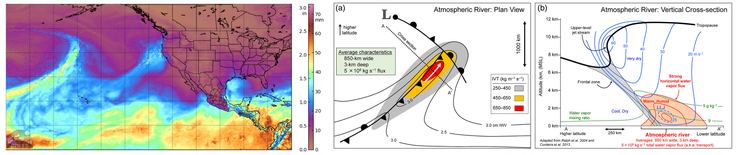
Machine Learning Techniques to Assign Observation Error for Airborne Radio Occultation Profiles in Atmospheric Rivers

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Atmospheric Rivers (ARs) determine water security in the West

- ARs are long filaments of water vapor transport in the lowest 3-4 km altitude that account for > 90 % of meridional midlatitude water vapor transport [1].
- Variability in AR frequency, intensity and landfall location impact water security in the American West.
- 84% of All Flood Damages over 40 years in the West are from ARs [2].
- In water year 2022, the lack of ARs led to 10% of the normal precipitation. Water security is a huge challenge in the West. [3]
- Skillful forecasting of ARs can allow for mitigation against flooding and drought impacts [4].
- For the assimilation of ARO to be most beneficial, an accurate estimate of observation error is required.

TPW from CIMSS



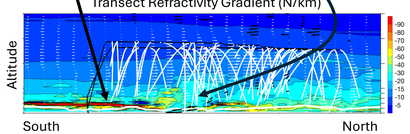
Ramos et al 2018

Hypothesis: AR Structures Affect Penetration Depth & Error

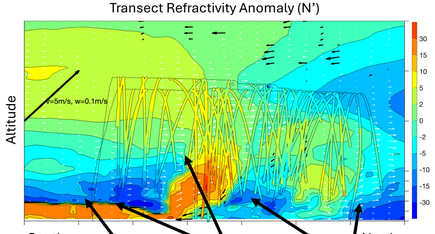
- The lower vertical extent of RO profiles (penetration depth) varies between the AR core and surrounding environments [5].
- It is hypothesized that penetration depth in and around ARs is a function of vertical gradient in refractivity $\frac{dN}{dz}$ [5].
- Refractivity anomaly shown at right illustrates high anomaly for very moist AR and boundary layer [7][9].

Large negative gradients in $\frac{dN}{dz}$ associated with subtropical high on warm side of AR limit penetration depth

Weaker gradient in AR core allows deeper penetration depth



Transect Refractivity Anomaly (N')



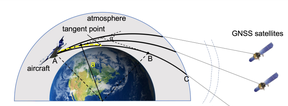
Dry air in the subtropical high trapping moisture

Enhanced Moisture

Dry/cold air behind the front

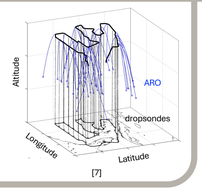
Airborne radio occultation (ARO) collects thermodynamic profiles of the middle & upper troposphere

- A GNSS receiver onboard the aircraft tracks refracted GNSS signals passing through the atmosphere.
- Refractivity profiles contain mid to upper-level pressure, temperature and moisture information.
- Slanted profiles stretch sideways ~400km from the flight tracks.
- Non-invasive observations are retrieved over land and restricted airspace



$$N = (n-1) \times 10^6 = 77.6\frac{p}{T} - 6.3938\frac{p_w}{T} + 3.75463 \times 10^5 \frac{p_w}{T^2}$$

[9]



[7]

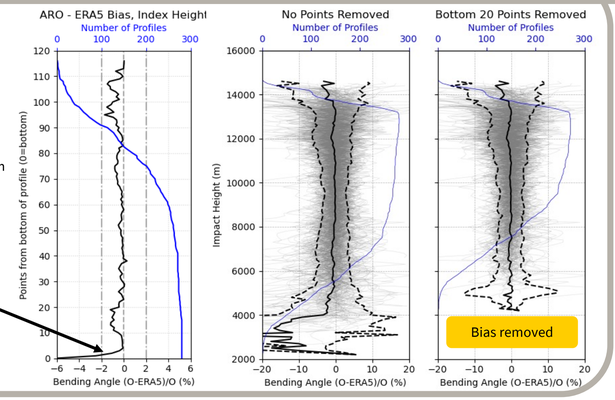
AR Recon collects observations in and around ARs

- Clouds and satellites in and above the AR limit the utility of satellite observations of ARs [4].
- The Center for Western Weather and Water Extremes (CW3E) has flown reconnaissance flights into ARs with ARO onboard.
- ARO complements other sensing techniques employed by AR Recon, such as dropsondes [7].
- 6,921 ARO profiles have been collected on 152 flights during AR Recon since 2018.

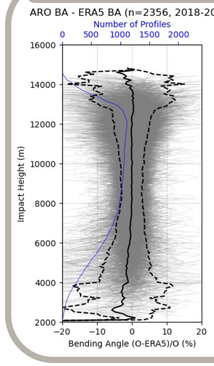
Result: Error is a function from distance from bottom of profile

- Analyzing 6 AR Recon flights from AR Recon '21 [6] indicates the bottom 20 points of profiles have higher apparent error with respect to ERA5.
- Since penetration depth varies across the AR, the location of this less accurate data will vary in height across the AR.
- Therefore, it is possible to more accurately predict observation error with an understanding of the surrounding environment.

Bias near bottom of profiles



ARO Observations of ARs are Assimilated by NWP



- Bending angle is assimilated in MPAS JEDI using ROPP 2D operator [8].
- ARO observations improve precipitation forecasts in the area of maximum precipitation for a landfalling AR event [8].
- Currently, latitude and height varying observation error estimate from spaceborne RO is used [8].
- While suitable for assimilation of global spaceborne RO data, this may not be representative of observation error for ARO in ARs
- Ability to dynamically weight ARO data based on atmospheric conditions will maximize ARO data impact when assimilated.

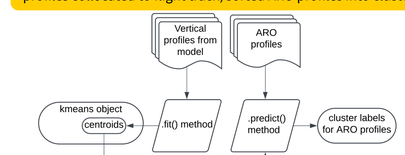
Post-processed and NRT ARO observations are available

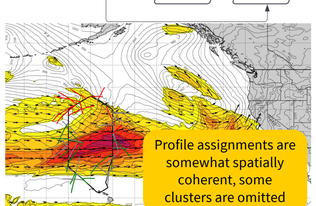
https://agsweb.ucsd.edu/gnss-aro/

Result: Use Machine Learning to Correlate Error

- Relationships like the one above may be intuitive, equally there may be many other less intuitive atmospheric factors affecting observation error.
- Unsupervised machine learning techniques are well-suited to sort ARO profiles into groups representative of different AR structures.
- Profiles in similar atmospheric conditions should have similar error characteristics. Profiles could be assigned error based on cluster.
- K-means clustering techniques are used to sort profiles into 4 clusters based on retrieved refractivity for each profile, interpolated to common heights.
- Clusters have distinct trends in refractivity, error trends are less obvious.
- More refinement is necessary to create a skilled predictive model.

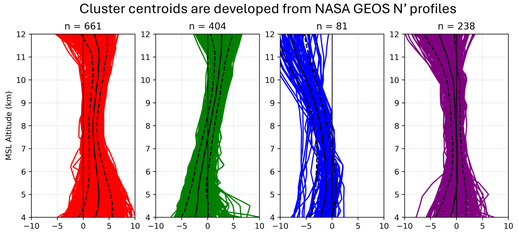
Developed k-means centroids from 1384 NASA GEOS model profiles collocated to flight track, sorted ARO profiles into clusters



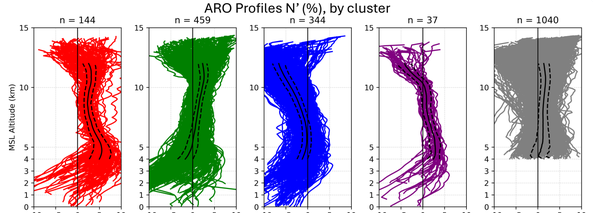


Profile assignments are somewhat spatially coherent, some clusters are omitted

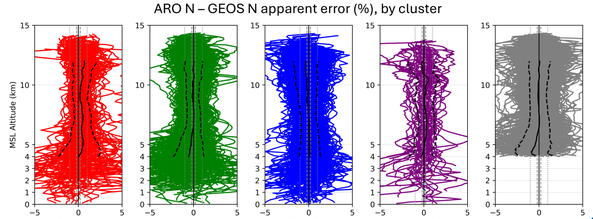
Cluster centroids are developed from NASA GEOS N' profiles



ARO Profiles N' (%), by cluster



ARO N – GEOS N apparent error (%), by cluster



Error Characteristics by Cluster

Cluster	12km bias	12km std	8km bias	8km std	4km bias	4km std
Red	1.34	2.28	0.41	0.87	4.52	2.31
Green	0.03	0.98	0.01	0.73	-0.56	1.77
Blue	-0.32	1.43	-0.06	0.94	0.12	1.21
Purple	-0.12	1.57	0.16	0.89	-0.32	1.39
Grey	0.08	1.20	-0.01	1.00	nan	nan

Conclusions

- ARO bending angle observation error can be characterized as a function of height, and distance from the bottom of the profile
- Model and ARO refractivity anomaly profiles can be clustered using unsupervised machine learning techniques
- Refractivity error within each cluster varies, its statistical significance needs to be assessed
- Further improvements to unsupervised clustering methods could improve ability to sort profiles by synoptic scale features
- Better characterization of ARO observations will allow for more accurate forecasting of impactful AR events, enabling community stakeholders to take action and mitigate some flood and drought impacts.

Acknowledgements

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