

F: 9JIGF<MK<M
B09K<MK<M

Sampling Synoptic Scale Patterns in the Western Hemisphere with Airborne Radio Occultation Observations during GARRP 2026

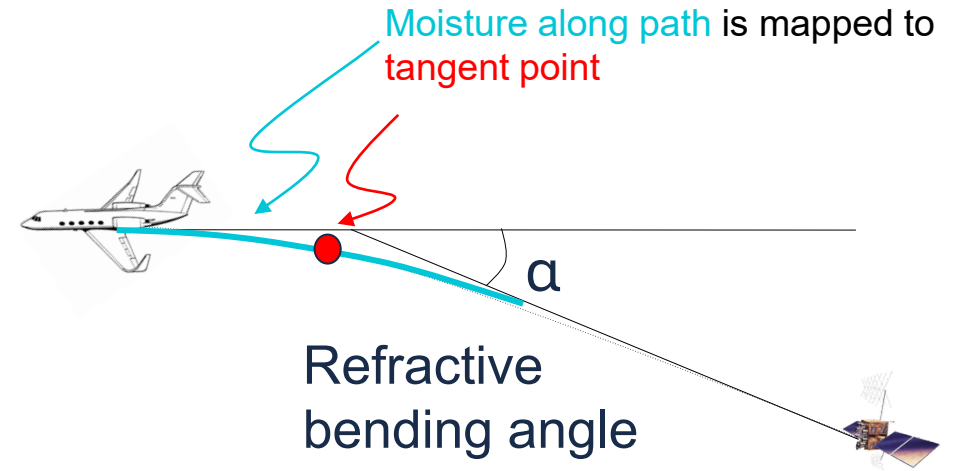
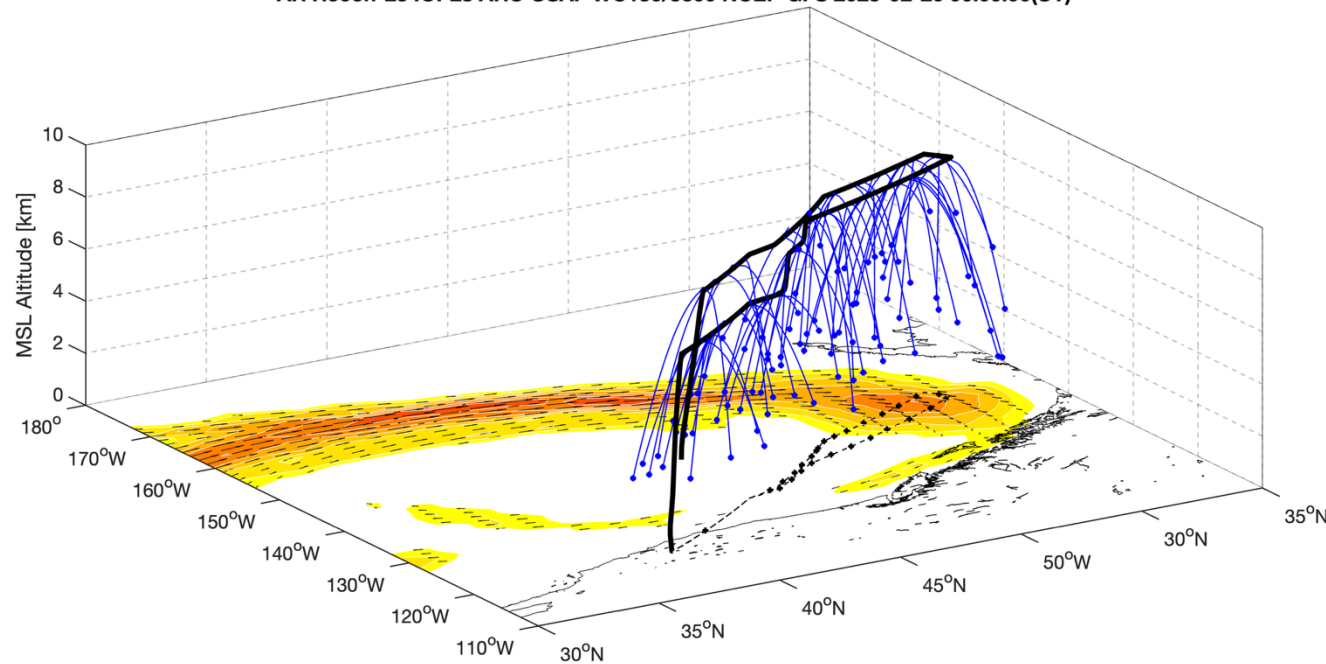
, G9@ 9JIGF< (=FFA=J1<&99K< A? ! 9G<(9Q! GJ<=A9< =FB E A + GGJ=< =F " 9NA<, ?@A" G<) =DD*GG

Talk Summary

- Overview of 2026 ARO efforts in all GARRP campaigns
- Discussion of interesting sequence of events with potential connections across the GARRP domain
- Future efforts

Airborne GNSS Radio Occultation Geometry

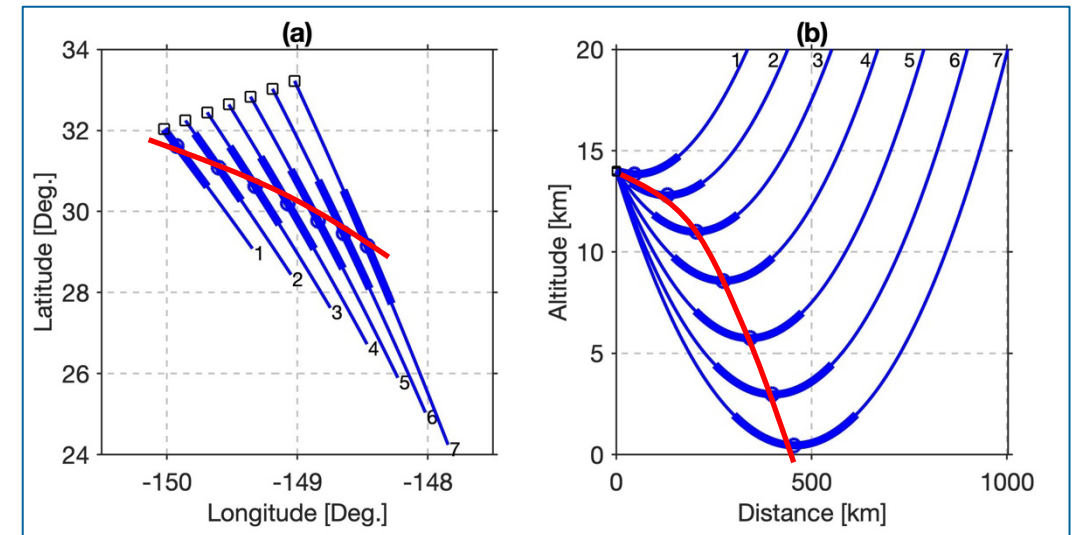
AR Recon-23 IOP28 ARO USAF WC130/5300 NCEP GFS 2023-02-26 00:00:00(UT)



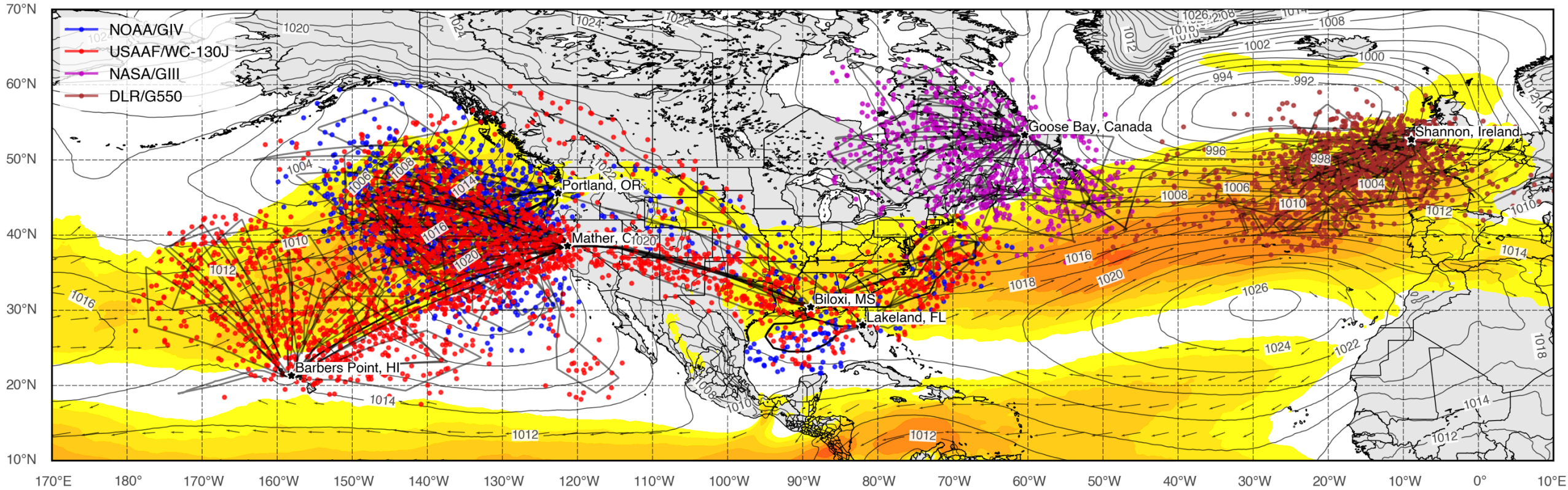
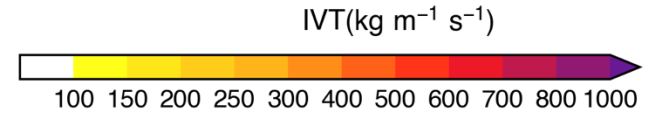
- Atmospheric refractivity is a function of pressure, temperature, water vapor pressure

$$N = (n - 1) \cdot 10^6 = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2}$$

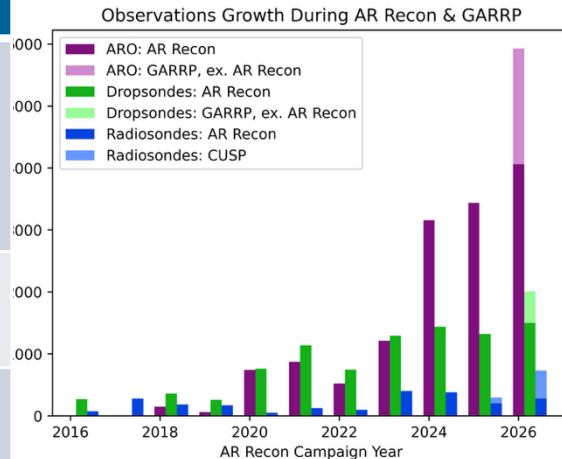
Haase et al., 2014, GRL.



GNSS ARO (final, colored dots), mean GFS IVT($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vectors, and mean SLP(hPa; contours)
 Flights were executed by NOAA/USAF/NASA/DLR aircraft in AR Recon 2026 (incl. NURTURE/NAWDIC) field campaign



AR Recon 2026	
Aircraft w/ ARO	NOAA G-IV 10 USAF WC-130s 1 NASA G-III 1 DLR G-550
Total flights	23 G-IV + 57 C-130 + 19 G-III + 18 G-550 = 117
Total profiles	5882



Airborne Radio Occultation Highlights in AR Recon 2026

J. Haase, B. Cao, N. Barton, K. Loo, the ARO team at IGPP/SIO

- ARO was deployed on NURTURE and NAWDIC aircraft for participation in GARRP.
- First profiles in high-latitude N Atlantic.
- NRT data from AR Recon G-IV, NURTURE G-III awaiting operational DA tests
- GARRP presents novel multi-basin sampling of AR pathways and hemispheric flow.

Airborne RO Payload Deployment Summary

- **AR RECON**

- Central Pacific (C-130) – Barbers Point, HI
- E Pacific (C-130) – Mather, CA
- NE Pacific (G-IV) – Portland, OR
- W Atlantic/GoM (C-130) – Biloxi, MS
- W Atlantic/GoM (G-IV) – Lakeland, FL

- **NURTURE**

- NW Atlantic (G-III) – Goose Bay, Canada

- **NAWDIC**

- NE Atlantic (HALO) – Shannon, Ireland

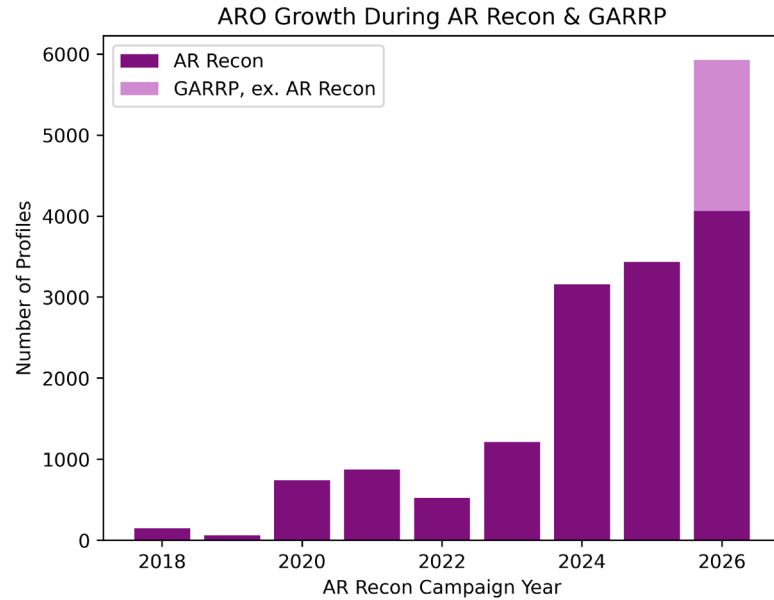
- ARO deployment expansion:

- NASA G-III (new platform)
- DLR G-550 (new partner/platform)

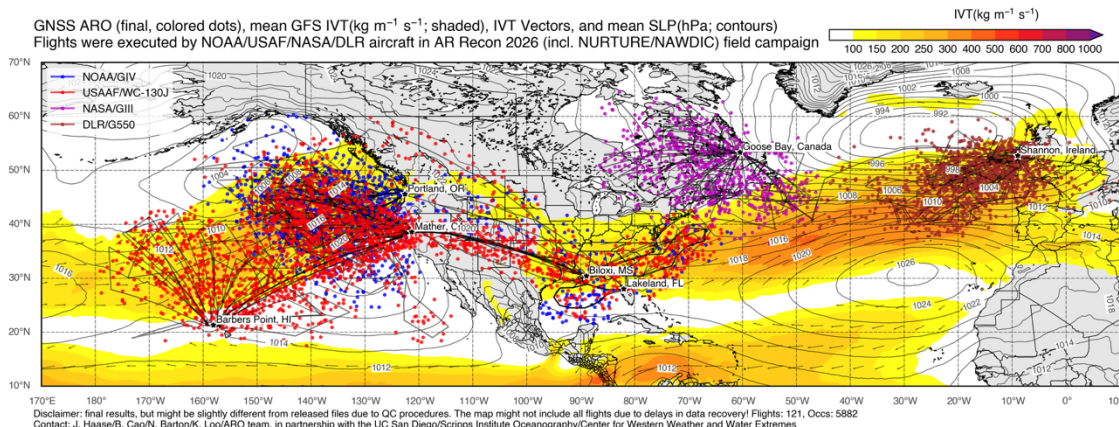
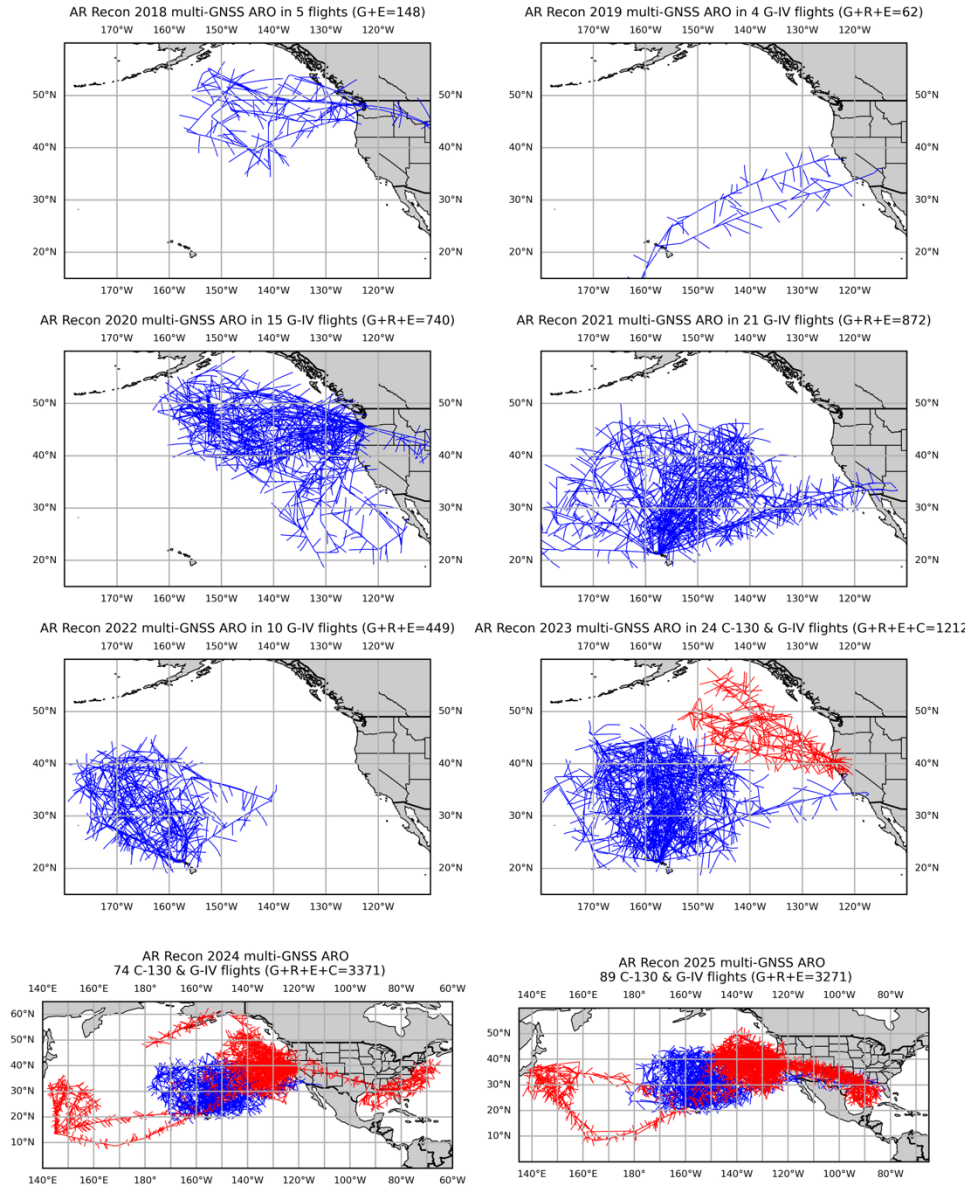
- Lower-troposphere OL tracking data available from G-IV and G-III

- Data retrieved and processed in near-real time from G-IV and G-III

Growth in ARO aircraft, flights, and observations



Growth in AR Recon multi-GNSS ARO profiles over time

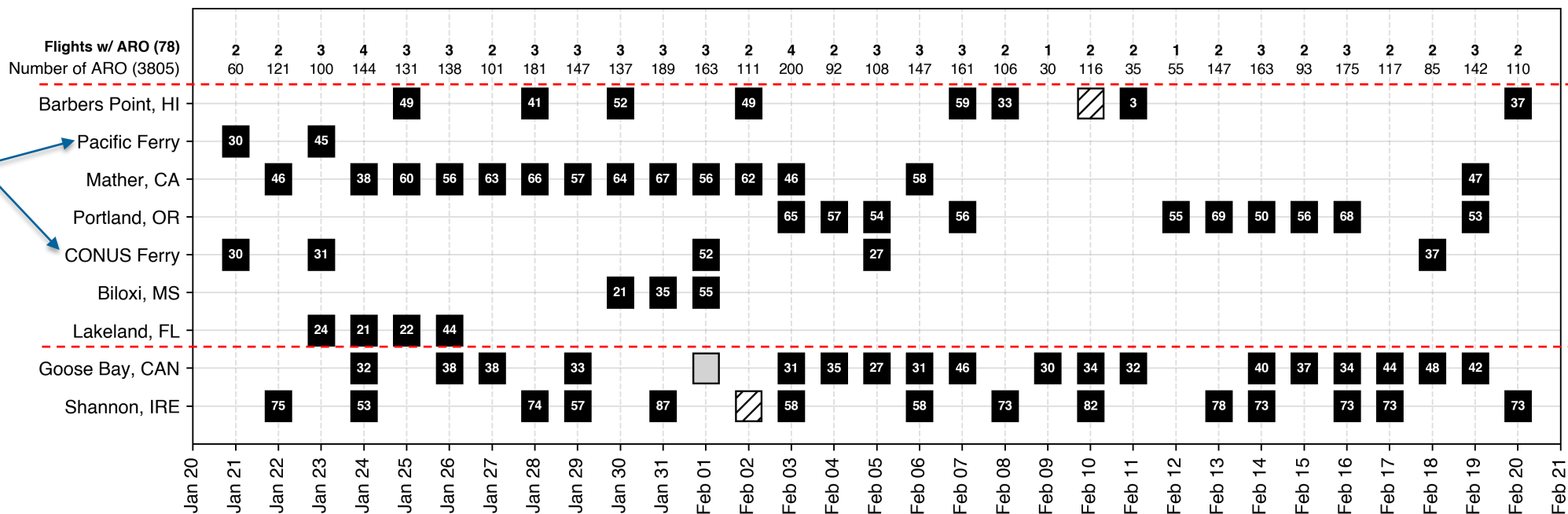


Northern Hemispheric GARRP Demo (22 Jan-20 Feb 2026, 30 days)

F. M. Ralph, AR Recon PI, Vijay Tallapragada Co-PI



3800 ARO profiles (v1)



AR RECON

NURTURE NAWDIC

AR-Recon

W ATL (C-130)
1 Nov – 31 Mar
Biloxi, MS

W ATL (G-IV)
6 Jan – 29 Jan
Lakeland, FL

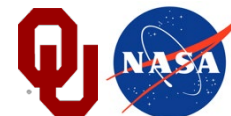
C PAC (C-130)
6 Jan – 5 Mar
Barbers Point, HI

NE PAC (G-IV)
2 Feb – 24 Mar
Portland, OR

E PAC (C-130)
6 Jan – Feb
Mather, CA



NURTURE



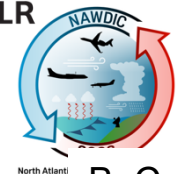
NW Atlantic (G-III)
26 Jan – 20 Feb
Goose Bay, Canada



NAWDIC

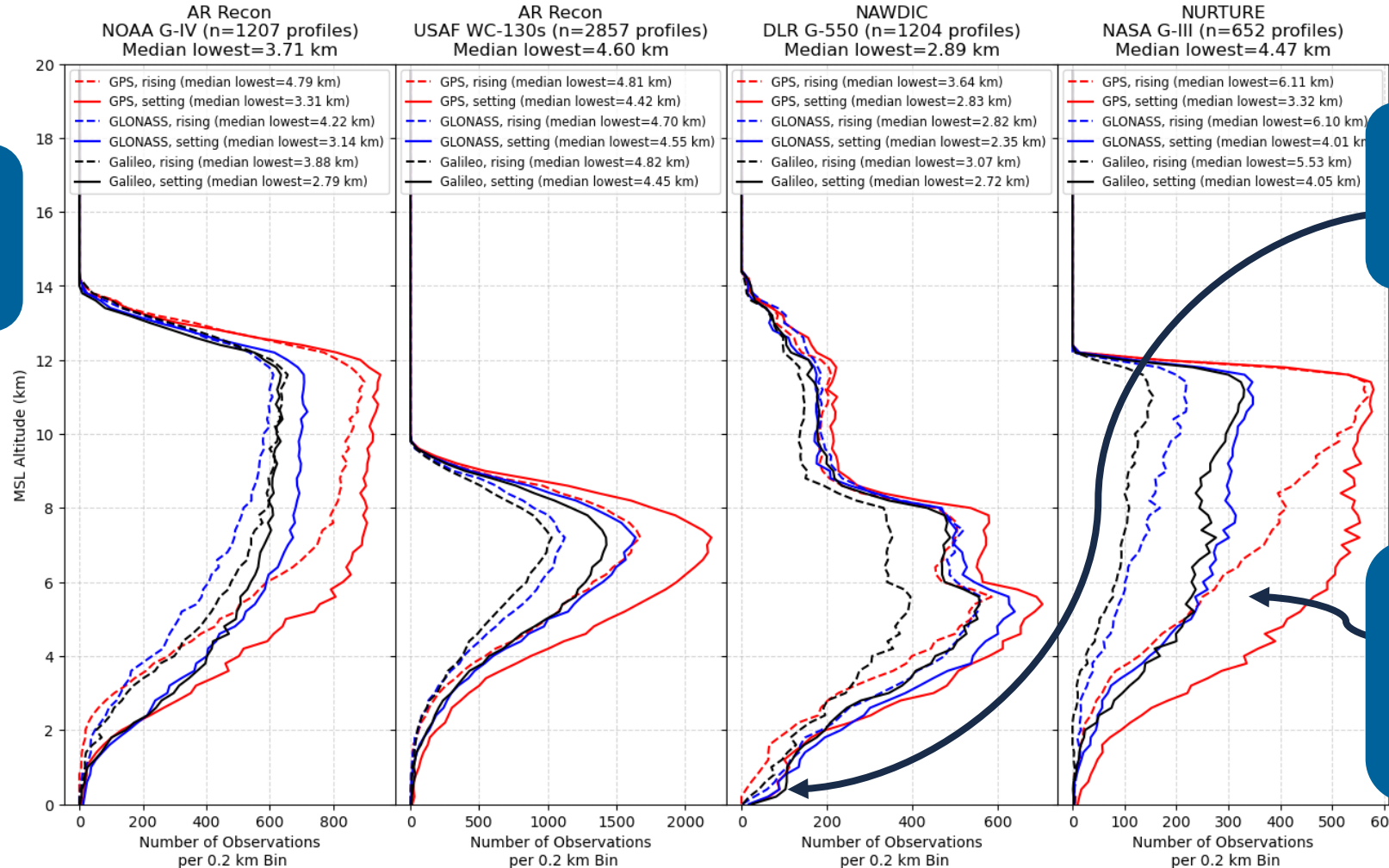


NE Atlantic (HALO)
13 Jan – 20 Feb
Shannon, Ireland



B. Cao

Penetration Depths Vary By Aircraft Type



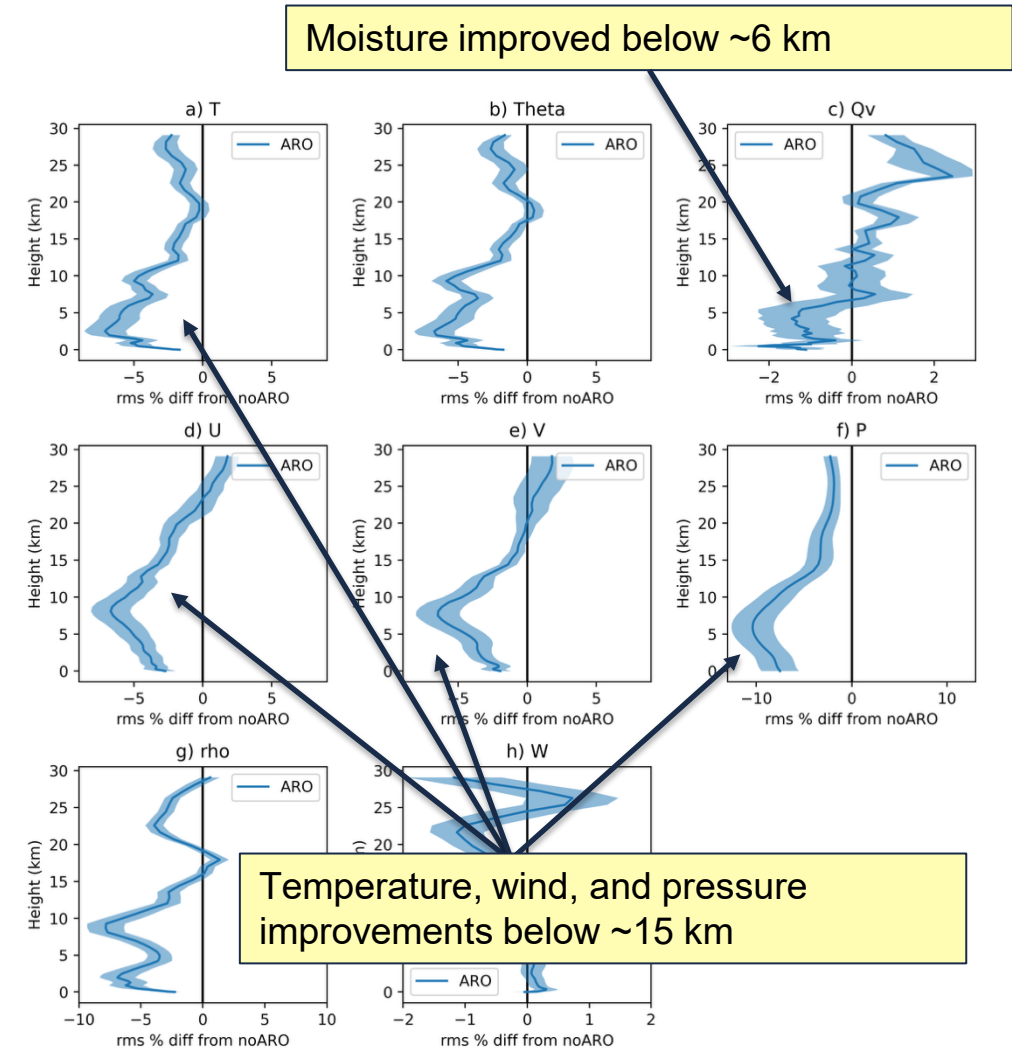
AR Recon aircraft fly at a single consistent altitude

~100 NAWDIC profiles penetrate to surface

NURTURE shows large differences between setting (solid) and rising (dashed) profiles

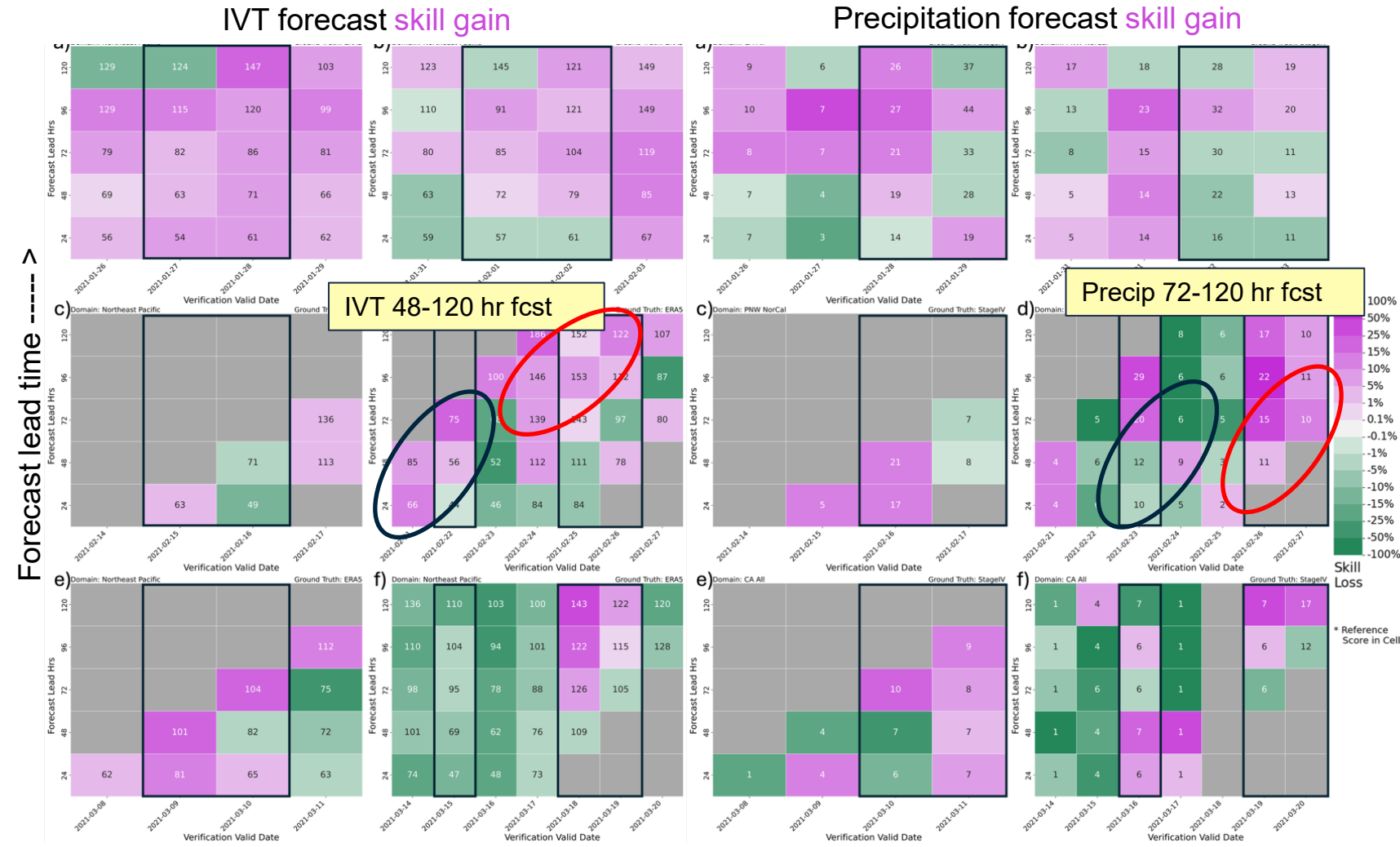
AR case studies of ARO data assimilation

- **February 2023 – C-130s in the East Pacific**
- Nghi Do – “Impact of Airborne Radio Occultation Observations on Short Term Precipitation Forecasts of an Atmospheric River”, GRL, 2025.
- **January 2023 – G-IV in the central Pacific**
- Ivette Hernández Baños- "Assimilating GNSS airborne radio occultation bending angles with MPAS–JEDI during a sequence of atmospheric rivers", JAMES, submitted
- Nghi Do- "Enhancing Atmospheric River Forecasts through GNSS ARO Data Assimilation in MPAS-JEDI: Sensitivity to Mesh Resolution", JGR, in prep January
- **Jan - March 2021 – G-IV in the central Pacific**
- Benjamin Davis- "Season-long Summary of Atmospheric River Forecast Impact from Assimilating Airborne Radio Occultation Data", MWR, submitted



Correspondence between IVT and Precipitation

- Assimilating ARO improves IVT and precipitation forecasts, particularly at >72 hours
- IVT forecasts improved leading up to and during precipitation events
- Precipitation forecasts improved, particularly at 96 and 120 hour lead times



Valid time ----->

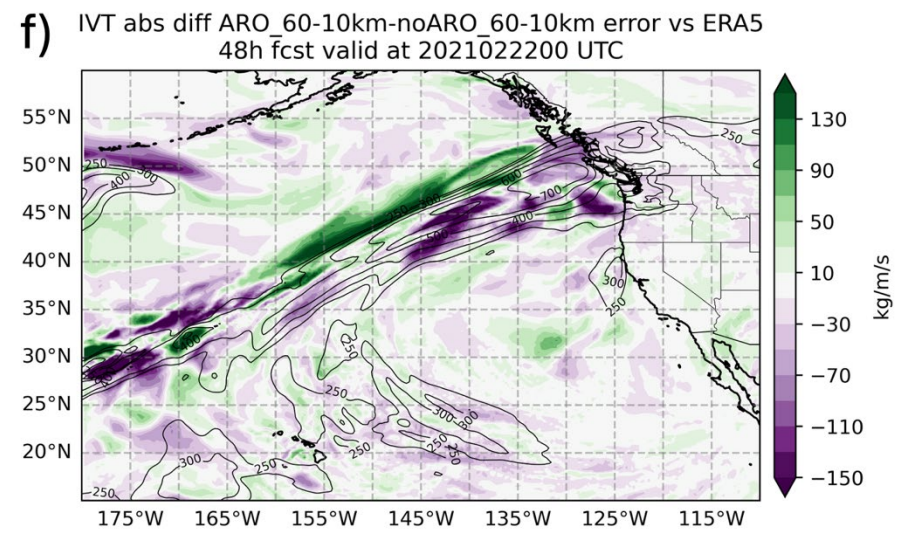
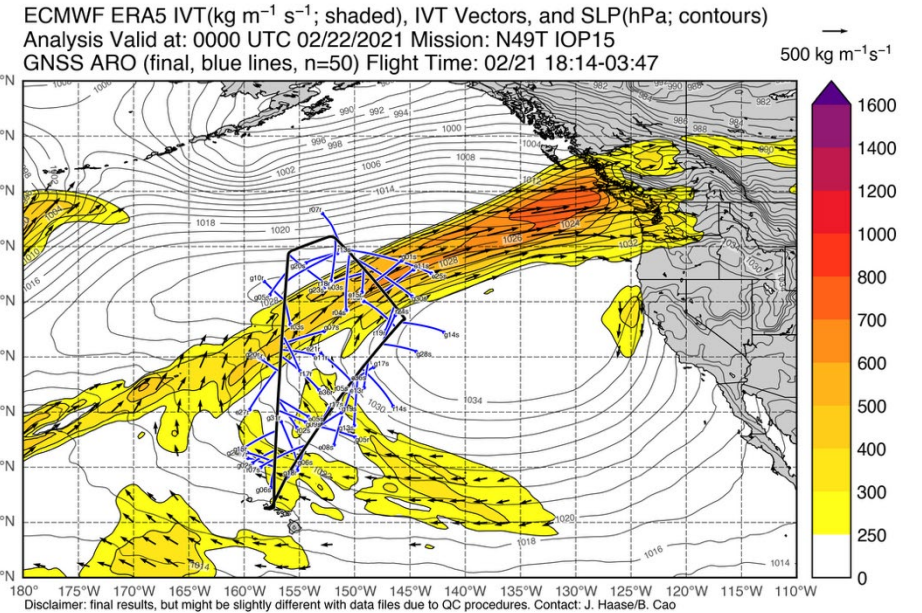
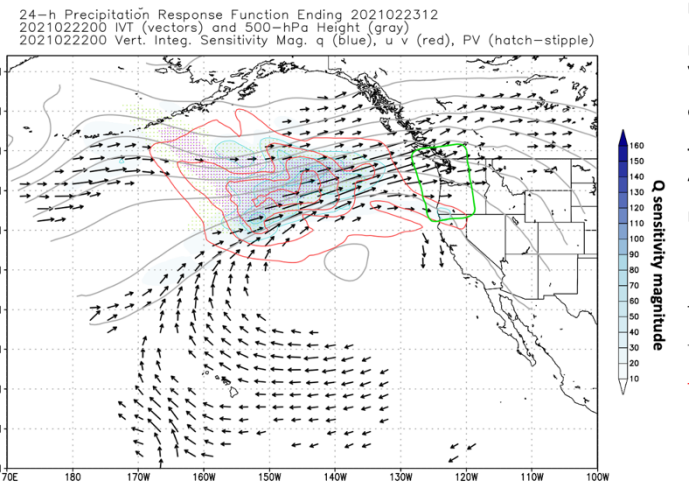
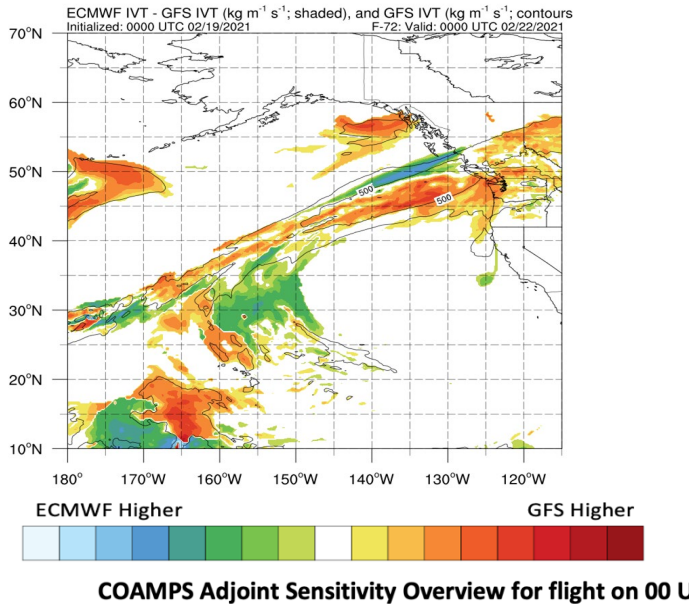
*RMSE of NoARO in cell

Relating flight planning decisions to DA outcomes

1. GFS vs ECMWF forecast show differences of AR core location at landfall
2. Sensitivity is high in essential atmospheric structures: AR core and trough on north side of AR
3. Flight is planned and executed providing observations in sensitive area
4. Result of ARO DA moves more IVT northwards towards agreement with EC forecast and reduces rainfall in Oregon

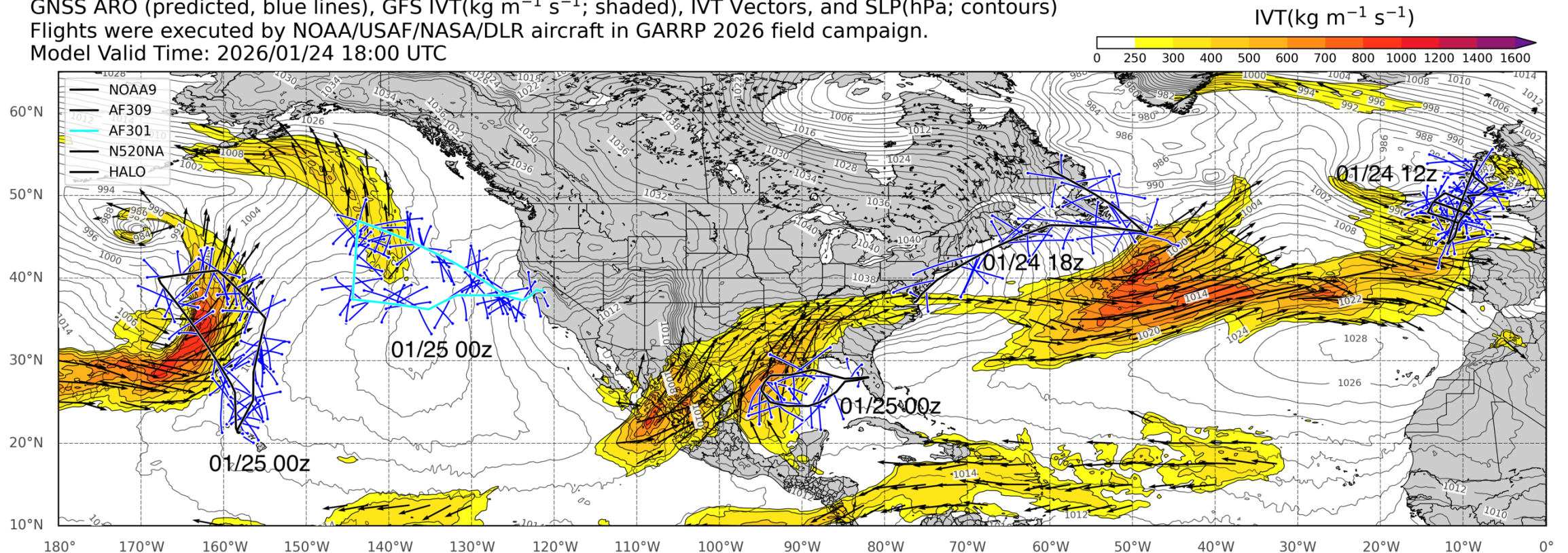
Improvements are seen beyond the target rainfall time window.

Init 00Z 19 Feb 2021
 Precip metric 12Z 22 -12Z 23 Feb 2021
 Flight 00Z 22 Feb 2022



Five aircraft flew over two on the same day over two oceanic basins

GNSS ARO (predicted, blue lines), GFS IVT($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vectors, and SLP(hPa; contours)
 Flights were executed by NOAA/USAF/NASA/DLR aircraft in GARRP 2026 field campaign.
 Model Valid Time: 2026/01/24 18:00 UTC

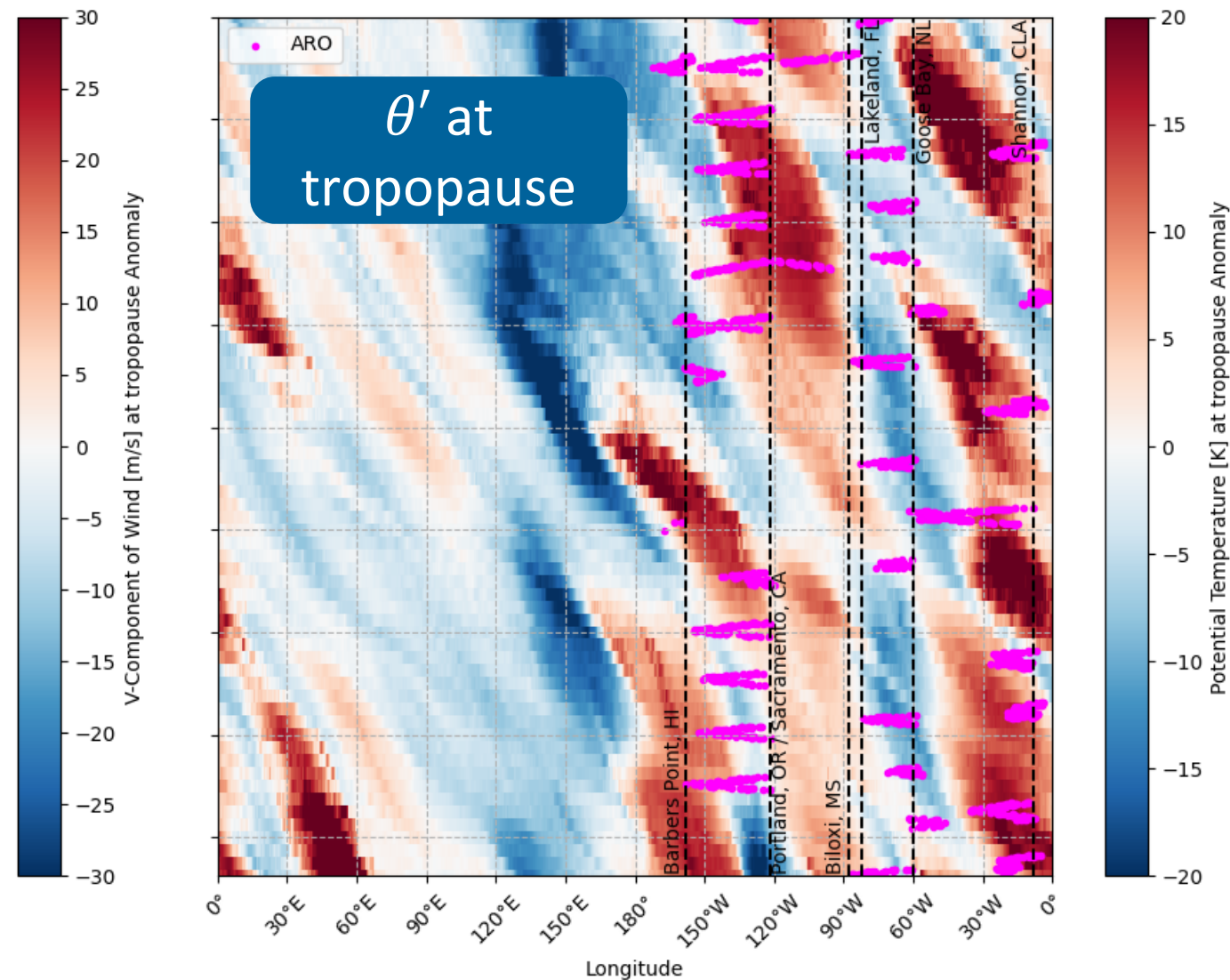
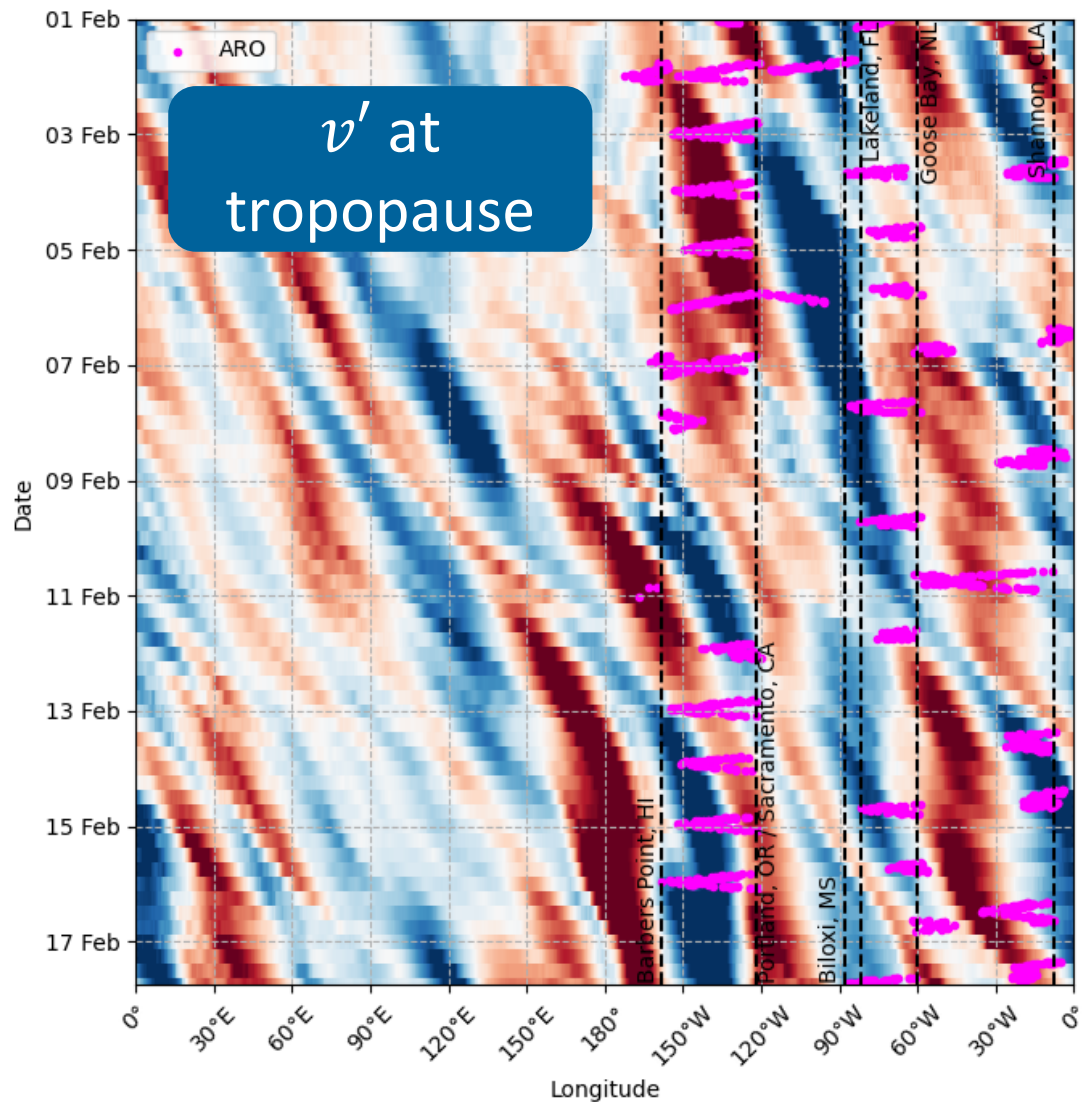


Disclaimer: predicted results, locations are accurate, profile extension might be slightly different in final products. The maps might not include all flights due to delays in data recovery!
 Contact: J. Haase/B. Cao/N. Barton/K. Loo/ARO team, in partnership with the UC San Diego/Scripps Institute Oceanography/Center for Western Weather and Water Extremes

Case Study

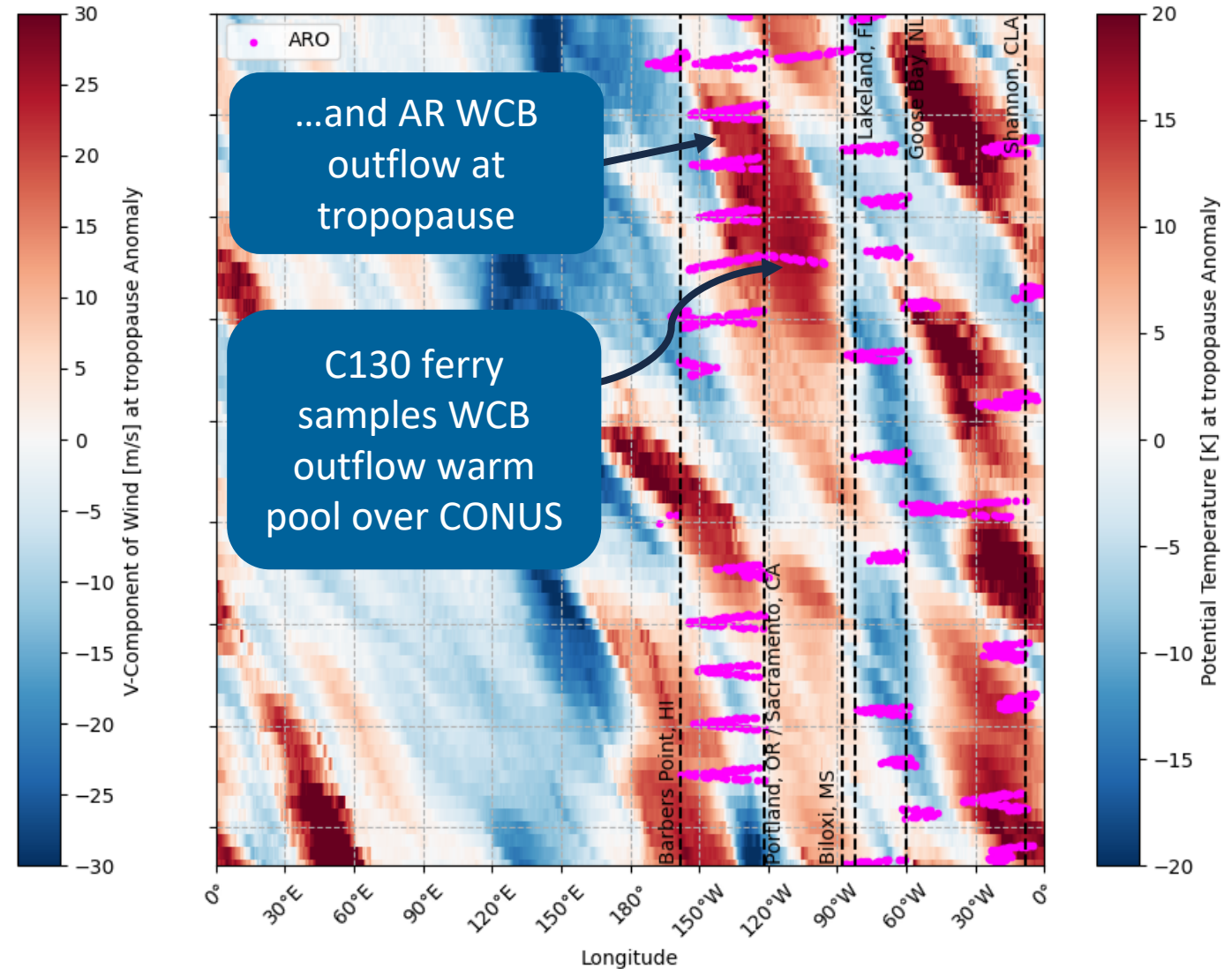
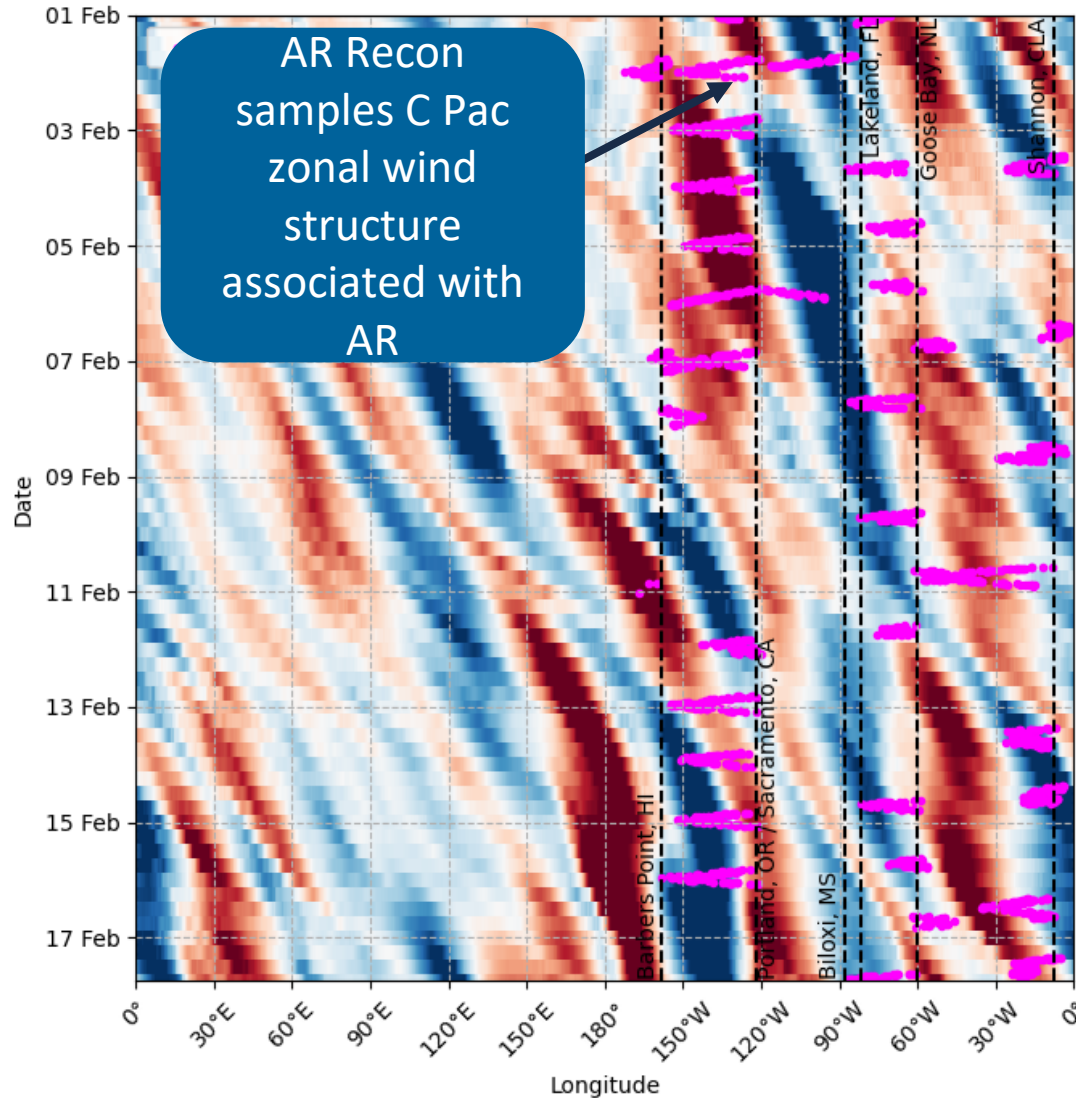
Hovmöller Diagrams - Tropopause

GFS Analysis, 2026-02-01 to 2026-02-17, 35° to 55°, Deviation from Time-Zonal Mean, Time Increases Downward



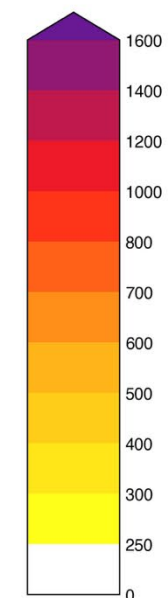
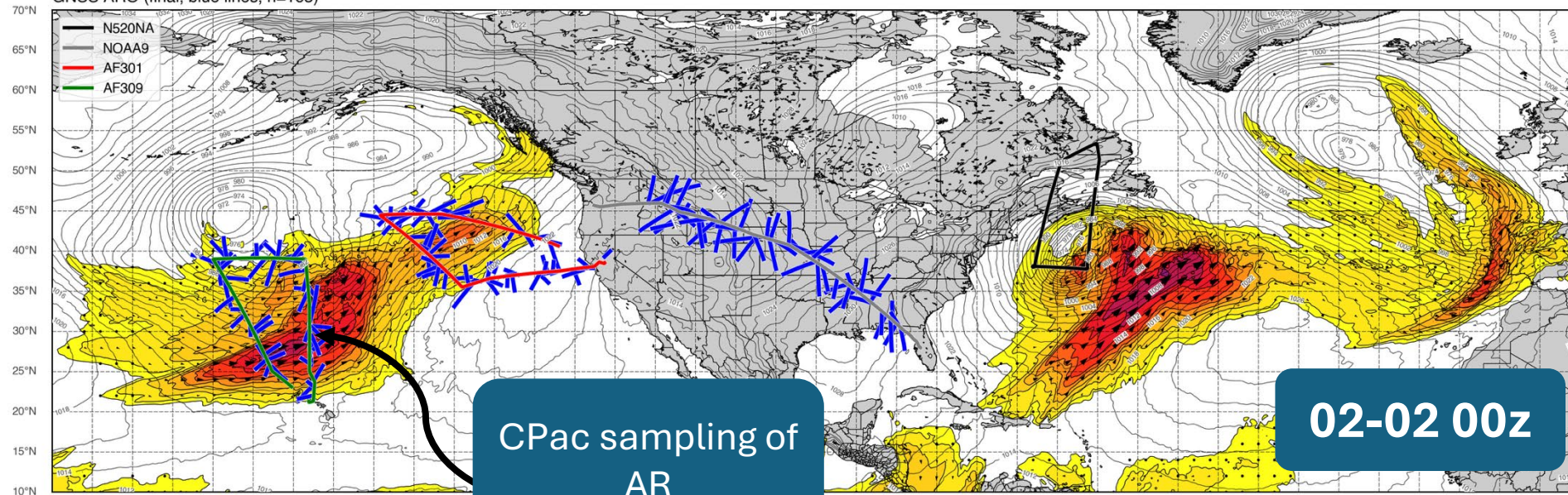
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NCEP GFS IVT($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vectors, and SLP(hPa; contours)
 Analysis Valid at: 0000 UTC 02/02/2026 Mission: AR2026
 GNSS ARO (final, blue lines, n=163)

$\rightarrow 500 \text{ kg m}^{-1} \text{s}^{-1}$

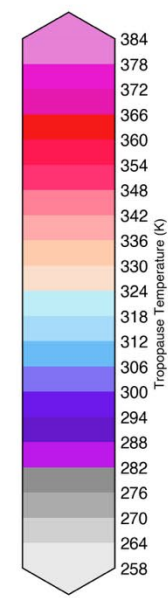
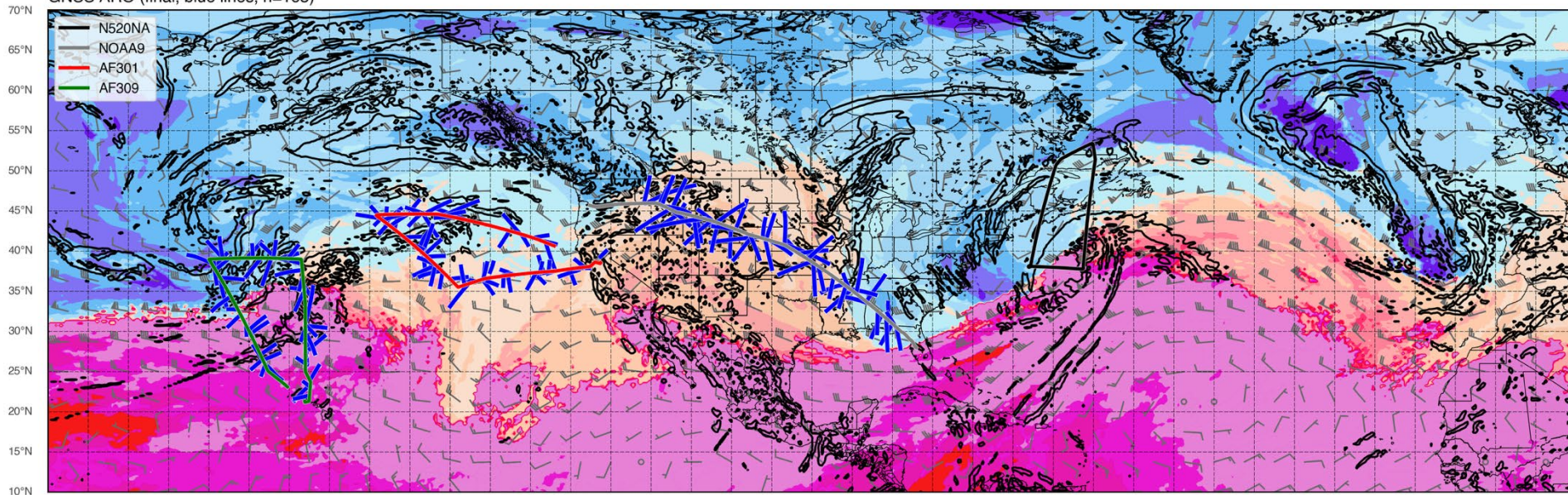


170°E 175°E 180° 175°W 170°W 165°W 160°W 155°W 150°W 145°W 140°W 90°W 85°W 80°W 75°W 70°W 65°W 60°W 55°W 50°W 45°W 40°W 35°W 30°W 25°W 20°W 15°W 10°W 5°W

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NCEP GFS Dynamic Tropopause Potential Temperature (shaded, K) & winds (barbs), 925-850hPa cycl. rel. vort. (black, $0.5 \times 10^{-4} \text{s}^{-1}$)
 Analysis Valid at: 0000 UTC 02/02/2026 Mission: AR2026
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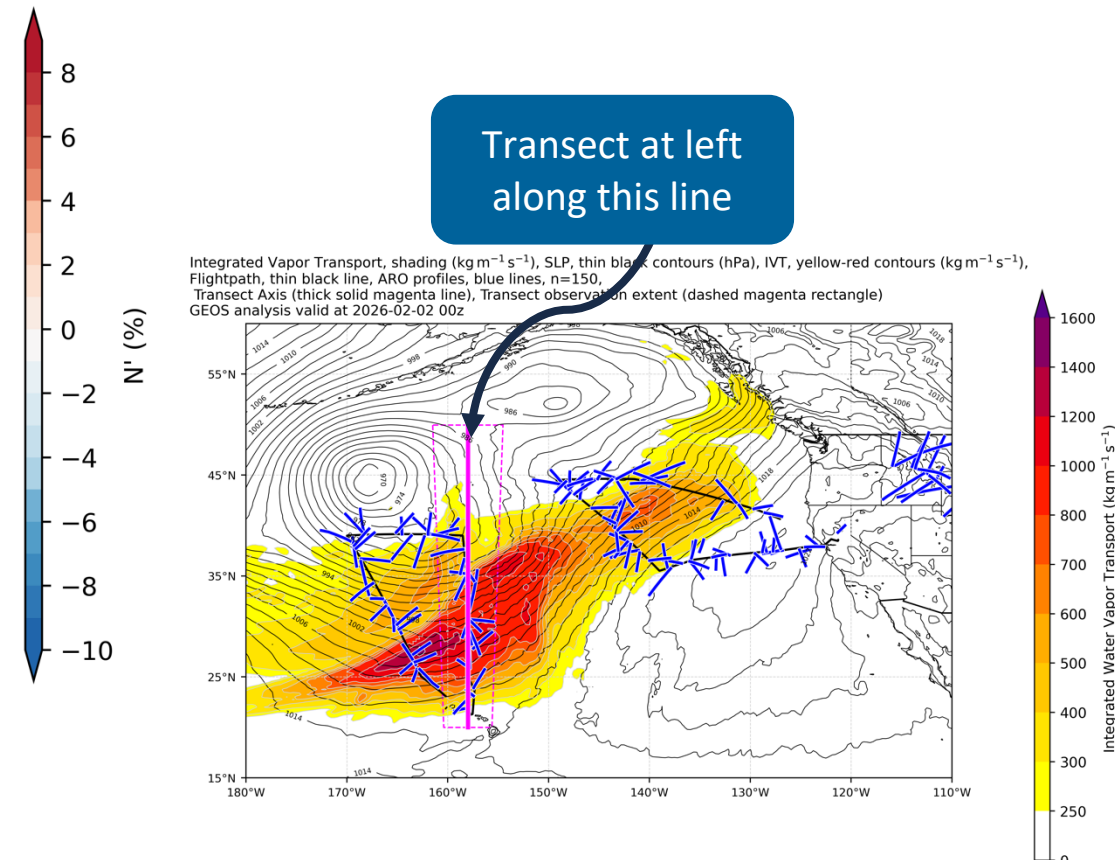
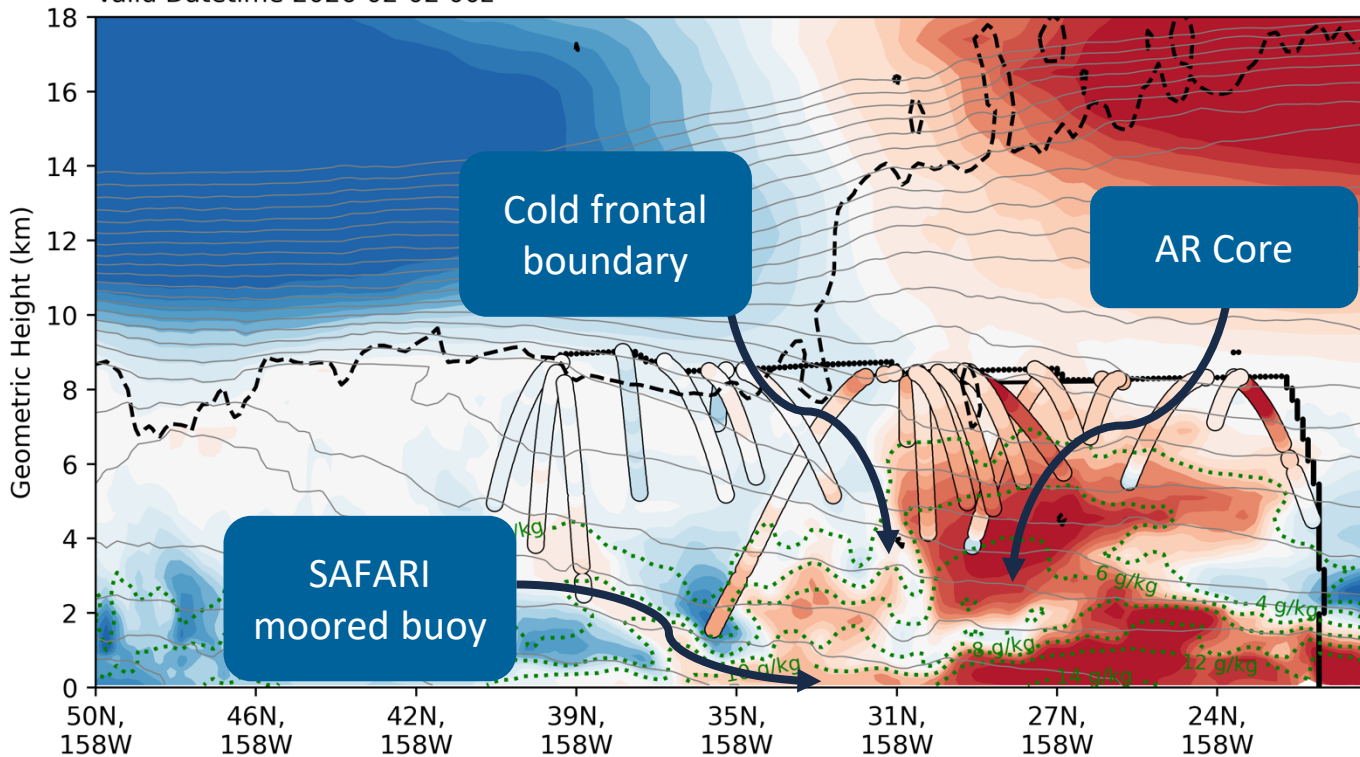
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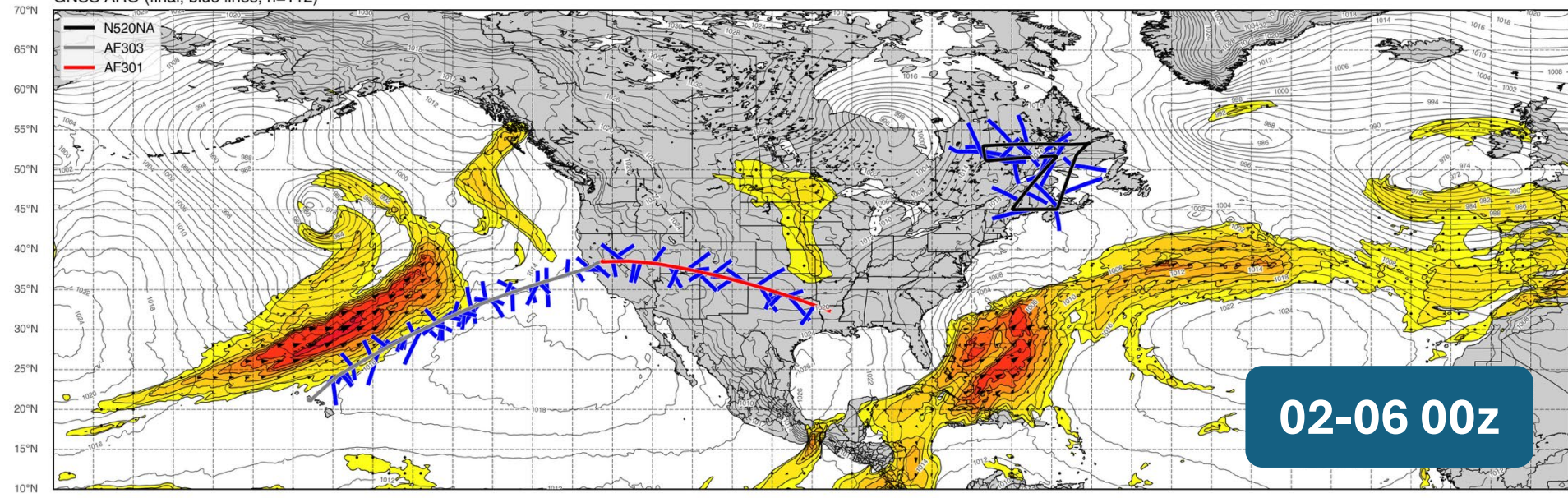
02-02 00z: AR Recon samples C Pac AR and associated trough

GEOS Refractivity Anomaly, shading (N', %), ARO N', shaded lines (%)
 Dynamic tropopause, black dashed contour ($2 \times 10^{-6} \text{ Km}^2 \text{ s}^{-1} \text{ kg}^{-1}$)
 Specific Humidity, green dotted contours (g/kg), Potential Temperature, thin grey solid contours (K)
 Valid Datetime 2026-02-02 00z



NCEP GFS IVT($\text{kg m}^{-1} \text{s}^{-1}$; shaded), and SLP(hPa; contours)
Analysis Valid at: 0000 UTC 02/06/2026 Mission: AR2026
GNSS ARO (final, blue lines, n=112)

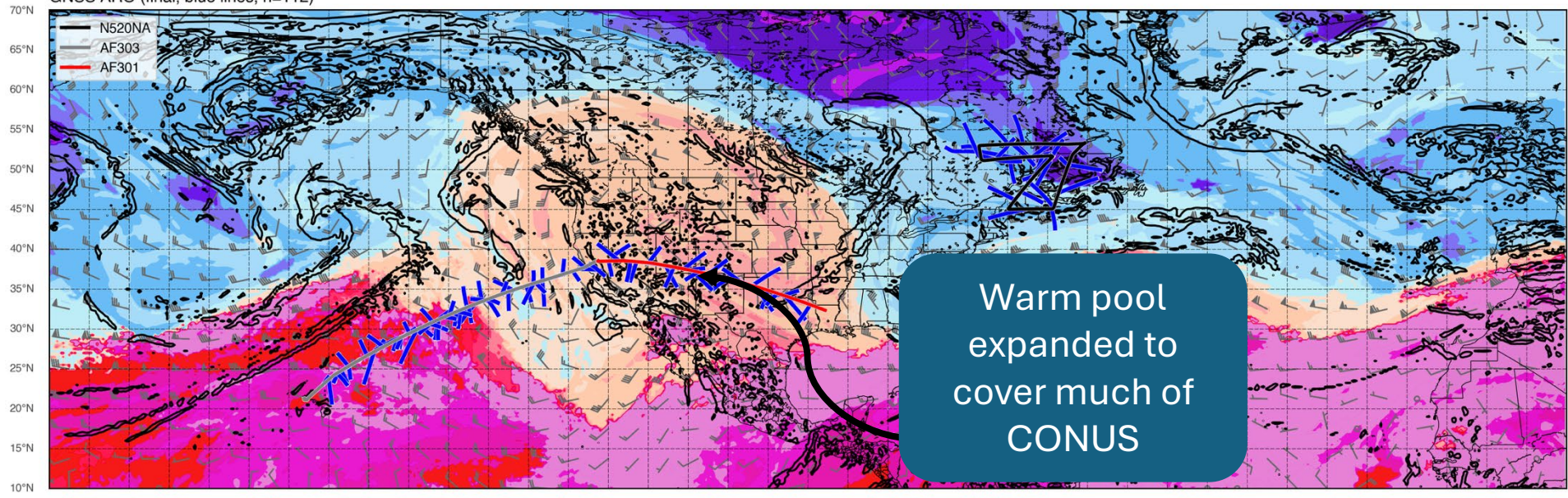
$\cdot 500 \text{ kg m}^{-1} \text{s}^{-1}$



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NCEP GFS Dynamic Tropopause Potential Temperature (shaded, K) & winds (barbs), 925-850hPa cycl. rel. vort. (black, $0.5 \times 10^{-4} \text{s}^{-1}$)
Analysis Valid at: 0000 UTC 02/06/2026 Mission: AR2026
GNSS ARO (final, blue lines, n=112)

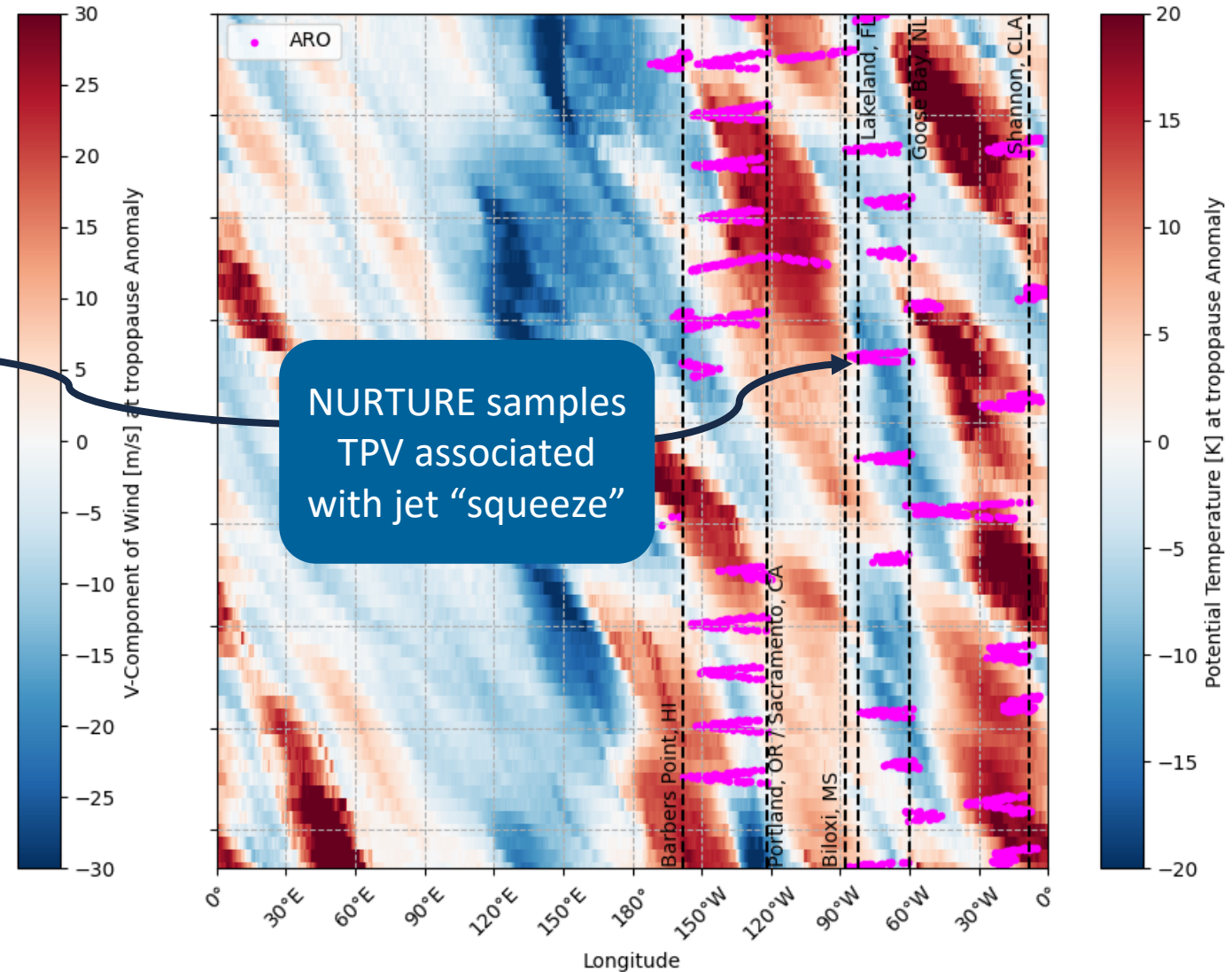
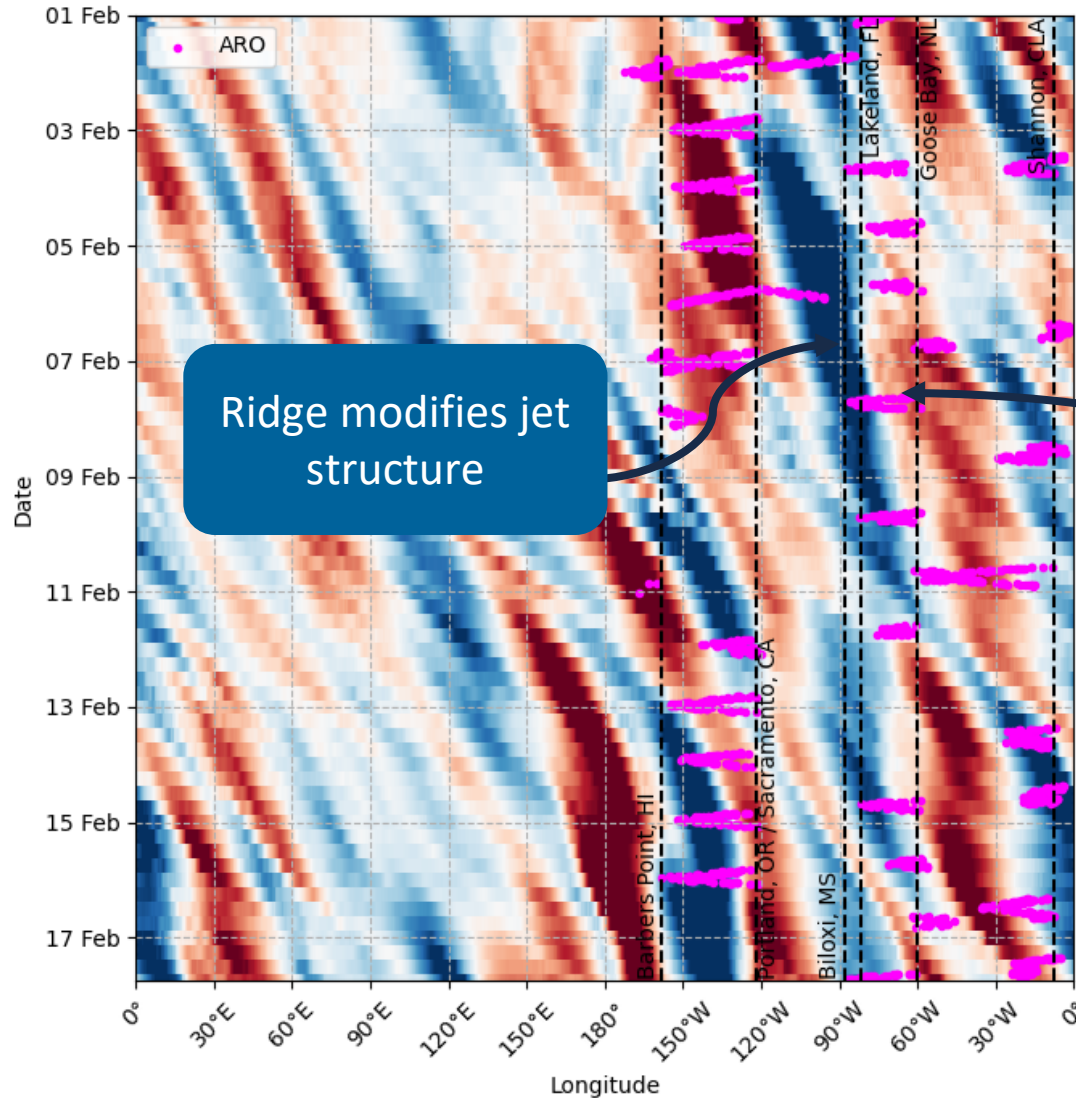


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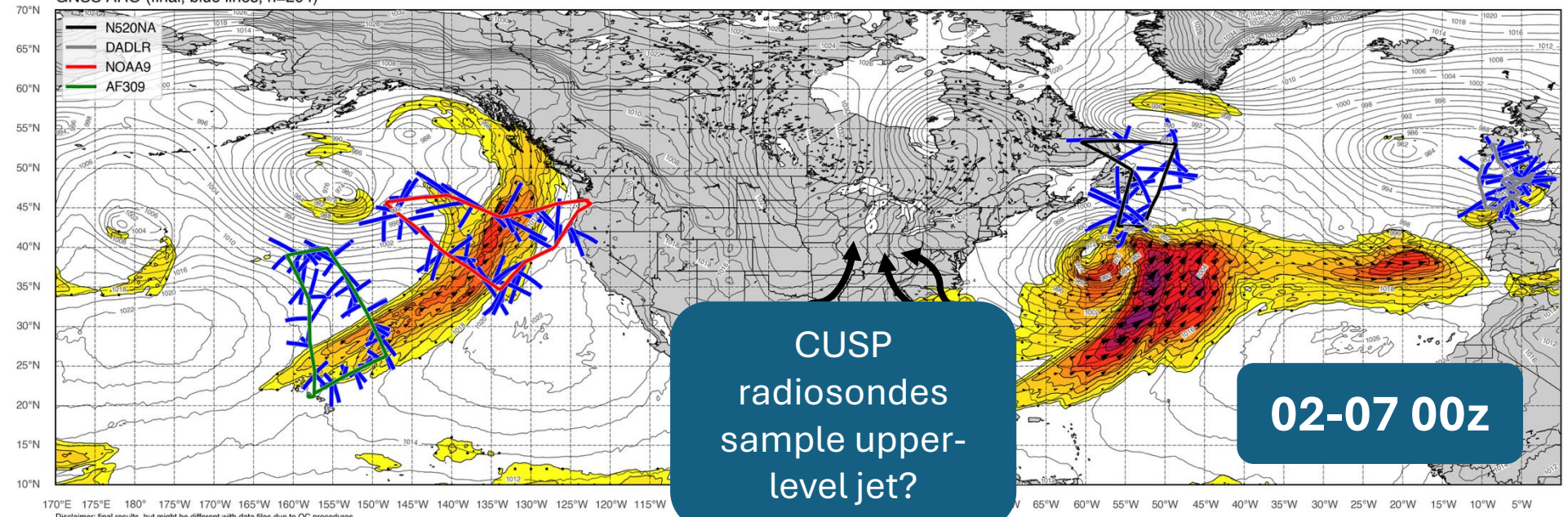
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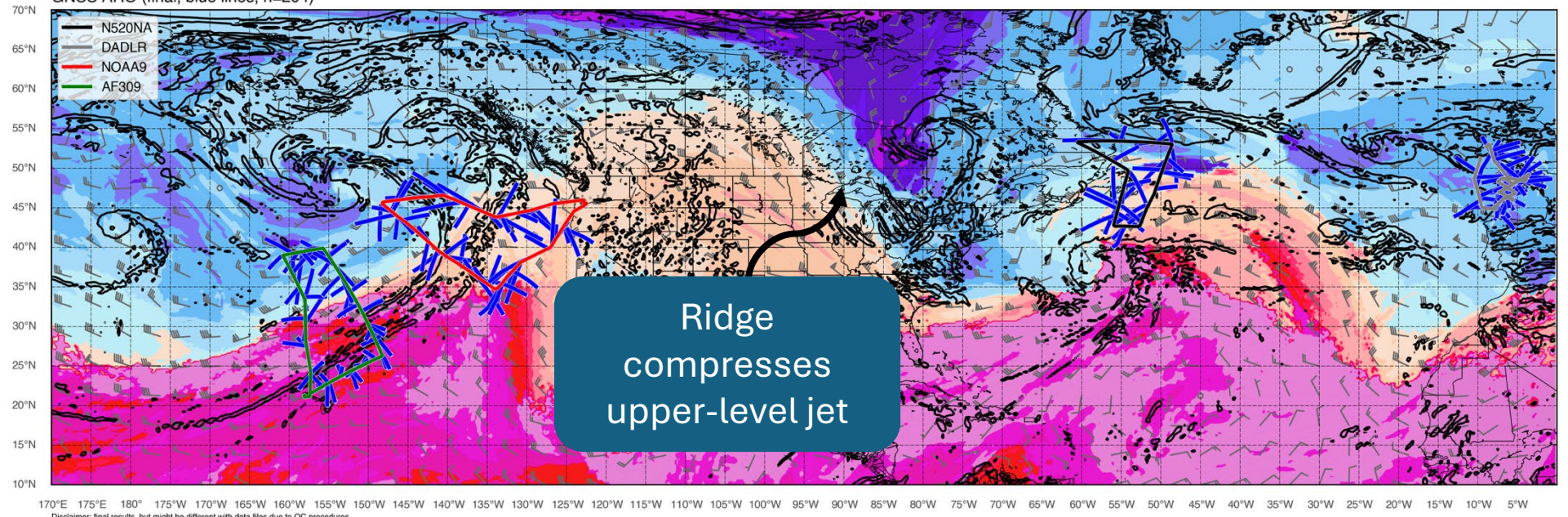
NCEP GFS IVT($\text{kg m}^{-1} \text{s}^{-1}$; shaded), IVT Vectors, and SLP(hPa; contours)
 Analysis Valid at: 0000 UTC 02/07/2026 Mission: AR2026
 GNSS ARO (final, blue lines, n=204)

500 $\text{kg m}^{-1} \text{s}^{-1}$

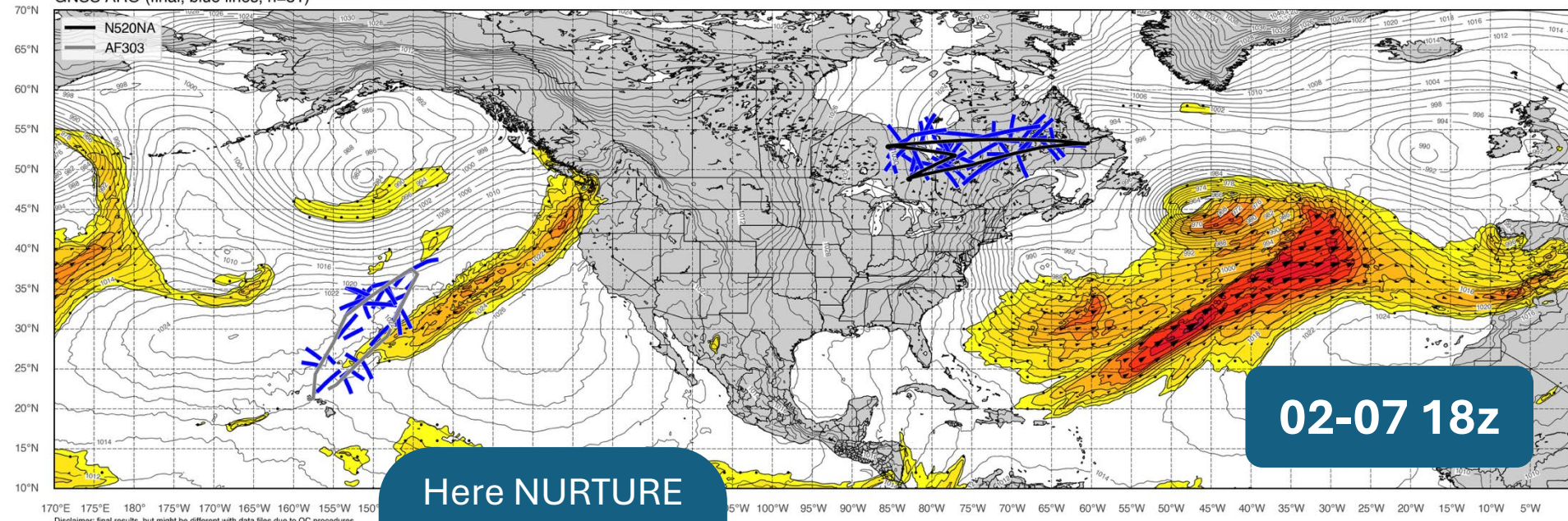


170°E 175°E 180° 175°W 170°W 165°W 160°W 155°W 150°W 145°W 140°W 135°W 130°W 125°W 120°W 115°W
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NCEP GFS Dynamic Tropopause Potential Temperature (shaded, K) & winds (barbs), 925-850hPa cycl. rel. vort. (black, $0.5 \times 10^{-4} \text{s}^{-1}$)
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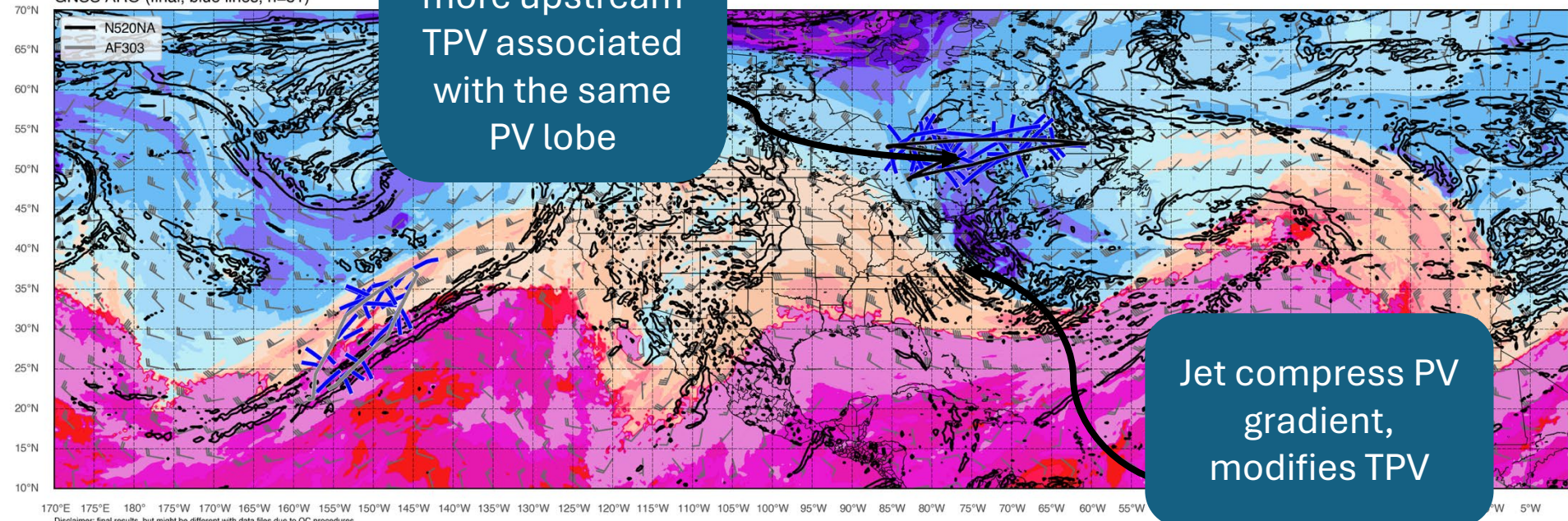


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Here NURTURE is sampling a more upstream TPV associated with the same PV lobe

NCEP GFS Dynamic Tropopause Potential T
Analysis Valid at: 1800 UTC 02/07/2026 Miss
GNSS ARO (final, blue lines, n=81)

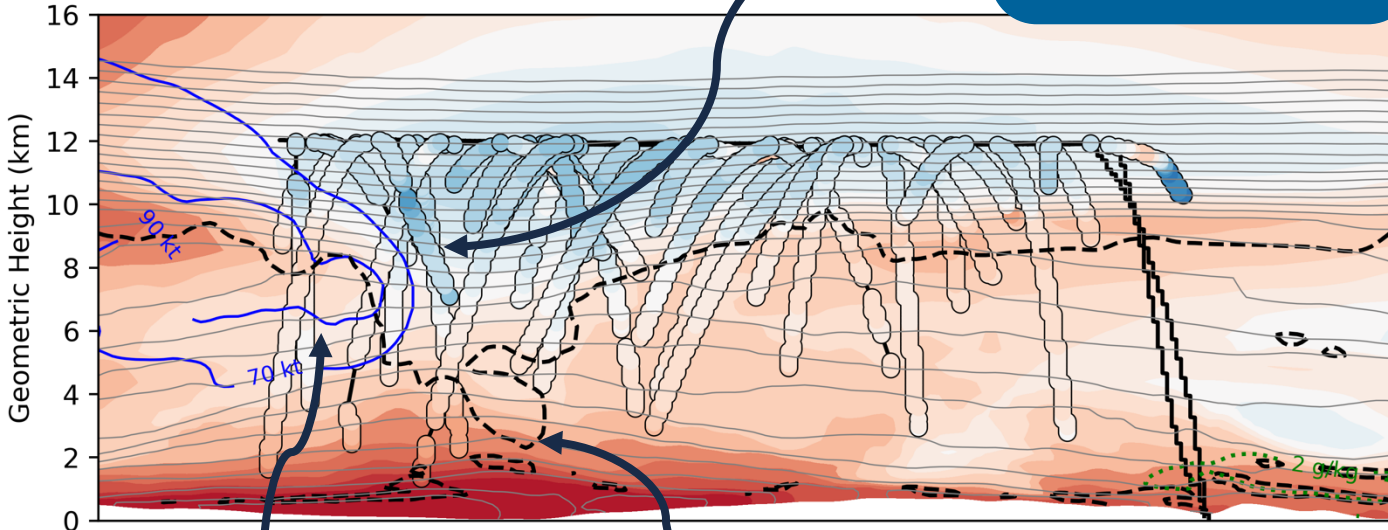


Jet compress PV gradient, modifies TPV

02-07 18z: NURTURE Flight samples TPV-jet interaction

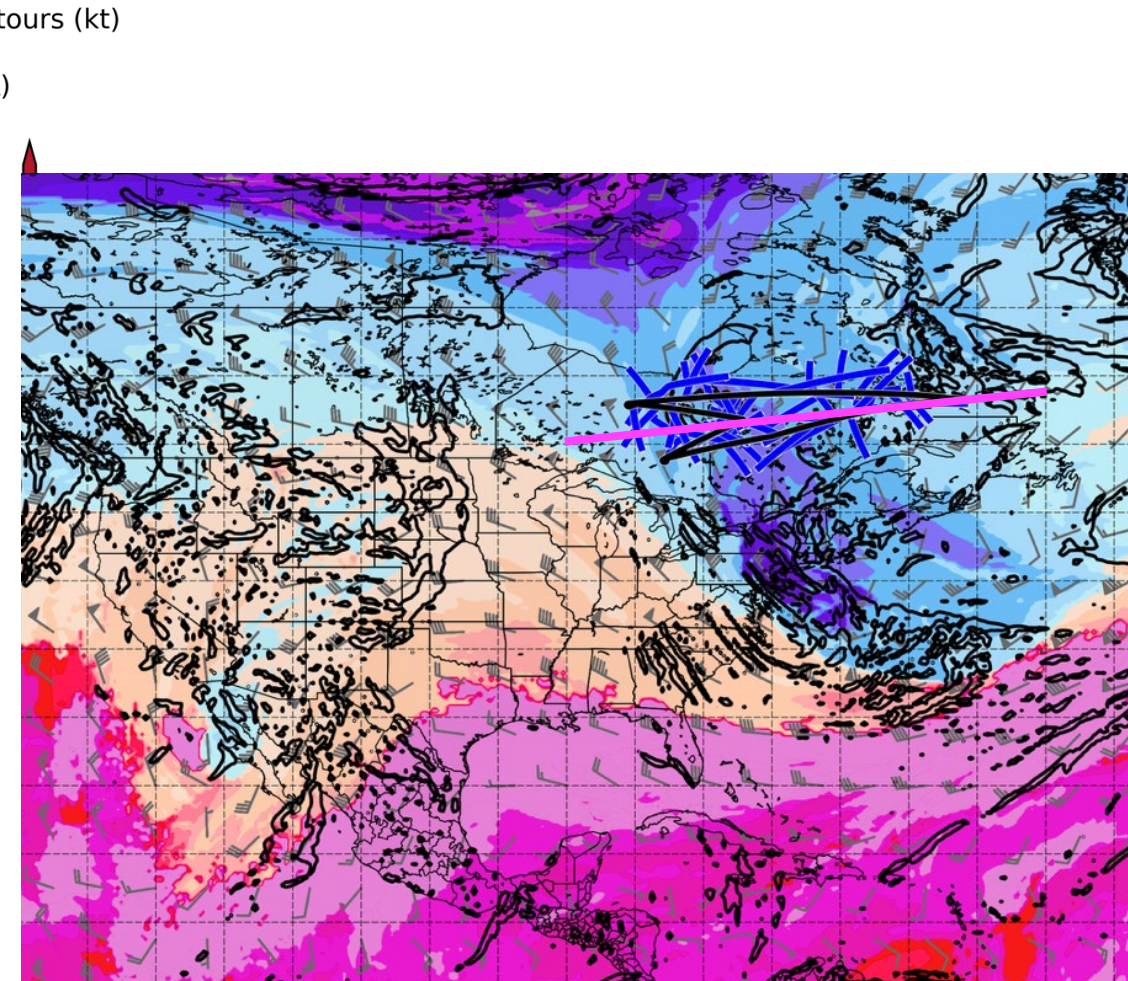
ARO shows stratospheric warm anomaly ($-N'$)

GEOS Refractivity Anomaly, shading (N' , %), ARO N' , shaded lines
 Dynamic tropopause, black dashed contour ($2 \times 10^{-6} \text{ K m}^2 \text{ s}^{-1} \text{ kg}^{-1}$)
 Specific Humidity, green dotted contours (g/kg), Potential Temperature (K)
 Valid Datetime 2026-02-07 18z



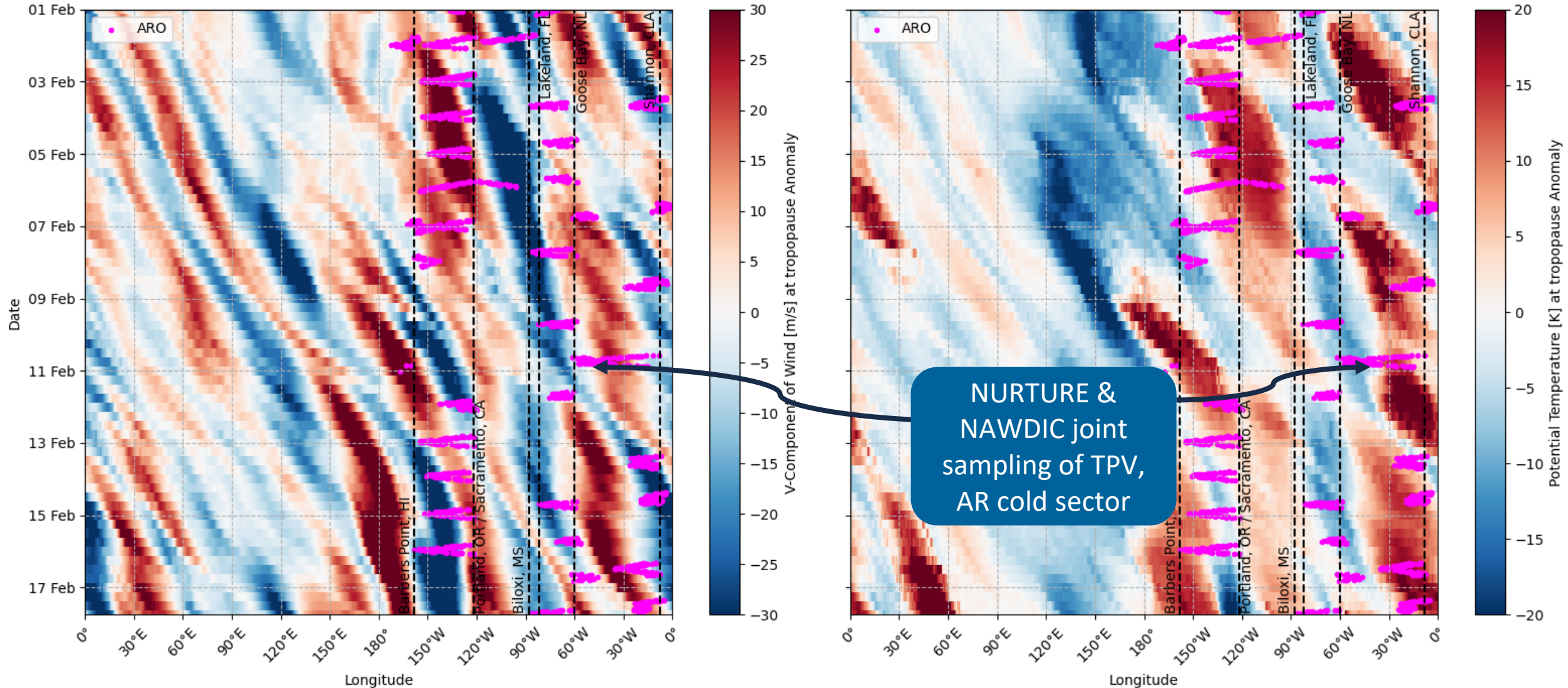
Upper level jet intrudes into western edge of TPV

TPV indicated by depressed tropopause



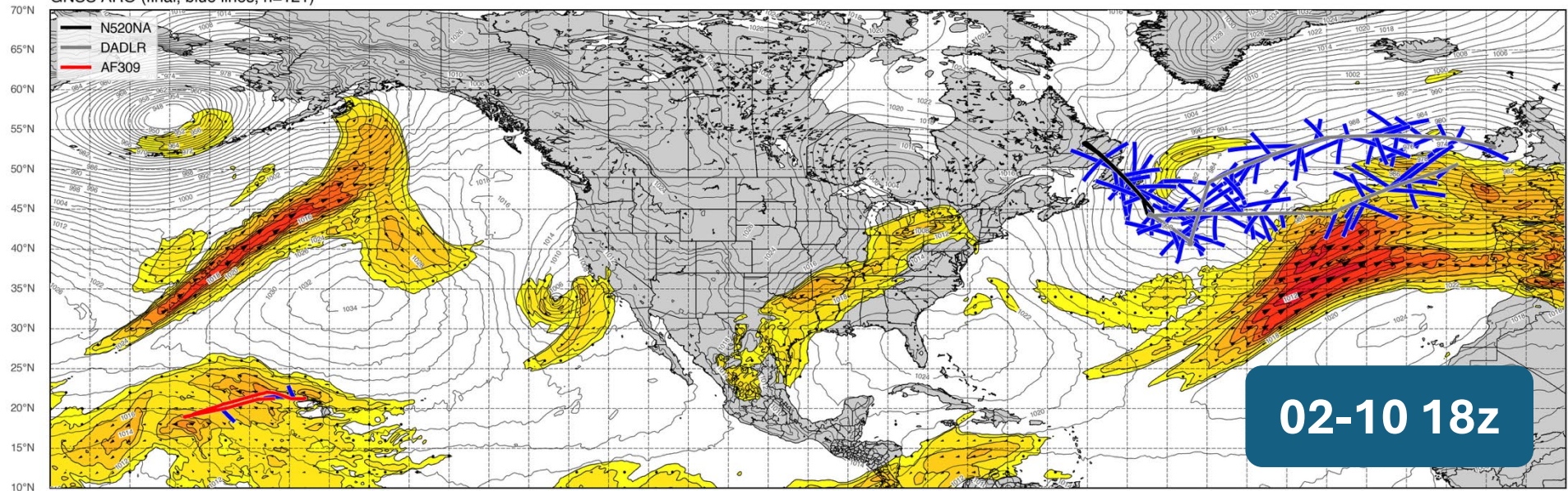
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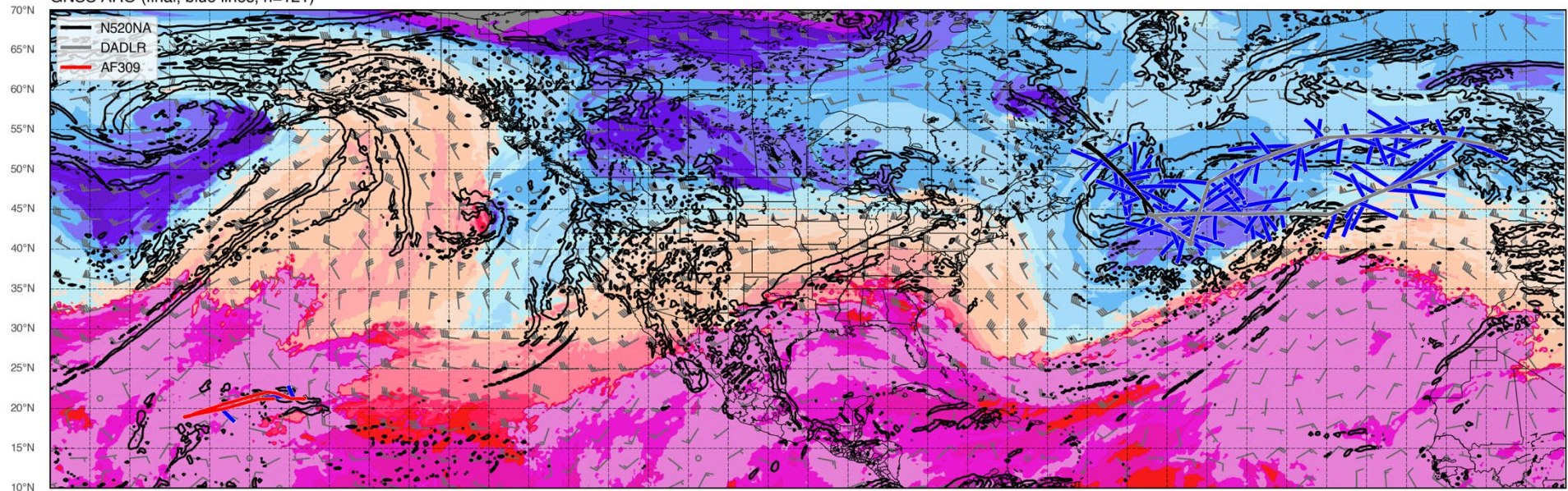
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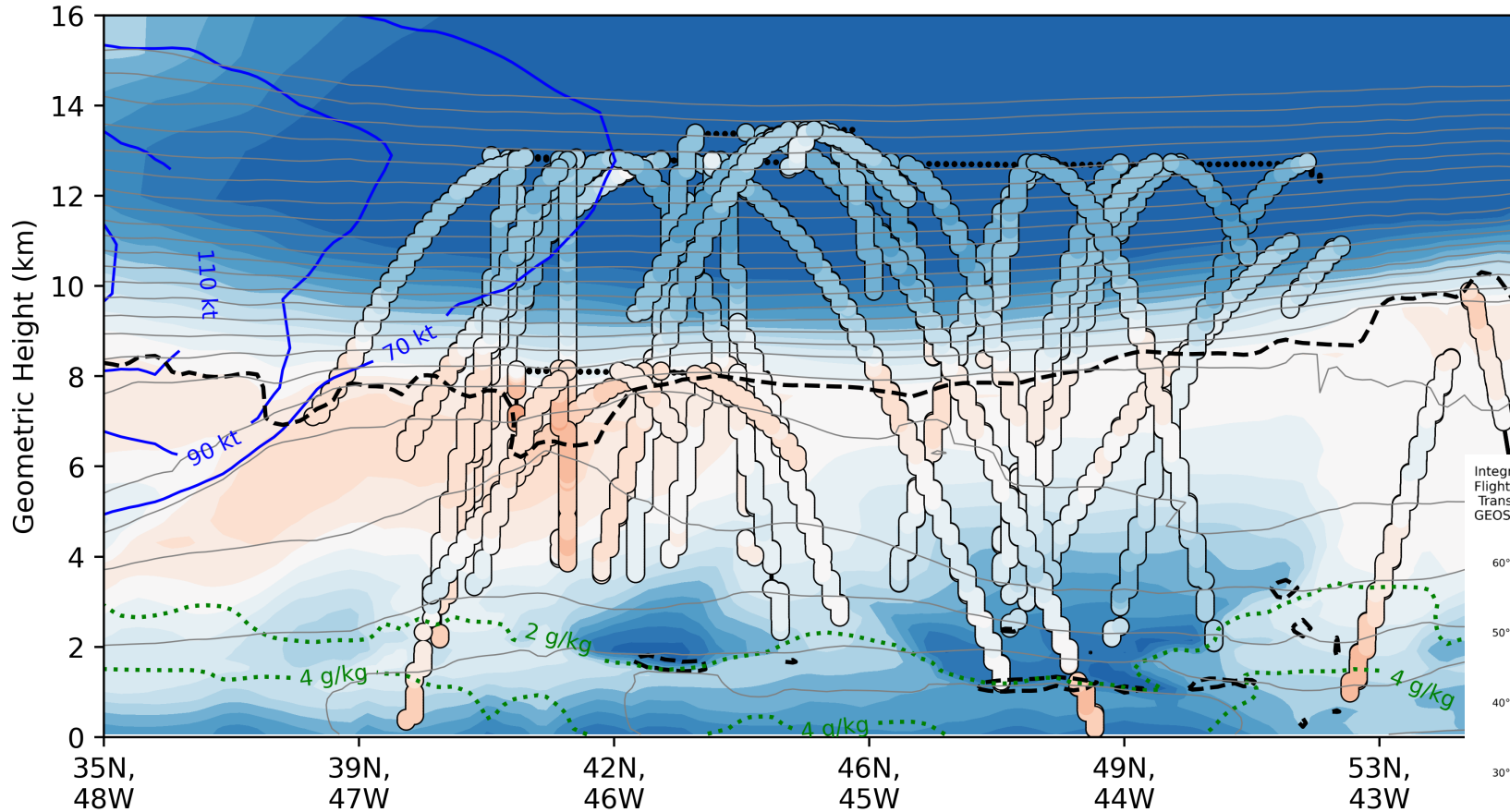


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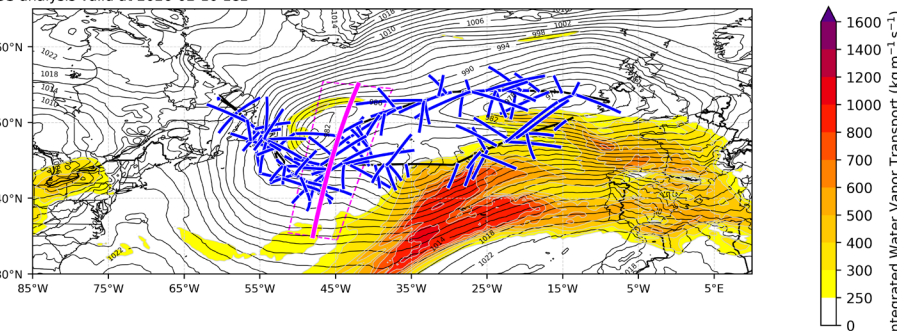
Disclaimer: final results, but might be different with data files due to QC procedures.
Contact: J. Haase/B. Cao/N. Barton/K. Loo, in partnership with the UC San Diego/SIO/CW3E

02-10 18z: TPV moves offshore

GEOS Refractivity Anomaly, shading (N', %), ARO N', shaded lines (%), Wind Speed, blue solid contours (kt)
 Dynamic tropopause, black dashed contour ($2 \times 10^{-6} \text{ K m}^2 \text{ s}^{-1} \text{ kg}^{-1}$)
 Specific Humidity, green dotted contours (g/kg), Potential Temperature, thin grey solid contours (K)
 Valid Datetime 2026-02-10 18z

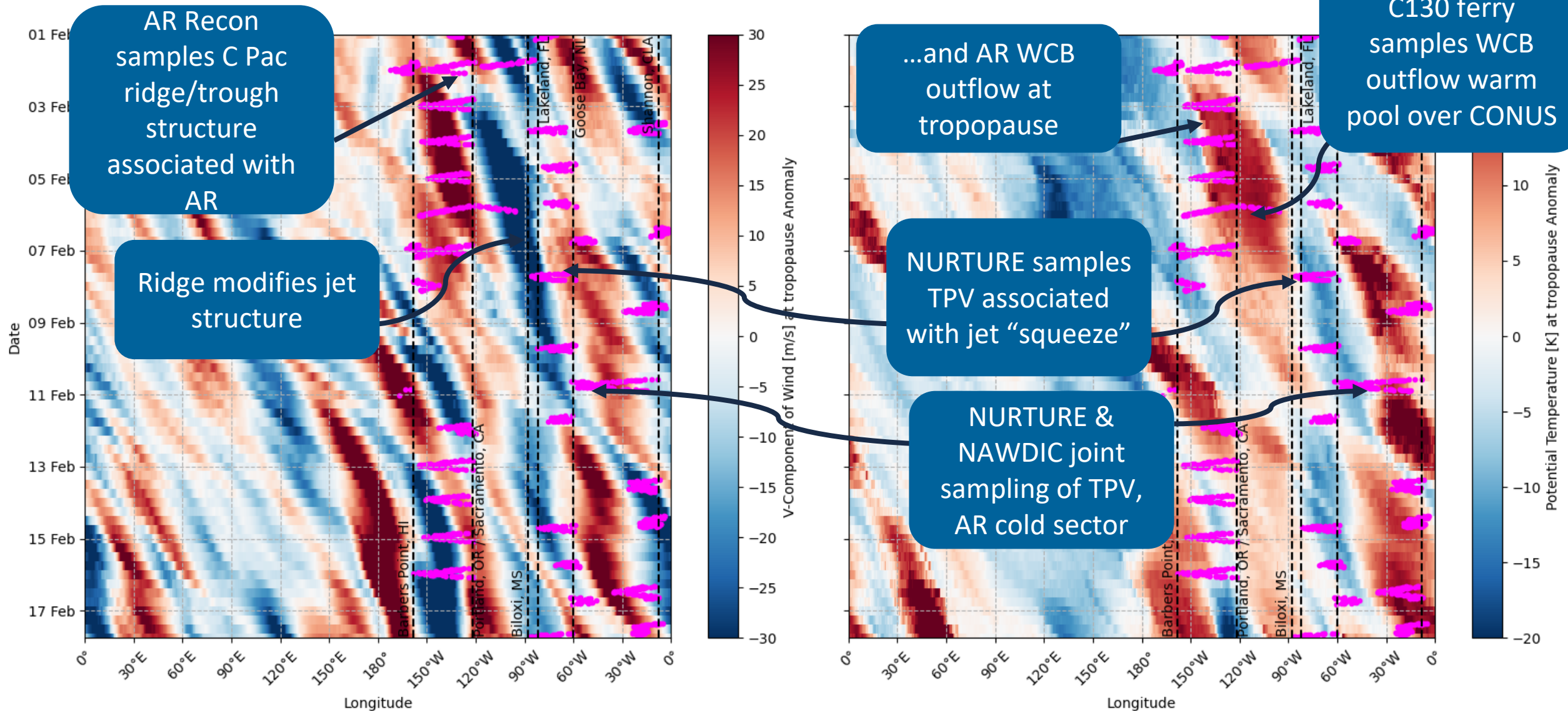


Integrated Vapor Transport, shading ($\text{kg m}^{-1} \text{ s}^{-1}$), SLP, thin black contours (hPa), IVT, yellow-red contours ($\text{kg m}^{-1} \text{ s}^{-1}$),
 Flightpath, thin black line, ARO profiles, blue lines, n=206,
 Transect Axis (thick solid magenta line), Transect observation extent (dashed magenta rectangle)
 GEOS analysis valid at 2026-02-10 18z



Hovmöller Diagrams - Tropopause

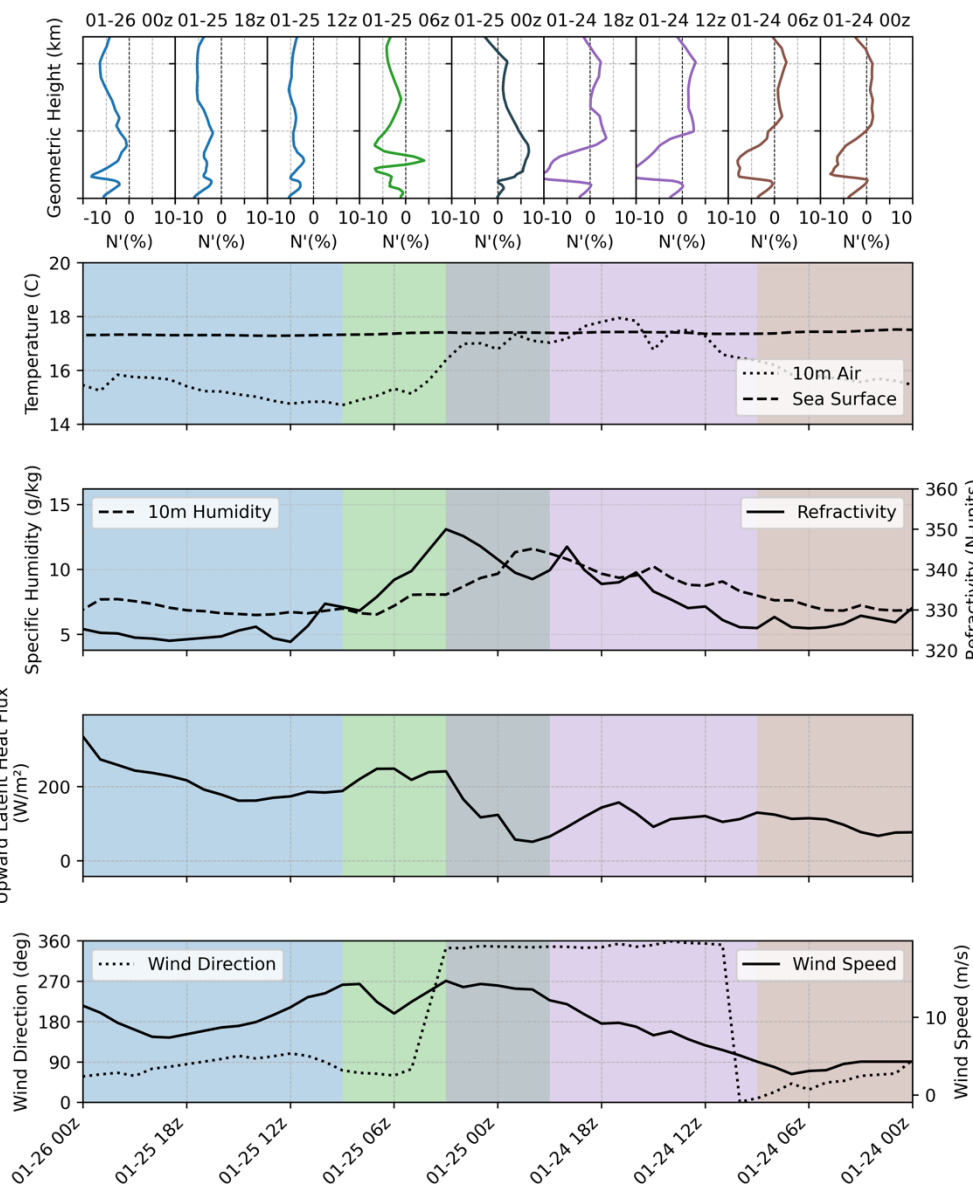
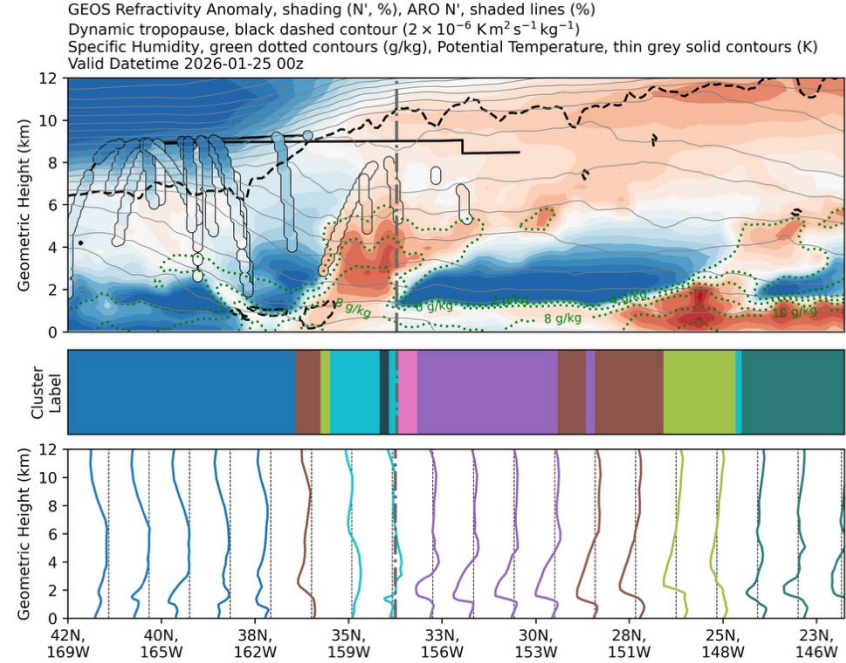
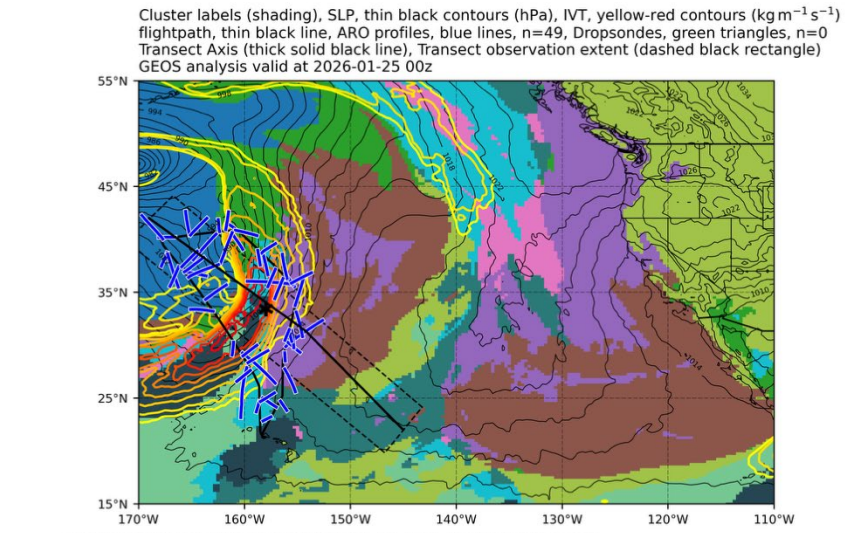
GFS Analysis, 2026-02-01 to 2026-02-17, 35° to 55°, Deviation from Time-Zonal Mean, Time Increases Downward

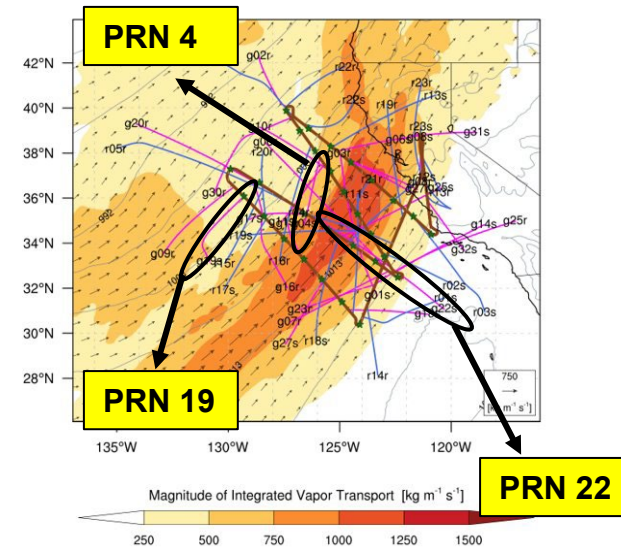
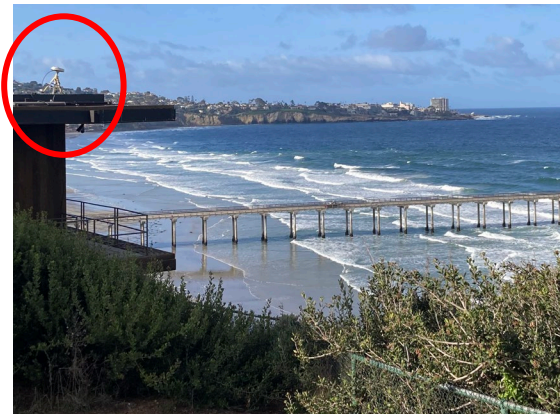


Future Efforts

ARO data collected during overflights of SAFARI moored buoy

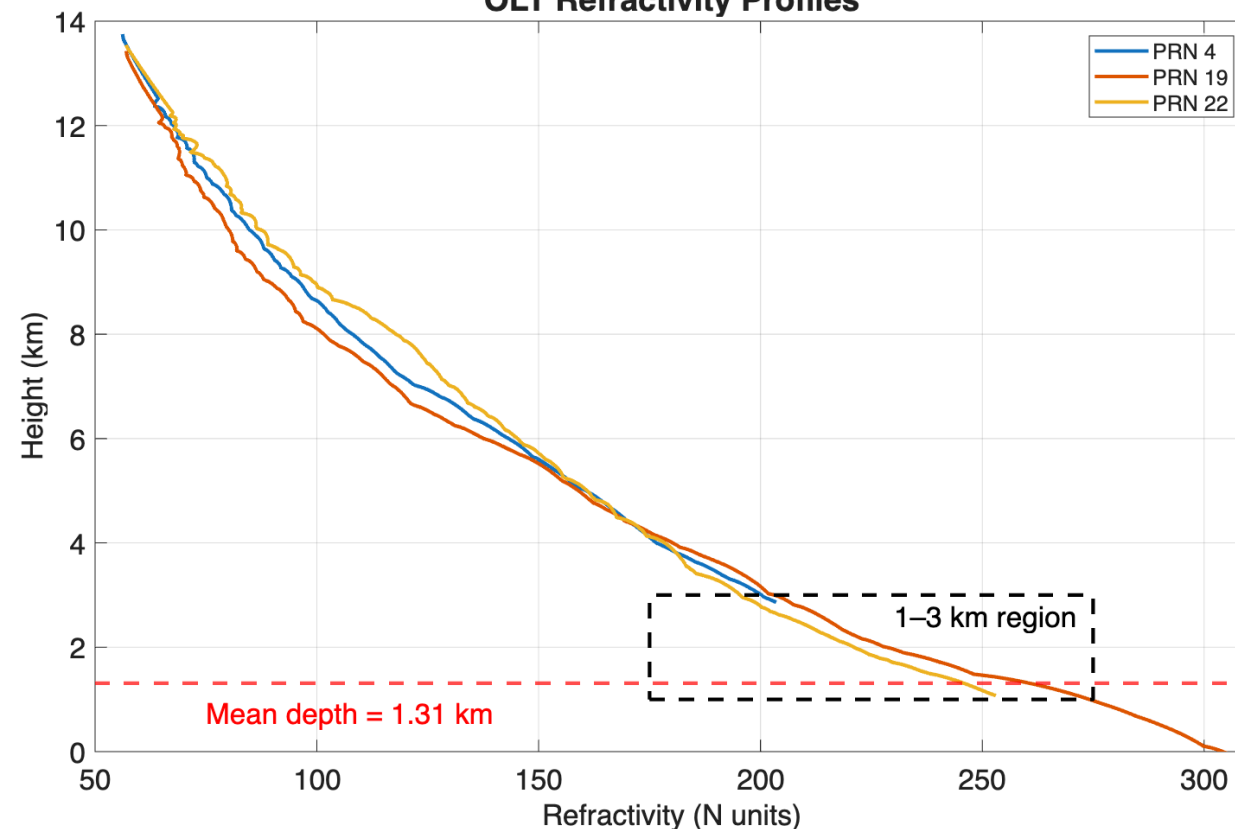
- SAFARI moored buoy provides continuous measurements of air-sea fluxes in N Central Pac
- AR Recon C-130s performed multiple buoy overflights in AR and non-AR conditions
- Prior work enables ML labeling of atmospheric structural regimes using N'
- How do air-sea fluxes vary between atmospheric structural regimes over space/time e.g. cold frontal passage over buoy?
- How can ARO data characterize tropospheric thermodynamic structure above the buoy, identify features related to air-sea fluxes?





OLT has been implemented on the **CalWater 2015 campaign** which provides a unique dataset combining: ARO and dropsonde, GISMOS GNSS recorder for OLT, surface flux measurements from R/V Ronald H. Brown. This makes it ideal for studying **air-sea interaction and surface flux and PBL relationships in an AR case**. OLT can track the signal down to depths (< 3 km) with challenging atmospheric conditions. Enables retrieval of atmospheric profiles closer to surface.

OLT Refractivity Profiles



- **Mini GISMOS – GNSS Instrument System for Multistatic and Occultation Sensing**
- **16 channel** instrument collecting occulted and reflected GNSS signals to **determine tropospheric water vapor characteristics** during long duration flights through storms
- Currently, **ARO with conventional GNSS receivers is unable to penetrate sharp refractivity gradients** due to complex signal propagation (multipath)
- Implement **Open-Loop Tracking (OLT)** on the **mini-GISMOS receivers to observe near the surface** in high refractivity gradient environments
- **Deployment** for lower troposphere data collection on NASA 777 in **NURTURE 2027**

Conclusions

- ARO systems deployed on all GARRP aircraft, yielding 5882 profiles from a combined 112 flights. All GARRP ARO Data (G-IV, WC-130s, G-III, G-550) available at https://agsweb.ucsd.edu/gnss-aro/ar2026/postProc_20260528/.
- ARO and other GARRP observations capture a series of synoptic-scale features that propagate across GARRP domain in early Feb 2026
- Data collected in 2026 provides numerous avenues of future research, including air-sea flux investigations, data assimilation experiments and future lower-troposphere instrument deployments

Acknowledgements

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- Development and deployment of ARO on the NOAA Gulfstream G-IV were supported through collaborations involving the, CW3E, NOAA NCEP, CA DWR, and the U.S. Army Corps of Engineers Forecast-Informed Reservoir Operations Program.