Atmospheric Rivers in 3 dimensions

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The ARO Team:

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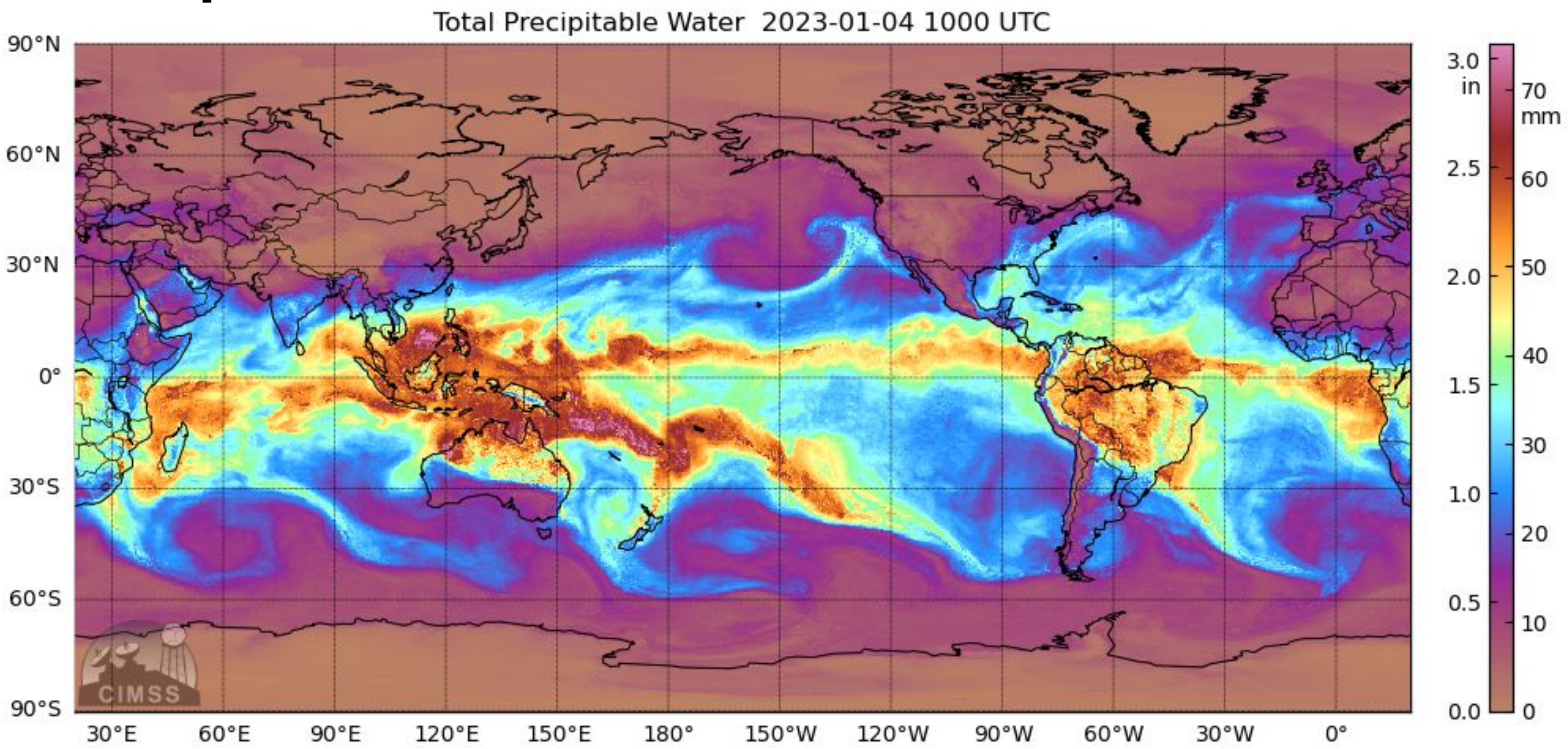
CW3E: Brian Kawzenuk, Marty Ralph, Anna Wilson

Announcements

- Postdoctoral research position open
- GNSS research analyst position open
- **Datasets: https://agsweb.ucsd.edu/gnss-aro/**
- Cao, B., Haase, J. S., Murphy Jr, M. J., & Wilson, A. M. (2024). Observing atmospheric rivers using multi-GNSS airborne radio occultation: system description and data evaluation. *Atmospheric Measurement Techniques Discussions*, *2024*, 1-44.
- **ARO ROPP Observation Operator: https://github.com/jhaaseresearch/sio-aro-ropp and JCSDA Skylab**
- Hordyniec, P., Haase, J. S., Murphy, M. J., Cao, B., Wilson, A. M., & Baños, I. H. (2024). Forward modeling of bending angles with a two-dimensional operator for GNSS airborne radio occultations in atmospheric rivers. *Authorea Preprints*. (submitted to JAMES)

- Posters:
- Ben Davis – Sentinel 6A SRO – 5A P2
- Bing Cao – ARO complete system description – 6A P2
- Haley Lowes-Bicay – Waves in Balloon RO – 25B P2
- Isabel Reinicke – ARO Open Loop Tracking – 26A P2
- Kate Lord – ARO phase matching retrievals – 11B P1
- Nghi Do – ARO data assimilation – 5B P2
- Noah Barton – ARO in hurricanes – 4B P2
- Pawel Hordyniec – PBL in ARs – 6B P2

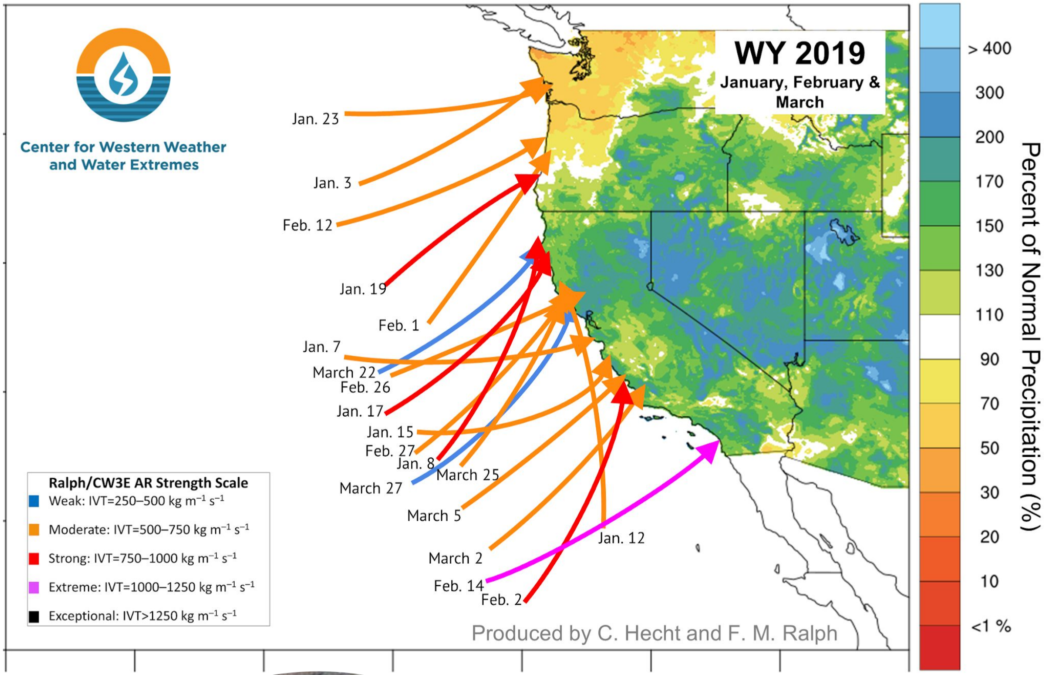
Atmospheric Rivers

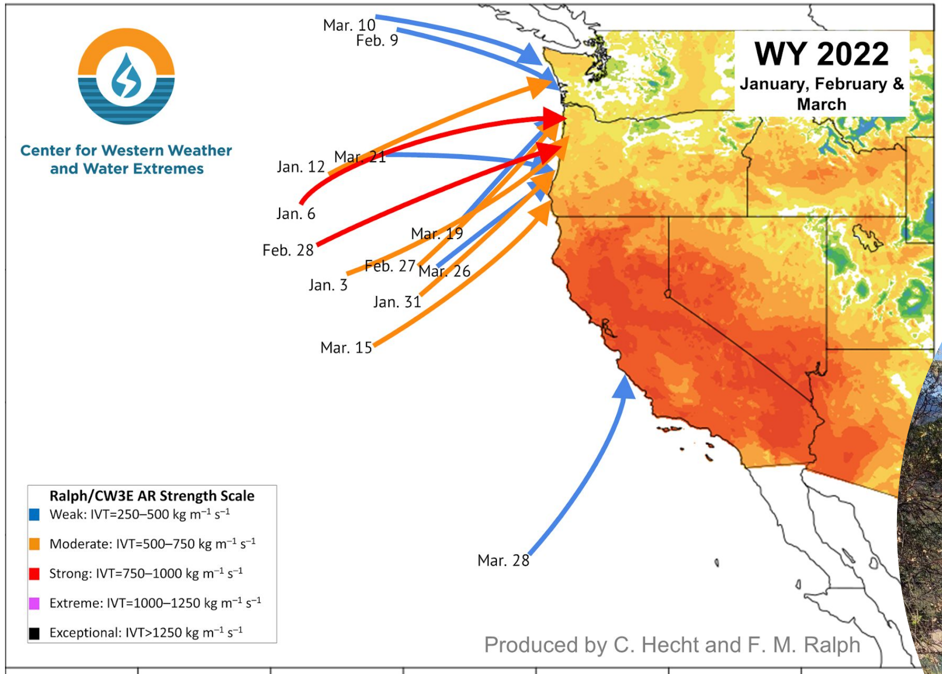


ARs are long narrow filaments of water vapor transport in the lowest 3-4 km altitude that account for > 90 % of meridional midlatitude water vapor transport (Zhu and Newell, 1998).

http://tropic.ssec.wisc.edu/real-time/mtpw2

Atmospheric Rivers: Flood versus Drought





84% of All Flood Damages over 40 years in the West are from ARs

Corringham, Ralph, Gershunov, Cayan and Talbot, Sci. Advances (2019)

In water year 2022, the lack of ARs led to 10% of the normal precipitation.
Water security is a huge challenge in the west.

Dettinger,J. Am. Water Resources, (2011)

Conceptual View of ARs and AR Reconnaissance Mission Design

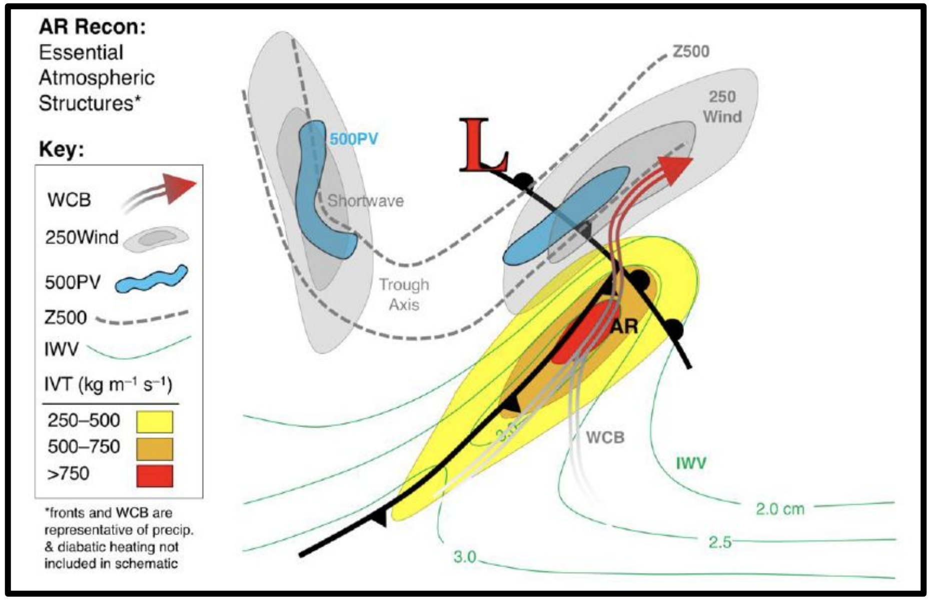


Figure: J. Cordeira, CW3E

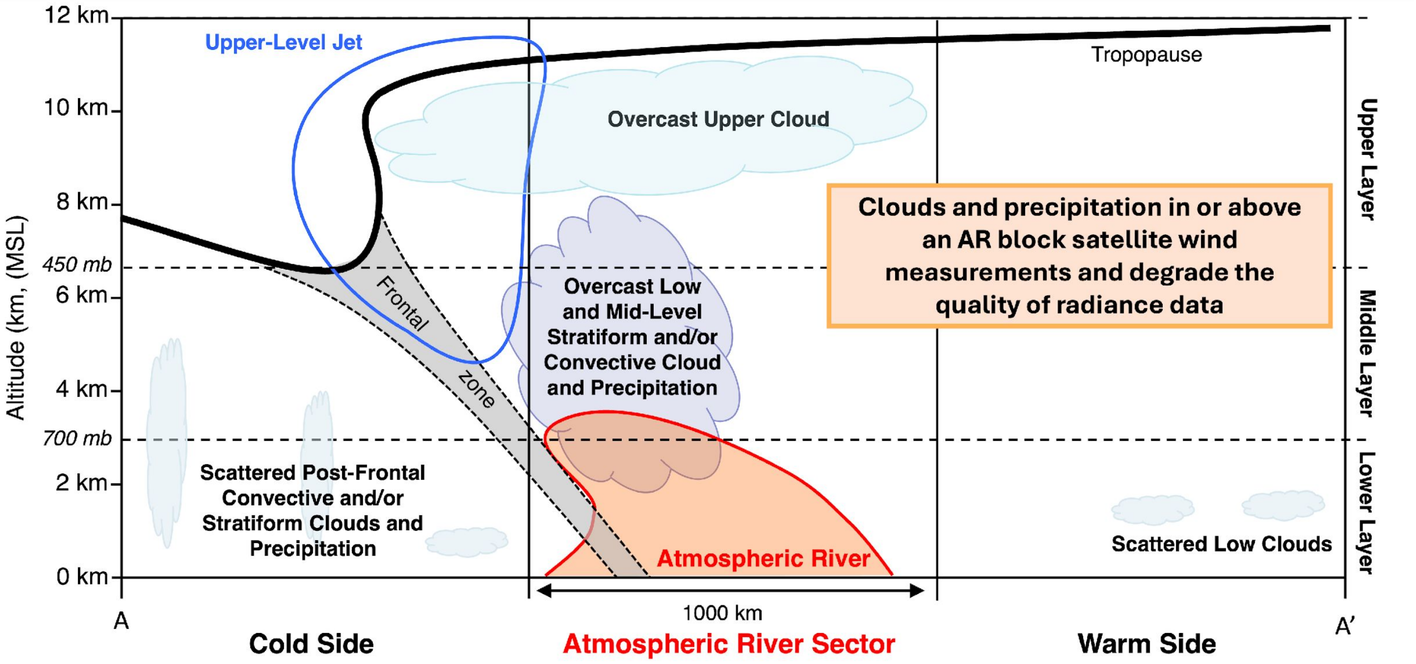
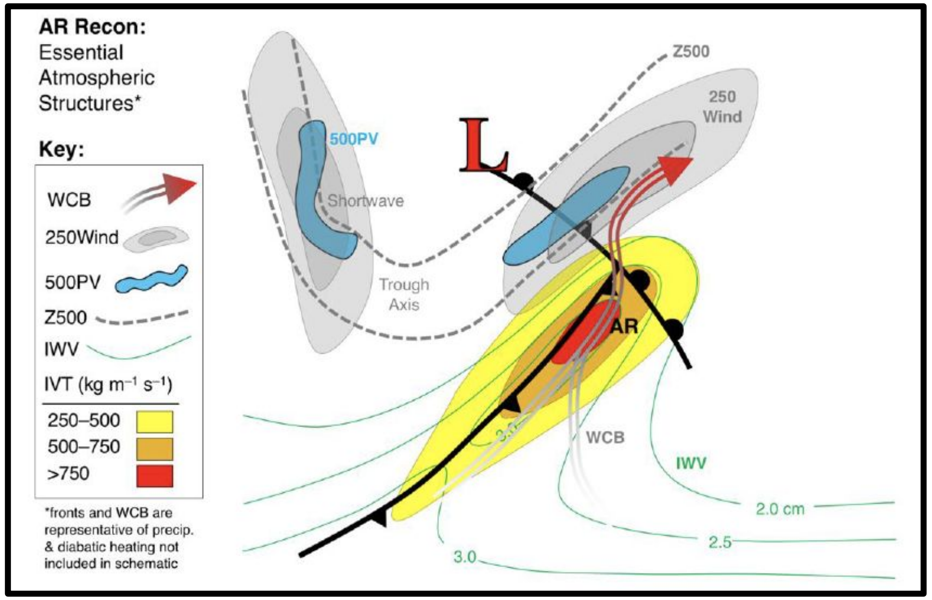


Figure: Zheng et al. 2021a, Ralph et al. 2017

- Sample essential atmospheric structures.
- Low predictability in zone of latent heat release during warm conveyor belt ascent.
- Enhances PV, feeds back into low-level jet.
- Also sample adjoint model sensitivity.

- Sample in the region where satellite radiance and wind observations are blocked by clouds and precipitation.

Conceptual View of ARs and AR Reconnaissance Mission Design



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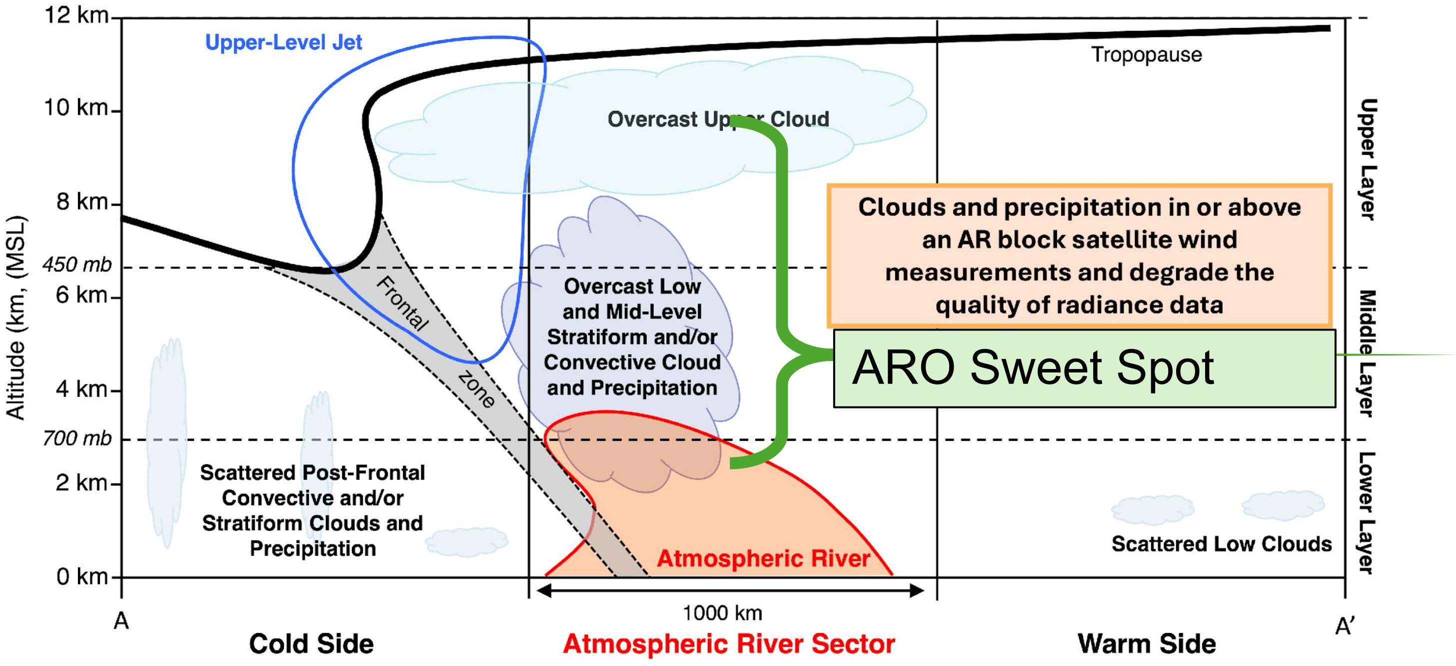

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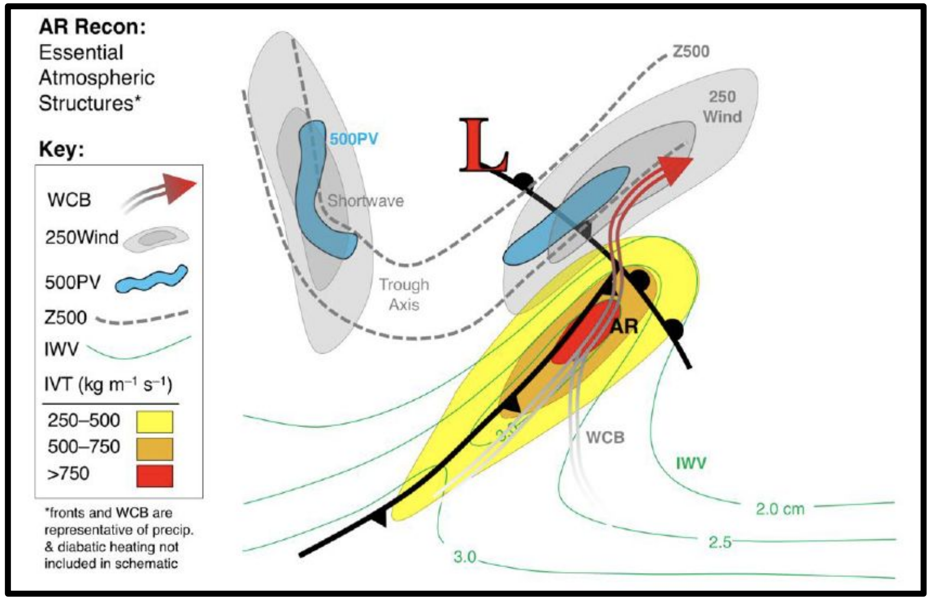

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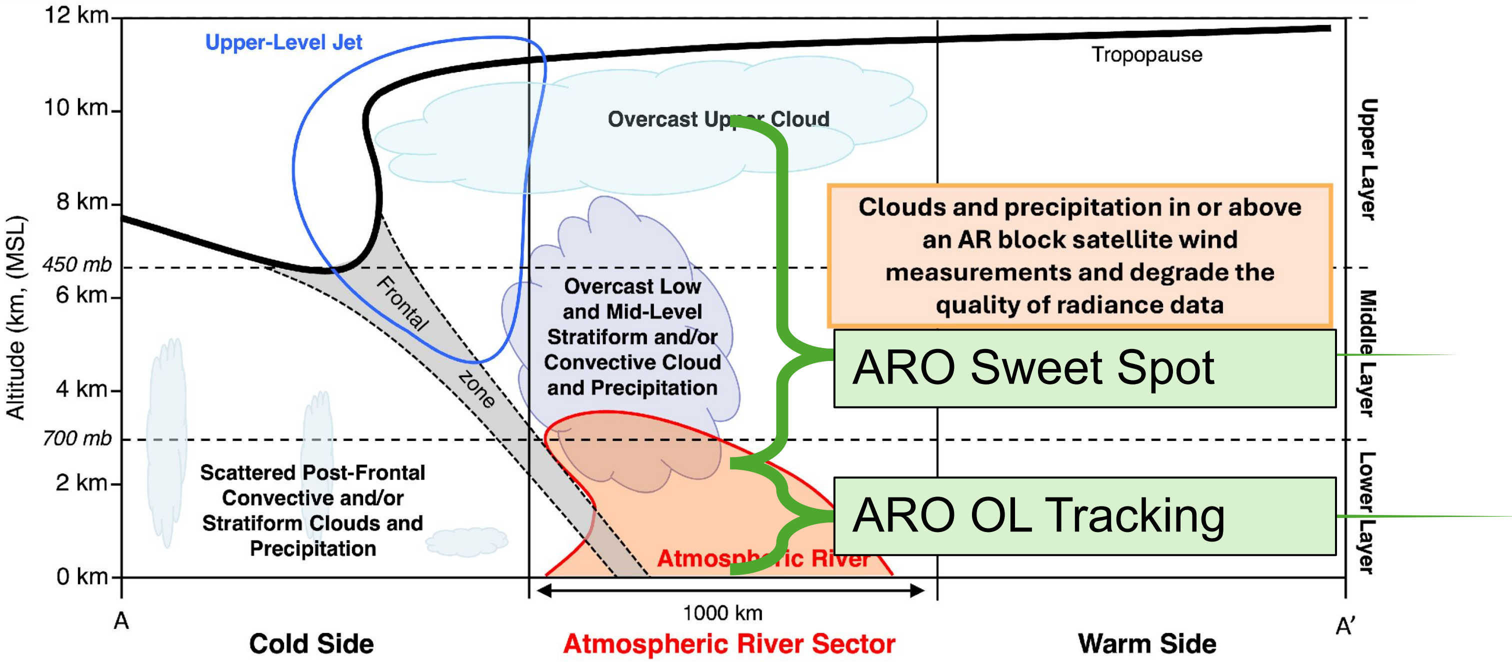

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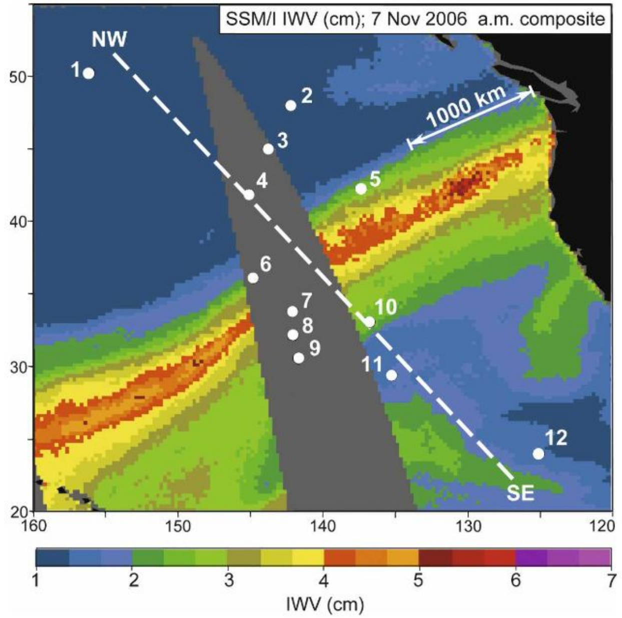
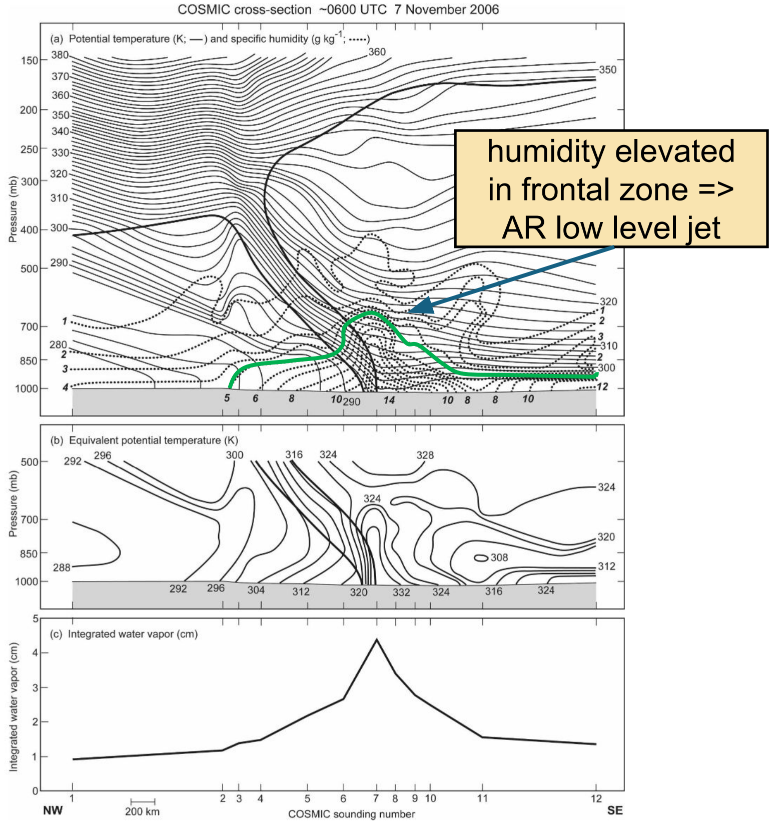
Transects of an AR from COSMIC-1

- Importance of moisture for the predictability of Pacific storms in atmospheric rivers is recognized
- Next frontier is enhancing RO usage in the troposphere
- Sampling of spaceborne RO is approaching that of ARO
- Concentration in time is important to reveal structures and their evolution
- Value in examining in detail the contribution of RO to mesoscale systems to develop intuition in terms of potential impacts.

Location of COSMIC-1 profiles used for transect



Interpolated humidity retrievals



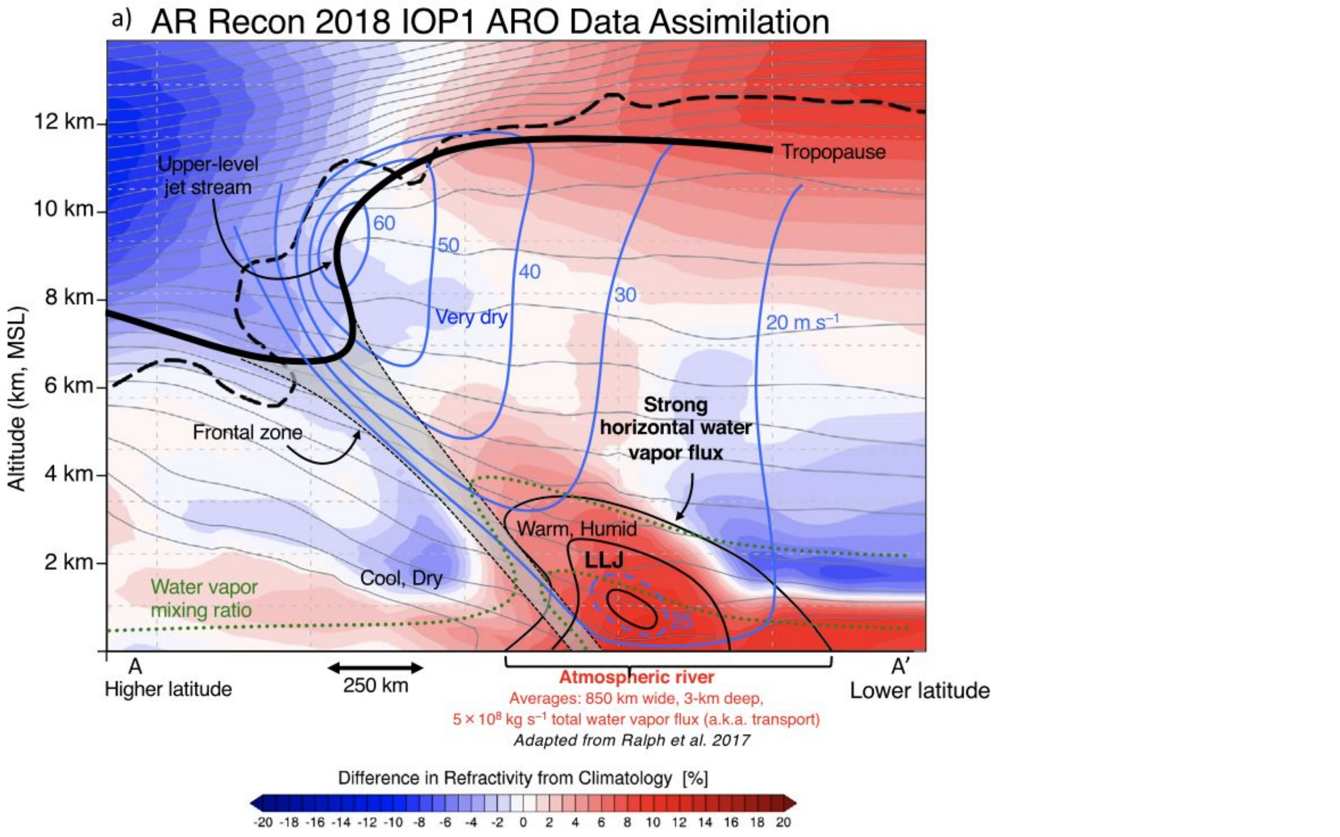
Neiman, P.J., Ralph, F.M., Wick, G.A., **Kuo, Y.H.**, Wee, T.K., Ma, Z., Taylor, G.H. and Dettinger, M.D., 2008. *Diagnosis of an intense atmospheric river impacting the Pacific Northwest: Storm summary and offshore vertical structure observed with COSMIC satellite retrievals. Monthly Weather Review, 136(11), pp.4398-4420.*

Refractivity anomaly N′

- Refractivity anomaly introduced in Haase et al., 2021.

$$\frac{(N - N_{climatology})}{N_{climatology}}$$

- Highlights vertical structure in atmospheric rivers.
- Separation of variations in UT/LS temperature and lower troposphere moisture.
- ARO assimilation in this example creates increments in mid and upper levels.



Haase, J.S., Murphy, M.J., Cao, B., Ralph, F.M., Zheng, M. and Delle Monache, L., 2021. Multi-GNSS airborne radio occultation observations as a complement to dropsondes in atmospheric river reconnaissance. Journal of Geophysical Research: Atmospheres, 126(21), p.e2021JD034865.

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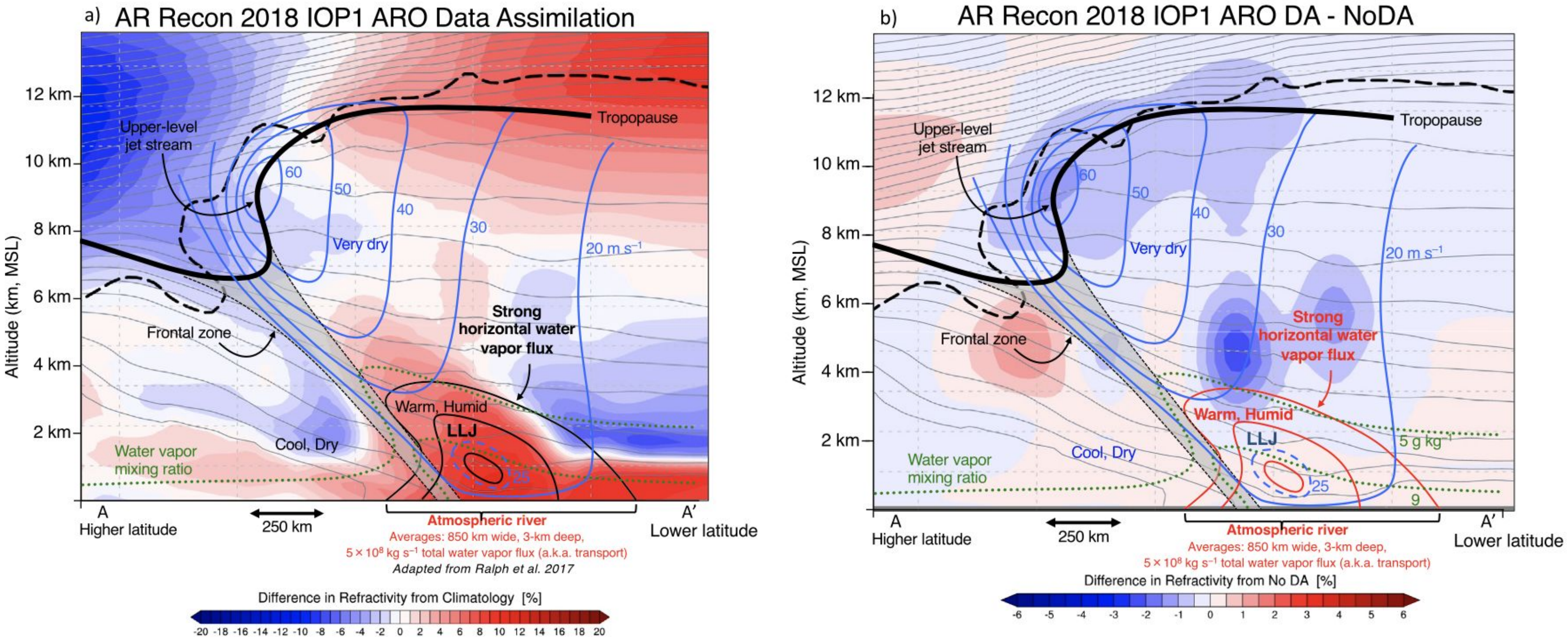

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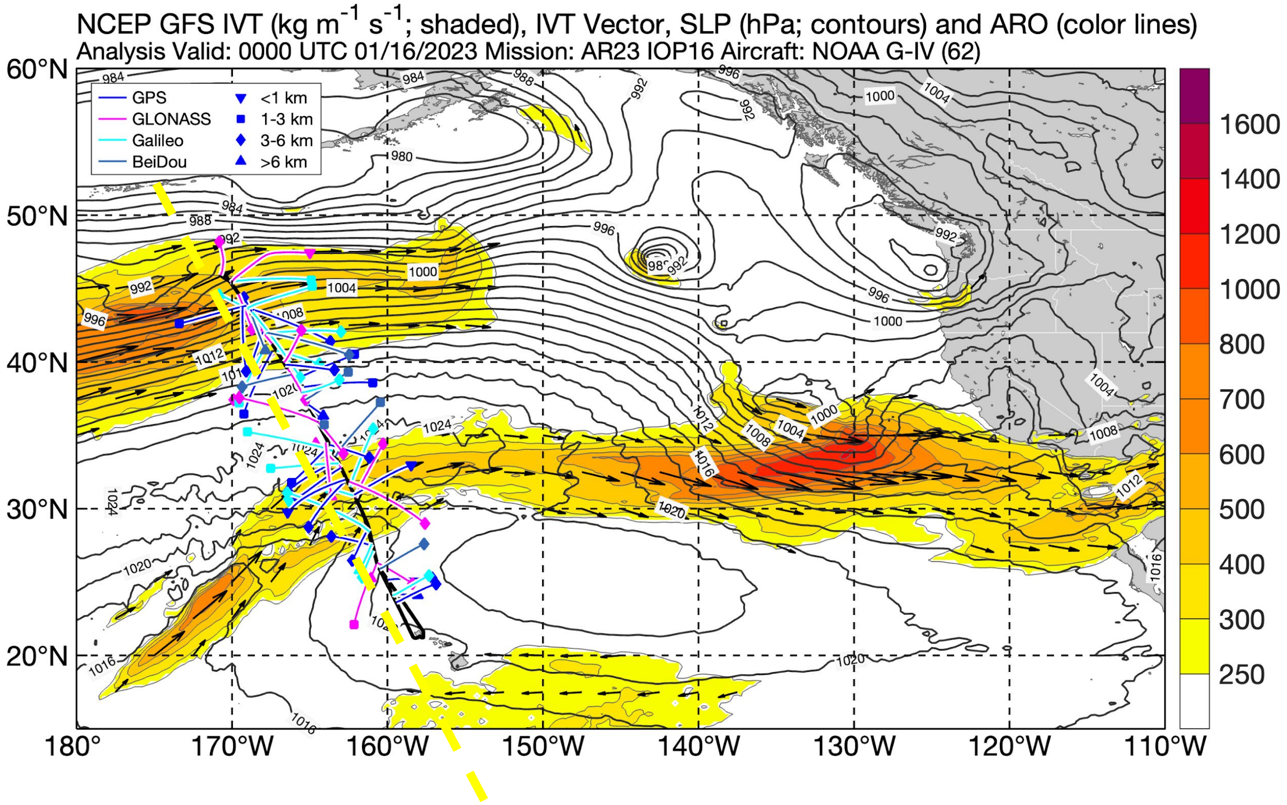
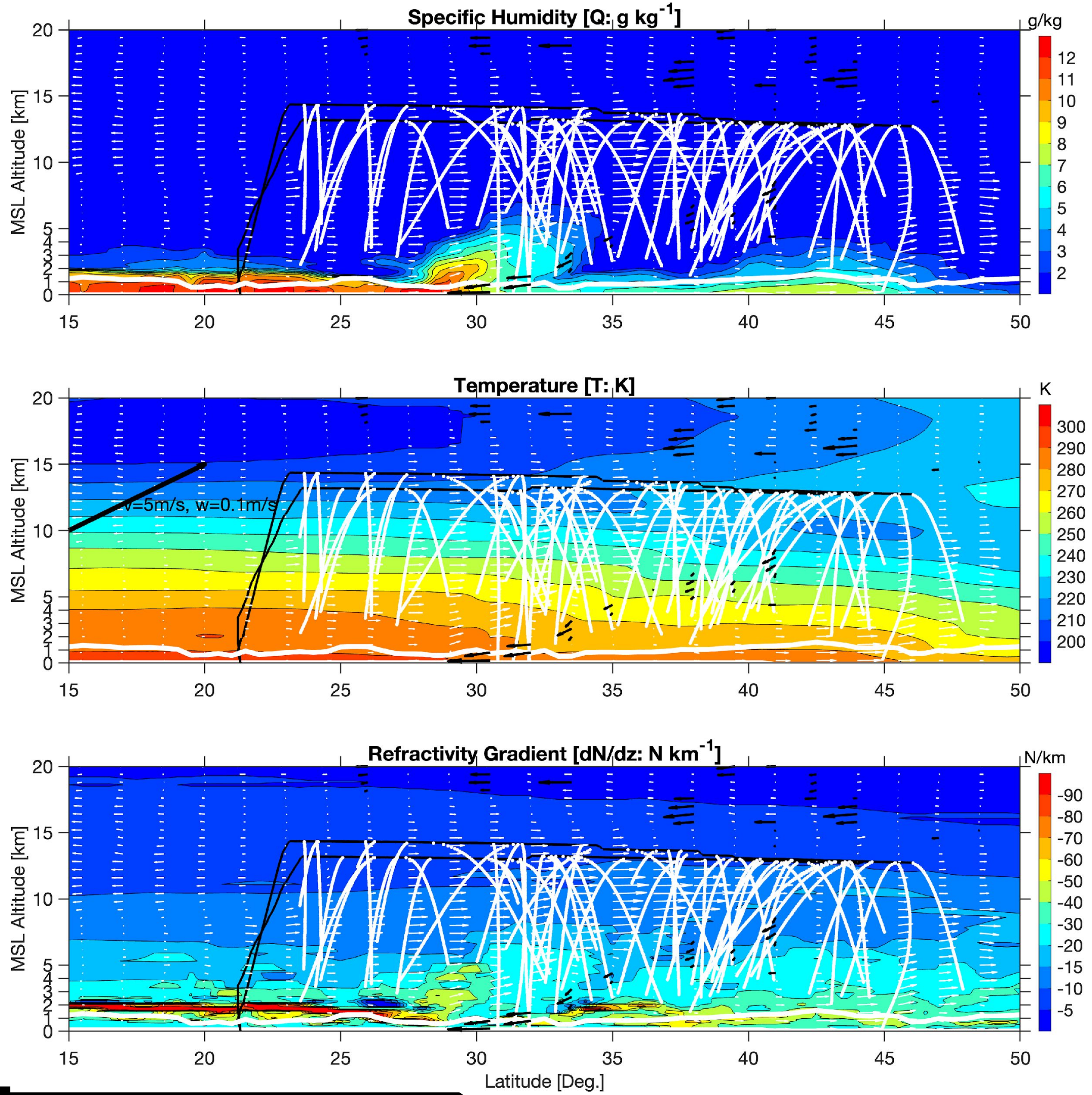
Example of an AR in 3D



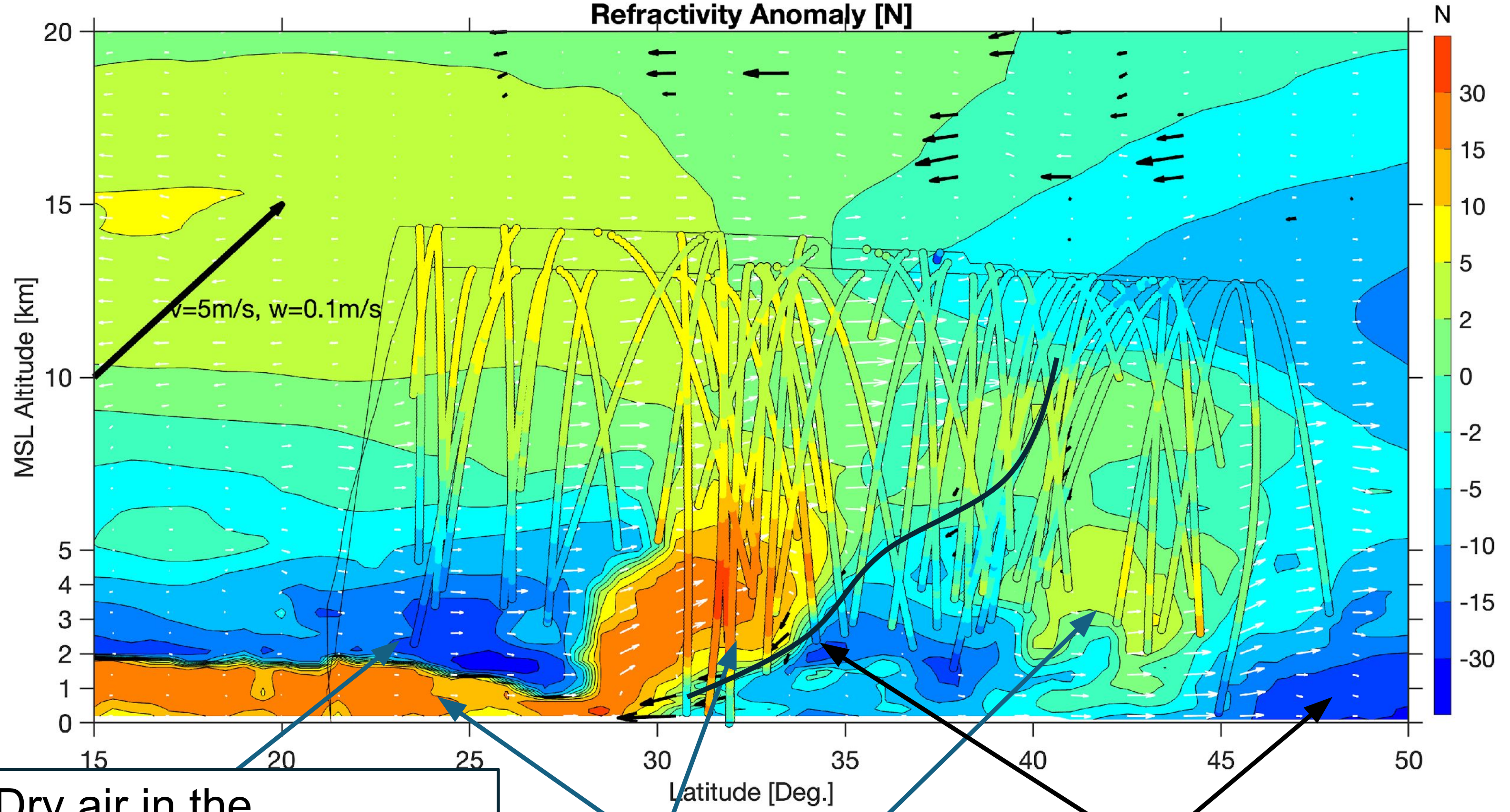
- AR Recon IOP16 2023-01-16 00Z
- Straight-line flight track traversed two ARs at different stages in their development.
- 27 dropsondes were launched, 14 on the outbound flight and 13 on the inbound flight.
- 62 multi-GNSS ARO profiles were retrieved on both sides of the track.



Transects from ERA5

- Specific humidity, temperature, meridional and vertical winds, and refractivity gradient from the ERA5 reanalysis were interpolated to the selected transect.
- Slanted ARO profiles are projected onto the same selected transect.
- Most profiles stop at 3-4 km altitude when the refractivity gradient reaches -30~-40 N/km.
- Deepest profiles are in the AR core where there is vertical mixing of moisture that disrupts the PBL.

ERA5 and ARO Refractivity Anomaly



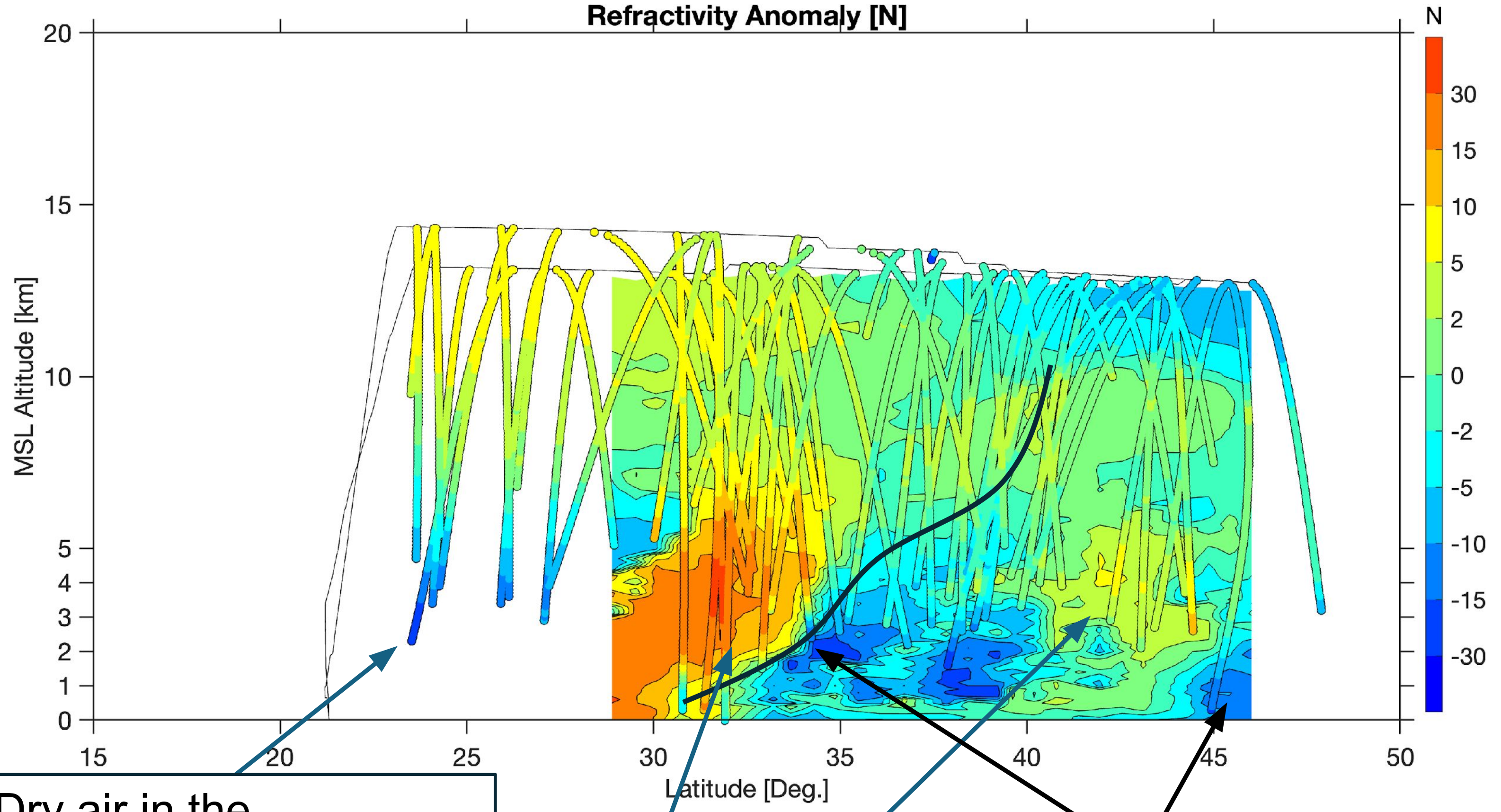
Dry air in the subtropical high trapping moisture in the

Enhanced Moisture

Dry/cold air intrusion behind the front

- Refractivity anomalies from the climatological mean
  - Background: ERA5 reanalysis
  - Overlay: ARO observations
- Scattered ARO profiles sense the same features as ERA5.
- ARO resolves lower troposphere structure, in particular dry air undercutting the frontal structure.

Dropsonde and ARO Refractivity Anomaly

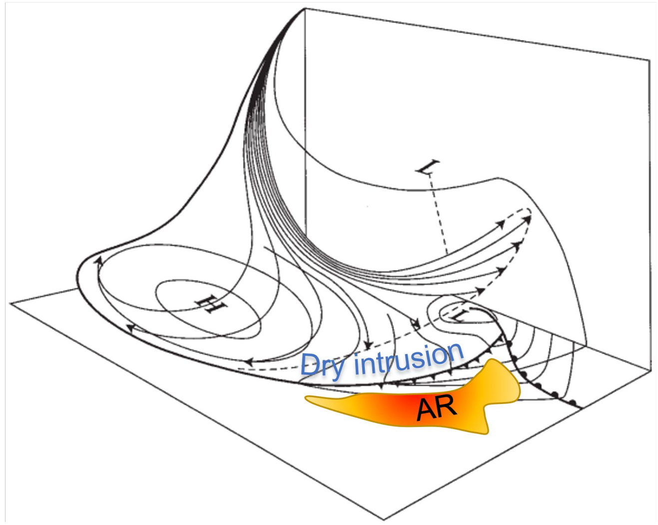


Dry air in the subtropical high trapping moisture in the

Enhanced Moisture

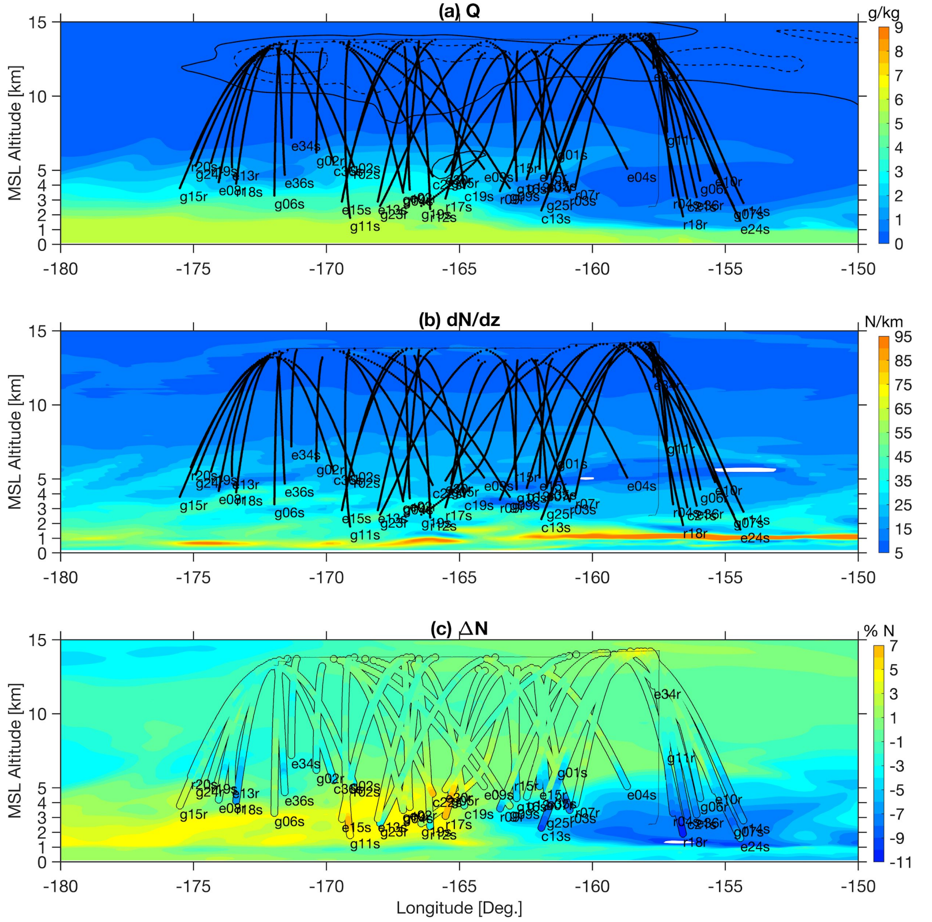
Dry/cold air intrusion behind the front

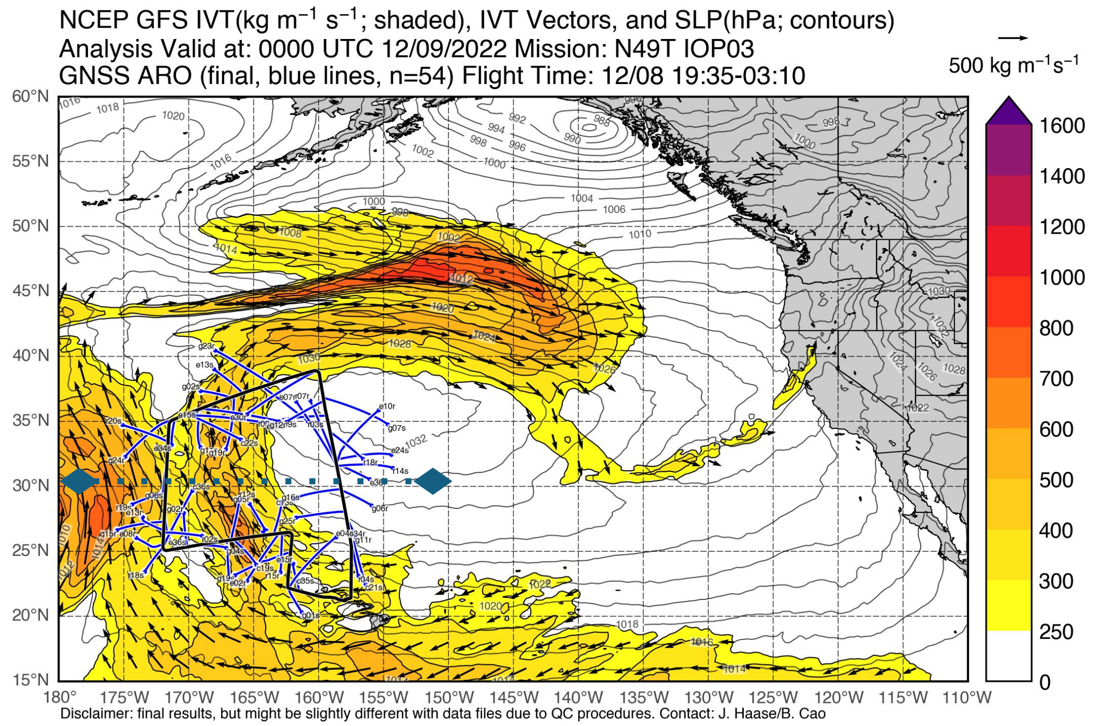
- ARO reproduces the same structures as the dropsondes at similar scales.



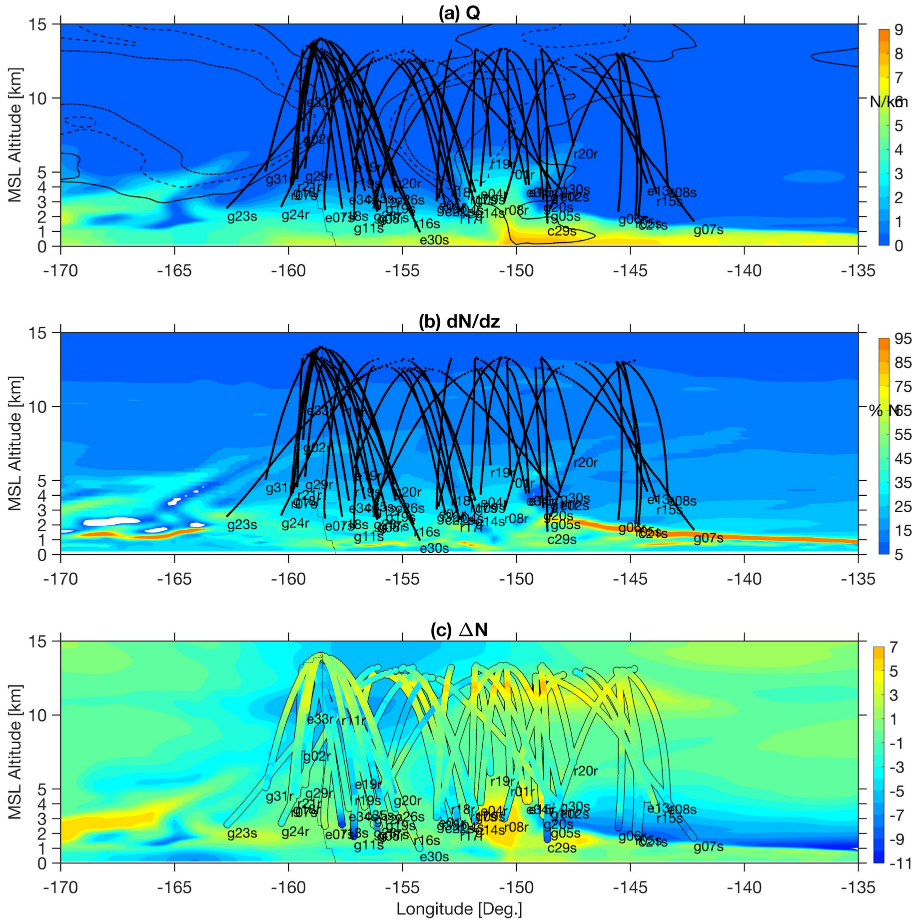
Dry intrusion schematic with rapid descent of dry air and strong damaging winds, Browning KA et al., (1997), QJRMS

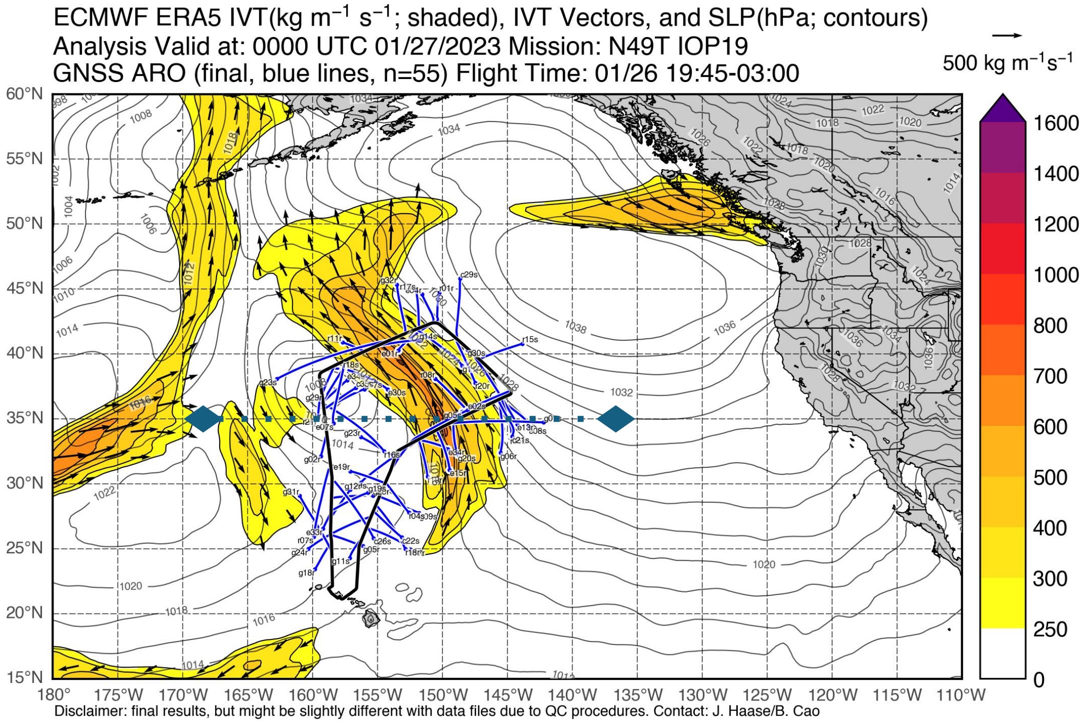
Refractivity Anomaly Transect IOP03 AR2023



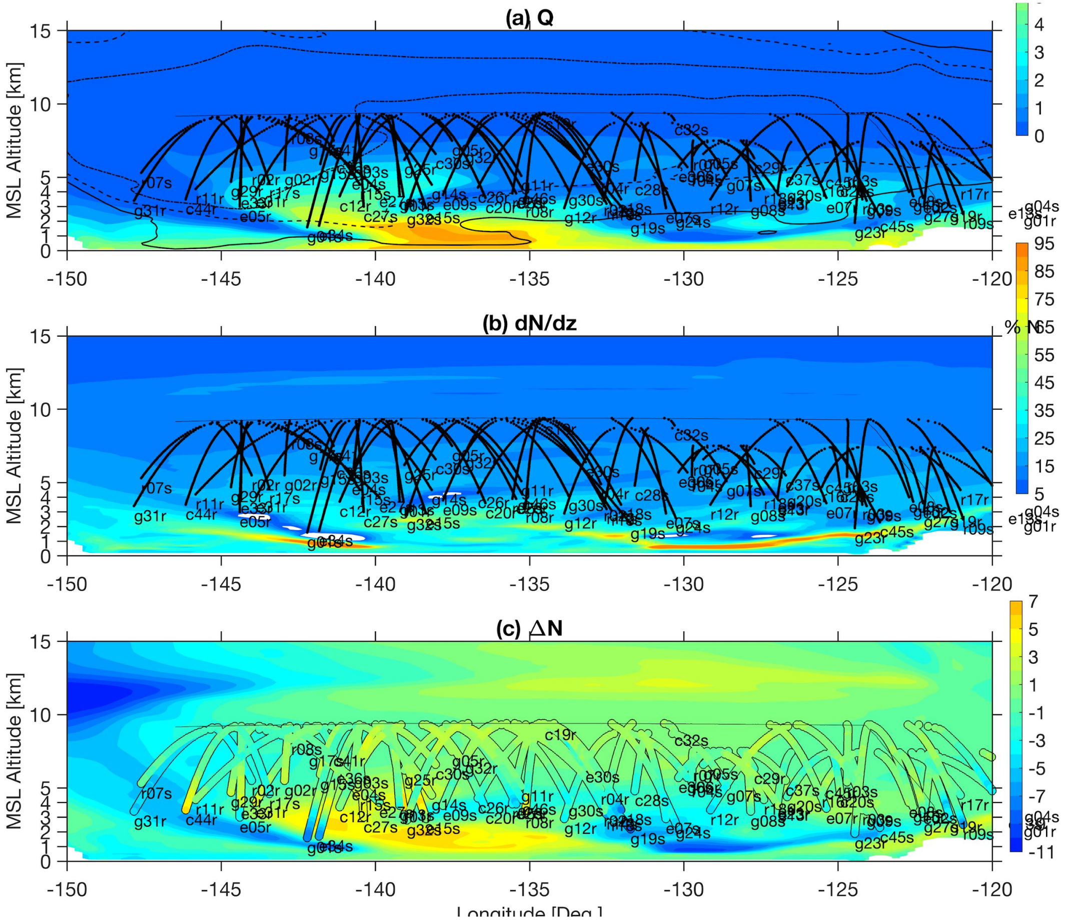


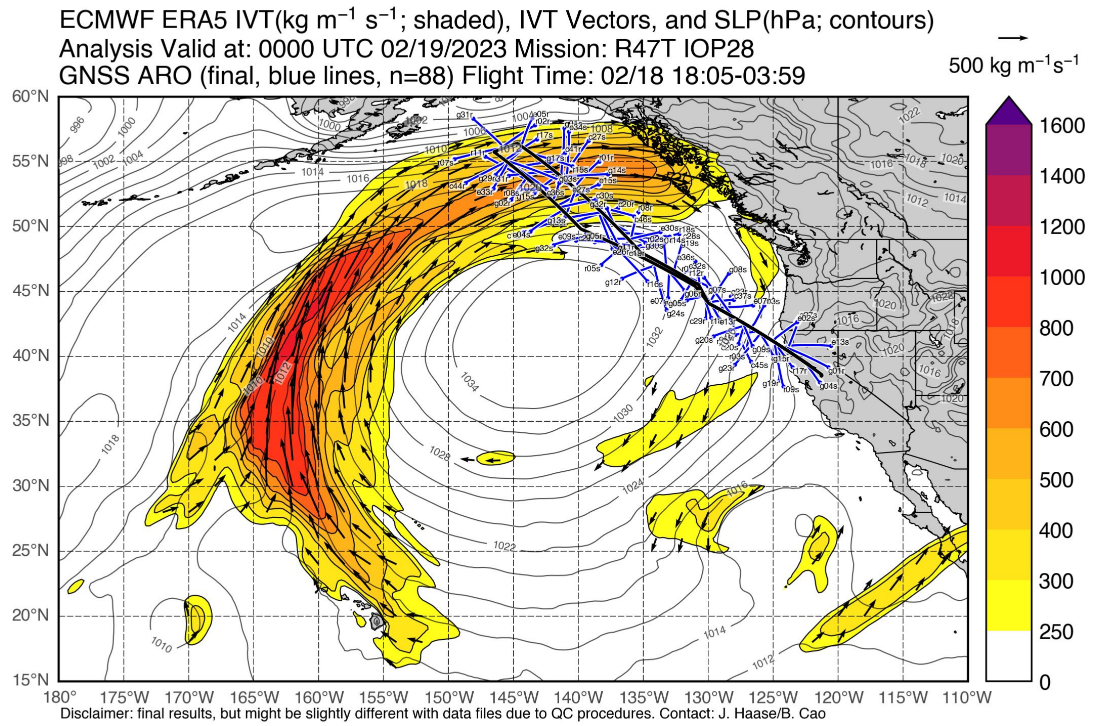
Refractivity transect IOP19 AR2023



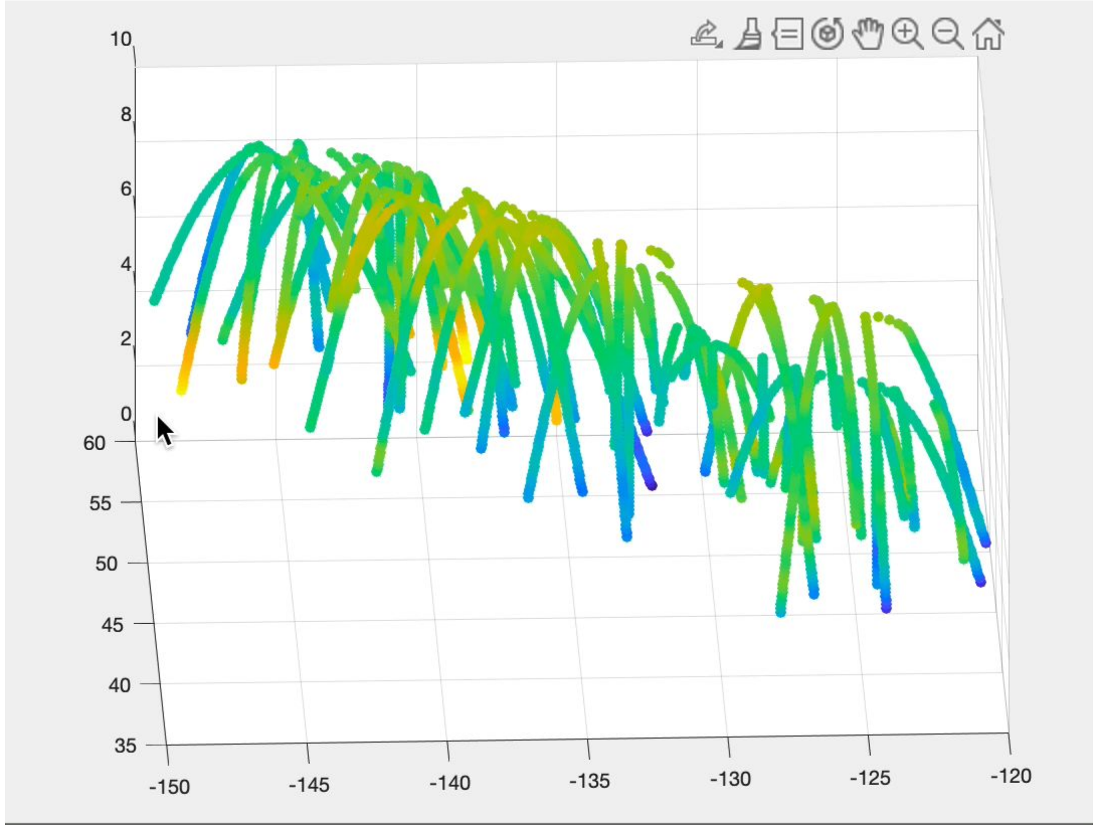


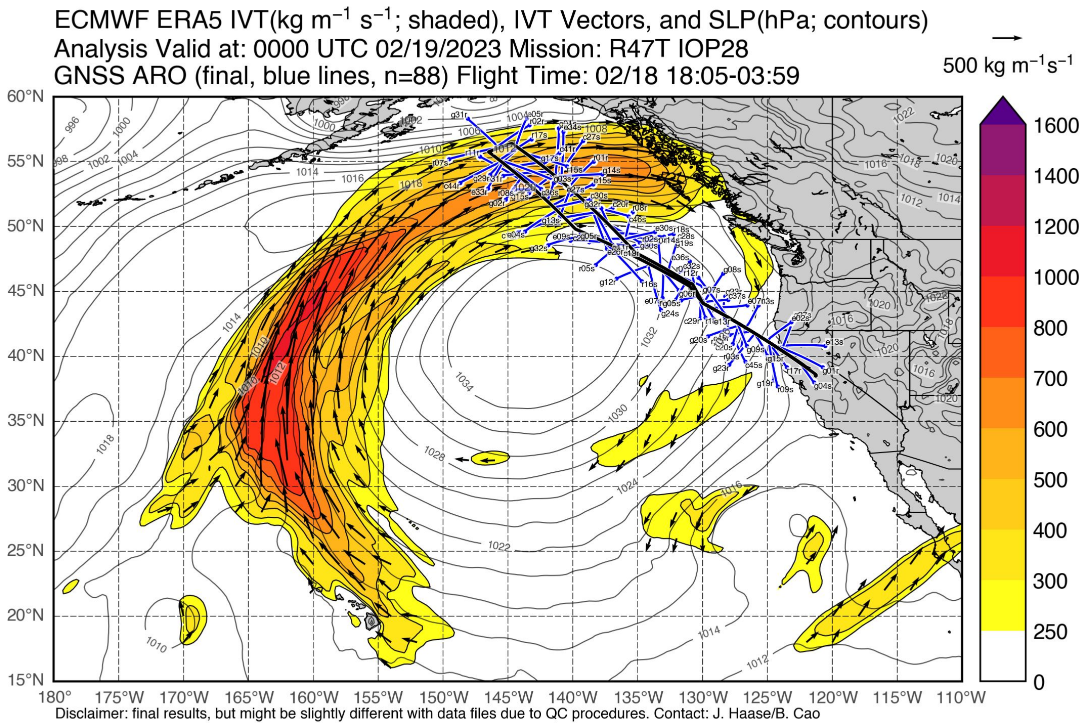
Refractivity Anomaly Transect IOP28 AR2023





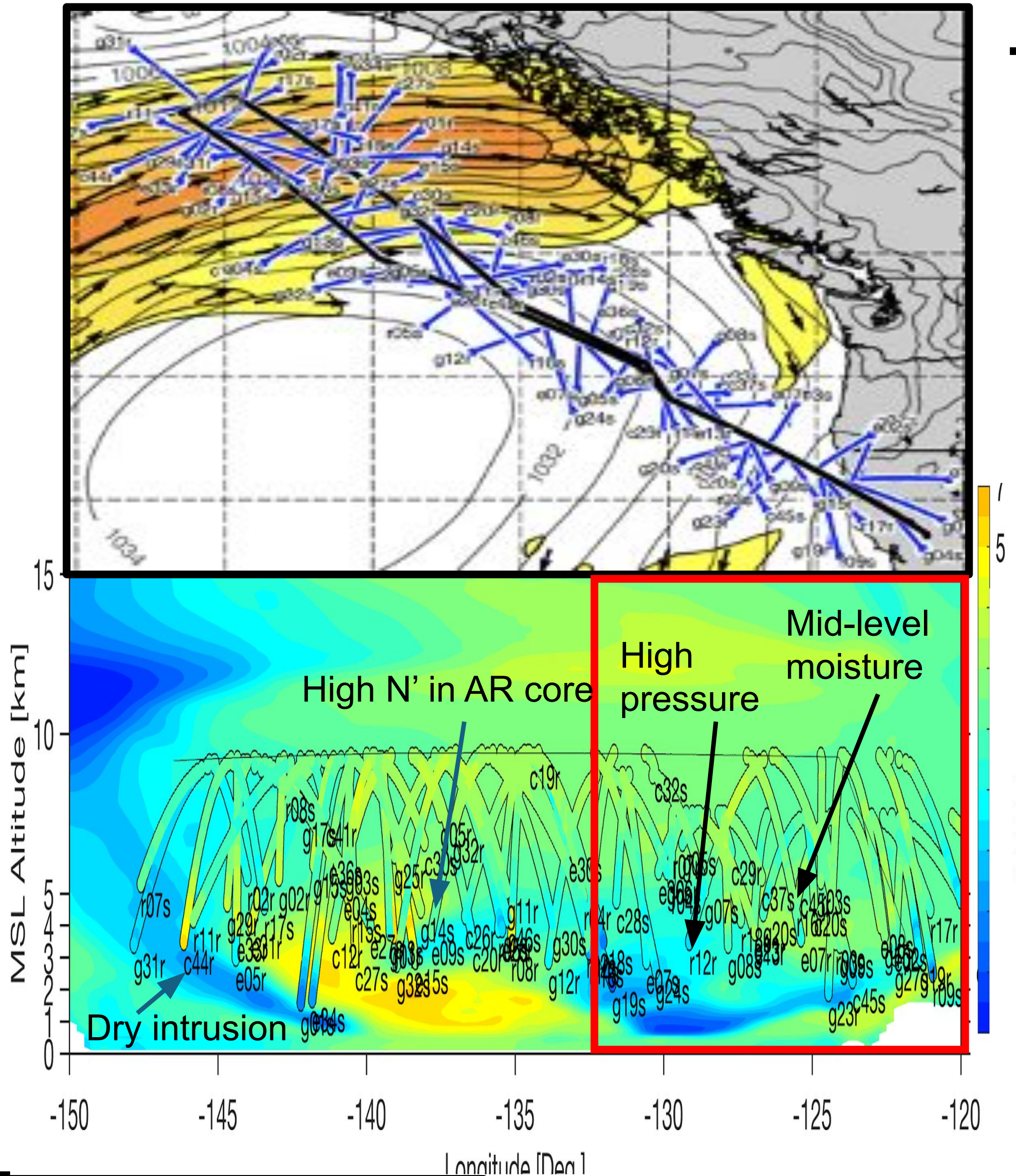
Refractivity Anomaly Transect IOP28 AR2023



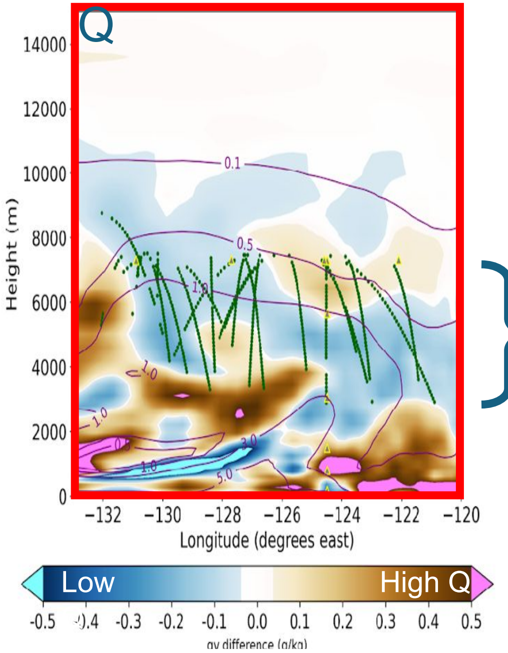


Transect IOP28 AR2023

- Data assimilation experiment with MPAS-JEDI
- Control – no ARO observations vs ARO observations assimilated
- Features that are observed in N’ are refined and improved when ARO is assimilated compared to control



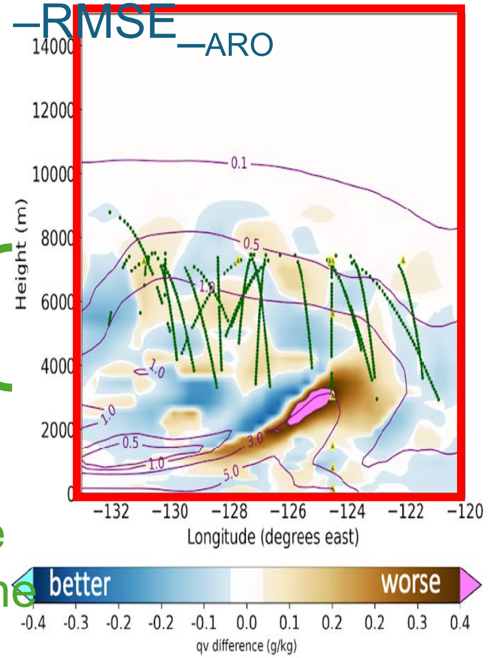
Control – ERA5 Q



Control experiment is too dry in the mid-levels

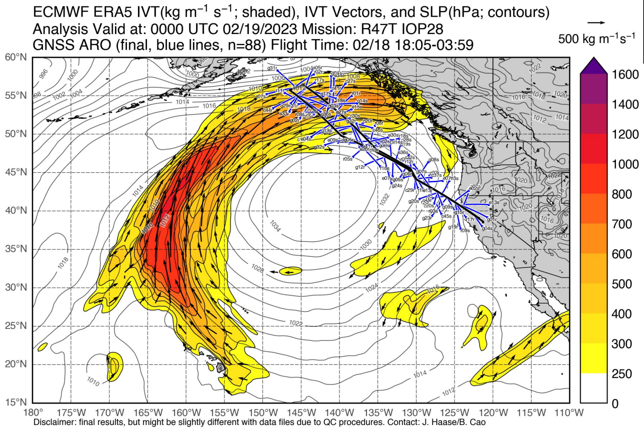
ARO experiment reduces the RMSE in the mid-levels

RMSE_Control – RMSE_ARO

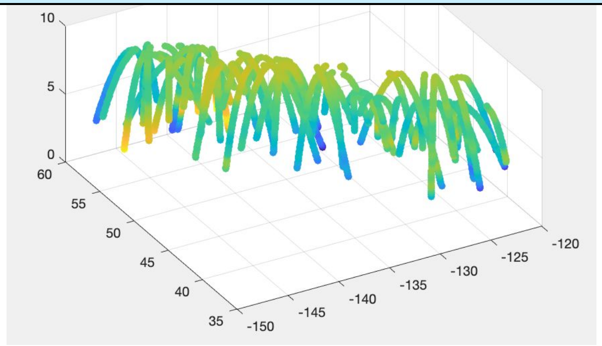


Forecast improvement from ARO data assimilation

Nghi Do, J.S. Haase, B. Cao, P. Hordyniec, I. Banos, Z. Liu Poster 5-B



Slanted profiles stretch from the flight track sideways up to ~450 km away.

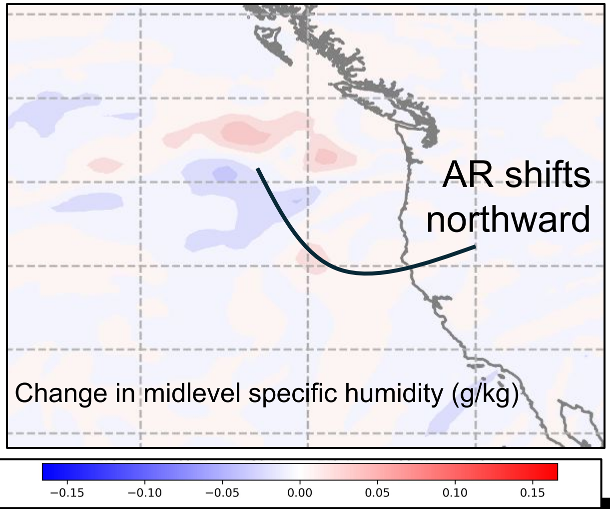


ARO has lower precipitation error in WA, OR, and ID linked to the reduced IVT error after assimilation

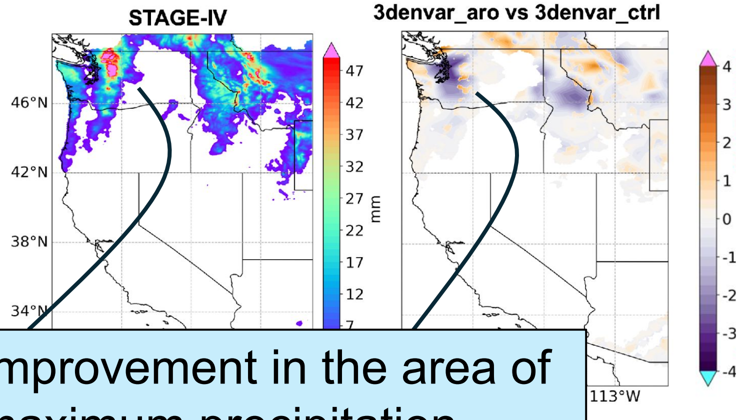
MPAS
Model for Prediction Across Scales

3D ensemble variational data assimilation experiments

- MPAS global model w/60 km mesh
- JEDI data assimilation system with 2D RO Operator
- 6 hr cycling DA with 30 ensemble members
- Control: surface pressure including buoys, conventional observations, dropsondes, AMV winds, GNSS RO
- ARO: Control + ARO



Verification against 24-h Stage-IV accumulated precipitation

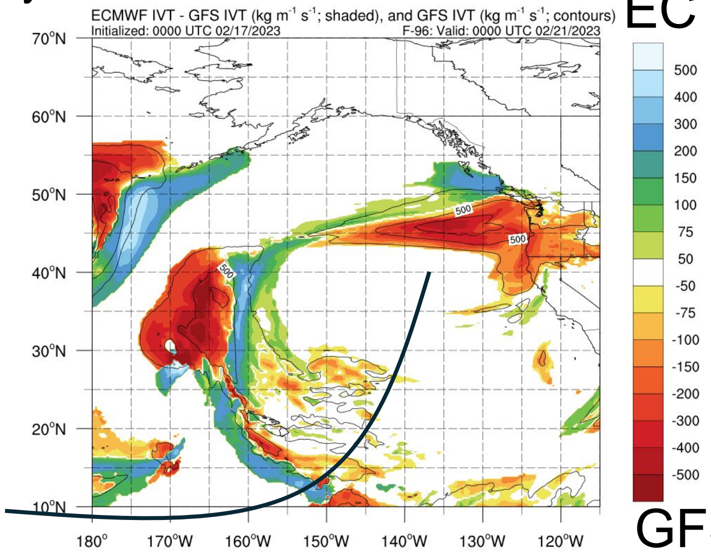


ctrl has lower error

aro has lower error

Improvement in the area of maximum precipitation

3-day forecast ECMWF minus GFS



IVT Core location is corrected and magnitude is reduced where it was poorly forecast.

Conclusions

- A higher resolution picture of AR structure is emerging when analyzed in terms of refractivity anomaly, given the density of profiles that ARO provides.
- ARO profiles constrain
  - the sloping nature of the AR core and dry postfrontal air beneath it
  - the location of mid-level moisture derived from ascent in the warm conveyor belt
  - the disruption of the marine boundary layer due to upward mixing of moisture at the AR core
  - descent of dry stratospheric air from the tropopause in the frontal zone
  - the top boundary of moisture beneath the subtropical high and high pressure in general
  - (Note: there is a difference between Ri PBL versus dN/dZ)
- This provides context for improvements seen in data assimilation experiments and more insight into the reason for DA impacts

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- ARO team: N. Contreras, E. Sawyer, C. Wang
- CW3E: F. Martin Ralph, Anna Wilson, Brian Kawzenuk, Minghua Zheng, Jay Cordeira, Luca Delle Monache
- JCSDA: Ben Ruston, Francois Vandenberghe and others
- NCAR: Zhiquan Liu and others