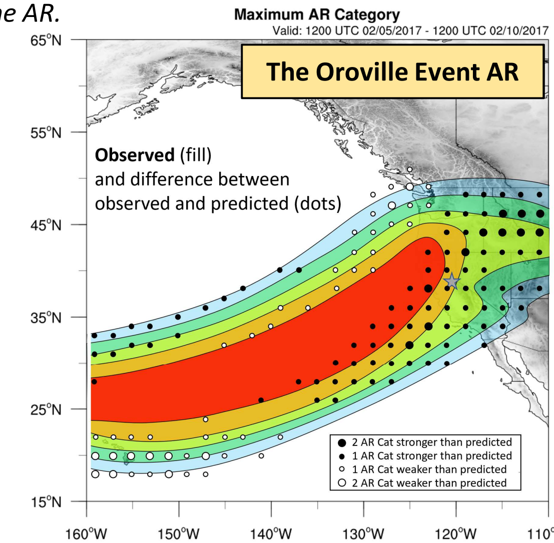
Step 1: Pick a location

Step 2: Determine a time period when IVT > 250 (using 3 hourly data) at that location, either in the past or as a forecast. The period when IVT continuously exceeds 250 determines the start and end times of the AR, and thus also the **AR Duration** for the AR event at that location.

Step 3: Determine **AR Intensity**
- Determine max IVT during the AR at that location
- This sets the AR Intensity and *preliminary* AR CAT

Step 4: Determine *final* value of **AR CAT** to assign
- If the AR Duration is > 48 h, then promote by 1 Category
- If the AR Duration is < 24 h, then demote by 1 Category

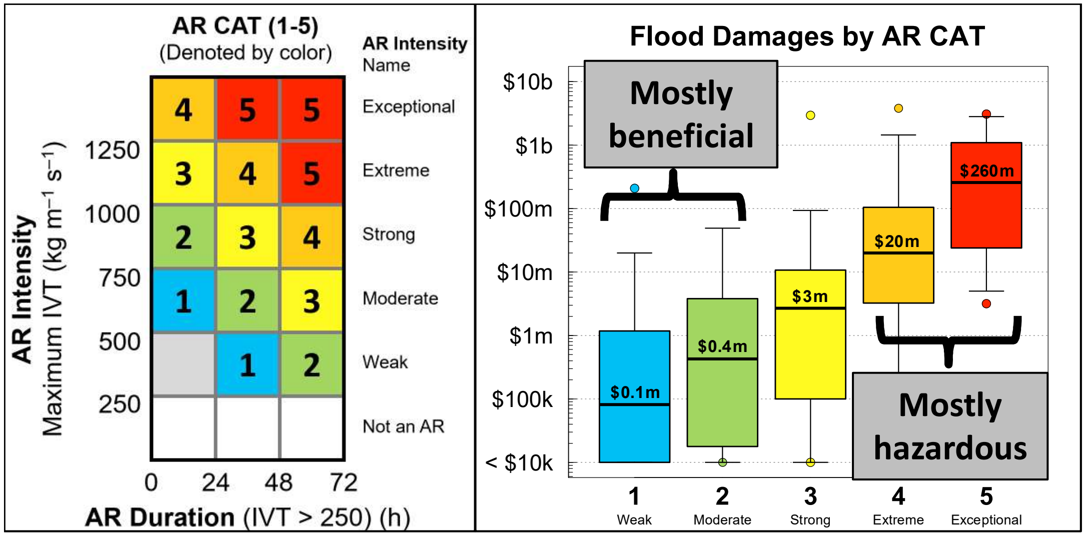




On the Web: CW3E.UCSD.EDU
On Twitter: @CW3E_Scripps

Center for Western Weather and Water Extremes

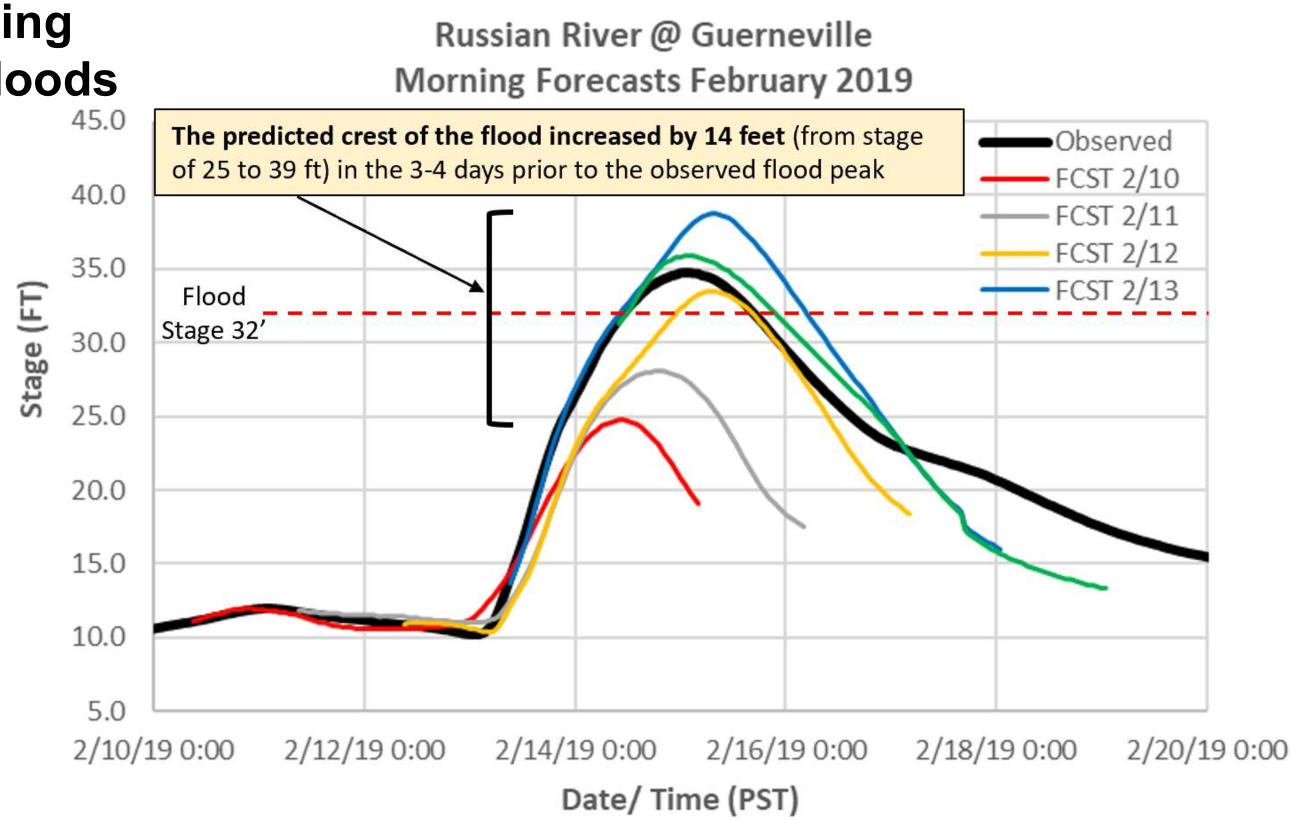
ARs drive flood damages in the western U.S.



Ralph et al. BAMS 2019 Corringham et al. Sci. Advances 2019

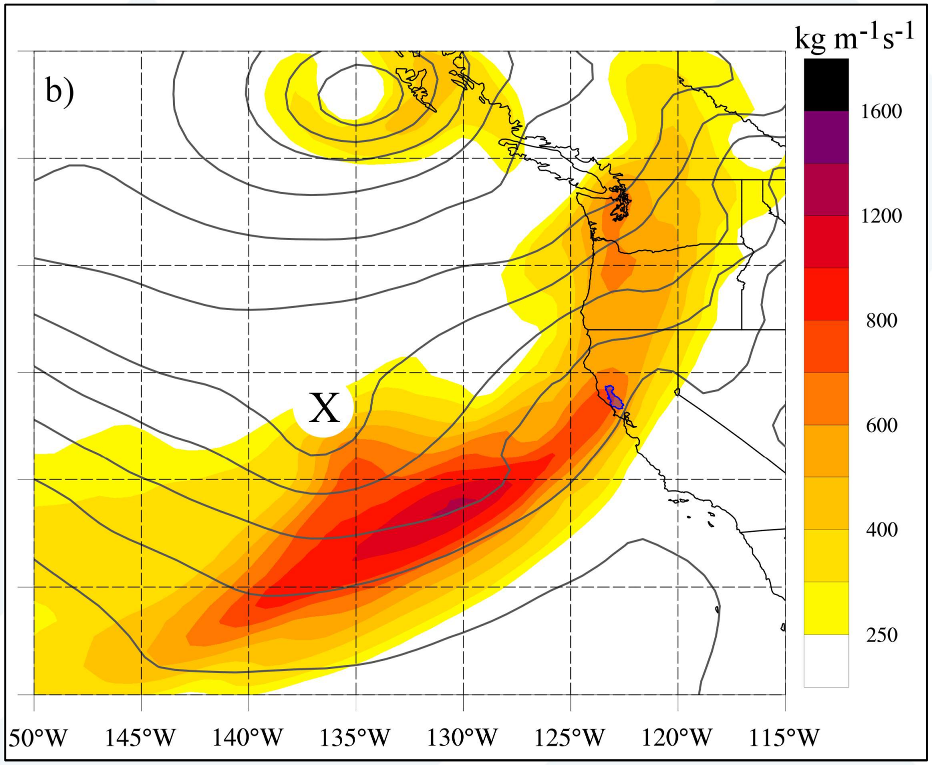
Flood damages increase exponentially with AR Category

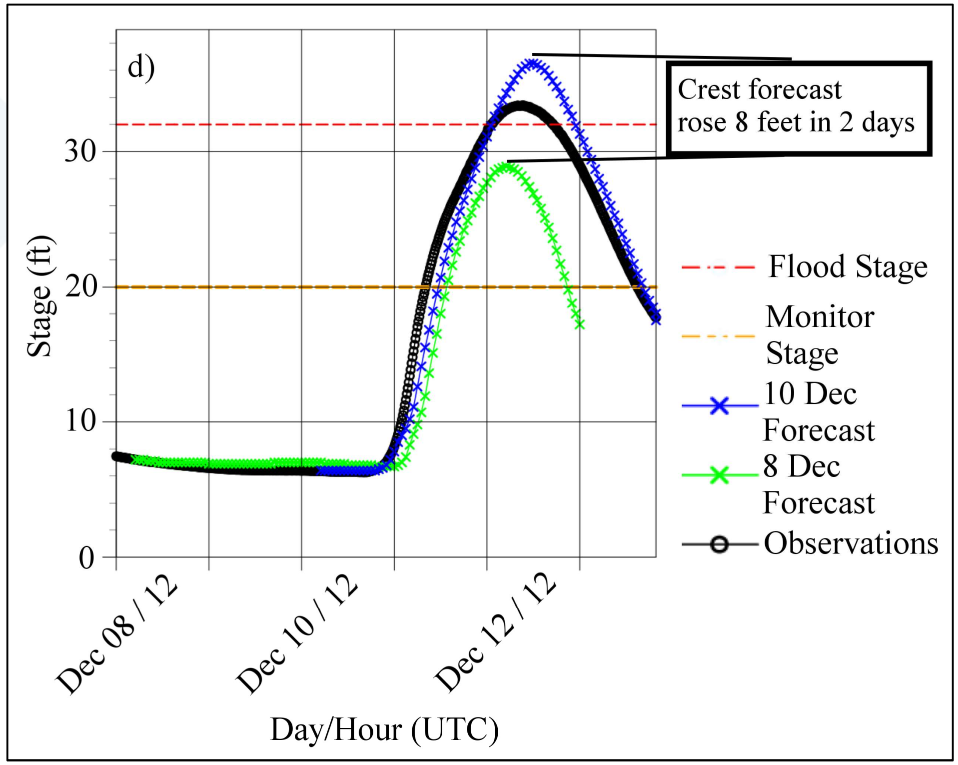
The Forecasting Challenge: Floods



Each line represents a different forecast (FCST) issued on either 10, 11, 12, 13 or 14 Feb, which were either 0, 1, 2, 3, or 4 days prior to when the flood crest was observed.

ERRORS IN PREDICTING THE STRUCTURE AND STRENGTH OF AN ATMOSPHERIC RIVER CAN CREATE MAJOR ERRORS IN FLOOD FORECASTS





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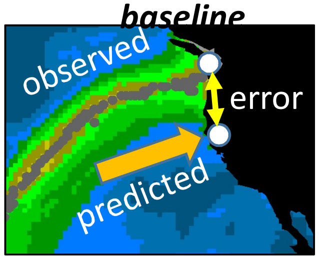
A. Martin, F.M. Ralph, A. Wilson, L. DeHaan, B. Kawzenuk
(J. Hydrometeor., 2019)

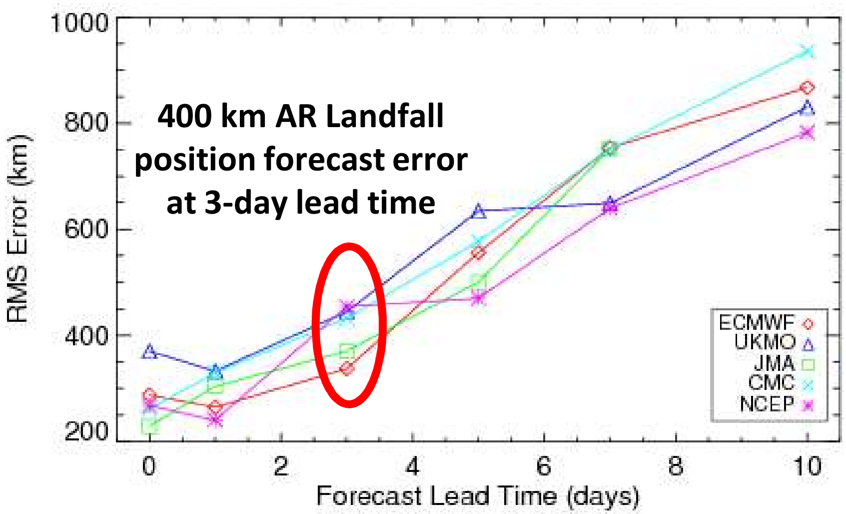
Atmospheric River Reconnaissance

FM Ralph (Scripps/CW3E), V Tallapragada (NWS/NCEP), J Doyle (NRL)

Water managers, transportation sector, agriculture, etc… require improved atmospheric river (AR) predictions

AR Forecast skill assessment establishes a performance baseline





Wick, G.A., P.J. Neiman, F.M. Ralph, and T.M. Hamill, 2013: Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. *Wea. Forecasting*, **28**, 1337-1352.

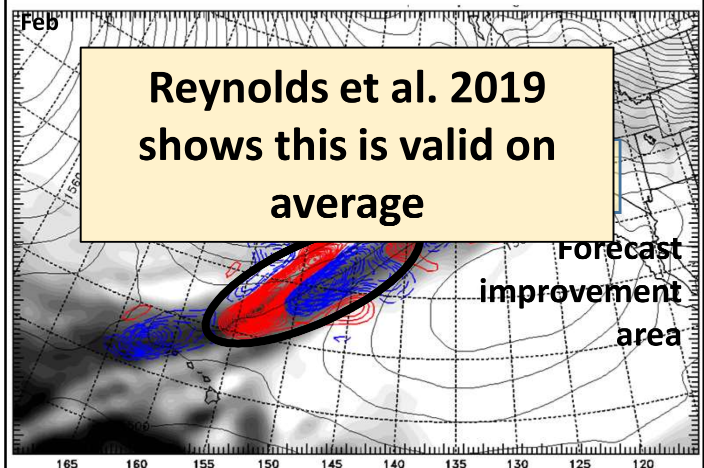
New Adjoint includes moisture – and finds AR is prime target

36-h Sensitivity (Analysis) 00Z 13 February (Final Time 12Z 14 February 2014)

J. Doyle, C. Reynolds, C. Amerault, F.M. Ralph

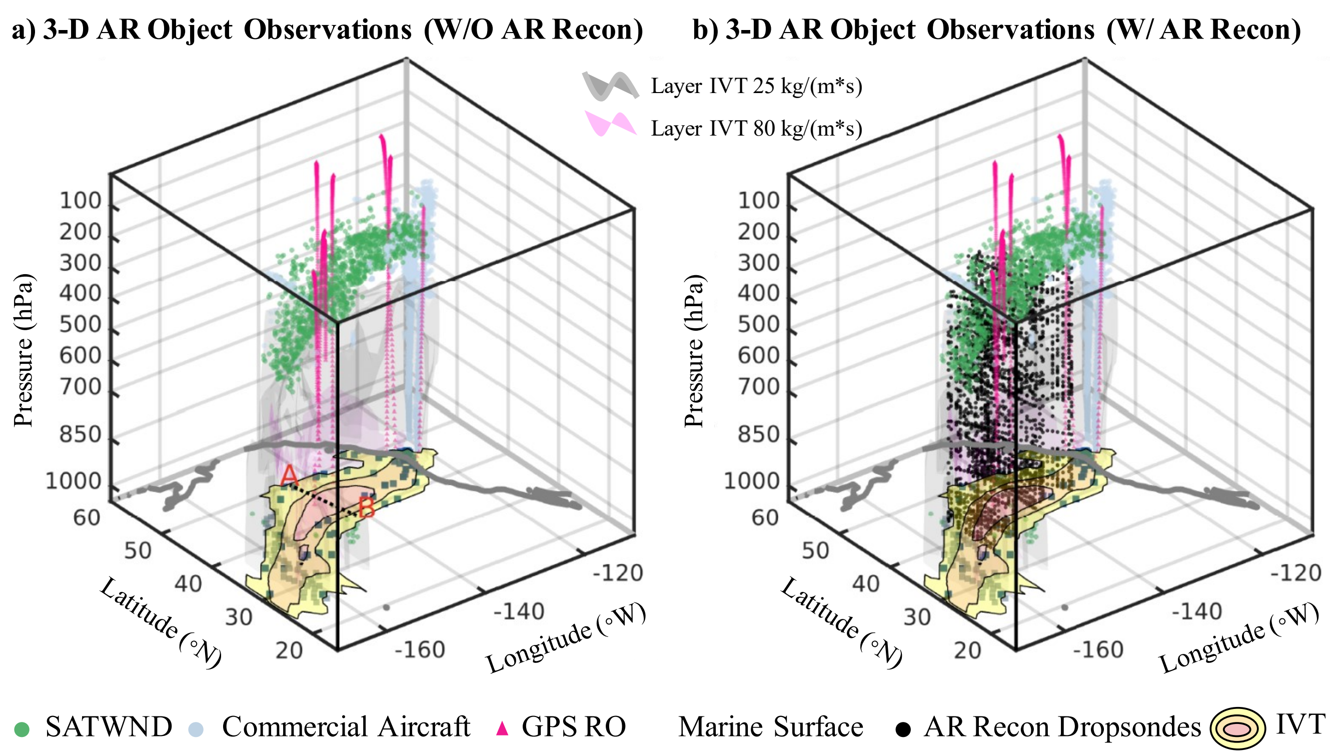
(International Atmospheric Rivers Conference 2016)

Color contours show the forecast sensitivity to 850 mb water vapor (grey shading) uncertainty at analysis time 00Z 13 Feb 2014 for a 36-h forecast over NorCal valid 12Z 14 Feb

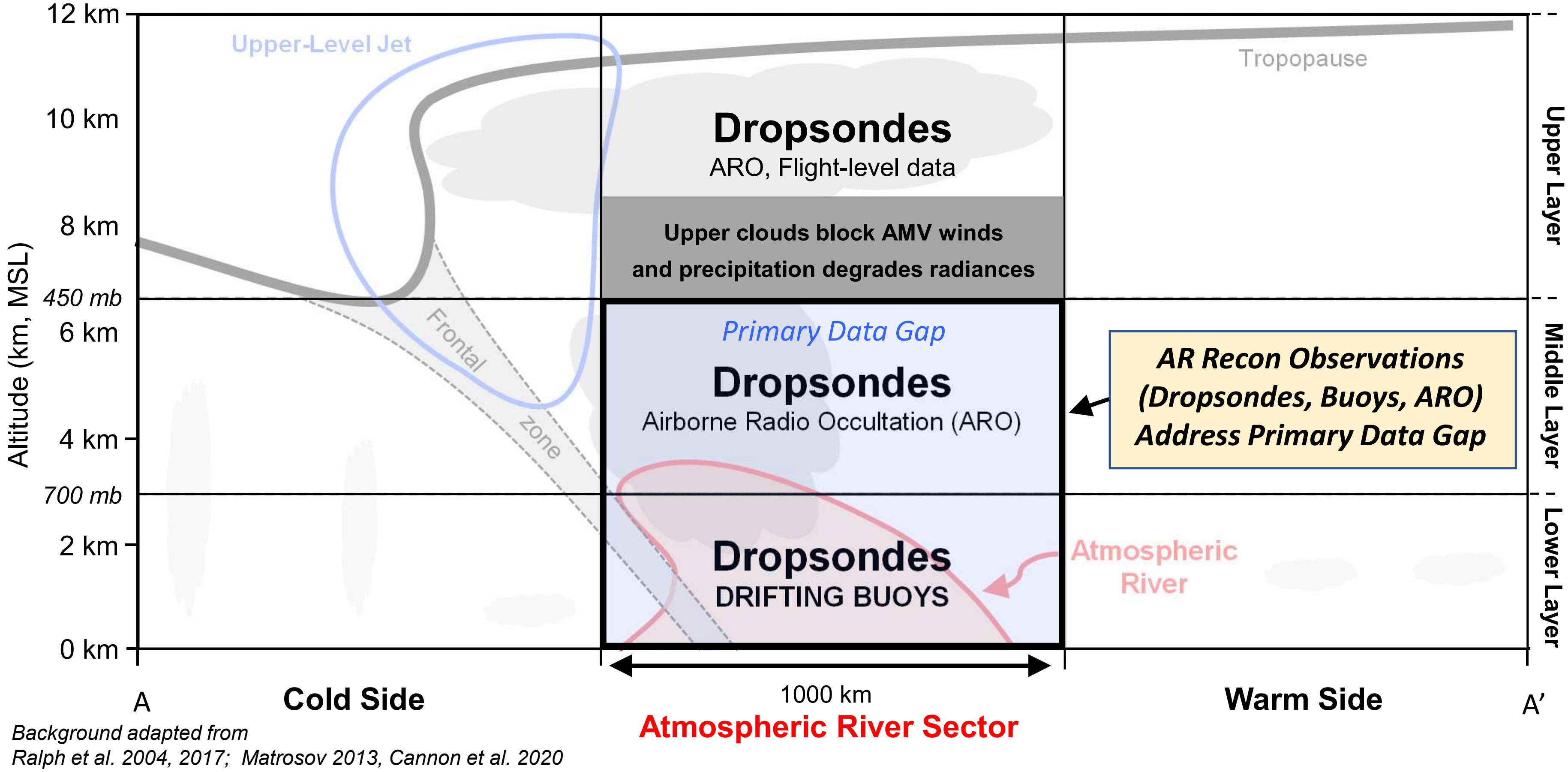


- Moisture sensitivity is strongest along AR axis; located > 2000 km upstream
- **Moisture sensitivity substantially larger than temp. or wind sensitivity.**

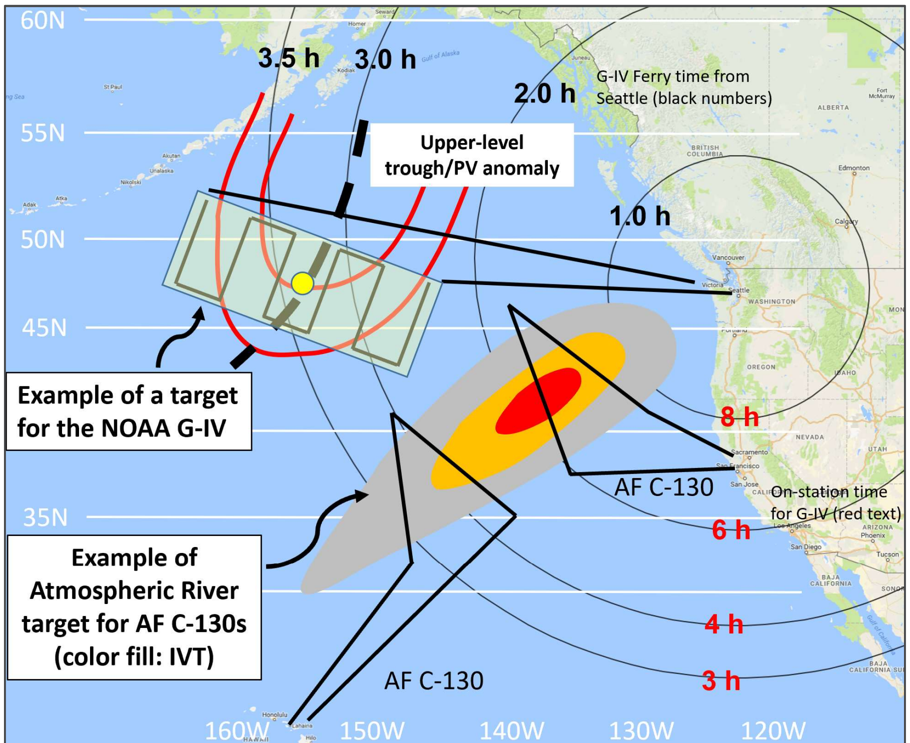
OBSERVATION DENSITY ANALYSIS

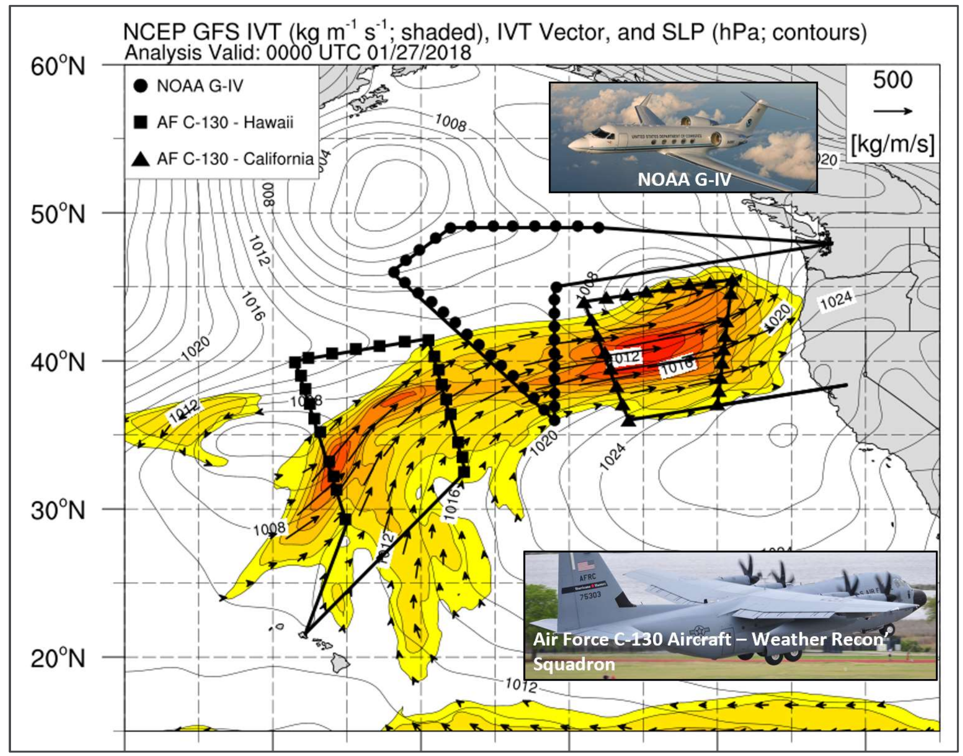


Lead: Minghua Zheng


12 km
10 km
8 km
450 mb
6 km
4 km
700 mb
2 km
0 km
Altitude (km, MSL)
Upper-Level Jet
Tropopause
Frontal zone
Dropsondes
ARO, Flight-level data
Upper clouds block AMV winds
and precipitation degrades radiances
Primary Data Gap
Dropsondes
Airborne Radio Occultation (ARO)
Dropsondes
DRIFTING BUOYS
AR Recon Observations
(Dropsondes, Buoys, ARO)
Address Primary Data Gap
Atmospheric
River
Upper Layer
Middle Layer
Lower Layer
A
Cold Side
1000 km
Atmospheric River Sector
Warm Side
A′
Background adapted from
Ralph et al. 2004, 2017; Matrosov 2013, Cannon et al. 2020

Atmospheric River Reconnaissance Sampling Concept and Example from 27 Jan 2018

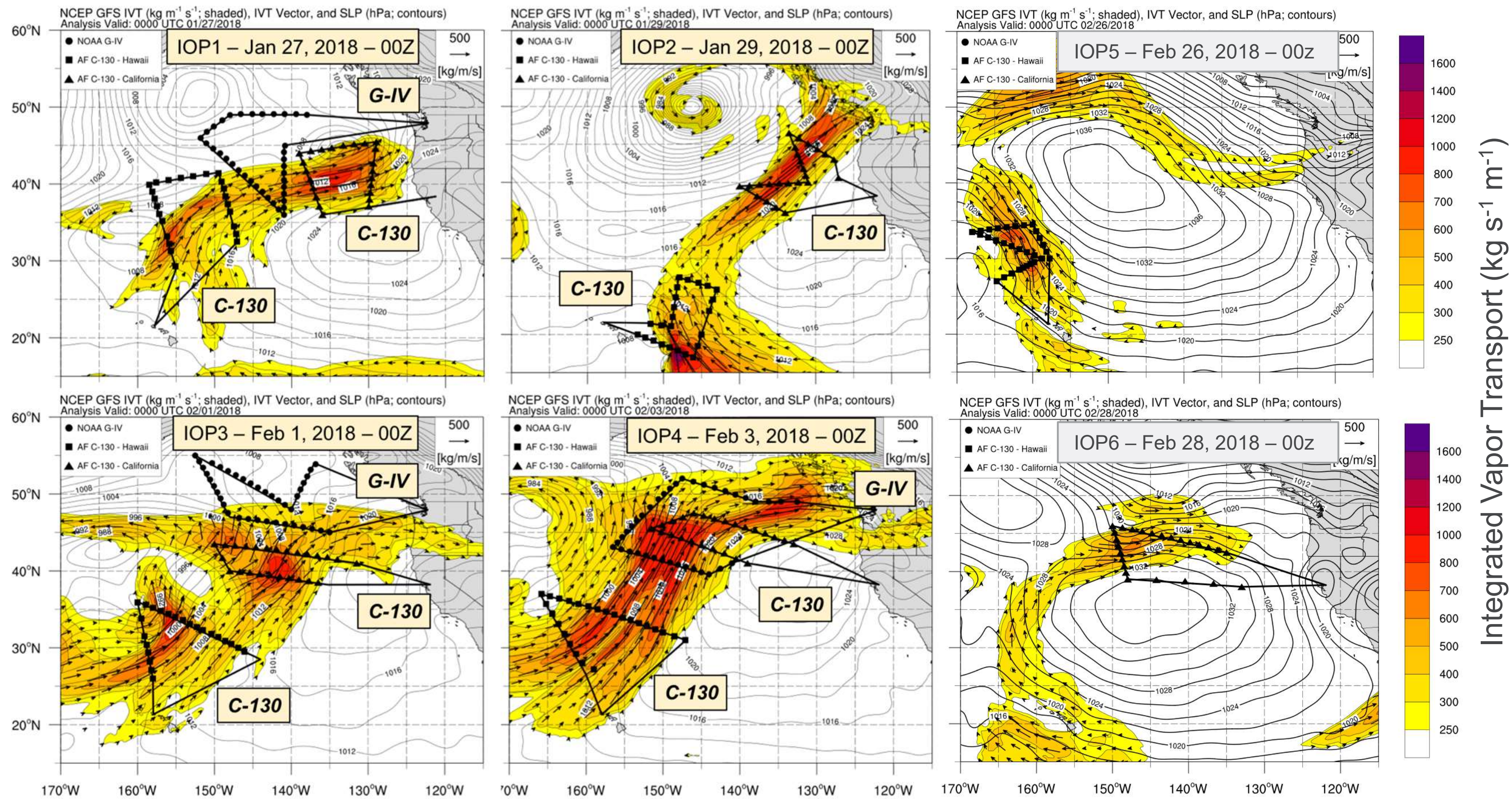




F. Martin Ralph (AR Recon PI; Scripps/CW3E), Vijay Tallaprgada (AR Recon Co-PI; NWS/NCEP) and AR Recon Team

Atmospheric River Reconnaissance 2018

Contacts: F. M. Ralph (PI; mralph@ucsd.edu); V. Tallapragada (Co-PI; vijay.tallapragada@noaa.gov)



AR Recon 2016 to 2021

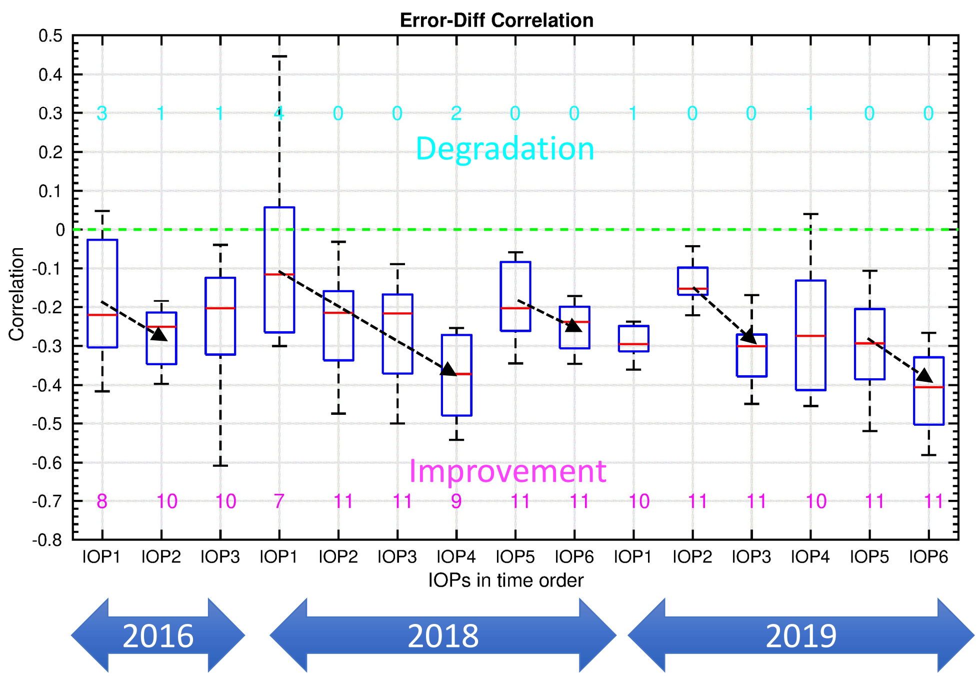
Two Air Force C-130s and NOAA's G-IV

- ✓ Feb 2016: 3 Storms (2 aircraft/storm; AF C-130s)
- ✓ Jan-Feb 2018: 6 Storms (3 aircraft/storm in 3 storms – 2 AF C-130s plus the NOAA G-IV (With Airborne GPS Radio Occultation, J. Haase); 2 C-130s in 1 storm; 1 C-130 in 2 storms)
- ✓ 1 Feb-14 Mar 2019:
  - Core program: 6 storms (2 AF C-130s/storm; 25 dropsondes/aircraft/storm flight; 300 sondes)
  - Addit'l data: 32 drifting buoys supplemented with barometers in AR Alley (L. Centurioni, B. Inglesby)
- ○ Jan-Mar 2020 **(ongoing)**: 16 storms (1-3 aircraft/storm)
- ○ 2021 and beyond: Long-term requirements captured in the US' National Winter Storm Operating Plan

- ○ **Target 2021: 24 IOPs with 3 aircraft sampling each storm**
- ✓ Interagency, International Steering Committee in place
  - Carry out assessments
  - Refine data assimilation methods
  - Create appropriate evaluation metrics
  - Provide impact results in peer-reviewed publications

Contacts
PI: F. M. Ralph (mralph@ucsd.edu)
Co-PI: V. Tallapragada
(vijay.tallapragada@noaa.gov)

Precip: % RMSE Reduction and Error-Diff Correlation—By IOP

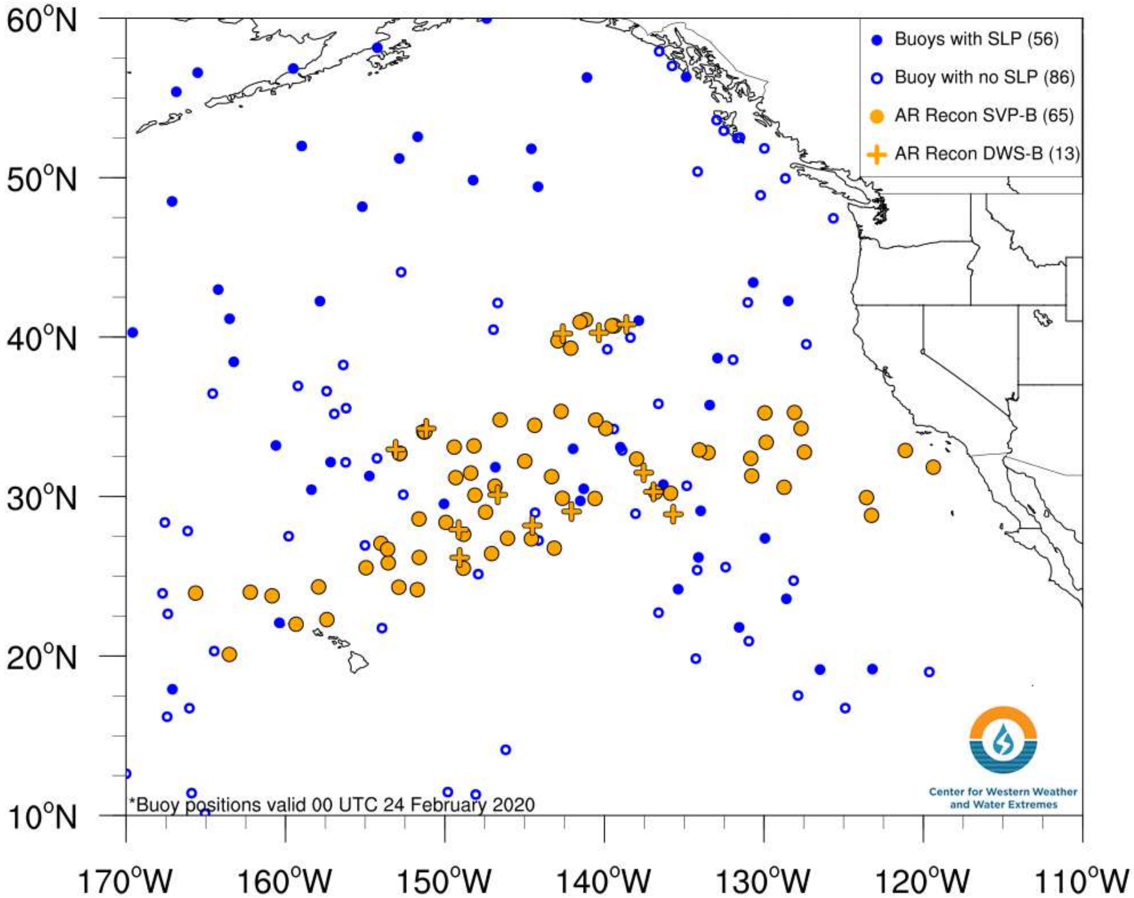


Improved IOP examples: 2016IOP2, 2018IOP4, 2019IOP6

Neutral IOP examples: 2018IOP1, 2018IOP5

The later IOPs in consecutive missions show largest improvement

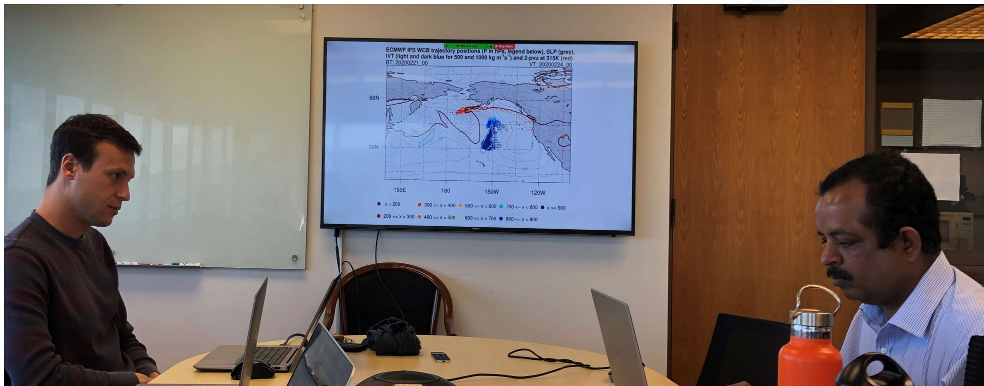
CW3E - AR RECON 2020 BUOY PROJECT



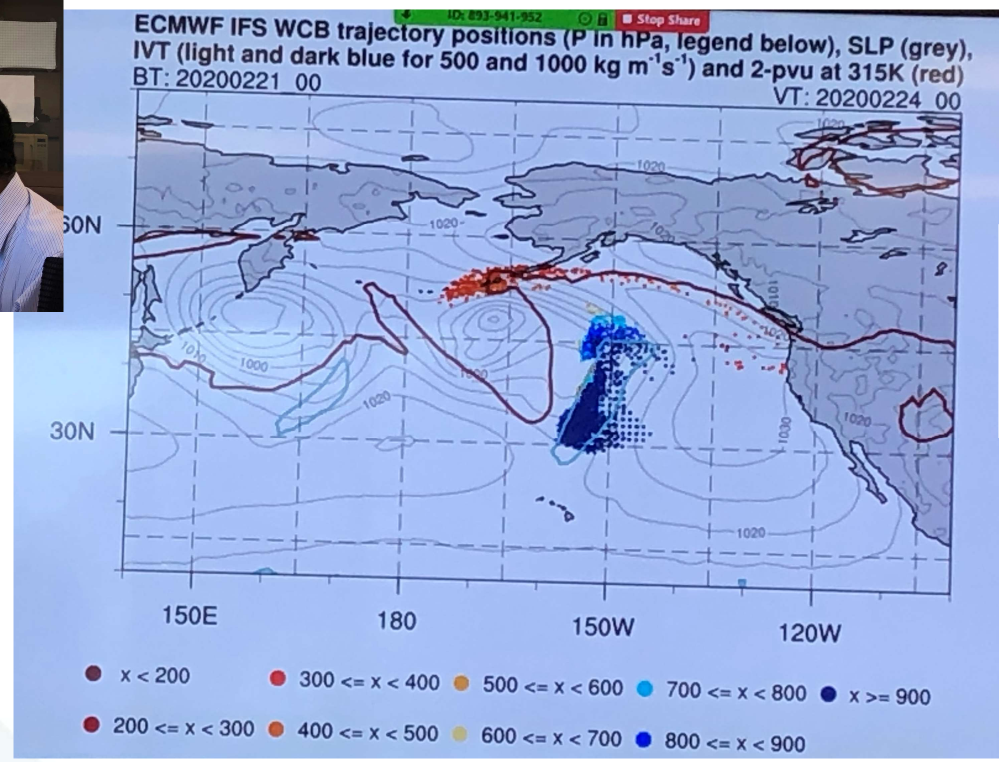
Purpose: To explore the potential of drifting buoys (with pressure sensors), in concert with AR Recon dropsondes and data assimilation efforts, to improve west coast forecasts of landfalling atmospheric rivers and precipitation. Supports California's Atmospheric Rivers Program (**PI: F.M. Ralph; CA Dept. of Water Resources – sponsor**).

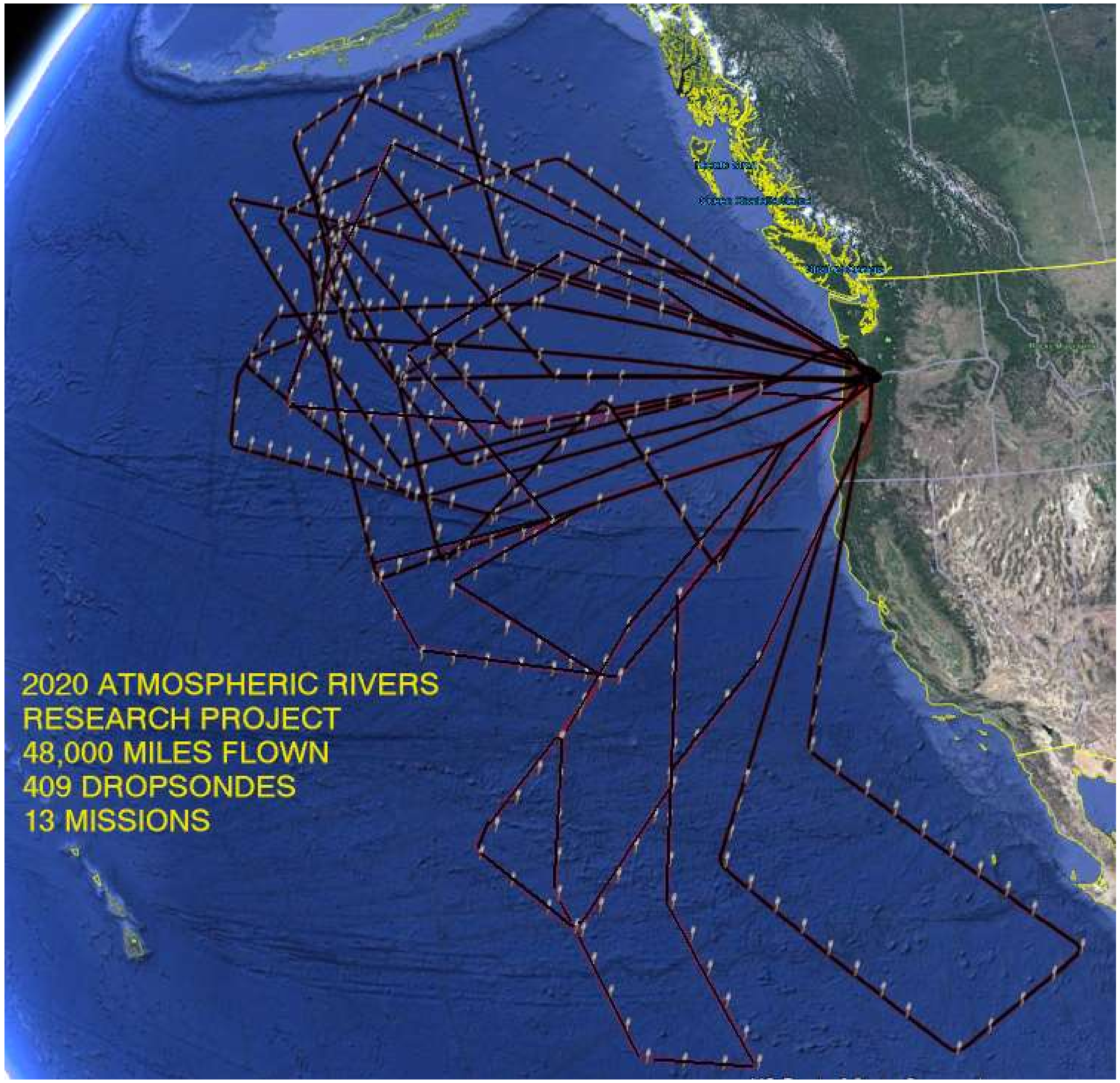
Partners: Deployment leverages the Global Drifter Program barometer upgrade program (**PI: Luca Centurioni, SIO; NOAA/OAR/OOMD – sponsor**); deployment is by the Air Force 53rd Weather Reconnaissance Squadron and by ship of opportunity arranged by L. Centurioni's group. Participation from the European Centre for Medium-Range Weather Forecasts (ECMWF) (**ECMWF Leads: Bruce Ingelby, David Lavers**).

WARM CONVEYOR BELT DIAGNOSTIC TOOL USED IN AR RECON-2020



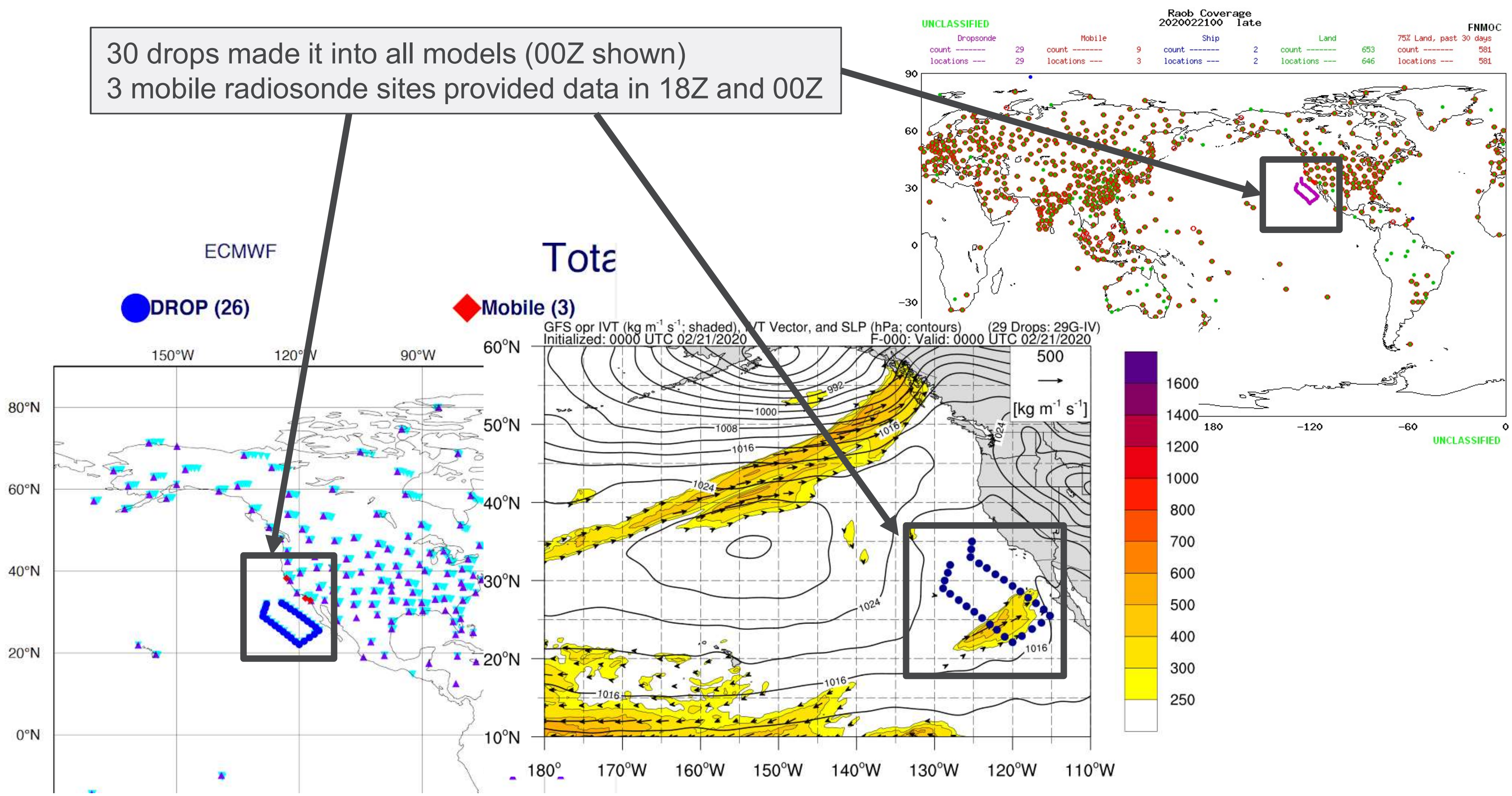
WCB Conditions are being considered in AR Recon 2020 flight planning: Products provided courtesy of H. Wernli, Hanin Binder and Maxi Boettcher




2020 ATMOSPHERIC RIVERS
RESEARCH PROJECT
48,000 MILES FLOWN
409 DROPSONDES
13 MISSIONS

Dropsondes Assimilated – IOP-10

30 drops made it into all models (00Z shown)
3 mobile radiosonde sites provided data in 18Z and 00Z

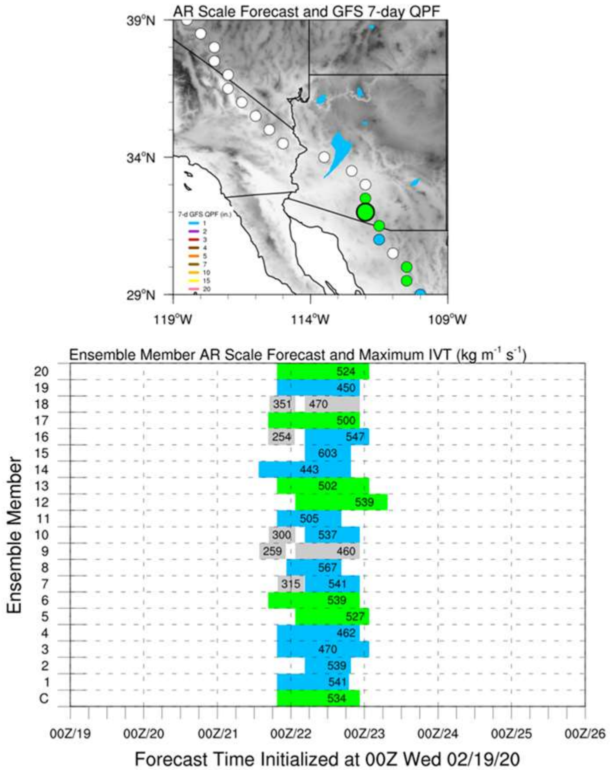


AR Scale Forecasts

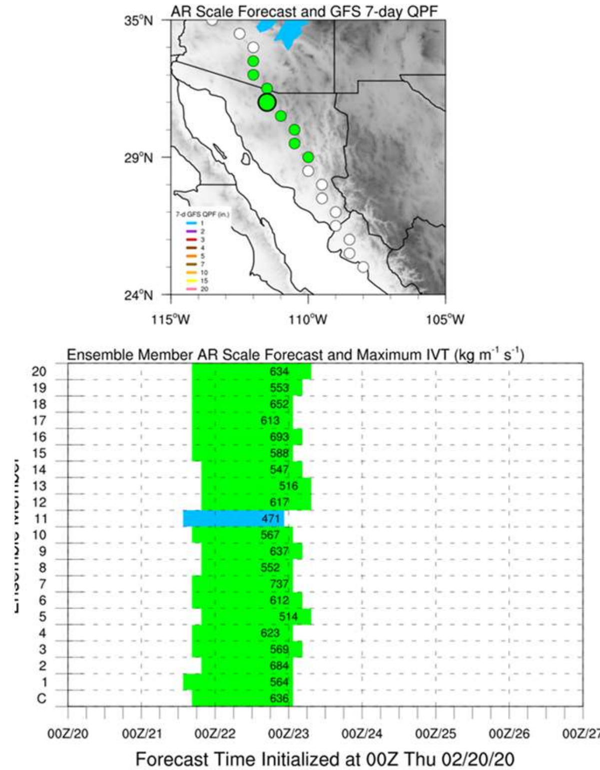
(Ralph et al. 2019, BAMS)

Center for Western Weather
and Water Extremes

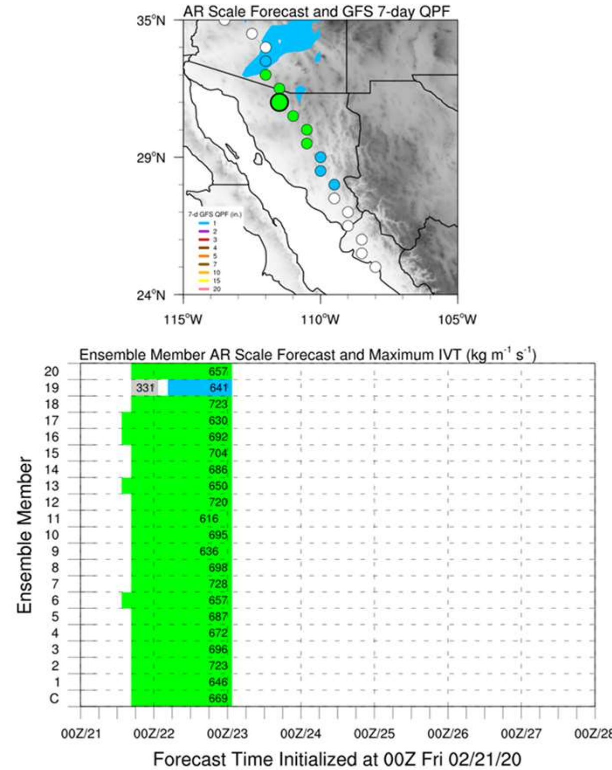
Issued: 00Z 19 Feb



Issued: 00Z 20 Feb



Issued: 00Z 21 Feb



Major storm "Dennis" just hit Europe - Here's how it looks using the AR Scale

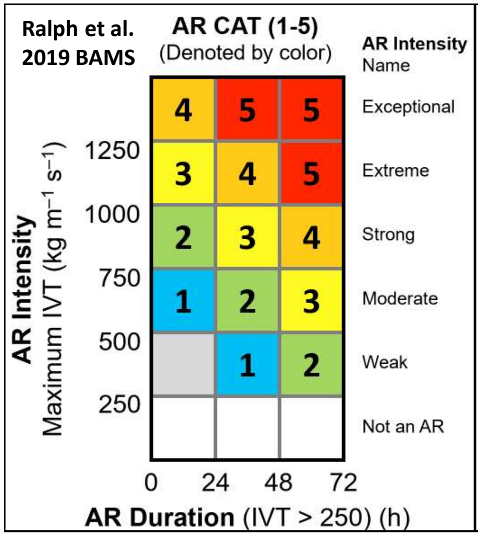

Storm Dennis, 2nd-strongest bomb cyclone on record in North Atlantic, causes severe flooding in Britain

The Washington Post

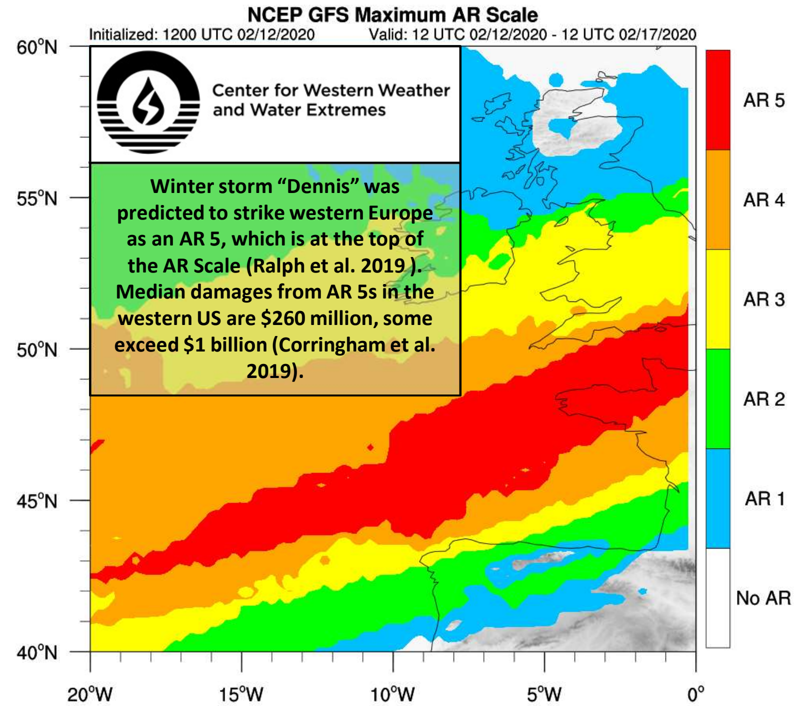
The storm dumped more than a month's worth of rain in parts of Wales in one day, flooding towns and prompting evacuations.

By Andrew Freedman

16 February 2020



The map to the right is an example of one of the CW3E AR Scale prototype displays, applied to storm "Dennis" that struck Western Europe on 14-16 Feb 2020.



Tools are being developed and tested at CW3E that assess the AR Scale ranking of predicted or recent ARs. Feedback on the prototype displays is being collected by forecasters and key forecast users. CW3E's AR Outlooks, and Storm Summaries now include the AR Scale. This information is being communicated to media when requested.

Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

F.M. Ralph, B. Kawzenuk, C. Hecht, J. Cordeira, J. Rutz (16 February 2020)

Atmospheric River Reconnaissance Workshop

29 June – 1 July 2020
Seaside Forum at the Scripps Institution of Oceanography, La Jolla, CA
Hosted by the Center for Western Weather and Water Extremes (CW3E.UCSD.EDU)

29 June – 1 July 2020

La Jolla, California

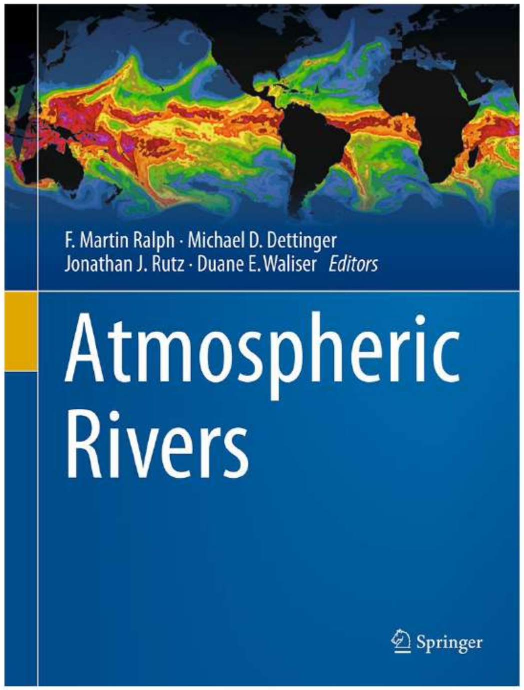
Atmospheric River Reconnaissance Strives to Improve Predictions of Land-falling Atmospheric Rivers and Their Associated Impacts in the Western U.S.

From 2015 to 2020, AR Recon grew from a concept to a field demonstration to an operational requirement and mission. It has gone from 3 storms flown over 2 weeks in 2016 to 12 flown over 8 weeks in 2020. It could reach 24 over 12 weeks in 2021. It uses two Air Force C-130s and the NOAA G-IV to carry out dropsonde missions and has partnered with the global drifter program to deploy roughly 100 drifting buoys with pressure sensors. Flight planning and calling of missions is carried out by a diverse team of scientists and forecasters, who consider input from multiple objective targeting methods and fundamental physical principles. A steering committee for modeling and data assimilation consisting of a multi-agency team of global modeling and science centers is working together to document and enhance impacts of the data.

WORKSHOP PURPOSE: DOCUMENT IMPACTS and ENVISION AR RECON IN 2025
The goals are to share results, to coordinate and inspire future work on data collection, data assimilation, metric development and impact assessment, and to discuss the research and operations partnership approach being developed in AR Recon.

The Workshop will bring together current participants and interested experts to share results of modeling, data assimilation and impact studies and to consider next steps for future field seasons. It will cover the following topics, using oral and poster sessions, as well as panel discussions:

- Flight planning, targeting and execution methods – refinements and expansion
- Verification and validation methods including use of the AR scale
- Data assimilation and impact studies, including new methods
- Evaluate potential impacts of AR Recon in the central and eastern US
- Identify leading sources of forecast errors, including role of mesoscale frontal waves
- Physical process studies enabled by AR Recon in support of western water applications
- Representing AR Recon in the NWSOP as a national mission focused on western water
- Potential for collaboration with European interests, including on warm conveyor belts
- Discuss a vision for AR Recon - 2025



1st ed. 2019, XX, 366 p. 172 illus., 160 illus. in color.

Printed book

Hardcover

81,99 € | £69.99 | $99.99
[1]87,73 € (D) | 90,19 € (A) | CHF

F.M. Ralph, M. Dettinger, J.J. Rutz, D.E. Waliser (Eds.)

Atmospheric Rivers

Available early 2020
Springer
20+ Contributing Authors

- Presents the latest research on a highly impactful extreme weather phenomenon with climatological importance both regionally and globally, and that has bearing on a variety of civil and commercial decision support areas
- Provides specific, research-based information on atmospheric rivers to help practitioners understand and explain the scientific basis of the weather pattern to non-practitioners and the general public
- Gives in-depth scientific information on atmospheric rivers within the broader topics of extratropical cyclones, weather and hydrological extremes, regional and global climate, as well as weather prediction and future climate projections

This book is the standard reference based on roughly 20 years of research on atmospheric rivers, emphasizing progress made on key research and applications questions and remaining knowledge gaps. The book presents the history of atmospheric-rivers research, the current state of scientific knowledge, tools, and policy-relevant (science-informed) problems that lend themselves to real-world application of the research—and how the topic fits into larger national and global contexts. This book is written by a global team of authors who have conducted and published the majority of critical research on atmospheric rivers over the past years. The book is intended to benefit practitioners in the fields of meteorology, hydrology and related disciplines, including students as well as senior researchers.

Center for Western Weather and Water Extremes

ATMOSPHERIC RIVER RECONNAISSANCE:

SUPPORTING WESTERN STORM PREDICTIONS AND WATER DECISIONS

F. Martin Ralph, PI (UC San Diego/SIO/CW3E)

Vijay Tallapragada Co-PI (NOAA/NWS/NCEP)

Jim Doyle (Naval Research Laboratory)

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AR Recon

Papers Published to Date (Results)

Demirdjian, R., Doyle, J.D., Reynolds, C.A. Norris, J.A., Michaelis, A.C., Ralph, F.M., 2019: A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model. Journal of the Atmospheric Sciences, 0, DOI 10.1175/JAS-D-19-0155.1

Guan, B., D. Waliser, and F. Ralph, 2017: An inter-comparison between reanalysis and dropsonde observations of the total water vapor transport in individual atmospheric rivers. Journal of Hydrometeorology, 19, 321-337, doi:10.1175/JHM-D-17-0114.1

Lavers, D.A., M.J. Rodwell, D.S. Richardson, F.M. Ralph, J.D. Doyle, C.A. Reynolds, V. Tallapragada, and F. Pappenberger, 2018: The Gauging and Modeling of Rivers in the Sky. Geophysical Research Letters, 45, https://doi.org/10.1029/2018GL079019

Ralph, F., S. Iacobellis, P. Neiman, J. Cordeira, J. Spackman, D. Waliser, G. Wick, A. White, and C. Fairall, 2017: Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers. Journal of Hydrometeorology, 18, 2577-2596. doi:10.1175/BAMS-D-15-00245.1

Reynolds, C.A., J.D. Doyle, F.M. Ralph, and R. Demirdjian, 2019: Adjoint Sensitivity of North Pacific Atmospheric River Forecasts. Mon. Wea. Rev., 147, 1871-1897, https://doi.org/10.1175/MWR-D-18-0347.1

Stone, R.E., C.A. Reynolds, J.D. Doyle, R. Langland, N. Baker, D.A. Lavers, and F.M. Ralph, 2019: Atmospheric River Reconnaissance Observation Impact in the Navy Global Forecast System. Mon. Wea. Rev., 0, https://doi.org/10.1175/MWR-D-19-0101.1

A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model

Reuben Demirdjian[1], Jim Doyle[2], Carolyn Reynolds[2], Joel Norris[1], Allison Michaelis[1], F. Martin Ralph[1]
[1]UCSD/SIO/CW3E, [2]NRL (*J. Atmos. Sci.* 2020, in press)

Purpose of Study

- Diagnose the dynamical processes linking the initial condition sensitivities offshore in an adjoint model to errors in forecasts of AR landfall and associated precipitation

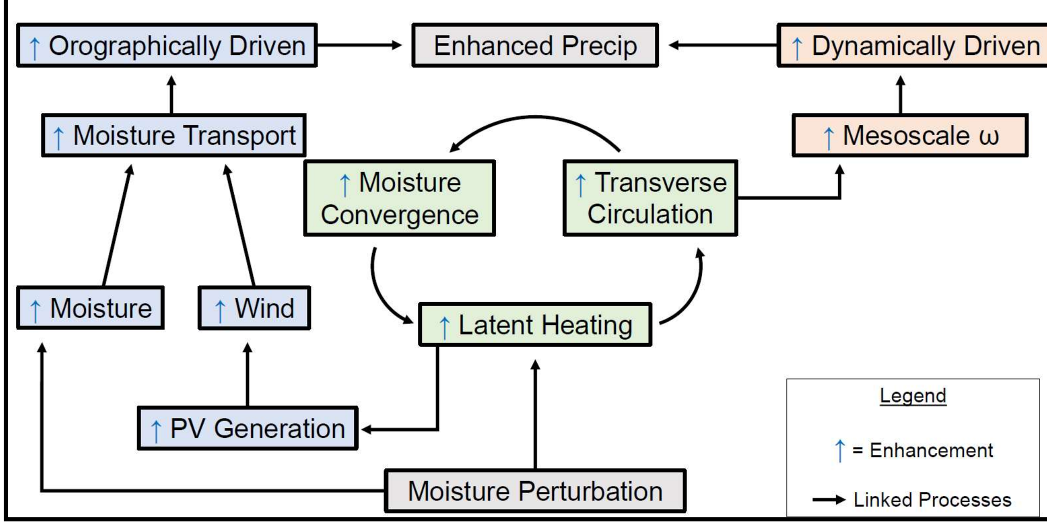
Why Bother?

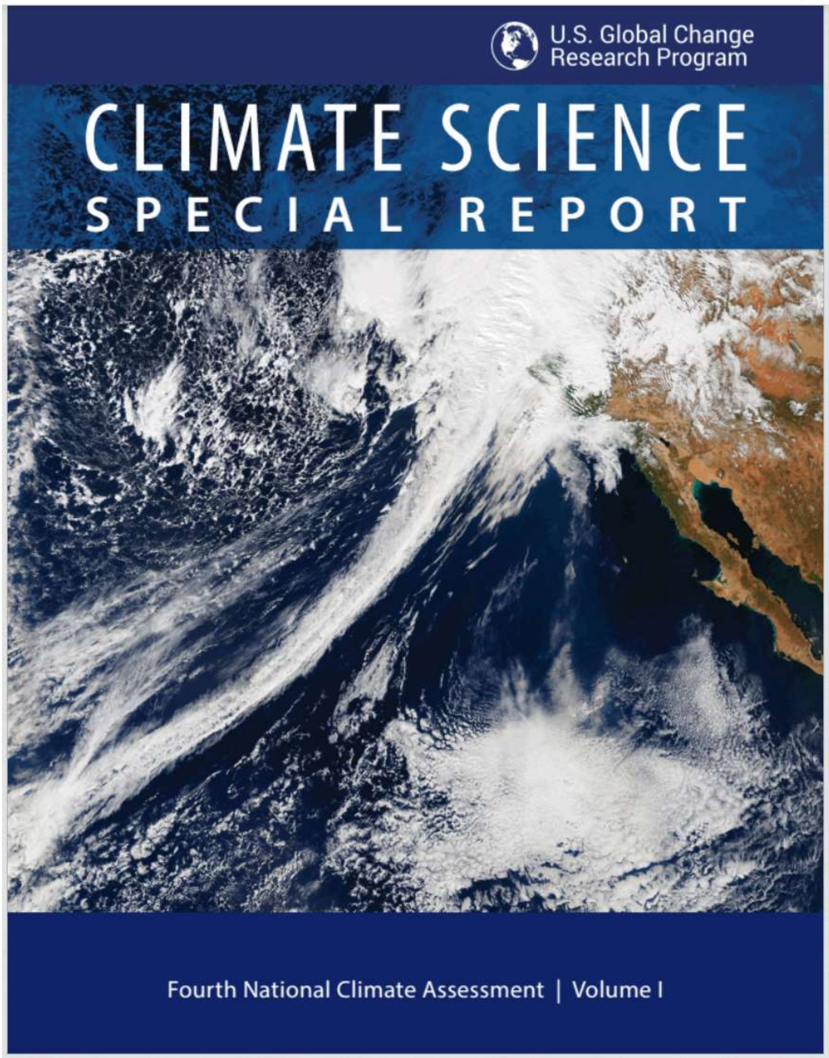
- To understand how errors in weather forecast model representation of AR initial conditions offshore can lead to errors in the prediction of AR landfall.

Result

- An error in water vapor initial condition within the AR modifies precipitation (both d*ynamically and orographically forced*) by amplifying the latent heating in a dynamical feedback process involving wind and PV anomalies that act to reinforce the initial perturbation.

Processes Leading to Changes in the Perturbed Run's Precipitation





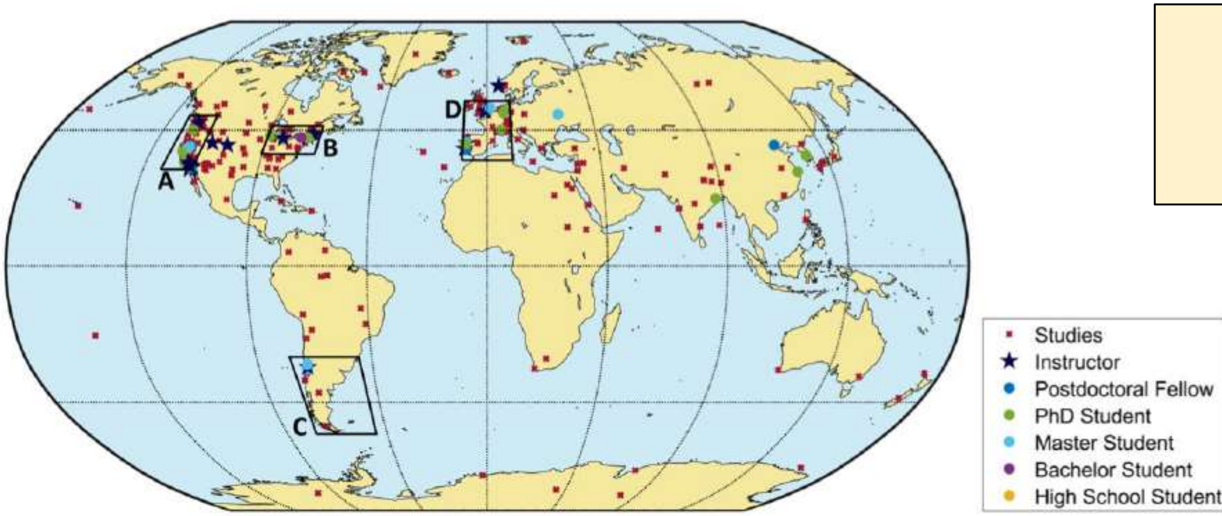
Atmospheric Rivers Highlighted in the U.S. Fourth National Climate Assessment, released on 3 November 2017

9

Extreme Storms

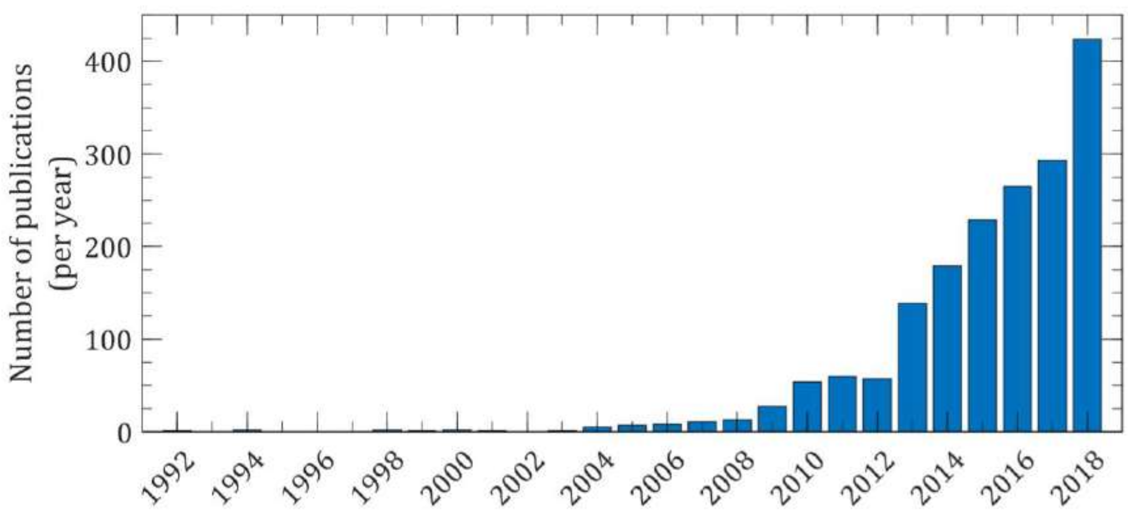
KEY FINDINGS

1. Hurricanes and Typhoons
2. Severe Thunderstorms
3. Winter storms
4. **Atmospheric Rivers (NEW in 4th Assessment)**



AR Are Being studied globally

Wilson et al. 2020 BAMS
AR Summer Colloquium
Meeting Summary
(in Press)



Rapid Growth in the Reference to ARs in Scientific Papers

Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers

F.M. Ralph, S. Iacobellus, P.J. Neiman, J. Cordeira, J.R. Spackman, D. Waliser, G. Wick, A.B. White, C. Fairall

J. Hydrometeorology (2017)

Method/Data: Uses 21 AR cases observed in 2005 - 2016 with full dropsonde transects.

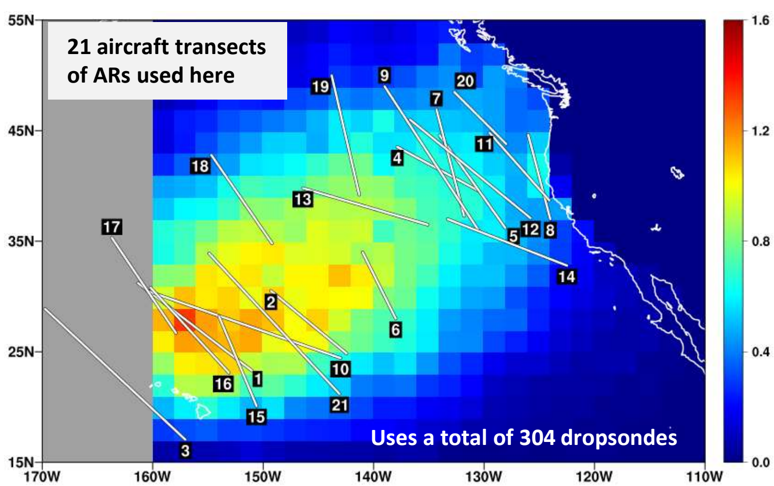
- AR edges best defined by using IVT = 250 kg m^{-1} s^{-1}

Conclusions*:

- Average width: 850 km
- 75% of water vapor transport occurs below 3 km MSL; < 1% occurs above 8 km MSL
- Average max IVT: ~800 kg m^{-1} s^{-1}

KEY FINDING

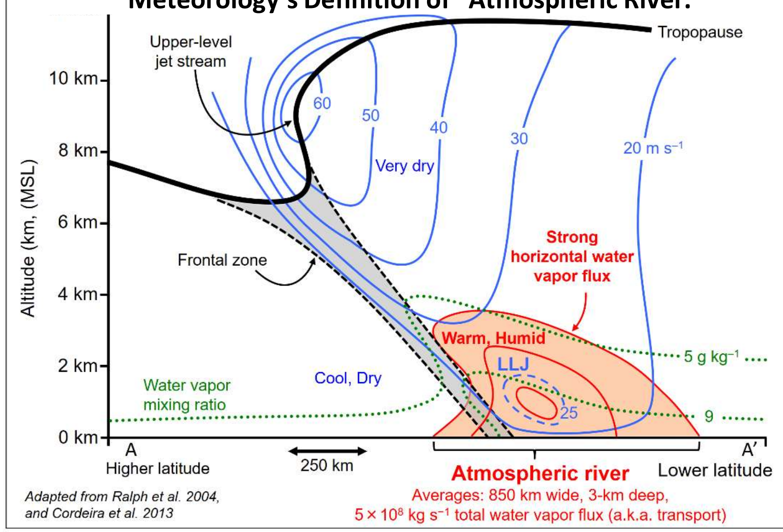
An average AR* transports 4.7 ± 2.0 x 10^8 kg s^{-1} of water vapor, which is equivalent to 2.6 times the average discharge of liquid water by the Amazon River



**These values represent averages for the Northeast Pacific Ocean in the January-March season*

Background image denotes weekly AR frequency during cool seasons (Nov -Feb).

Synthesis from 21 observed ARs; Used in the Glossary of Meteorology's Definition of "Atmospheric River."



International Atmospheric Rivers Conference IARC-2018

Seaside Forum at UC San Diego's Scripps Institution of Oceanography La Jolla, CA, 25-28 June 2018

Hosted by the "Center for Western Weather and Water Extremes"

Bringing together a diverse, cross-disciplinary community of scientists, engineers, forecasters and managers to discuss atmospheric river science and applications.

Center for Western Weather and Water Extremes

SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

First Circular: November 15, 2019

3IARC: Third International Atmospheric Rivers Conference
October 5-9, 2020

Atmospheric rivers (ARs) play a key role in the global water cycle as the primary mechanism conveying water vapor through mid-latitude regions. The precipitation that ARs deliver in many parts of the world, especially through orographic precipitation processes, is important for water resources; but it also regularly is a hazard, triggering floods and landslides, as well as coastal wind storms. The aims of the 2020 International Atmospheric Rivers Conference are:

- to understand dynamical and physical processes in ARs
- to describe the AR impact on hydrology, environment and society
- to evaluate the Atmospheric River Tracking Method Intercomparison Project's (ARTMIP)
- to assess current forecasting capabilities and developing applications
- to project ARs in a warmer world and understand their natural variability

Students are strongly encouraged to attend. Scholarships are available, as well as slots for student speakers.

Scientific Steering Committee:

Marty Ralph, Anna Wilson, Reuben Demirdjian (CW3E, UCSD, US); Hans Christian Steen-Larsen (U. of Bergen, Norway); Jon Rutz (US National Weather Service); Roberto Rondanelli, James McPhee (Universidad de Chile); Jorge Eiras-Barca (U. Vigo, Spain); Christine Albano (Desert Research Institute, US); Natalia Tilinina (Shirshov Institute of Oceanology, Russia); Mike Warner (US Army Corps of Engineers); Alexandre Ramos (University of Lisbon, Portugal); Maximiliano Viale (IANIGIA, Argentina)

For further information, please contact the *Local Organizing Committee*

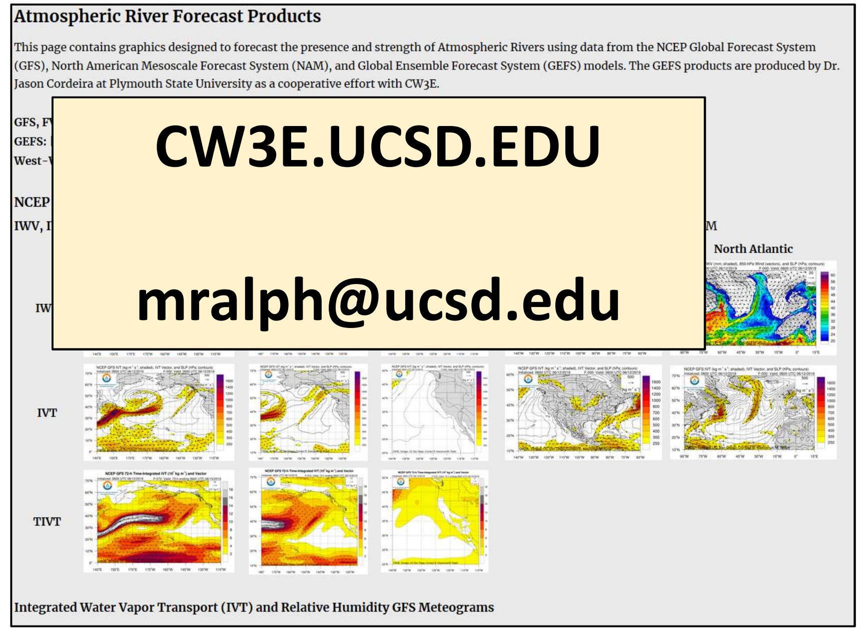
René Garreaud (rgarreau@dgf.uchile.cl) and Raul Valenzuela (rvalenzuela@dgf.uchile.cl)

Conference web site: http://www.dgf.uchile.cl/3IARC (available Dec 2019)

Center for Western Weather and Water Extremes

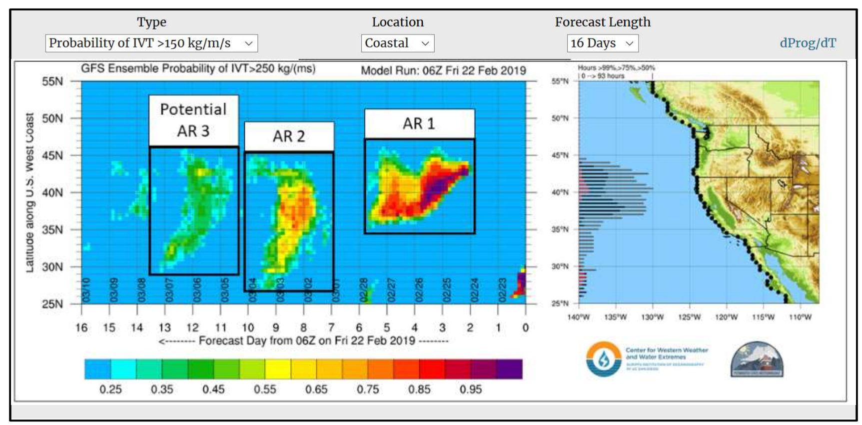
Geofísica
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS UNIVERSIDAD DE CHILE

(CR)²
Center for Climate and Resilience Research



CW3E.UCSD.EDU

mralph@ucsd.edu



Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

WEST COAST FORECAST CHALLENGES AND DEVELOPMENT OF ATMOSPHERIC RIVER RECONNAISSANCE

F. Martin Ralph
Director, Center for Western Weather and Water Extremes

Warm Conveyor Belt Workshop
European Center for Medium Range Weather Forecasting
10 March 2020, Virtual Meeting

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

Glossary of Meteorology

Added May 2017. Process described in Ralph, Dettinger, Cairns, Galarneau, Eylander, 2018, *Bull. Amer. Meteor. Soc.*, ***99***, pp 837-839.

ATMOSPHERIC RIVER

A long, narrow and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward, e.g., by mountains or by ascent in the warm-conveyor-belt. Horizontal water vapor transport in the mid-latitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.

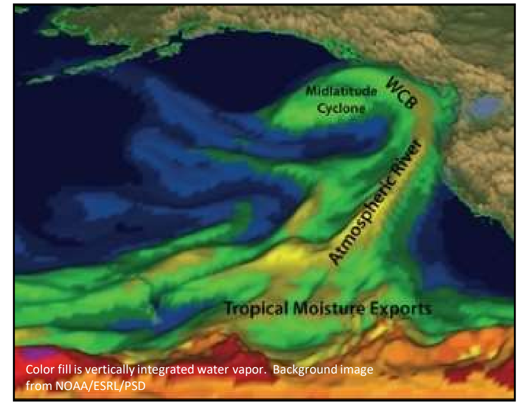
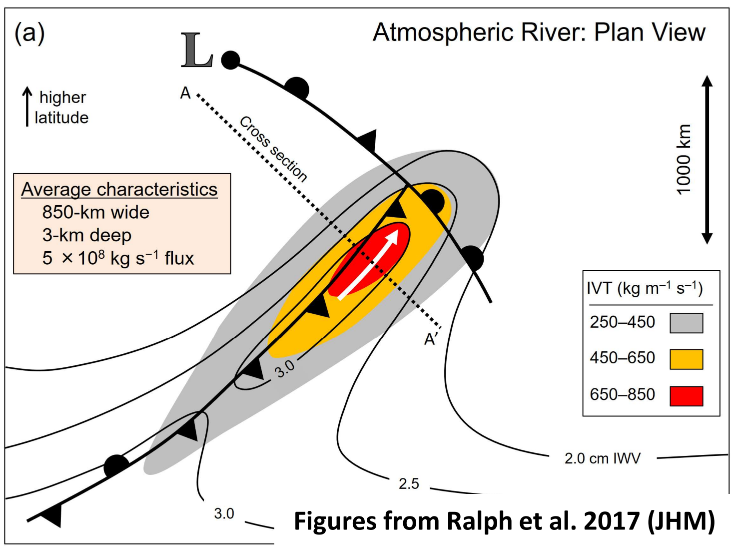
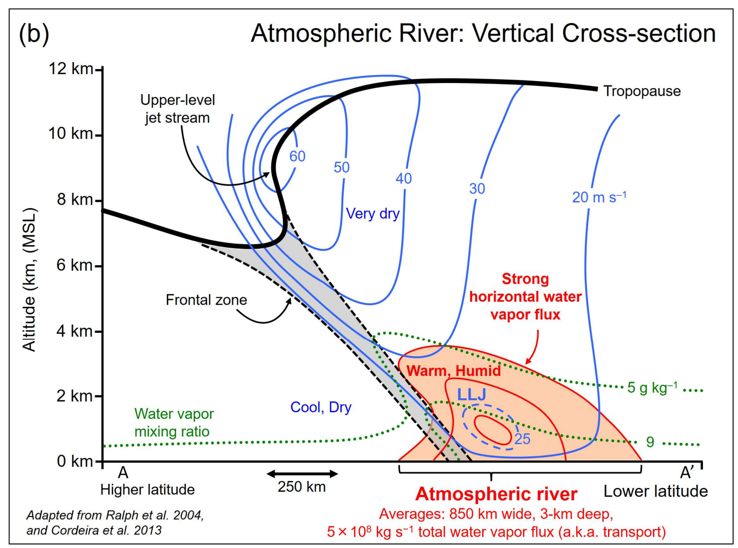


Fig. from Dettinger, Ralph, Lavers, EOS 2015

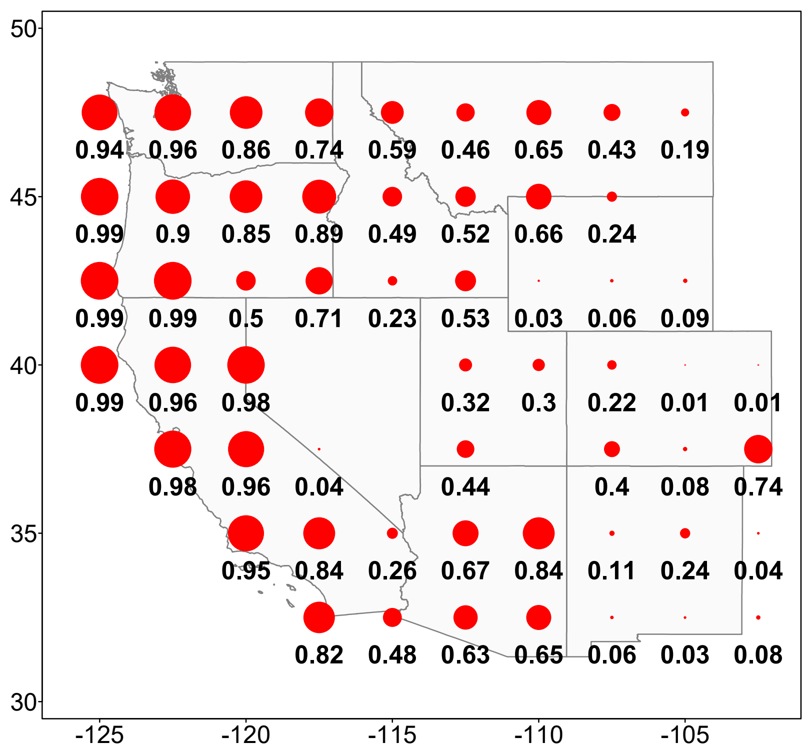




Figures from Ralph et al. 2017 (JHM)

ARs drive economic flood losses

Proportion of Economic Losses Due to ARs



84% of insured losses in the 11 western states were caused by ARs

Post-Fire debris flows pose a serious hazard. This case killed >20 people near Montecito, CA.

T. Corringham, 2018

SCRIPPS INSTITUTION OF OCEANOGRAPHY

A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

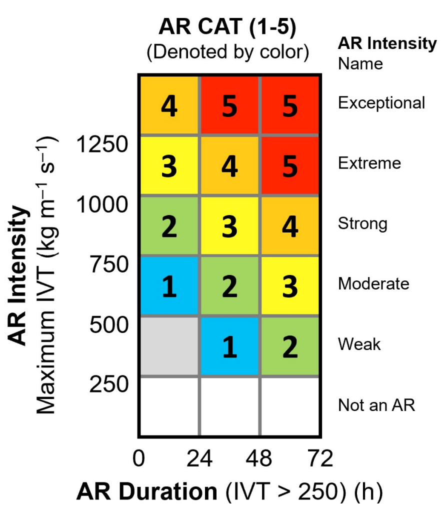
F. Martin Ralph (SIO/CW3E), J. J. Rutz (NWS), J. M. Cordeira (Plymouth State), M. Dettinger (USGS), M. Anderson (CA DWR), D. Reynolds (CIRES), L. Schick (USACE), C. Smallcomb (NWS); *Bull. Amer. Meteor. Soc. 269-289 (2019);*

The AR CAT level of an AR Event* is based on its *Duration* and max *Intensity* (IVT)*****

** An "AR Event" refers to the existence of AR conditions at a specific location for a specific period of time.*
*** How long IVT>250 at that location. If duration is <24 h, reduce AR CAT by 1, if longer than 48 h, add 1.*
**** This is the max IVT at the location of interest during the AR.*

IMPACTS

- AR Cat 5 – Primarily hazardous
- AR Cat 4 – Mostly hazardous, also beneficial
- AR Cat 3 – Balance of beneficial and hazardous
- AR Cat 2 – Mostly beneficial, also hazardous
- AR Cat 1 – Primarily beneficial



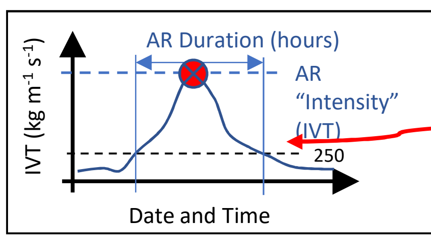
Determining AR Intensity and AR Category

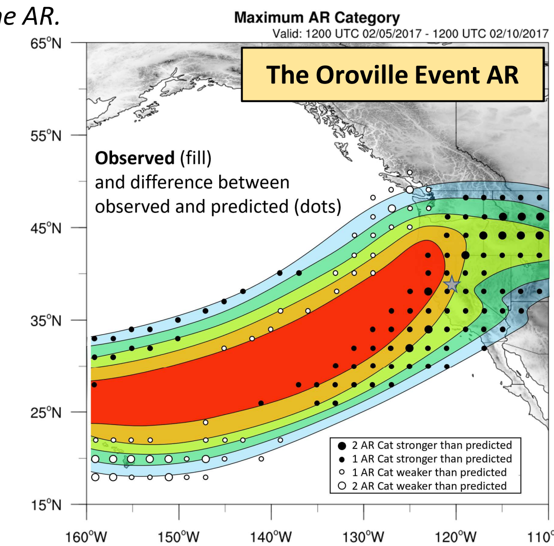
Step 1: Pick a location

Step 2: Determine a time period when IVT > 250 (using 3 hourly data) at that location, either in the past or as a forecast. The period when IVT continuously exceeds 250 determines the start and end times of the AR, and thus also the **AR Duration** for the AR event at that location.

Step 3: Determine **AR Intensity**
- Determine max IVT during the AR at that location
- This sets the AR Intensity and *preliminary* AR CAT

Step 4: Determine *final* value of **AR CAT** to assign
- If the AR Duration is > 48 h, then promote by 1 Category
- If the AR Duration is < 24 h, then demote by 1 Category

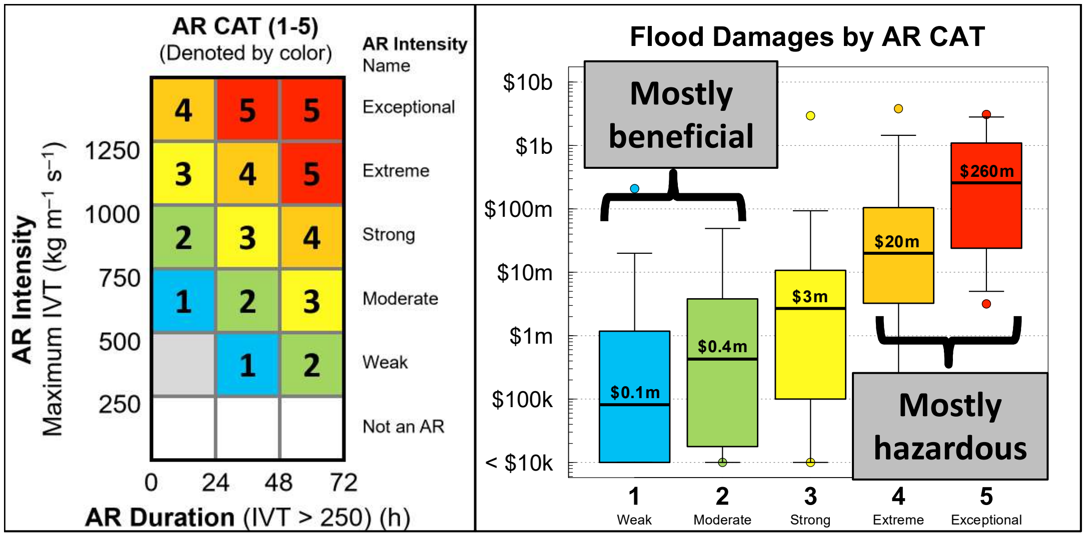




On the Web: CW3E.UCSD.EDU
On Twitter: @CW3E_Scripps

Center for Western Weather and Water Extremes

ARs drive flood damages in the western U.S.

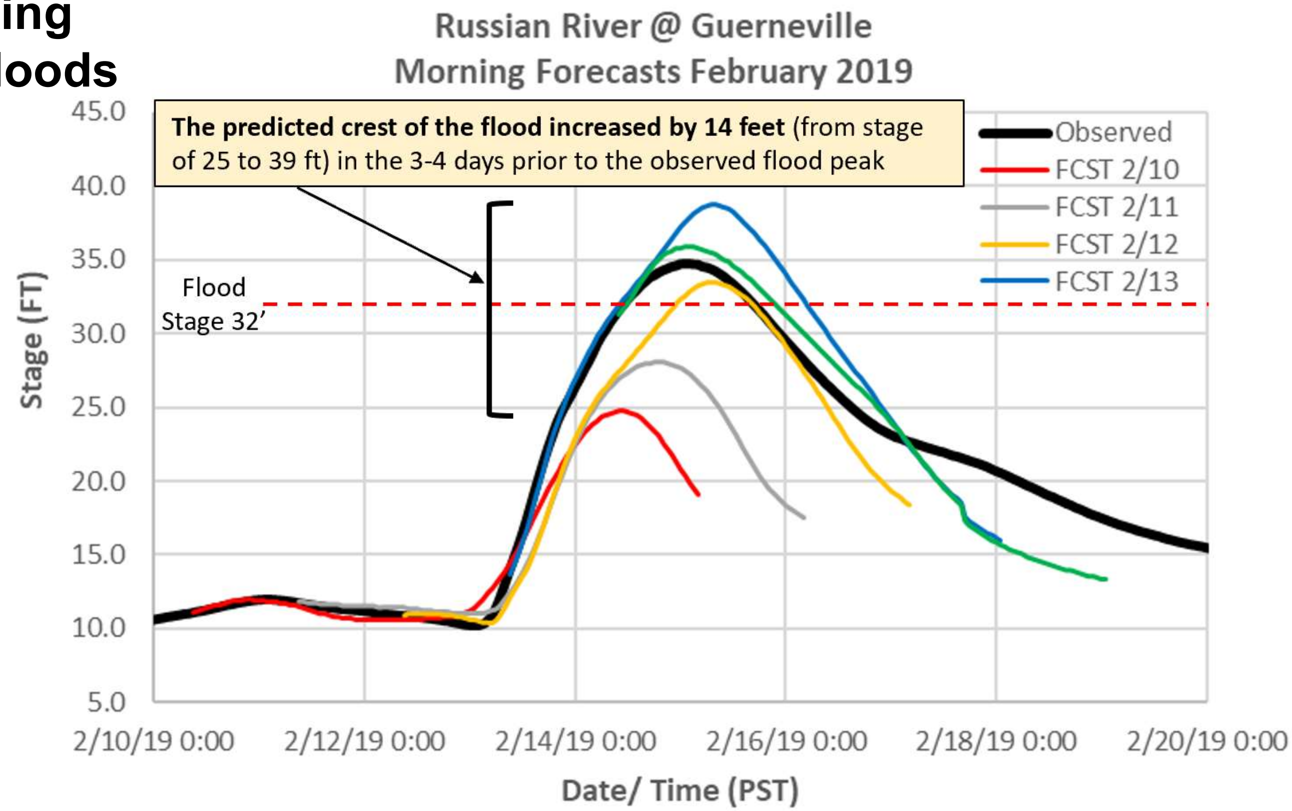


Ralph et al. BAMS 2019

Corringham et al. Sci. Advances 2019

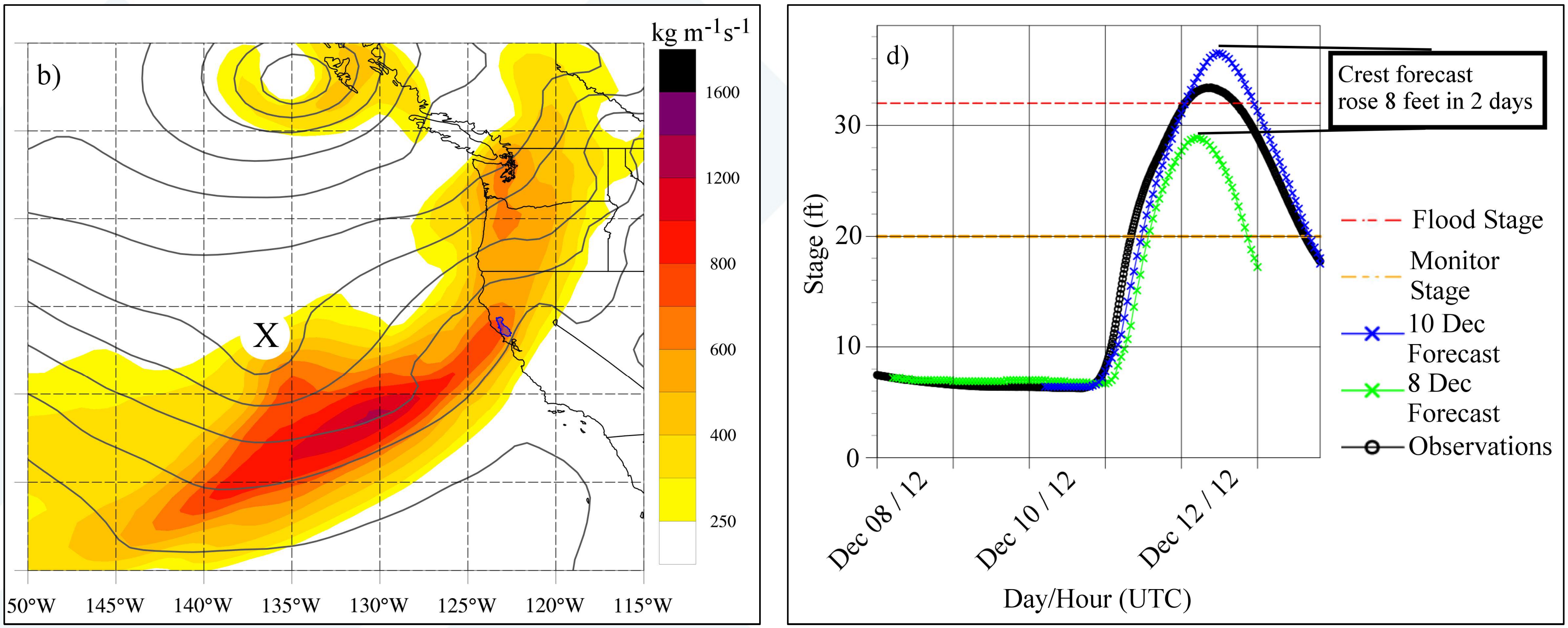
Flood damages increase exponentially with AR Category

The Forecasting Challenge: Floods



Each line represents a different forecast (FCST) issued on either 10, 11, 12, 13 or 14 Feb, which were either 0, 1, 2, 3, or 4 days prior to when the flood crest was observed.

ERRORS IN PREDICTING THE STRUCTURE AND STRENGTH OF AN ATMOSPHERIC RIVER CAN CREATE MAJOR ERRORS IN FLOOD FORECASTS



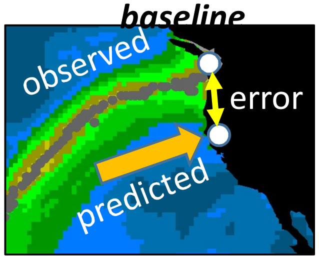
A. Martin, F.M. Ralph, A. Wilson, L. DeHaan, B. Kawzenuk
(J. Hydrometeor., 2019)

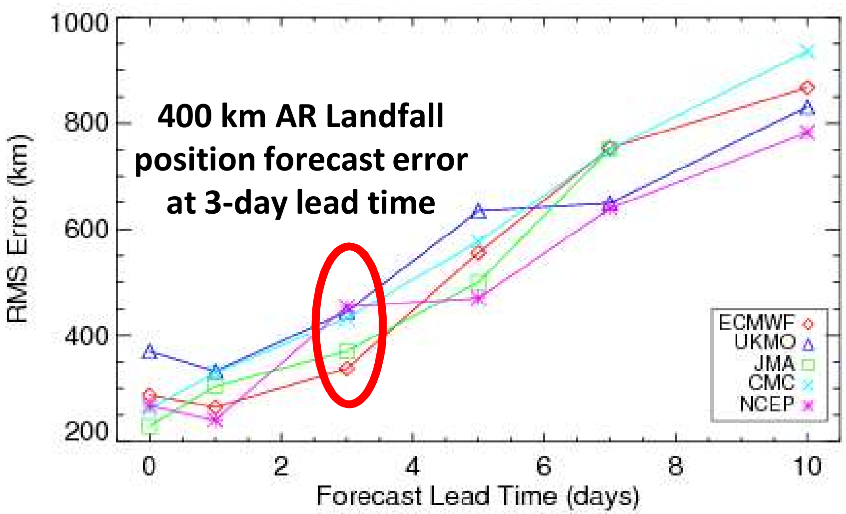
Atmospheric River Reconnaissance

FM Ralph (Scripps/CW3E), V Tallapragada (NWS/NCEP), J Doyle (NRL)

Water managers, transportation sector, agriculture, etc… require improved atmospheric river (AR) predictions

AR Forecast skill assessment establishes a performance baseline





Wick, G.A., P.J. Neiman, F.M. Ralph, and T.M. Hamill, 2013: Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. *Wea. Forecasting*, **28**, 1337-1352.

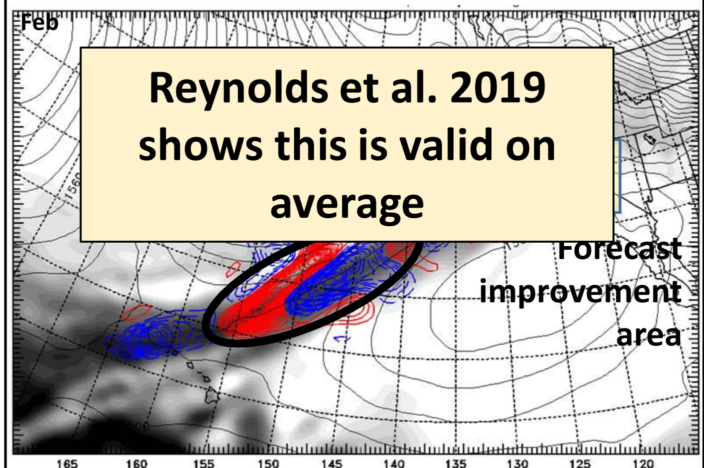
New Adjoint includes moisture – and finds AR is prime target

36-h Sensitivity (Analysis) 00Z 13 February (Final Time 12Z 14 February 2014)

J. Doyle, C. Reynolds, C. Amerault, F.M. Ralph

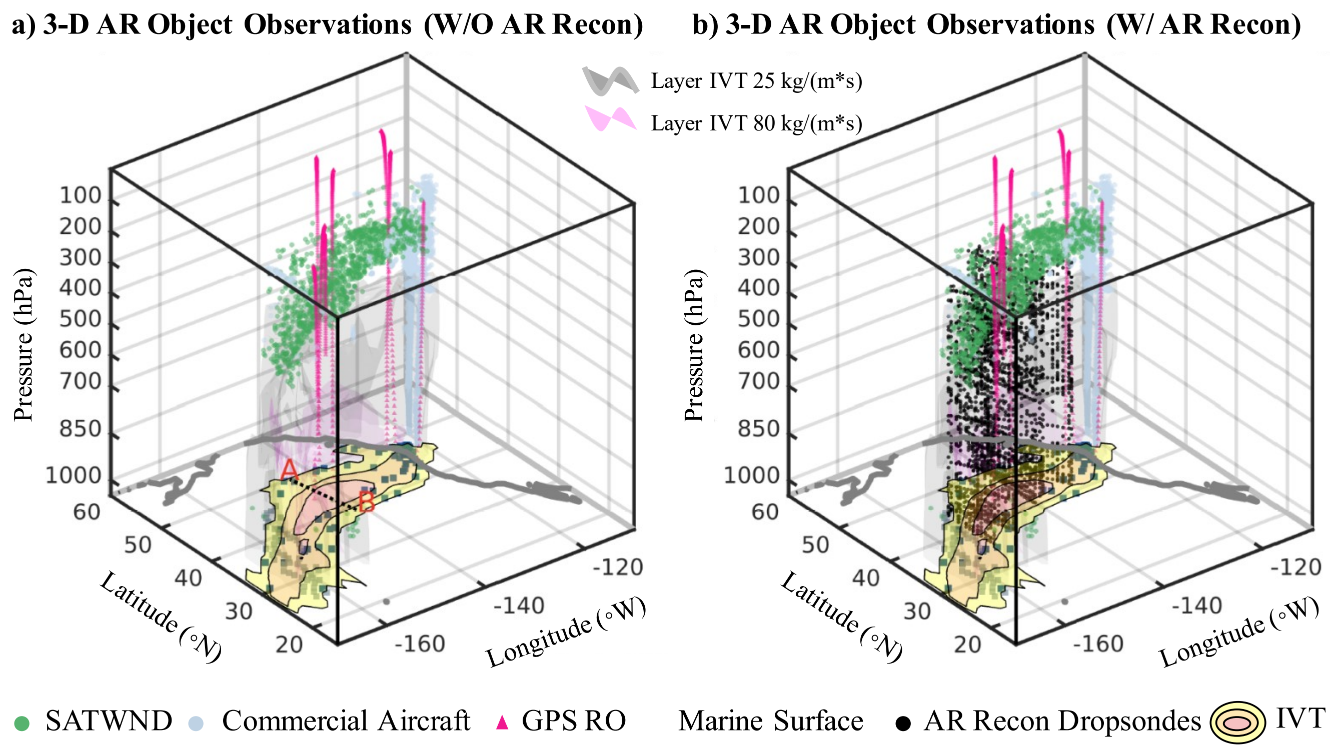
(International Atmospheric Rivers Conference 2016)

Color contours show the forecast sensitivity to 850 mb water vapor (grey shading) uncertainty at analysis time 00Z 13 Feb 2014 for a 36-h forecast over NorCal valid 12Z 14 Feb

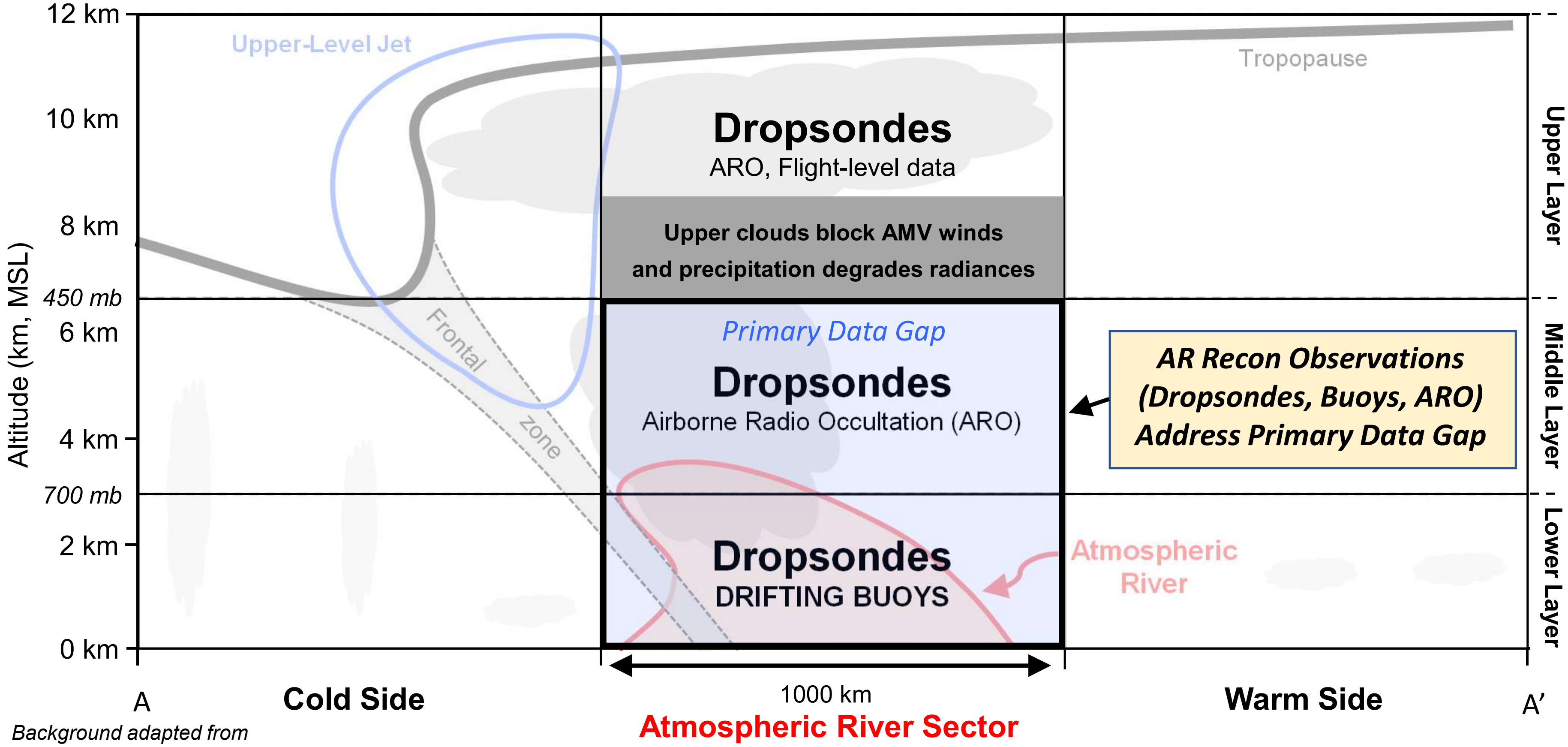


- Moisture sensitivity is strongest along AR axis; located > 2000 km upstream
- **Moisture sensitivity substantially larger than temp. or wind sensitivity.**

OBSERVATION DENSITY ANALYSIS

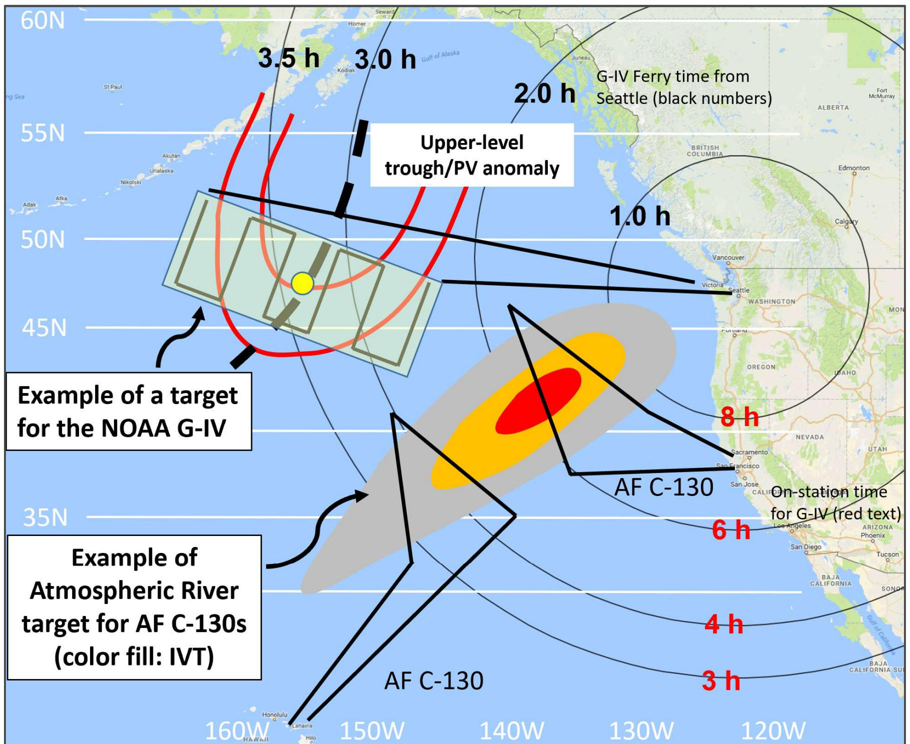


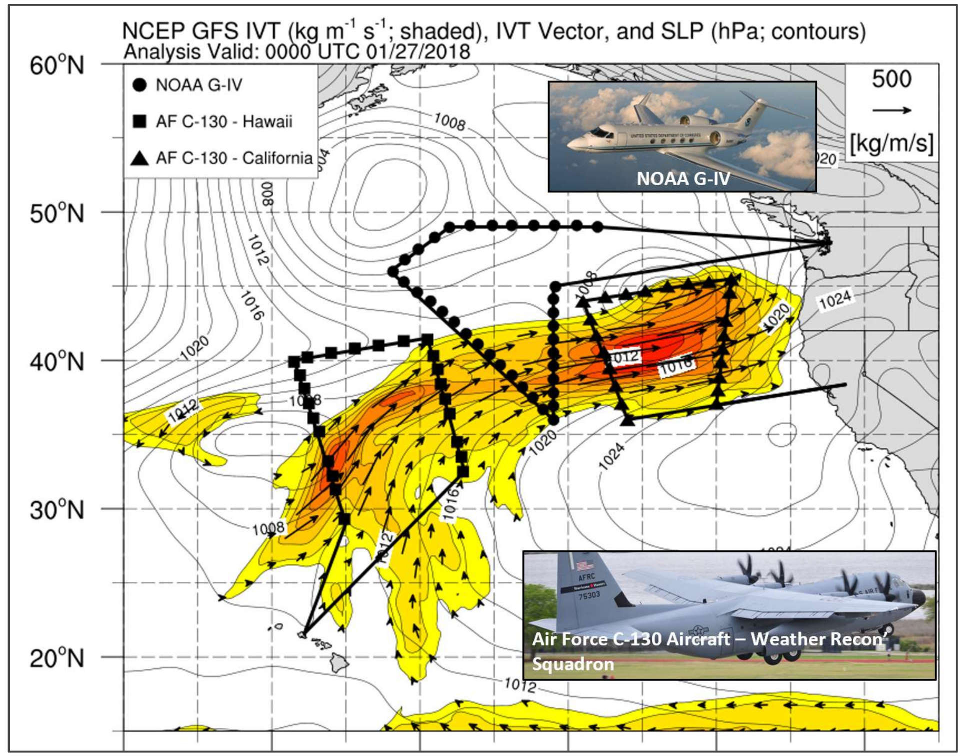
Lead: Minghua Zheng



Background adapted from
Ralph et al. 2004, 2017; Matrosov 2013, Cannon et al. 2020

Atmospheric River Reconnaissance Sampling Concept and Example from 27 Jan 2018

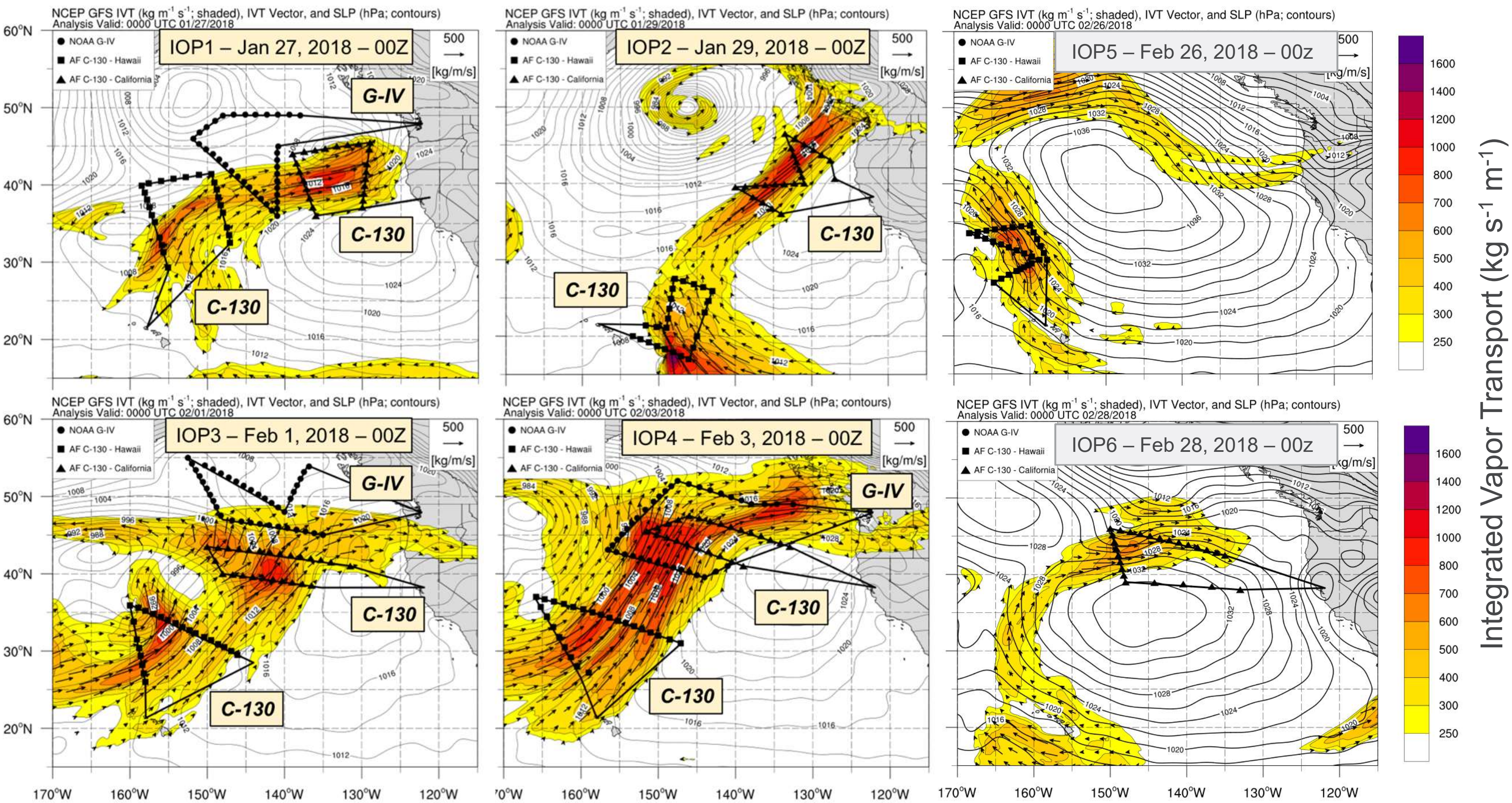




F. Martin Ralph (AR Recon PI; Scripps/CW3E), Vijay Tallaprgada (AR Recon Co-PI; NWS/NCEP) and AR Recon Team

Atmospheric River Reconnaissance 2018

Contacts: F. M. Ralph (PI; mralph@ucsd.edu); V. Tallapragada (Co-PI; vijay.tallapragada@noaa.gov)



AR Recon 2016 to 2021

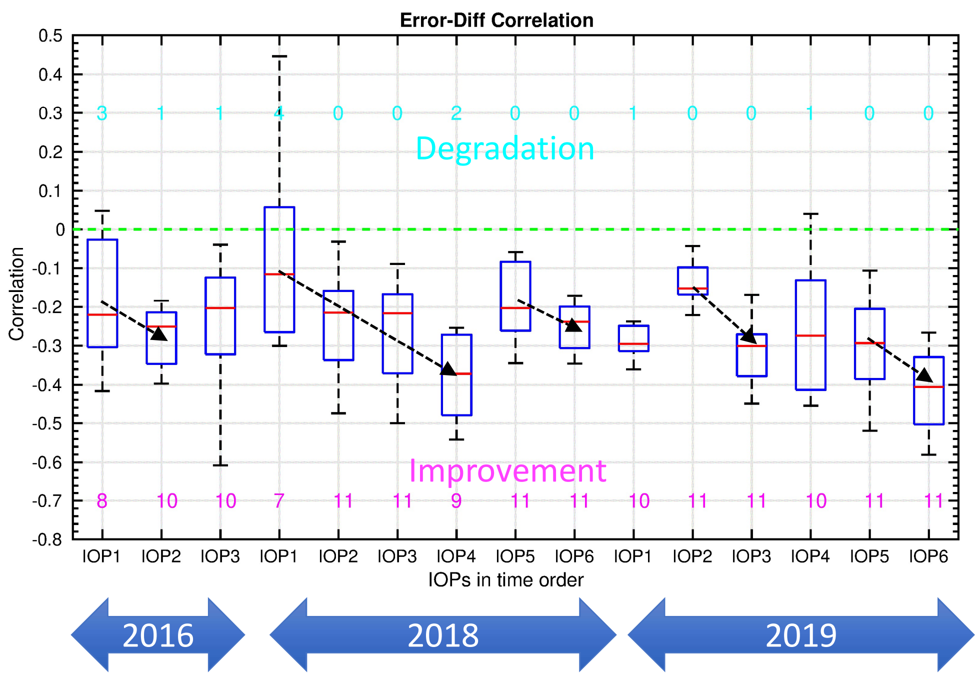
Two Air Force C-130s and NOAA's G-IV

- ✓ Feb 2016: 3 Storms (2 aircraft/storm; AF C-130s)
- ✓ Jan-Feb 2018: 6 Storms (3 aircraft/storm in 3 storms – 2 AF C-130s plus the NOAA G-IV (With Airborne GPS Radio Occultation, J. Haase); 2 C-130s in 1 storm; 1 C-130 in 2 storms)
- ✓ 1 Feb-14 Mar 2019:
  Core program: 6 storms (2 AF C-130s/storm; 25 dropsondes/aircraft/storm flight; 300 sondes)
  Addit'l data: 32 drifting buoys supplemented with barometers in AR Alley (L. Centurioni, B. Inglesby)
- ○ Jan-Mar 2020 **(ongoing):** 16 storms (1-3 aircraft/storm)
- ○ 2021 and beyond: Long-term requirements captured in the US' National Winter Storm Operating Plan

- ○ **Target 2021: 24 IOPs with 3 aircraft sampling each storm**
- ✓ Interagency, International Steering Committee in place
  - Carry out assessments
  - Refine data assimilation methods
  - Create appropriate evaluation metrics
  - Provide impact results in peer-reviewed publications

Contacts
PI: F. M. Ralph (mralph@ucsd.edu)
Co-PI: V. Tallapragada
(vijay.tallapragada@noaa.gov)

Precip: % RMSE Reduction and Error-Diff Correlation—By IOP

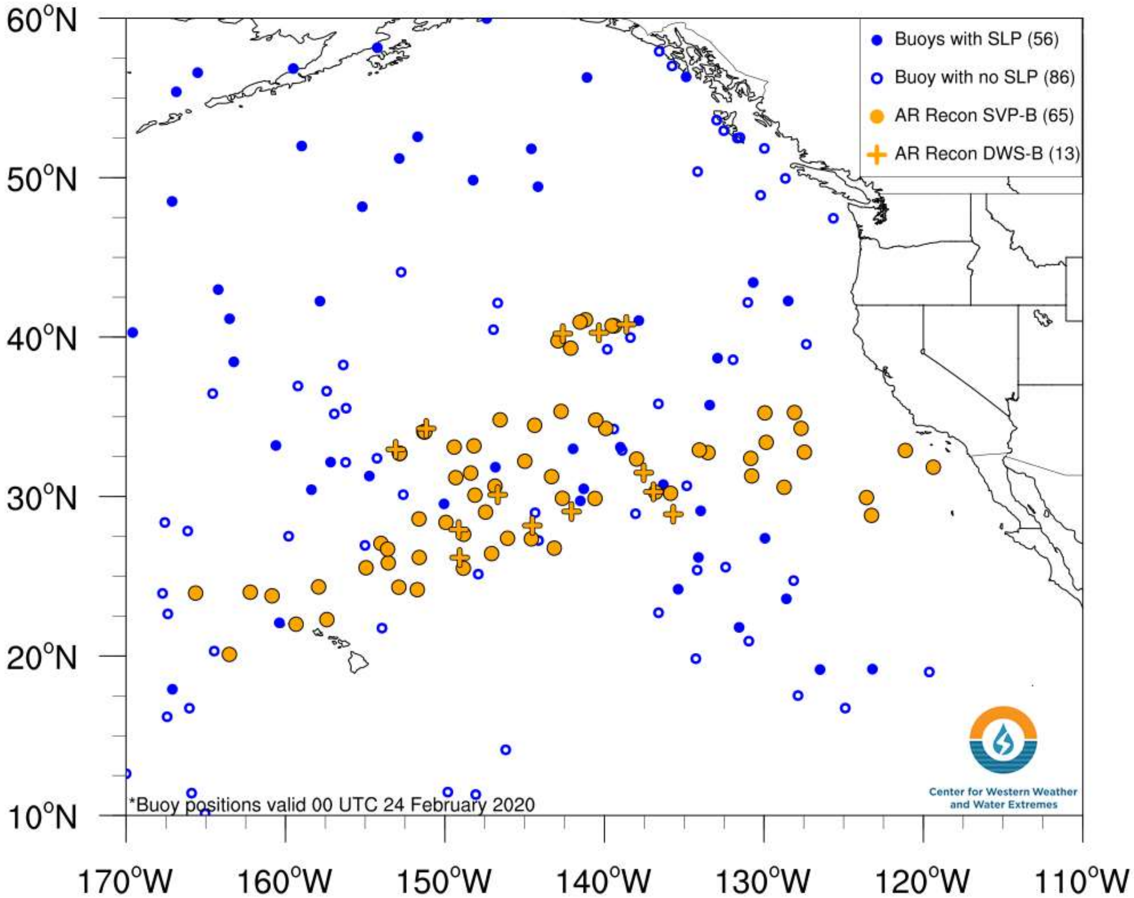


Improved IOP examples: 2016IOP2, 2018IOP4, 2019IOP6

Neutral IOP examples: 2018IOP1, 2018IOP5

The later IOPs in consecutive missions show largest improvement

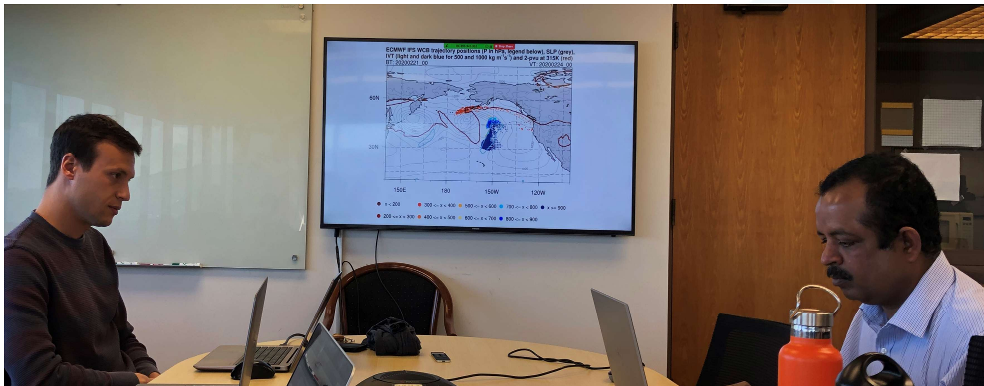
CW3E - AR RECON 2020 BUOY PROJECT

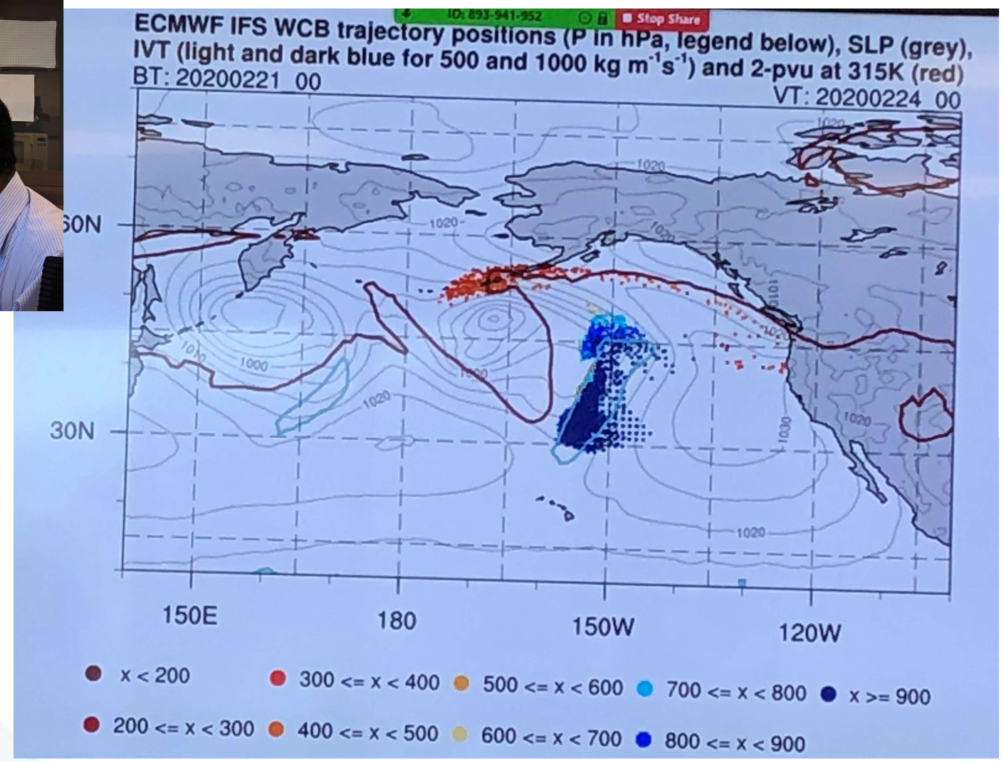


Purpose: To explore the potential of drifting buoys (with pressure sensors), in concert with AR Recon dropsondes and data assimilation efforts, to improve west coast forecasts of landfalling atmospheric rivers and precipitation. Supports California's Atmospheric Rivers Program (**PI: F.M. Ralph; CA Dept. of Water Resources – sponsor**).

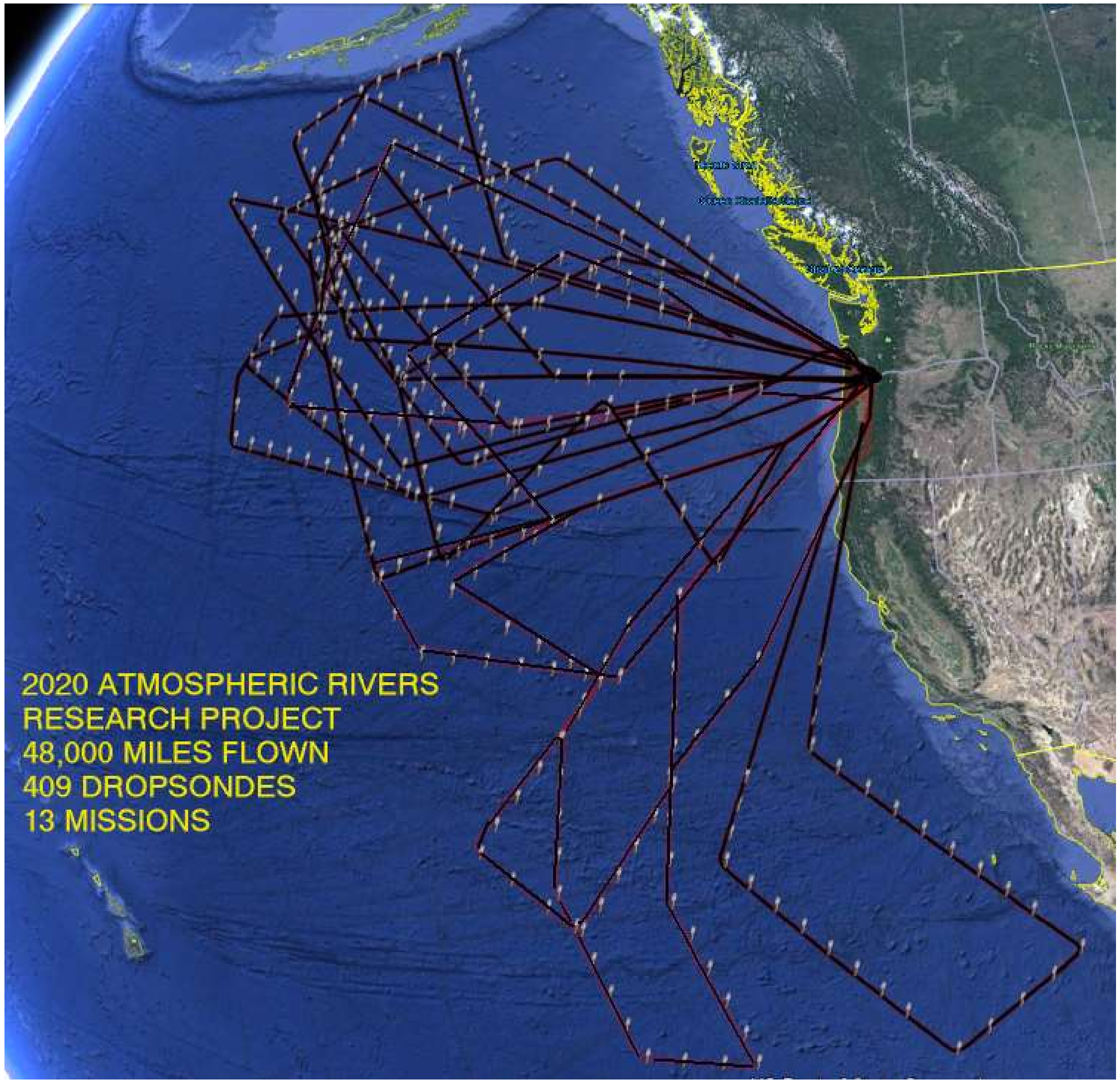
Partners: Deployment leverages the Global Drifter Program barometer upgrade program (**PI: Luca Centurioni, SIO; NOAA/OAR/OOMD – sponsor**); deployment is by the Air Force 53rd Weather Reconnaissance Squadron and by ship of opportunity arranged by L. Centurioni's group. Participation from the European Centre for Medium-Range Weather Forecasts (ECMWF) (**ECMWF Leads: Bruce Ingelby, David Lavers**).

WARM CONVEYOR BELT DIAGNOSTIC TOOL USED IN AR RECON-2020



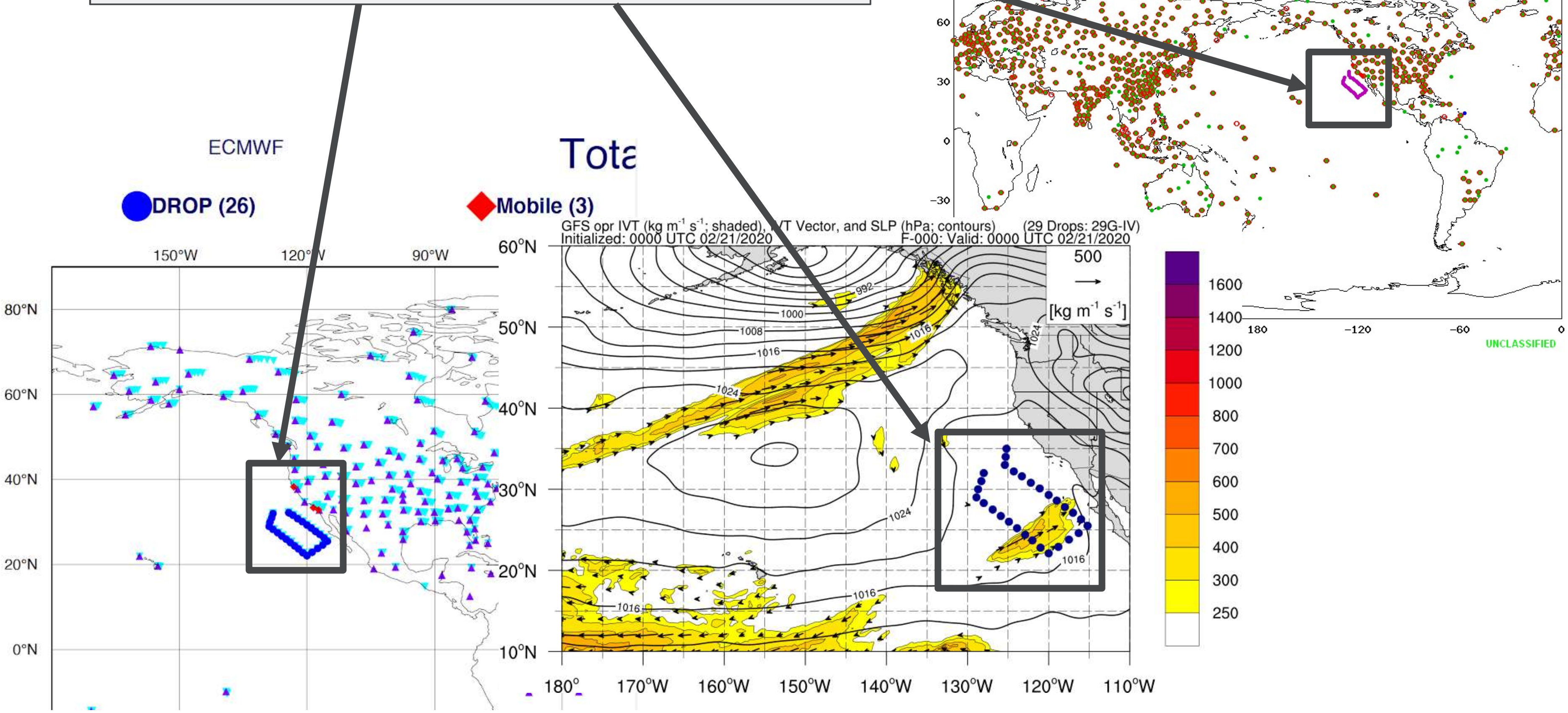


WCB Conditions are being considered in AR Recon 2020 flight planning: Products provided courtesy of H. Wernli, Hanin Binder and Maxi Boettcher


2020 ATMOSPHERIC RIVERS
RESEARCH PROJECT
48,000 MILES FLOWN
409 DROPSONDES
13 MISSIONS

Dropsondes Assimilated – IOP-10

30 drops made it into all models (00Z shown)
3 mobile radiosonde sites provided data in 18Z and 00Z

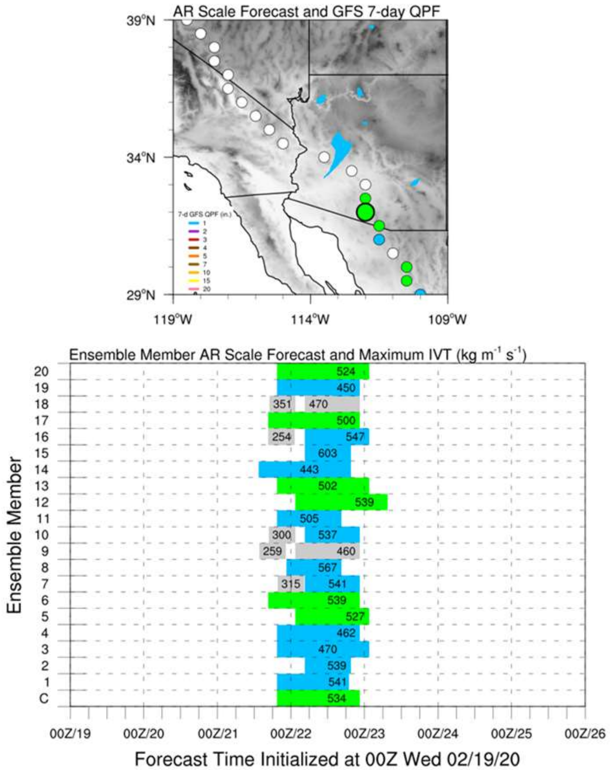


AR Scale Forecasts

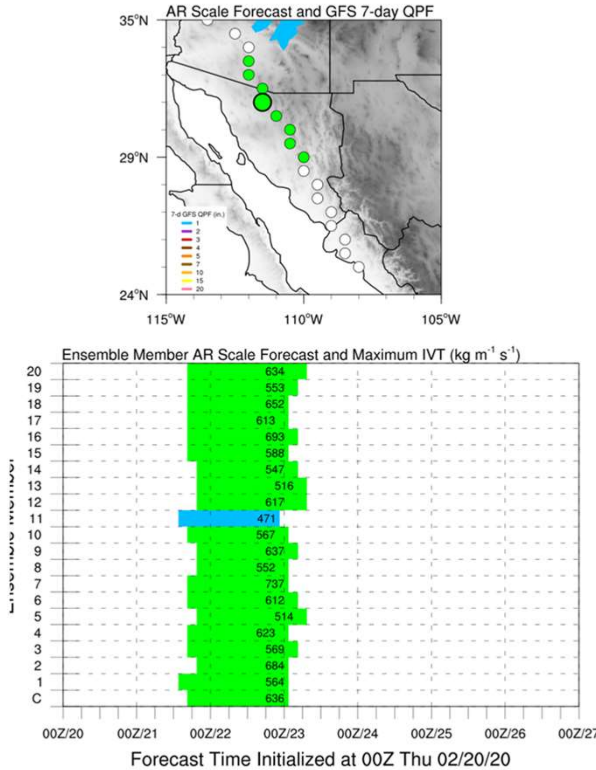
(Ralph et al. 2019, BAMS)

Center for Western Weather and Water Extremes

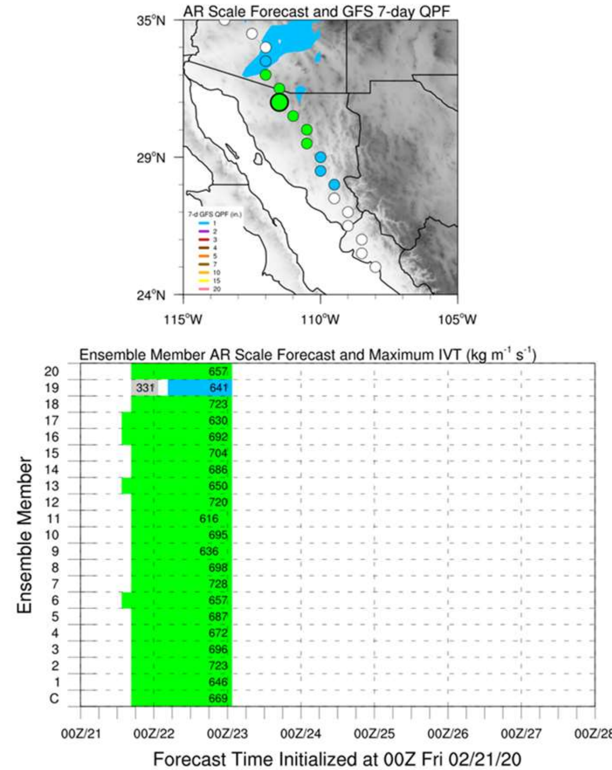
Issued: 00Z 19 Feb



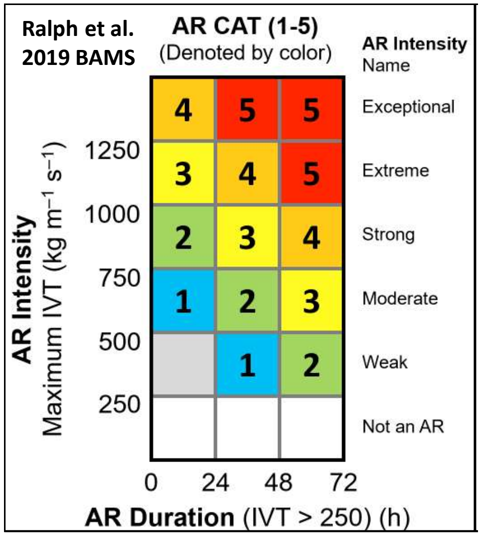
Issued: 00Z 20 Feb



Issued: 00Z 21 Feb



Major storm "Dennis" just hit Europe - Here's how it looks using the AR Scale



The map to the right is an example of one of the CW3E AR Scale prototype displays, applied to storm "Dennis" that struck Western Europe on 14-16 Feb 2020.

Tools are being developed and tested at CW3E that assess the AR Scale ranking of predicted or recent ARs. Feedback on the prototype displays is being collected by forecasters and key forecast users. CW3E's AR Outlooks, and Storm Summaries now include the AR Scale. This information is being communicated to media when requested.

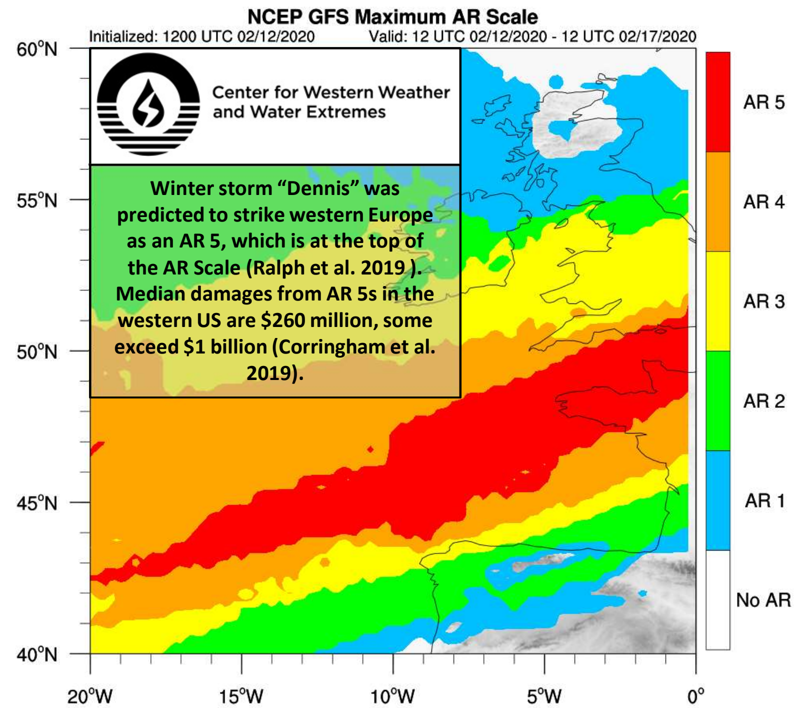
Storm Dennis, 2nd-strongest bomb cyclone on record in North Atlantic, causes severe flooding in Britain

The Washington Post

The storm dumped more than a month's worth of rain in parts of Wales in one day, flooding towns and prompting evacuations.

By Andrew Freedman

16 February 2020



F.M. Ralph, B. Kawzenuk, C. Hecht, J. Cordeira, J. Rutz (16 February 2020)

Atmospheric River Reconnaissance Workshop

29 June – 1 July 2020
Seaside Forum at the Scripps Institution of Oceanography, La Jolla, CA
Hosted by the Center for Western Weather and Water Extremes (CW3E.UCSD.EDU)

29 June – 1 July 2020

La Jolla, California

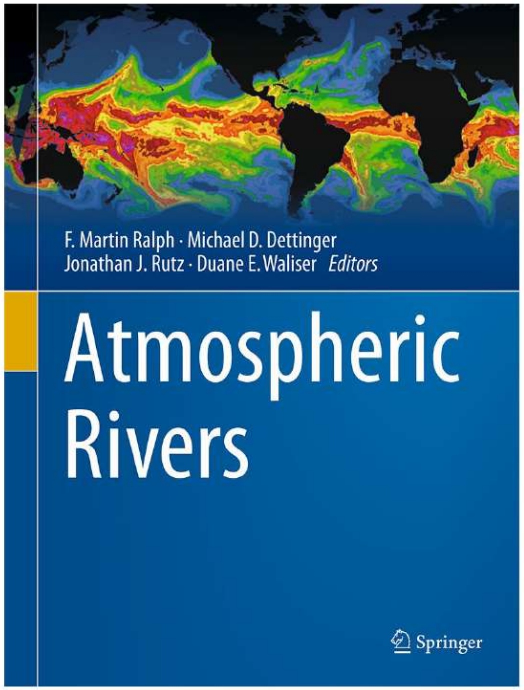
Atmospheric River Reconnaissance Strives to Improve Predictions of Land-falling Atmospheric Rivers and Their Associated Impacts in the Western U.S.

From 2015 to 2020, AR Recon grew from a concept to a field demonstration to an operational requirement and mission. It has gone from 3 storms flown over 2 weeks in 2016 to 12 flown over 8 weeks in 2020. It could reach 24 over 12 weeks in 2021. It uses two Air Force C-130s and the NOAA G-IV to carry out dropsonde missions and has partnered with the global drifter program to deploy roughly 100 drifting buoys with pressure sensors. Flight planning and calling of missions is carried out by a diverse team of scientists and forecasters, who consider input from multiple objective targeting methods and fundamental physical principles. A steering committee for modeling and data assimilation consisting of a multi-agency team of global modeling and science centers is working together to document and enhance impacts of the data.

WORKSHOP PURPOSE: DOCUMENT IMPACTS and ENVISION AR RECON IN 2025
The goals are to share results, to coordinate and inspire future work on data collection, data assimilation, metric development and impact assessment, and to discuss the research and operations partnership approach being developed in AR Recon.

The Workshop will bring together current participants and interested experts to share results of modeling, data assimilation and impact studies and to consider next steps for future field seasons. It will cover the following topics, using oral and poster sessions, as well as panel discussions:

- Flight planning, targeting and execution methods – refinements and expansion
- Verification and validation methods including use of the AR scale
- Data assimilation and impact studies, including new methods
- Evaluate potential impacts of AR Recon in the central and eastern US
- Identify leading sources of forecast errors, including role of mesoscale frontal waves
- Physical process studies enabled by AR Recon in support of western water applications
- Representing AR Recon in the NWSOP as a national mission focused on western water
- Potential for collaboration with European interests, including on warm conveyor belts
- Discuss a vision for AR Recon - 2025



1st ed. 2019, XX, 366 p. 172 illus., 160 illus. in color.

Printed book

Hardcover

81,99 € | £69.99 | $99.99

[1]87,73 € (D) | 90,19 € (A) | CHF

F.M. Ralph, M. Dettinger, J.J. Rutz, D.E. Waliser (Eds.)

Atmospheric Rivers

Available early 2020
Springer
20+ Contributing Authors

- Presents the latest research on a highly impactful extreme weather phenomenon with climatological importance both regionally and globally, and that has bearing on a variety of civil and commercial decision support areas
- Provides specific, research-based information on atmospheric rivers to help practitioners understand and explain the scientific basis of the weather pattern to non-practitioners and the general public
- Gives in-depth scientific information on atmospheric rivers within the broader topics of extratropical cyclones, weather and hydrological extremes, regional and global climate, as well as weather prediction and future climate projections

This book is the standard reference based on roughly 20 years of research on atmospheric rivers, emphasizing progress made on key research and applications questions and remaining knowledge gaps. The book presents the history of atmospheric-rivers research, the current state of scientific knowledge, tools, and policy-relevant (science-informed) problems that lend themselves to real-world application of the research—and how the topic fits into larger national and global contexts. This book is written by a global team of authors who have conducted and published the majority of critical research on atmospheric rivers over the past years. The book is intended to benefit practitioners in the fields of meteorology, hydrology and related disciplines, including students as well as senior researchers.

Center for Western Weather and Water Extremes

ATMOSPHERIC RIVER RECONNAISSANCE:

SUPPORTING WESTERN STORM PREDICTIONS AND WATER DECISIONS

F. Martin Ralph, PI (UC San Diego/SIO/CW3E)

Vijay Tallapragada Co-PI (NOAA/NWS/NCEP)

Jim Doyle (Naval Research Laboratory)

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AR Recon

Papers Published to Date (Results)

Demirdjian, R., Doyle, J.D., Reynolds, C.A. Norris, J.A., Michaelis, A.C., Ralph, F.M., 2019: A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model. Journal of the Atmospheric Sciences, 0, DOI 10.1175/JAS-D-19-0155.1

Guan, B., D. Waliser, and F. Ralph, 2017: An inter-comparison between reanalysis and dropsonde observations of the total water vapor transport in individual atmospheric rivers. Journal of Hydrometeorology, 19, 321-337, doi:10.1175/JHM-D-17-0114.1

Lavers, D.A., M.J. Rodwell, D.S. Richardson, F.M. Ralph, J.D. Doyle, C.A. Reynolds, V. Tallapragada, and F. Pappenberger, 2018: The Gauging and Modeling of Rivers in the Sky. Geophysical Research Letters, 45, https://doi.org/10.1029/2018GL079019

Ralph, F., S. Iacobellis, P. Neiman, J. Cordeira, J. Spackman, D. Waliser, G. Wick, A. White, and C. Fairall, 2017: Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers. Journal of Hydrometeorology, 18, 2577-2596. doi:10.1175/BAMS-D-15-00245.1

Reynolds, C.A., J.D. Doyle, F.M. Ralph, and R. Demirdjian, 2019: Adjoint Sensitivity of North Pacific Atmospheric River Forecasts. Mon. Wea. Rev., 147, 1871-1897, https://doi.org/10.1175/MWR-D-18-0347.1

Stone, R.E., C.A. Reynolds, J.D. Doyle, R. Langland, N. Baker, D.A. Lavers, and F.M. Ralph, 2019: Atmospheric River Reconnaissance Observation Impact in the Navy Global Forecast System. Mon. Wea. Rev., 0, https://doi.org/10.1175/MWR-D-19-0101.1

A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model

Reuben Demirdjian[1], Jim Doyle[2], Carolyn Reynolds[2], Joel Norris[1], Allison Michaelis[1], F. Martin Ralph[1]
[1]UCSD/SIO/CW3E, [2]NRL (*J. Atmos. Sci.* 2020, in press)

Purpose of Study

- Diagnose the dynamical processes linking the initial condition sensitivities offshore in an adjoint model to errors in forecasts of AR landfall and associated precipitation

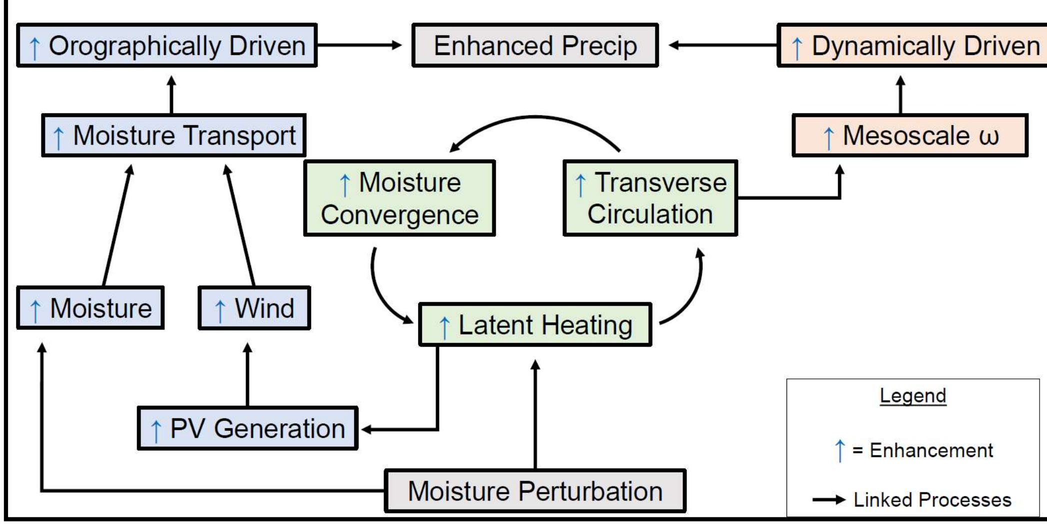
Why Bother?

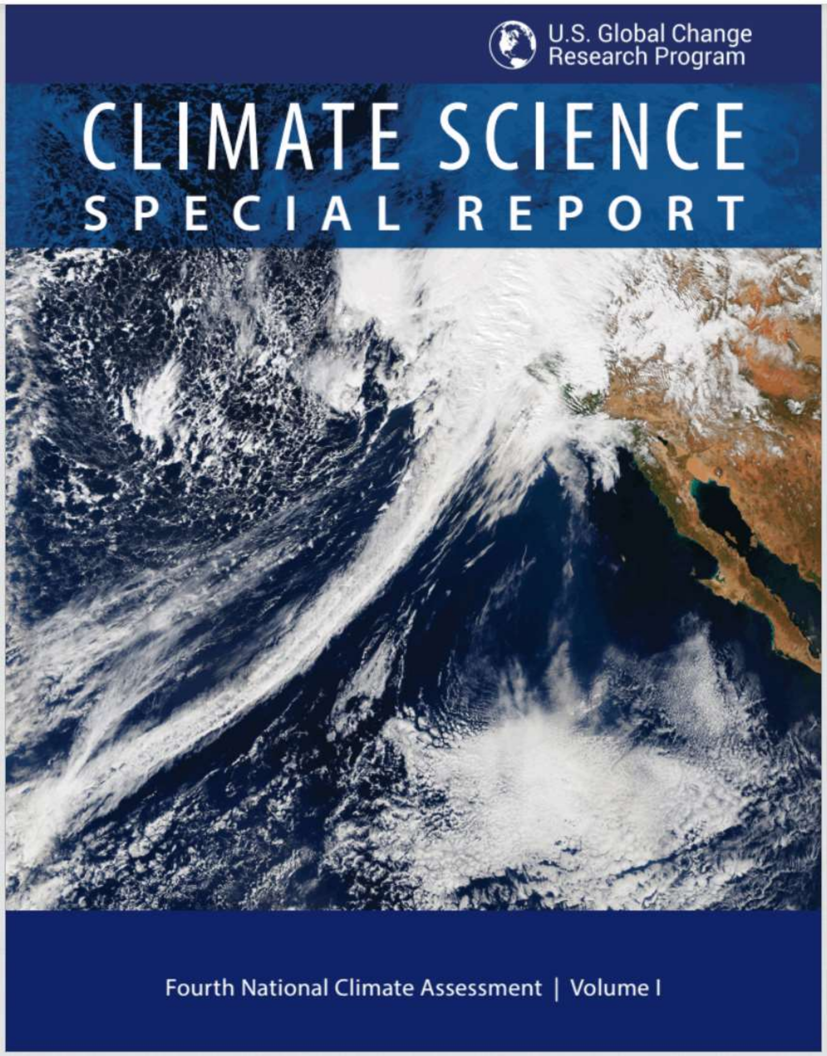
- To understand how errors in weather forecast model representation of AR initial conditions offshore can lead to errors in the prediction of AR landfall.

Result

- An error in water vapor initial condition within the AR modifies precipitation (both d*ynamically and orographically forced*) by amplifying the latent heating in a dynamical feedback process involving wind and PV anomalies that act to reinforce the initial perturbation.

Processes Leading to Changes in the Perturbed Run's Precipitation

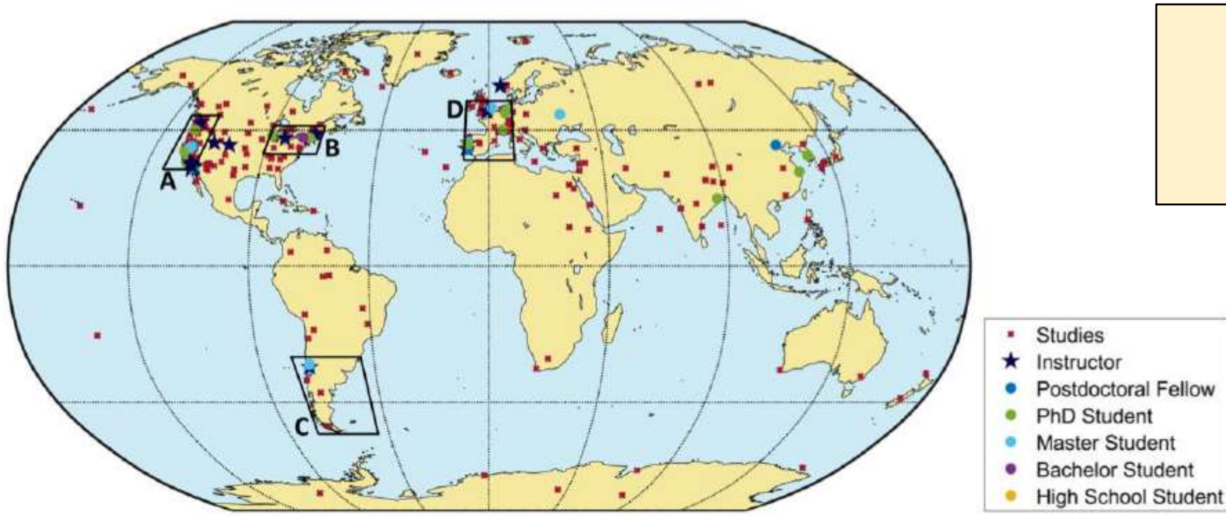




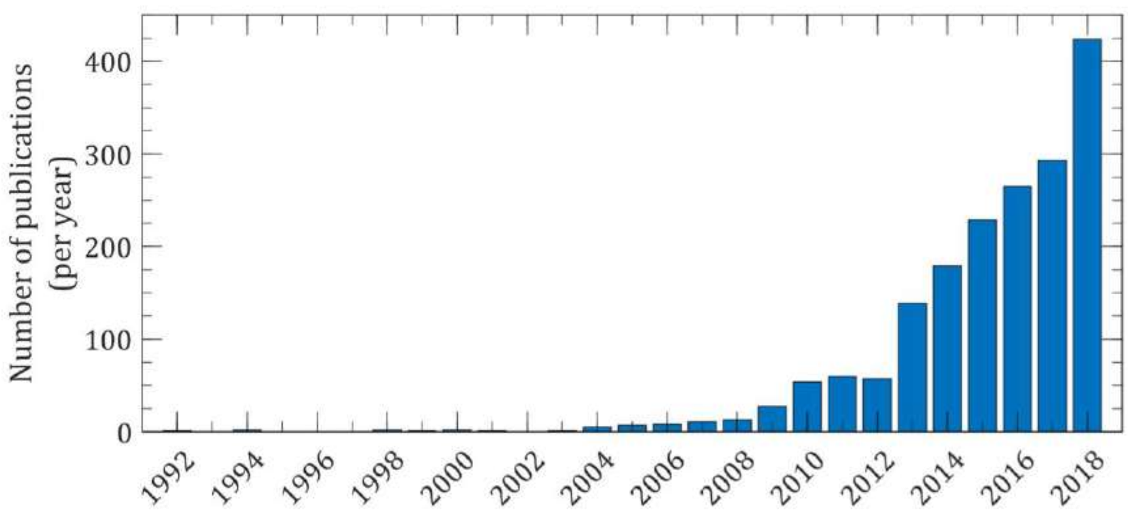
Atmospheric Rivers Highlighted in the U.S. Fourth National Climate Assessment, released on 3 November 2017

1. Hurricanes and Typhoons
2. Severe Thunderstorms
3. Winter storms
4. **Atmospheric Rivers (NEW in 4th Assessment)**

AR Are Being studied globally



Wilson et al. 2020 BAMS
AR Summer Colloquium
Meeting Summary
(in Press)



Rapid Growth in the Reference to ARs in Scientific Papers

Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers

F.M. Ralph, S. Iacobellus, P.J. Neiman, J. Cordeira, J.R. Spackman, D. Waliser, G. Wick, A.B. White, C. Fairall

J. Hydrometeorology (2017)

Method/Data: Uses 21 AR cases observed in 2005 - 2016 with full dropsonde transects.

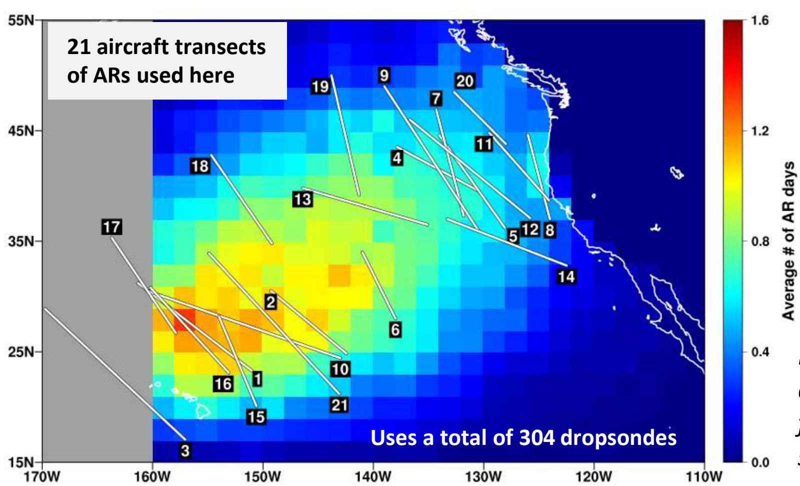
- AR edges best defined by using IVT = 250 kg m^{-1} s^{-1}

Conclusions*:

- Average width: 850 km
- 75% of water vapor transport occurs below 3 km MSL; < 1% occurs above 8 km MSL
- Average max IVT: ~800 kg m^{-1} s^{-1}

KEY FINDING

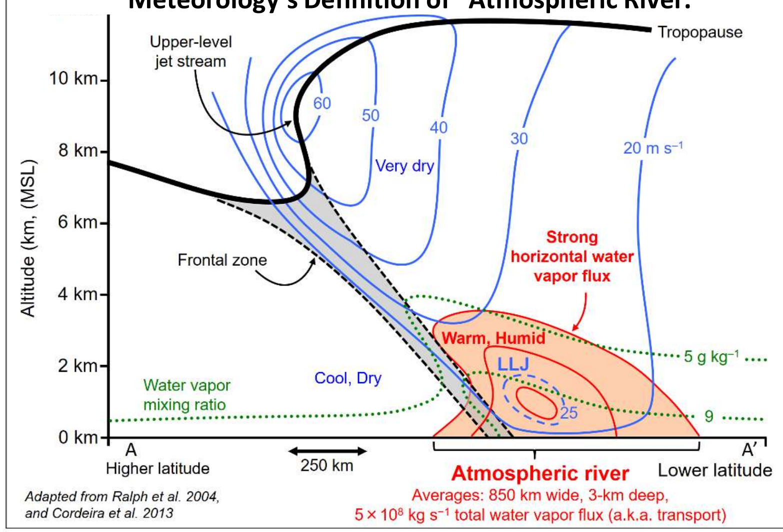
An average AR* transports 4.7 ± 2.0 x 10^8 kg s^{-1} of water vapor, which is equivalent to 2.6 times the average discharge of liquid water by the Amazon River



**These values represent averages for the Northeast Pacific Ocean in the January-March season*

Background image denotes weekly AR frequency during cool seasons (Nov -Feb).

Synthesis from 21 observed ARs; Used in the Glossary of Meteorology's Definition of "Atmospheric River."




International
Atmospheric Rivers Conference
IARC-2018
Seaside Forum at UC San Diego’s
Scripps Institution of Oceanography
La Jolla, CA, 25-28 June 2018
Hosted by the “Center for Western
Weather and Water Extremes”
Bringing together a diverse, cross-disciplinary
community of scientists, engineers, forecasters and managers
to discuss atmospheric river science and applications.
Center for Western Weather
and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY
AT UC SAN DIEGO

First Circular: November 15, 2019

3IARC: Third International Atmospheric Rivers Conference

October 5-9, 2020

Atmospheric rivers (ARs) play a key role in the global water cycle as the primary mechanism conveying water vapor through mid-latitude regions. The precipitation that ARs deliver in many parts of the world, especially through orographic precipitation processes, is important for water resources; but it also regularly is a hazard, triggering floods and landslides, as well as coastal wind storms. The aims of the 2020 International Atmospheric Rivers Conference are:

- to understand dynamical and physical processes in ARs
- to describe the AR impact on hydrology, environment and society
- to evaluate the Atmospheric River Tracking Method Intercomparison Project's (ARTMIP)
- to assess current forecasting capabilities and developing applications
- to project ARs in a warmer world and understand their natural variability

Students are strongly encouraged to attend. Scholarships are available, as well as slots for student speakers.

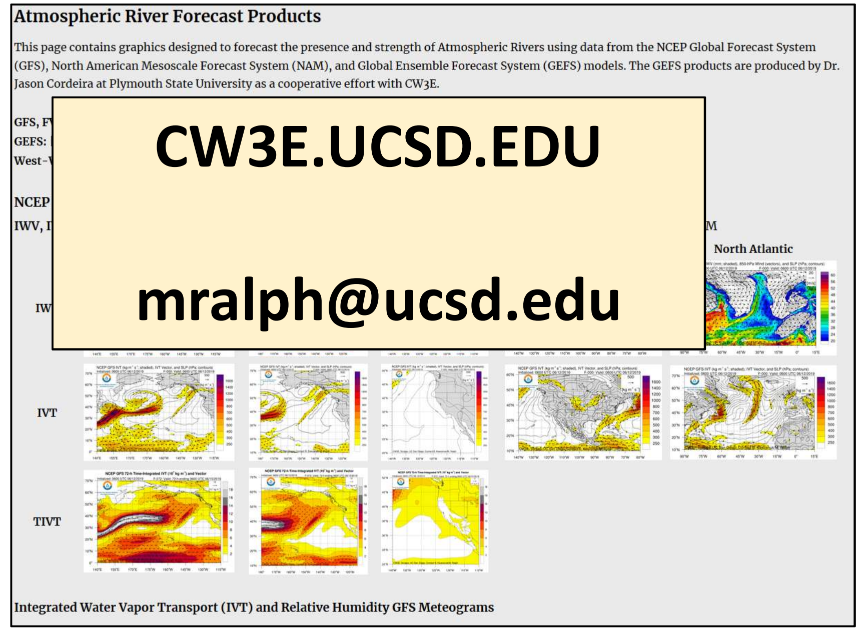
Scientific Steering Committee:

Marty Ralph, Anna Wilson, Reuben Demirdjian (CW3E, UCSD, US); Hans Christian Steen-Larsen (U. of Bergen, Norway); Jon Rutz (US National Weather Service); Roberto Rondanelli, James McPhee (Universidad de Chile); Jorge Eiras-Barca (U. Vigo, Spain); Christine Albano (Desert Research Institute, US); Natalia Tilinina (Shirshov Institute of Oceanology, Russia); Mike Warner (US Army Corps of Engineers); Alexandre Ramos (University of Lisbon, Portugal); Maximiliano Viale (IANIGIA, Argentina)

For further information, please contact the *Local Organizing Committee*

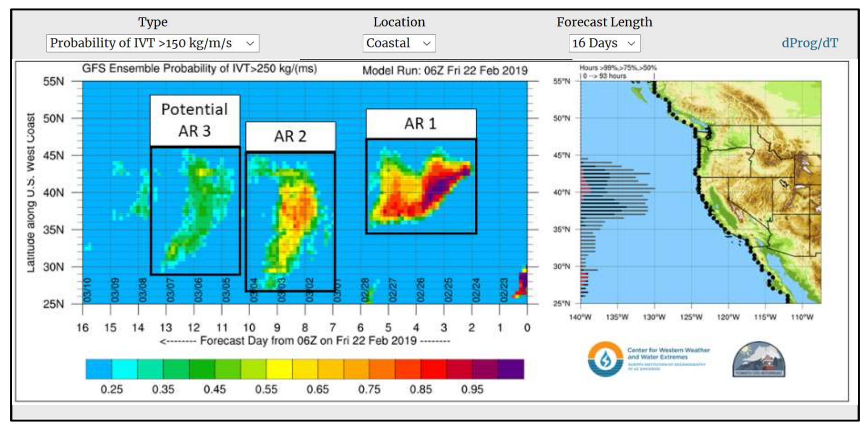
René Garreaud (rgarreau@dgf.uchile.cl) and Raul Valenzuela (rvalenzuela@dgf.uchile.cl)

Conference web site: http://www.dgf.uchile.cl/3IARC (available Dec 2019)



CW3E.UCSD.EDU

mralph@ucsd.edu



Center for Western Weather and Water Extremes
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WEST COAST FORECAST CHALLENGES AND DEVELOPMENT OF ATMOSPHERIC RIVER RECONNAISSANCE

F. Martin Ralph
Director, Center for Western Weather and Water Extremes

Warm Conveyor Belt Workshop
European Center for Medium Range Weather Forecasting
10 March 2020, Virtual Meeting

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Glossary of Meteorology

Added May 2017. Process described in Ralph, Dettinger, Cairns, Galarneau, Eylander, 2018, *Bull. Amer. Meteor. Soc.*, ***99***, pp 837-839.

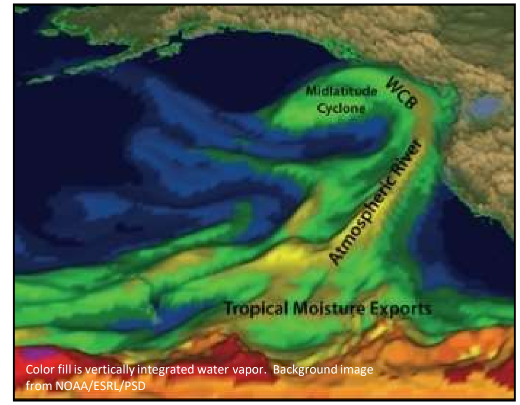
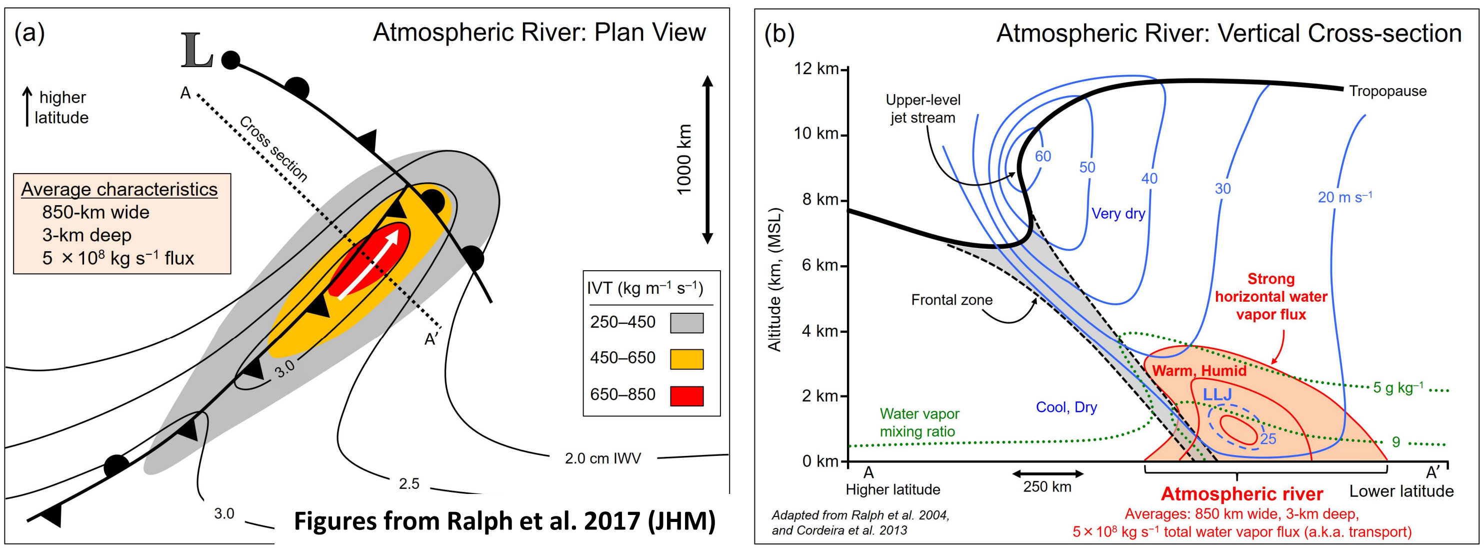


Fig. from Dettinger, Ralph, Lavers, EOS 2015

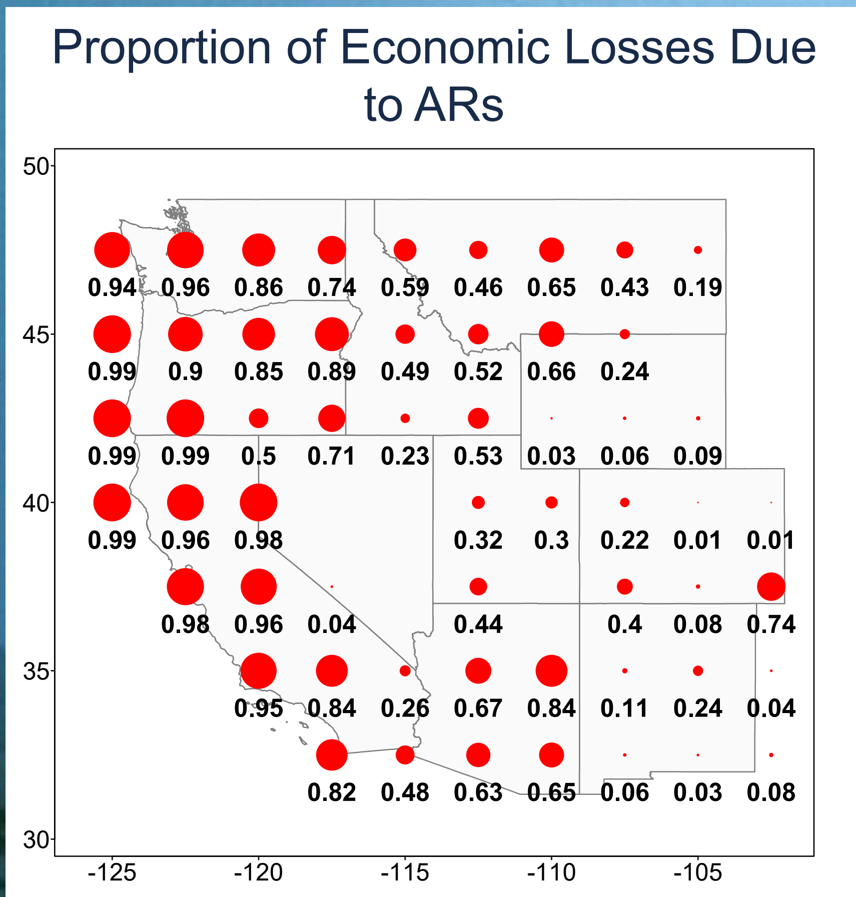
ATMOSPHERIC RIVER

A long, narrow and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward, e.g., by mountains or by ascent in the warm-conveyor-belt. Horizontal water vapor transport in the mid-latitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.



Figures from Ralph et al. 2017 (JHM)

ARs drive economic flood losses



84% of insured losses in the 11 western states were caused by ARs

Post-Fire debris flows pose a serious hazard. This case killed >20 people near Montecito, CA.

T. Corringham, 2018

SCRIPPS INSTITUTION OF OCEANOGRAPHY

A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

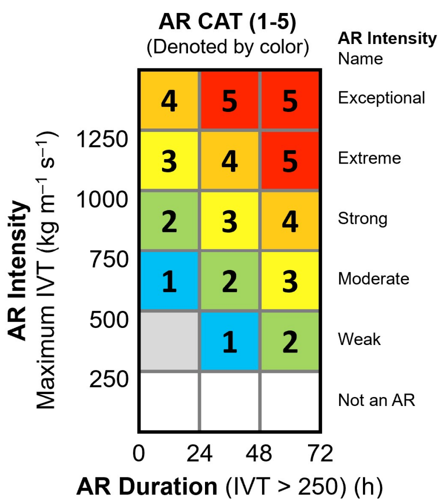
F. Martin Ralph (SIO/CW3E), J. J. Rutz (NWS), J. M. Cordeira (Plymouth State), M. Dettinger (USGS), M. Anderson (CA DWR), D. Reynolds (CIRES), L. Schick (USACE), C. Smallcomb (NWS); *Bull. Amer. Meteor. Soc. 269-289 (2019);*

The AR CAT level of an AR Event* is based on its *Duration* and max *Intensity* (IVT)*****

** An "AR Event" refers to the existence of AR conditions at a specific location for a specific period of time.*
*** How long IVT>250 at that location. If duration is <24 h, reduce AR CAT by 1, if longer than 48 h, add 1.*
**** This is the max IVT at the location of interest during the AR.*

IMPACTS

- AR Cat 5 – Primarily hazardous
- AR Cat 4 – Mostly hazardous, also beneficial
- AR Cat 3 – Balance of beneficial and hazardous
- AR Cat 2 – Mostly beneficial, also hazardous
- AR Cat 1 – Primarily beneficial



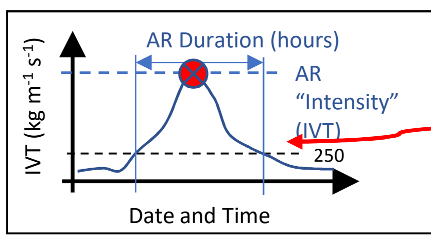
Determining AR Intensity and AR Category

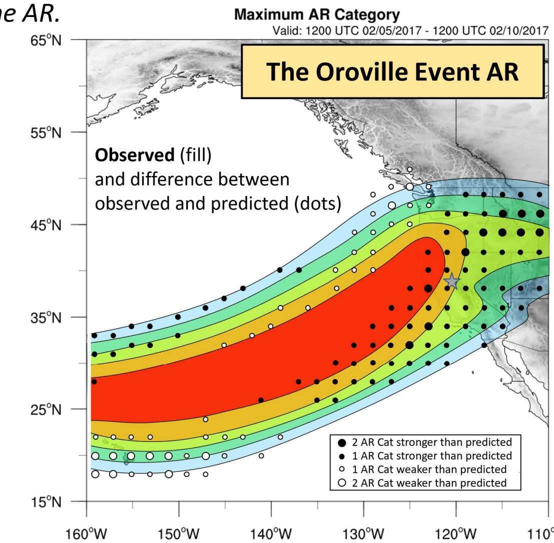
Step 1: Pick a location

Step 2: Determine a time period when IVT > 250 (using 3 hourly data) at that location, either in the past or as a forecast. The period when IVT continuously exceeds 250 determines the start and end times of the AR, and thus also the **AR Duration** for the AR event at that location.

Step 3: Determine **AR Intensity**
- Determine max IVT during the AR at that location
- This sets the AR Intensity and *preliminary* AR CAT

Step 4: Determine *final* value of **AR CAT** to assign
- If the AR Duration is > 48 h, then promote by 1 Category
- If the AR Duration is < 24 h, then demote by 1 Category

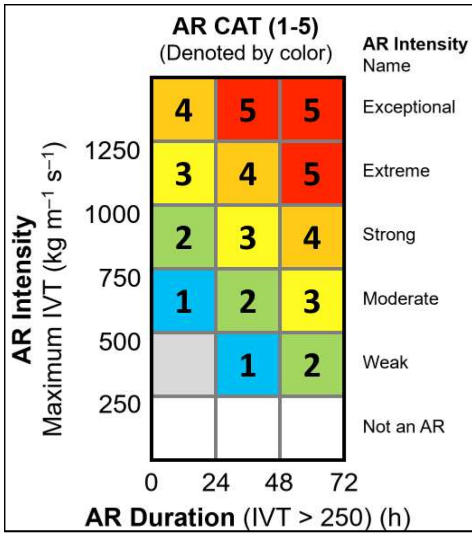




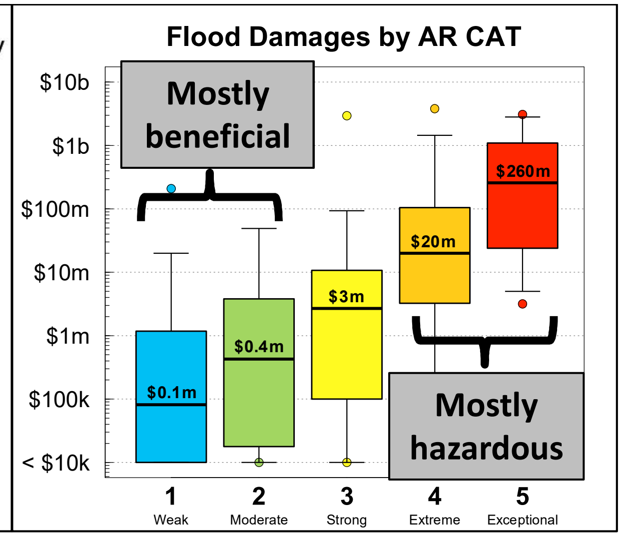
On the Web: CW3E.UCSD.EDU
On Twitter: @CW3E_Scripps

Center for Western Weather and Water Extremes

ARs drive flood damages in the western U.S.



Ralph et al. BAMS 2019

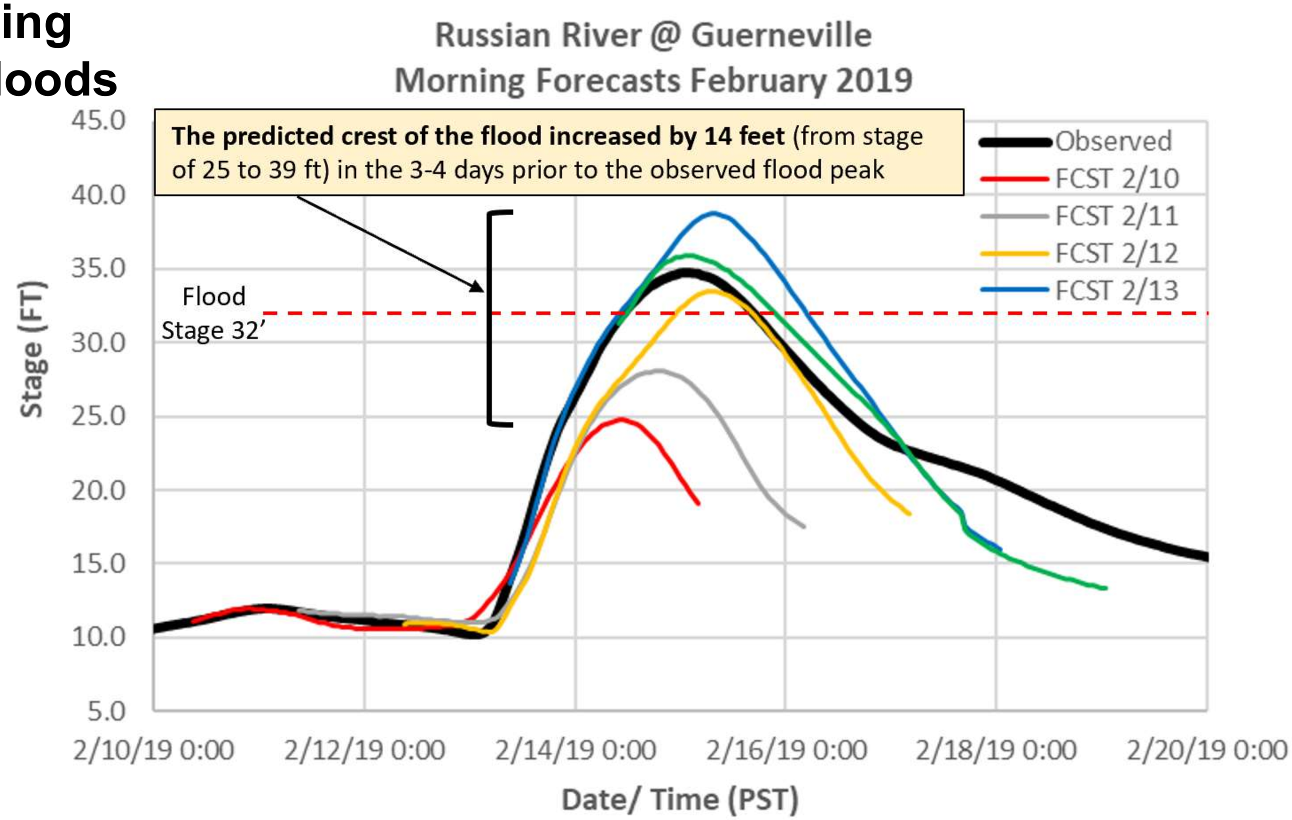


Corringham et al. Sci. Advances 2019

Flood damages increase exponentially with AR Category

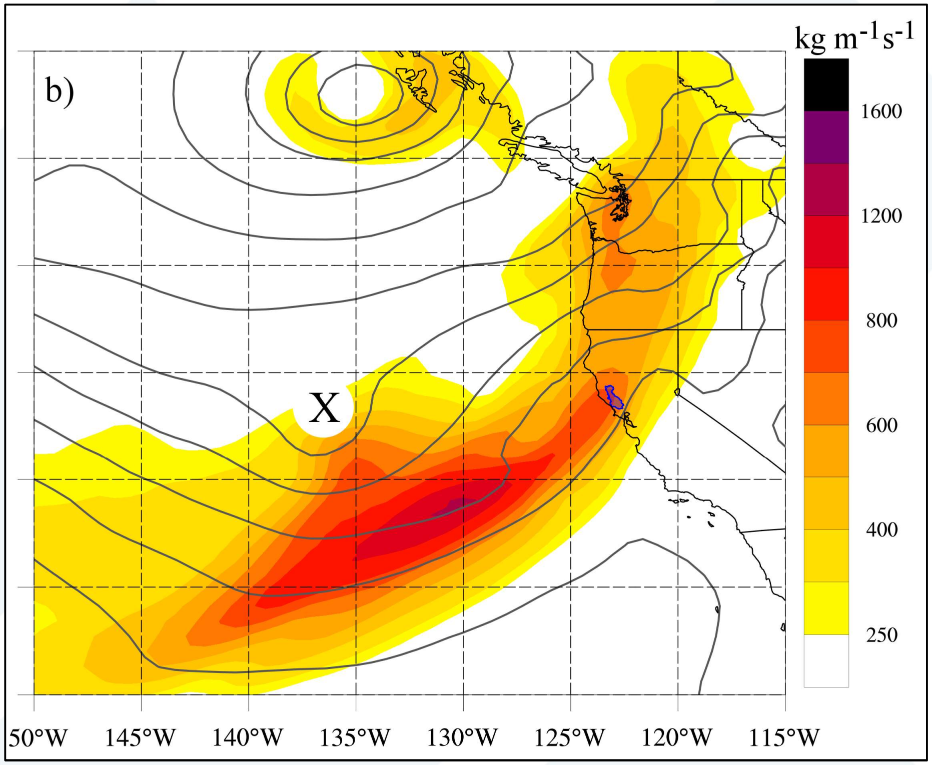
Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

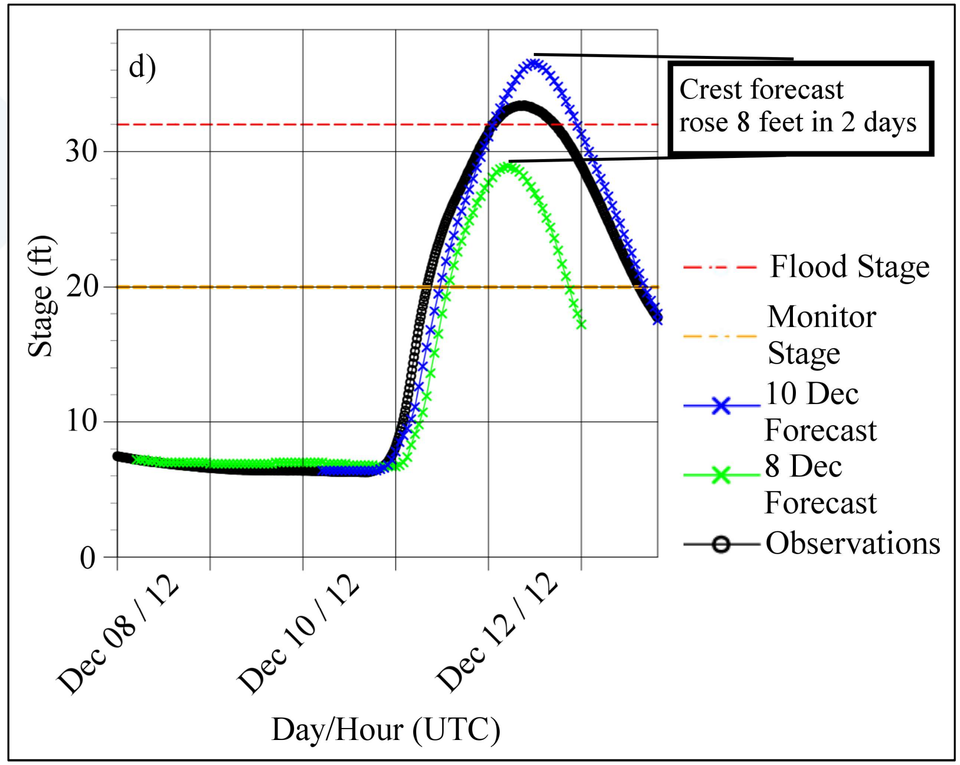
The Forecasting Challenge: Floods



Each line represents a different forecast (FCST) issued on either 10, 11, 12, 13 or 14 Feb, which were either 0, 1, 2, 3, or 4 days prior to when the flood crest was observed.

ERRORS IN PREDICTING THE STRUCTURE AND STRENGTH OF AN ATMOSPHERIC RIVER CAN CREATE MAJOR ERRORS IN FLOOD FORECASTS





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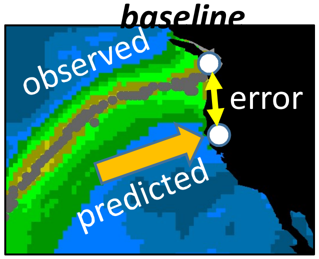
A. Martin, F.M. Ralph, A. Wilson, L. DeHaan, B. Kawzenuk
(J. Hydrometeor., 2019)

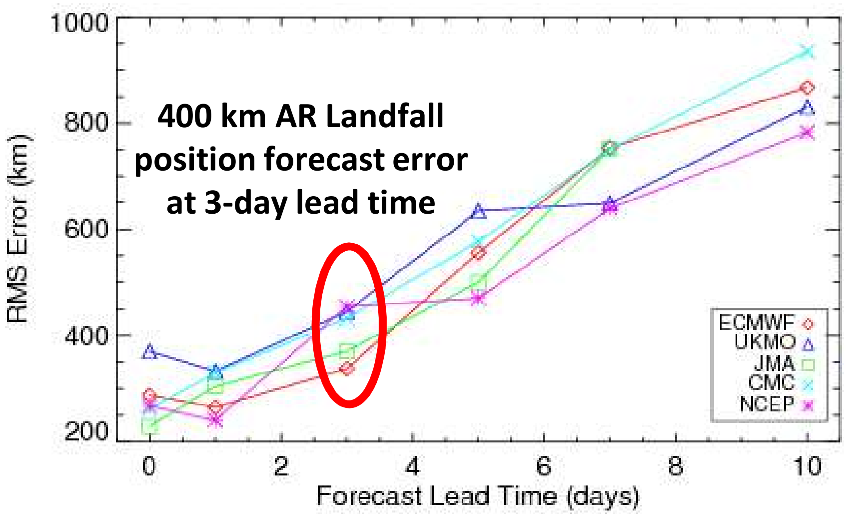
Atmospheric River Reconnaissance

FM Ralph (Scripps/CW3E), V Tallapragada (NWS/NCEP), J Doyle (NRL)

Water managers, transportation sector, agriculture, etc… require improved atmospheric river (AR) predictions

AR Forecast skill assessment establishes a performance baseline





Wick, G.A., P.J. Neiman, F.M. Ralph, and T.M. Hamill, 2013: Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. *Wea. Forecasting*, **28**, 1337-1352.

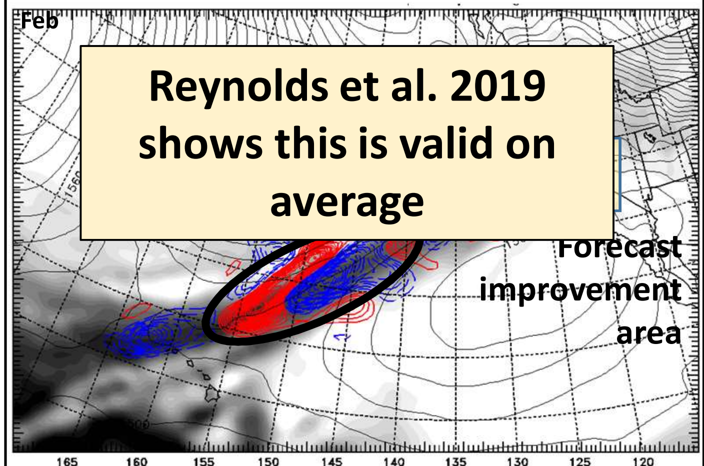
New Adjoint includes moisture – and finds AR is prime target

36-h Sensitivity (Analysis) 00Z 13 February (Final Time 12Z 14 February 2014)

J. Doyle, C. Reynolds, C. Amerault, F.M. Ralph

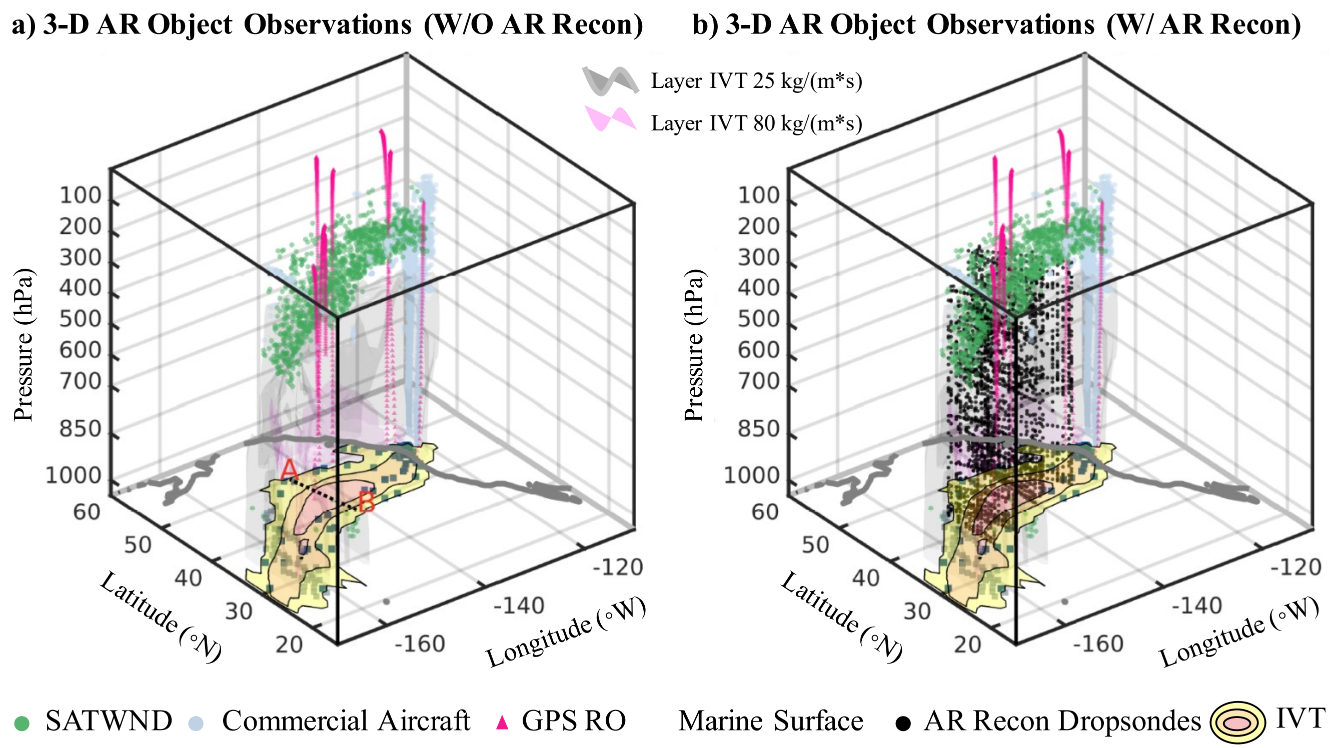
(International Atmospheric Rivers Conference 2016)

Color contours show the forecast sensitivity to 850 mb water vapor (grey shading) uncertainty at analysis time 00Z 13 Feb 2014 for a 36-h forecast over NorCal valid 12Z 14 Feb

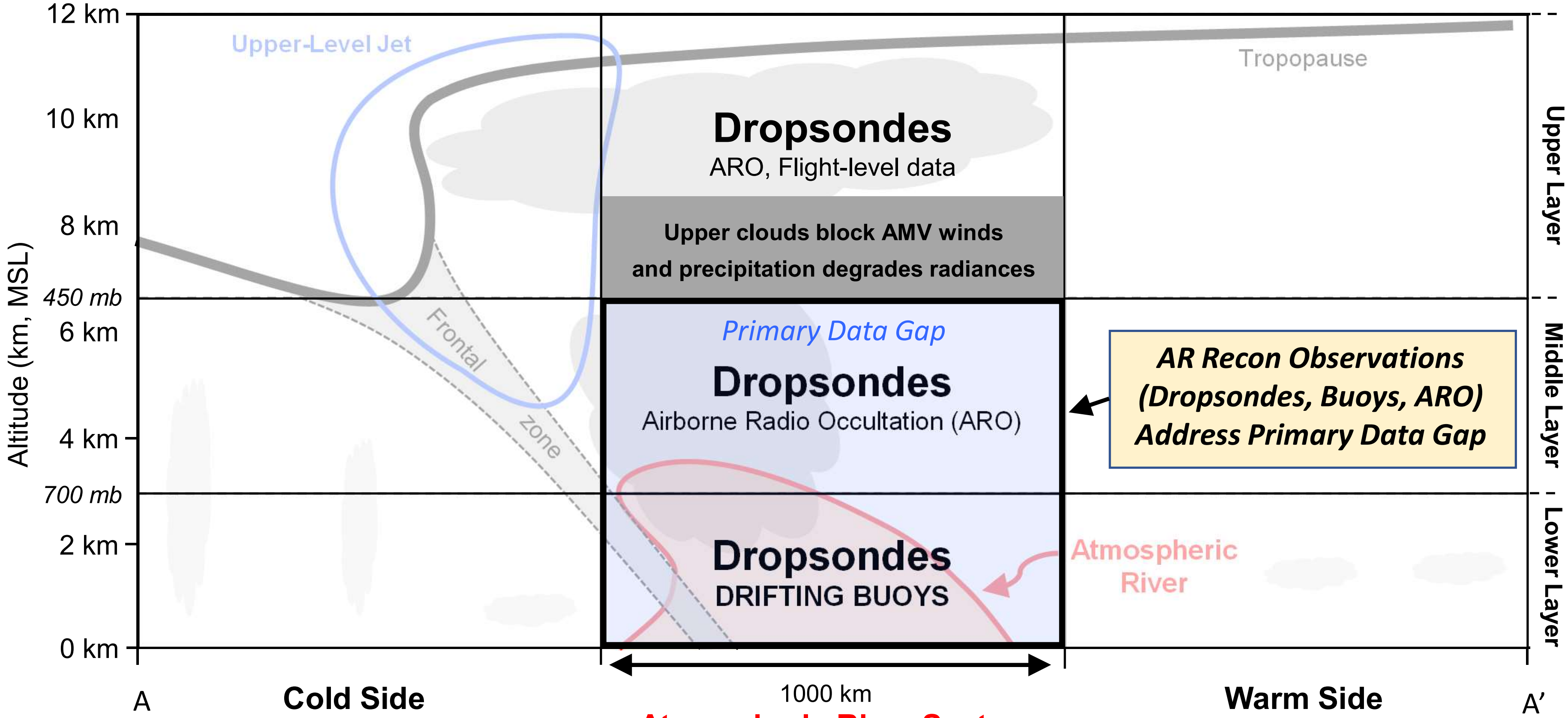


- Moisture sensitivity is strongest along AR axis; located > 2000 km upstream
- **Moisture sensitivity substantially larger than temp. or wind sensitivity.**

OBSERVATION DENSITY ANALYSIS

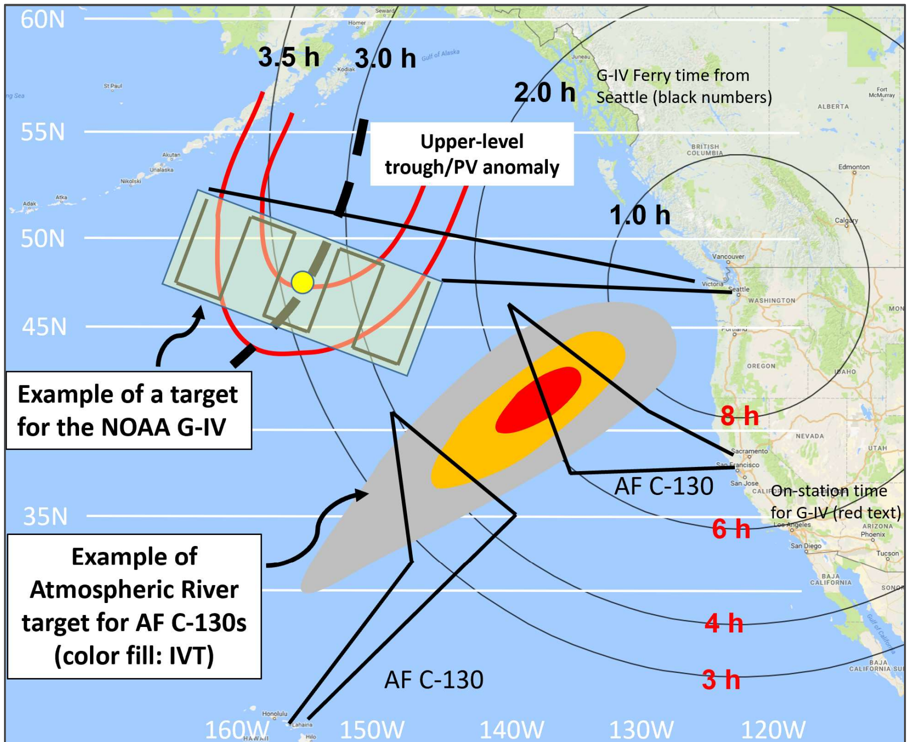


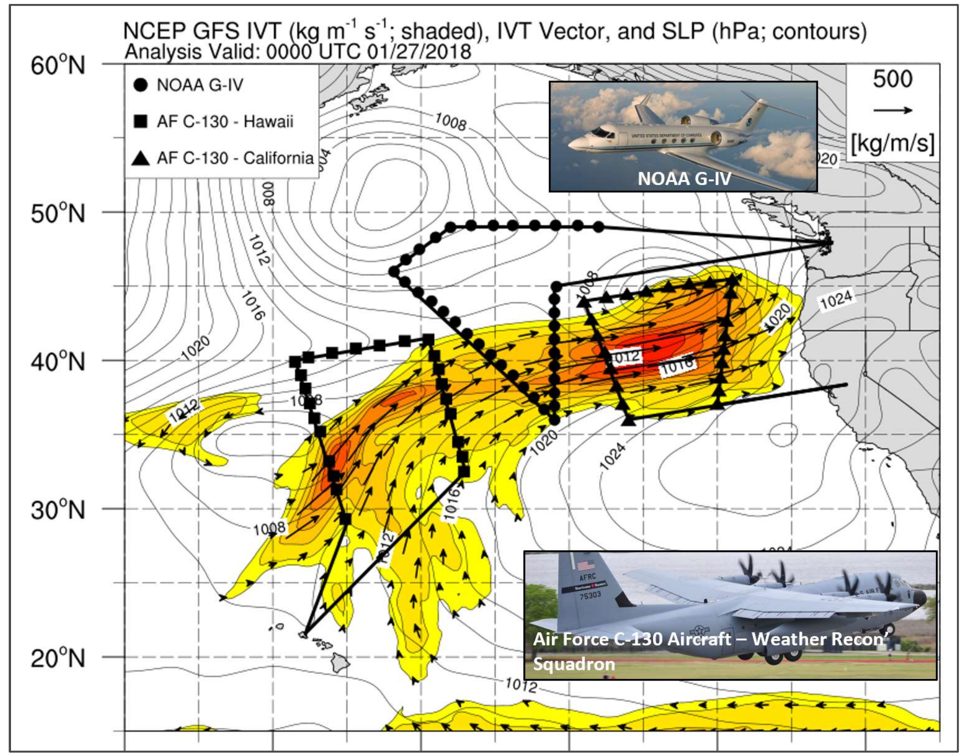
Lead: Minghua Zheng



Background adapted from
Ralph et al. 2004, 2017; Matrosov 2013, Cannon et al. 2020

Atmospheric River Reconnaissance Sampling Concept and Example from 27 Jan 2018

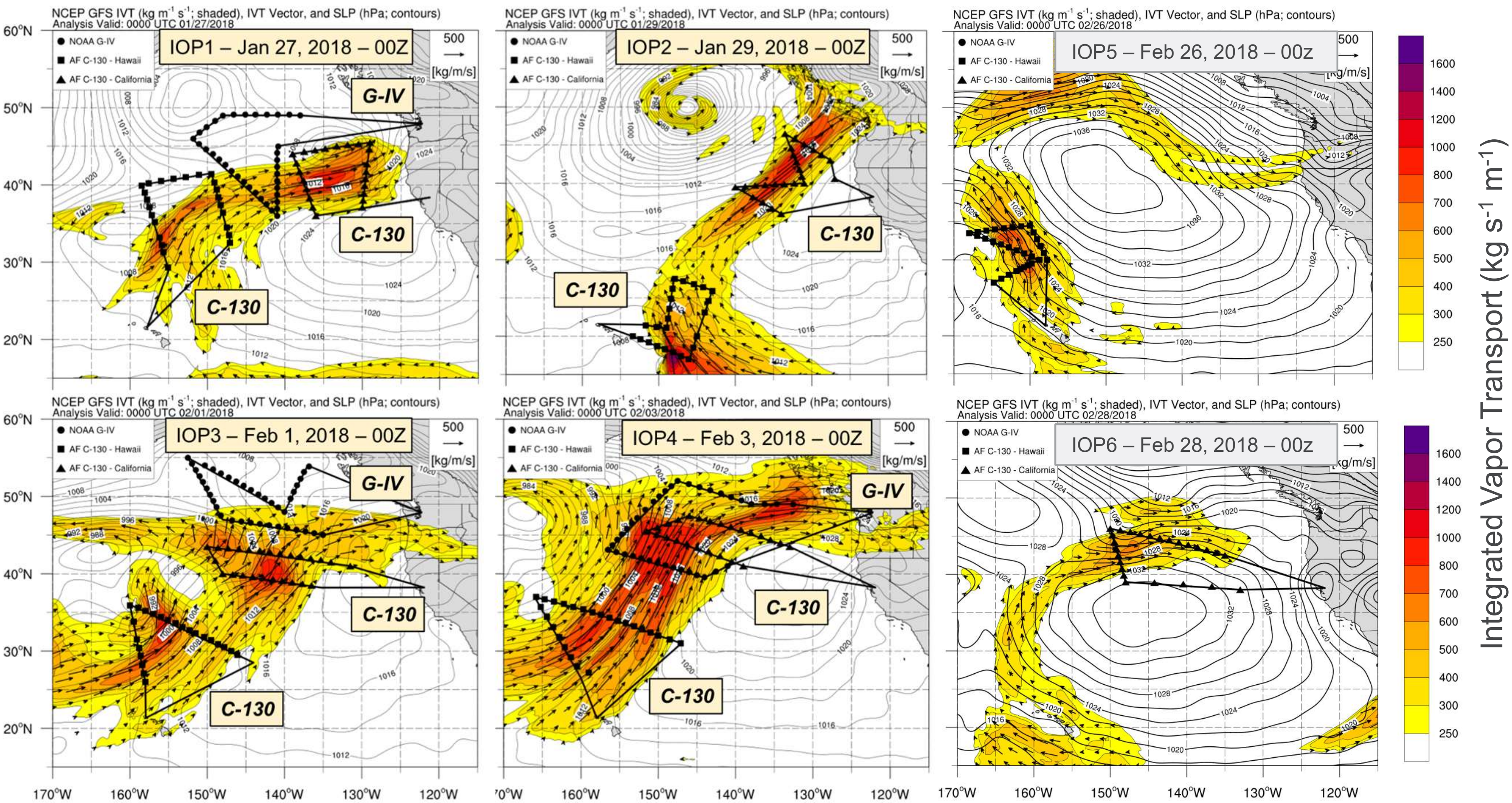




F. Martin Ralph (AR Recon PI; Scripps/CW3E), Vijay Tallaprgada (AR Recon Co-PI; NWS/NCEP) and AR Recon Team

Atmospheric River Reconnaissance 2018

Contacts: F. M. Ralph (PI; mralph@ucsd.edu); V. Tallapragada (Co-PI; vijay.tallapragada@noaa.gov)



AR Recon 2016 to 2021

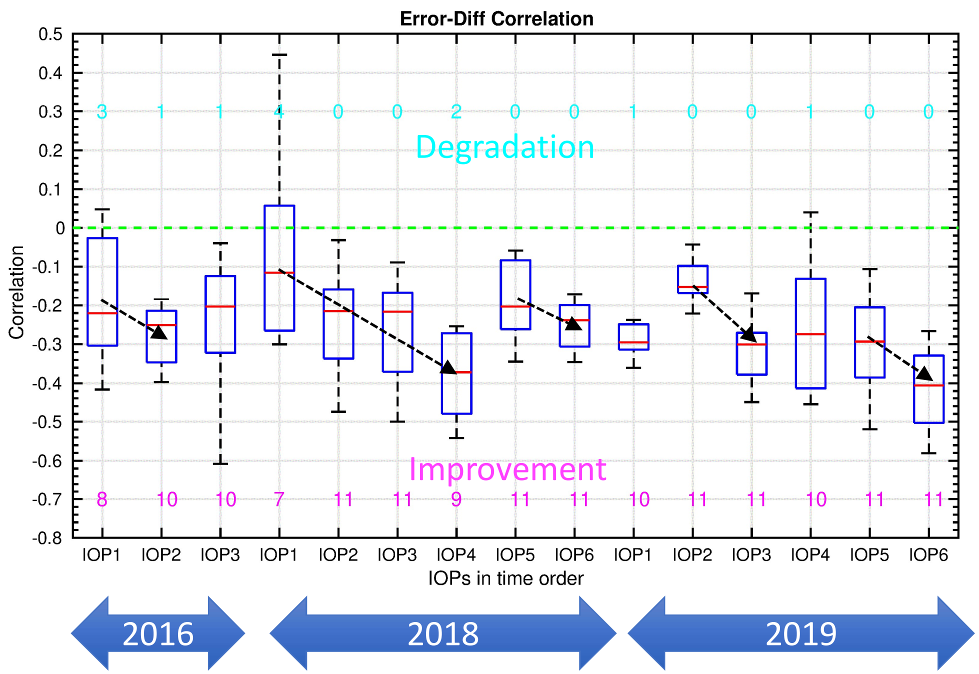
Two Air Force C-130s and NOAA's G-IV

- ✓ Feb 2016: 3 Storms (2 aircraft/storm; AF C-130s)
- ✓ Jan-Feb 2018: 6 Storms (3 aircraft/storm in 3 storms – 2 AF C-130s plus the NOAA G-IV (With Airborne GPS Radio Occultation, J. Haase); 2 C-130s in 1 storm; 1 C-130 in 2 storms)
- ✓ 1 Feb-14 Mar 2019:
  Core program: 6 storms (2 AF C-130s/storm; 25 dropsondes/aircraft/storm flight; 300 sondes)
  Addit'l data: 32 drifting buoys supplemented with barometers in AR Alley (L. Centurioni, B. Inglesby)
- ○ Jan-Mar 2020 **(ongoing):** 16 storms (1-3 aircraft/storm)
- ○ 2021 and beyond: Long-term requirements captured in the US' National Winter Storm Operating Plan

- ○ **Target 2021: 24 IOPs with 3 aircraft sampling each storm**
- ✓ Interagency, International Steering Committee in place
  - Carry out assessments
  - Refine data assimilation methods
  - Create appropriate evaluation metrics
  - Provide impact results in peer-reviewed publications

Contacts
PI: F. M. Ralph (mralph@ucsd.edu)
Co-PI: V. Tallapragada
(vijay.tallapragada@noaa.gov)

Precip: % RMSE Reduction and Error-Diff Correlation—By IOP

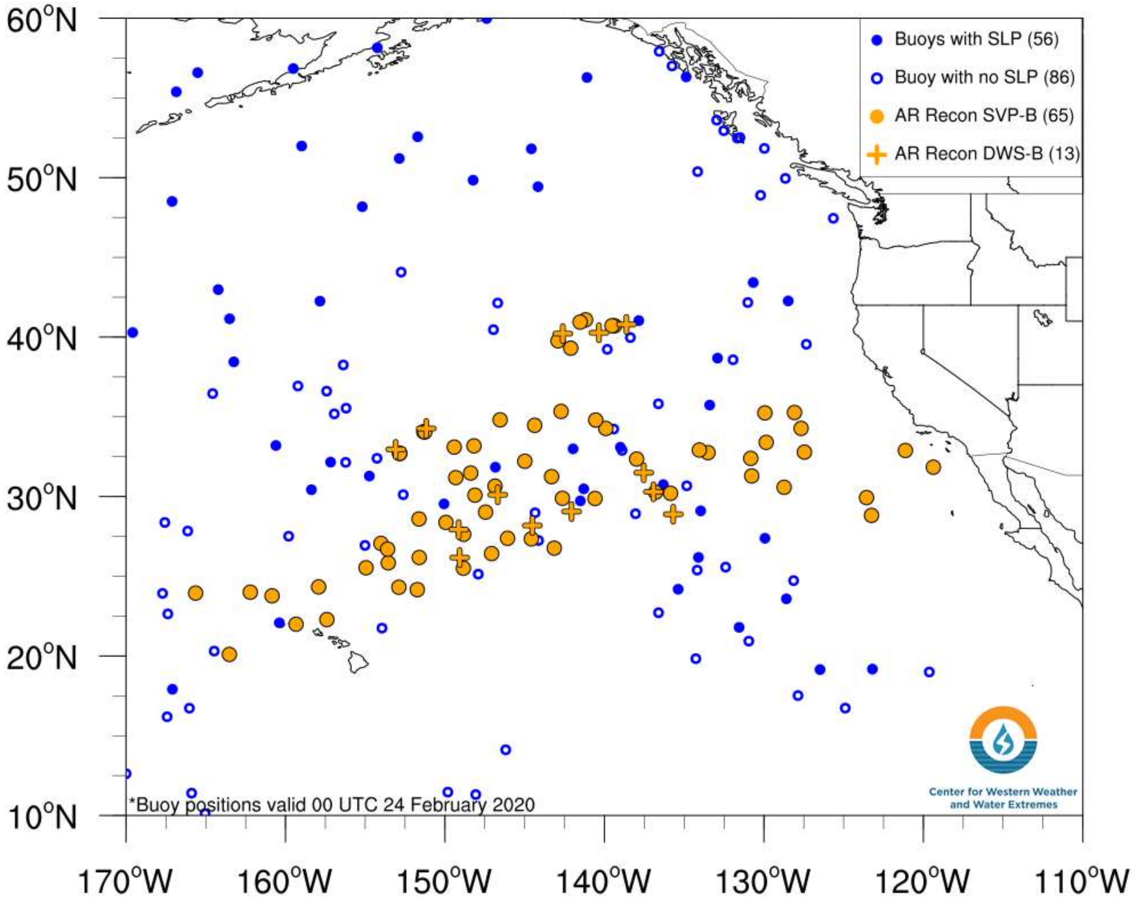


Improved IOP examples: 2016IOP2, 2018IOP4, 2019IOP6

Neutral IOP examples: 2018IOP1, 2018IOP5

The later IOPs in consecutive missions show largest improvement

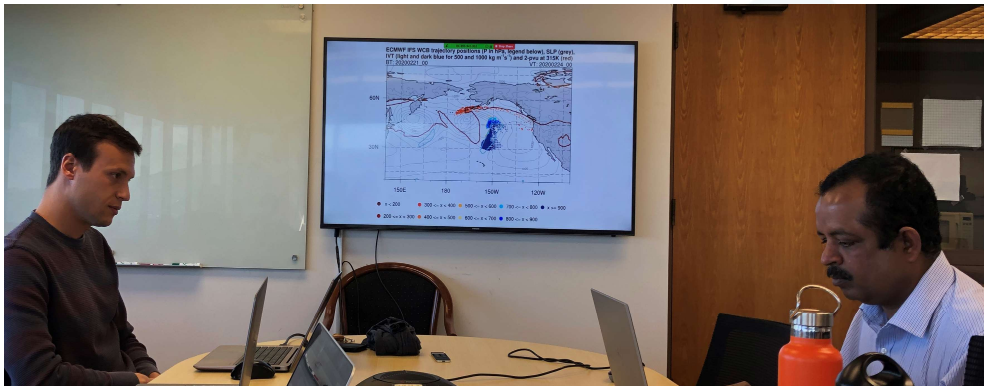
CW3E - AR RECON 2020 BUOY PROJECT

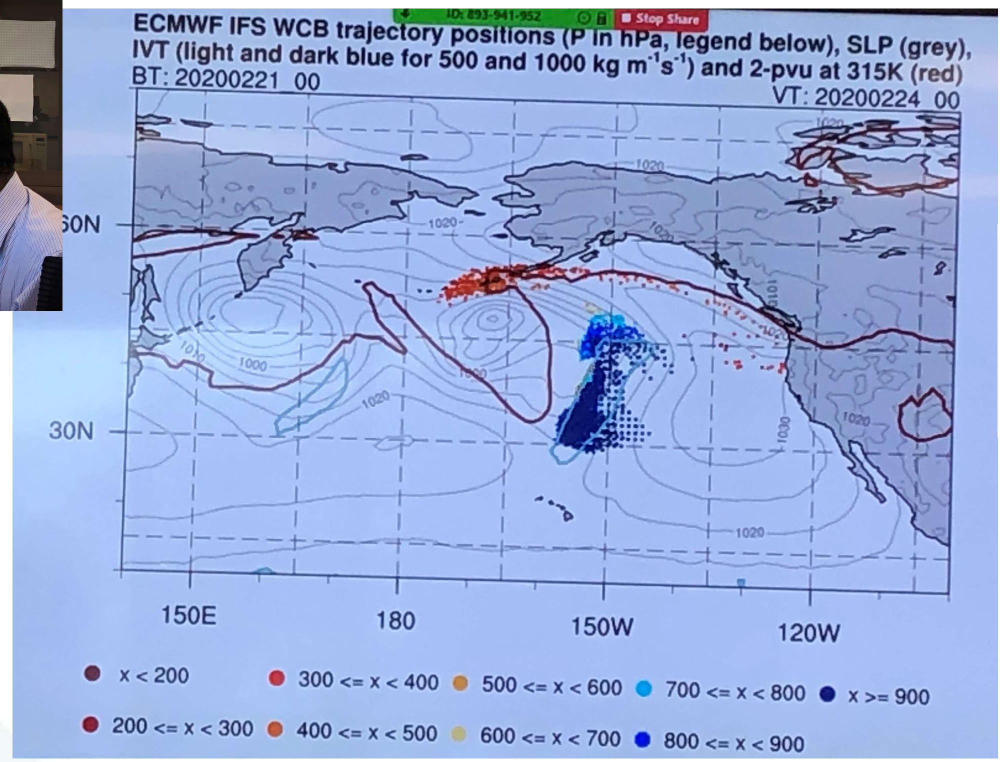


Purpose: To explore the potential of drifting buoys (with pressure sensors), in concert with AR Recon dropsondes and data assimilation efforts, to improve west coast forecasts of landfalling atmospheric rivers and precipitation. Supports California's Atmospheric Rivers Program (**PI: F.M. Ralph; CA Dept. of Water Resources – sponsor**).

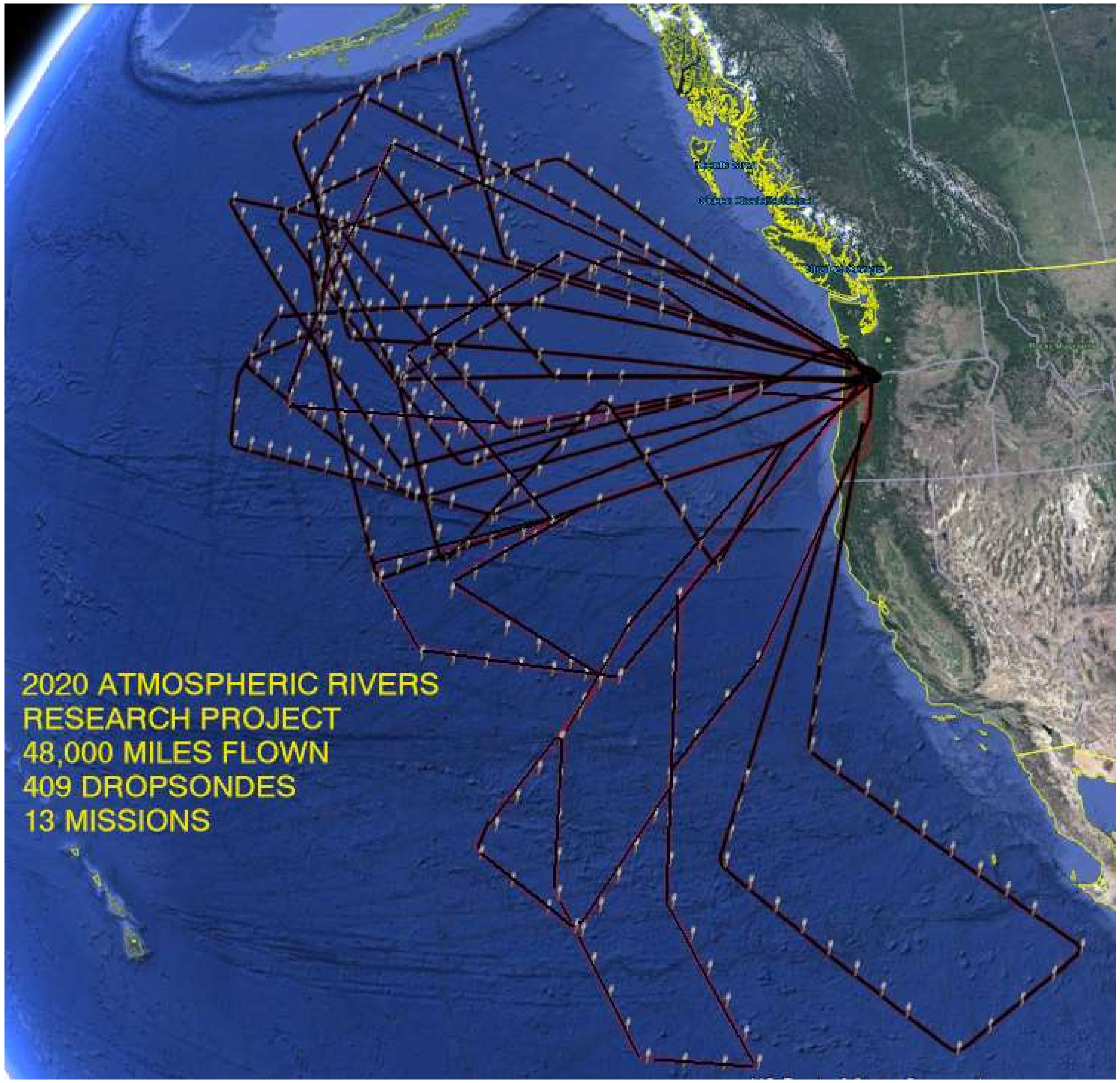
Partners: Deployment leverages the Global Drifter Program barometer upgrade program (**PI: Luca Centurioni, SIO; NOAA/OAR/OOMD – sponsor**); deployment is by the Air Force 53rd Weather Reconnaissance Squadron and by ship of opportunity arranged by L. Centurioni's group. Participation from the European Centre for Medium-Range Weather Forecasts (ECMWF) (**ECMWF Leads: Bruce Ingelby, David Lavers**).

WARM CONVEYOR BELT DIAGNOSTIC TOOL USED IN AR RECON-2020



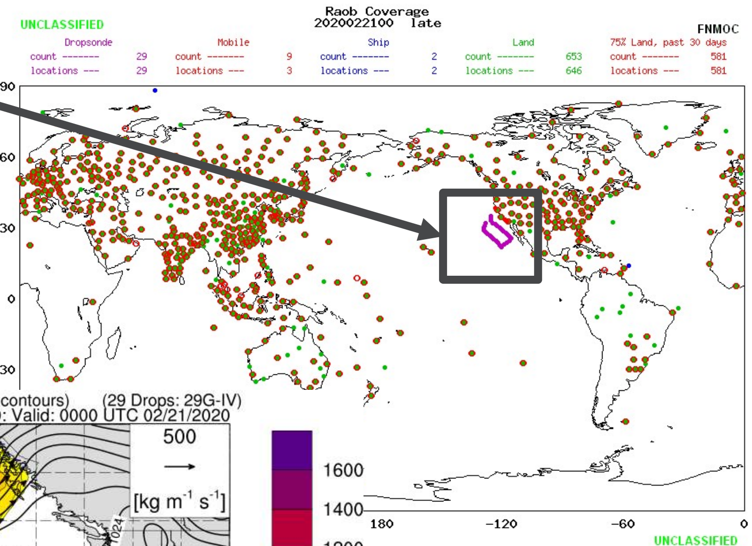


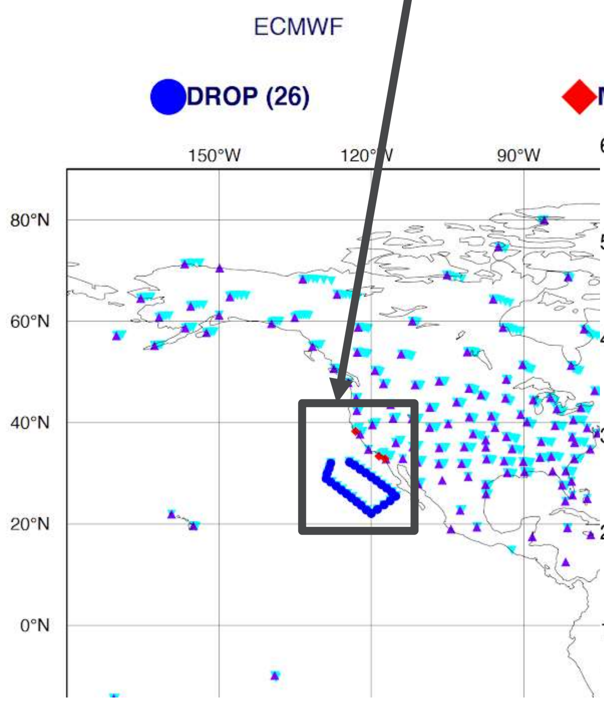
WCB Conditions are being considered in AR Recon 2020 flight planning: Products provided courtesy of H. Wernli, Hanin Binder and Maxi Boettcher

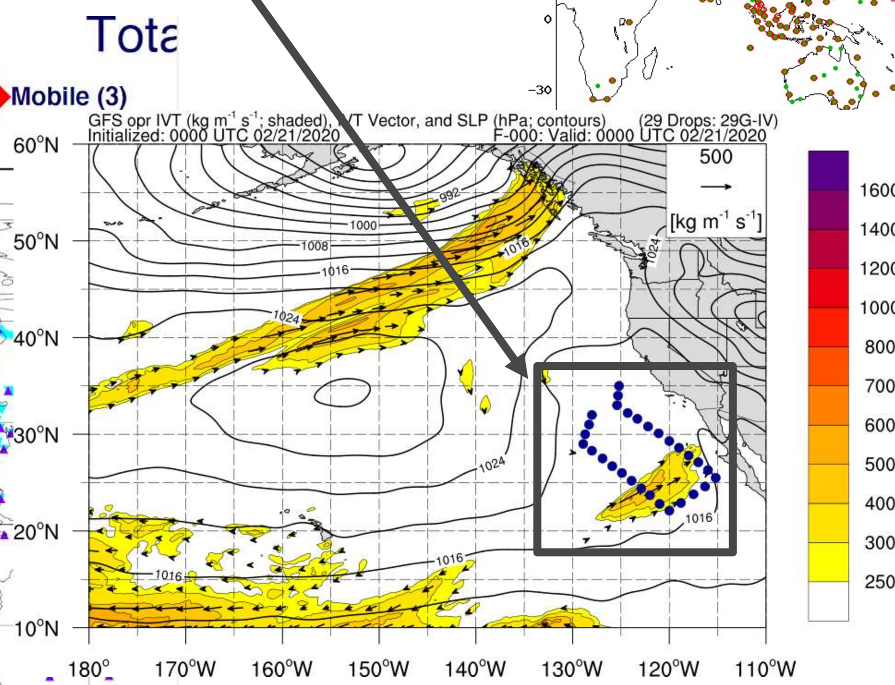

2020 ATMOSPHERIC RIVERS
RESEARCH PROJECT
48,000 MILES FLOWN
409 DROPSONDES
13 MISSIONS

Dropsondes Assimilated – IOP-10

30 drops made it into all models (00Z shown)
3 mobile radiosonde sites provided data in 18Z and 00Z





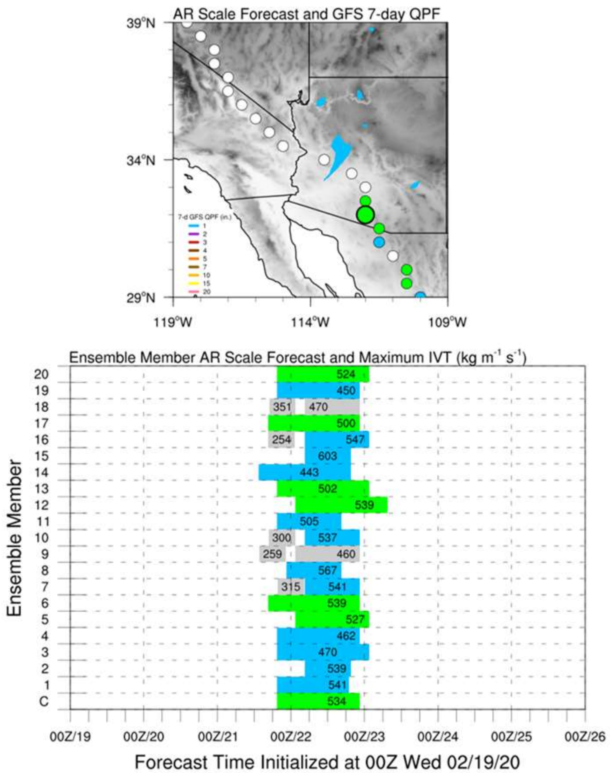


AR Scale Forecasts

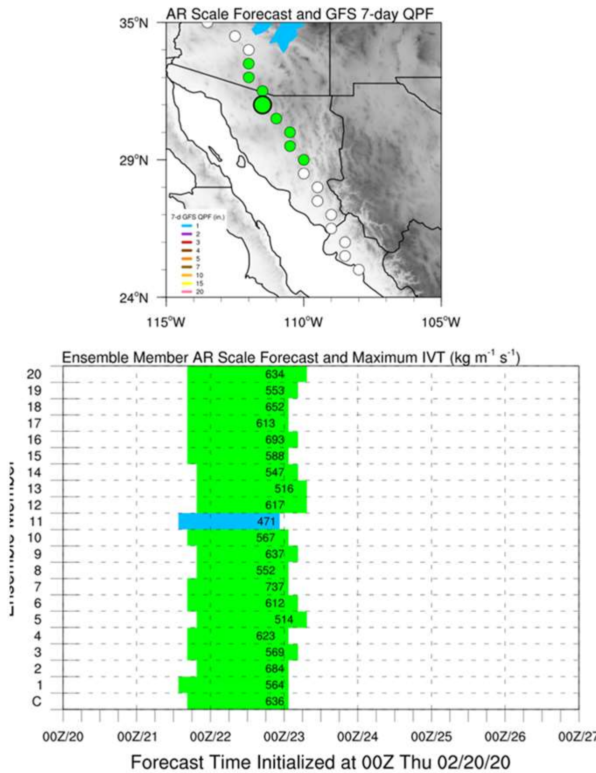
(Ralph et al. 2019, BAMS)

Center for Western Weather and Water Extremes

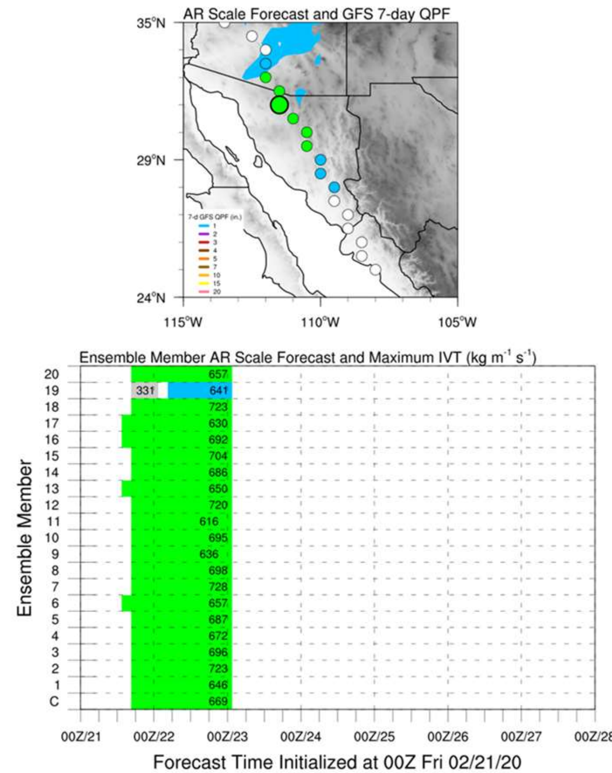
Issued: 00Z 19 Feb



Issued: 00Z 20 Feb



Issued: 00Z 21 Feb

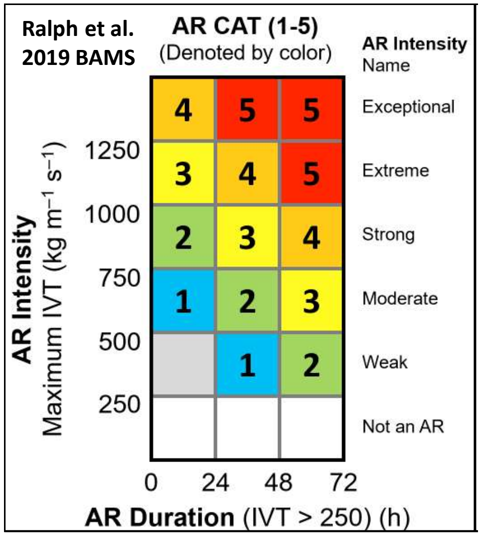


Major storm "Dennis" just hit Europe - Here's how it looks using the AR Scale

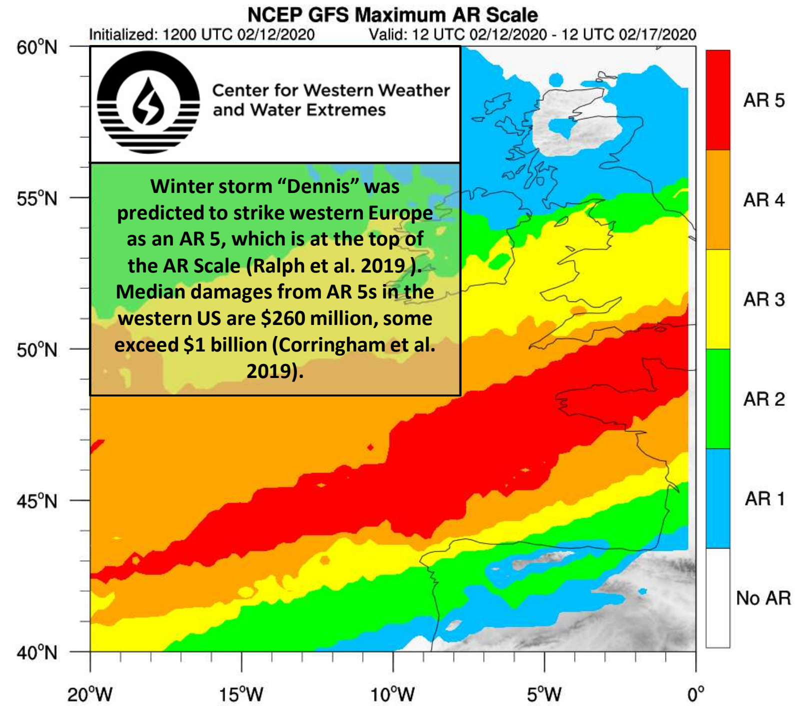
Storm Dennis, 2nd-strongest bomb cyclone on record in North Atlantic, causes severe flooding in Britain The Washington Post

The storm dumped more than a month's worth of rain in parts of Wales in one day, flooding towns and prompting evacuations.

By Andrew Freedman *16 February 2020*



The map to the right is an example of one of the CW3E AR Scale prototype displays, applied to storm "Dennis" that struck Western Europe on 14-16 Feb 2020.



Tools are being developed and tested at CW3E that assess the AR Scale ranking of predicted or recent ARs. Feedback on the prototype displays is being collected by forecasters and key forecast users. CW3E's AR Outlooks, and Storm Summaries now include the AR Scale. This information is being communicated to media when requested.

Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

F.M. Ralph, B. Kawzenuk, C. Hecht, J. Cordeira, J. Rutz (16 February 2020)

Atmospheric River Reconnaissance Workshop

29 June – 1 July 2020
Seaside Forum at the Scripps Institution of Oceanography, La Jolla, CA
Hosted by the Center for Western Weather and Water Extremes (CW3E.UCSD.EDU)

29 June – 1 July 2020

La Jolla, California

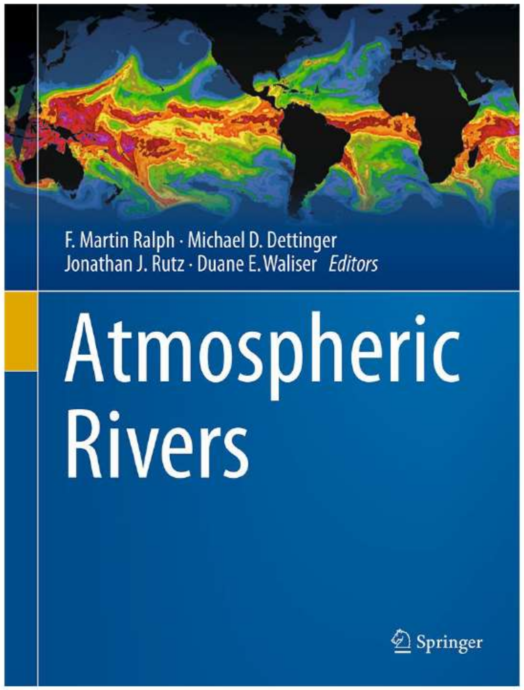
Atmospheric River Reconnaissance Strives to Improve Predictions of Land-falling Atmospheric Rivers and Their Associated Impacts in the Western U.S.

From 2015 to 2020, AR Recon grew from a concept to a field demonstration to an operational requirement and mission. It has gone from 3 storms flown over 2 weeks in 2016 to 12 flown over 8 weeks in 2020. It could reach 24 over 12 weeks in 2021. It uses two Air Force C-130s and the NOAA G-IV to carry out dropsonde missions and has partnered with the global drifter program to deploy roughly 100 drifting buoys with pressure sensors. Flight planning and calling of missions is carried out by a diverse team of scientists and forecasters, who consider input from multiple objective targeting methods and fundamental physical principles. A steering committee for modeling and data assimilation consisting of a multi-agency team of global modeling and science centers is working together to document and enhance impacts of the data.

WORKSHOP PURPOSE: DOCUMENT IMPACTS and ENVISION AR RECON IN 2025
The goals are to share results, to coordinate and inspire future work on data collection, data assimilation, metric development and impact assessment, and to discuss the research and operations partnership approach being developed in AR Recon.

The Workshop will bring together current participants and interested experts to share results of modeling, data assimilation and impact studies and to consider next steps for future field seasons. It will cover the following topics, using oral and poster sessions, as well as panel discussions:

- Flight planning, targeting and execution methods – refinements and expansion
- Verification and validation methods including use of the AR scale
- Data assimilation and impact studies, including new methods
- Evaluate potential impacts of AR Recon in the central and eastern US
- Identify leading sources of forecast errors, including role of mesoscale frontal waves
- Physical process studies enabled by AR Recon in support of western water applications
- Representing AR Recon in the NWSOP as a national mission focused on western water
- Potential for collaboration with European interests, including on warm conveyor belts
- Discuss a vision for AR Recon - 2025



1st ed. 2019, XX, 366 p. 172 illus., 160 illus. in color.

Printed book

Hardcover

81,99 € | £69.99 | $99.99
[1]87,73 € (D) | 90,19 € (A) | CHF

F.M. Ralph, M. Dettinger, J.J. Rutz, D.E. Waliser (Eds.)

Atmospheric Rivers

Available early 2020
Springer
20+ Contributing Authors

- **Presents the latest research on a highly impactful extreme weather phenomenon with climatological importance both regionally and globally, and that has bearing on a variety of civil and commercial decision support areas**
- **Provides specific, research-based information on atmospheric rivers to help practitioners understand and explain the scientific basis of the weather pattern to non-practitioners and the general public**
- **Gives in-depth scientific information on atmospheric rivers within the broader topics of extratropical cyclones, weather and hydrological extremes, regional and global climate, as well as weather prediction and future climate projections**

This book is the standard reference based on roughly 20 years of research on atmospheric rivers, emphasizing progress made on key research and applications questions and remaining knowledge gaps. The book presents the history of atmospheric-rivers research, the current state of scientific knowledge, tools, and policy-relevant (science-informed) problems that lend themselves to real-world application of the research—and how the topic fits into larger national and global contexts. This book is written by a global team of authors who have conducted and published the majority of critical research on atmospheric rivers over the past years. The book is intended to benefit practitioners in the fields of meteorology, hydrology and related disciplines, including students as well as senior researchers.

Center for Western Weather and Water Extremes

ATMOSPHERIC RIVER RECONNAISSANCE:

SUPPORTING WESTERN STORM PREDICTIONS AND WATER DECISIONS

F. Martin Ralph, PI (UC San Diego/SIO/CW3E)

Vijay Tallapragada Co-PI (NOAA/NWS/NCEP)

Jim Doyle (Naval Research Laboratory)

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AR Recon

Papers Published to Date (Results)

Demirdjian, R., Doyle, J.D., Reynolds, C.A. Norris, J.A., Michaelis, A.C., Ralph, F.M., 2019: A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model. Journal of the Atmospheric Sciences, 0, DOI 10.1175/JAS-D-19-0155.1

Guan, B., D. Waliser, and F. Ralph, 2017: An inter-comparison between reanalysis and dropsonde observations of the total water vapor transport in individual atmospheric rivers. Journal of Hydrometeorology, 19, 321-337, doi:10.1175/JHM-D-17-0114.1

Lavers, D.A., M.J. Rodwell, D.S. Richardson, F.M. Ralph, J.D. Doyle, C.A. Reynolds, V. Tallapragada, and F. Pappenberger, 2018: The Gauging and Modeling of Rivers in the Sky. Geophysical Research Letters, 45, https://doi.org/10.1029/2018GL079019

Ralph, F., S. Iacobellis, P. Neiman, J. Cordeira, J. Spackman, D. Waliser, G. Wick, A. White, and C. Fairall, 2017: Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers. Journal of Hydrometeorology, 18, 2577-2596. doi:10.1175/BAMS-D-15-00245.1

Reynolds, C.A., J.D. Doyle, F.M. Ralph, and R. Demirdjian, 2019: Adjoint Sensitivity of North Pacific Atmospheric River Forecasts. Mon. Wea. Rev., 147, 1871-1897, https://doi.org/10.1175/MWR-D-18-0347.1

Stone, R.E., C.A. Reynolds, J.D. Doyle, R. Langland, N. Baker, D.A. Lavers, and F.M. Ralph, 2019: Atmospheric River Reconnaissance Observation Impact in the Navy Global Forecast System. Mon. Wea. Rev., 0, https://doi.org/10.1175/MWR-D-19-0101.1

A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model

Reuben Demirdjian[1], Jim Doyle[2], Carolyn Reynolds[2], Joel Norris[1], Allison Michaelis[1], F. Martin Ralph[1]
[1]UCSD/SIO/CW3E, [2]NRL (*J. Atmos. Sci.* 2020, in press)

Purpose of Study

- Diagnose the dynamical processes linking the initial condition sensitivities offshore in an adjoint model to errors in forecasts of AR landfall and associated precipitation

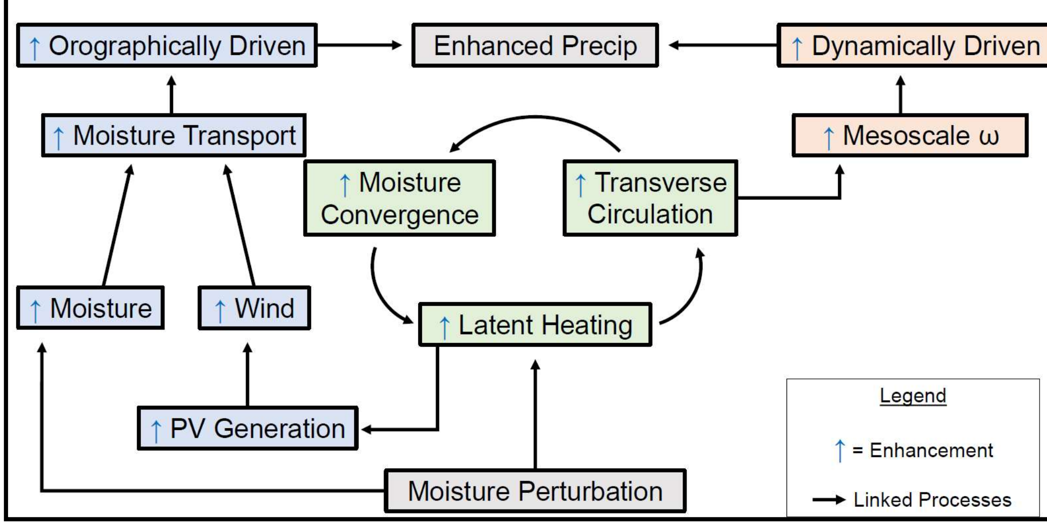
Why Bother?

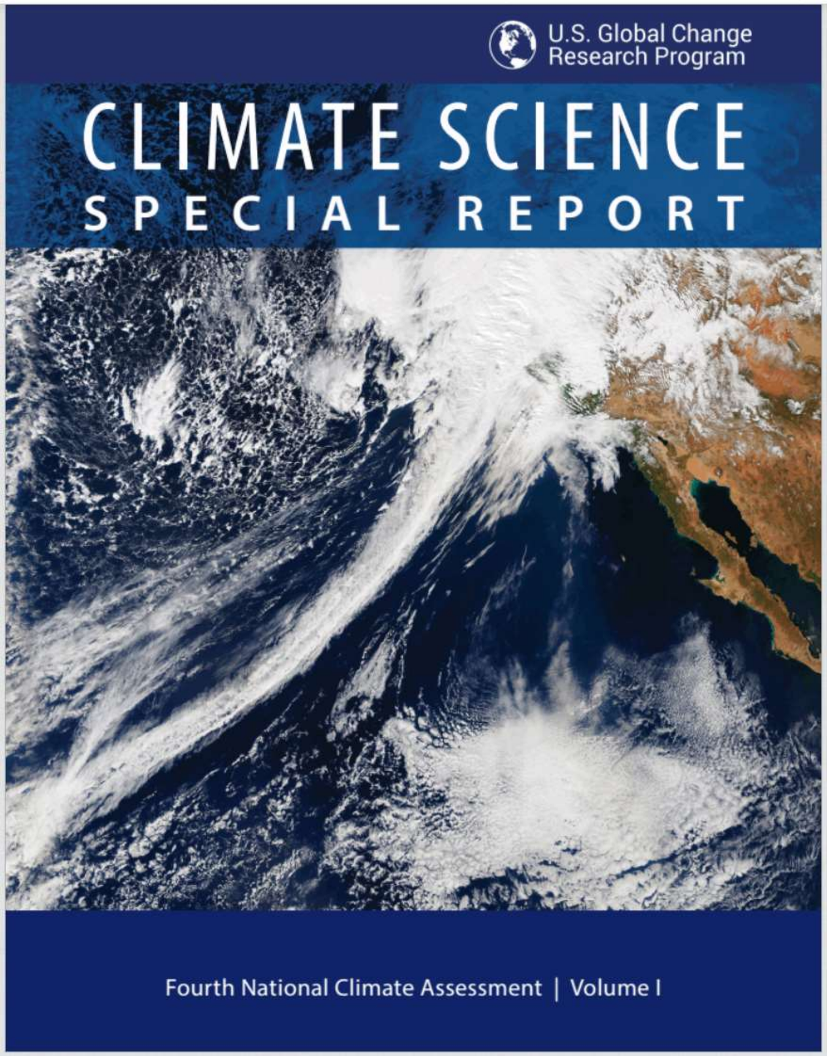
- To understand how errors in weather forecast model representation of AR initial conditions offshore can lead to errors in the prediction of AR landfall.

Result

- An error in water vapor initial condition within the AR modifies precipitation (both d*ynamically and orographically forced*) by amplifying the latent heating in a dynamical feedback process involving wind and PV anomalies that act to reinforce the initial perturbation.

Processes Leading to Changes in the Perturbed Run's Precipitation





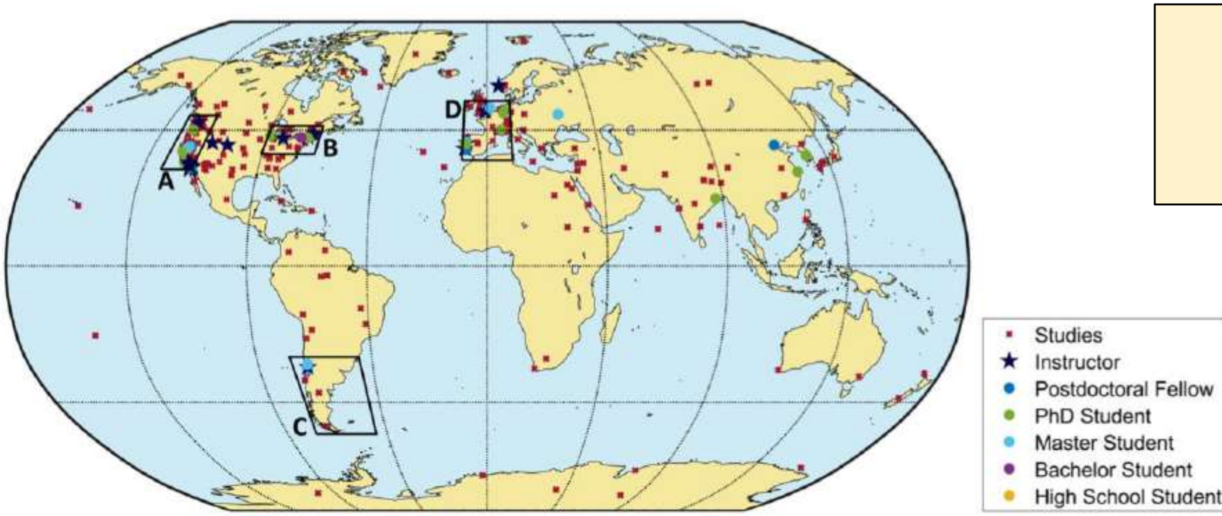
Atmospheric Rivers Highlighted in the U.S. Fourth National Climate Assessment, released on 3 November 2017

9

Extreme Storms

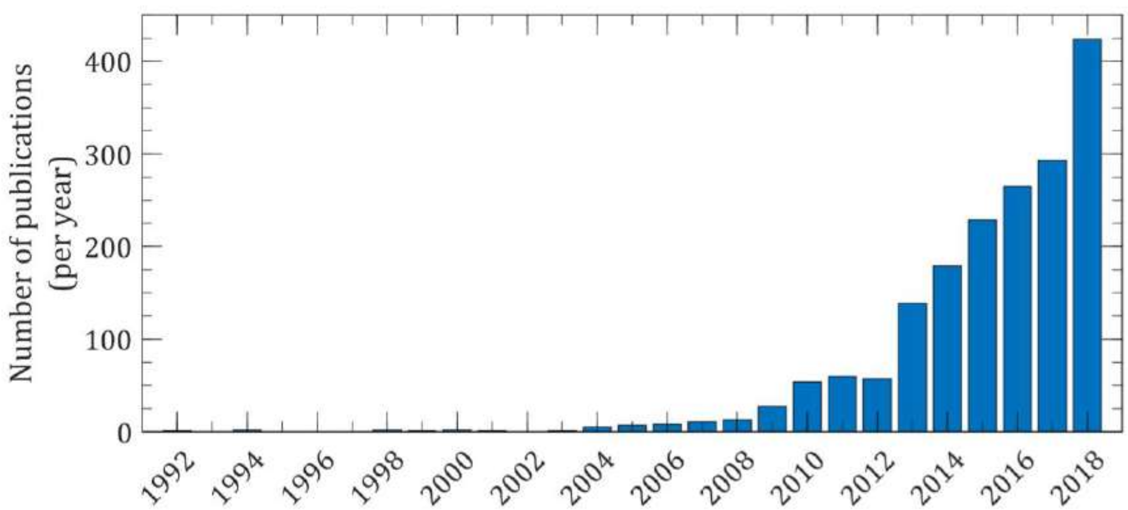
KEY FINDINGS

1. Hurricanes and Typhoons
2. Severe Thunderstorms
3. Winter storms
4. **Atmospheric Rivers (NEW in 4th Assessment)**



AR Are Being studied globally

Wilson et al. 2020 BAMS
AR Summer Colloquium
Meeting Summary
(in Press)



Rapid Growth in the Reference to ARs in Scientific Papers

Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers

F.M. Ralph, S. Iacobellus, P.J. Neiman, J. Cordeira, J.R. Spackman, D. Waliser, G. Wick, A.B. White, C. Fairall

J. Hydrometeorology (2017)

Method/Data: Uses 21 AR cases observed in 2005 - 2016 with full dropsonde transects.

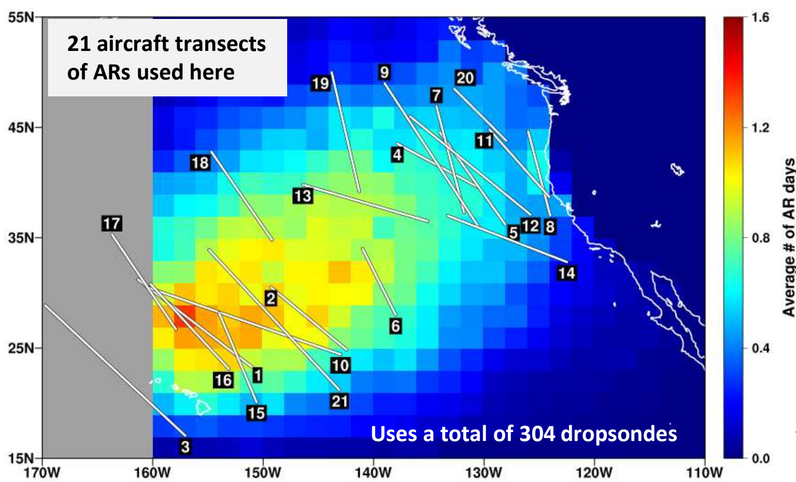
- AR edges best defined by using IVT = 250 kg m^{-1} s^{-1}

Conclusions*:

- Average width: 850 km
- 75% of water vapor transport occurs below 3 km MSL; < 1% occurs above 8 km MSL
- Average max IVT: ~800 kg m^{-1} s^{-1}

KEY FINDING

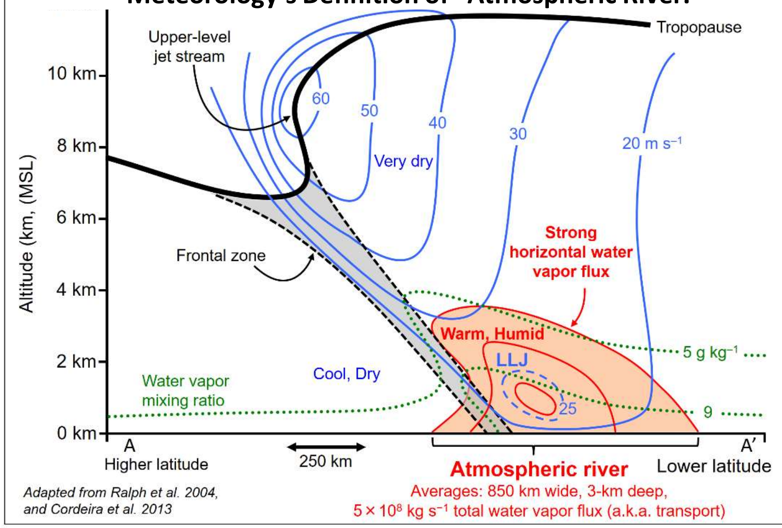
An average AR* transports 4.7 ± 2.0 x 10^8 kg s^{-1} of water vapor, which is equivalent to 2.6 times the average discharge of liquid water by the Amazon River



These values represent averages for the Northeast Pacific Ocean in the January-March season

Background image denotes weekly AR frequency during cool seasons (Nov -Feb).

Synthesis from 21 observed ARs; Used in the Glossary of Meteorology's Definition of "Atmospheric River."




International
Atmospheric Rivers Conference
IARC-2018
Seaside Forum at UC San Diego's
Scripps Institution of Oceanography
La Jolla, CA, 25-28 June 2018
Hosted by the "Center for Western
Weather and Water Extremes"
Bringing together a diverse, cross-disciplinary
community of scientists, engineers, forecasters and managers
to discuss atmospheric river science and applications.
Center for Western Weather
and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY
AT UC SAN DIEGO

First Circular: November 15, 2019

Atmospheric rivers (ARs) play a key role in the global water cycle as the primary mechanism conveying water vapor through mid-latitude regions. The precipitation that ARs deliver in many parts of the world, especially through orographic precipitation processes, is important for water resources; but it also regularly is a hazard, triggering floods and landslides, as well as coastal wind storms. The aims of the 2020 International Atmospheric Rivers Conference are:

- to understand dynamical and physical processes in ARs
- to describe the AR impact on hydrology, environment and society
- to evaluate the Atmospheric River Tracking Method Intercomparison Project's (ARTMIP)
- to assess current forecasting capabilities and developing applications
- to project ARs in a warmer world and understand their natural variability

Students are strongly encouraged to attend. Scholarships are available, as well as slots for student speakers.

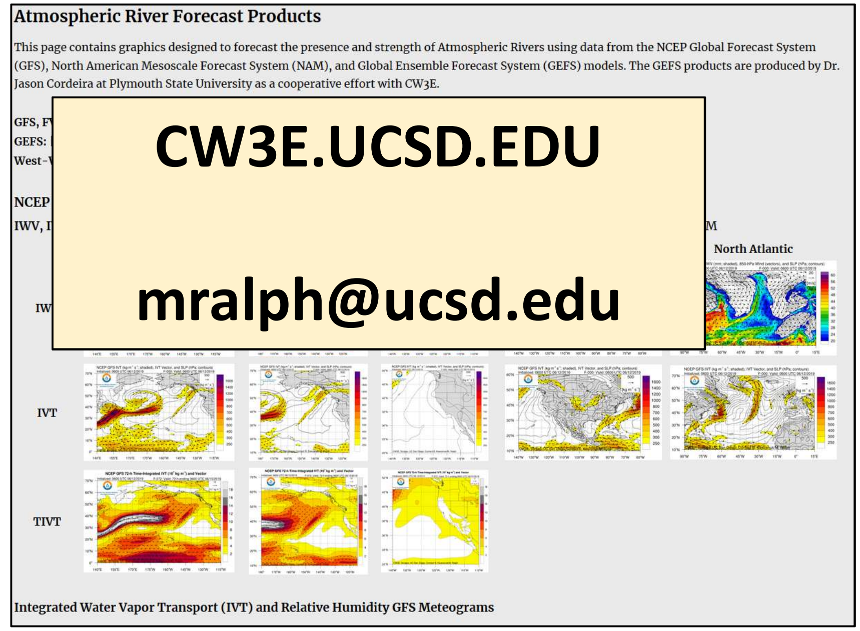
Scientific Steering Committee:

Marty Ralph, Anna Wilson, Reuben Demirdjian (CW3E, UCSD, US); Hans Christian Steen-Larsen (U. of Bergen, Norway); Jon Rutz (US National Weather Service); Roberto Rondanelli, James McPhee (Universidad de Chile); Jorge Eiras-Barca (U. Vigo, Spain); Christine Albano (Desert Research Institute, US); Natalia Tilinina (Shirshov Institute of Oceanology, Russia); Mike Warner (US Army Corps of Engineers); Alexandre Ramos (University of Lisbon, Portugal); Maximiliano Viale (IANIGIA, Argentina)

For further information, please contact the *Local Organizing Committee*

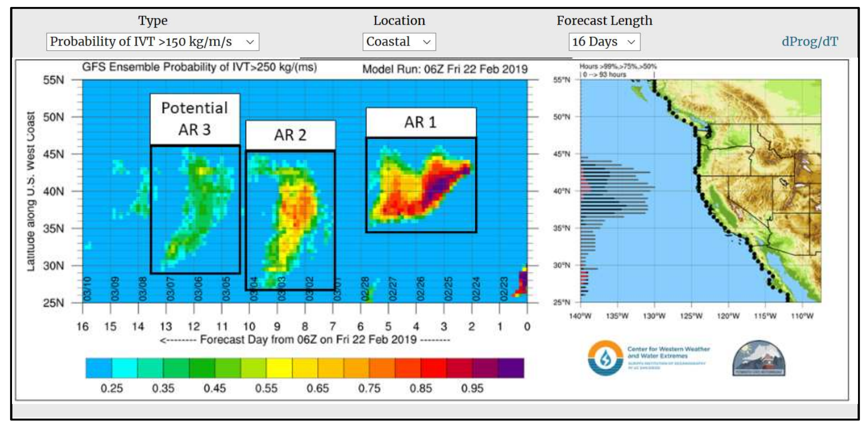
René Garreaud (rgarreau@dgf.uchile.cl) and Raul Valenzuela (rvalenzuela@dgf.uchile.cl)

Conference web site: http://www.dgf.uchile.cl/3IARC (available Dec 2019)



CW3E.UCSD.EDU

mralph@ucsd.edu



WEST COAST FORECAST CHALLENGES AND DEVELOPMENT OF ATMOSPHERIC RIVER RECONNAISSANCE

Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

F. Martin Ralph
Director, Center for Western Weather and Water Extremes

Warm Conveyor Belt Workshop
European Center for Medium Range Weather Forecasting
10 March 2020, Virtual Meeting

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

Glossary of Meteorology

Added May 2017. Process described in Ralph, Dettinger, Cairns, Galarneau, Eylander, 2018, *Bull. Amer. Meteor. Soc.*, ***99***, pp 837-839.

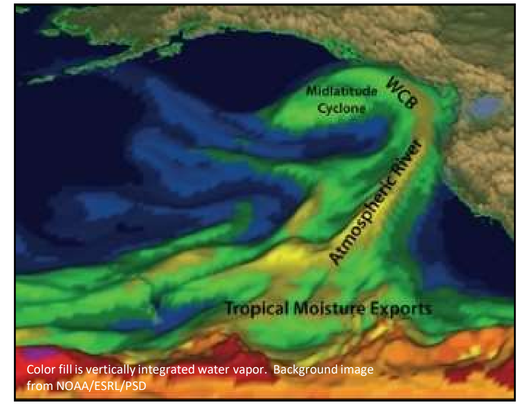
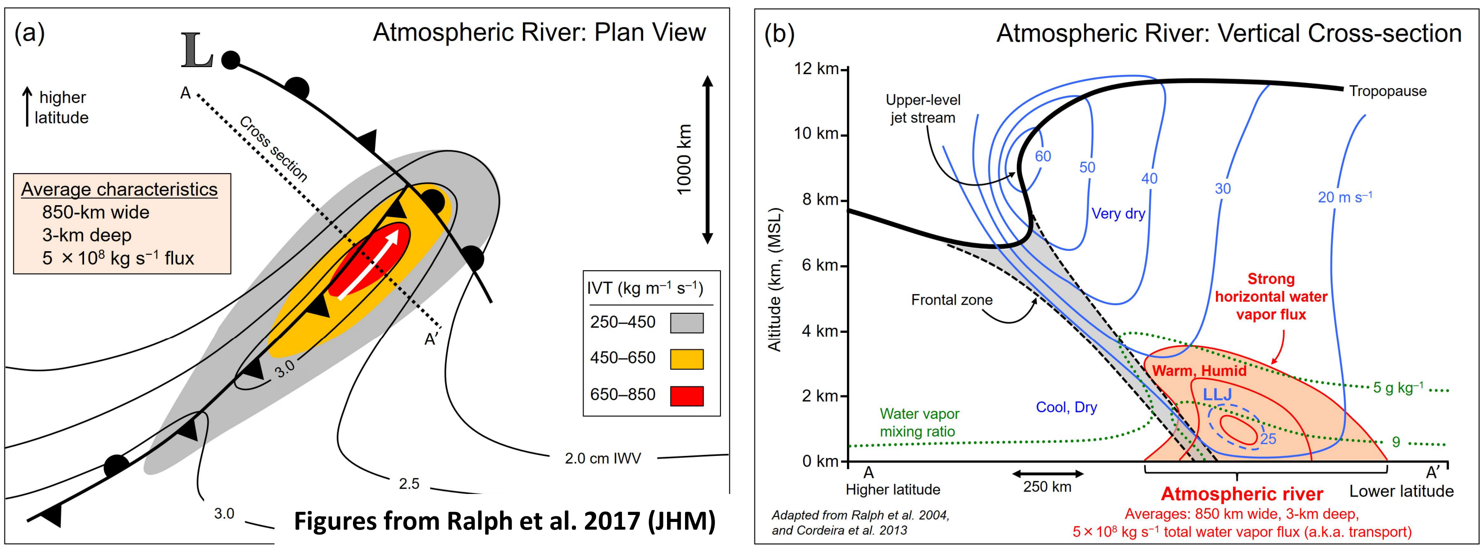


Fig. from Dettinger, Ralph, Lavers, EOS 2015

ATMOSPHERIC RIVER

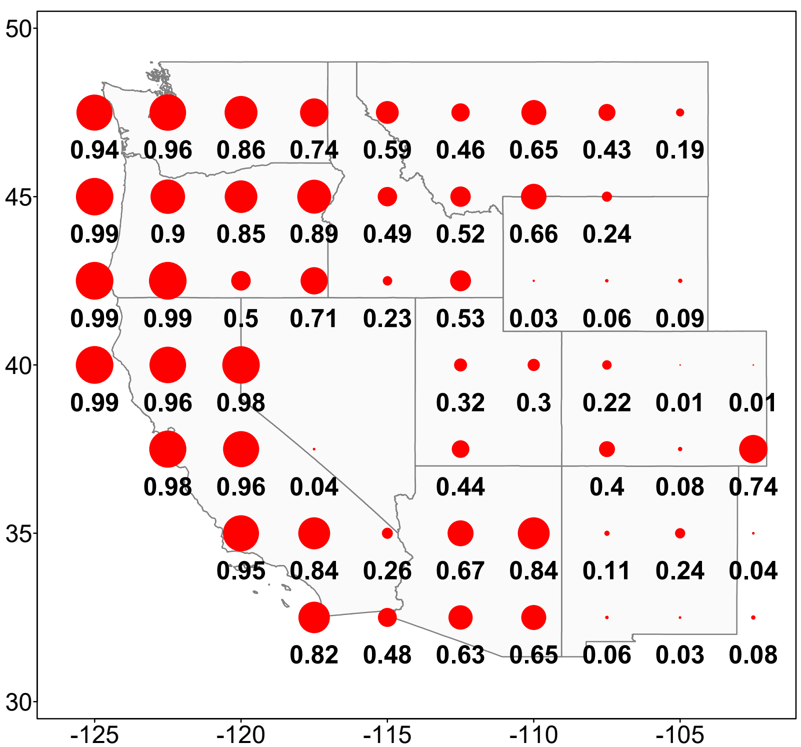
A long, narrow and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward, e.g., by mountains or by ascent in the warm-conveyor-belt. Horizontal water vapor transport in the mid-latitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.



Figures from Ralph et al. 2017 (JHM)

ARs drive economic flood losses

Proportion of Economic Losses Due to ARs



84% of insured losses in the 11 western states were caused by ARs

Post-Fire debris flows pose a serious hazard. This case killed >20 people near Montecito, CA.

T. Corringham, 2018

SCRIPPS INSTITUTION OF OCEANOGRAPHY

A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

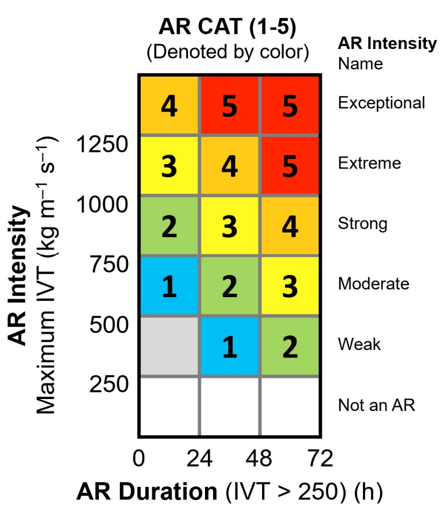
F. Martin Ralph (SIO/CW3E), J. J. Rutz (NWS), J. M. Cordeira (Plymouth State), M. Dettinger (USGS), M. Anderson (CA DWR), D. Reynolds (CIRES), L. Schick (USACE), C. Smallcomb (NWS); *Bull. Amer. Meteor. Soc. 269-289 (2019);*

The AR CAT level of an AR Event* is based on its *Duration* and max *Intensity* (IVT)*****

** An "AR Event" refers to the existence of AR conditions at a specific location for a specific period of time.*
*** How long IVT>250 at that location. If duration is <24 h, reduce AR CAT by 1, if longer than 48 h, add 1.*
**** This is the max IVT at the location of interest during the AR.*

IMPACTS

- AR Cat 5 – Primarily hazardous
- AR Cat 4 – Mostly hazardous, also beneficial
- AR Cat 3 – Balance of beneficial and hazardous
- AR Cat 2 – Mostly beneficial, also hazardous
- AR Cat 1 – Primarily beneficial



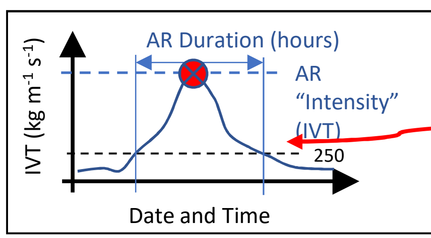
Determining AR Intensity and AR Category

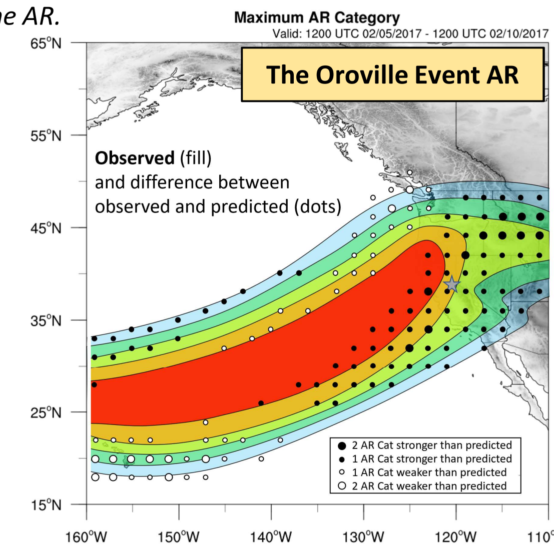
Step 1: Pick a location

Step 2: Determine a time period when IVT > 250 (using 3 hourly data) at that location, either in the past or as a forecast. The period when IVT continuously exceeds 250 determines the start and end times of the AR, and thus also the **AR Duration** for the AR event at that location.

Step 3: Determine **AR Intensity**
- Determine max IVT during the AR at that location
- This sets the AR Intensity and *preliminary* AR CAT

Step 4: Determine *final* value of **AR CAT** to assign
- If the AR Duration is > 48 h, then promote by 1 Category
- If the AR Duration is < 24 h, then demote by 1 Category

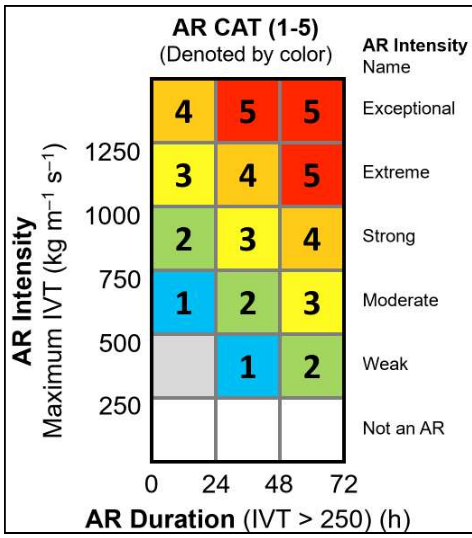




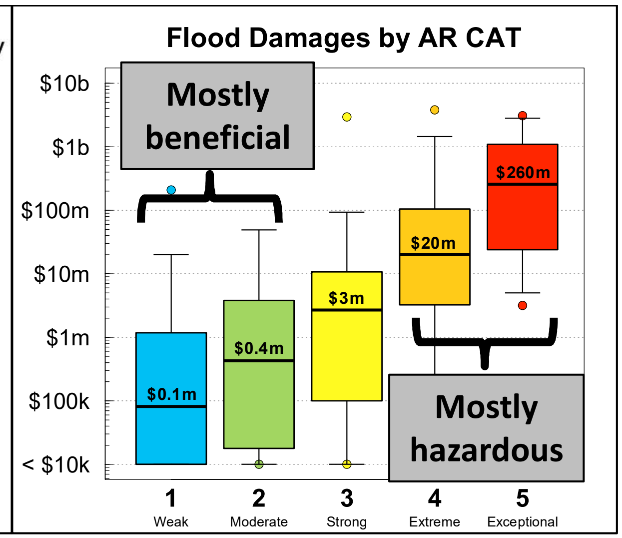
On the Web: CW3E.UCSD.EDU
On Twitter: @CW3E_Scripps

Center for Western Weather and Water Extremes

ARs drive flood damages in the western U.S.



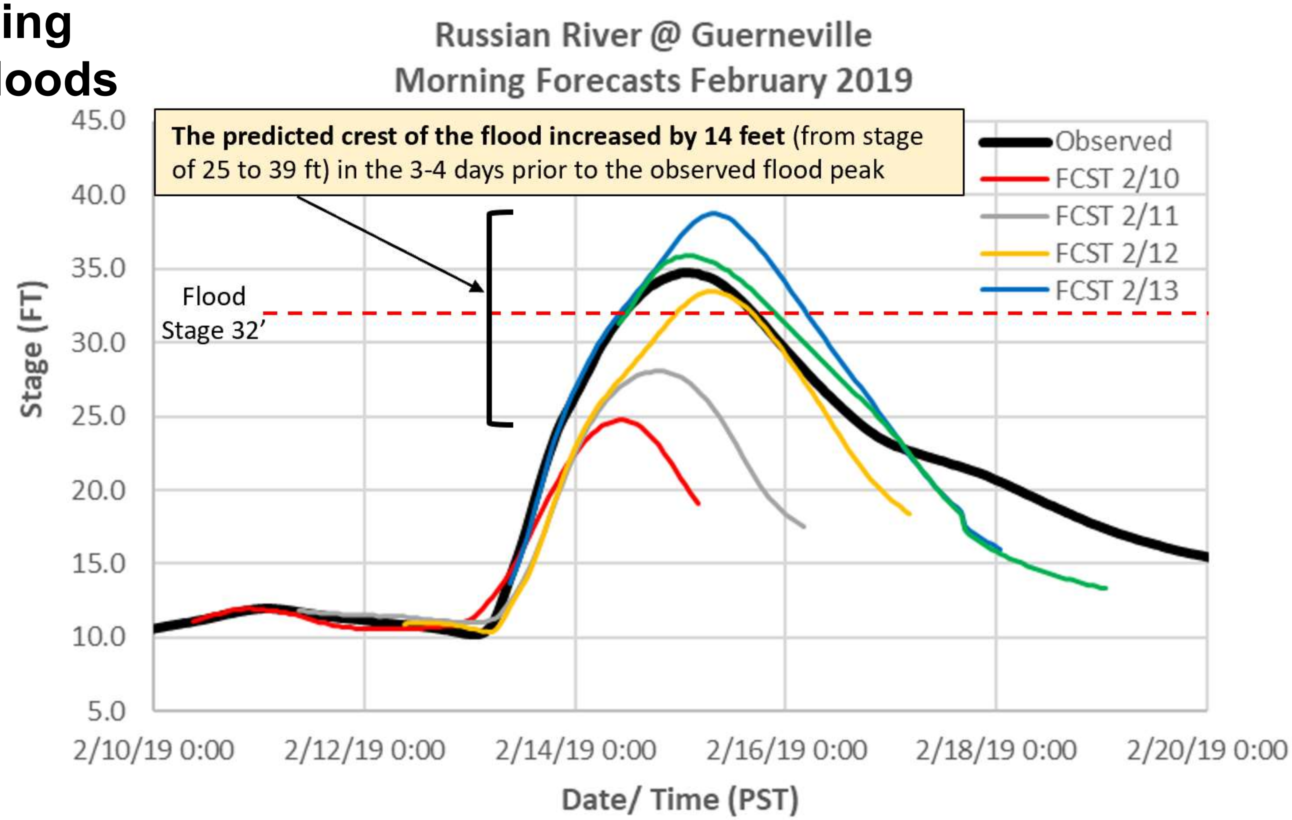
Ralph et al. BAMS 2019



Corringham et al. Sci. Advances 2019

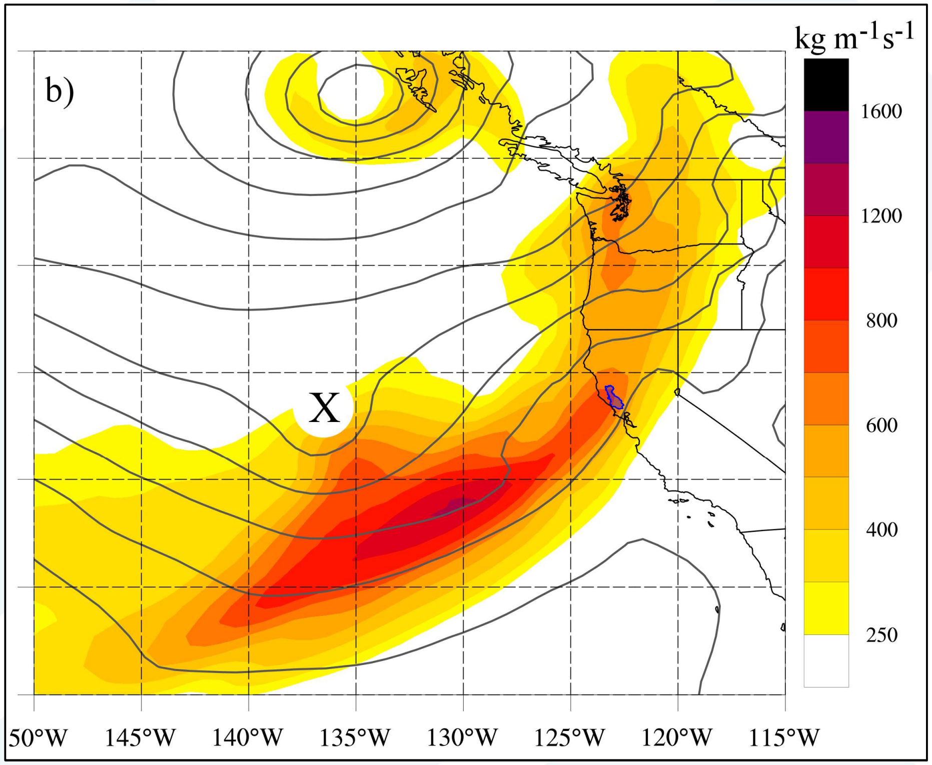
Flood damages increase exponentially with AR Category

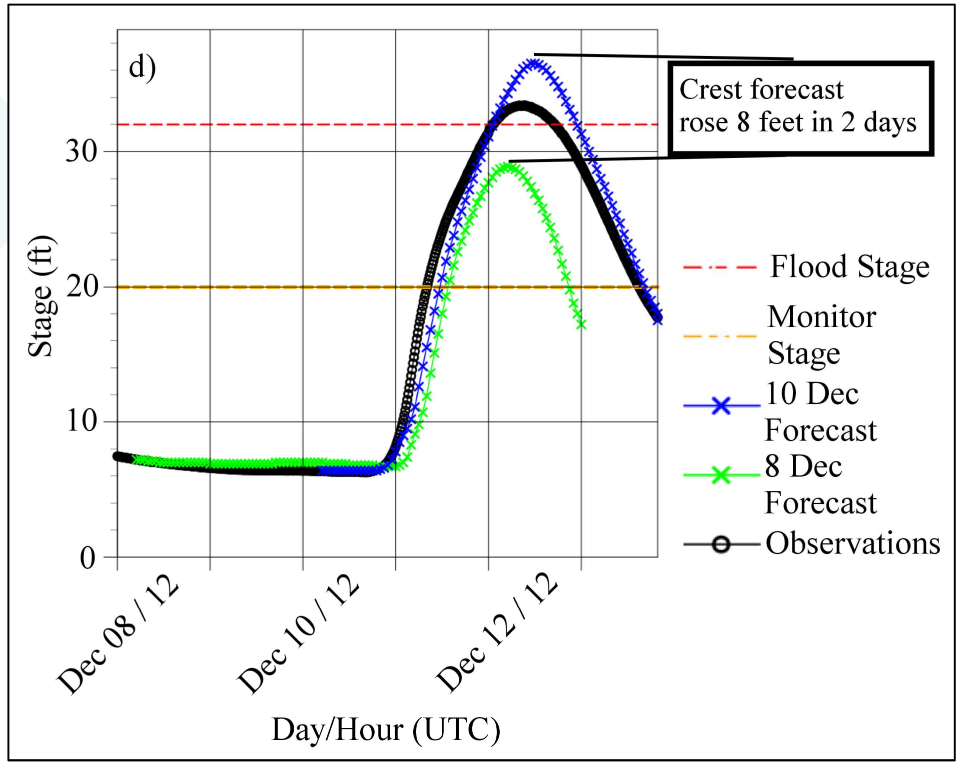
The Forecasting Challenge: Floods



Each line represents a different forecast (FCST) issued on either 10, 11, 12, 13 or 14 Feb, which were either 0, 1, 2, 3, or 4 days prior to when the flood crest was observed.

ERRORS IN PREDICTING THE STRUCTURE AND STRENGTH OF AN ATMOSPHERIC RIVER CAN CREATE MAJOR ERRORS IN FLOOD FORECASTS





UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY | Center for Western Weather and Water Extremes

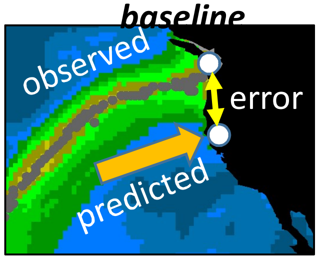
A. Martin, F.M. Ralph, A. Wilson, L. DeHaan, B. Kawzenuk
(J. Hydrometeor., 2019)

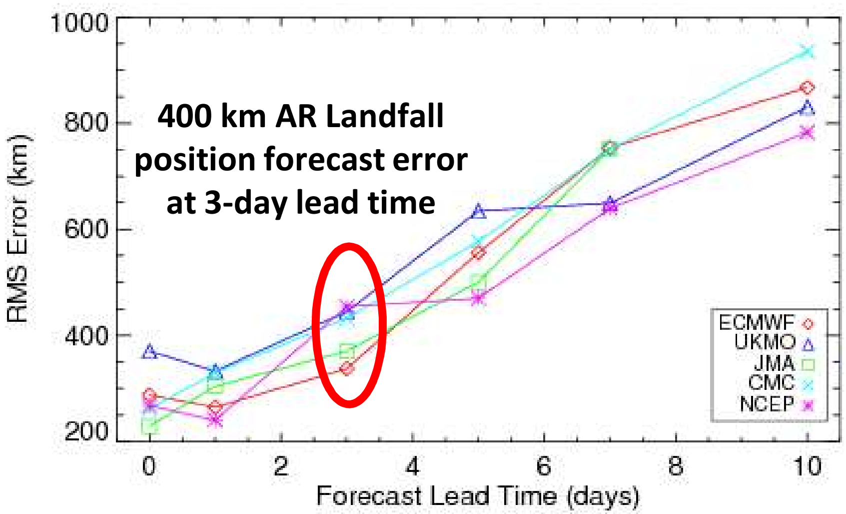
Atmospheric River Reconnaissance

FM Ralph (Scripps/CW3E), V Tallapragada (NWS/NCEP), J Doyle (NRL)

Water managers, transportation sector, agriculture, etc… require improved atmospheric river (AR) predictions

AR Forecast skill assessment establishes a performance baseline





Wick, G.A., P.J. Neiman, F.M. Ralph, and T.M. Hamill, 2013: Evaluation of forecasts of the water vapor signature of atmospheric rivers in operational numerical weather prediction models. *Wea. Forecasting*, **28**, 1337-1352.

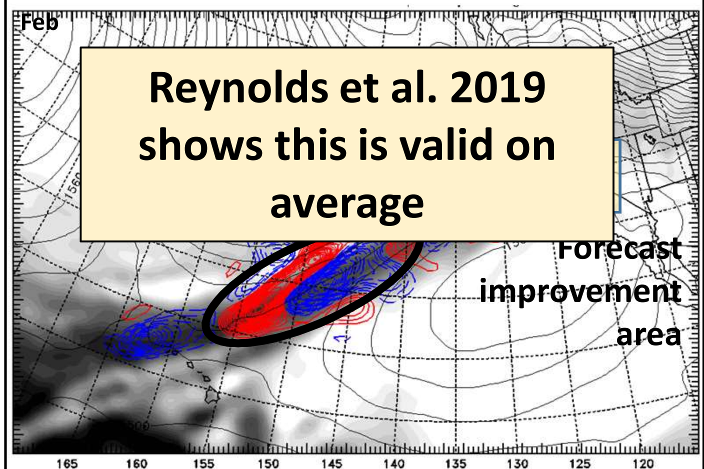
New Adjoint includes moisture – and finds AR is prime target

36-h Sensitivity (Analysis) 00Z 13 February (Final Time 12Z 14 February 2014)

J. Doyle, C. Reynolds, C. Amerault, F.M. Ralph

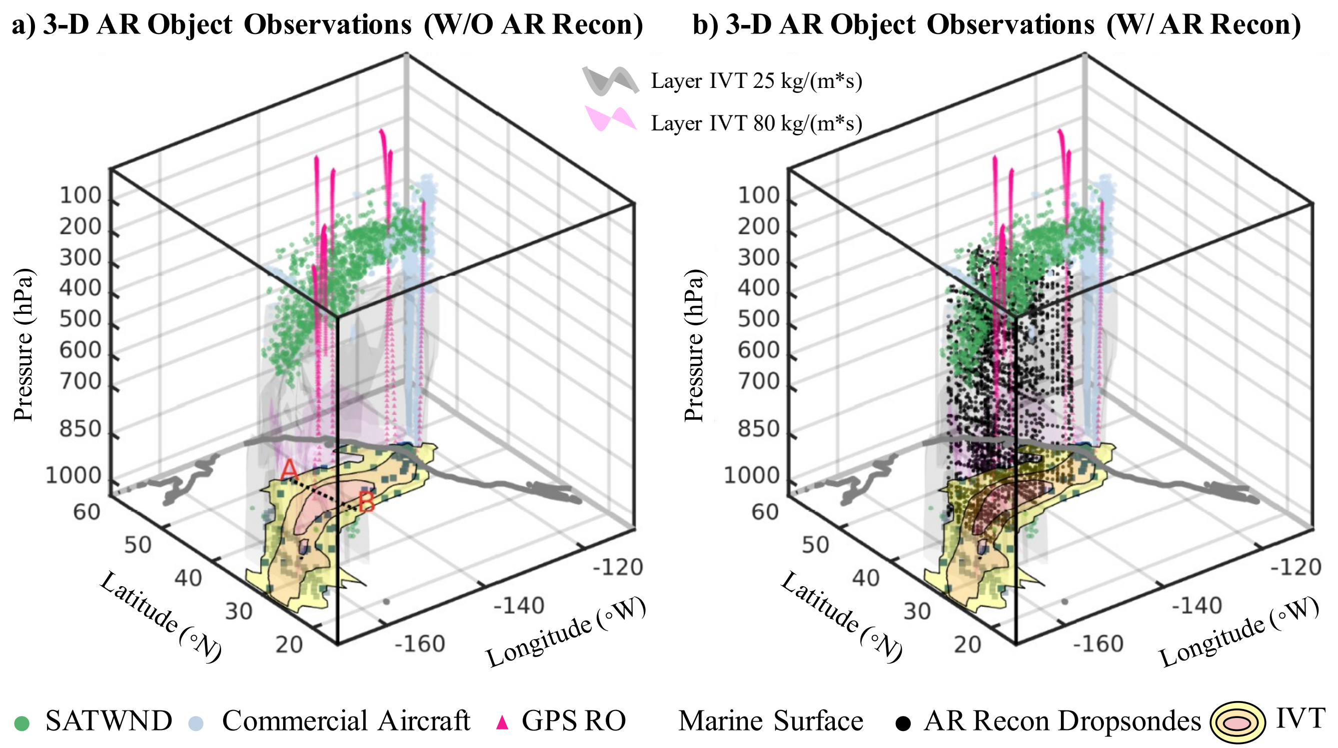
(International Atmospheric Rivers Conference 2016)

Color contours show the forecast sensitivity to 850 mb water vapor (grey shading) uncertainty at analysis time 00Z 13 Feb 2014 for a 36-h forecast over NorCal valid 12Z 14 Feb

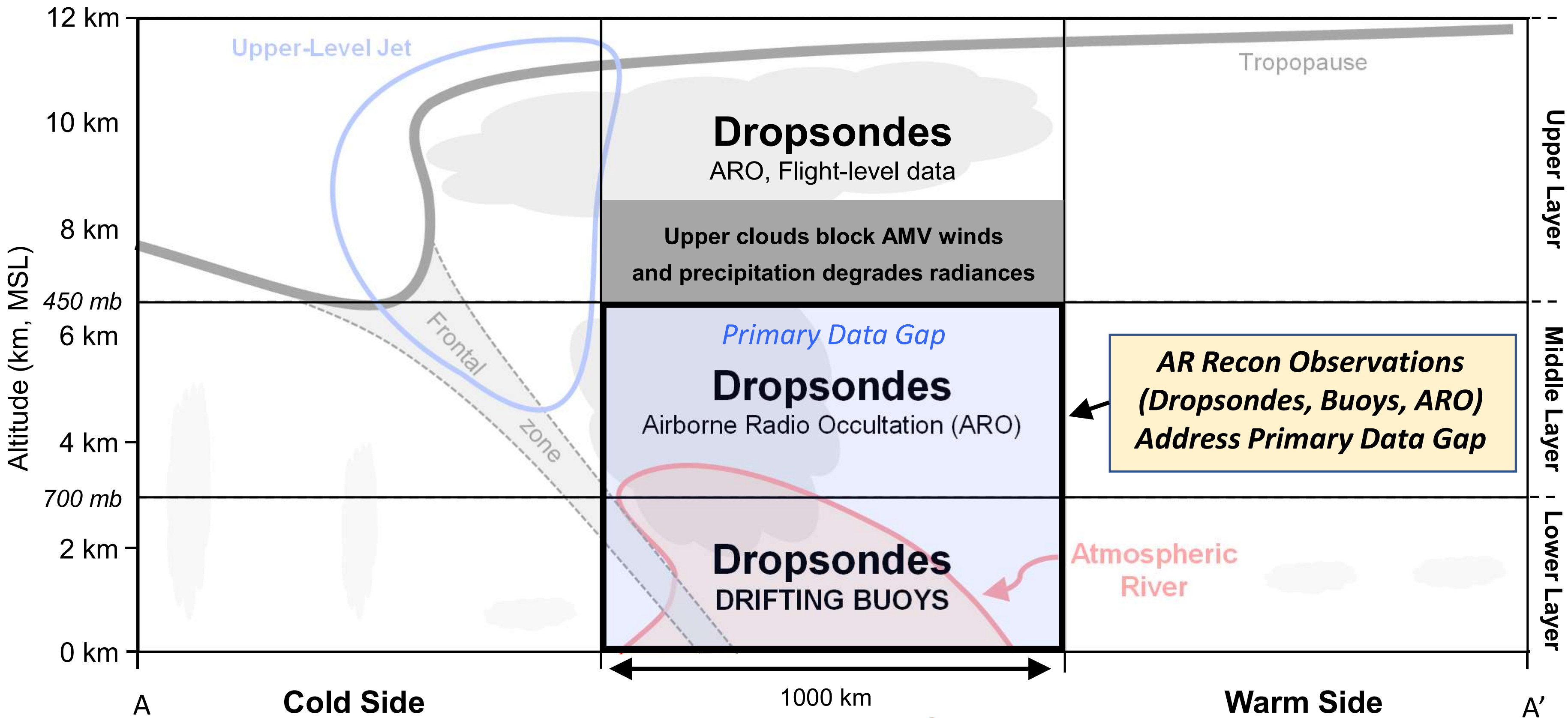


- Moisture sensitivity is strongest along AR axis; located > 2000 km upstream
- **Moisture sensitivity substantially larger than temp. or wind sensitivity.**

OBSERVATION DENSITY ANALYSIS

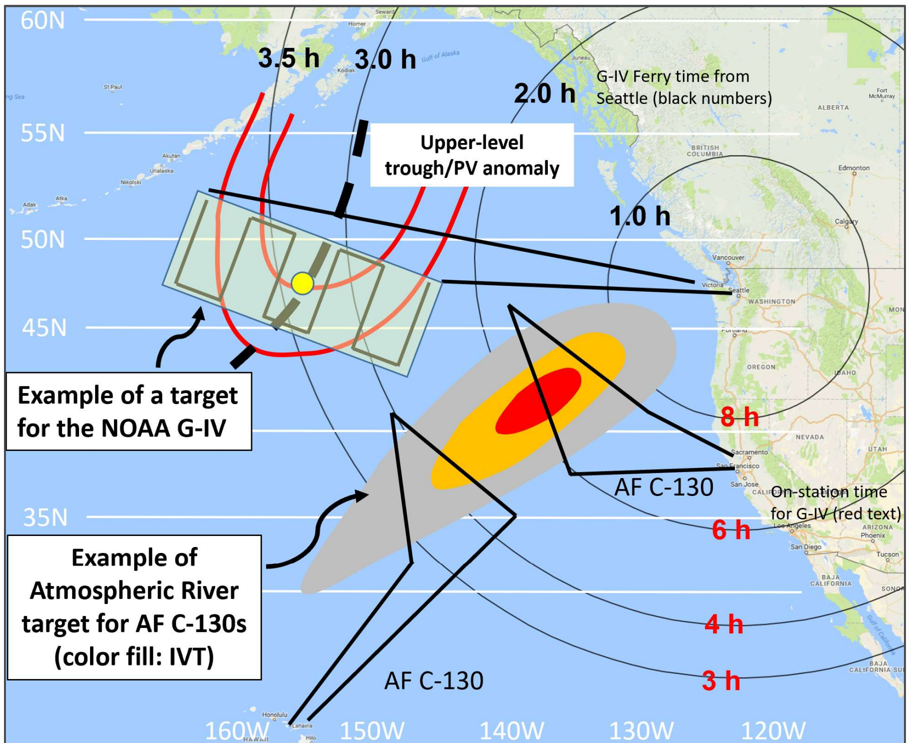


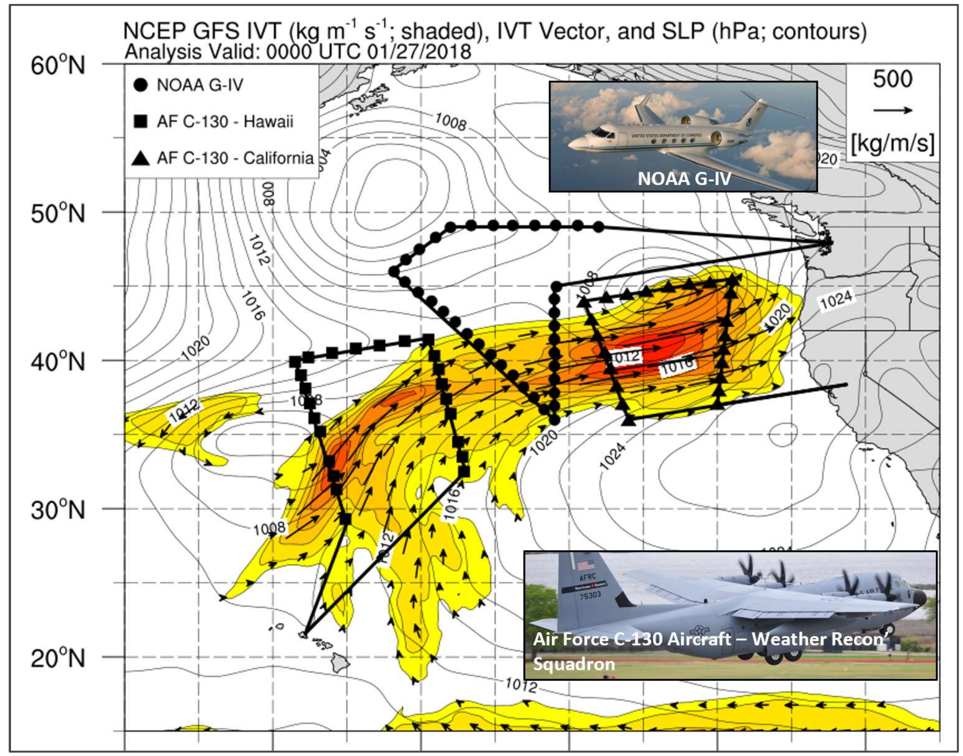
Lead: Minghua Zheng



Background adapted from
Ralph et al. 2004, 2017; Matrosov 2013, Cannon et al. 2020

Atmospheric River Reconnaissance Sampling Concept and Example from 27 Jan 2018

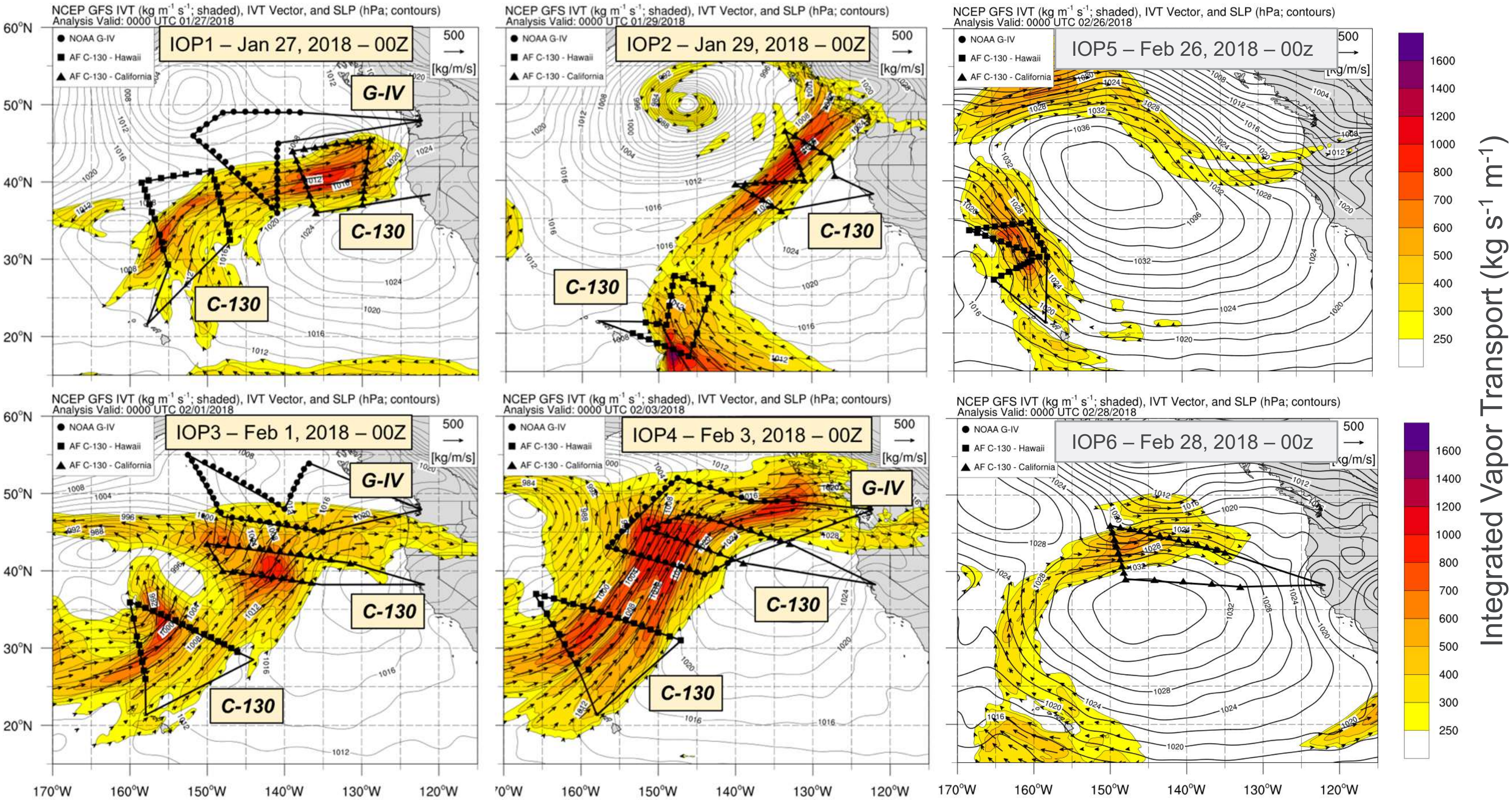




F. Martin Ralph (AR Recon PI; Scripps/CW3E), Vijay Tallaprgada (AR Recon Co-PI; NWS/NCEP) and AR Recon Team

Atmospheric River Reconnaissance 2018

Contacts: F. M. Ralph (PI; mralph@ucsd.edu); V. Tallapragada (Co-PI; vijay.tallapragada@noaa.gov)



AR Recon 2016 to 2021

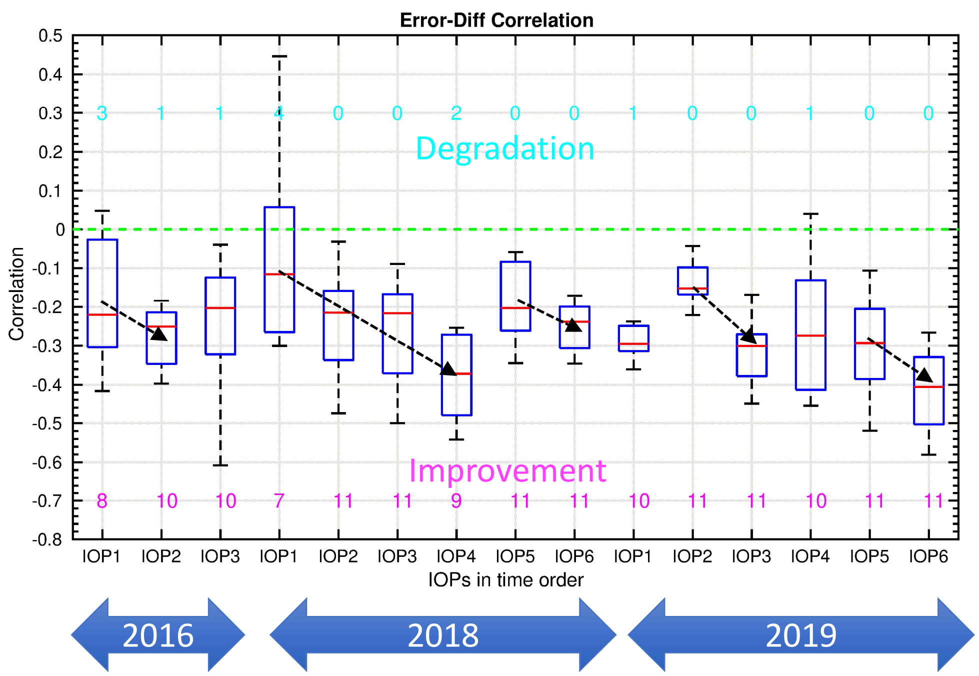
Two Air Force C-130s and NOAA's G-IV

- ✓ Feb 2016: 3 Storms (2 aircraft/storm; AF C-130s)
- ✓ Jan-Feb 2018: 6 Storms (3 aircraft/storm in 3 storms – 2 AF C-130s plus the NOAA G-IV (With Airborne GPS Radio Occultation, J. Haase); 2 C-130s in 1 storm; 1 C-130 in 2 storms)
- ✓ 1 Feb-14 Mar 2019:
  - Core program: 6 storms (2 AF C-130s/storm; 25 dropsondes/aircraft/storm flight; 300 sondes)
  - Addit'l data: 32 drifting buoys supplemented with barometers in AR Alley (L. Centurioni, B. Inglesby)
- ○ Jan-Mar 2020 **(ongoing):** 16 storms (1-3 aircraft/storm)
- ○ 2021 and beyond: Long-term requirements captured in the US' National Winter Storm Operating Plan

- ○ **Target 2021: 24 IOPs with 3 aircraft sampling each storm**
- ✓ Interagency, International Steering Committee in place
  - Carry out assessments
  - Refine data assimilation methods
  - Create appropriate evaluation metrics
  - Provide impact results in peer-reviewed publications

Contacts
PI: F. M. Ralph (mralph@ucsd.edu)
Co-PI: V. Tallapragada
(vijay.tallapragada@noaa.gov)

Precip: % RMSE Reduction and Error-Diff Correlation—By IOP

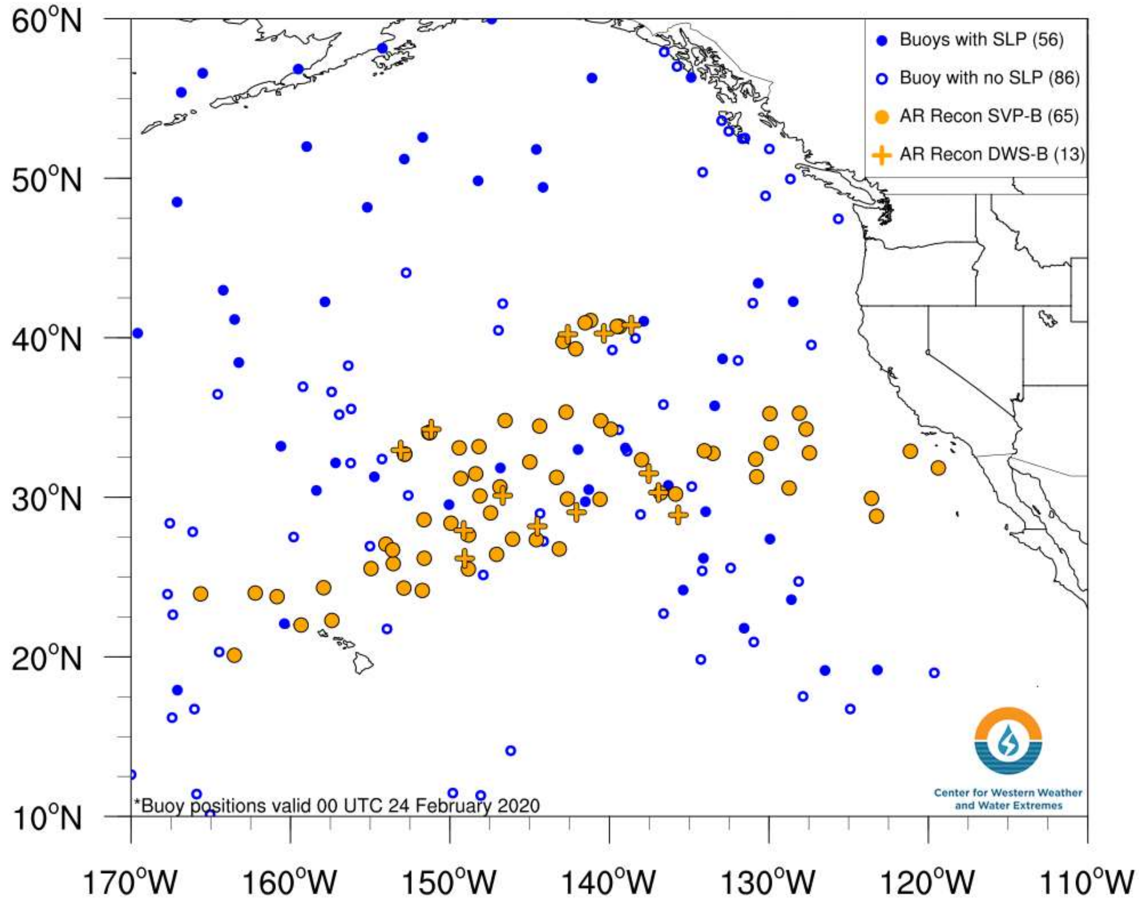


Improved IOP examples: 2016IOP2, 2018IOP4, 2019IOP6

Neutral IOP examples: 2018IOP1, 2018IOP5

The later IOPs in consecutive missions show largest improvement

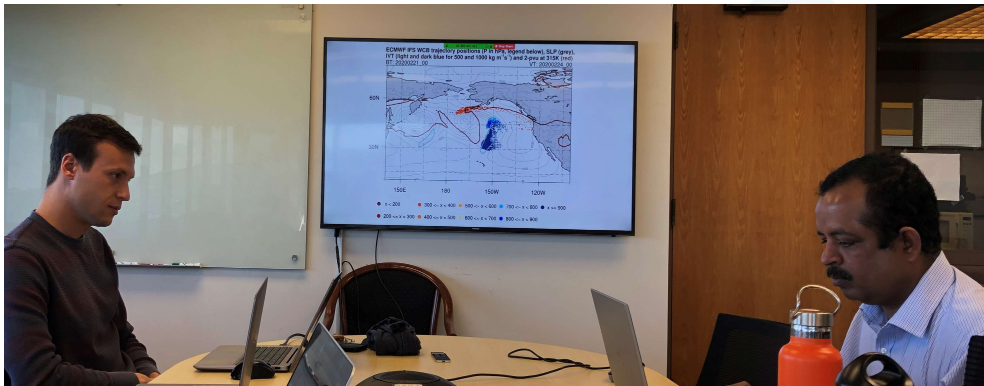
CW3E - AR RECON 2020 BUOY PROJECT

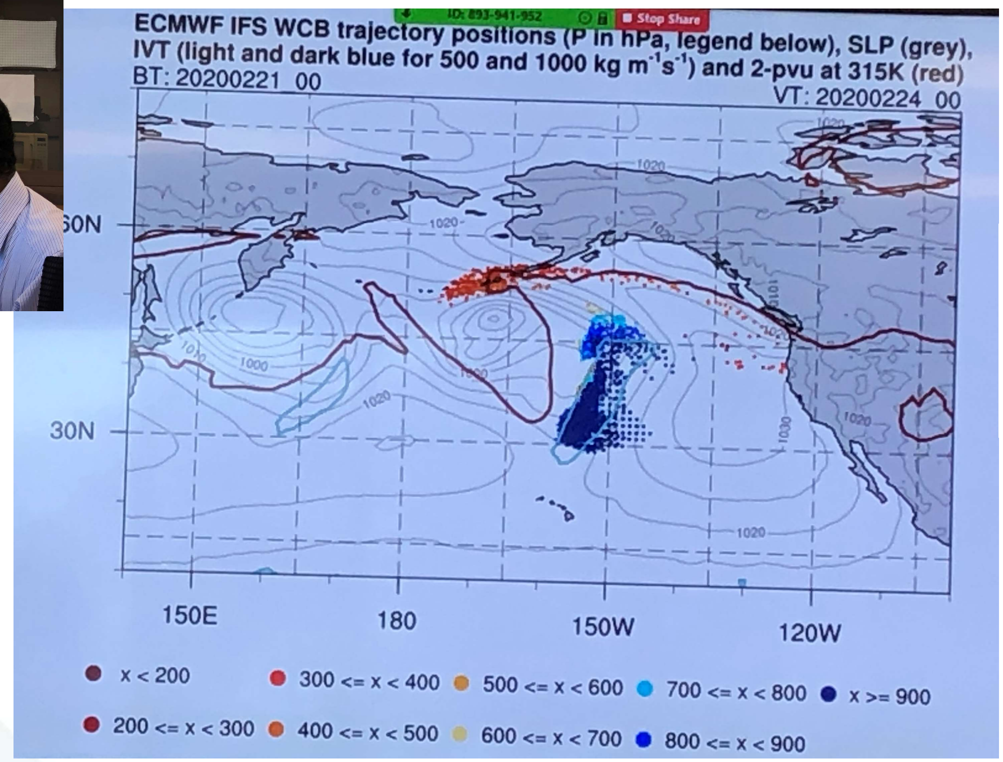


Purpose: To explore the potential of drifting buoys (with pressure sensors), in concert with AR Recon dropsondes and data assimilation efforts, to improve west coast forecasts of landfalling atmospheric rivers and precipitation. Supports California's Atmospheric Rivers Program (**PI: F.M. Ralph; CA Dept. of Water Resources – sponsor**).

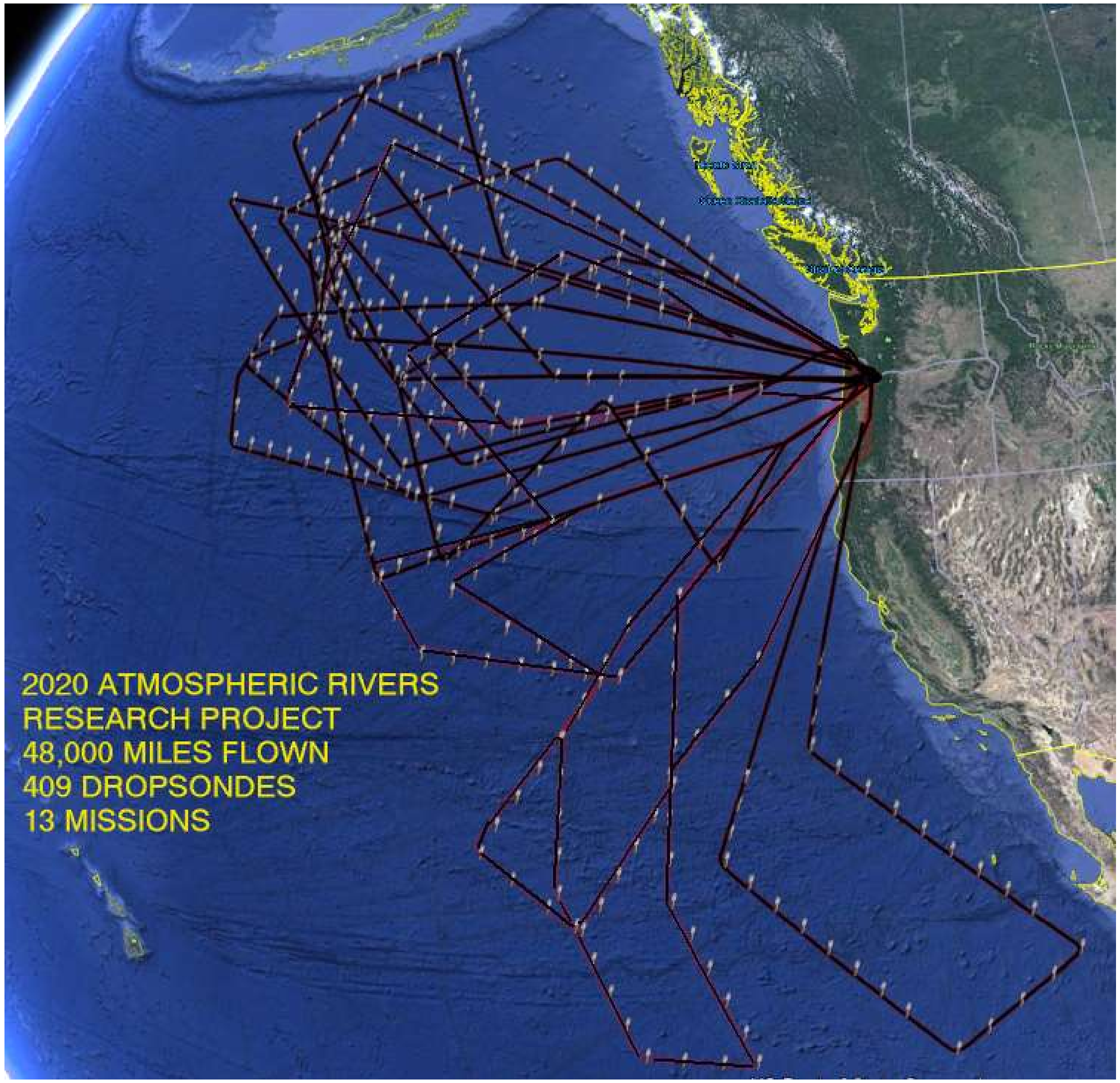
Partners: Deployment leverages the Global Drifter Program barometer upgrade program (**PI: Luca Centurioni, SIO; NOAA/OAR/OOMD – sponsor**); deployment is by the Air Force 53rd Weather Reconnaissance Squadron and by ship of opportunity arranged by L. Centurioni's group. Participation from the European Centre for Medium-Range Weather Forecasts (ECMWF) (**ECMWF Leads: Bruce Ingelby, David Lavers**).

WARM CONVEYOR BELT DIAGNOSTIC TOOL USED IN AR RECON-2020



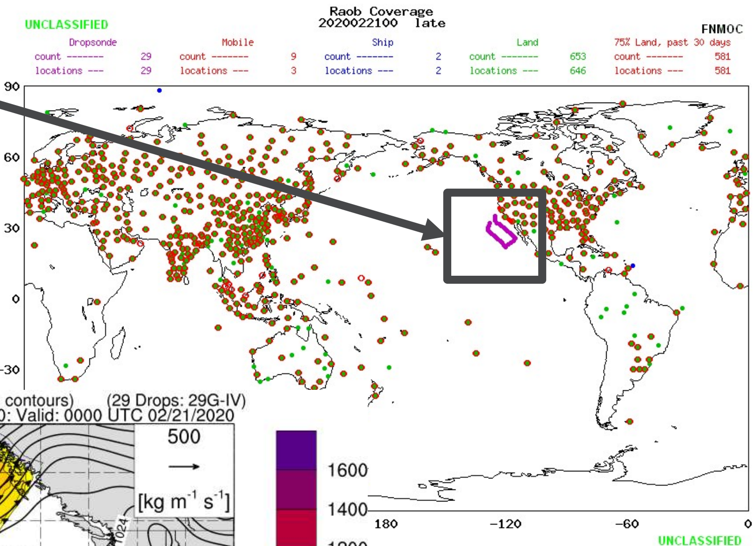


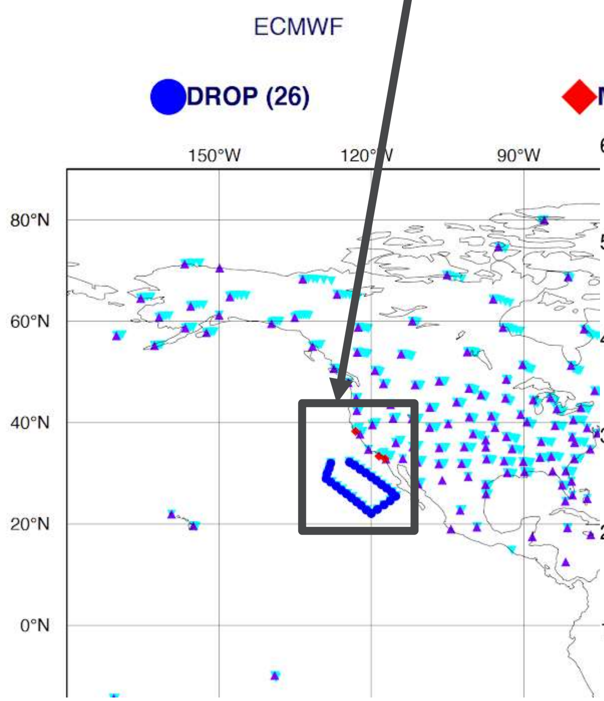
WCB Conditions are being considered in AR Recon 2020 flight planning: Products provided courtesy of H. Wernli, Hanin Binder and Maxi Boettcher

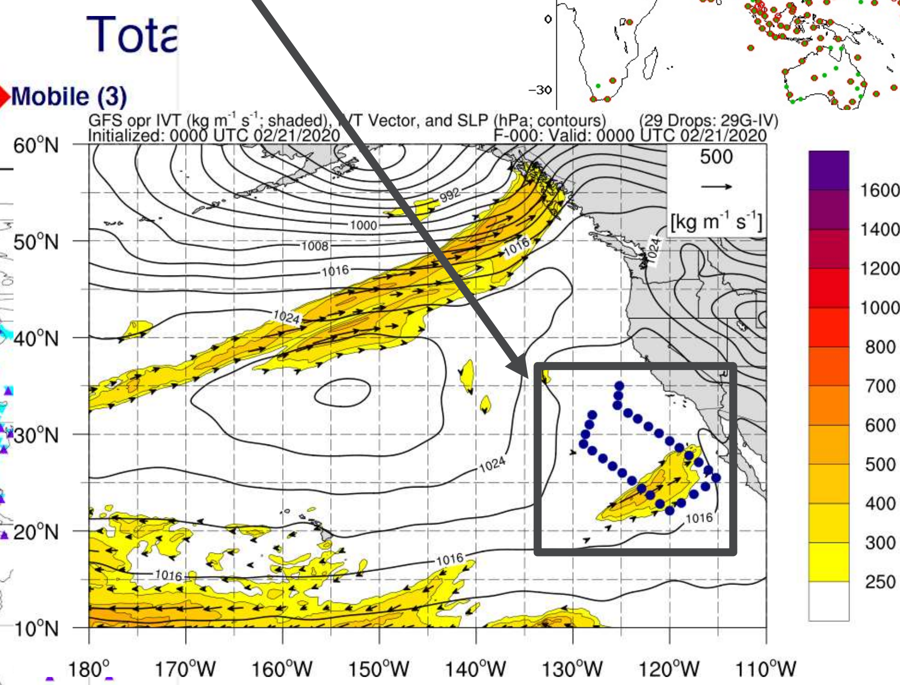

2020 ATMOSPHERIC RIVERS
RESEARCH PROJECT
48,000 MILES FLOWN
409 DROPSONDES
13 MISSIONS

Dropsondes Assimilated – IOP-10

30 drops made it into all models (00Z shown)
3 mobile radiosonde sites provided data in 18Z and 00Z





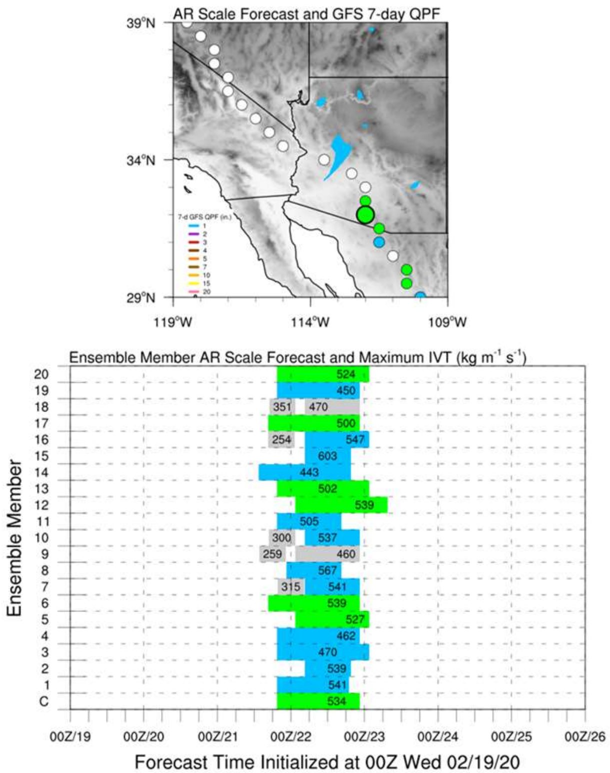


AR Scale Forecasts

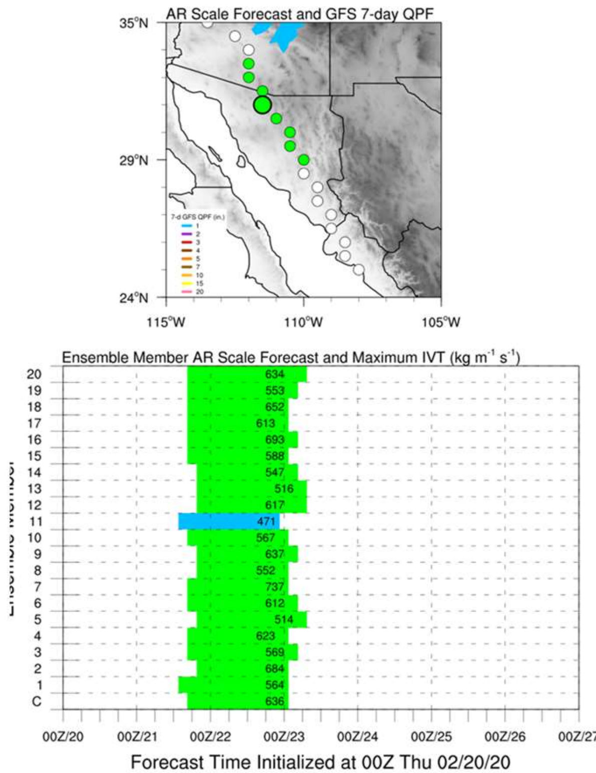
(Ralph et al. 2019, BAMS)

Center for Western Weather and Water Extremes

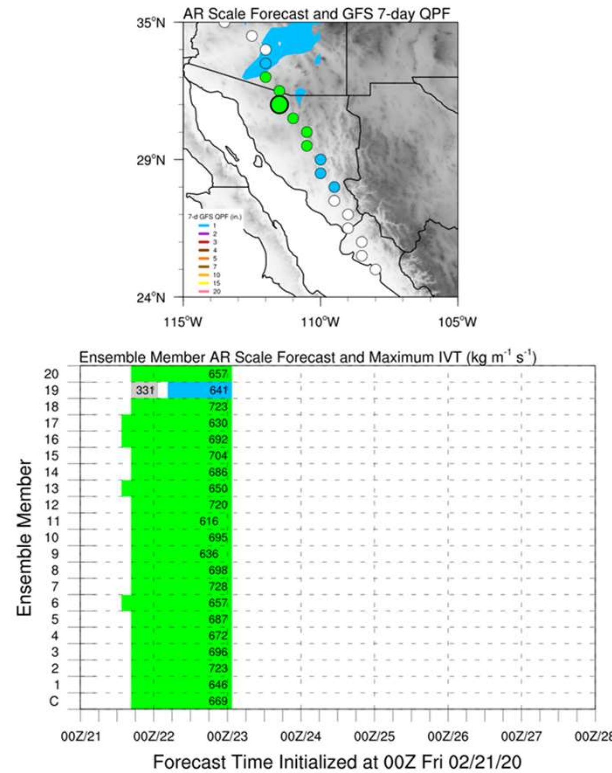
Issued: 00Z 19 Feb



Issued: 00Z 20 Feb



Issued: 00Z 21 Feb

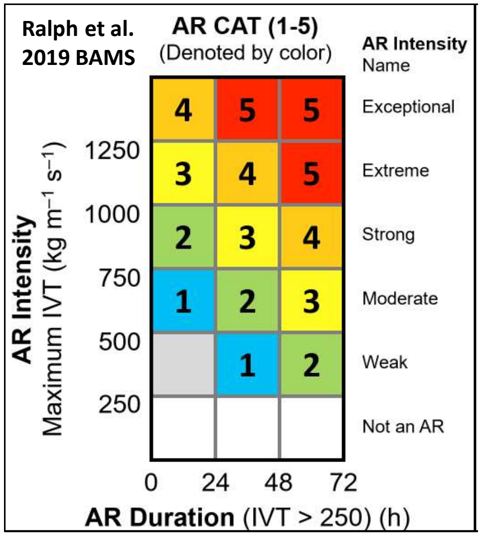


Major storm “Dennis” just hit Europe - Here's how it looks using the AR Scale

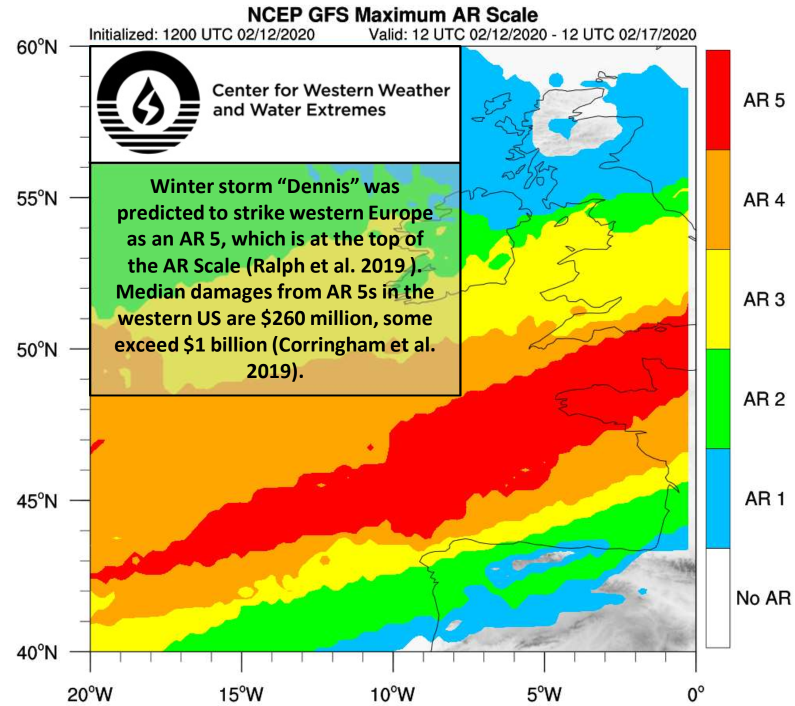
Storm Dennis, 2nd-strongest bomb cyclone on record in North Atlantic, causes severe flooding in Britain The Washington Post

The storm dumped more than a month's worth of rain in parts of Wales in one day, flooding towns and prompting evacuations.

By Andrew Freedman *16 February 2020*



The map to the right is an example of one of the CW3E AR Scale prototype displays, applied to storm “Dennis” that struck Western Europe on 14-16 Feb 2020.



Tools are being developed and tested at CW3E that assess the AR Scale ranking of predicted or recent ARs. Feedback on the prototype displays is being collected by forecasters and key forecast users. CW3E’s AR Outlooks, and Storm Summaries now include the AR Scale. This information is being communicated to media when requested.

F.M. Ralph, B. Kawzenuk, C. Hecht, J. Cordeira, J. Rutz (16 February 2020)

Atmospheric River Reconnaissance Workshop

29 June – 1 July 2020
Seaside Forum at the Scripps Institution of Oceanography, La Jolla, CA
Hosted by the Center for Western Weather and Water Extremes (CW3E.UCSD.EDU)

Atmospheric River Reconnaissance Strives to Improve Predictions of Land-falling Atmospheric Rivers and Their Associated Impacts in the Western U.S.

From 2015 to 2020, AR Recon grew from a concept to a field demonstration to an operational requirement and mission. It has gone from 3 storms flown over 2 weeks in 2016 to 12 flown over 8 weeks in 2020. It could reach 24 over 12 weeks in 2021. It uses two Air Force C-130s and the NOAA G-IV to carry out dropsonde missions and has partnered with the global drifter program to deploy roughly 100 drifting buoys with pressure sensors. Flight planning and calling of missions is carried out by a diverse team of scientists and forecasters, who consider input from multiple objective targeting methods and fundamental physical principles. A steering committee for modeling and data assimilation consisting of a multi-agency team of global modeling and science centers is working together to document and enhance impacts of the data.

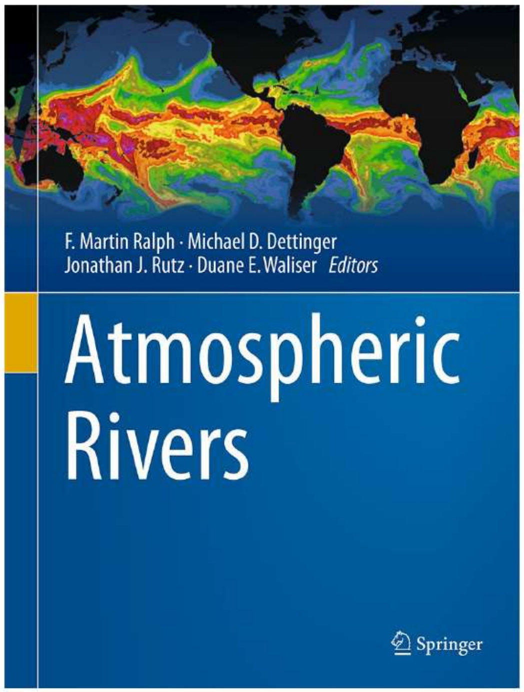
WORKSHOP PURPOSE: DOCUMENT IMPACTS and ENVISION AR RECON IN 2025
The goals are to share results, to coordinate and inspire future work on data collection, data assimilation, metric development and impact assessment, and to discuss the research and operations partnership approach being developed in AR Recon.

The Workshop will bring together current participants and interested experts to share results of modeling, data assimilation and impact studies and to consider next steps for future field seasons. It will cover the following topics, using oral and poster sessions, as well as panel discussions:

- Flight planning, targeting and execution methods – refinements and expansion
- Verification and validation methods including use of the AR scale
- Data assimilation and impact studies, including new methods
- Evaluate potential impacts of AR Recon in the central and eastern US
- Identify leading sources of forecast errors, including role of mesoscale frontal waves
- Physical process studies enabled by AR Recon in support of western water applications
- Representing AR Recon in the NWSOP as a national mission focused on western water
- Potential for collaboration with European interests, including on warm conveyor belts
- Discuss a vision for AR Recon - 2025

29 June – 1 July 2020

La Jolla, California



1st ed. 2019, XX, 366 p. 172 illus., 160 illus. in color.

Printed book

Hardcover

81,99 € | £69.99 | $99.99
[1]87,73 € (D) | 90,19 € (A) | CHF

F.M. Ralph, M. Dettinger, J.J. Rutz, D.E. Waliser (Eds.)

Atmospheric Rivers

Available early 2020
Springer
20+ Contributing Authors

- **Presents the latest research on a highly impactful extreme weather phenomenon with climatological importance both regionally and globally, and that has bearing on a variety of civil and commercial decision support areas**
- **Provides specific, research-based information on atmospheric rivers to help practitioners understand and explain the scientific basis of the weather pattern to non-practitioners and the general public**
- **Gives in-depth scientific information on atmospheric rivers within the broader topics of extratropical cyclones, weather and hydrological extremes, regional and global climate, as well as weather prediction and future climate projections**

This book is the standard reference based on roughly 20 years of research on atmospheric rivers, emphasizing progress made on key research and applications questions and remaining knowledge gaps. The book presents the history of atmospheric-rivers research, the current state of scientific knowledge, tools, and policy-relevant (science-informed) problems that lend themselves to real-world application of the research—and how the topic fits into larger national and global contexts. This book is written by a global team of authors who have conducted and published the majority of critical research on atmospheric rivers over the past years. The book is intended to benefit practitioners in the fields of meteorology, hydrology and related disciplines, including students as well as senior researchers.

Center for Western Weather and Water Extremes

ATMOSPHERIC RIVER RECONNAISSANCE:

SUPPORTING WESTERN STORM PREDICTIONS AND WATER DECISIONS

F. Martin Ralph, PI (UC San Diego/SIO/CW3E)

Vijay Tallapragada Co-PI (NOAA/NWS/NCEP)

Jim Doyle (Naval Research Laboratory)

UC San Diego | SCRIPPS INSTITUTION OF OCEANOGRAPHY

AR Recon

Papers Published to Date (Results)

Demirdjian, R., Doyle, J.D., Reynolds, C.A. Norris, J.A., Michaelis, A.C., Ralph, F.M., 2019: A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model. Journal of the Atmospheric Sciences, 0, DOI 10.1175/JAS-D-19-0155.1

Guan, B., D. Waliser, and F. Ralph, 2017: An inter-comparison between reanalysis and dropsonde observations of the total water vapor transport in individual atmospheric rivers. Journal of Hydrometeorology, 19, 321-337, doi:10.1175/JHM-D-17-0114.1

Lavers, D.A., M.J. Rodwell, D.S. Richardson, F.M. Ralph, J.D. Doyle, C.A. Reynolds, V. Tallapragada, and F. Pappenberger, 2018: The Gauging and Modeling of Rivers in the Sky. Geophysical Research Letters, 45, https://doi.org/10.1029/2018GL079019

Ralph, F., S. Iacobellis, P. Neiman, J. Cordeira, J. Spackman, D. Waliser, G. Wick, A. White, and C. Fairall, 2017: Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers. Journal of Hydrometeorology, 18, 2577-2596. doi:10.1175/BAMS-D-15-00245.1

Reynolds, C.A., J.D. Doyle, F.M. Ralph, and R. Demirdjian, 2019: Adjoint Sensitivity of North Pacific Atmospheric River Forecasts. Mon. Wea. Rev., 147, 1871-1897, https://doi.org/10.1175/MWR-D-18-0347.1

Stone, R.E., C.A. Reynolds, J.D. Doyle, R. Langland, N. Baker, D.A. Lavers, and F.M. Ralph, 2019: Atmospheric River Reconnaissance Observation Impact in the Navy Global Forecast System. Mon. Wea. Rev., 0, https://doi.org/10.1175/MWR-D-19-0101.1

A Case Study of the Physical Processes Associated with the Atmospheric River Initial Condition Sensitivity from an Adjoint Model

Reuben Demirdjian[1], Jim Doyle[2], Carolyn Reynolds[2], Joel Norris[1], Allison Michaelis[1], F. Martin Ralph[1]
[1]UCSD/SIO/CW3E, [2]NRL (*J. Atmos. Sci.* 2020, in press)

Purpose of Study

- Diagnose the dynamical processes linking the initial condition sensitivities offshore in an adjoint model to errors in forecasts of AR landfall and associated precipitation

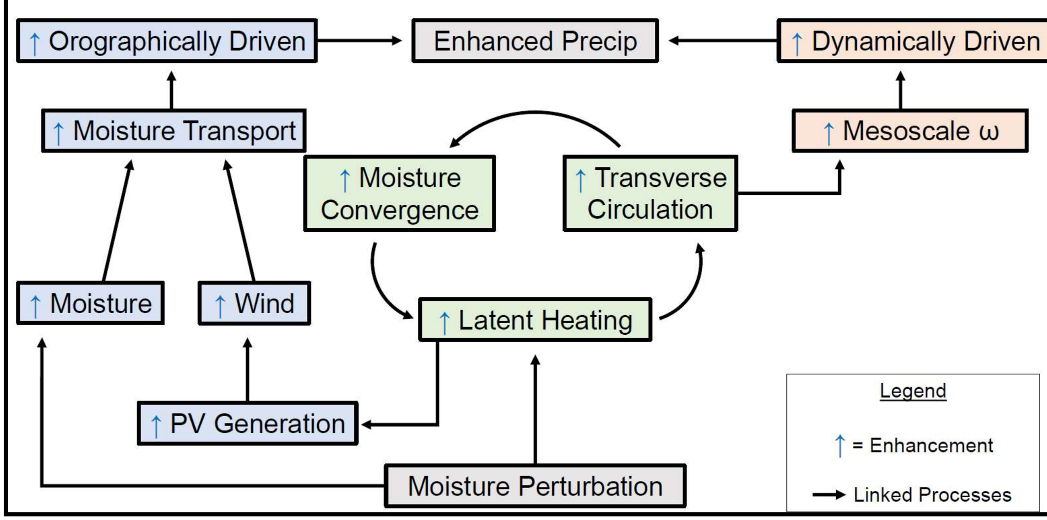
Why Bother?

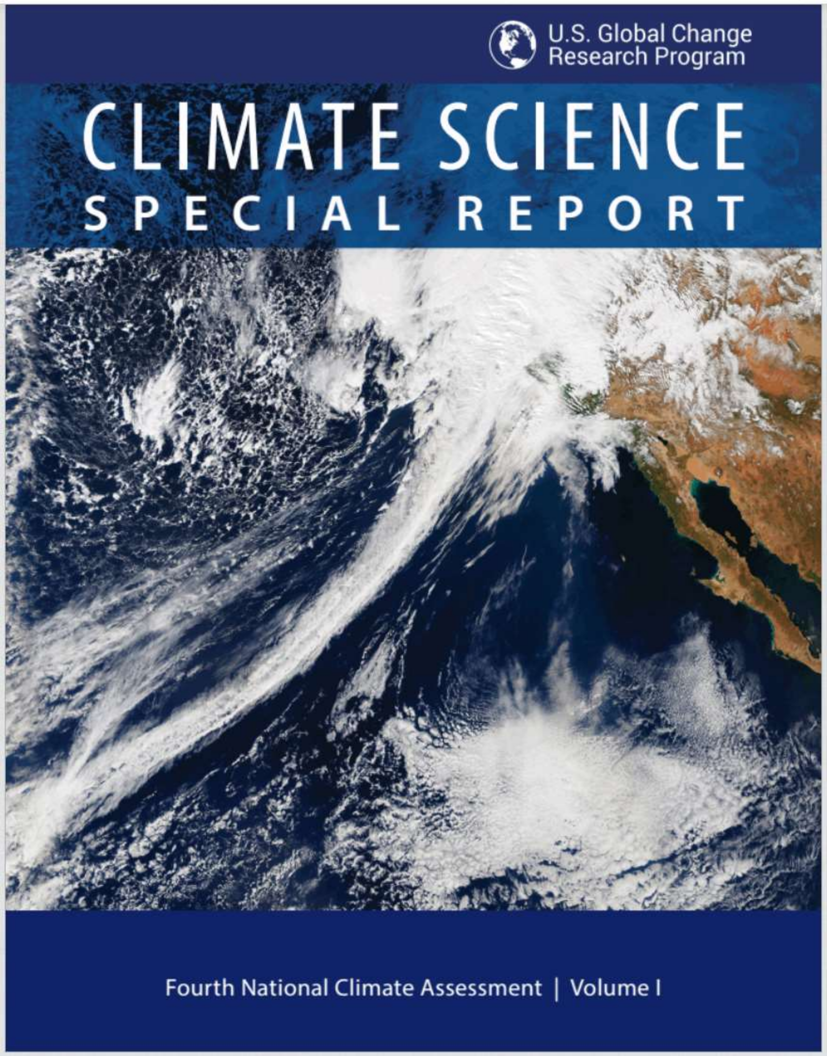
- To understand how errors in weather forecast model representation of AR initial conditions offshore can lead to errors in the prediction of AR landfall.

Result

- An error in water vapor initial condition within the AR modifies precipitation (both d*ynamically and orographically forced*) by amplifying the latent heating in a dynamical feedback process involving wind and PV anomalies that act to reinforce the initial perturbation.

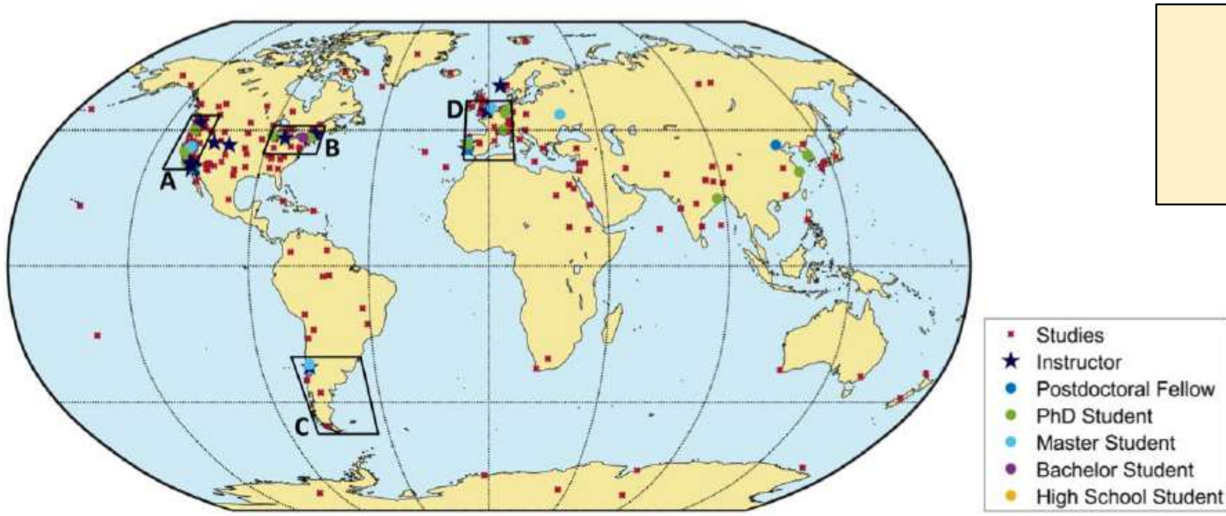
Processes Leading to Changes in the Perturbed Run's Precipitation





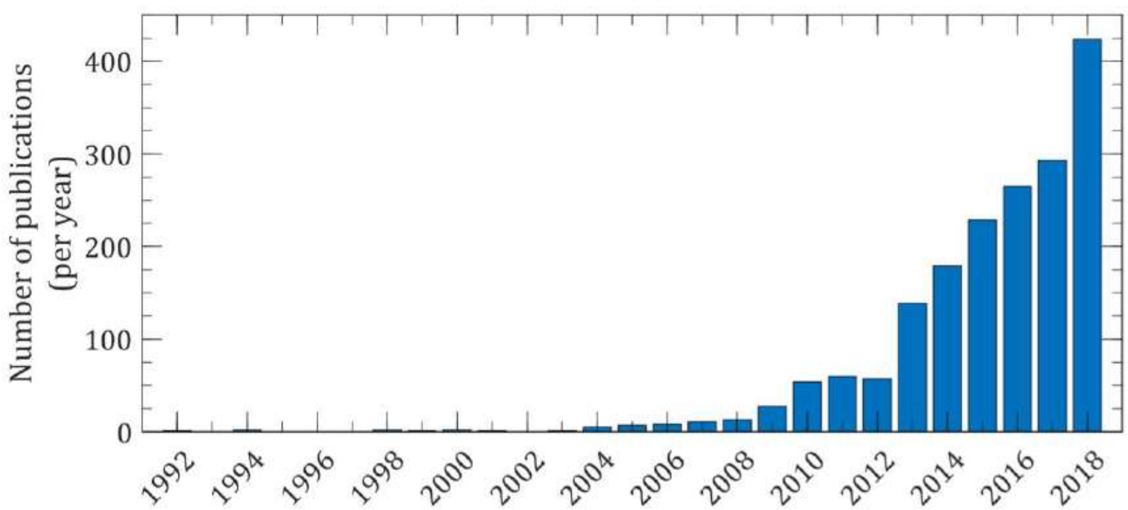
Atmospheric Rivers Highlighted in the U.S. Fourth National Climate Assessment, released on 3 November 2017

1. Hurricanes and Typhoons
2. Severe Thunderstorms
3. Winter storms
4. **Atmospheric Rivers (NEW in 4th Assessment)**



AR Are Being studied globally

Wilson et al. 2020 BAMS
AR Summer Colloquium
Meeting Summary
(in Press)



Rapid Growth in the Reference to ARs in Scientific Papers

Dropsonde Observations of Total Integrated Water Vapor Transport within North Pacific Atmospheric Rivers

F.M. Ralph, S. Iacobellus, P.J. Neiman, J. Cordeira, J.R. Spackman, D. Waliser, G. Wick, A.B. White, C. Fairall

J. Hydrometeorology (2017)

Method/Data: Uses 21 AR cases observed in 2005 - 2016 with full dropsonde transects.

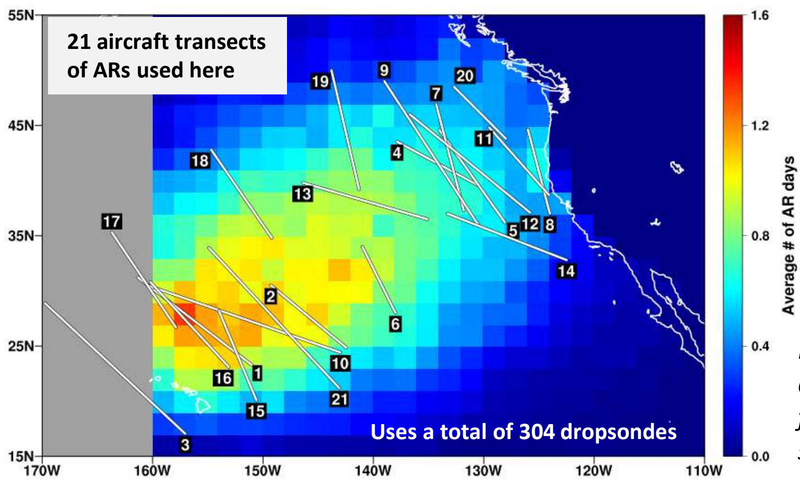
- AR edges best defined by using IVT = 250 kg m^{-1} s^{-1}

Conclusions*:

- Average width: 850 km
- 75% of water vapor transport occurs below 3 km MSL; < 1% occurs above 8 km MSL
- Average max IVT: ~800 kg m^{-1} s^{-1}

KEY FINDING

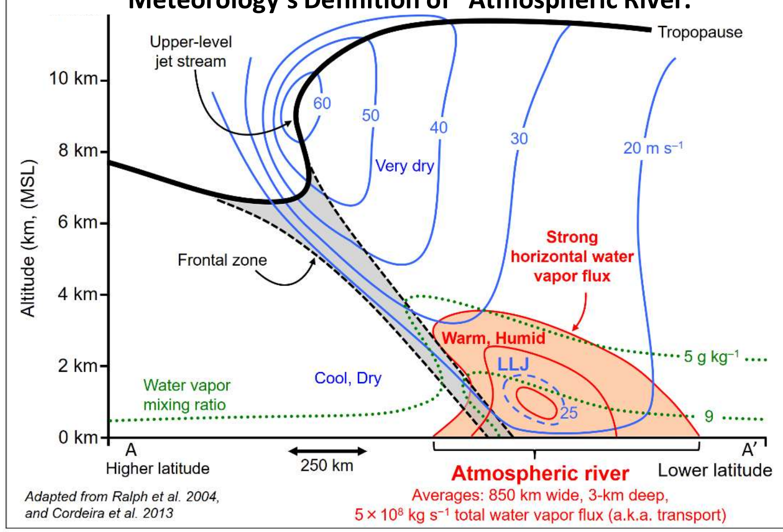
An average AR* transports 4.7 ± 2.0 x 10^8 kg s^{-1} of water vapor, which is equivalent to 2.6 times the average discharge of liquid water by the Amazon River



**These values represent averages for the Northeast Pacific Ocean in the January-March season*

Background image denotes weekly AR frequency during cool seasons (Nov -Feb).

Synthesis from 21 observed ARs; Used in the Glossary of Meteorology's Definition of "Atmospheric River."




International
Atmospheric Rivers Conference
IARC-2018
Seaside Forum at UC San Diego’s
Scripps Institution of Oceanography
La Jolla, CA, 25-28 June 2018
Hosted by the “Center for Western Weather and Water Extremes”
Bringing together a diverse, cross-disciplinary community of scientists, engineers, forecasters and managers to discuss atmospheric river science and applications.
Center for Western Weather and Water Extremes
SCRIPPS INSTITUTION OF OCEANOGRAPHY AT UC SAN DIEGO

First Circular: November 15, 2019

3IARC: Third International Atmospheric Rivers Conference

October 5-9, 2020

Atmospheric rivers (ARs) play a key role in the global water cycle as the primary mechanism conveying water vapor through mid-latitude regions. The precipitation that ARs deliver in many parts of the world, especially through orographic precipitation processes, is important for water resources; but it also regularly is a hazard, triggering floods and landslides, as well as coastal wind storms. The aims of the 2020 International Atmospheric Rivers Conference are:

- to understand dynamical and physical processes in ARs
- to describe the AR impact on hydrology, environment and society
- to evaluate the Atmospheric River Tracking Method Intercomparison Project's (ARTMIP)
- to assess current forecasting capabilities and developing applications
- to project ARs in a warmer world and understand their natural variability

Students are strongly encouraged to attend. Scholarships are available, as well as slots for student speakers.

Scientific Steering Committee:

Marty Ralph, Anna Wilson, Reuben Demirdjian (CW3E, UCSD, US); Hans Christian Steen-Larsen (U. of Bergen, Norway); Jon Rutz (US National Weather Service); Roberto Rondanelli, James McPhee (Universidad de Chile); Jorge Eiras-Barca (U. Vigo, Spain); Christine Albano (Desert Research Institute, US); Natalia Tilinina (Shirshov Institute of Oceanology, Russia); Mike Warner (US Army Corps of Engineers); Alexandre Ramos (University of Lisbon, Portugal); Maximiliano Viale (IANIGIA, Argentina)

For further information, please contact the *Local Organizing Committee*

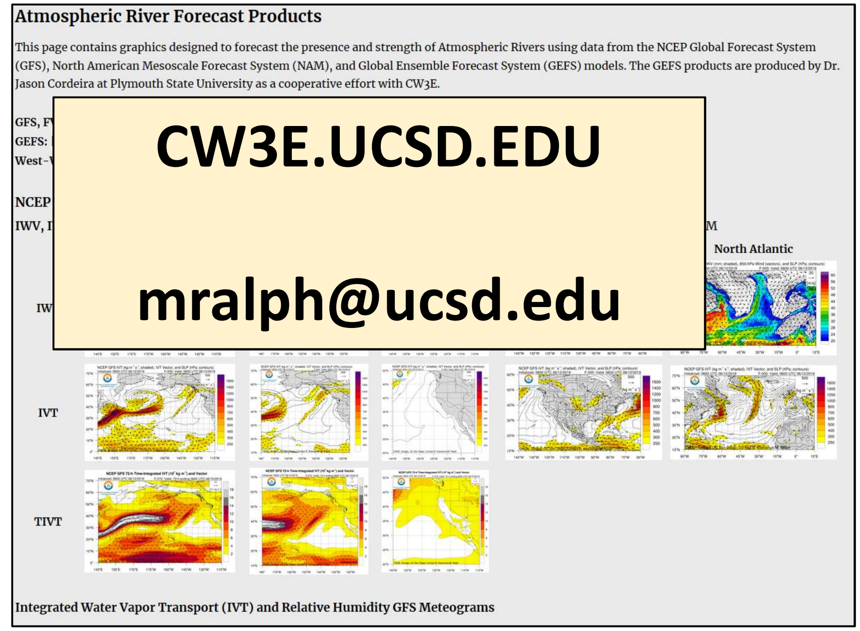
René Garreaud (rgarreau@dgf.uchile.cl) and Raul Valenzuela (rvalenzuela@dgf.uchile.cl)

Conference web site: http://www.dgf.uchile.cl/3IARC (available Dec 2019)

Center for Western Weather and Water Extremes

Geofísica
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
UNIVERSIDAD DE CHILE

$(CR)^2$
Center for Climate and Resilience Research



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mralph@ucsd.edu