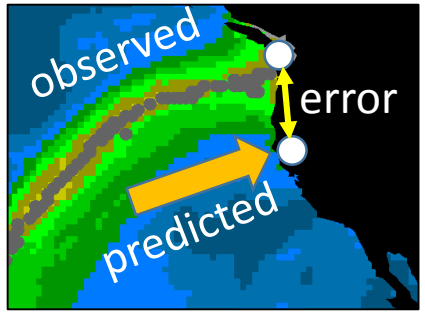
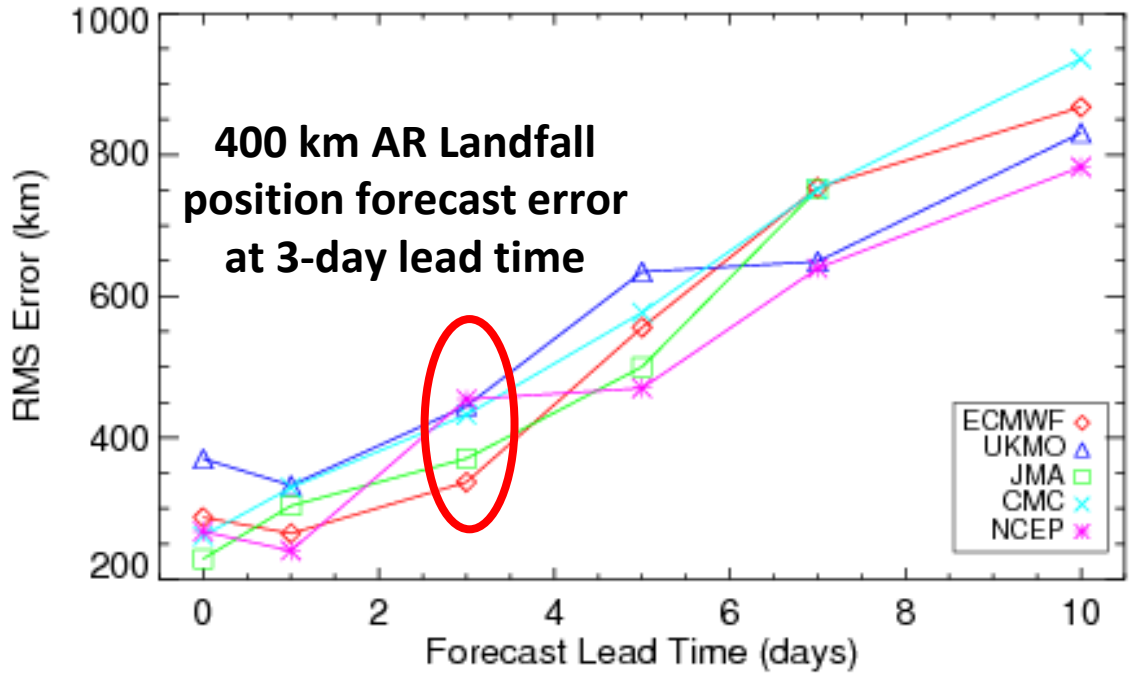
Atmospheric River Reconnaissance

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.

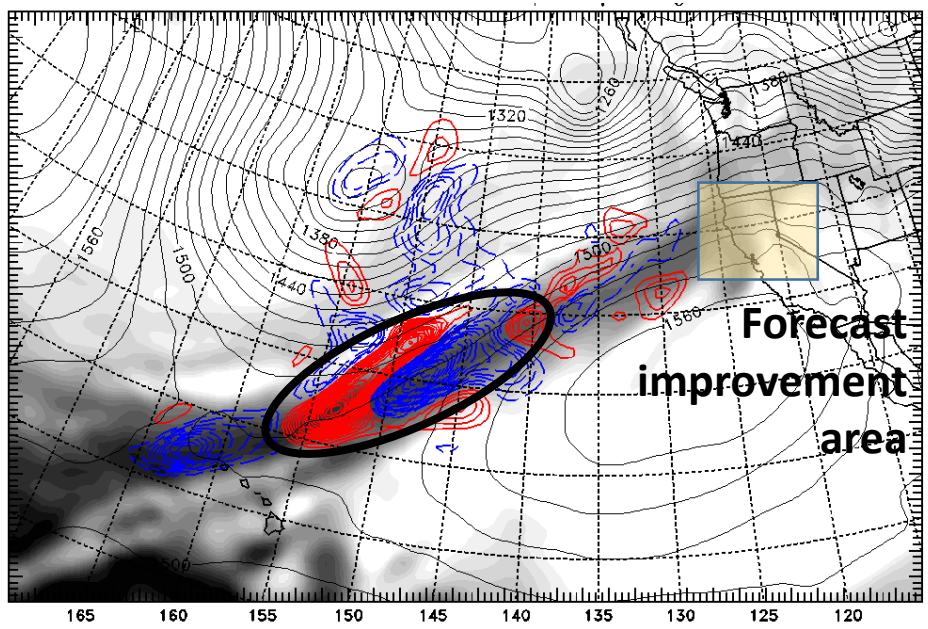
New Adjoint includes moisture – and finds AR is prime target

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

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

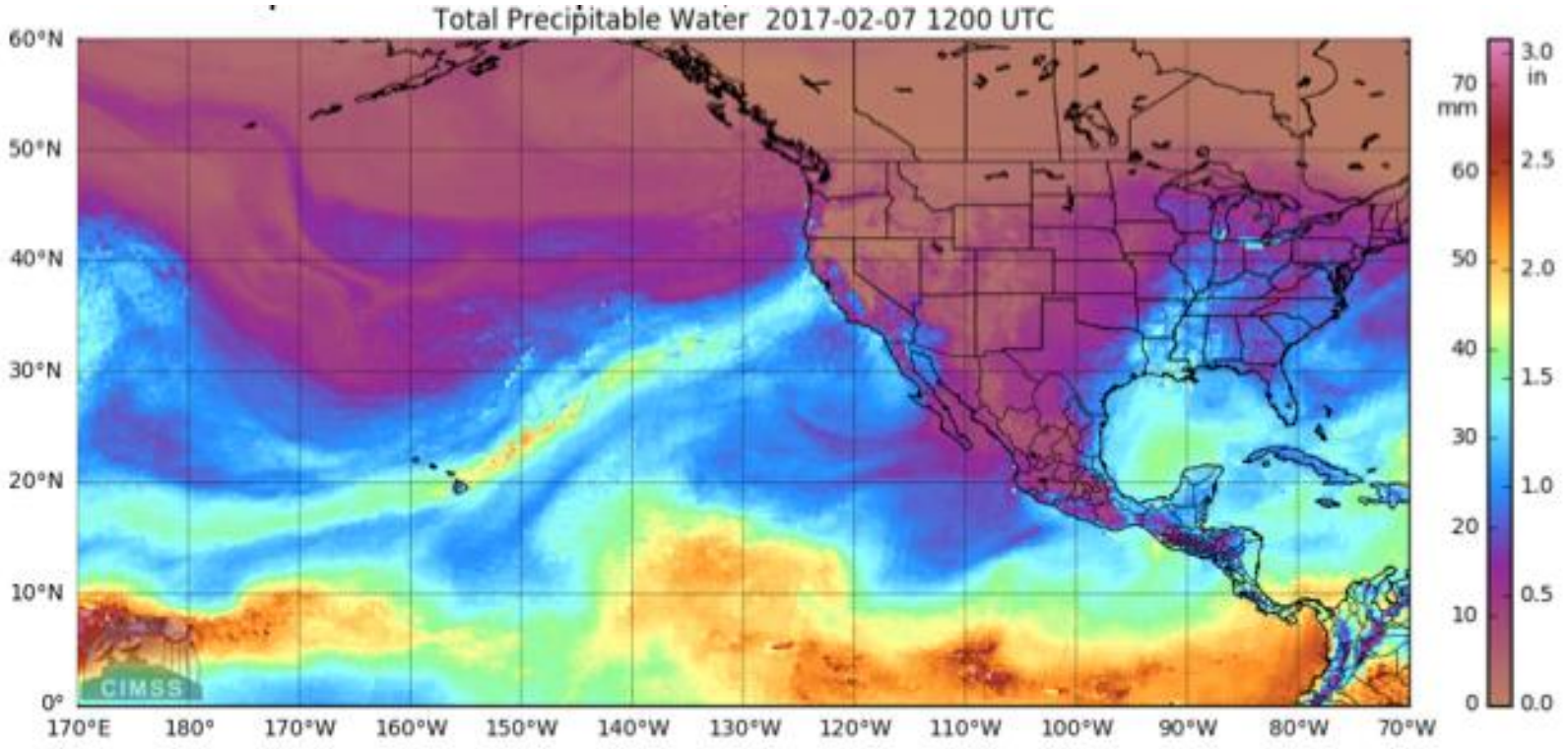
(International Atmospheric Rivers Conference 2016)

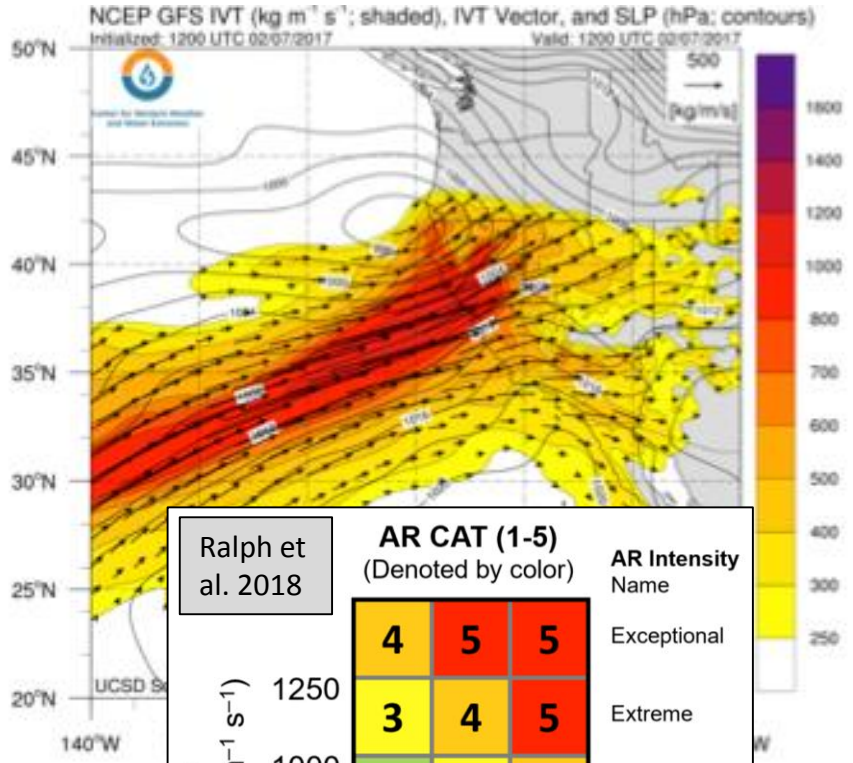
Color contours show the forecast sensitivity to 850 mb water vapor (grey shading) uncertainty at analysis time 00Z 13 Feb 2014 for a 36-h forecast over NorCal valid 12Z 14 Feb



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

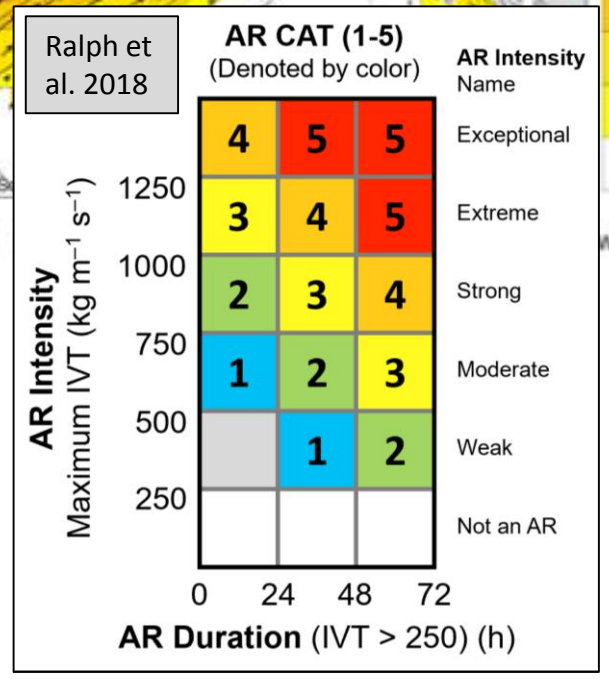
Was the Oroville Incident Related to an AR?





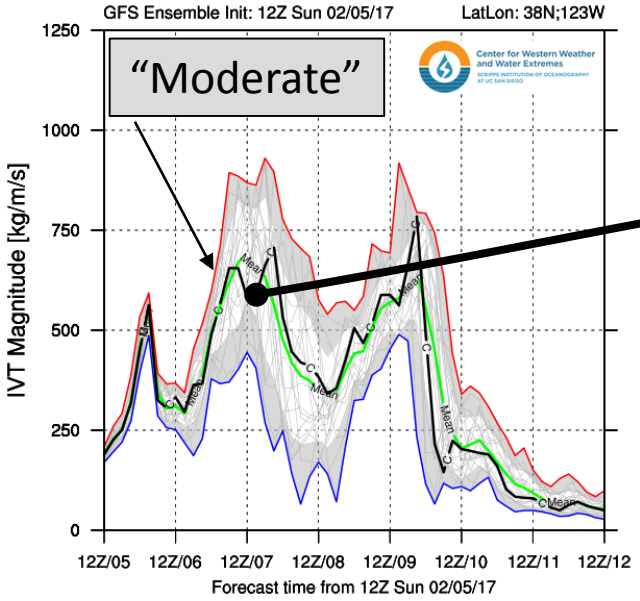
Yes. An AR of "**Extreme**" intensity hit the area.

And, it was an "**AR-CAT 5**" on the new AR Scale, based on its "intensity" and its duration.

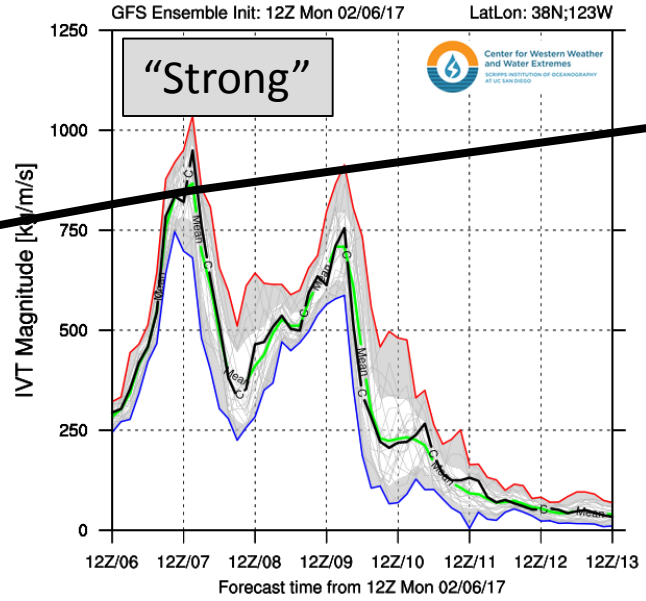


NCEP GEFS dProg/dt Example from February 2017 – "Oroville Case" (dam spillway issue)

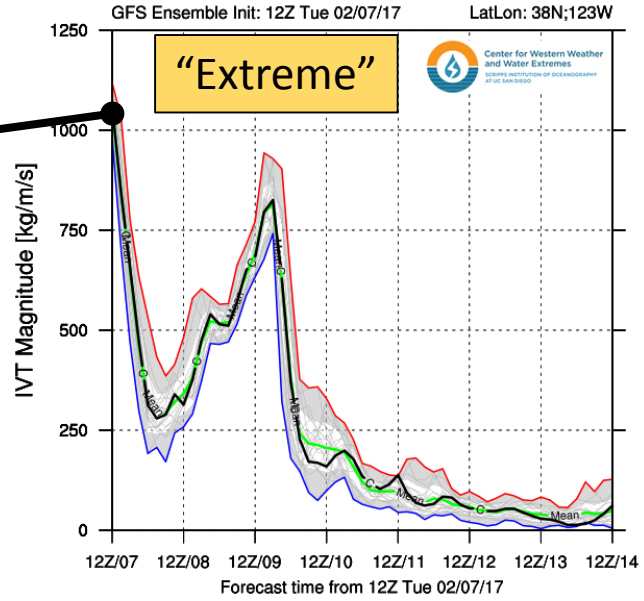
Oroville Dam Spillway



Init: 12Z/5 Feb



Init: 12Z/6 Feb



Init: 12Z/7 Feb

Image Description: 7-day forecasts of the NCEP GEFS IVT [kg m^{-1} s^{-1}] at 38N, 123W. The following is indicated at each forecast time: ensemble member maximum (red), ensemble member minimum (blue), ensemble mean (green), ensemble control (black), ensemble standard deviation (white shading), and each individual member (thin gray). Time advances from left to right.

Key: Variability in north-south shift of ARs result in increases or decreases in IVT magnitude at the coast. In this case the ARs ultimately ended up **stronger.**

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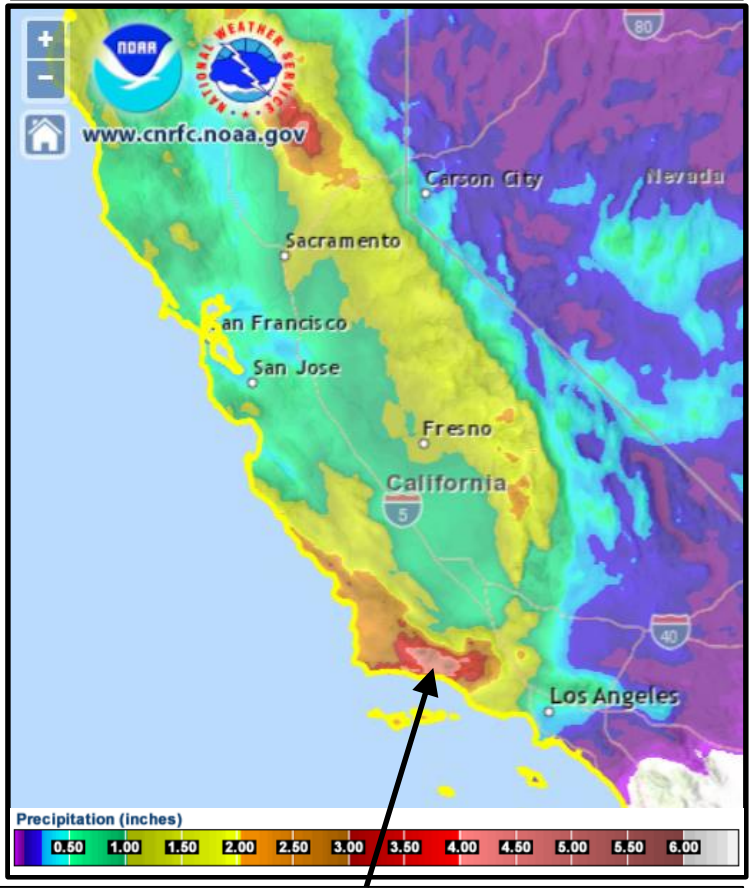
F. M. Ralph (mralph@ucsd.edu) and J. Cordeira

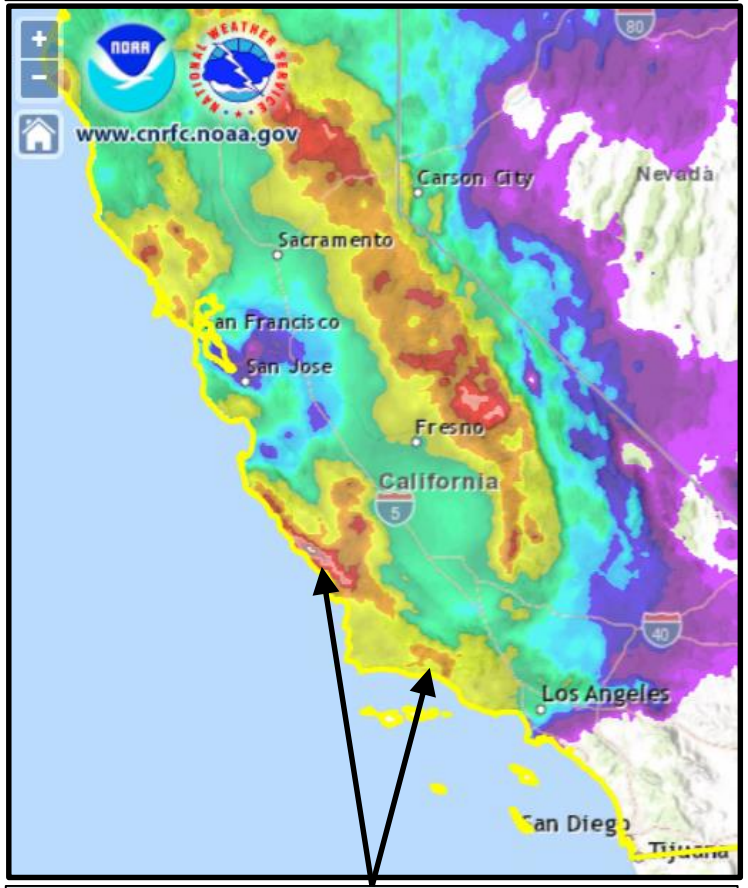
AR Outlook: 22 March 2018

CNRFC 24-hr QPF issued 20 March valid 5 AM PDT 21 to 5 AM 22 March 2018



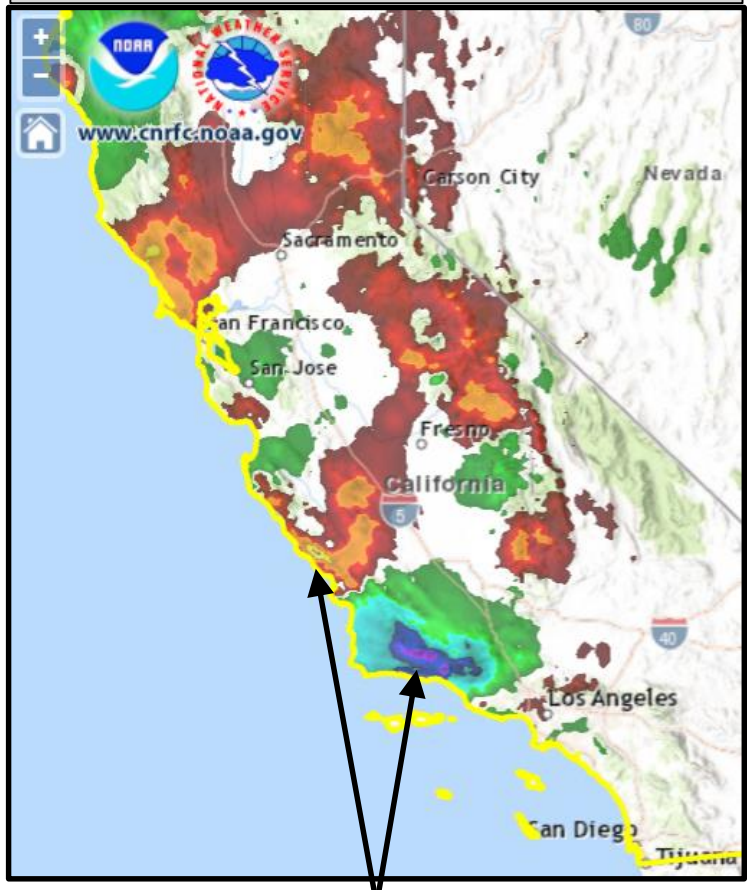
The 24-hr accumulated precipitation forecast for the period ending at 5 am PDT 22 March had a maximum accumulation of

CNRFC 24-hr QPE valid 5 AM PDT 21 to 5 AM 22 March 2018



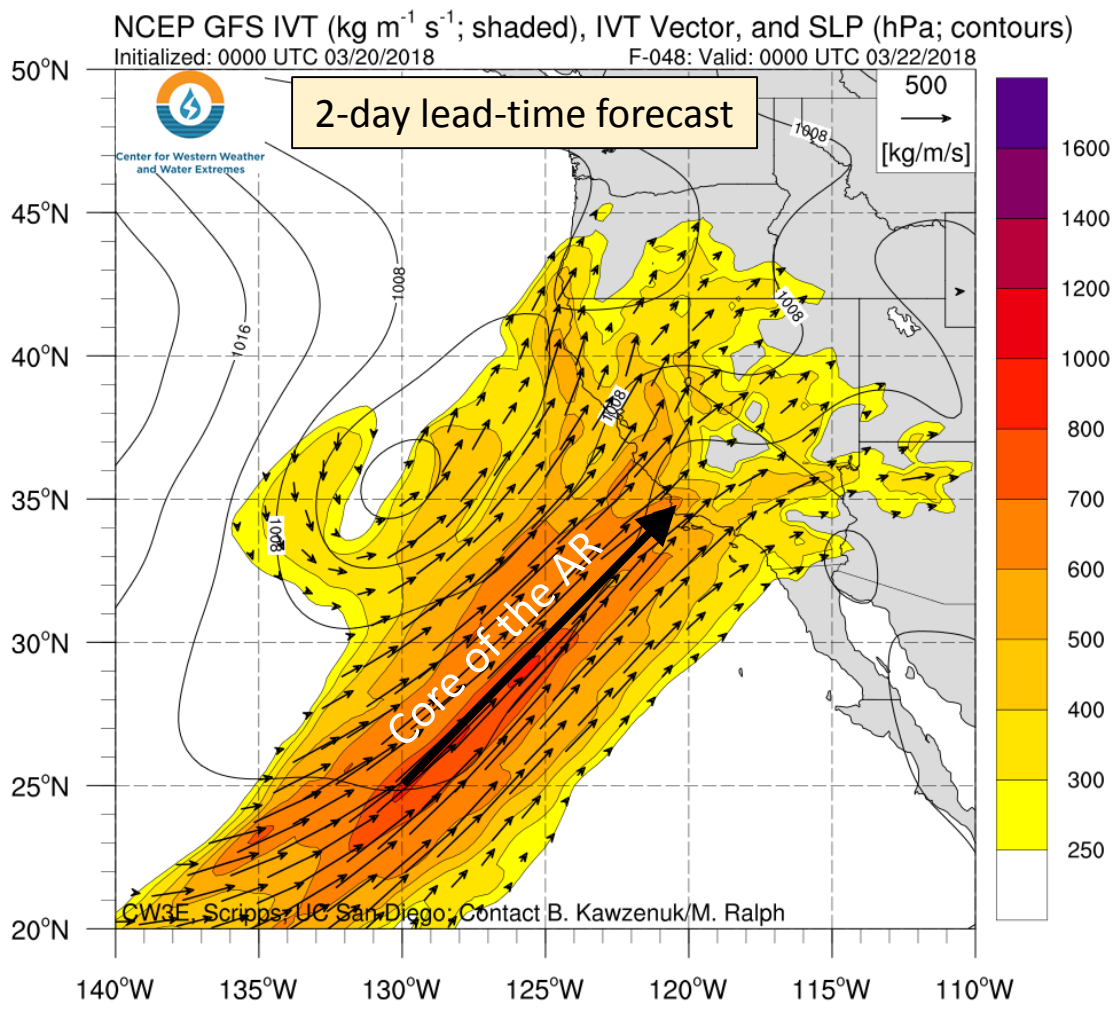
The 24-hr quantitative precipitation estimate (QPE) indicated that ~6 inches fell along the Coastal Mts. and ~2 inches fell over the Santa Ynez Mts.

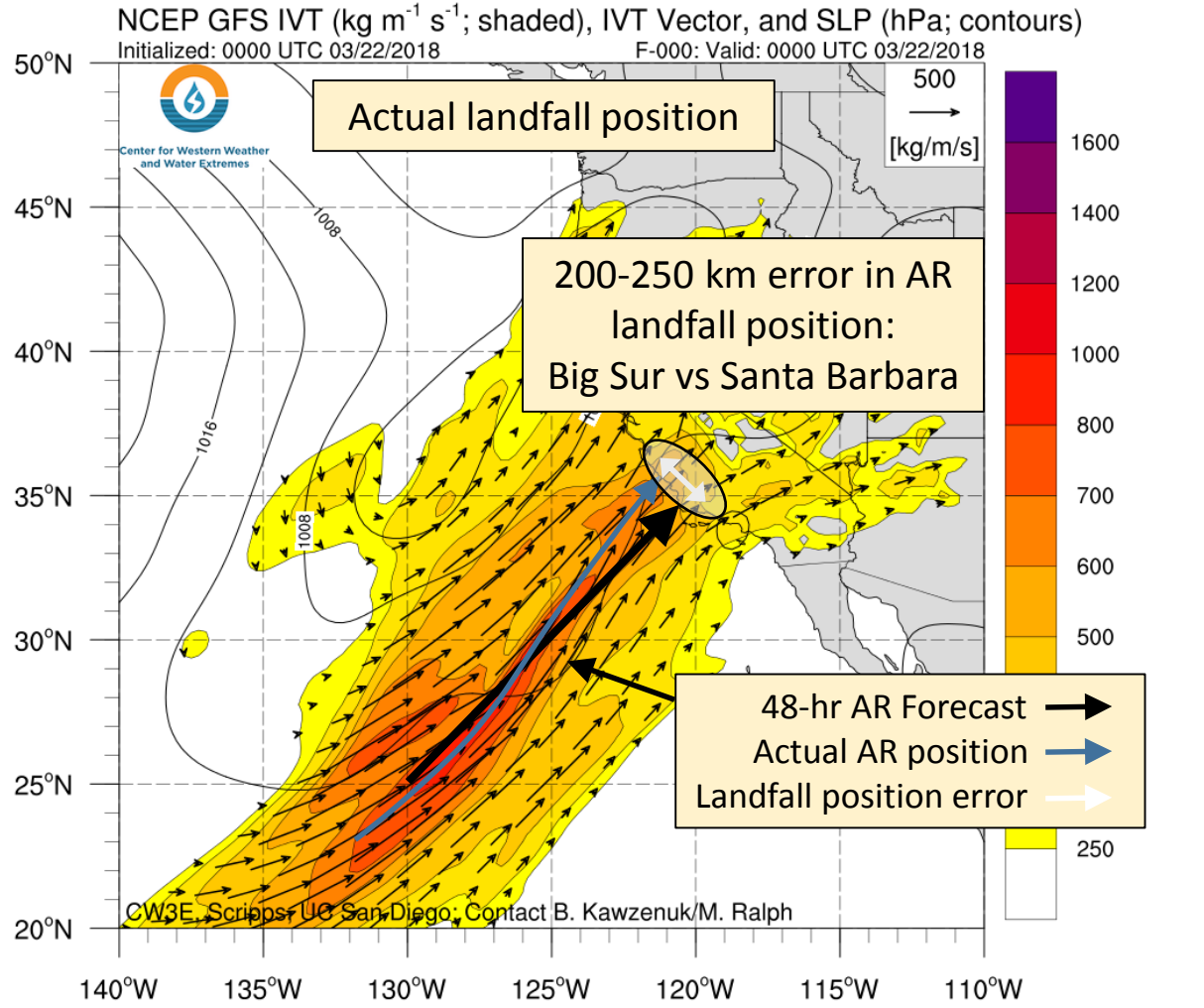
CNRFC 24-hr Verification (QPF–QPE) Valid 5 AM PDT 21 to 22 March 2018



The QPE accumulations resulted in a over forecast of ~3 in. over the Santa Ynez Mts. and an under forecast of ~3 in. over Big Sur

AR Outlook: 22 March 2018





- **The errors in the precipitation forecasts were partly driven by errors in weather model forecast of AR landfall location**
- **The forecast issued at 5 PM PT on Mon. 19 March predicted that the core of the AR 2 days later would be located just west of Santa Barbara at 5 PM PT Wed. 21 March, and would have produced up to 10 inches of rain in the mountains above Santa Barbara**
- **However, the observations (GFA analysis) showed that the core of the AR was instead over Big Sur (~200-250 km from the predicted position). Big Sur did receive up to 9-10 inches of rain, while mountains above Santa Barbara 4-5 inches**

AR Forecast Evaluation: 22 March 2018

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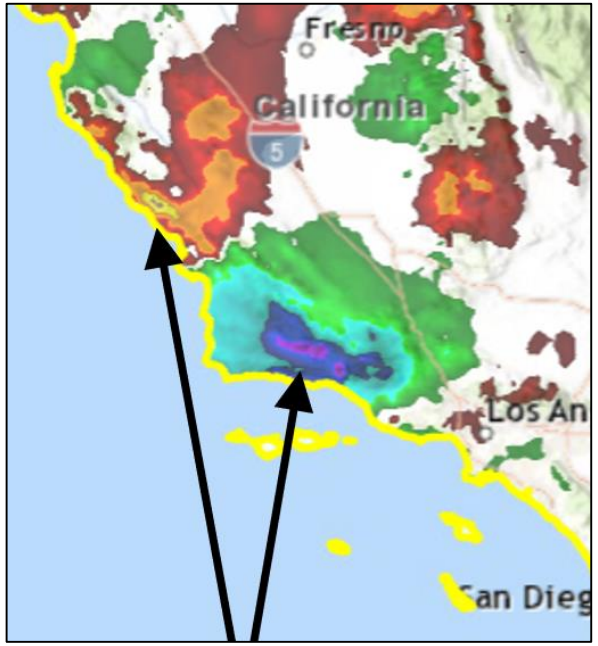
Big Sur
Observed
Max AR rainfall

200-250 km landfall position forecast error

Santa Barbara
Predicted Max AR rainfall



Precipitation forecast error pattern was a dipole, representing mostly a position error in the location of the heavy precipitation

AR Recon – 2018 Flight Operations Planning and Execution

NWS Co-PI
V. Tallapragada (NCEP) – Co-PI
A. Edman (NWS WR) – Co-PI

AR Recon PI and Mission Director
F.M. Ralph (SIO/CIMEC & CW3E)
J. Doyle (NRL) – Alternate
Coordinators: A. Wilson, J. Kalansky, F. Cannon (CW3E)

Flight Execution
Major A. Lundry (AF C-130s)
J. Parrish (NOAA G-IV)
"Flight Directors"

C-130 & G-IV Crews; CARCAH

AR Core Target Planning
Two C-130s
J. Rutz (NWS WR) – Primary
J. Cordeira (Plym. St.)– Alternate
AR Core Target - Advisors
C. Reynolds (NRL) - backup
C. Smallcomb (NWS)
D. Lavers (ECMWF)
R. Demirdjian (SIO/CW3E)

iterate

Flight Track Assessment
Air Force Navigator
NOAA (Parrish/Cowan)
Coordinator: F. Cannon (CW3E)

iterate

Secondary Target Planning
NOAA G-IV
C. Davis (NCAR) – Primary
T. Galarneau (U.AZ) – Alternate
Secondary Target - Advisors
J. Doyle (NRL)
L. Bosart (SUNY Albany)
R. Demirdjian (SIO/CW3E)
TBD

Daily Forecasts, Flight Summaries and Planning 800 AM PT*

**Meetings led by either Cordeira, Rutz, Lavers, or alternate*

**Attended by "primary" and "alternate" from each group (not by all members of each group)*

Planning Data and Flight Summaries

Moist Adjoint Team
C. Reynolds (NRL) – Primary
J. Doyle (NRL) – Alternate
R. Demirdjian (SIO/CW3E) - Support

Flight Summaries
TBD - (SIO/CW3E) – PDocs/GrStud

AR Recon Forecasting Team
J. Cordeira (Plymouth St.) – Primary
D. Lavers (ECMWF) – Alternate
J. J. Rutz (NWS WR) – Alternate
C. Hecht (SIO/CW3E) - Alternate
B. Kawzenuk (SIO/CW3E)
K. Howard (NCEP), Other TBD

Modeling and Data Assimilation SC
F.M. Ralph (SIO/CW3E) – Co-Chair
V. Tallapragada (NCEP) – Co-Chair
J. Doyle (NRL),
C. Davis (NCAR)
F. Pappenberger (ECMWF),
A. Subramanian (SIO/CW3E)

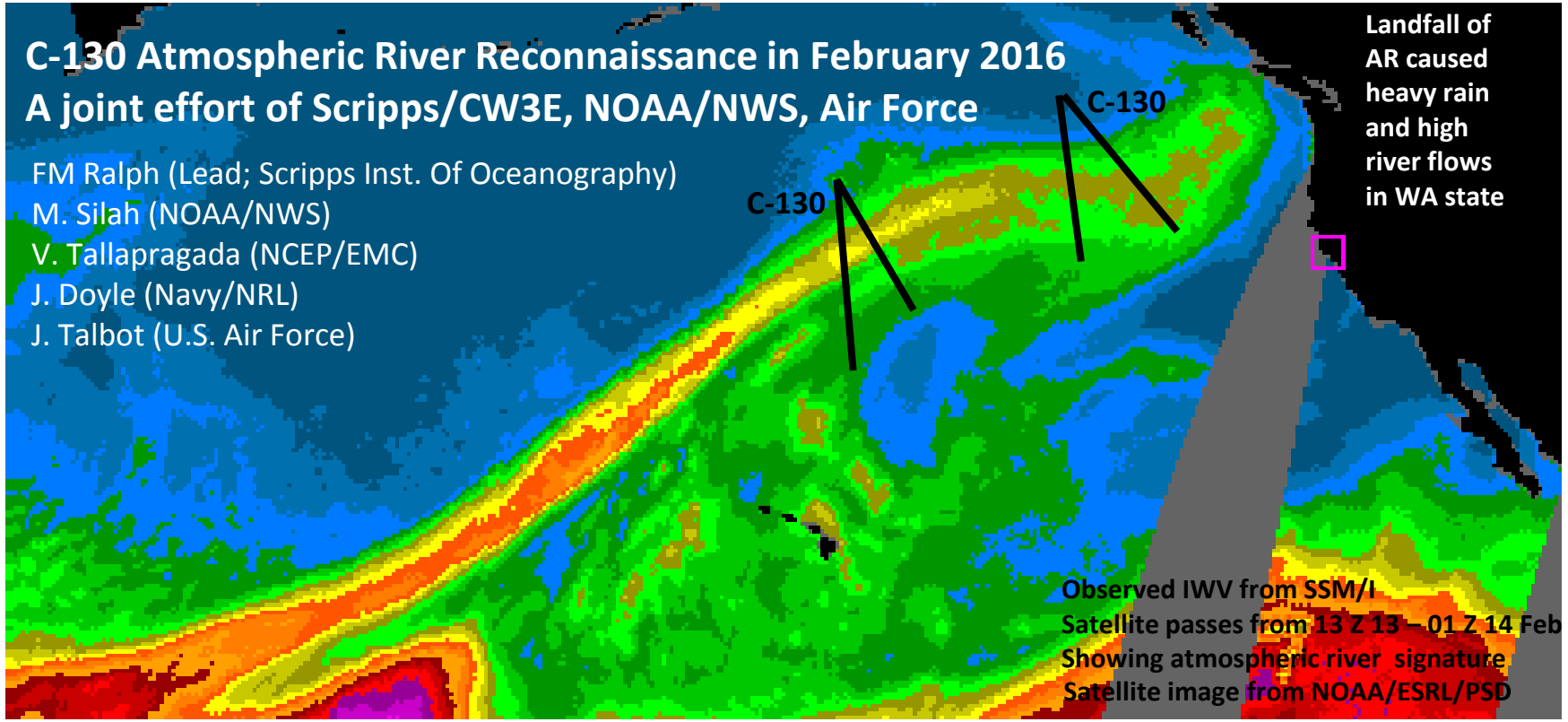
Key dates
19 January: commit where to deploy the 2nd C-130

25 Jan - 10 Feb: G-IV is available for 3 storm flights from Seattle

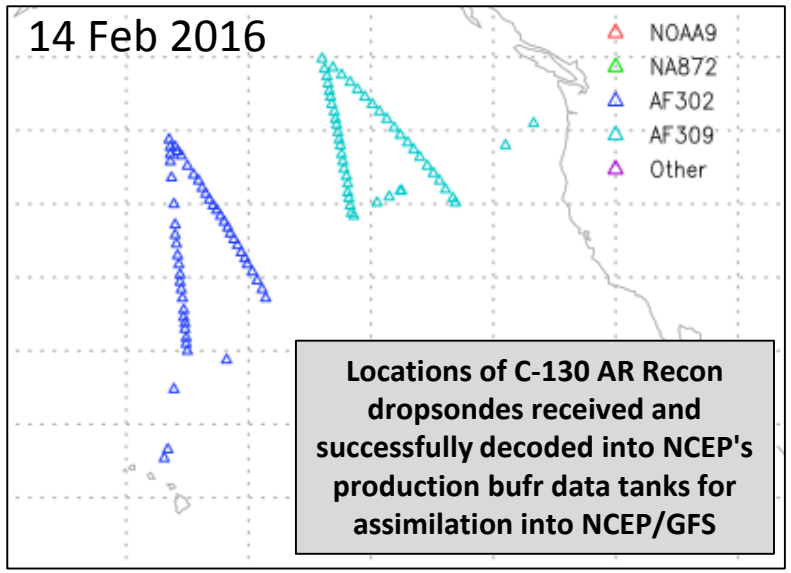
25 Jan - 27 Feb: two C-130s available for 6 storm flts from Hawaii, Seattle, Travis AFB or San Diego

C-130 Atmospheric River Reconnaissance in February 2016
A joint effort of Scripps/CW3E, NOAA/NWS, Air Force

FM Ralph (Lead; Scripps Inst. Of Oceanography)
M. Silah (NOAA/NWS)
V. Tallapragada (NCEP/EMC)
J. Doyle (Navy/NRL)
J. Talbot (U.S. Air Force)



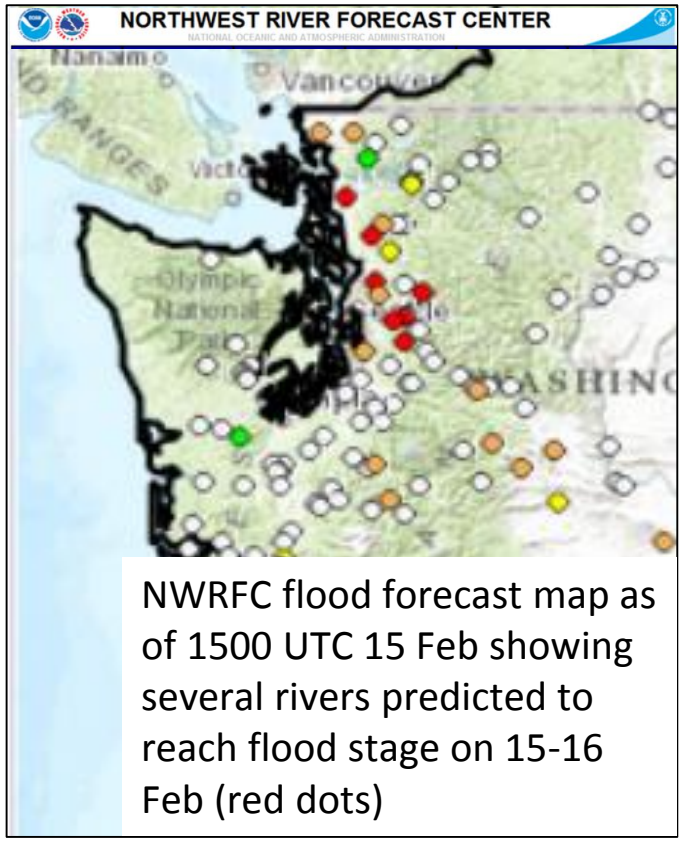
1st C-130 AR Recon Mission
13-14 Feb 2016
Dropsondes released for the 0000 UTC 14 Feb 2016 GFS data assimilation window



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

Air Force C-130 Aircraft – Weather Recon' Squadron

Center for Western Weather and Water Extremes



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

2018
Atmospheric River Reconnaissance Flight Strategies

Center time: 0000 UTC
Dropsonde deployment window:
2100 – 0300 UTC

Each aircraft has a range of about 3500 nm

F.M. Ralph (AR Recon PI) and AR Recon Team

60N
55N
50N
45N
35N
160W
150W
140W
130W
120W
3.5 h
3.0 h
2.0 h
1.0 h
G-IV Ferry time from Seattle (black numbers)
Upper-level trough/PV anomaly
Example of a target for the NOAA G-IV
Example of Atmospheric River target for AF C-130s (color fill: IVT)
AF C-130
AF C-130
On-station time for G-IV (red text)
8 h
6 h
4 h
3 h

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AR Recon – 2018: IOP 1 on 26-27 Jan 2018

Key sponsors include US Army Corps of Engineers, and California Dept. of Water Resources

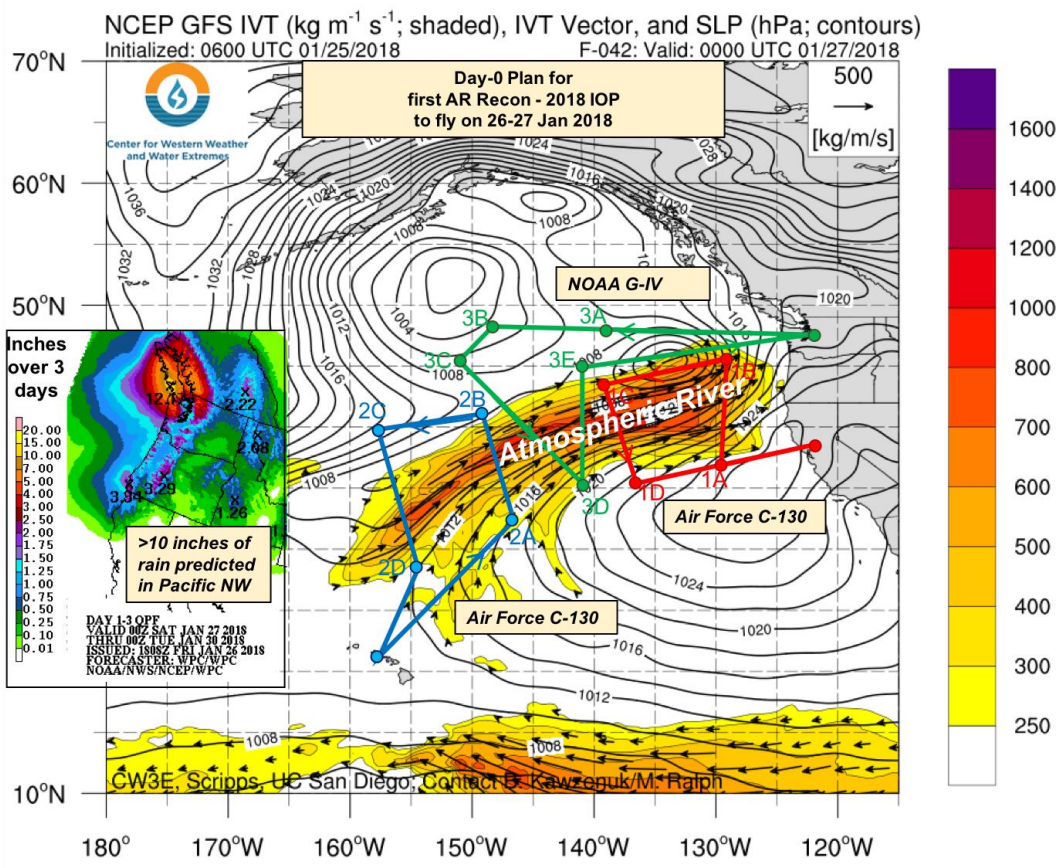
Center time for dropsondes: 0000 UTC 27 Jan 2018

Number of dropsondes planned: 27, 26, 36 (C-130 H, C-130 C, G-IV)

- Mission Director: F. Martin Ralph (PI; Scripps/CW3E)
- Co-PIs: Vijay Tallapragada (NWS/NCEP), Andy Edman (NWS/Western Region)
- C-130 Flight Planning lead: Jon Rutz (NWS)
- G-IV Flight Planning Lead: Chris Davis (NCAR)
- Forecasting Lead: Jay Cordeira (Plymouth St. Univ.)
- Moist Adjoint Lead: Jim Doyle/Carolyn Reynolds (NRL)
- GPS sensor lead: Jennifer Haase (Scripps/IGPP and CW3E)
- AR Recon Coordinator: Anna Wilson (Scripps/CW3E)
- Flight Track Coordinator: Forest Cannon (Scripps/CW3E)
- Air Force C-130 Flight Director: Ashley Lundry (AF/53rd Weather Recon)
- NOAA G-IV Flight Director: Jack Parrish (NOAA/AOC)


Air Force C-130 Aircraft – Weather Recon' Squadron


NOAA G-IV



Modeling Partners

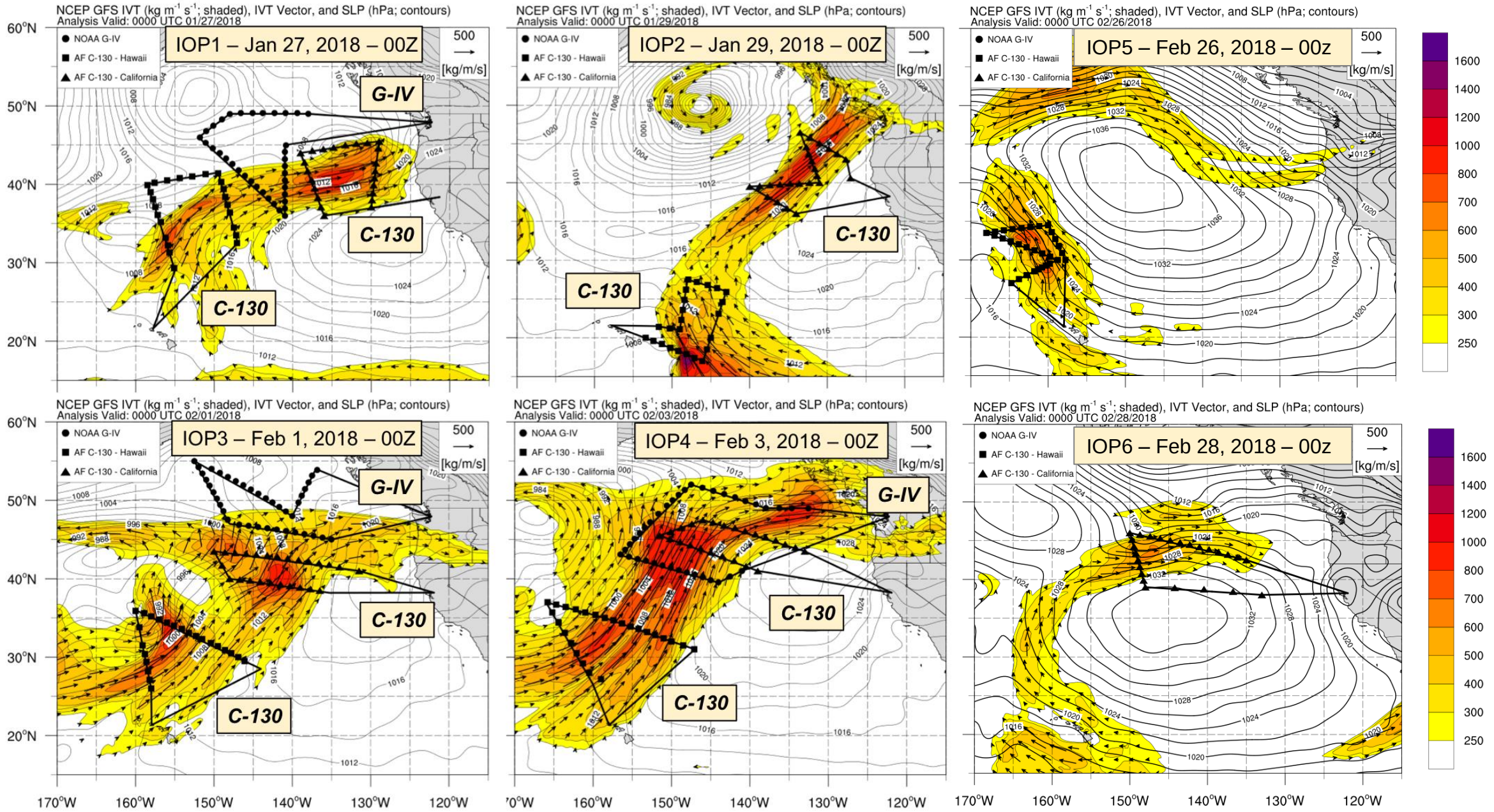
NWS/NCEP US NAVY
ECMWF NCAR

Forecaster	Chad Hecht (Scripps/CW3E)	Moist Adjoint support	Reuben Demirdjian (CW3E)
Forecaster	David Lavers (ECMWF)	Flight Planning ("alternate")	Tom Galarneau (Univ. AZ)
Forecaster	Philippe Papin (NRL)	Onboard Scientist	Jon Rutz (NWS)
Forecaster	Aneesh Subramanian (Scripps/CW3E)	Onboard Scientist	Reuben Demirdjian (CW3E)
		Onboard Scientist (GPS)	Bing Cao (Scripps/IGPP)

Atmospheric River Reconnaissance 2018

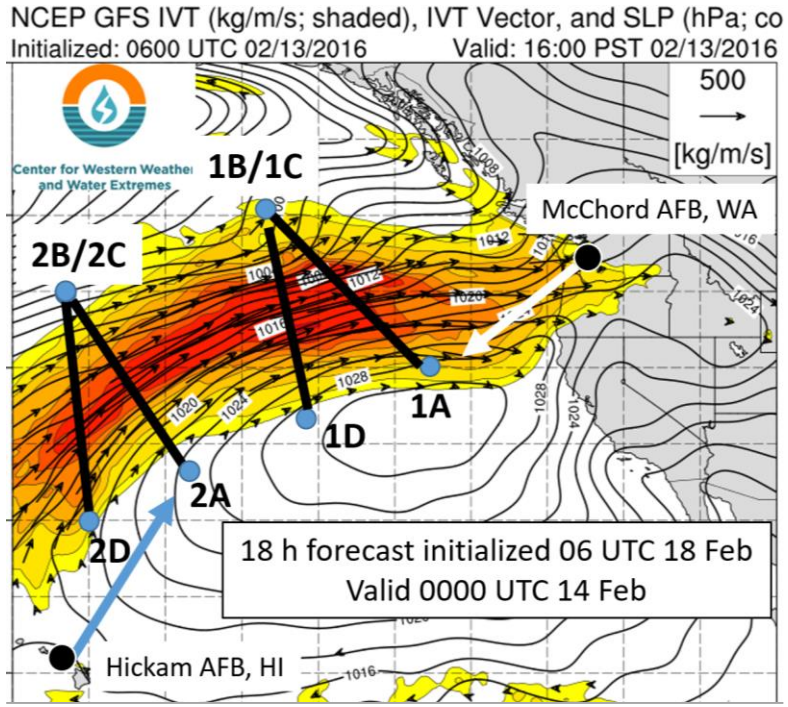
Center for Western Weather and Water Extremes

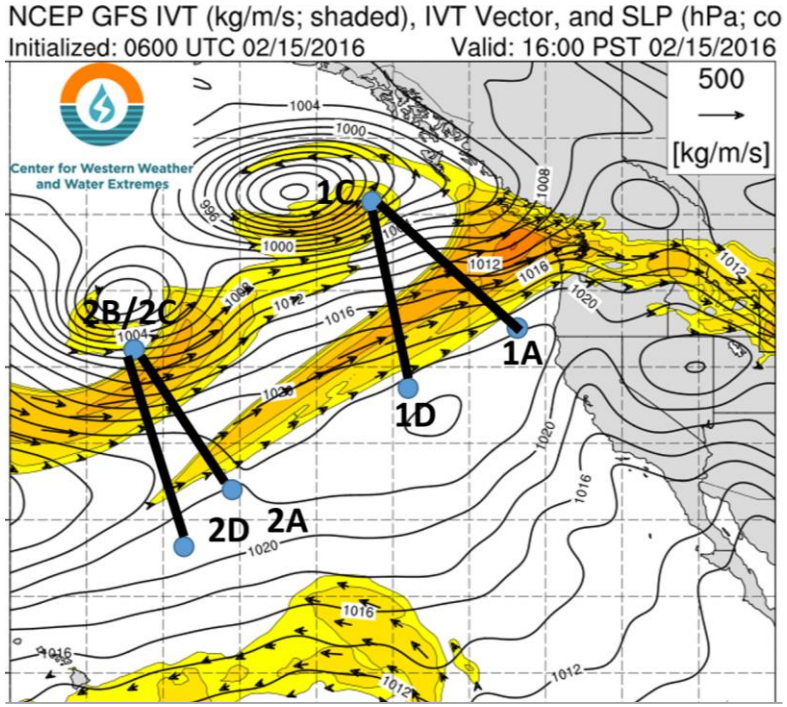
Contacts: F. M. Ralph (PI; mralph@ucsd.edu); V. Tallapragada (Co-PI; vijay.tallapragada@noaa.gov)

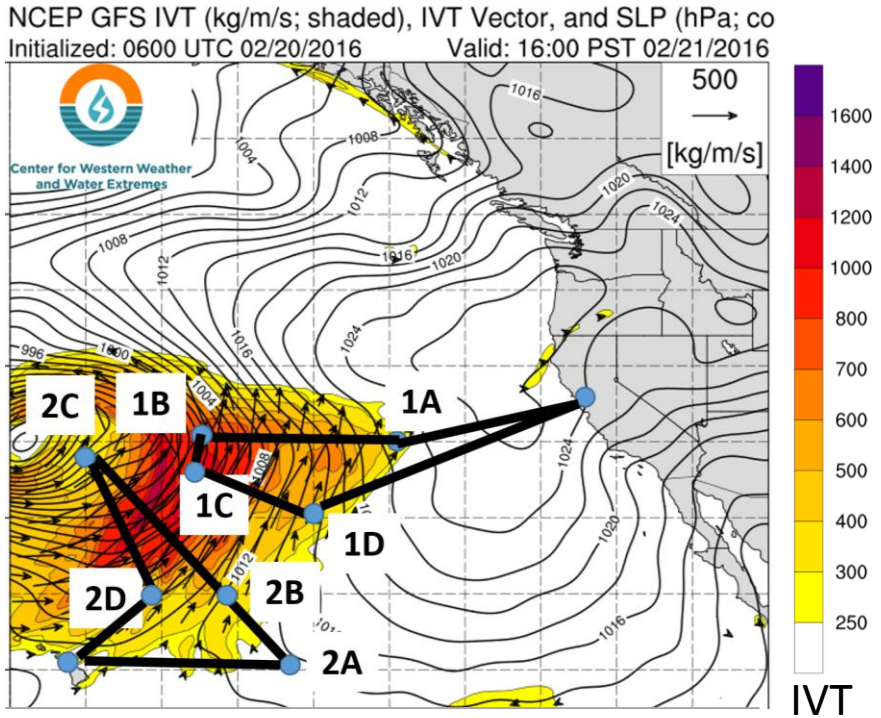


Atmospheric River Reconnaissance 2016

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







AR Recon – 2019: Requesting 3 Aircraft to Sample 9 Storms

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

- ✓ Feb 2016: 3 Storms (2 aircraft per storm)
- ✓ Jan-Feb 2018: 6 Storms (3 aircraft per storm in 3 storms; 2 aircraft in 1 storm; 1 aircraft in 2 storms)
- ○ Jan-Mar 2019 (Requested): 9 storms (3 aircraft per storm)
- ○ **Target total number of cases: 18 storms, with 1, 2 or 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

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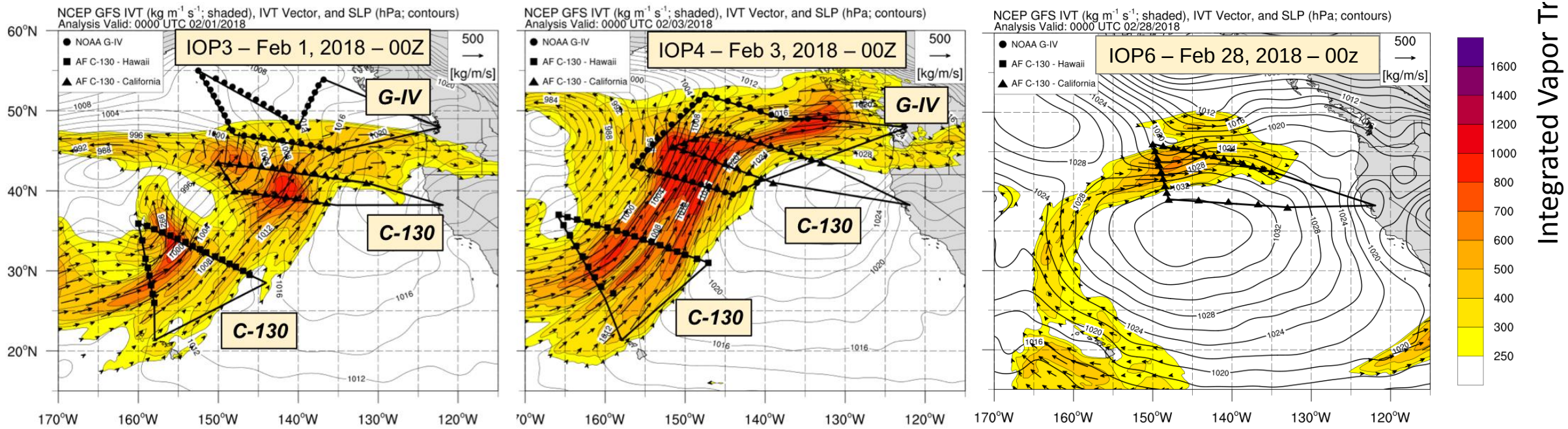
Contacts
F. M. Ralph (mralph@ucsd.edu)
V. Tallapragada (vijay.tallapragada@noaa.gov)

AR Recon Modeling and Data Assimilation Steering Committee

Formation of an “AR DA Steering Committee” and “AR DA Technical Work Plan”

Steering Committee

- F. Martin Ralph – (UCSD/Scripps/CW3E) - AR Recon PI and AR DA SC Co-Chair
- Vijay Tallapragada (NOAA/NWS/NCEP) – AR Recon Co-PI and AR DA SC Co-Chair
- Jim Doyle (NRL)
- Aneesh Subramanian (UCSD/Scripps/CW3E)
- Chris Davis (NCAR/MMM)
- Florian Pappenberger (ECMWF)



Diagnostics of Atmospheric Rivers in a Recent Field Campaign

David Lavers[1], Mark Rodwell[1], David Richardson[1], Marty Ralph[2], Jim Doyle[3], Carolyn Reynolds[3], Florian Pappenberger[1]

[1]ECMWF, Reading, U.K.

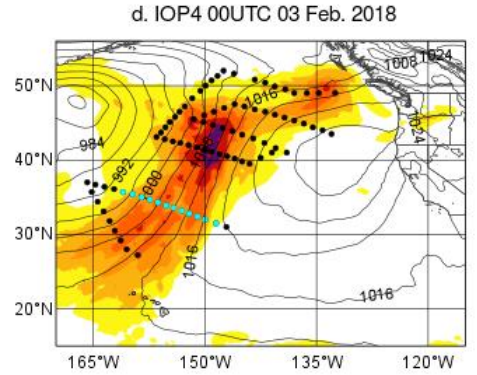
[2]CW3E, Scripps Institution of Oceanography, University of California, San Diego

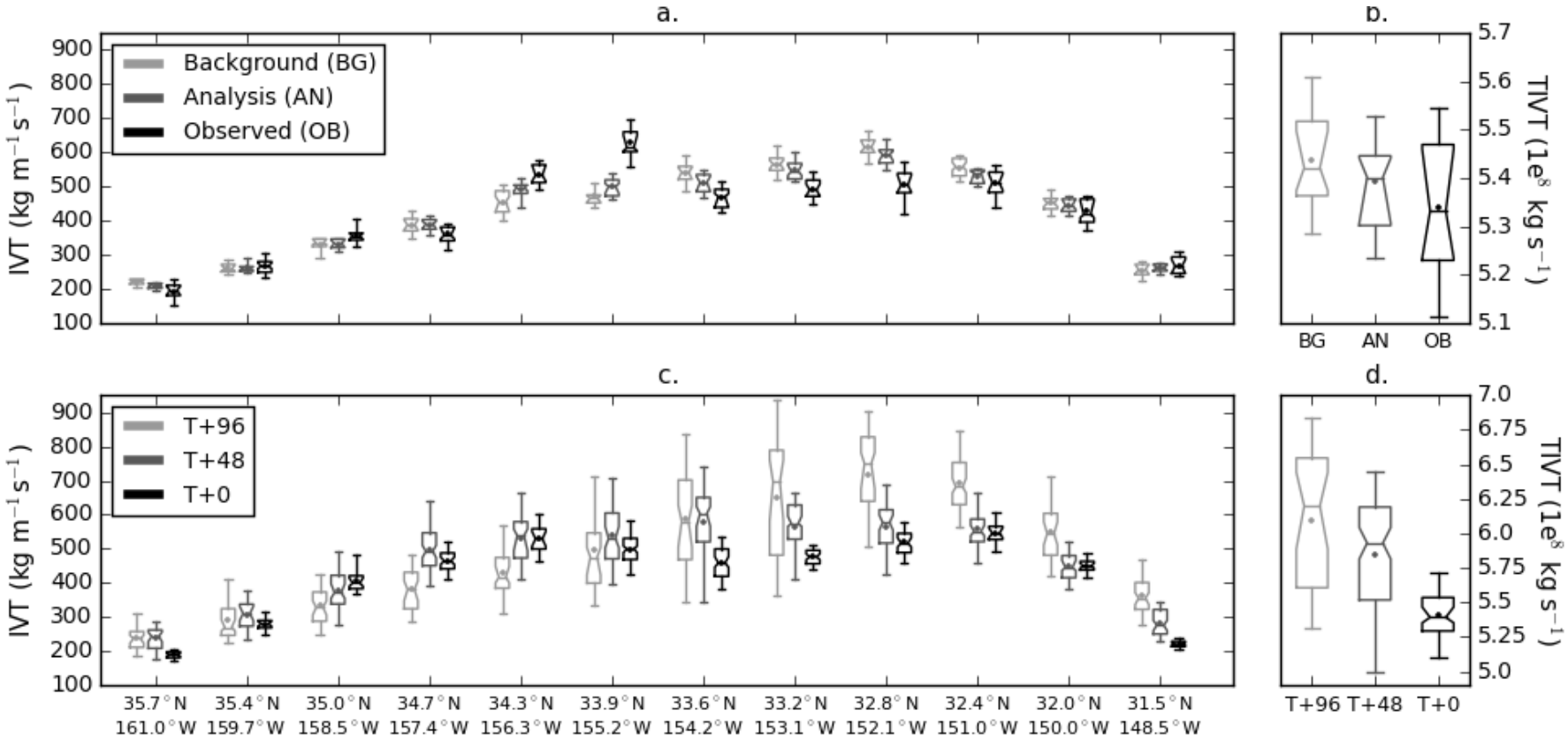
[3]Naval Research Laboratory, Monterey, California

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

This research was partly funded by IMPREX. IMPREX has received funding from the EU's Horizon 2020 Research and Innovation Programme under Grant Agreement Nº 641811

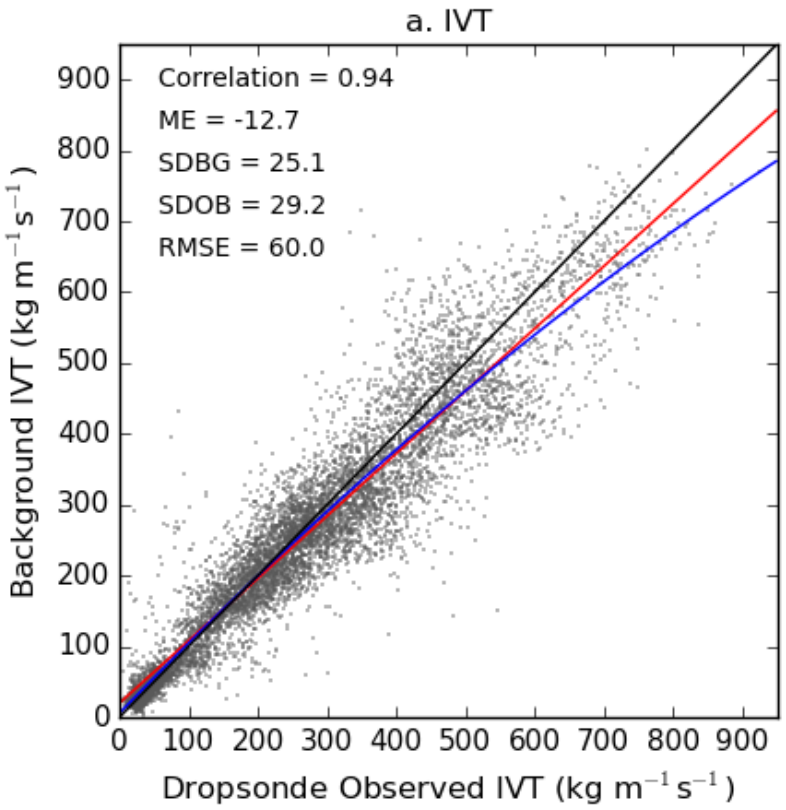
An example AR transect

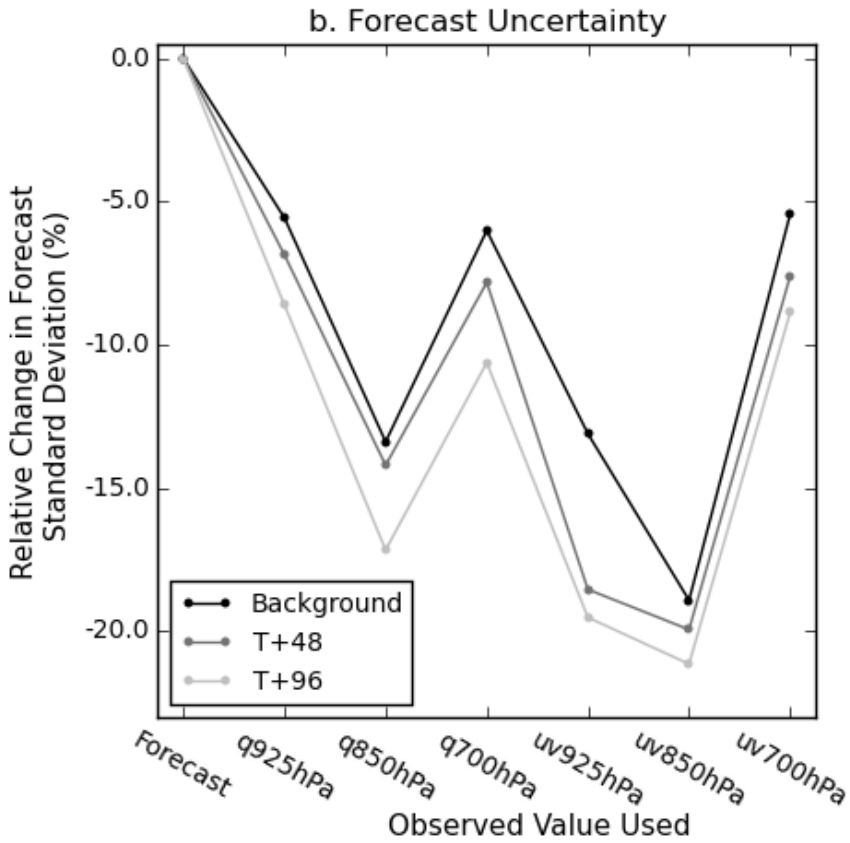




Lavers, D. A., et al. (2018). The gauging and modeling of rivers in the sky. *Geophysical Research Letters*, 45.

Water vapour flux (IVT) uncertainty





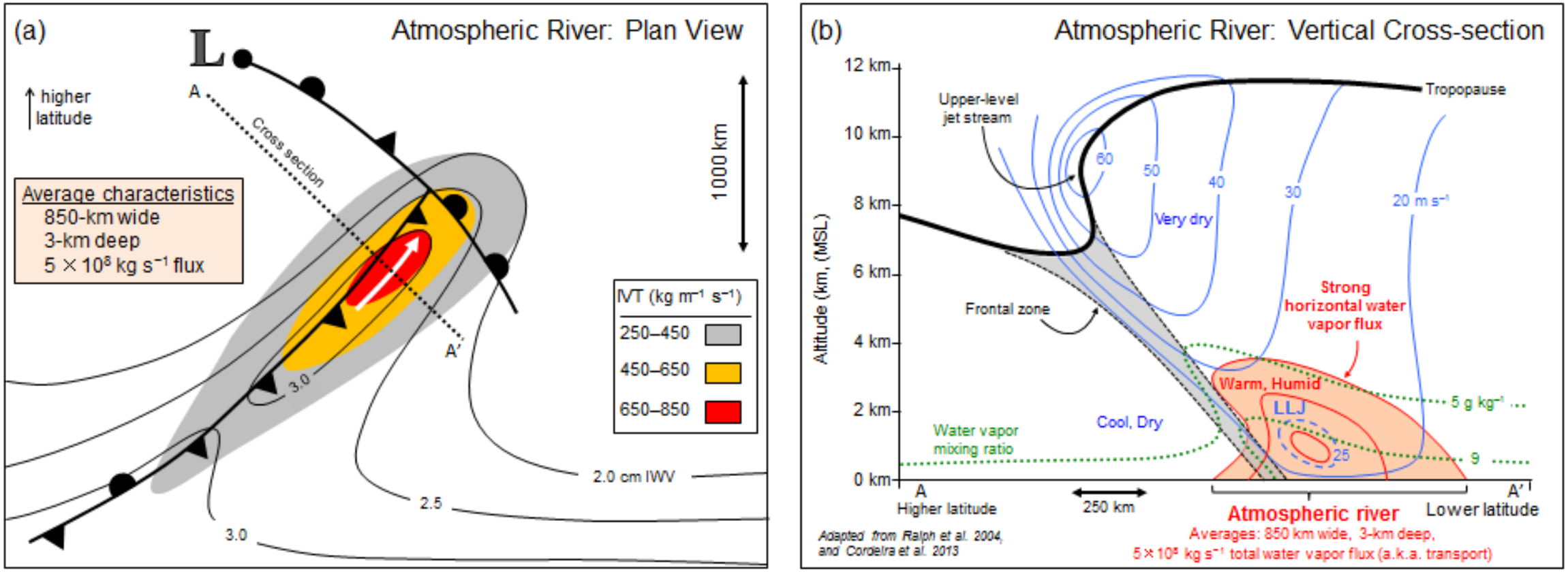
Lavers, D. A., et al. (2018). The gauging and modeling of rivers in the sky. *Geophysical Research Letters*, 45.

Conclusions

- Six IOPs during AR Recon in January / February 2018.
- AR structure and IVT magnitude generally well captured.
- High IVT uncertainty mostly due to uncertainties in winds at the top of and above the planetary boundary layer (850 hPa).
- Specific humidity is also subject to relatively large uncertainties.
- Uncertainty grows with lead time.

Lavers, D. A., et al. (2018). The gauging and modeling of rivers in the sky. *Geophysical Research Letters*, 45.

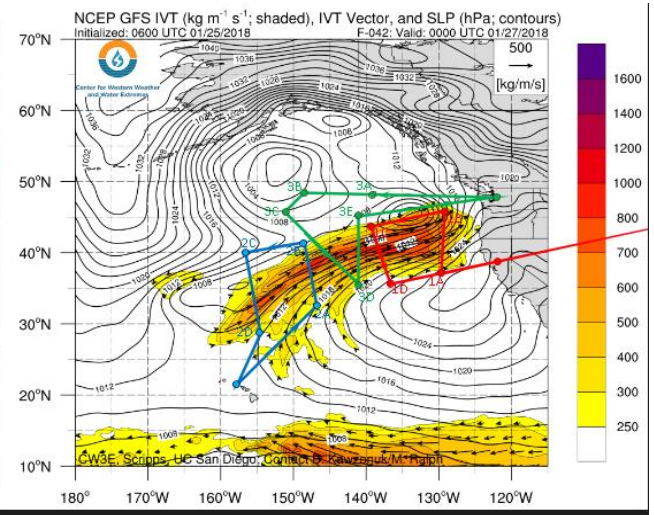
Atmospheric Rivers

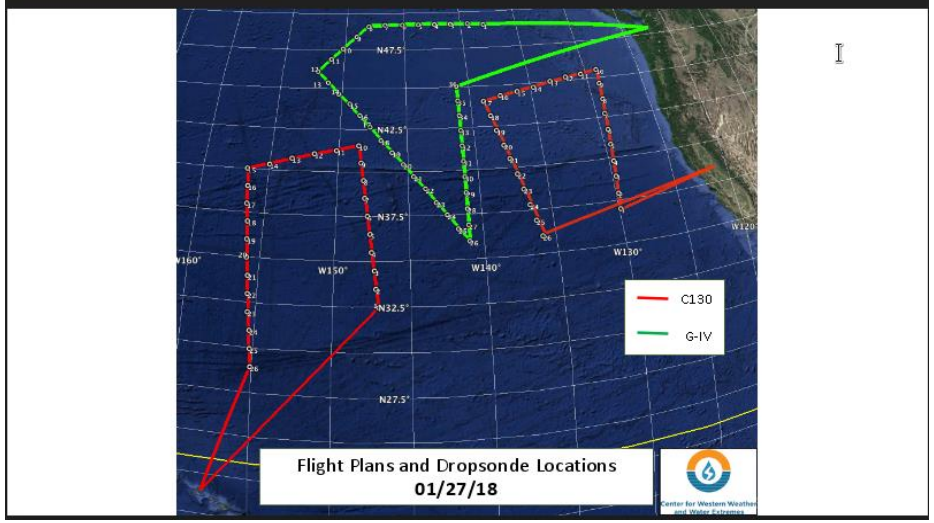


Images from the AMS Glossary of Meteorology
(Ralph et al., 2017, *J. Hydrometeor.* and 2018 *Bull. Amer. Meteor. Soc.)*

ECMWF Supports Atmospheric River Reconnaissance (AR recon)

C-130 CA	Lat	Lon
Travis AFB	38.37	-121.3
1A	37	-130
1B	45.5	-129
1C	44	-139
1D	36	-136
C-130 HI	**Lat**	**Lon**
HI. AFB	21.59	-157.8
2A	32.5	-147
2B	41.5	-148.5
2C	40	-156.5
2D	29	-155
G-IV	**Lat**	**Lon**
SEA	47.91	-122.28
3A	50	-128
3B	49	-148
3C	46	-152
3D	36	-141
3E	45	-141

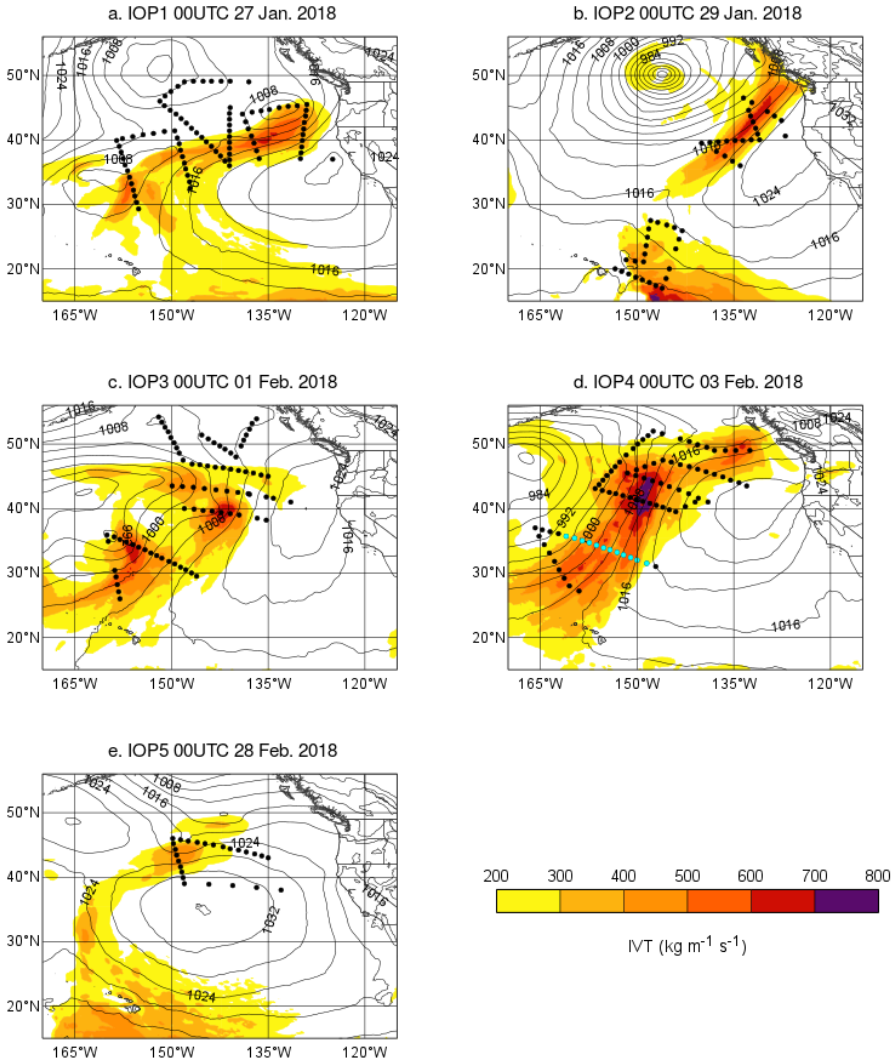




- January / February 2018.
- Six Intensive Observation Periods (IOPs).
- Three aircraft (NOAA GIV and two C130s).
- ARs are important for extreme rainfall and atmospheric circulation and predictability.
- Opportunity to identify model problems.

ECMWF
EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

Five IOPs

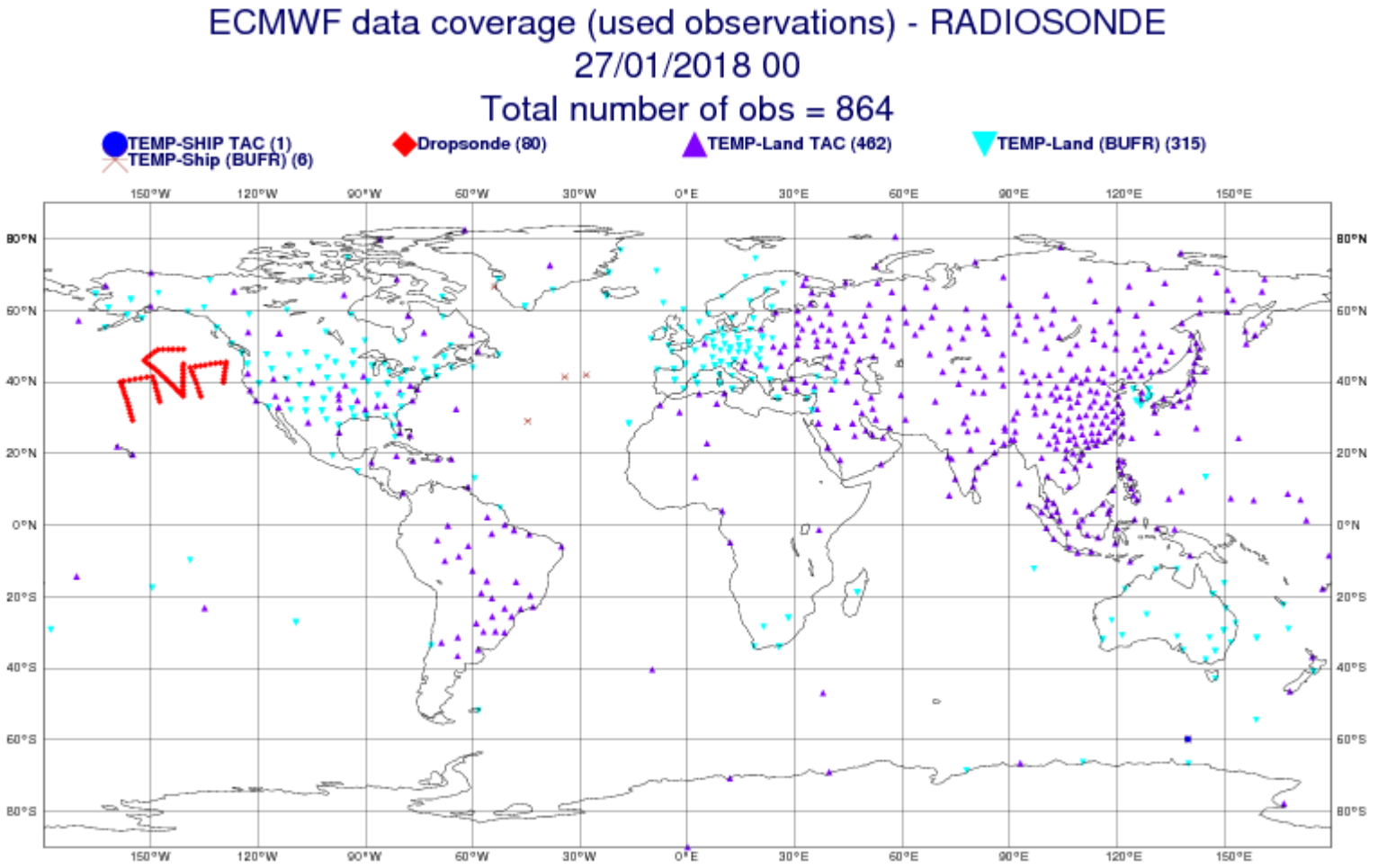


Lavers, D. A., et al. (2018). The gauging and modeling of rivers in the sky. *Geophysical Research Letters*, 45.

Analysis

- Dropsondes were assimilated in real-time.
- Use ECMWF ensemble of data assimilations (EDA). The 25 members produce the 50 perturbed ensemble forecasts.
- Water vapour flux (IVT) calculated at each dropsonde location.
- Assess the background, analysis, and observed values.
- AR transects evaluated and IVT uncertainties investigated.

Assimilated dropsondes

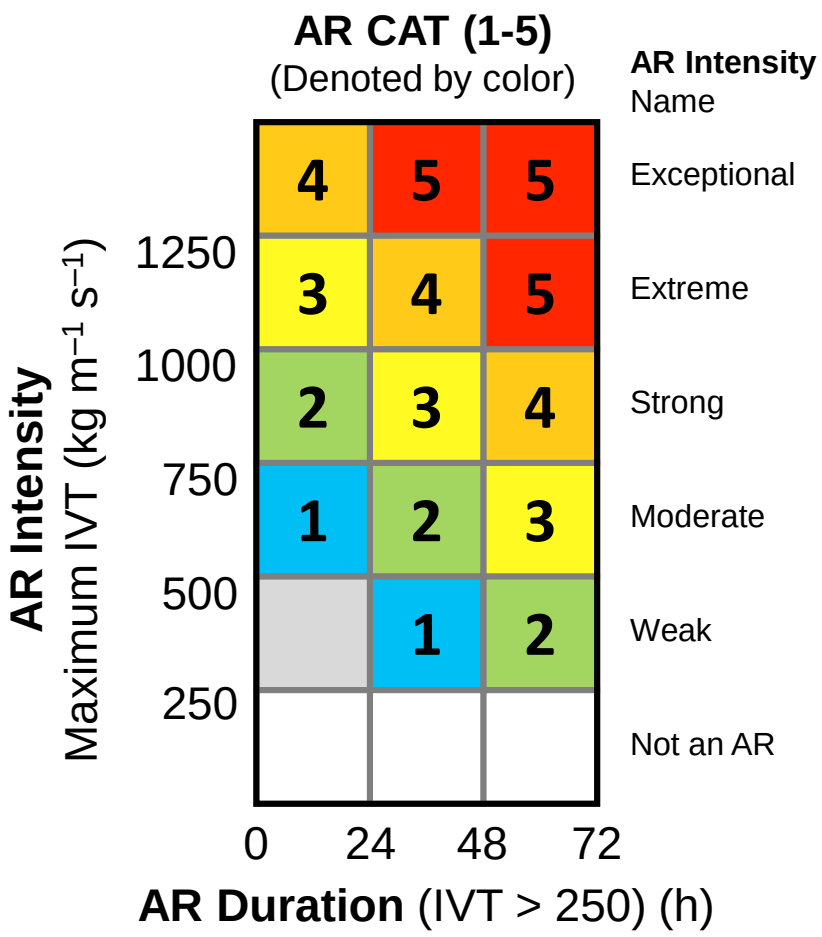


A Scale to Characterize the Strength and Impacts of Atmospheric Rivers

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. (accepted pending revision;revised June 2018)*

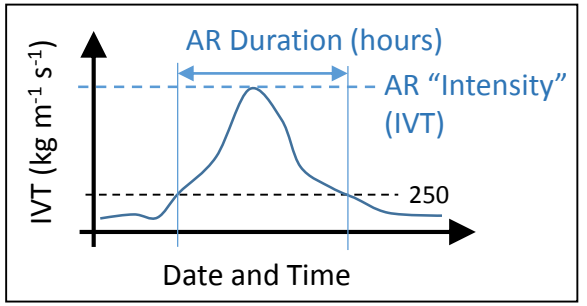
The AR CAT level of an AR Event* is based on its *Duration* and max *Intensity* (IVT)*****

** 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

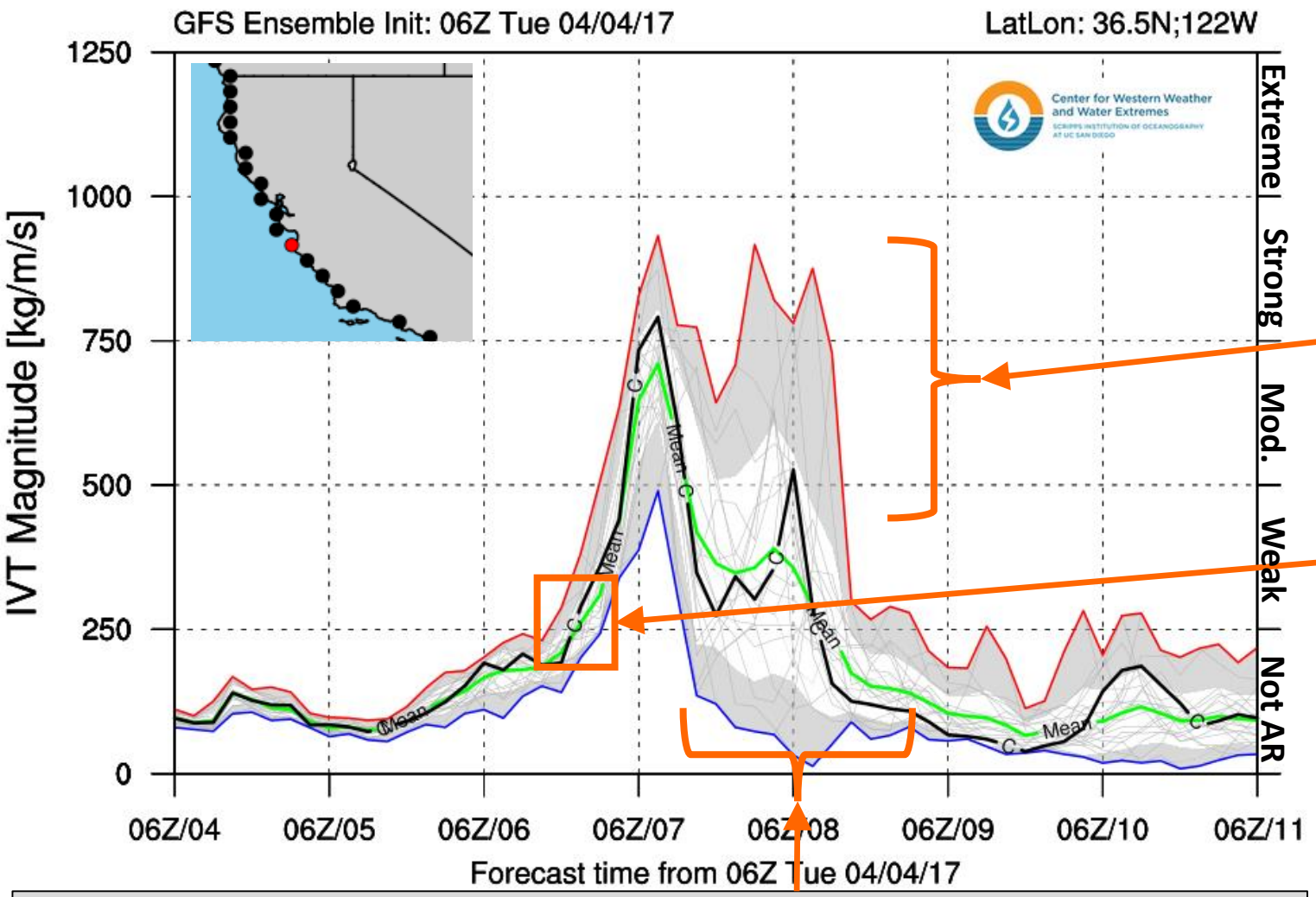
Step 4: Determine *final* value of **AR CAT** to assign
- If the AR Duration is > 48 h, then promote by 1 Category
- If the AR Duration is < 24 h, then demote by 1 Category

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

Center for Western Weather and Water Extremes

Early example of use of AR Intensity Scale: 4 April 2017

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



There is more uncertainty in IVT magnitude associated with the development of the mesoscale frontal wave, which creates large uncertainty in the duration of AR conditions over Monterey

Monterey, CA could experience strong AR conditions IVT> 750 kg m^{-1} s^{-1}

Magnitude of AR over Monterey

- Maximum possible IVT ~ 900 kg m^{-1} s^{-1}
- Mean IVT ~ 800 kg m^{-1} s^{-1}
- Uncertainty ~ +/– 12%

High Confidence in onset of AR conditions:

- 1 PM PT Thursday 06 April +/– 4 h

Duration of AR conditions

- Weak: ~36 hours +/– 20 h
- Moderate: ~10 hours +/– 20 h
- Strong ~3 hours +/– 3 h

For California DWR's AR Program

AR intensity scale by F.M. Ralph and collaborators
Case summary: C. Hecht 1 PM PT Tues. 04 April 2017