



Center for Western Weather
and Water Extremes

SCRIPPS INSTITUTION OF OCEANOGRAPHY
AT UC SAN DIEGO

UC San Diego



Atmospheric River Reconnaissance

F. Martin Ralph

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27 June 2023
ECMWF, Reading UK

How can we improve how far in advance we can predict ARs? – AR Recon

ATMOSPHERIC RIVER RECONNAISSANCE

Filling Gaps in Pacific Weather Observations

- Lavers et al. 2018 GRL
- Ralph et al. 2019 BAMS
- Reynolds et al. 2019 MWR
- Lavers et al. 2020 Wea Fore
- Lavers et al. 2020 Nature Comms
- Stone et al. 2020 MWR
- Cobb et al. 2021 MWR
- Haase et al. 2021 JGR
- Prince et al. 2021 GRL
- Zheng et al. 2021 BAMS
- Zhang and Ralph 2021 MWR
- Cobb et al. 2022 WAF
- Wilson et al. 2022 BAMS

Dozens of papers overall, with several each in 2022 and 2023

GPS SATELLITE

AIRBORNE RADIO SODALITY

TOPOLAR

DROPSONDE

DRIFTING BUOY

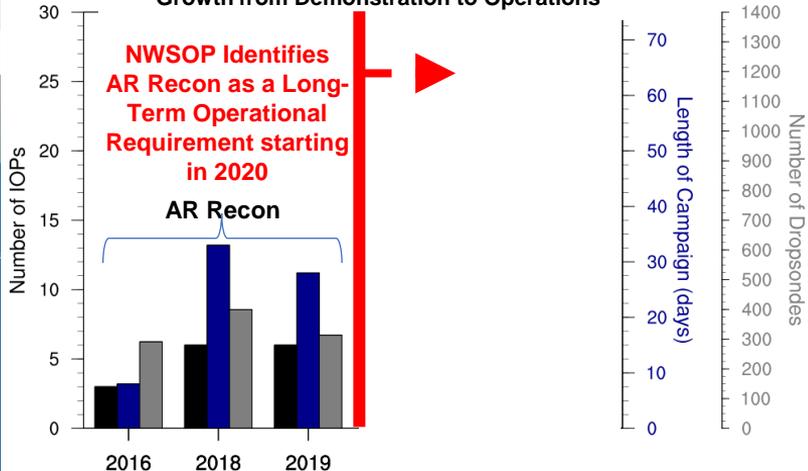
CLOUD TOP



2022/23
39 IOPs, 48 flights
1 Nov – 31 Mar (with gaps)

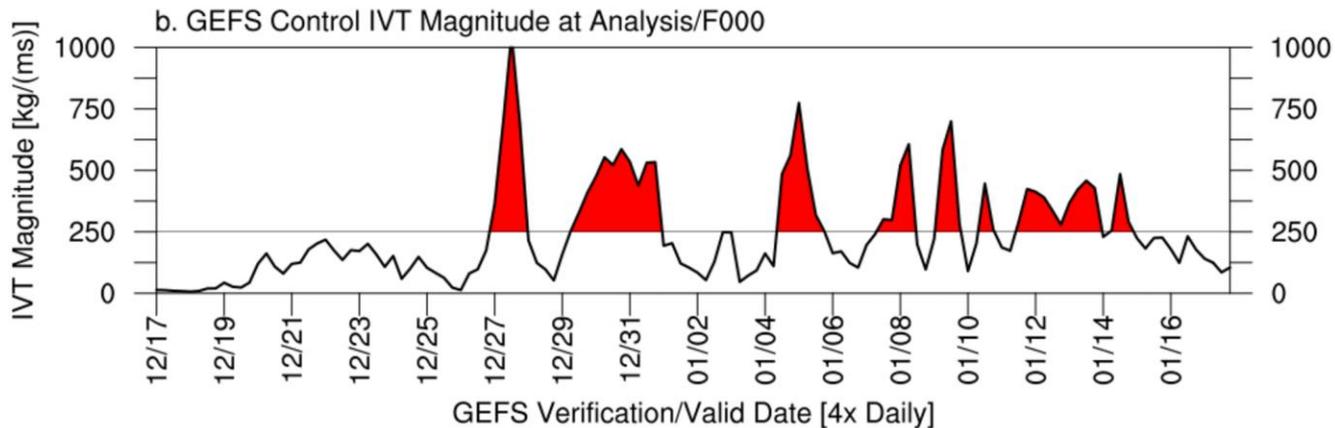
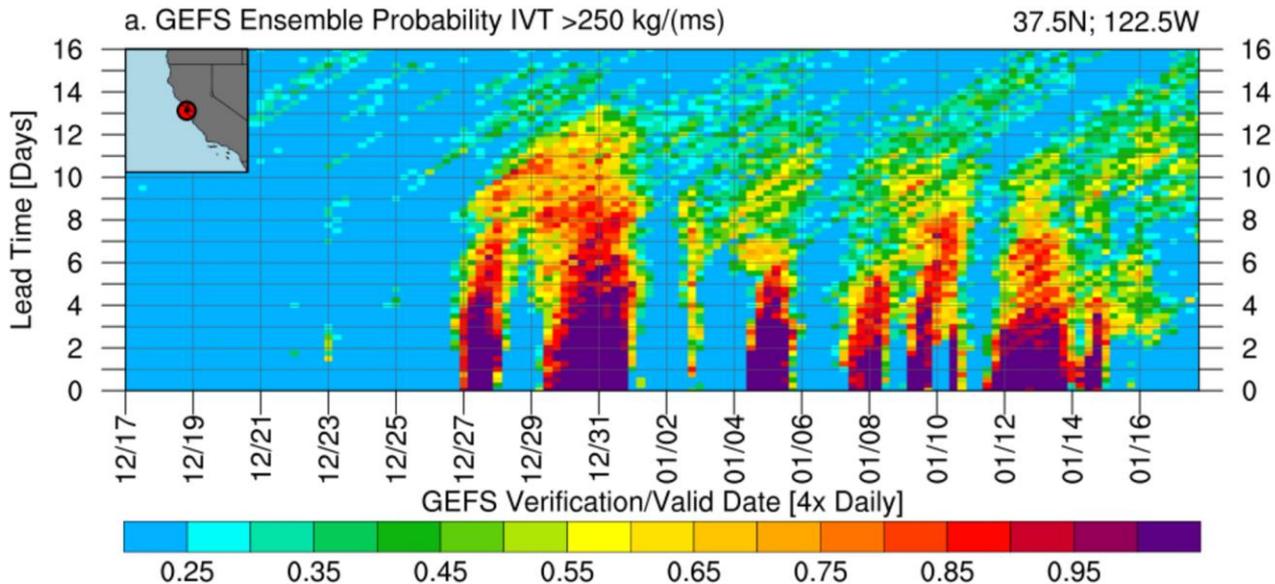
Pace (minus gaps) and need:
60 IOPs/winter in NE Pacific

Atmospheric River Reconnaissance: Growth from Demonstration to Operations





J. Cordeira





AR RECON 2023

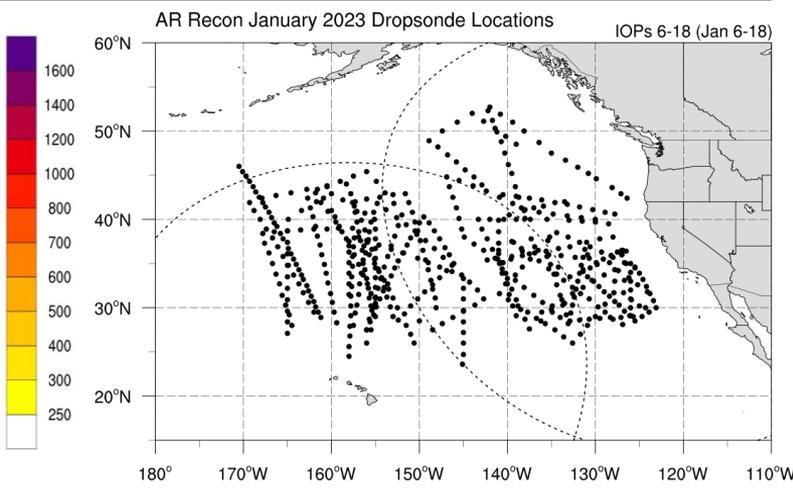
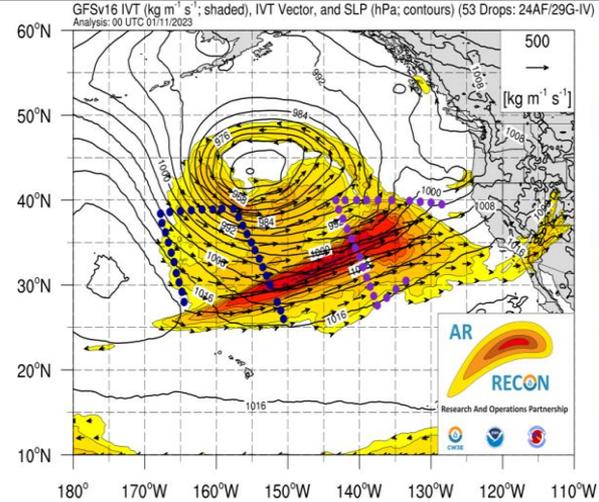
Status 25 January 2023

4 USAF C-130 aircraft based at Mather Field in Sacramento, California
 1 NOAA G-IV Jet based in Honolulu, Hawaii (through January 2023)

Jan 2023 Longest Flight Sequence on Record
included IOPs for 13 consecutive days*



*IOP = Intensive Observing Period, indicate days when AR Recon flights are flown



Key support from California Department of Water Resources/AR Program and US Army Corps of Engineers/FIRO Program



F. Martin Ralph, PI (UC San Diego/SIO/CW3E)
 Vijay Tallapragada, Co-PI (NOAA/NWS/NCEP)



Earth Information Center opens at NASA's D.C. headquarters

NEW IN TOWN | The exhibit opens Monday in the previously empty lobby of the space agency's downtown headquarters



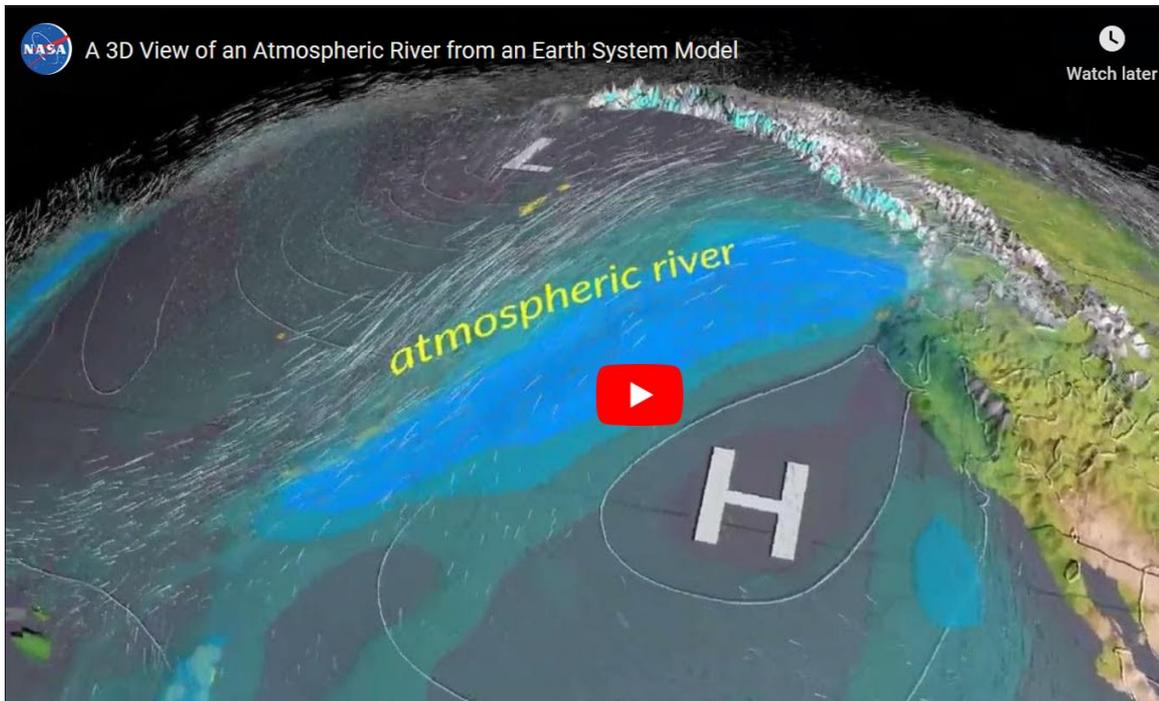
By Sophia Solano

June 26, 2023 at 6:00 a.m. EDT

NASA is transforming the lobby of its downtown D.C. headquarters into a new exhibit that invites visitors to take a glimpse of Earth from space. I got in for an early press tour of this only-in-Washington destination. Where else can you wander into an otherwise ordinary-looking office building and find yourself encountering the results of cutting-edge space research? Here's what you should know before you go.

What it is: [NASA's Earth Information Center](#) is a physical and virtual exhibit that shows all the ways the agency and its collaborators view Earth from space, and how tracking patterns in air temperature and quality, climate, water levels, and ecosystems can help us understand and fight climate change.

NASA's Major new earth science display in their Headquarters lobby opened in 2023 highlights Atmospheric Rivers



<https://gis.earthdata.nasa.gov/portal/apps/sites/#!/earth-information-center/pages/virtual-tour>



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Vision for AR Recon 5-Year Expansion 2024-28



NOAA Science Advisory Board's "Priorities for Weather Research" report in response to Congressional Directive Recommended expanding AR Recon

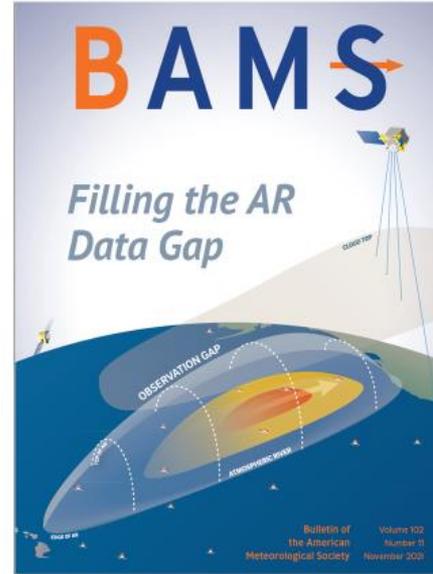


OD-8.1. Implement a multi-phase program to improve the understanding and forecasting of ARs that leverages current and future aircraft, buoy, and satellite capabilities. The program should build upon existing capabilities and programs to expand coverage in space and time and improve forecasts through advanced data assimilation (OD-3), as well as integration of ocean surface and mixed layer observations (OD-7).

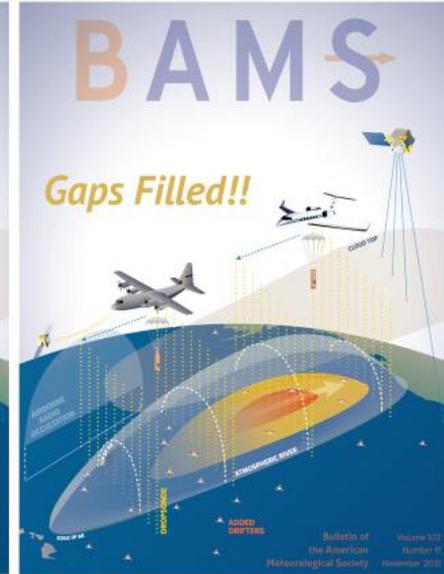
OD-8.2. Adopt a research and operations partnership approach, including engagement of the international and academic communities.

OD-8.3. The program development and implementation should create new forecast skill metrics targeting extreme precipitation prediction in the west and the phenomenon, ARs, that produces it. It should target socio-economic impact considerations including for use in reservoir operations to mitigate drought and flood impacts.

Cover

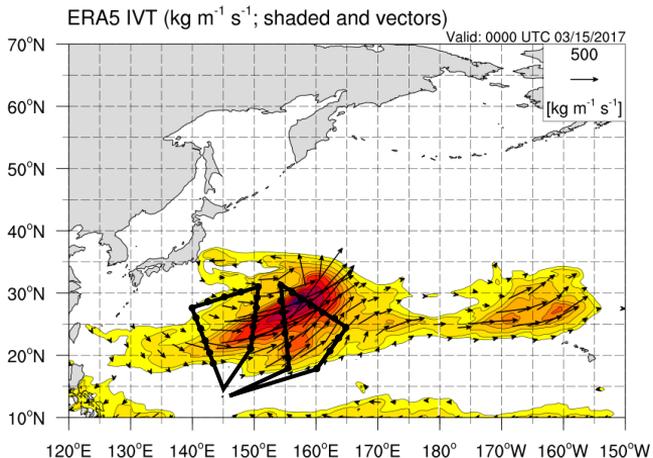


Inside front Cover – first ever for BAMS



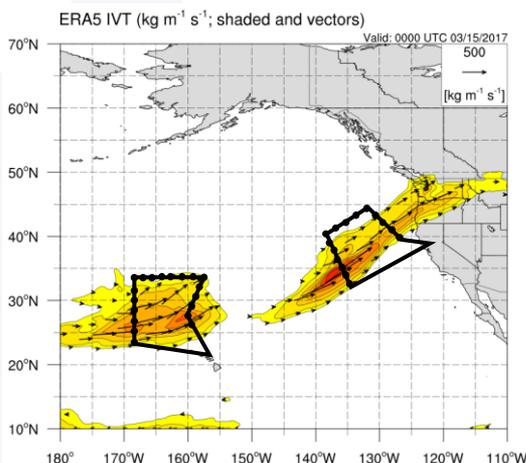
Winter 2023/24: “WestPac Expansion”

WestPac



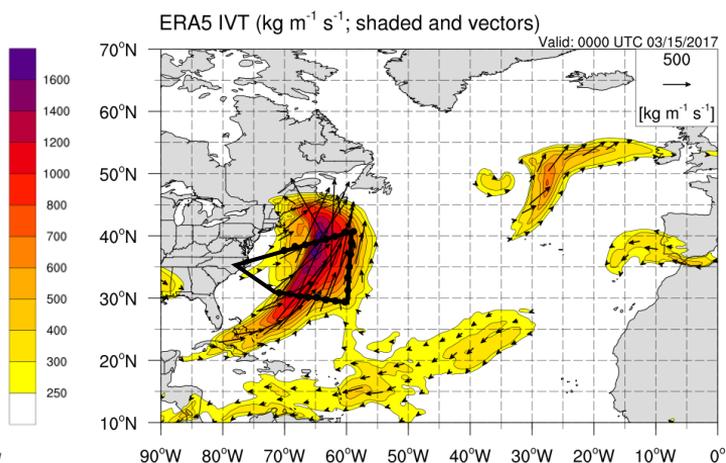
- Initial Demo
- 2-3 weeks during Jan–Feb 2024
- 1-2 AF C-130s

EastPac



- Full Season
- 1 Nov – 31 Mar
- 4 Aircraft (3 AF C-130s and 1 NOAA G-IV)

Atlantic



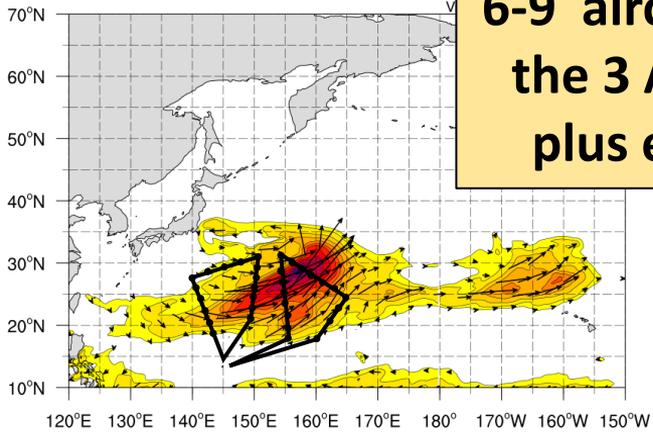
- US Demo*
- 3-4 IOPs (Jan–Feb 2024)
- 1 Aircraft (in addition to 3 in EastPac)

*with one AF C-130 sampling ARs over Gulf of Mexico or off U.S. East Coast for Nor'Easters, **and coordinated radiosonde launches from NWS sites**

Winter 2025/26: “GARRP – Pilot Study”

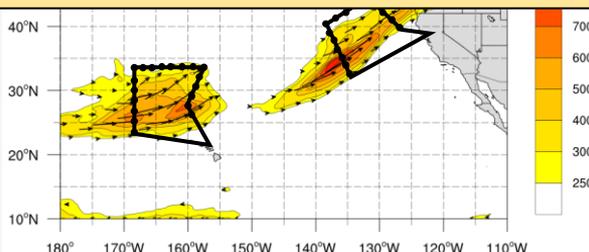
WestPac

ERA5 IVT ($\text{kg m}^{-1} \text{s}^{-1}$; shaded and vectors)



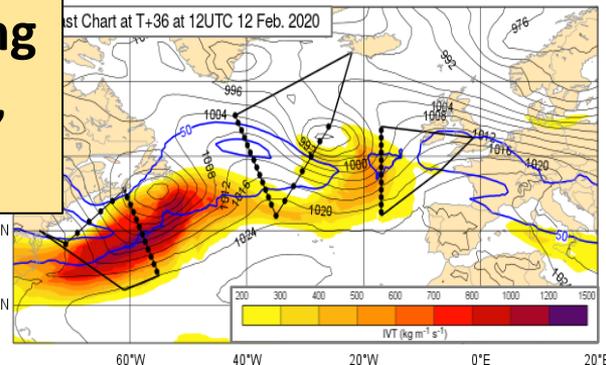
Jan-Feb 2026 GARRP Demo

6-9 aircraft simultaneously sampling the 3 ARs in the two ocean basins, plus extra radiosondes over land



Atlantic

Best Chart at T+36 at 12UTC 12 Feb. 2020



Lavers, D.A., F.M. Ralph, D.S. Richardson and F. Pappenberger (*Communication Earth Environ*, 2020)

- **Full Demo**
- **6 weeks** during Jan–Feb 2026
- 2 AF C-130s, **plus an international partner aircraft (South Korea, Japan...?)**

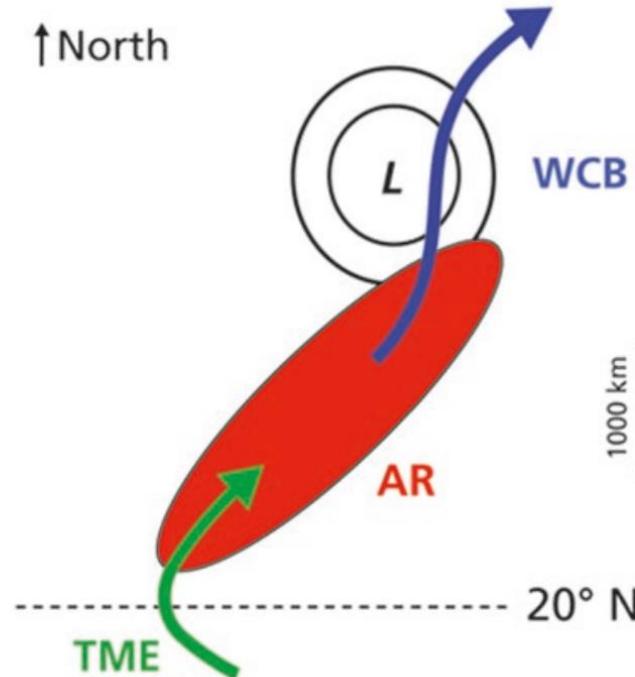
- Full Season
- 1 Nov – 31 Mar
- 4 Aircraft (3 AF C-130s and 1 NOAA G-550)

- **NAWDIC****
- Jan–Feb 2026
- 1 AF C-130, plus **2 European aircraft for 5 IOPs, simultaneous with EastPac and WestPac IOPs**

***with one AF C-130 sampling ARs over Gulf of Mexico or off U.S. East Coast for Nor'Easters, and coordinated radiosonde launches from both NWS and University partners*

Fig. 2.8 Schematic of a TME–AR–WCB configuration related to an extratropical cyclone (label “L”). Parts of the AR overlap with TME trajectories, and others with WCB trajectories. The main ascent phase of the WCB does not overlap with the AR, because of strong condensation and rain-out. Such a configuration is observed (e.g., Fig. 2.12) but should not be regarded as representative of all ARs and/or extratropical cyclones

Water vapor transport phenomena in an extratropical cyclone (L)



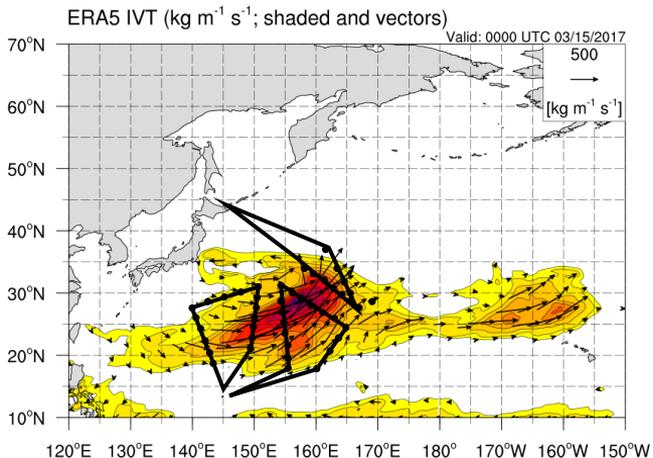
**NAWDIC-AR Recon 2026
Opportunity to Connect
AR+WCB+TME?**

AR Atmospheric River
WCB Warm Conveyor Belt
TME Tropical Moisture Export

Note that these phenomena can occur individually, or two of them together, or—as shown here—all three together

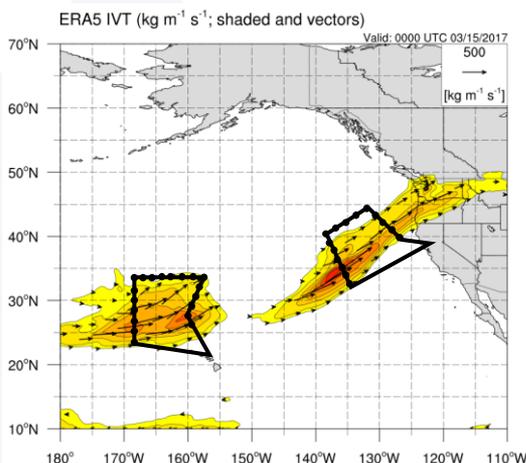
Winter 2027/28: “GARRP – 2028”

WestPac



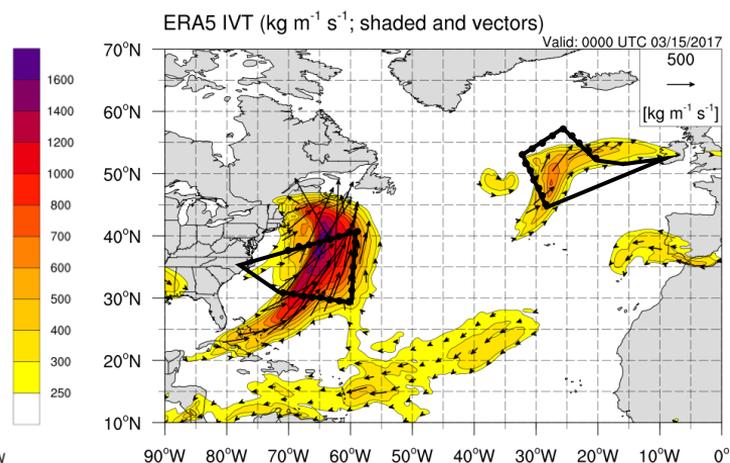
- Full Demo
- Jan–Mar 2028
- 2 AF C-130s, plus an international partner aircraft (South Korea, Japan...?)

EastPac



- Full Season
- 1 Nov – 31 Mar
- 3 Aircraft (2 AF C-130s and 1 NOAA G-IV)

Atlantic



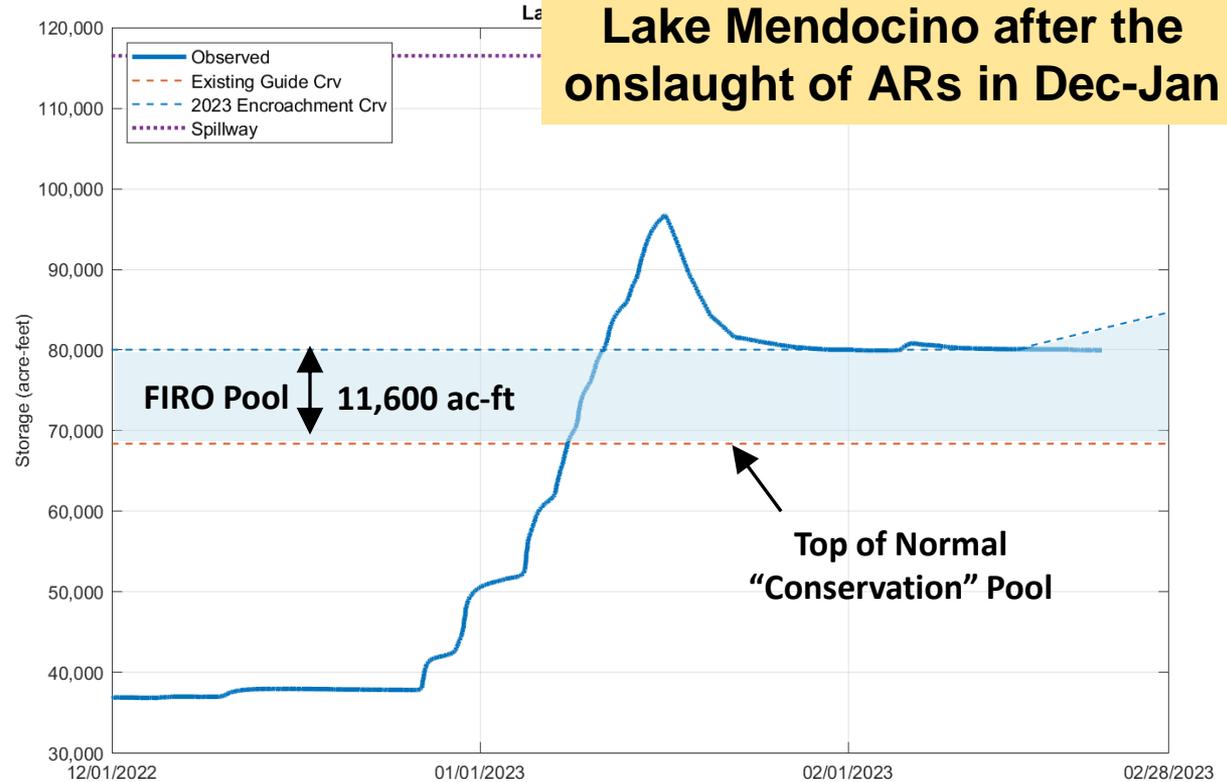
- Full East Coast** Jan–Mar 2028
- 1 AF C-130 (western Atlantic)
- And an international European partner?

**with one AF C-130 sampling ARs over Gulf of Mexico or off U.S. East Coast for Nor'Easters, and coordinated radiosonde launches from both NWS and University partners

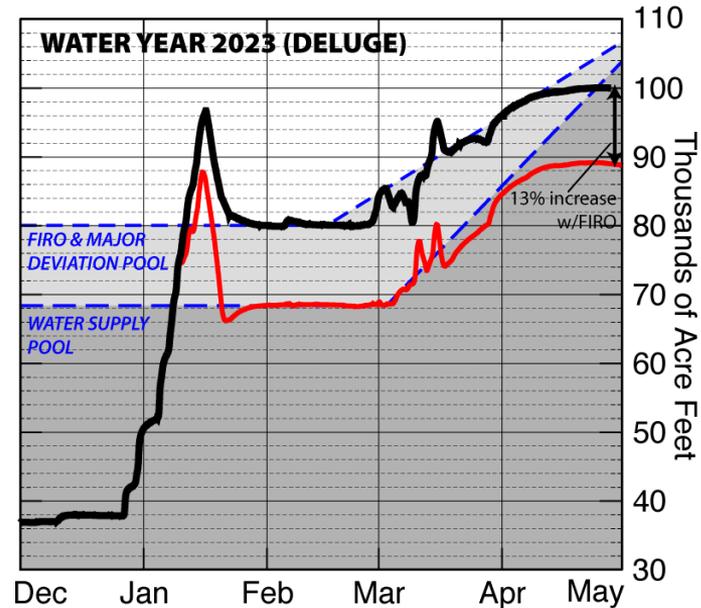
GARRP = Global Atmospheric River Recon Program

Water Year 2023 Lake Mendocino Storage

**Water Year 2023
FIRO allowed retention of an
extra 11,600 acre feet at
Lake Mendocino after the
onslaught of ARs in Dec-Jan**



Actual (with FIRO; thick black line) and modeled (without; red line) storage histories at Lake Mendocino during Water years 2020 and 2023.

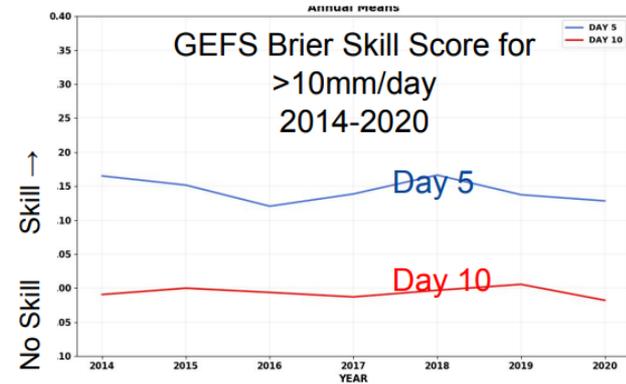
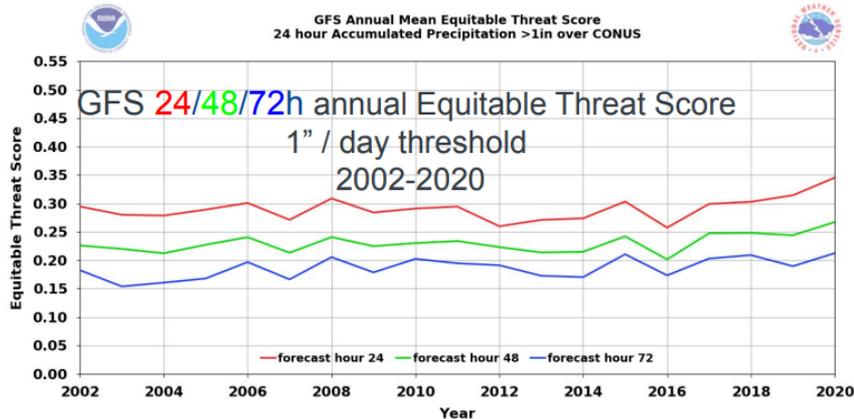


Key FIRO Finding

Better forecasts of extreme precipitation, streamflow and thus the storms that produce them, can enable greater flexibility in operating many reservoirs, creating greater water supply reliability and reducing flood risk

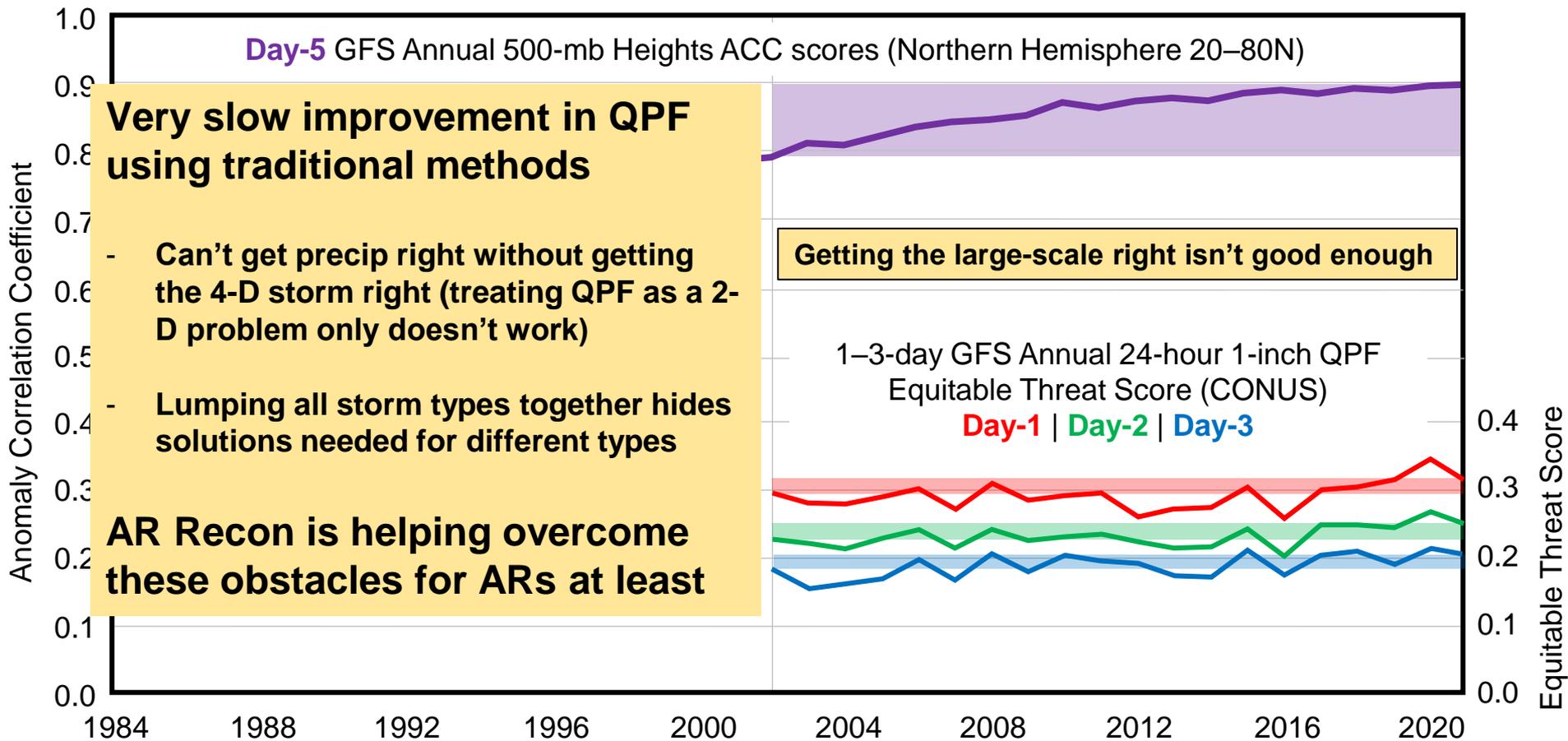
Imperative to Improve Precipitation Forecasts

Painfully slow improvement over past 20 years





Moving the needle on headline skill scores



Predictability of horizontal water vapor transport relative to precipitation: Enhancing situational awareness for forecasting western U.S. extreme precipitation and flooding

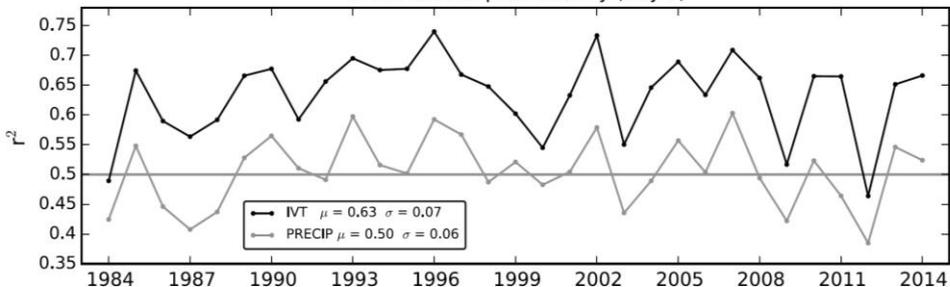
David A. Lavers, Duane E. Waliser, F. Martin Ralph, Michael D. Dettinger, *Geophys. Res. Lett.* 2016

Purpose: Determine if IVT (represents a proxy for atmospheric rivers) has greater predictability than precipitation

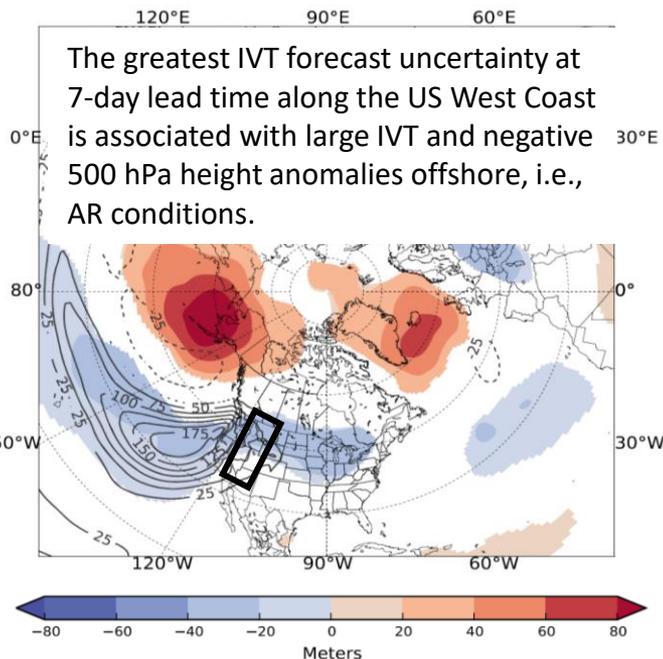
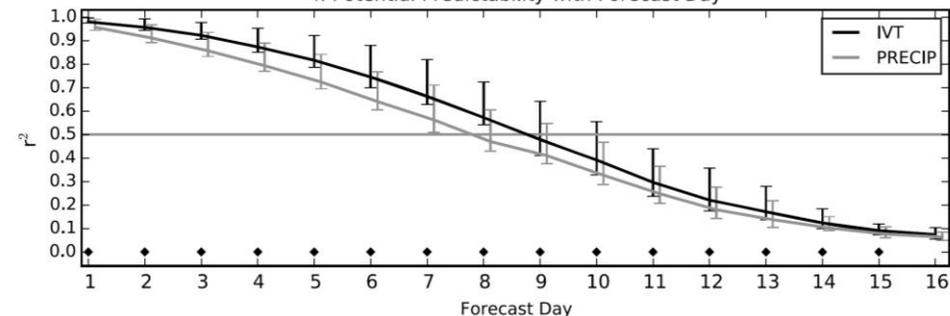
Method: Apply the potential predictability concept to NCEP global ensemble reforecasts over 31 winters

Result: IVT is more predictable than precipitation in the region 30-50°N, 120-125°W.

e. Interannual predictability (Day 7)

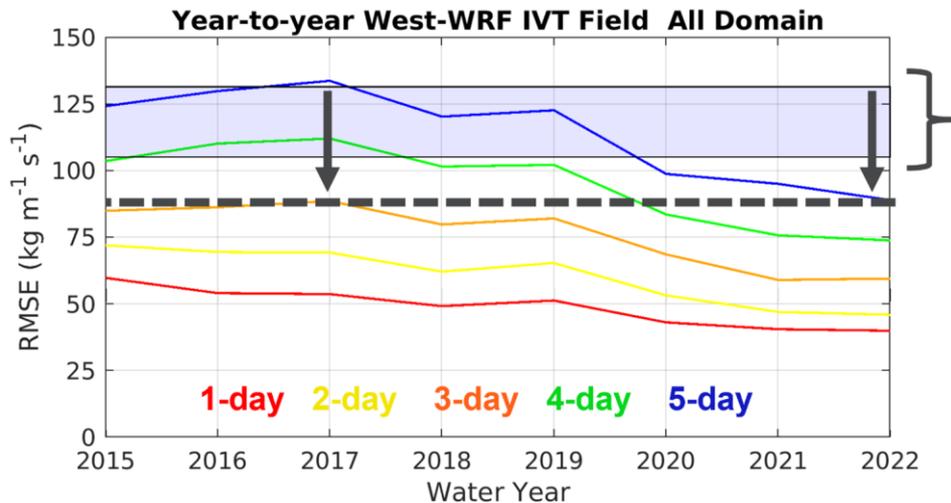


f. Potential Predictability with Forecast Day



Composite mean of the 500 hPa geopotential height anomalies at the analysis time (shading, in meters) and of the ensemble mean IVT forecast anomalies (contours, dashed where less than climatology) during the 140 largest ensemble spreads on forecast day 7. Colored and contoured regions indicate areas where the composite mean is different from zero at the 90% significance level.

How can we improve how far in advance we can predict ARs? – West WRF



Shaded area represents min/max RMSE from 30-year West-WRF 5-day reforecst

Research is improving the skill of predicting ARs

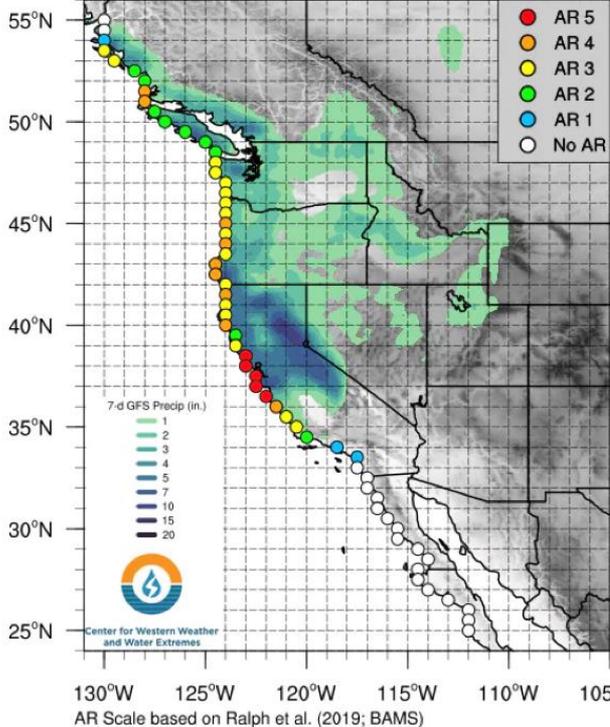
- WY2022 RMSE is lower than the minimum value found in the 30-year West-WRF Reforecast
- 5-day forecast errors are as good as 3-day forecasts were pre-WY2018 (35% reduction)
- 10–25% less error than GFS in predicting AR intensity at 1–7 days lead time



Maximum Forecast AR Scale

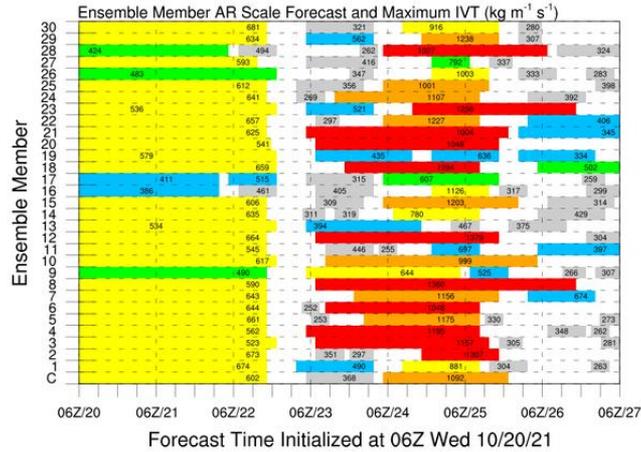
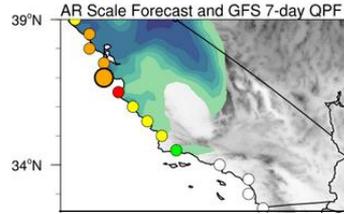
Forecast valid 7-day Period: 12Z 10/19/21 - 12Z 10/26/2021

GEFS Control

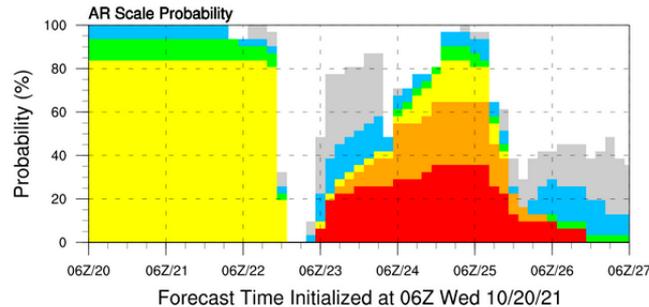


AR Scale based on Ralph et al. (2019; BAMS)

Forecast for the maximum atmospheric river (AR) intensity over the next week. (Center for



Forecast Time Initialized at 06Z Wed 10/20/21



GEFS + EPS = 80 members

AR5: 30%

AR4: 35%

AR3: 30%

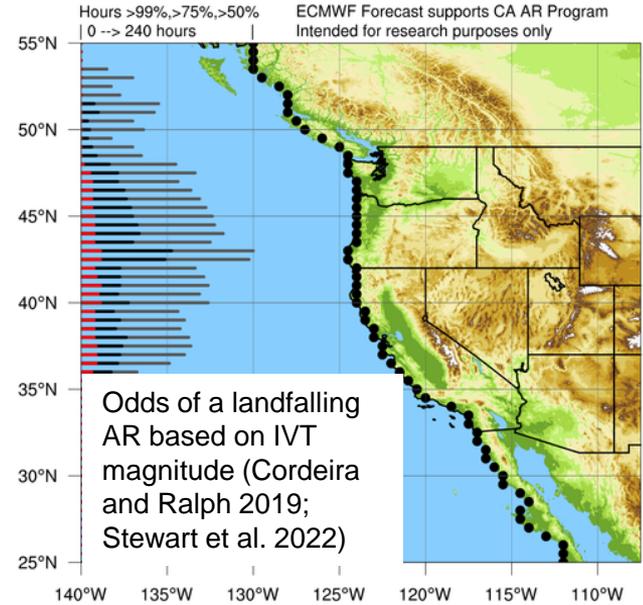
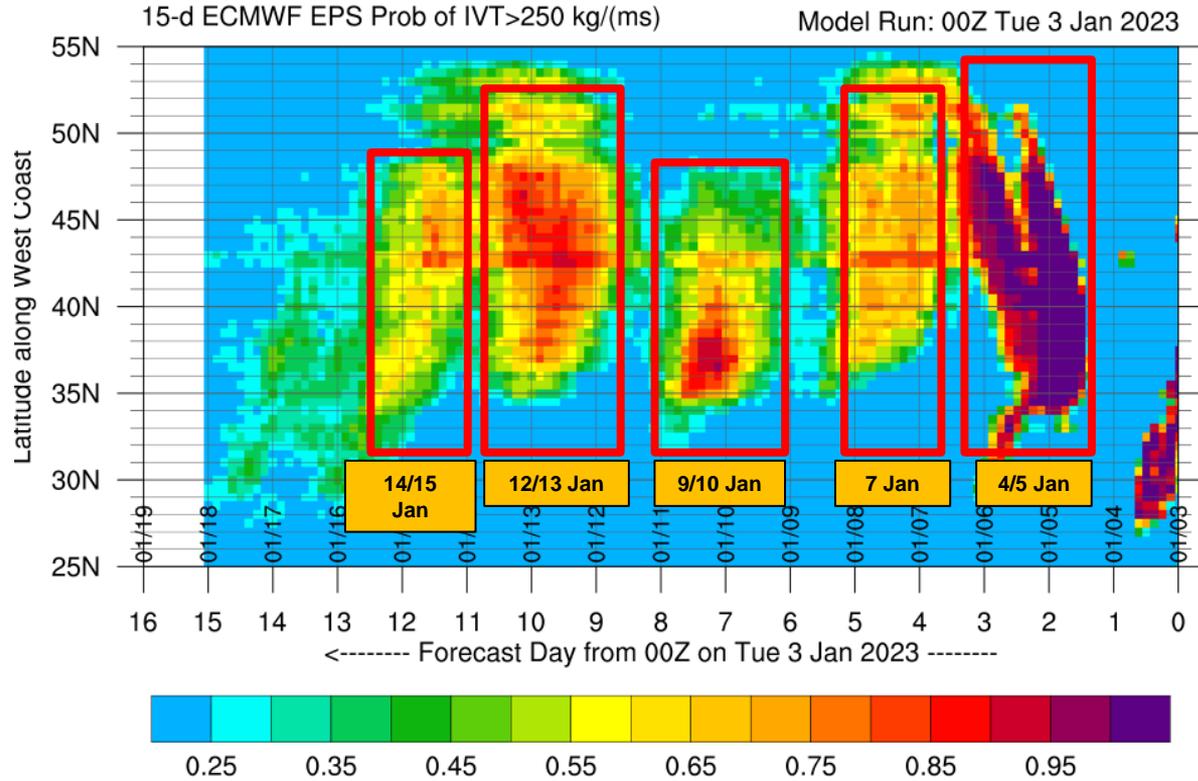
AR4 or AR5: 65%

AR3, 4 or 5: 95%

Atmospheric River Struck as an "AR5" on CW3E's AR Scale

Record daily rainfall at key locations, and record of 13% of annual rain for N. Sierra - in 1 day

How far in advance can we predict landfalling ARs?



How far in advance can we predict landfalling ARs?

Lead Time Prediction of Landfalling ARs 27 Dec 22 - 17 Jan 23

[GEFS AR Landfall Tool Probability of IVT mag. ≥ 250 kg/ms increasing above 75%]

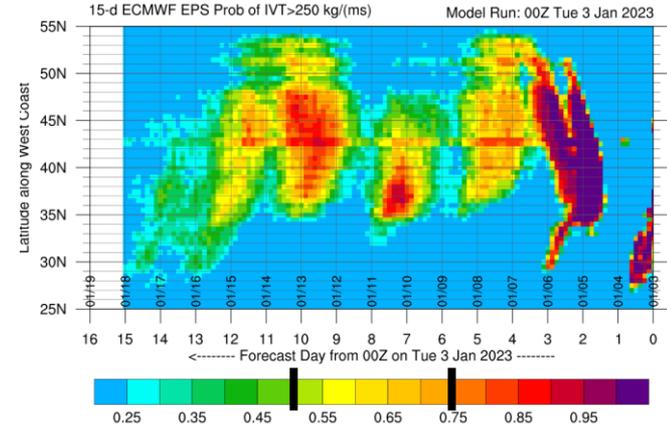
14

Lead time is defined as probability increasing above 75% and staying above 50%



12

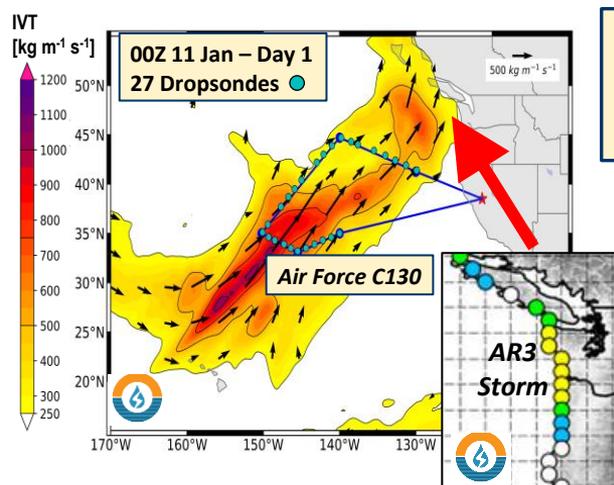
- Average for AR Duration
- At Time of Maximum IVT



During the impactful AR Family Dec 2022– Jan 2023 showed as much as a 9-day lead time with most ARs near 6 days lead time.

FIRO-required minimum lead time for forecasts of a possible AR landfall for Lake Mendocino

J. Cordeira, CWSE



Atmospheric River Reconnaissance 2022

Preliminary Assessment of Impact on Heavy Precipitation Forecast in GFS During the Sequence of 3 days of AR Recon flights from 11-13 Jan 2022

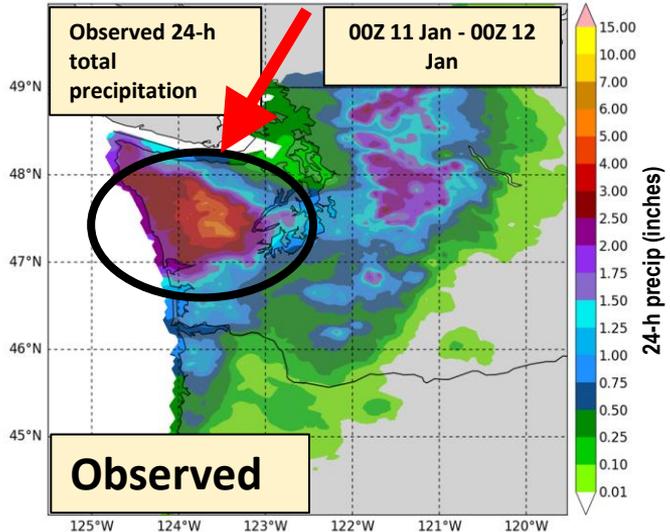
AR Recon flight substantially reduced errors in the 1-2-day lead-time forecast of heavy precipitation from an AR3 storm

The region had been experiencing flooding already this winter, and WA had requested a Presidential Disaster Declaration for earlier AR storms that had hit in Nov-Dec 2021, before AR Recon season began on 11 Jan 2022.



Research And Operations Partnership
 F. Martin Ralph (UCSD/SIO/CW3E) - PI
 Vijay Tallapragada (NWS/NCEP) - Co-PI

Max > 6 inches in 1 day





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Why SHOULD AR Recon Improve Forecasts?





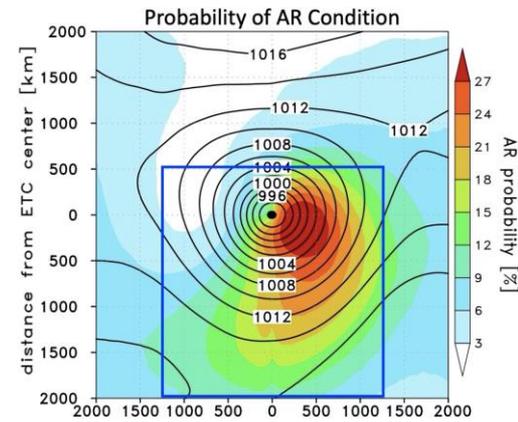
The Influence of Antecedent Atmospheric River Conditions on Extratropical Cyclogenesis

Zhenhai Zhang and F. Martin Ralph

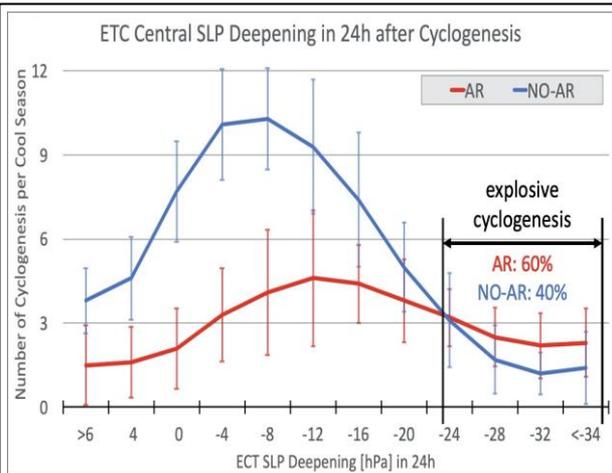
(Monthly Weather Review, 2021)

Purpose: The impacts of extratropical cyclones (ETCs) on atmospheric rivers (ARs) are widely recognized. However, does a pre-existing (antecedent) AR nearby have any influence on ETC genesis?

Methods: ETCs and ARs are detected objectively and independently over the North Pacific during the 1979-2009 cool seasons (November-March) with reanalysis, including 3137 ETC genesis cases.



Composite AR probability and SLP. AR ETC-genesis: an AR exists in the blue box at or before ETC genesis.



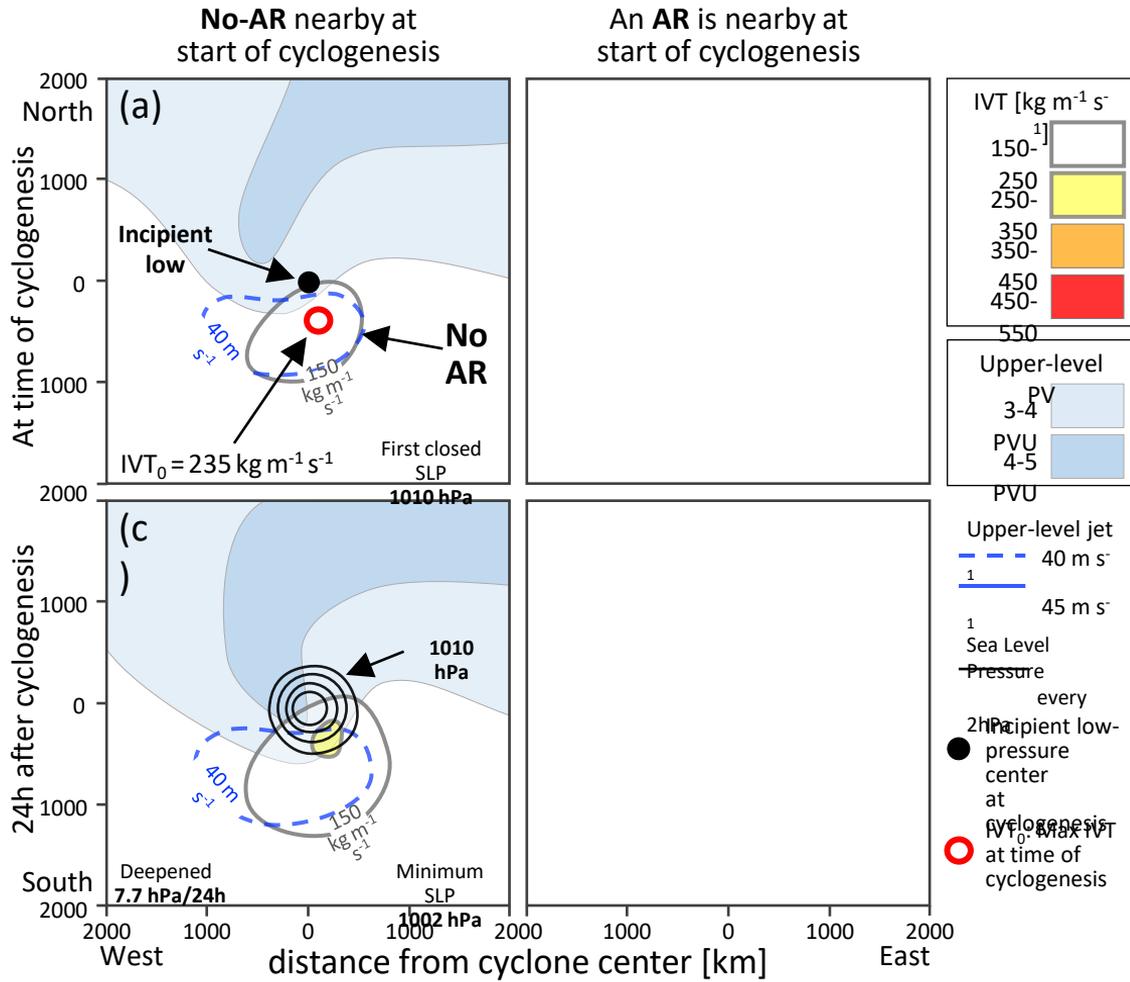
ETC SLP deepening in 24h after genesis

35% of ETC genesis are associated with an antecedent AR

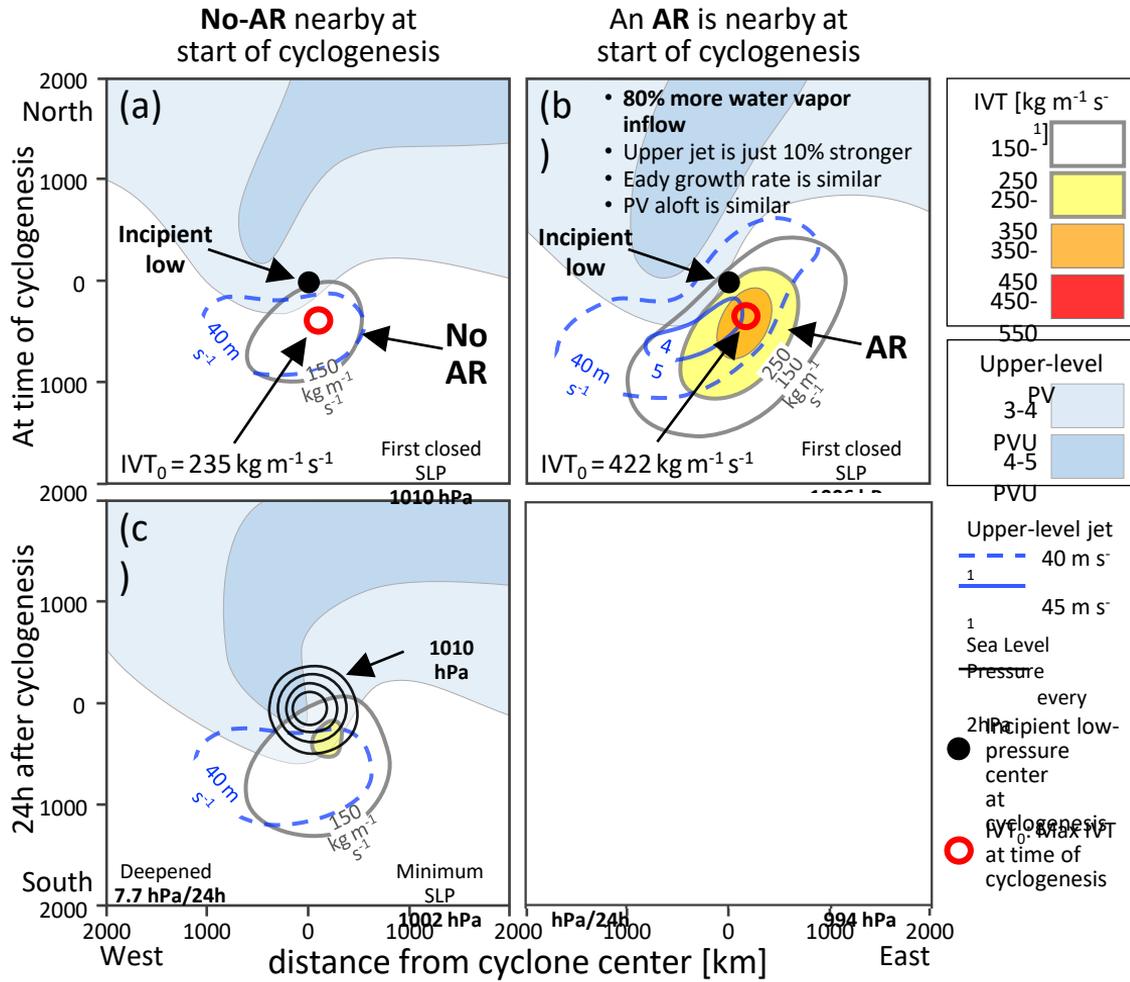
60% of explosive ETC genesis are associated with an AR

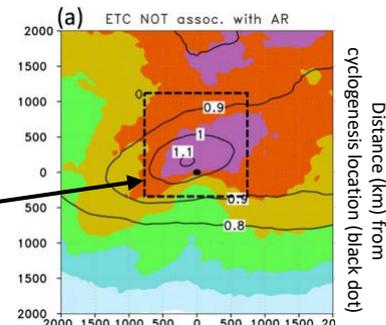
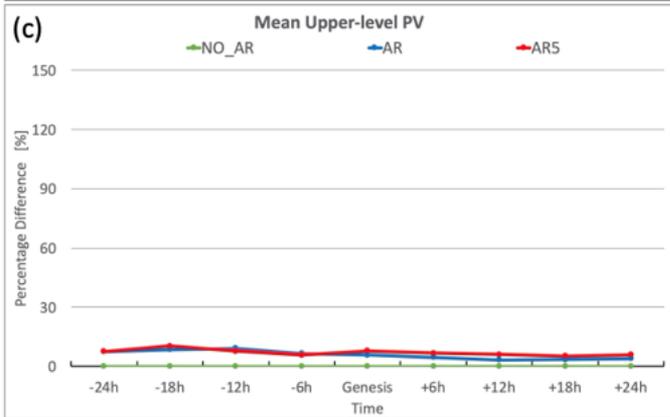
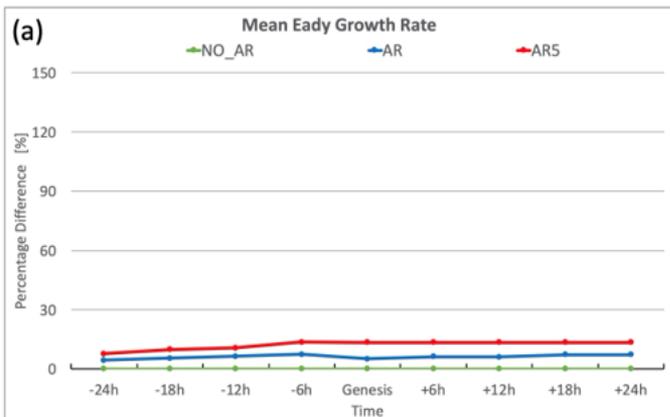
Cyclogenesis with an Antecedent AR is associated with stronger cyclone deepening rates

Composites derived from
3137 extratropical
cyclogenesis events in the
North Pacific
**35% include an antecedent
AR**
65% have no antecedent AR



Composites derived from 3137 extratropical cyclogenesis events in the North Pacific
35% include an antecedent AR
65% have no antecedent AR





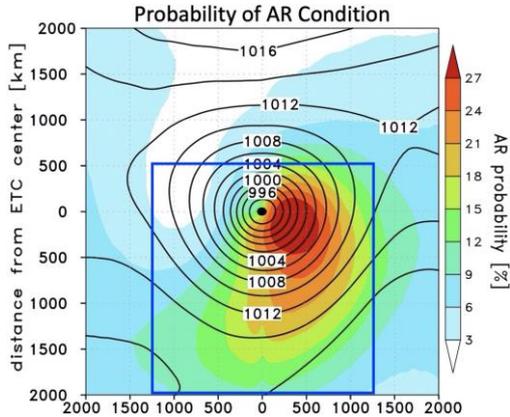
Temperature gradient [colors; $K (1000 \text{ km})^{-1}$] at 850 hPa and Eady growth rate (thin black contours) at 850–500 hPa

Figure 14. (a) Normalized difference (% , with respect to the value of cyclogenesis not associated with an antecedent AR) of mean Eady growth rate within the dashed black box in Figure 11 for cyclogenesis associated with an antecedent AR (blue) and an antecedent exceptional AR (red) from 24h before (-24h) to 24h after (+24h) cyclogenesis. (b), (c), and (d) are the same as (a), but for the normalized difference of mean IVT, upper-level PV, and latent heating rate respectively.

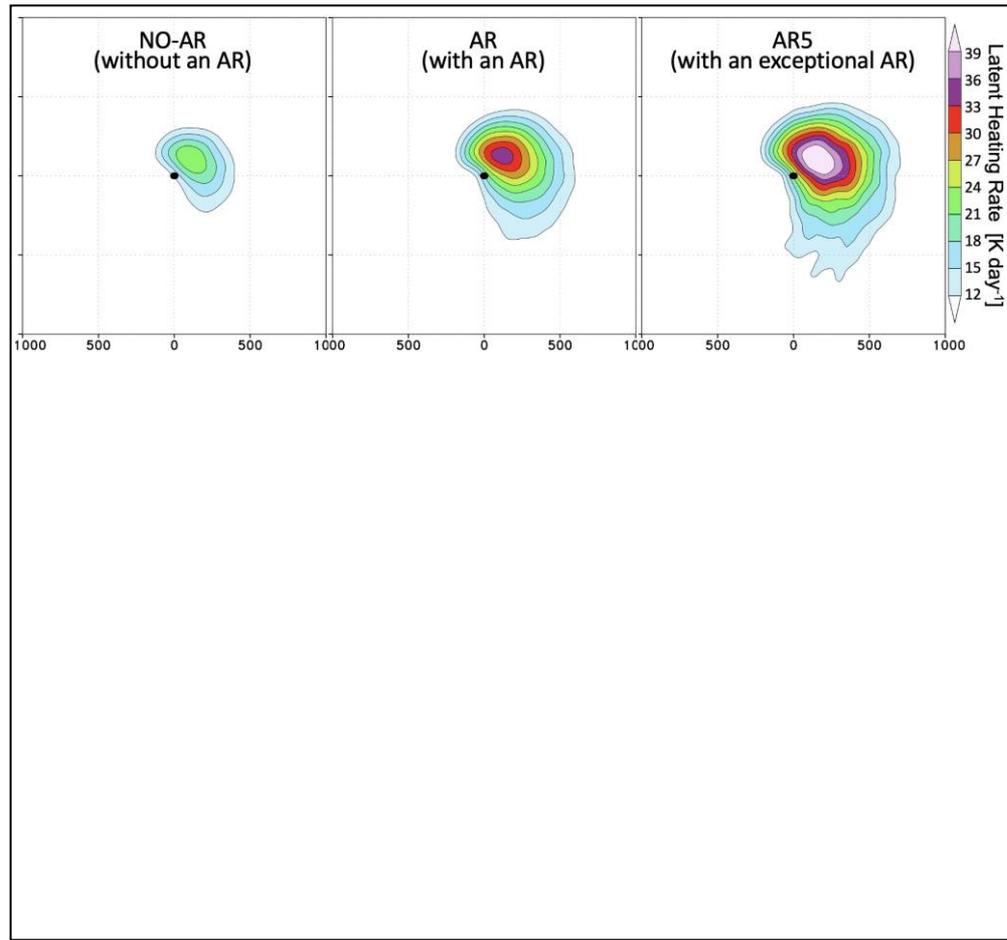
Composites derived from
3137 extratropical
cyclogenesis events in the
North Pacific

**35% include an antecedent
AR**

65% have no antecedent AR



Composite AR probability and SLP. AR ETC-genesis:
an AR exists in the blue box at or before ETC
genesis.



CW3E

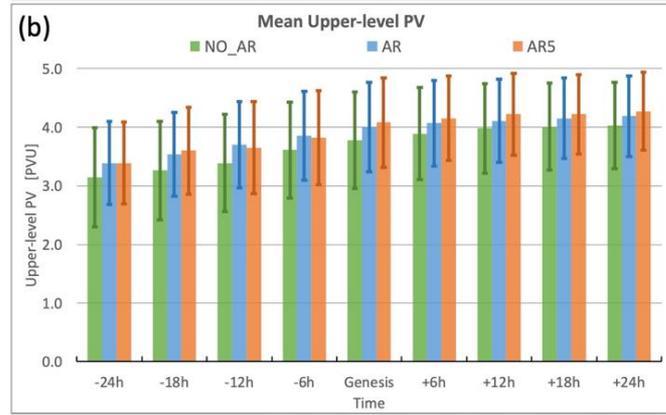
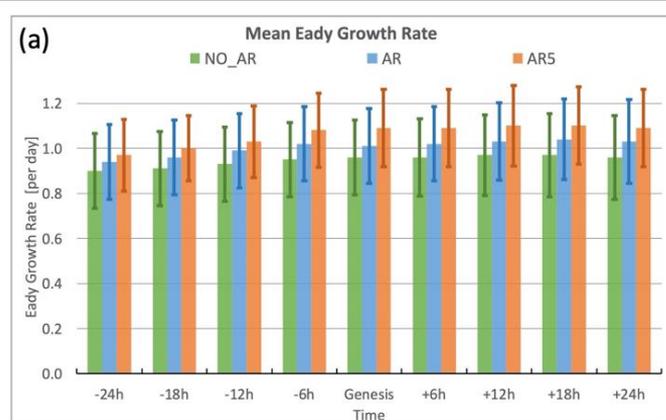
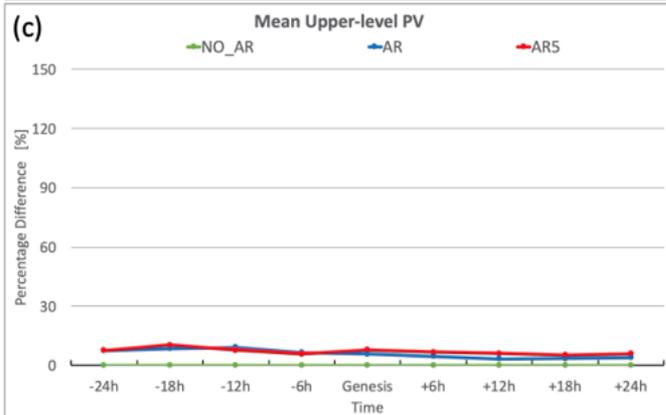
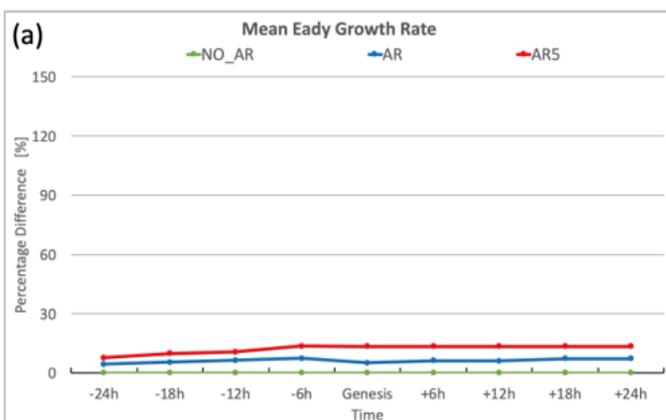


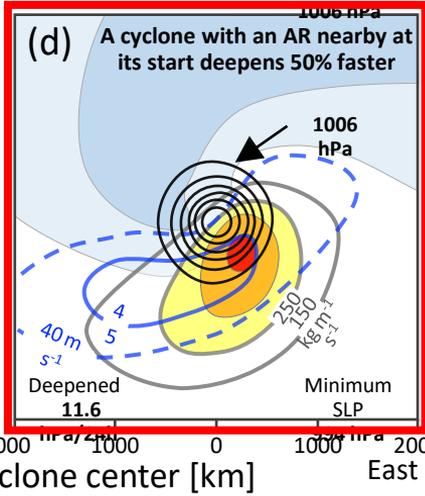
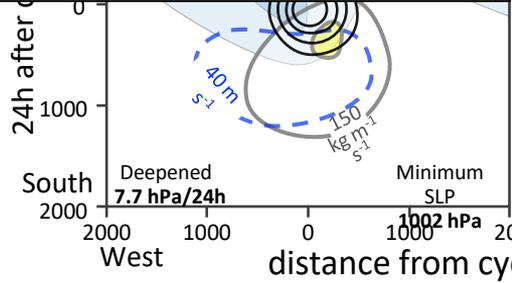
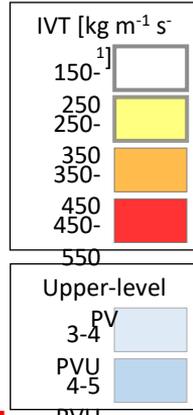
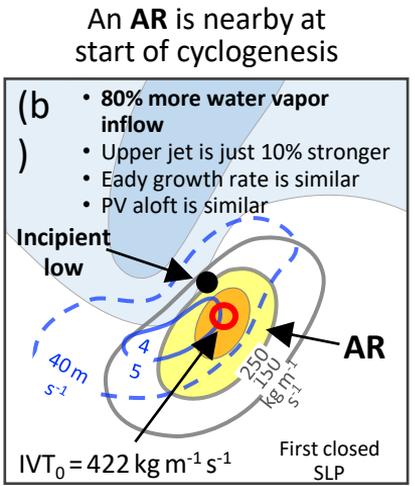
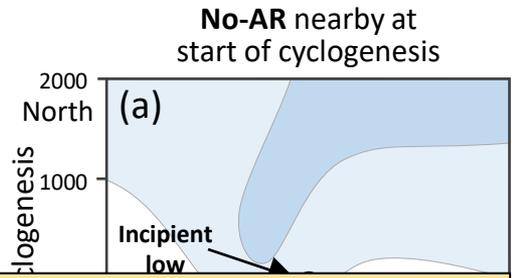
Figure 13. Same as Figure 10, but for (a) mean Eady growth rate (day^{-1}) at 850-500 hPa within the dashed black box in Figure 11; (b) mean upper-level (300-200 hPa) PV (PVU) within the dashed black box in Figure 12.

Figure 14. (a) Normalized difference (% with respect to an antecedent AR) of mean Eady growth rate of cyclogenesis associated with an antecedent AR (blue) and an antecedent exceptional AR (red) from 24h before (-24h) to 24h after (+24h) cyclogenesis. (b), (c), and (d) are the same as (a), but for the normalized difference of mean IVT, upper-level PV, and latent heating rate respectively.

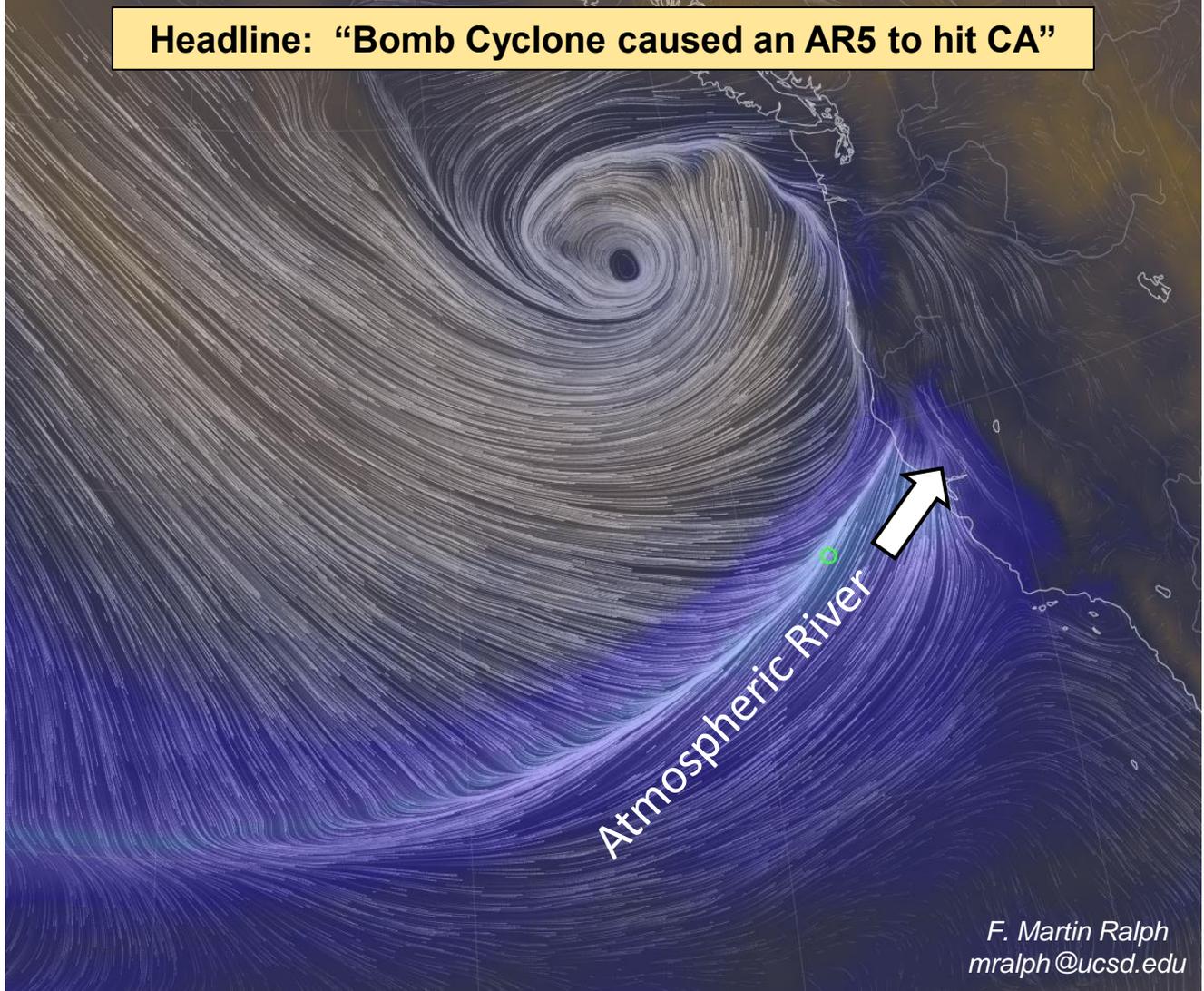
Composites derived from 3137 extratropical cyclogenesis events in the North Pacific
35% include an antecedent AR
65% have no antecedent AR

Results:

- ETCs that develop associated with an antecedent AR receive nearly 80% more water vapor inflow
- Latent heat release is significantly enhanced (>60%)
- Accelerates ETC deepening over the 24 h after initial cyclogenesis is detected (>50%)
- In contrast, neither low-level baroclinicity nor upper-level potential vorticity exhibit statistically significant differences between ETC genesis events with and without an antecedent AR.



Headline: "Bomb Cyclone caused an AR5 to hit CA"



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Extratropical Cyclogenesis with an Antecedent Atmospheric River

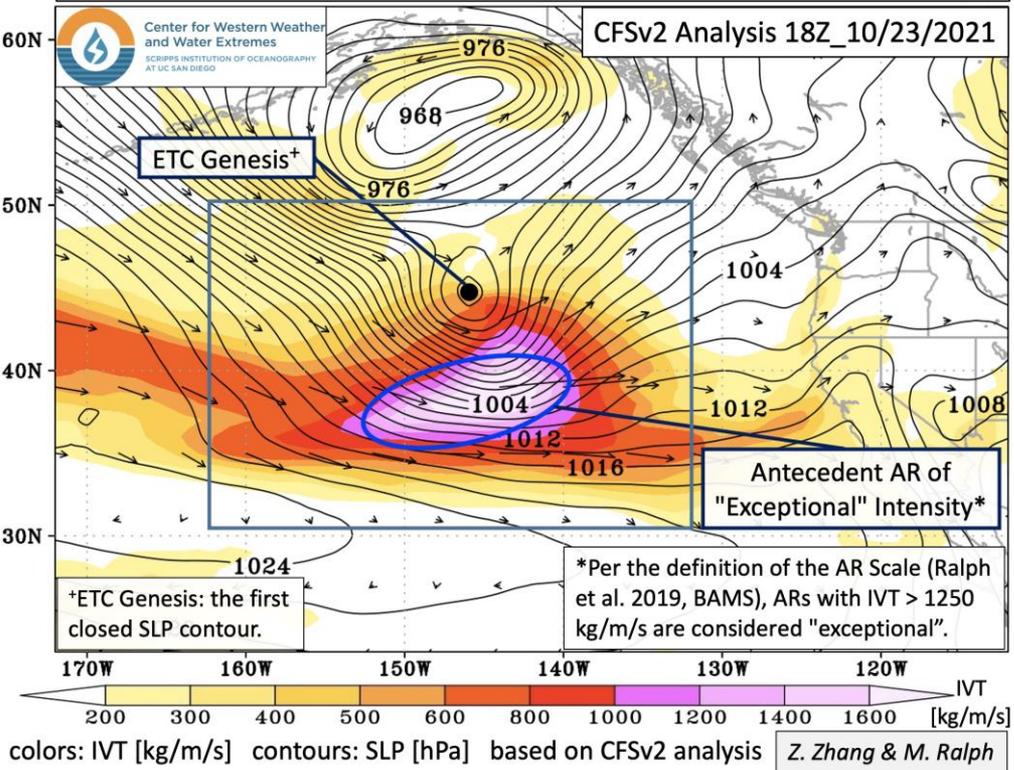
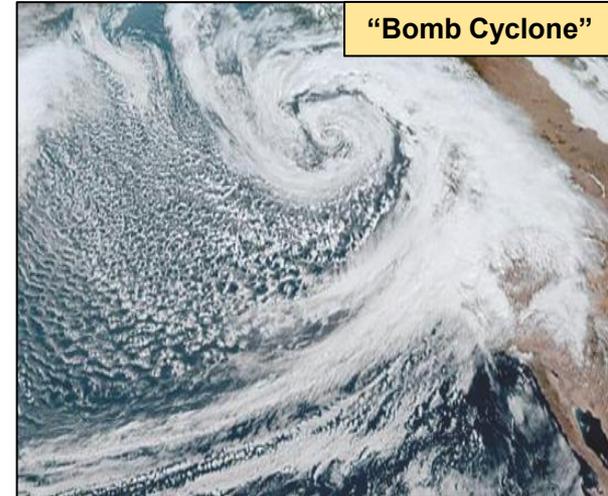
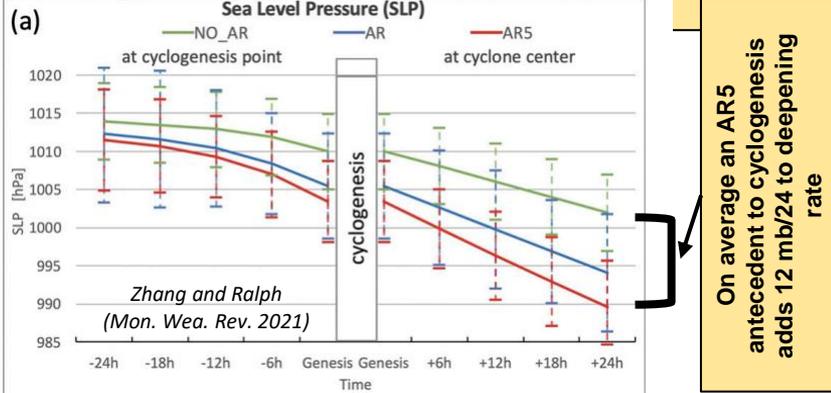


Fig. 1: Extratropical cyclogenesis with an exceptionally strong antecedent AR over the North Pacific at 18Z 10/23/2021 based on the CFSv2 analysis. The colors and vectors are IVT (kg/m/s), and the contours are sea level pressure (hPa, every 2 hPa).



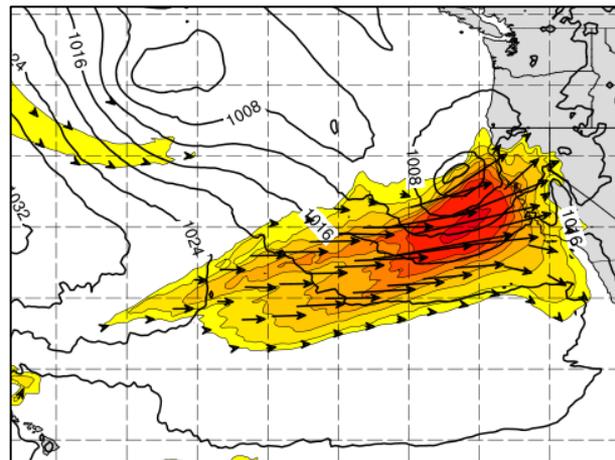
Did the Bomb Cyclone cause the AR5 to hit CA?

OR... Did the antecedent AR amplify (or even cause*) the cyclogenesis to reach "Bomb"



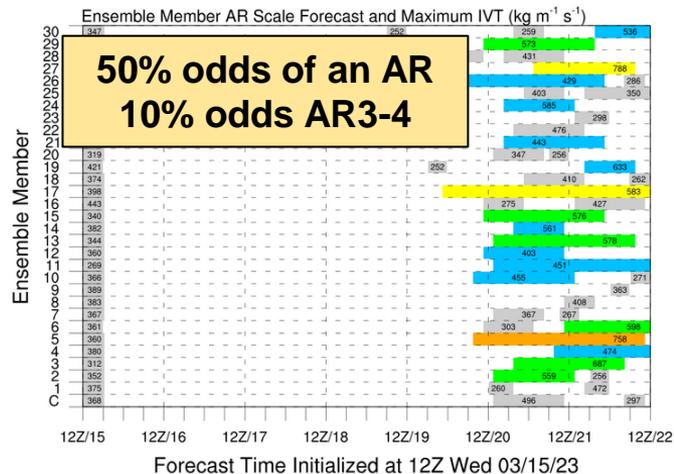
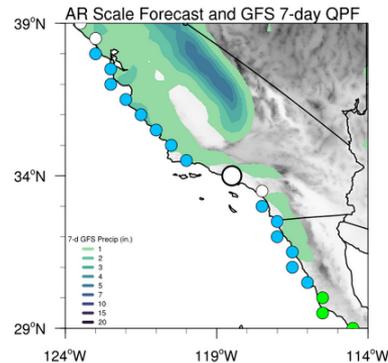
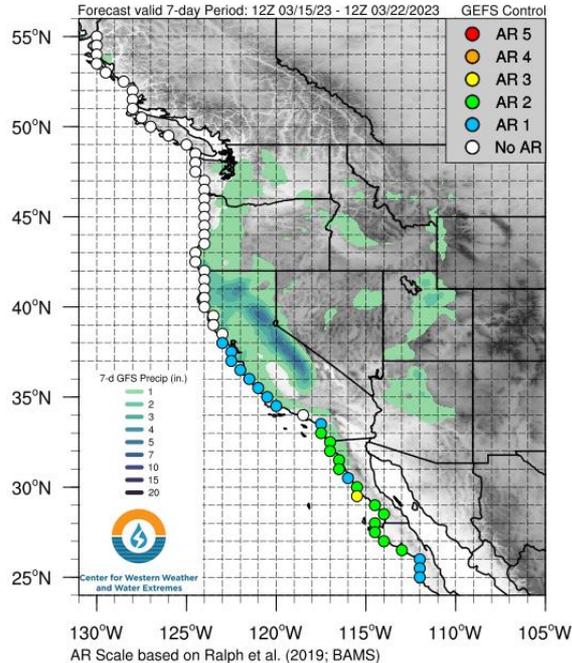
Incoming Atmospheric River California 20-21 March 2023

NCEP GFS IVT ($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vector, and SLP (hPa; contours)
 Initialized: 1200 UTC 03/15/2023 F-123: Valid: 1500 UTC 03/20/2023



Maximum Forecast AR Scale

Forecast valid 7-day Period: 12Z 03/15/23 - 12Z 03/22/2023





Center for Western Weather
and Water Extremes

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AT UC SAN DIEGO

THANK YOU

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27 June 2023
ECMWF, Reading UK