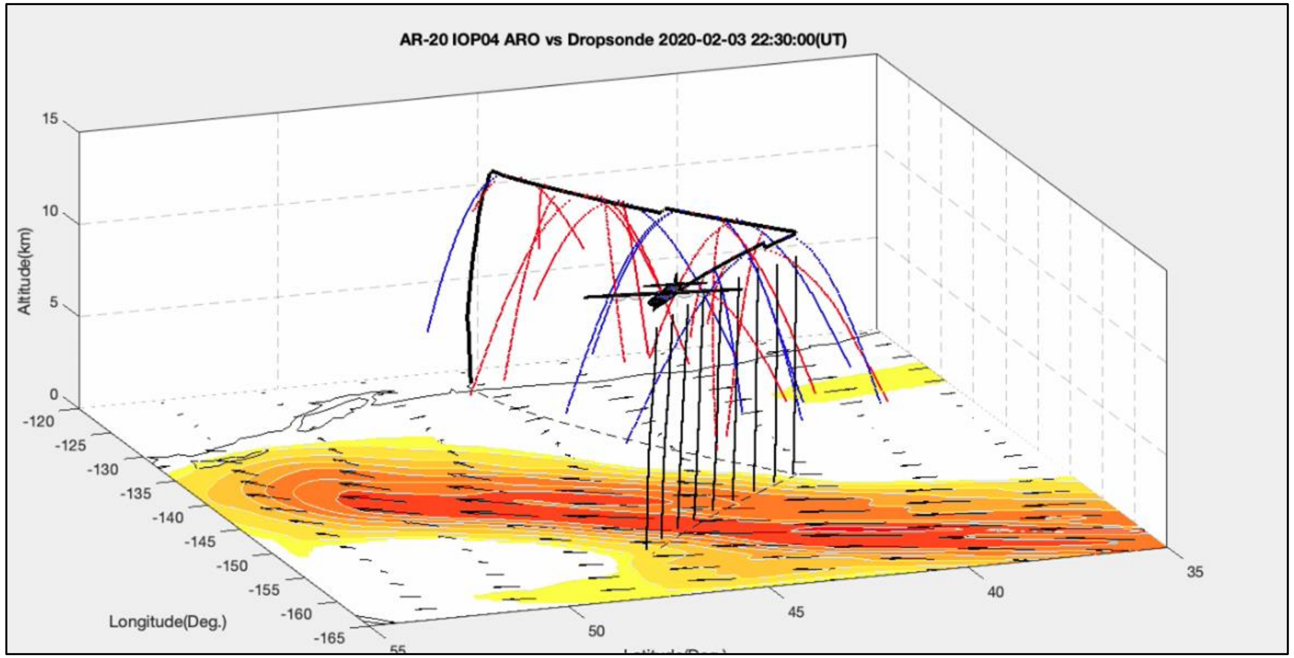
AR Recon2023 Airborne Radio Occultation Observations in Zonal ARs and Cutoff Lows



Bing Cao, ***Jennifer S. Haase*** (jhaase@ucsd.edu)

M.J. Murphy, P. Hordyniec, N. Do,

N. Contreras, P. Lee, K. Lord,

I. Hernández Banos

AF 403rd:

C. Register, M. Gehl, R. Evans, R. Kober

AF 53rd:

Ryan Rickert, C. Dyke, K. McLaughlin

NOAA AOC:

A. Lundry, N. Underwood, G. Defao, S. Otero

Research And Operations Partnership

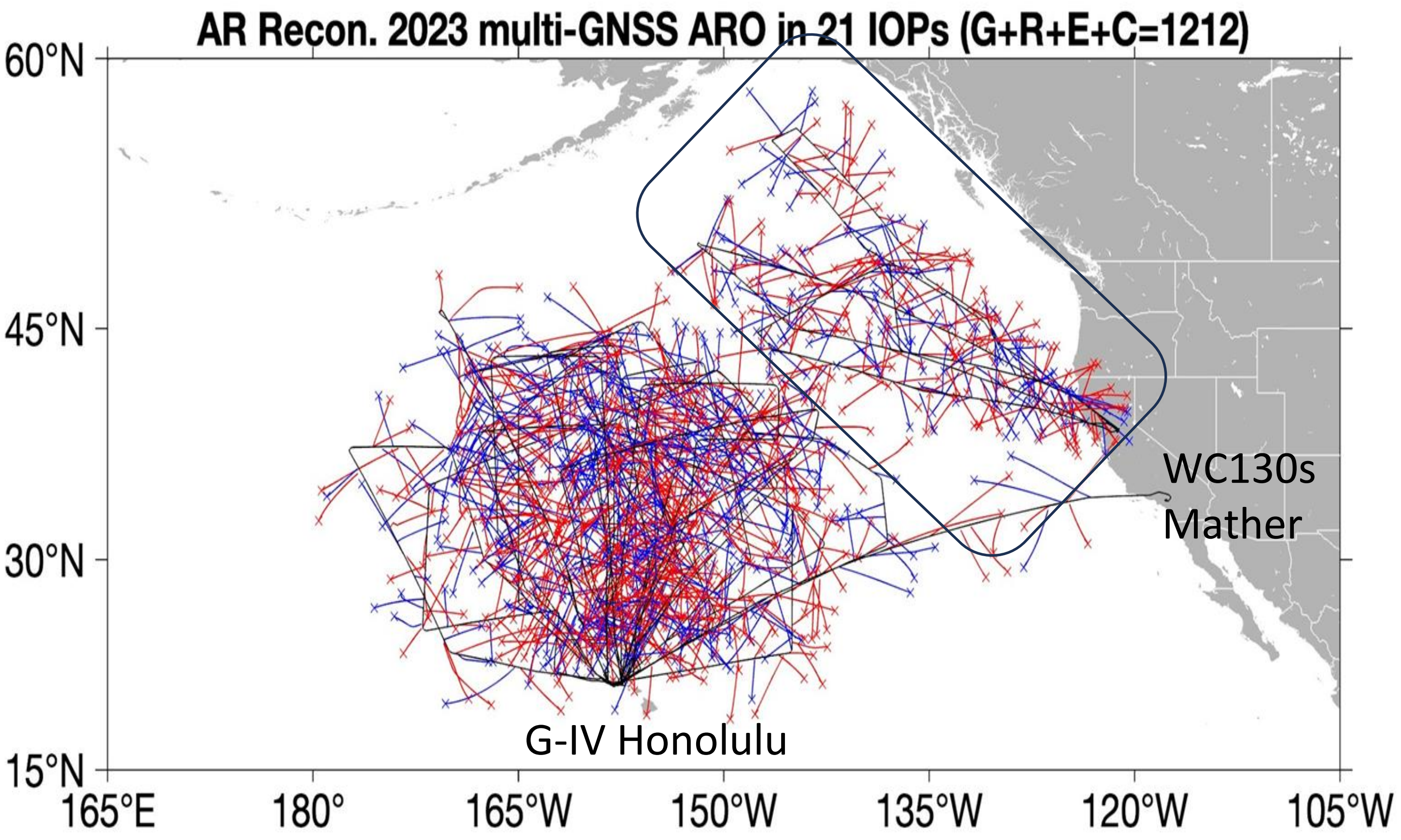
SCRIPPS INSTITUTION OF OCEANOGRAPHY

UCSD

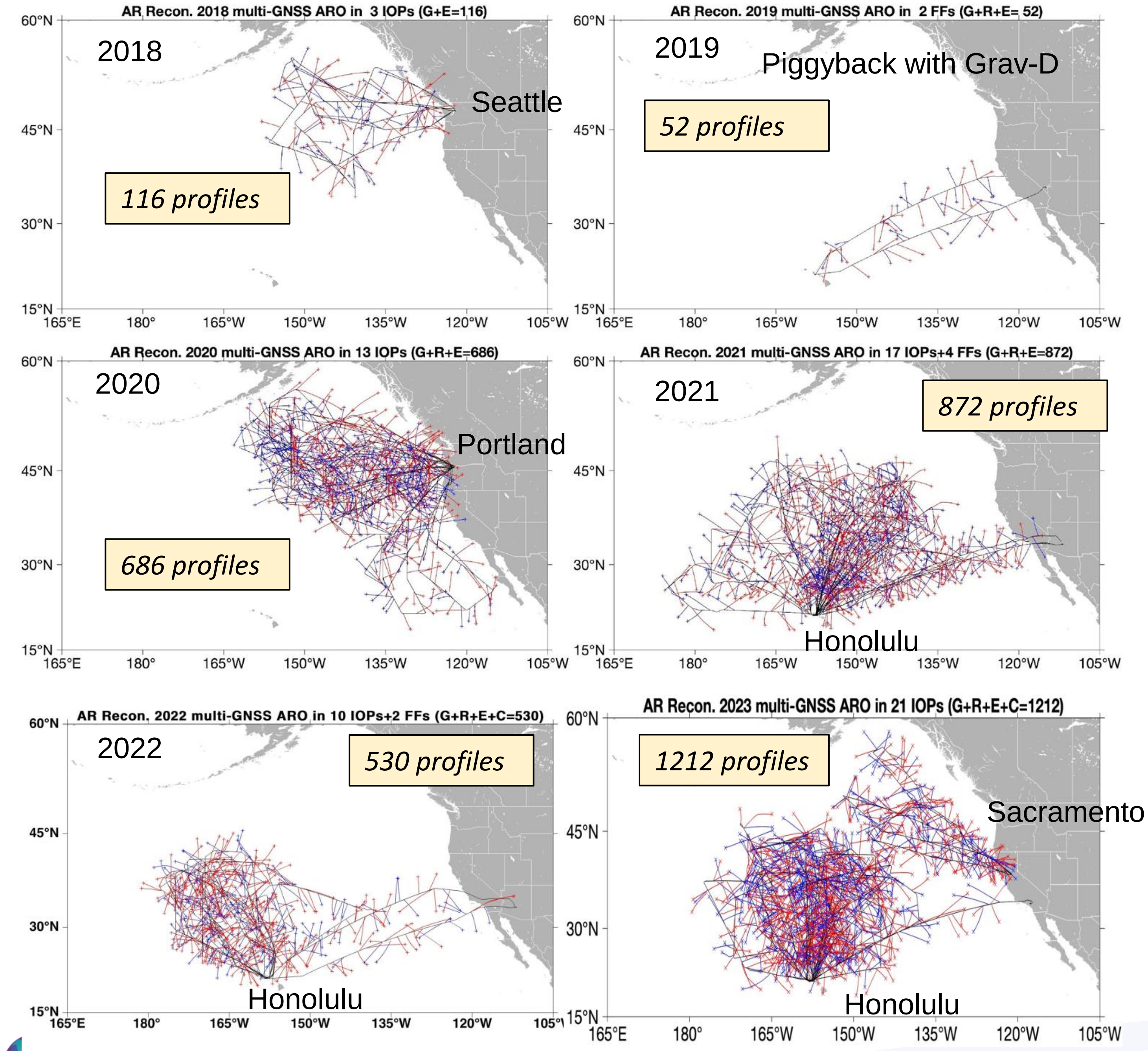
Summary

- AR Recon 2023
- Dec 2022 – Jan 2023 a long sequence of zonally oriented ARs impacting CA
  - ARO measurements by the GIV out of Hawaii
- Mid Feb 2023 – Mar 2023 dominated by cut-off lows and cyclogenesis near the coast
  - New! ARO measurements by the C-130s out of Sacramento, CA
- Dataset coverage and quality
- Preliminary data assimilation results using MPAS-JEDI and 2D ARO observation operator

Total flights in AR Recon 2023



Year	Total	Flights	G	R	E	C
2023 G-IV	**933**	18	350	251	245	87
2023 C-130	**279**	3	97	72	57	53



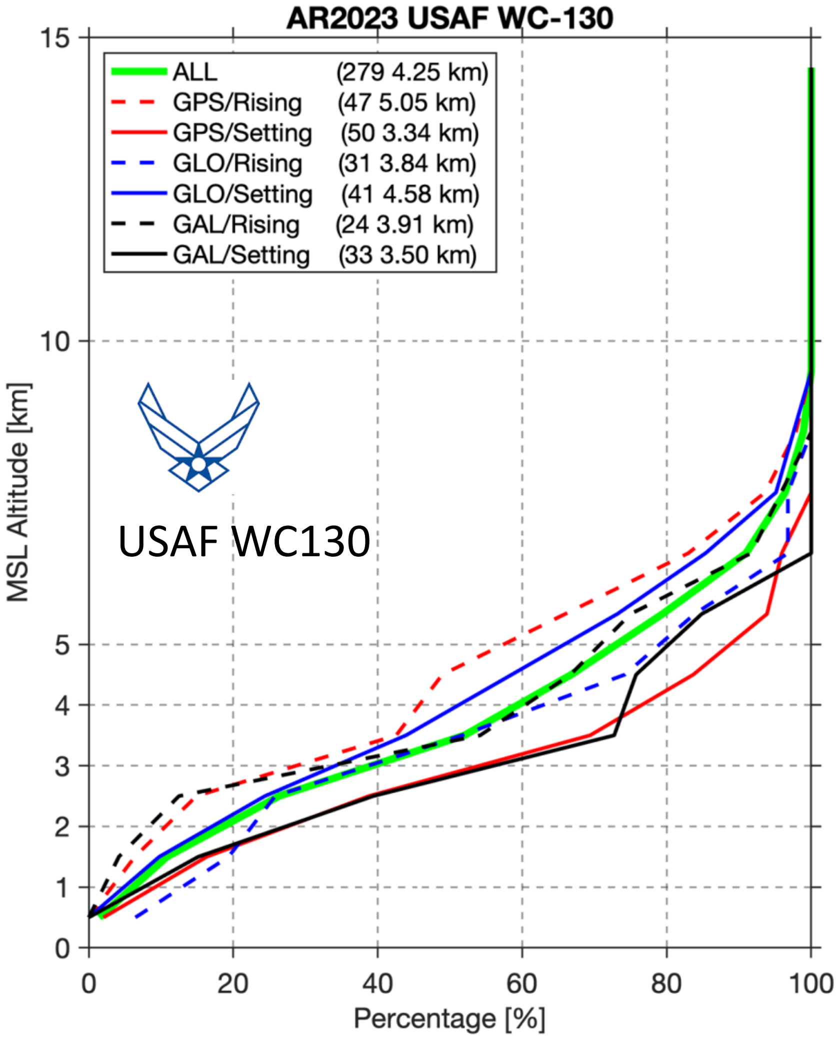
Year	Total	G	R	E	C	Flights
2018	116	78		39		3
2019	52	24	13	15		2
2020	686	335	154	197		13
2021	872	374	255	243		21
2022	530	199	142	119	70	12
2023 G-IV	933	350	251	245	87	18
2023 C-130	279	97	72	57	53	3

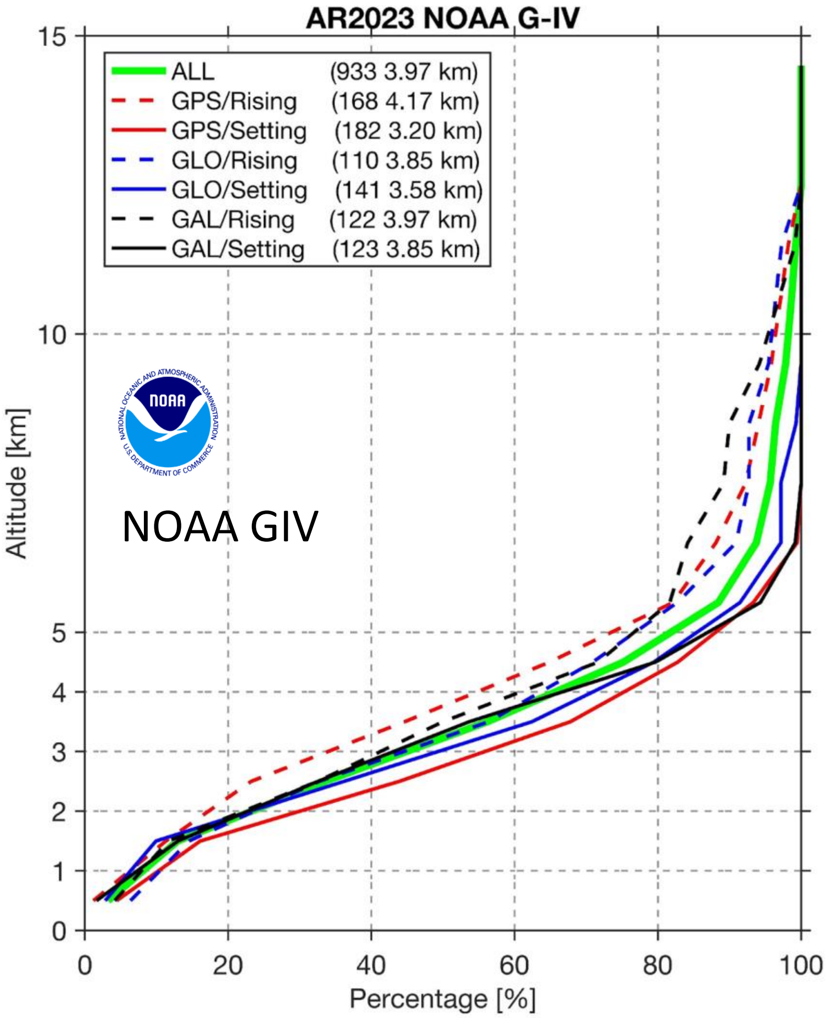
OCEANOGRAPHY

Haase, Cao – SIO/UCSD

UCSD

Lowest penetration depth





Upper limit: WC-130 cruise altitudes 9--10 km

Lower limit: median 4.25 km.

20 % go below 2 km.

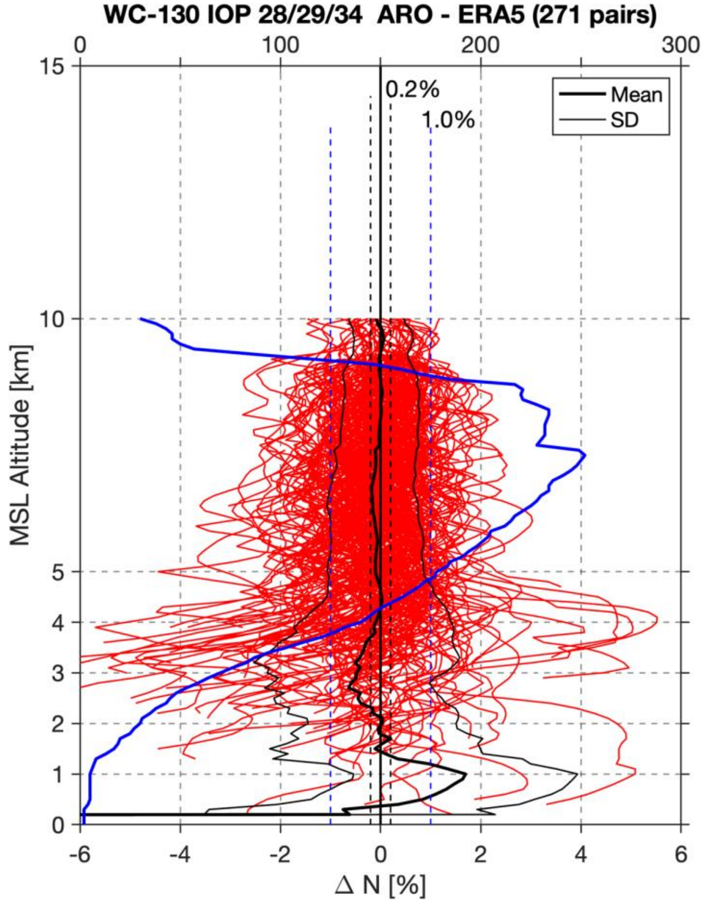
40 % go below 3 km.

60 % go below 4 km.

The lower limit is similar to that of the G-IV (4.25 km vs. 3.97 km).

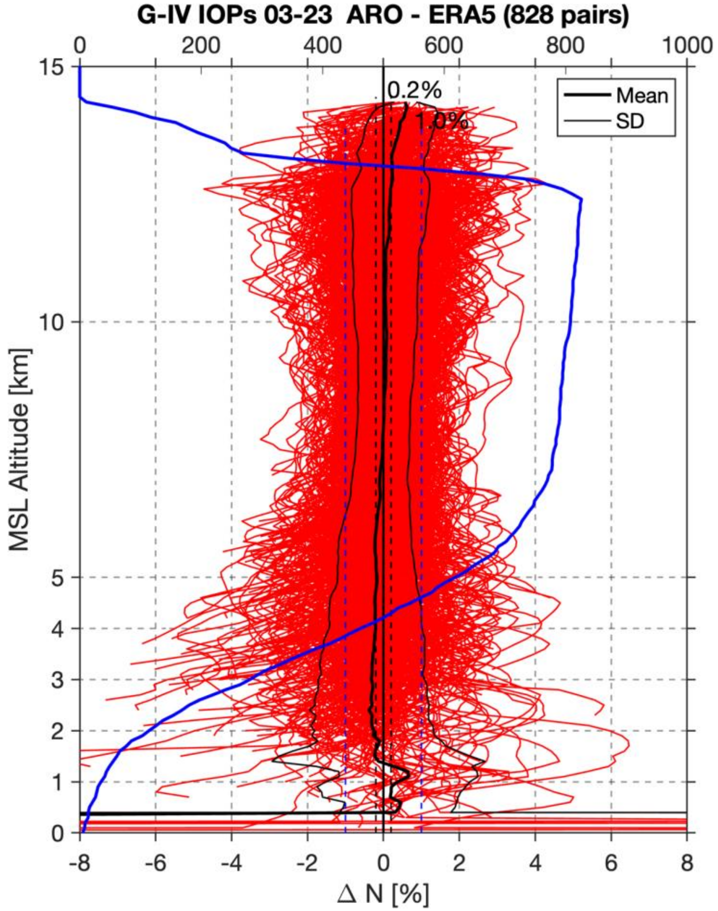
A second mini-GISMOS lower troposphere recorder will be delivered end of June, available for the C-130s.

Accuracy of the profiles vs ERA5



USAF WC-130

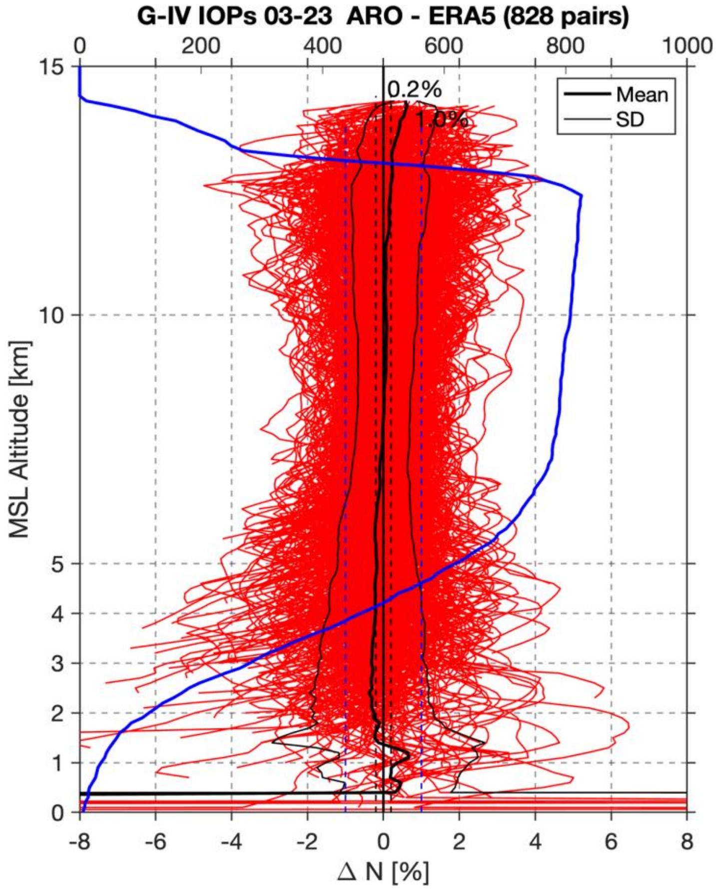
- Slant ARO profiles are compared to ERA5 analysis products at the closest grid point to each tangent point.
- Mean difference within 0.2%
- STD difference within 1.0 % above 5 km
- STD difference within 2.0 % below 5 km.



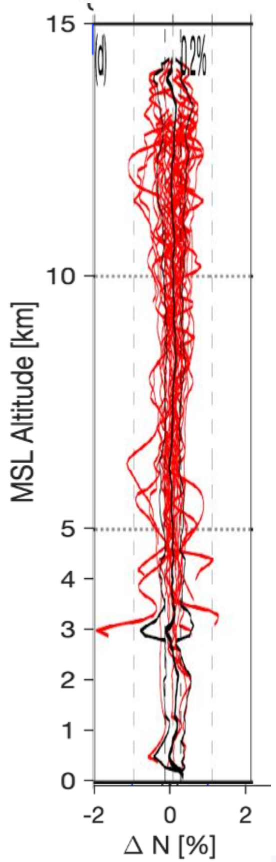
NOAA G-IV

NOAA GIV Near Real Time data quality

Post-Processed – ERA5 differences



Postprocessed - Near Real Time differences

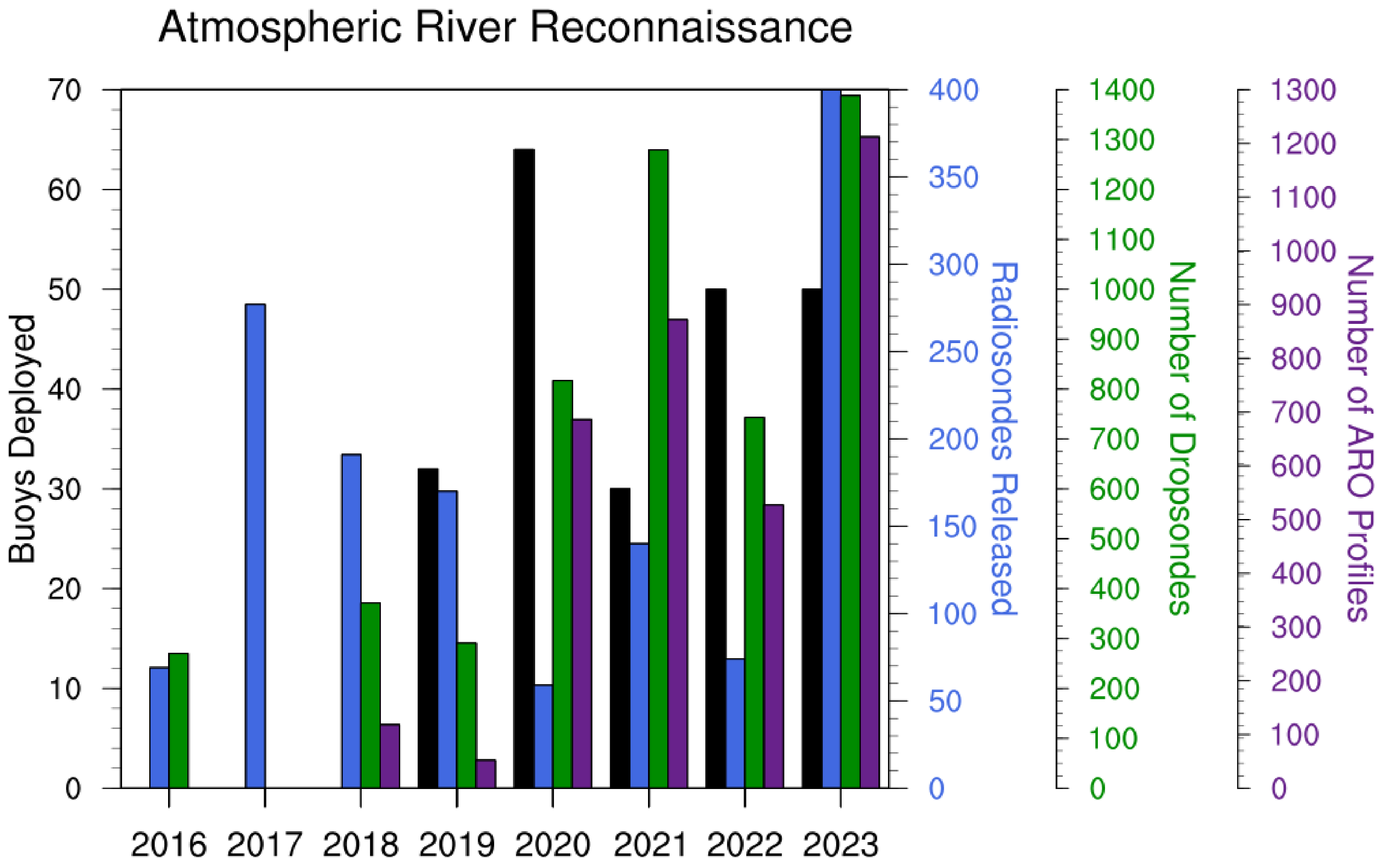


- Verified 30-min latency after successful data reception.
- 0.2 % increase in error over the post-processed refractivity uncertainties of 1-2 %.
- 0.5-1 % increase in error over the post-processed bending angle uncertainties of 5-10 %.
- For 2023 limited to GPS+GLONASS satellites, about 2/3 of the profiles.
- Now enabled for Galileo.

SCRIPPS INSTITUTION OF OCEANOGRAPHY

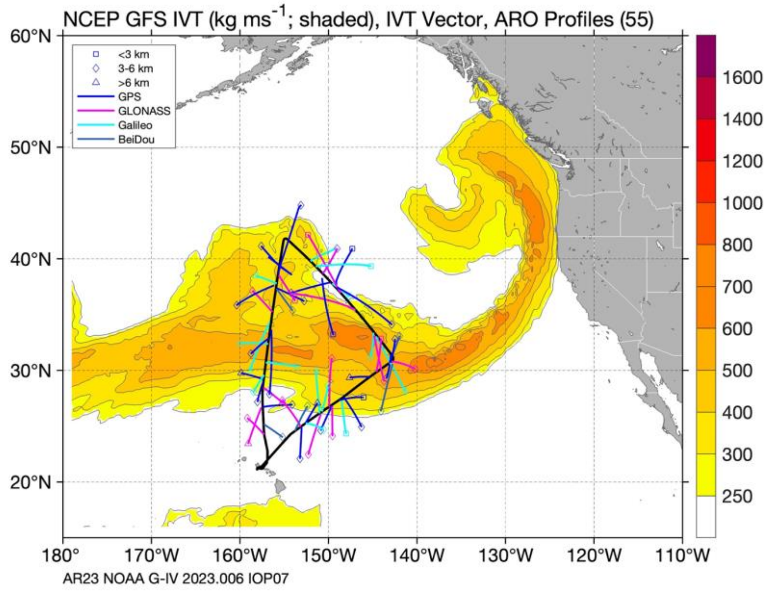
UCSD

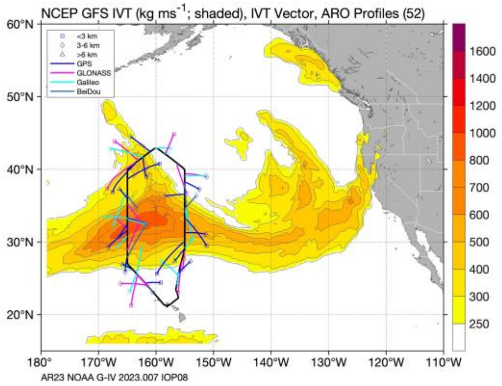
Growth in ARO capabilities

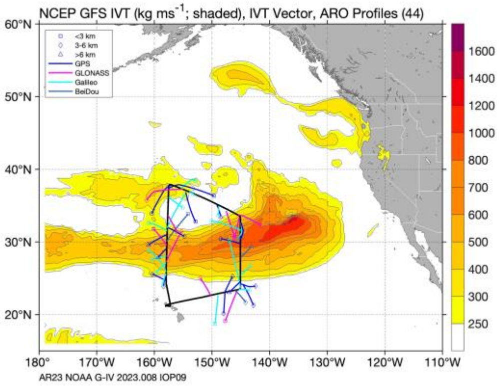


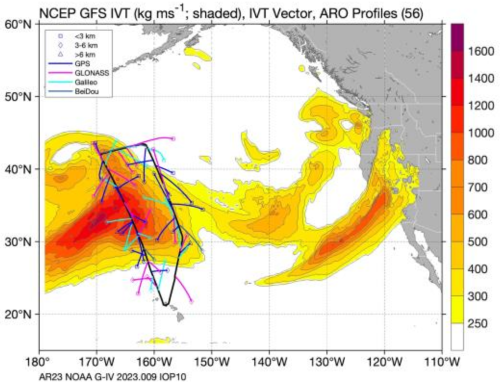
Courtesy of Brian Kawzenuk

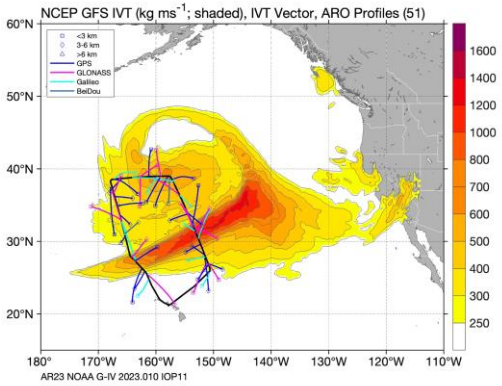
NOAA GIV Flights

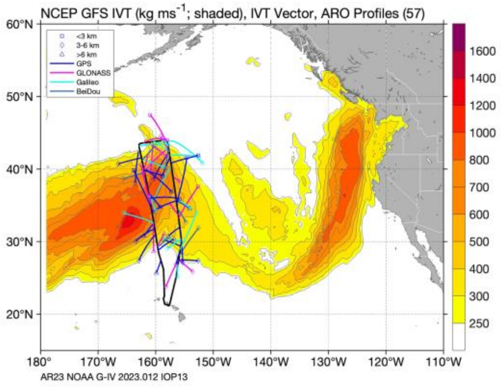


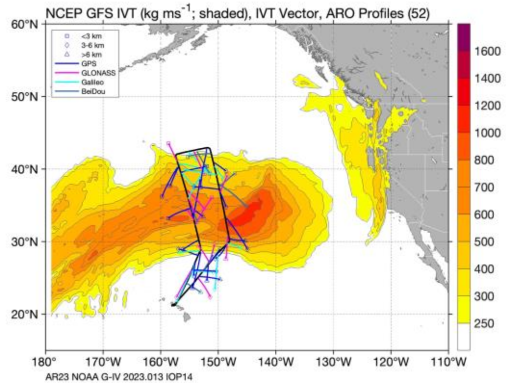


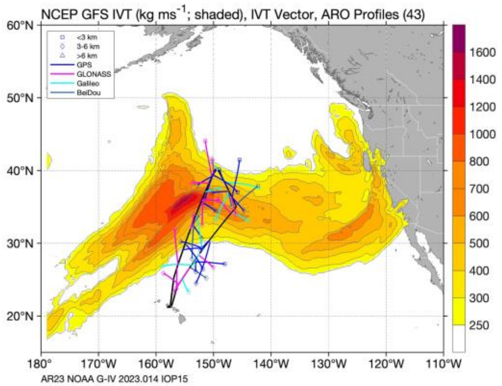


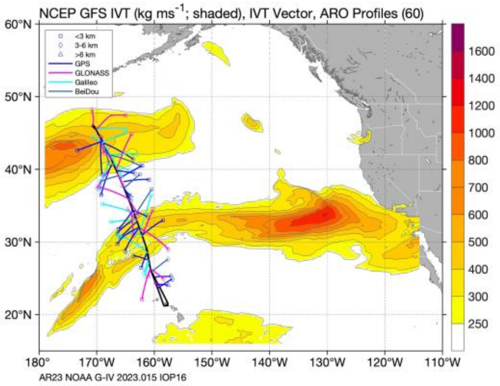


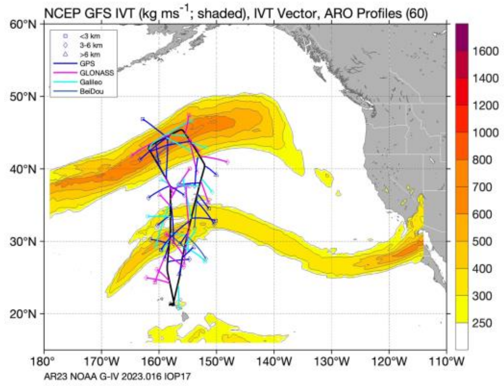










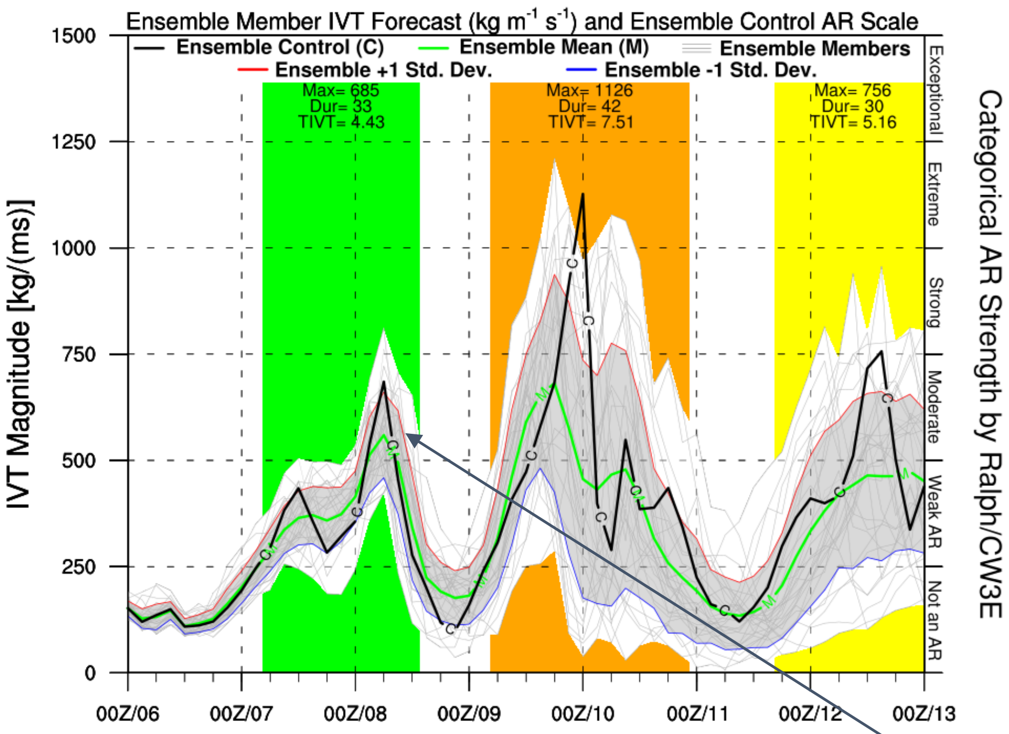


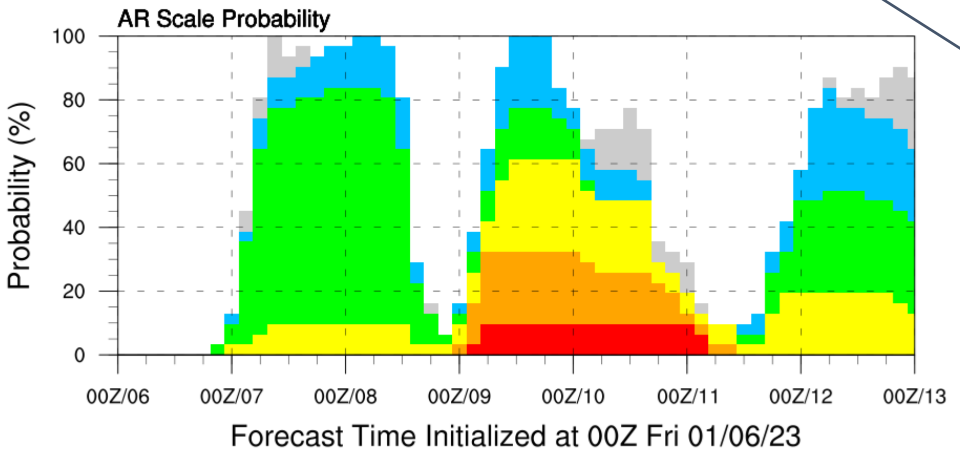
1/6/23 – 1/16/23
IOP07 – IOP17
74 flight hours
532 occultation profiles

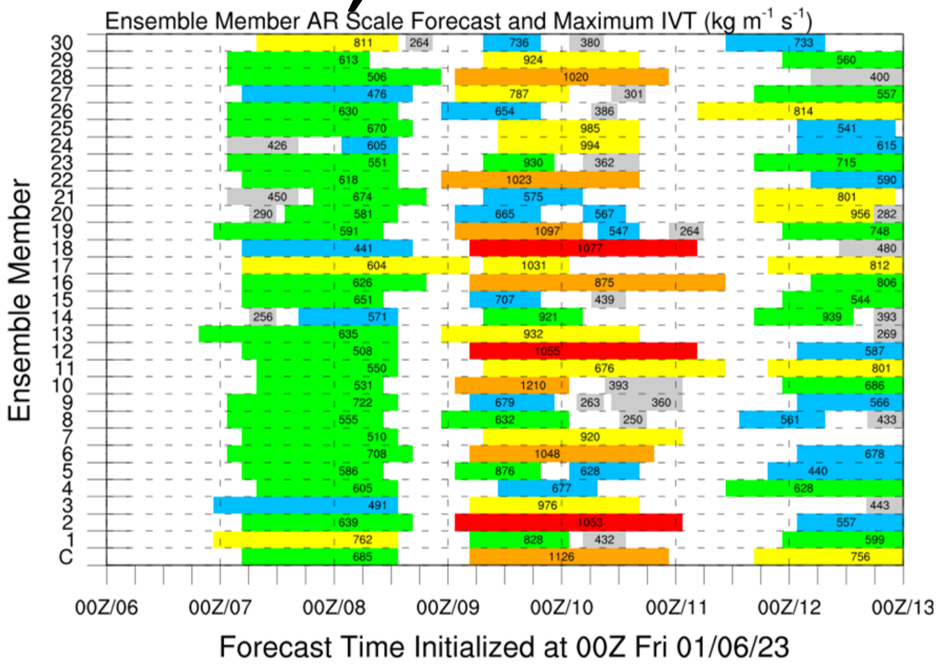
SCRIPPS INSTITUTION OF OCEANOGRAPHY

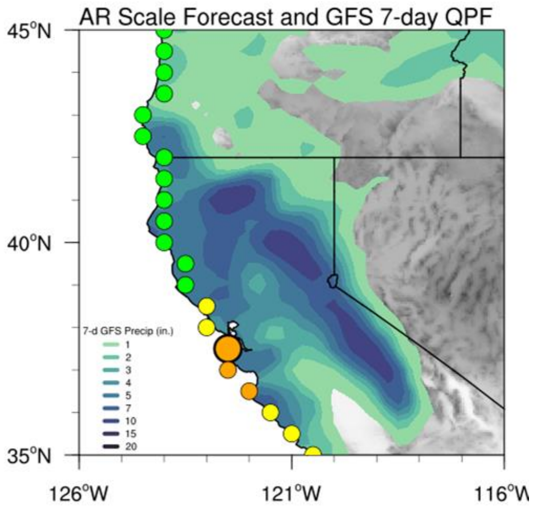
GEFS 7-day AR Scale: 37.5°N, 122.5°W

GFS Ensemble Inititialized: 00Z Fri 01/06/23







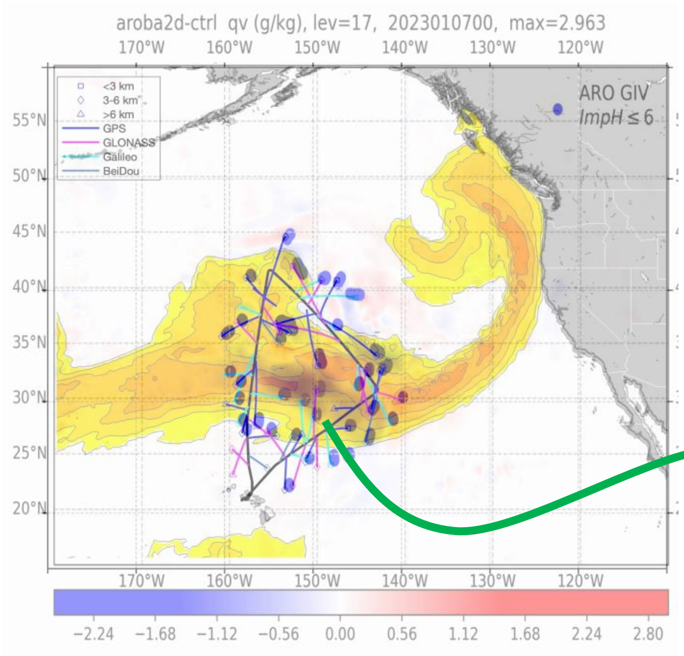


Max AR Scale	# of Ensemble Members	% of Ensemble Members
0	0	0%
1	5	16%
2	23 (C)	74%
3	3	10%
4	0	0%
5	0	0%

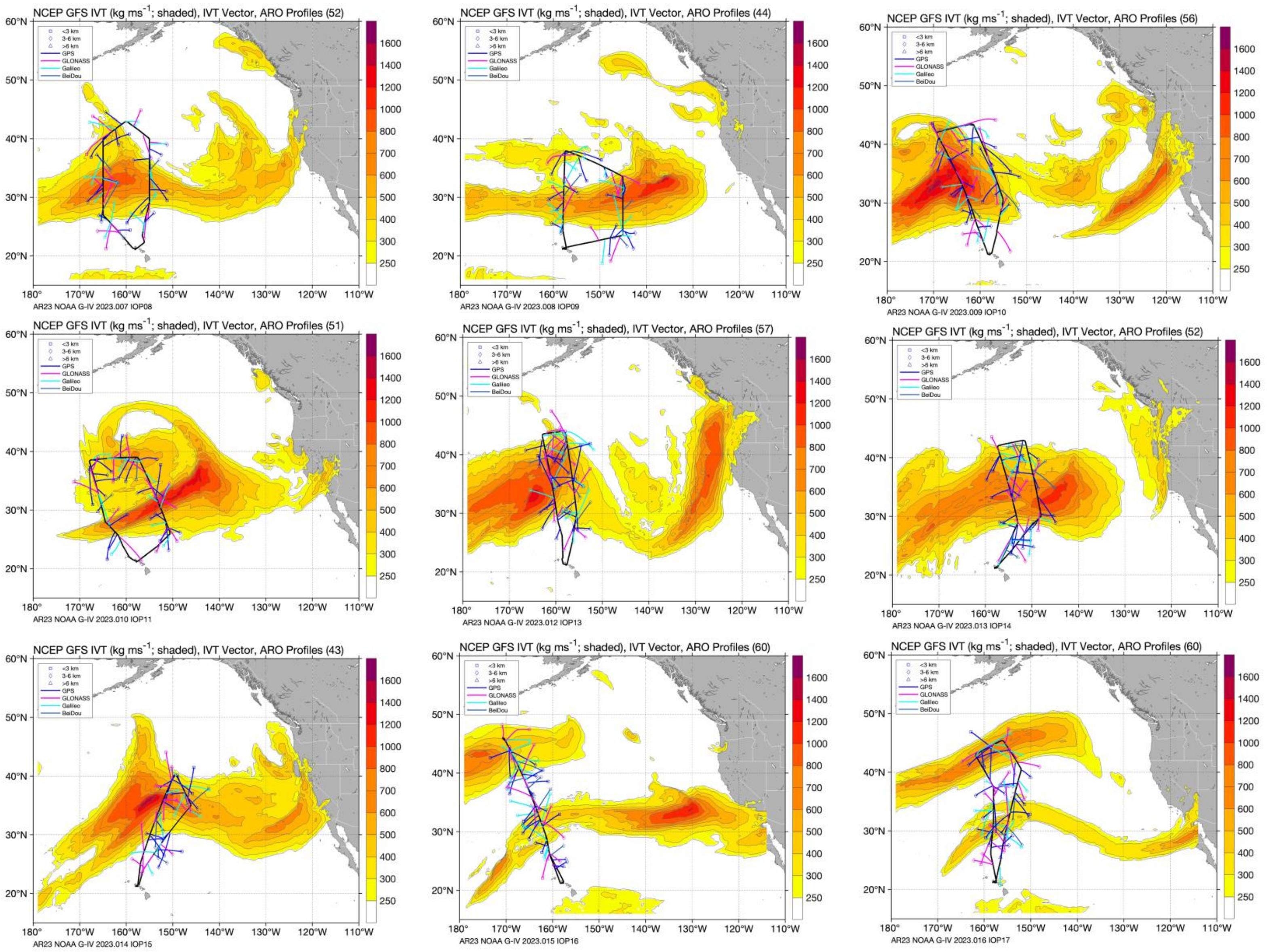
CW3E

UCSD

NOAA GIV Flights

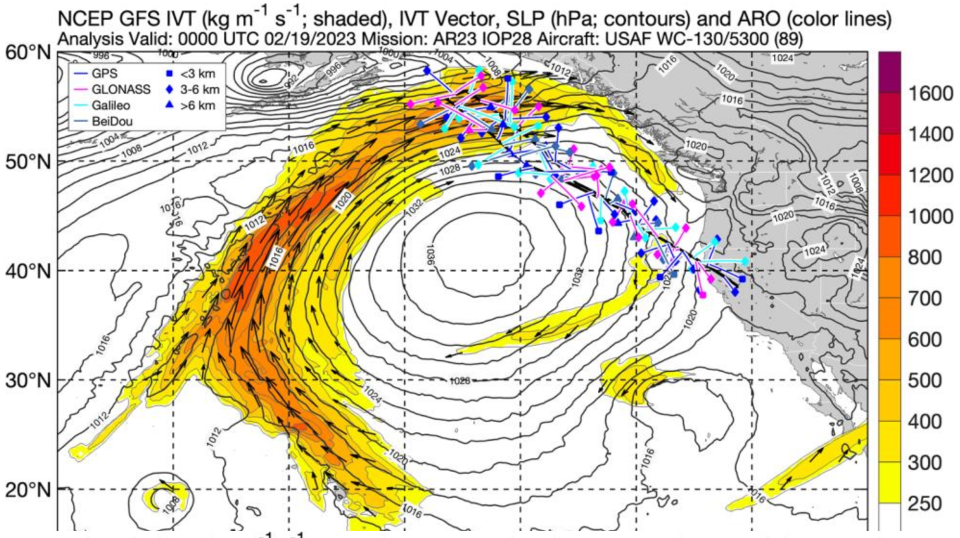


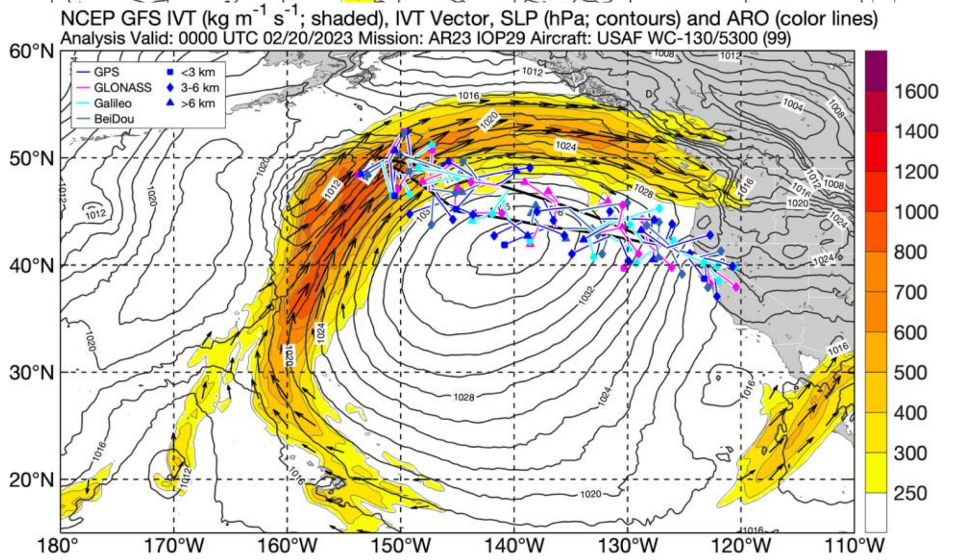
Decrease in moisture from comparison of ARO data assimilation experiment vs control experiment without ARO

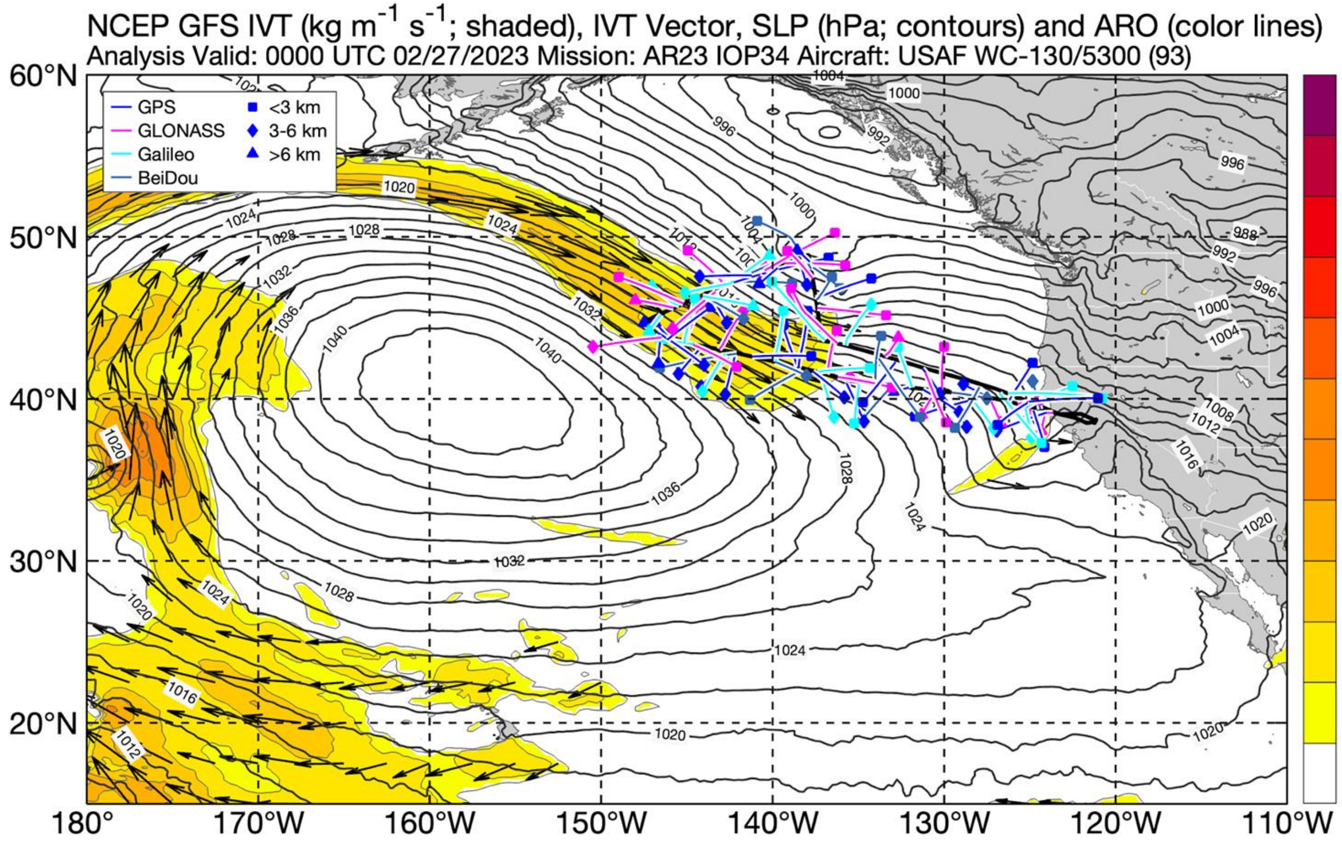


See Poster:
Airborne Radio Occultation (ARO) data assimilation using JEDI-MPAS for an 11-flight sequence of California ARs, I. Banos et al.

C-130 Flights 2/18/23 – 2/19/23 and 2/26/23

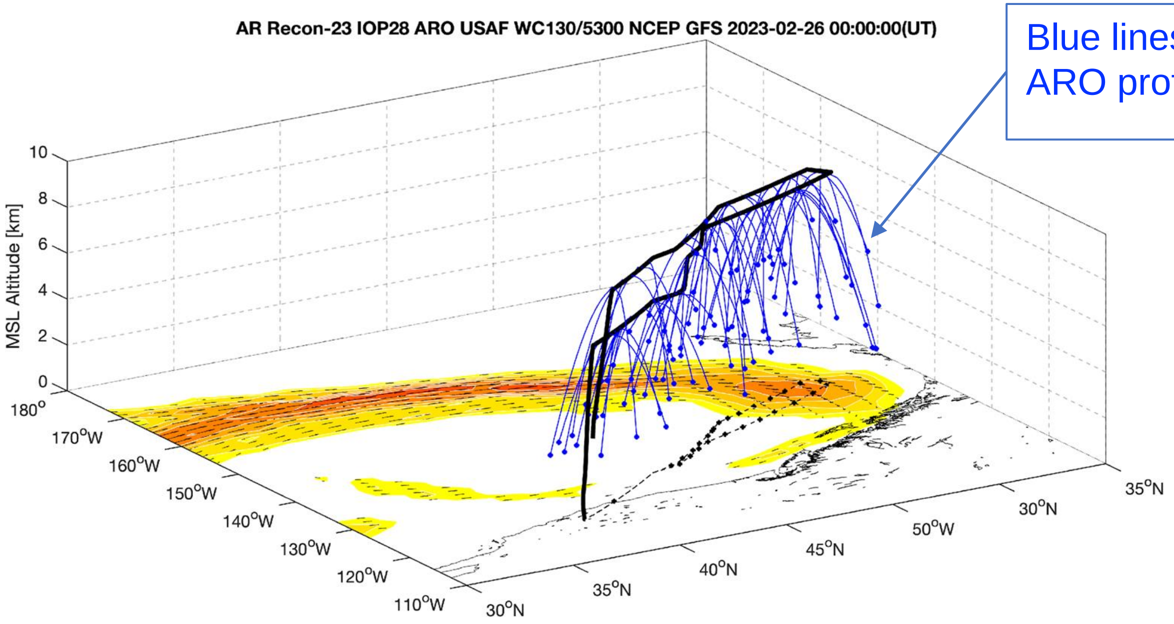




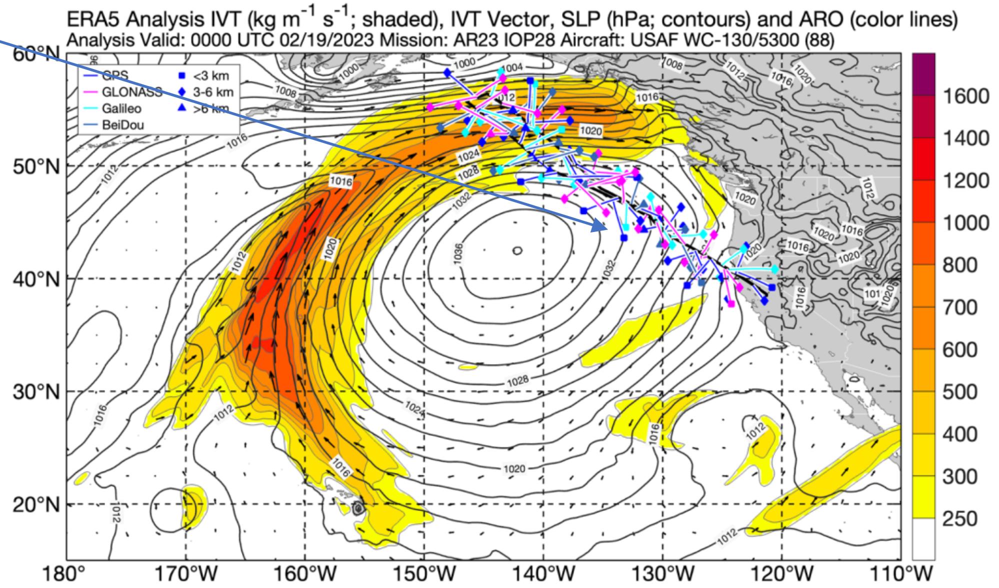


2/18/23 – 2/19/23 + 2/26/23
30.3 Flight Hours, 281 occultation profiles

ARO data assimilation experiment – AR Recon 2023

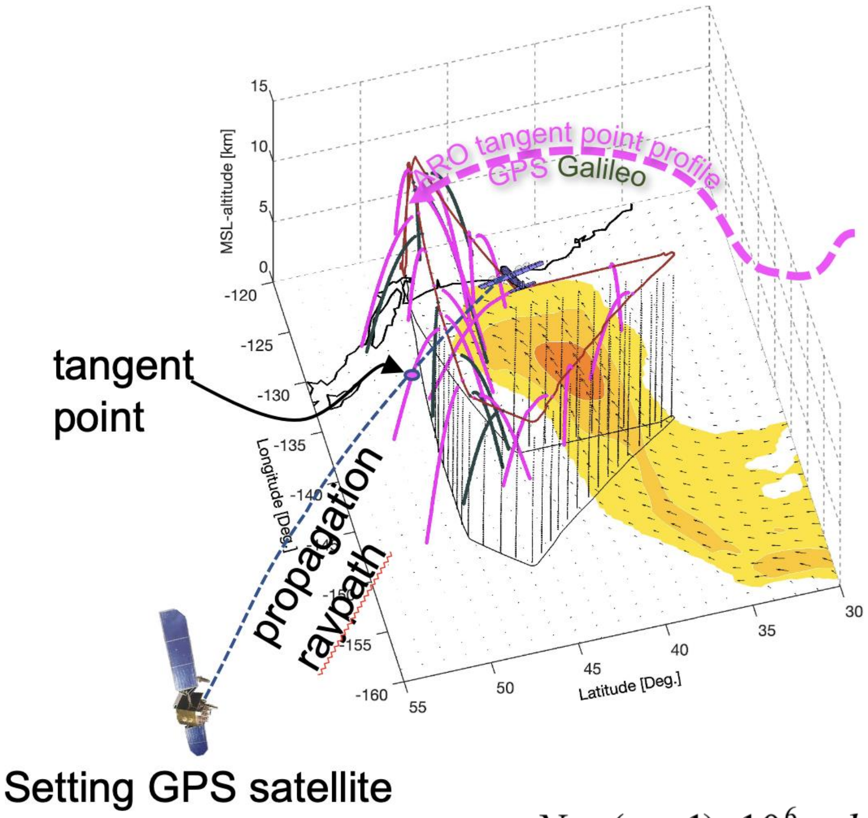


Blue lines are slant ARO profiles



- Slanted profiles stretch from the flight track sideways up to 400 km away.
- They are distributed around the target and expand the aircraft sensing area.
- Non-invasive observations can be retrieved over land and restricted airspace.
- First ARO bending angle data assimilation tests: C-130 flights 18-19 February 2023

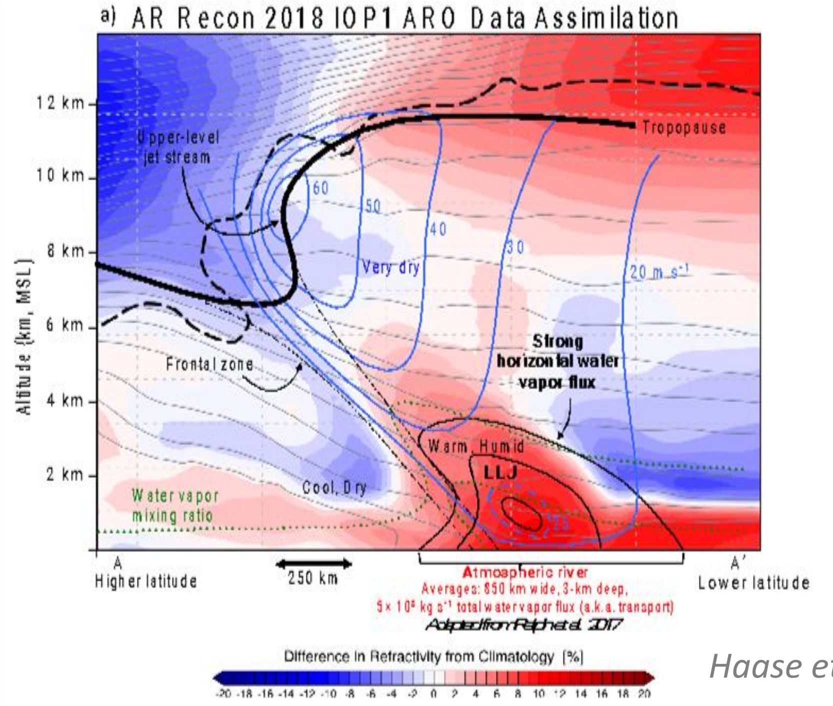
Data assimilation approach: 2D ray propagation



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

- We usually assume that the refractivity can be represented by a value at the tangent point.

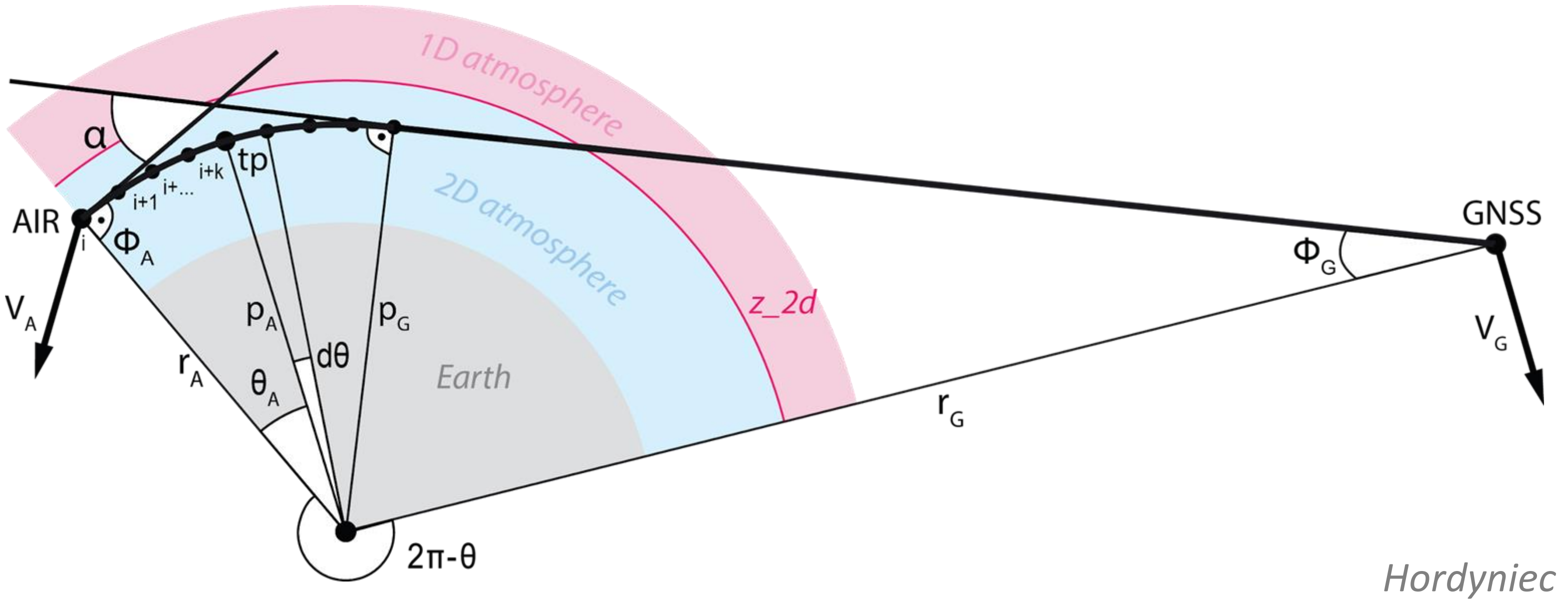
- In the DA, we want to avoid the assumption that a horizontal raypath can be represented by a single point measurement.
- It is clearly not true, as seen below.



Haase et al., JGR, 2021

Data assimilation approach: 2D ray propagation

- The forward observation operator calculates the contribution to the refractive bending of the ray path from the 31 points surrounding the tangent point, with spacing ~30 km.
- Thus, the impact is spread out horizontally around the tangent point.



Hordyniec et al., 2023, in prep.

ARO Data Assimilation Experiment

- Goal: investigate the impacts of assimilating ARO bending angle observations on the analysis and prediction of winds and precipitation in ARs using JEDI-MPAS with a global quasi-uniform 60 km grid and the LETKF DA method
- Observations and verification in the Northeast Pacific domain
- Period: 18Z Feb 18, 2023 to 00Z Feb 20, 2023
- Assimilate at 6 hour intervals

Experiments	Assimilated observations	
ctrl	sondes (radiosondes and dropsondes), aircraft, atmospheric motion vectors from geostationary and LEO satellites	
aroba2d	ctrl	GNSS ARO 2D bending angle (ROPP 2D operator)

Work done with Nghi Do and Ivette Hernandez Baños

ARO Data Assimilation Experiment

<u>JEDI-MPAS</u>

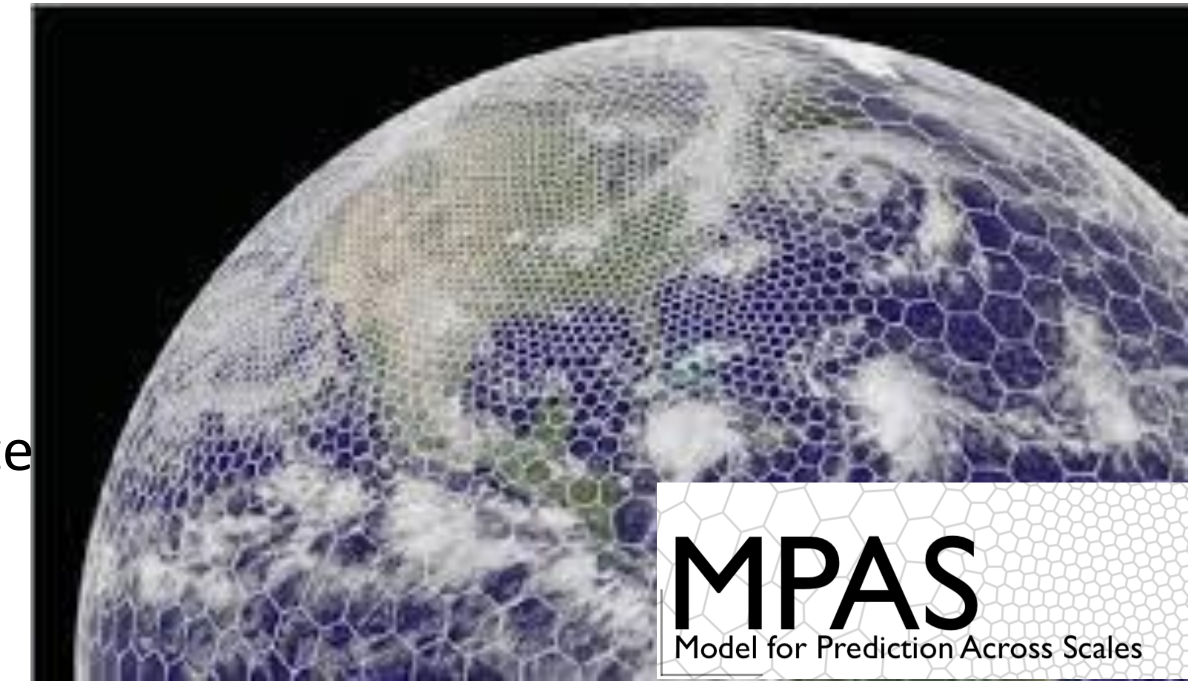
MPAS-A:

- ❖ **non-hydrostatic** dynamical core
- ❖ **unstructured** mesh
- ❖ **height-based terrain-following** vertical coordinate
- ❖ **55 levels**, 30km top
- ❖ 30 km – 60 km dual resolution horizontally

MPAS-A pysical parameterizations

Parameterization	Scheme
Convection	New Tiedtke (Tiedtke, 1989; Zhang and Wang, 2017)
Microphysics	WSM6 (Hong and Lim, 2006)
Land surface	Noah (Chen and Dudhia, 2001)
Boundary layer	YSU (Hong et al., 2006)
Surface layer	Monin–Obukhov (Jiménez et al., 2012)
Radiation, longwave/shortwave	RRTMG (Iacono et al., 2008)
Cloud fraction for radiation	Xu–Randall (Xu and Randall, 1996)
Gravity wave drag by orography	YSU (Choi and Hong, 2015)

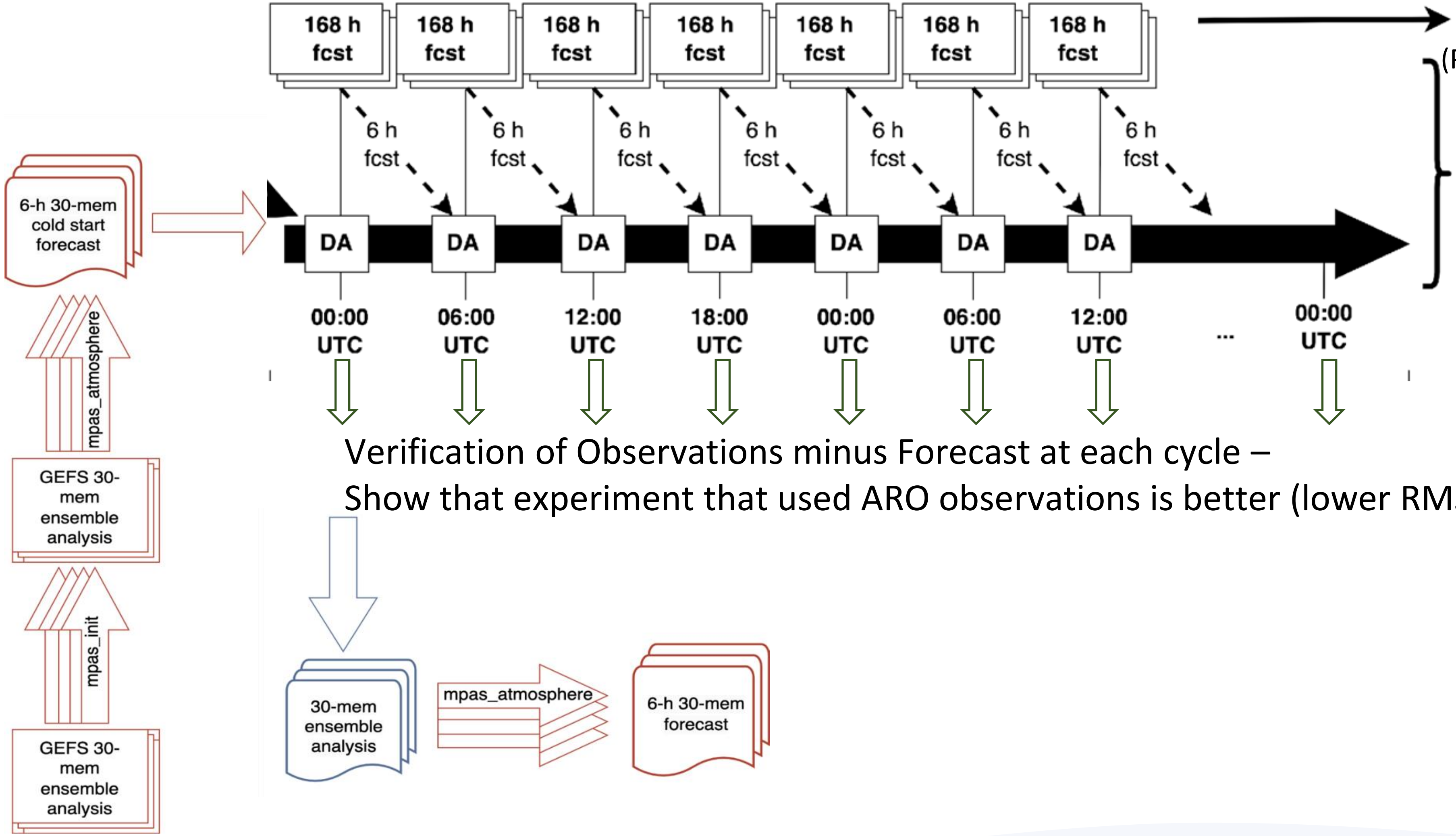
Table 2 in Liu et al. (2022)



Available Methods in JEDI-MPAS:

- HofX
- 3DVar with multivariate background error covariance
- 3D/4DEnVar
- Hybrid-3DEnVar
- EDA
- LETKF

Cycling Data Assimilation Experiment



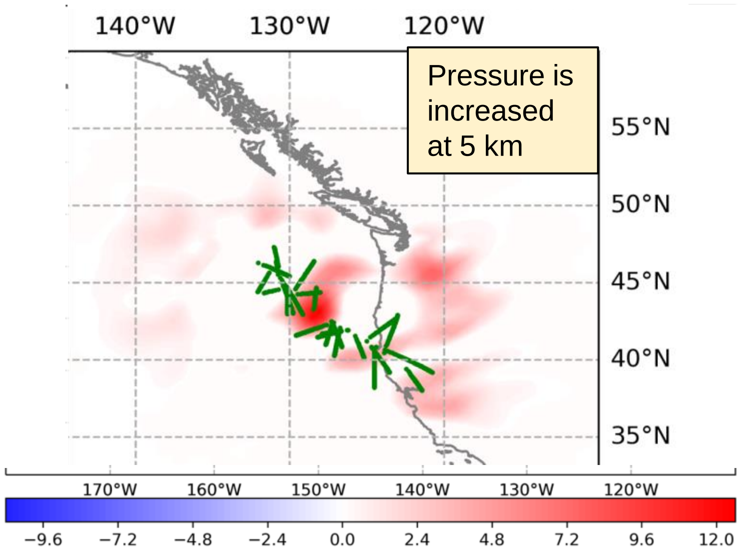
MPAS deterministic run

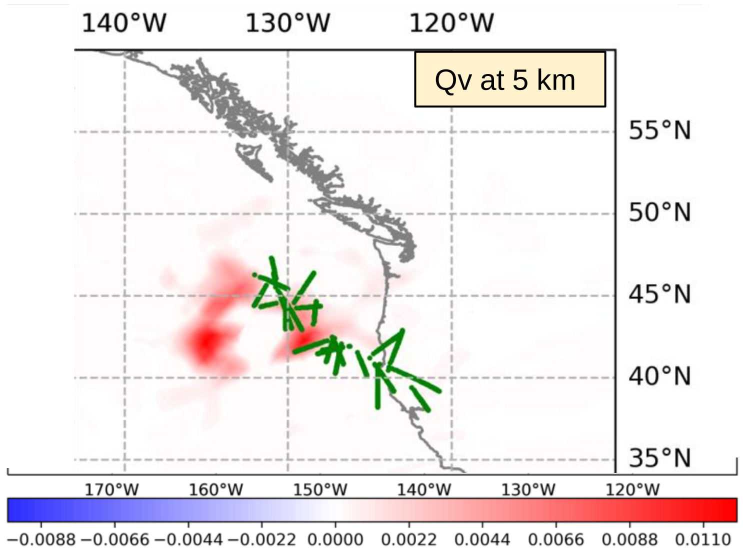
(Precip verification not yet completed)

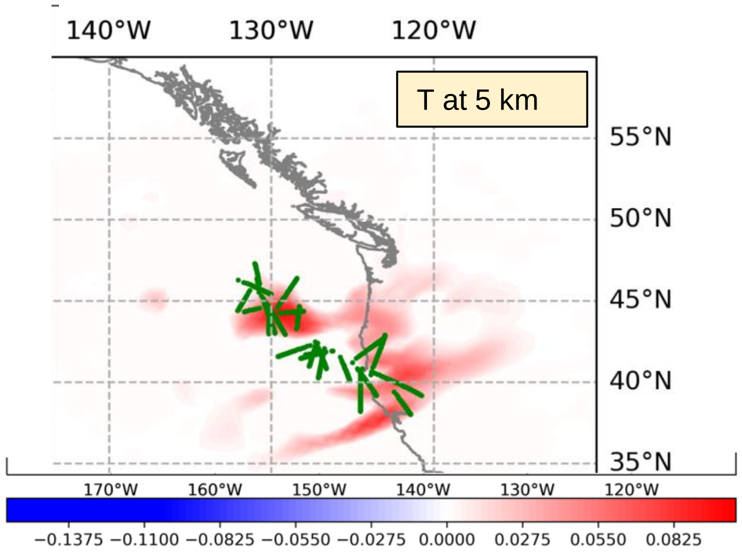
Cycling DA with LETKF MPAS-JEDI using MPAS 6h forecast as background

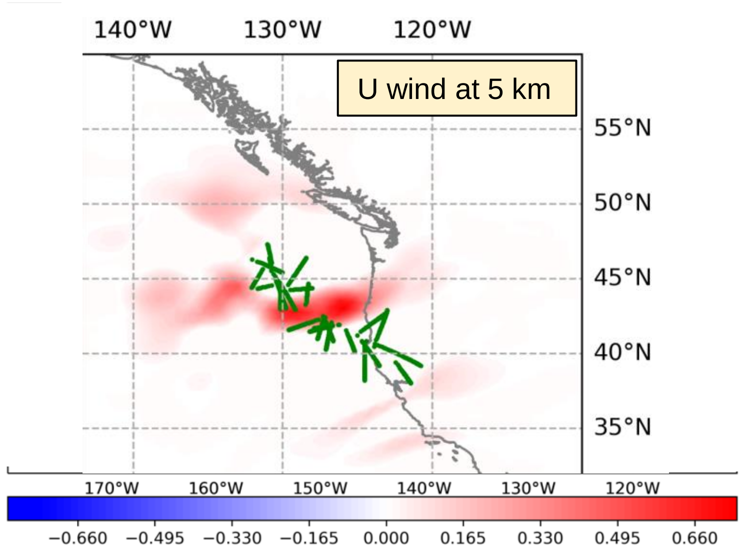
Verification of Observations minus Forecast at each cycle –
Show that experiment that used ARO observations is better (lower RMSE than control)

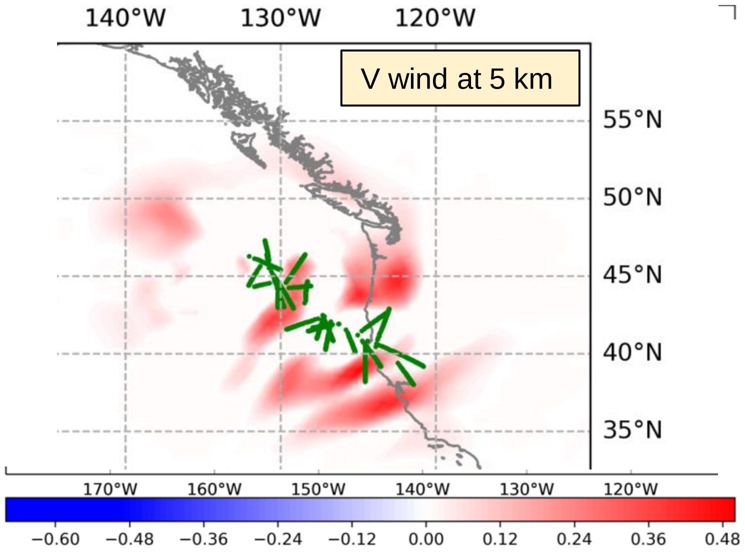
Increment after 1st cycle (ARO minus CTRL)





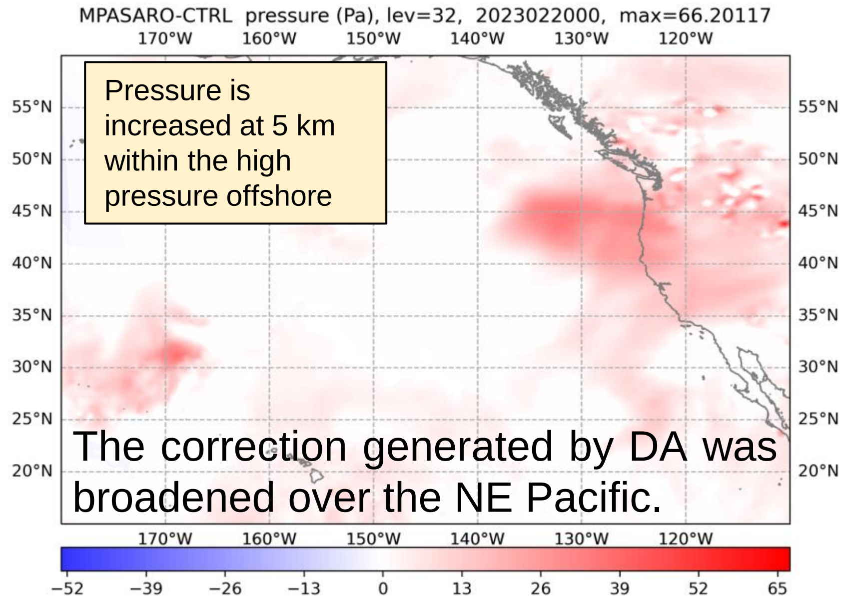




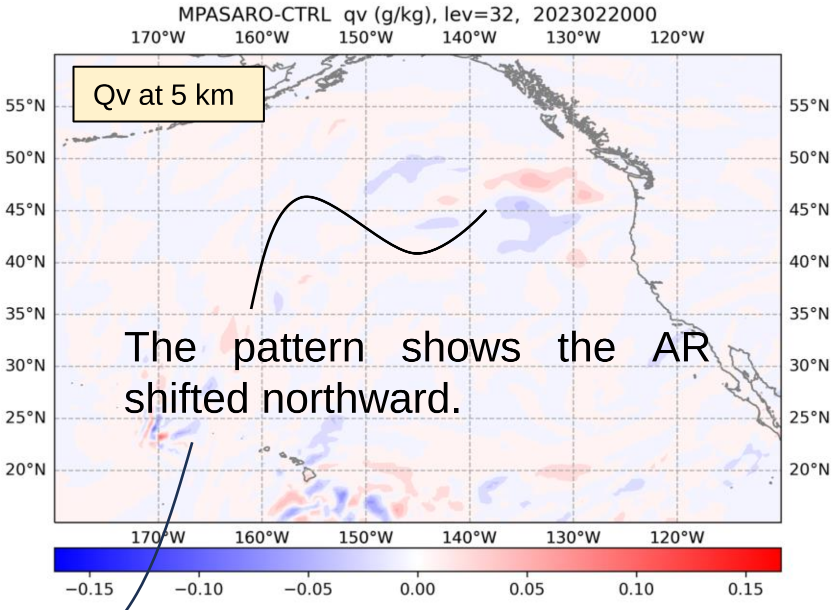


After one cycle of data assimilation, the ARO observations create significant modifications to pressure, moisture, temperature, and wind fields in the coastal Pacific Northwest and northern California, compared to the control.

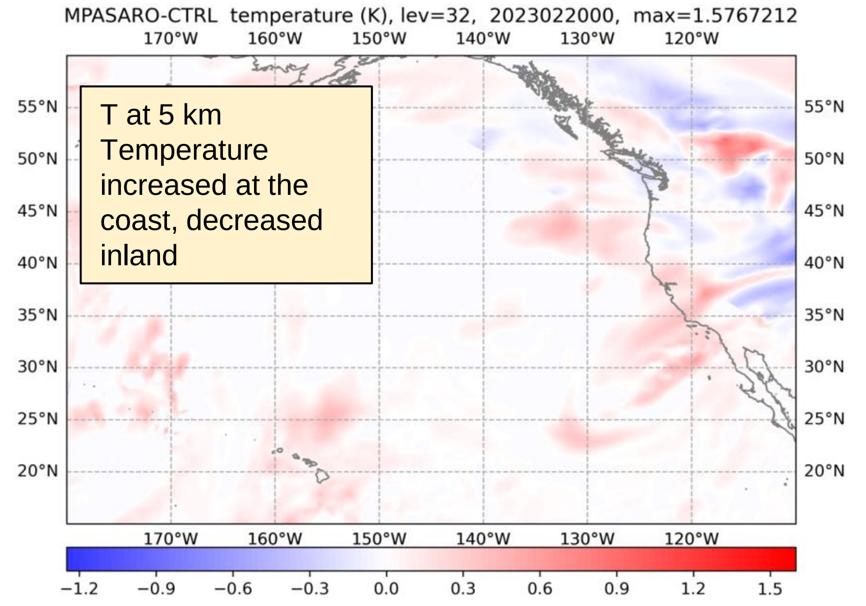
Results after 6 cycles, at the end of the DA period

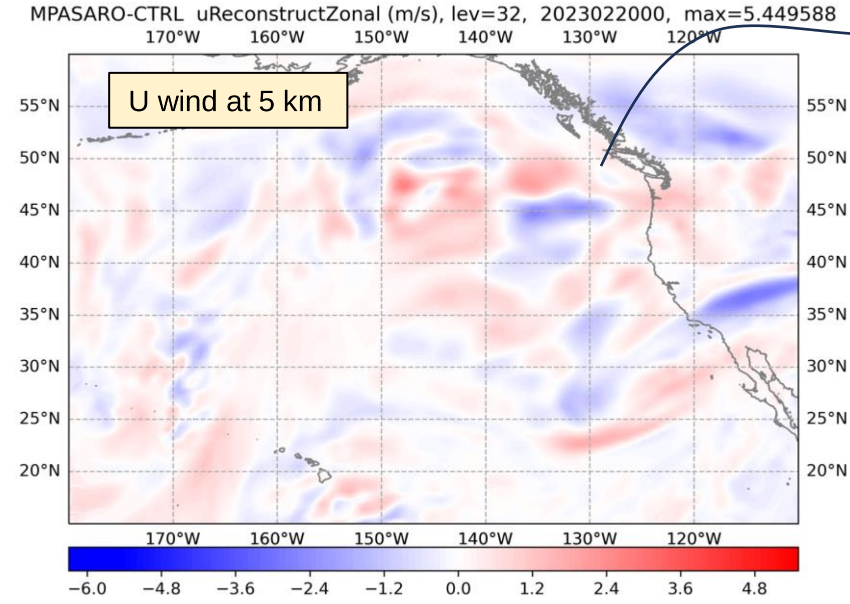


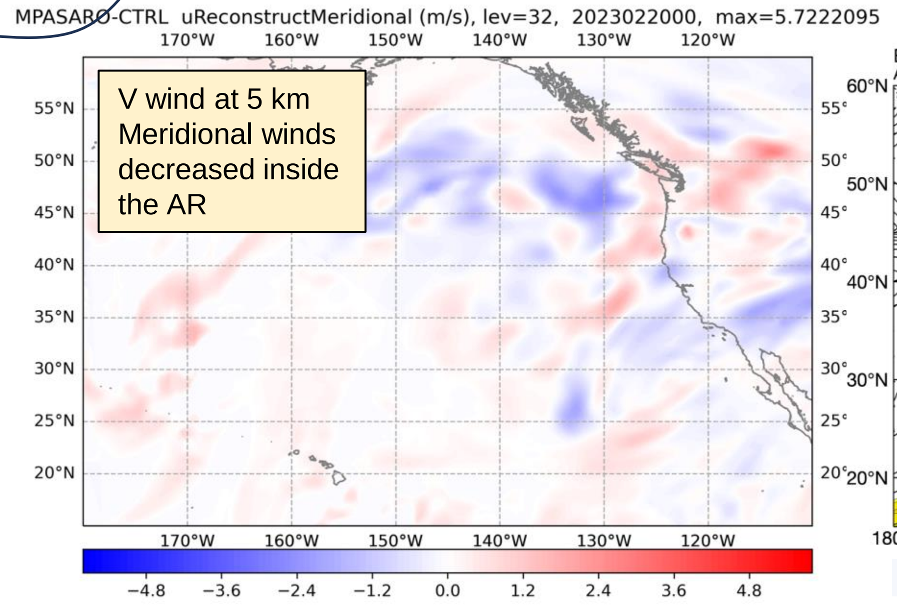
The correction generated by DA was broadened over the NE Pacific.

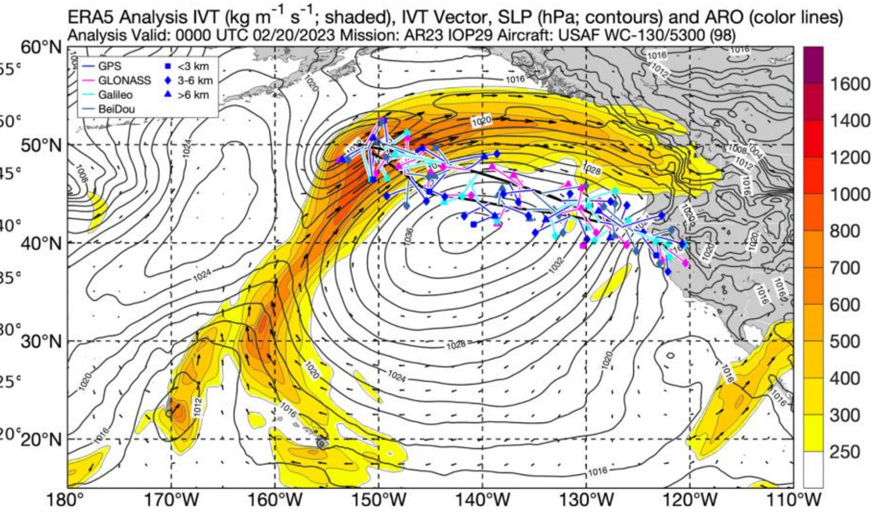


The pattern shows the AR shifted northward.



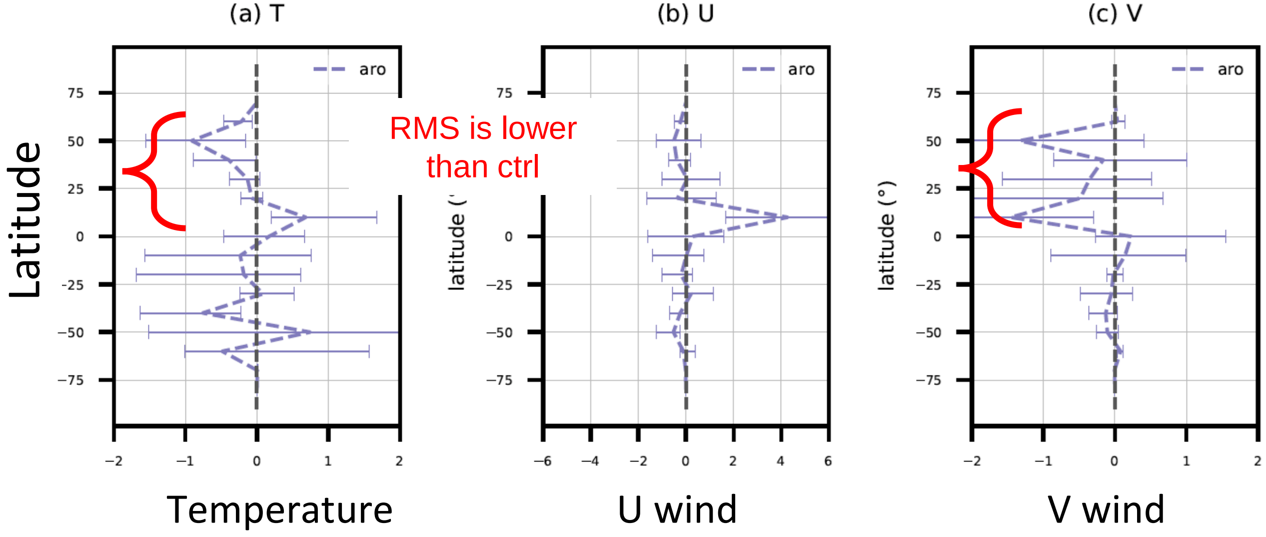




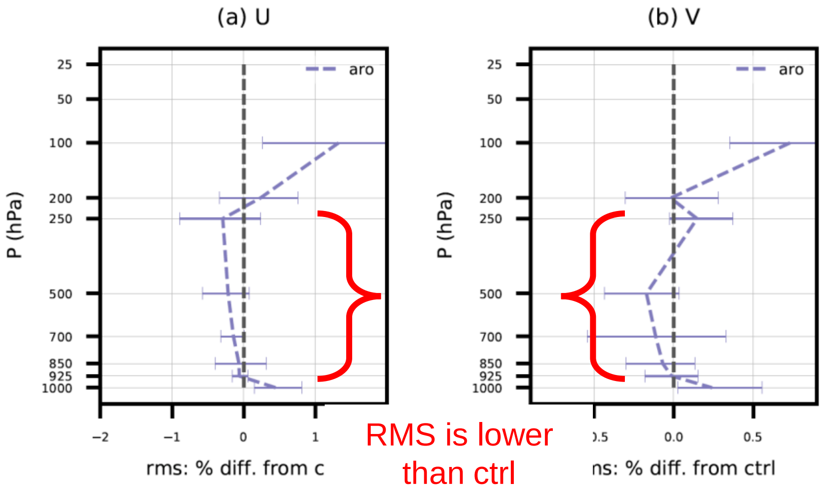


Verification

Verification: aircraft temperature and winds are fit better in ARO experiment in mid-latitudes

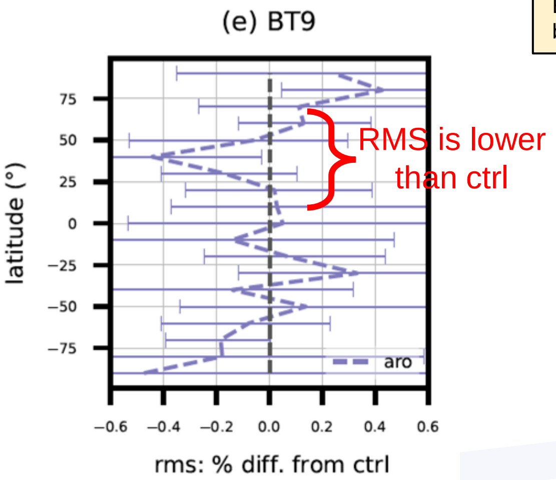


Verification: satellite winds are fit better in ARO experiment below 200 hPa

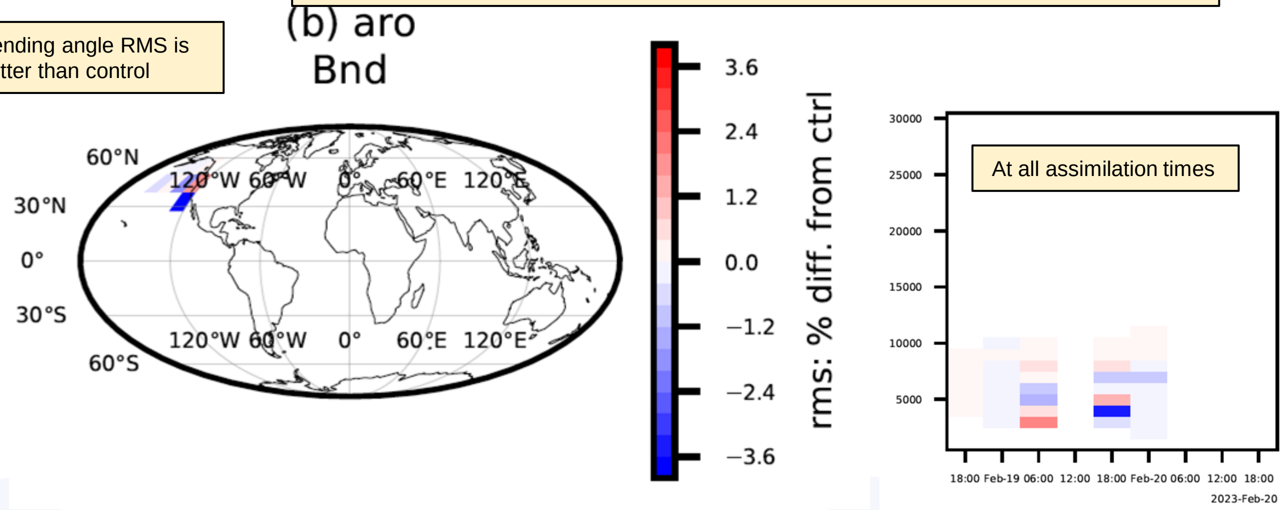


In a global model, preliminary results show the impact is measurable, especially in the AR Recon region.

Verification: AMSU-A satellite radiances fit better in ARO experiment in 15-50º N latitude corresponding to AR recon region. (Ch9 sensitive to temperature)



Bending angle RMS is better than control



Conclusions

- ARO profiles retrieved from the C-130s (80+ profiles per 9 hr flight) with the new upgraded antennas show good quality, comparable to the NOAA GIV.
- Near real time ARO retrievals are shown to have a negligible increase in uncertainty (~0.2 % refractivity) over the post-processed results.
- Implementation of ARO on C-130s flying out of Sacramento made it possible to evaluate impacts in two types of weather regimes: zonal ARs (see Baños poster) and cut-off lows near the coast.
- Preliminary data assimilation results show the C-130 ARO observations have impact on all model fields in the coastal and near offshore regions.
- Analysis verification shows improved RMSE compared to the control, with precipitation forecast verification still pending.

Summary of Achievements in AR Recon 2023

NOAA G-IV

- ✓900+ ARO profiles were retrieved from all 18 executed IOPs (03-23) in **Dec 2022 and Jan 2023**.
- ✓Real-time ARO raw data transmission via SATCOM was initiated from IOP7 (01/07) and running well onwards.
- ✓The first trial of the first phase of near real-time ARO processing was done on IOP11 (01/11).

USAF WC-130s

- ✓L1 only ARO data 12 flights
- ✓L1+L2 precise ARO data 3 flights
- ✓Total 15 out of 16 flights
- ✓IOP24--39 starting **Feb-Mar 2023**.
- ✓280 ARO profiles were retrieved in 3 IOPs (28, 29, and 34) from aircraft 5300, equipped with an upgraded antenna.
- ✓Successful demonstration of the ARO capability onboard larger and slower aircraft.
- ✓Preliminary data assimilation results will be shown.

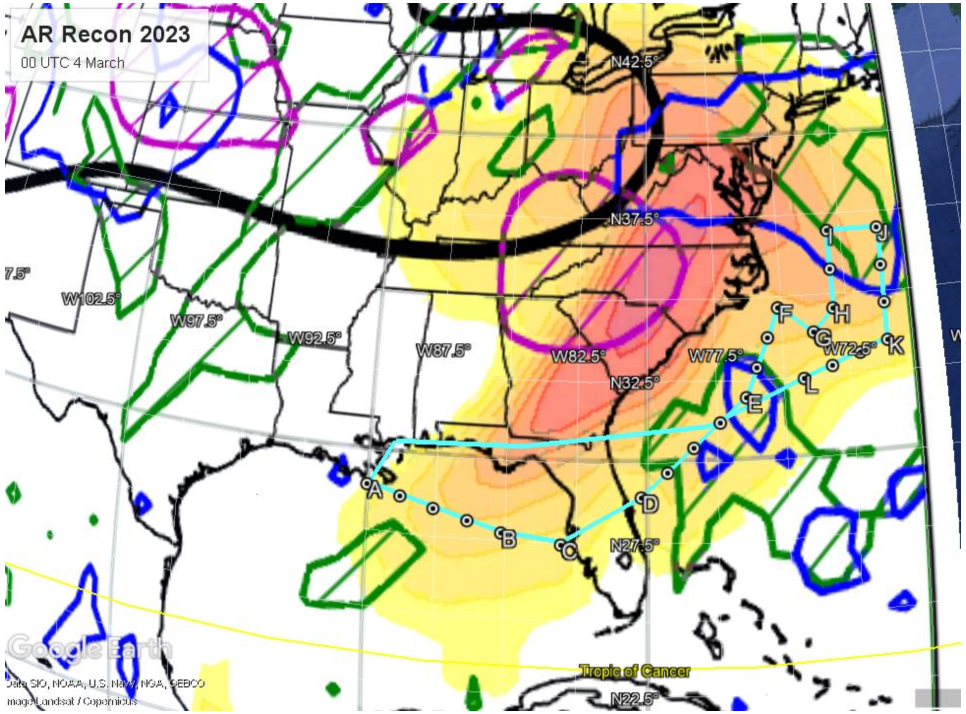
Acknowledgements

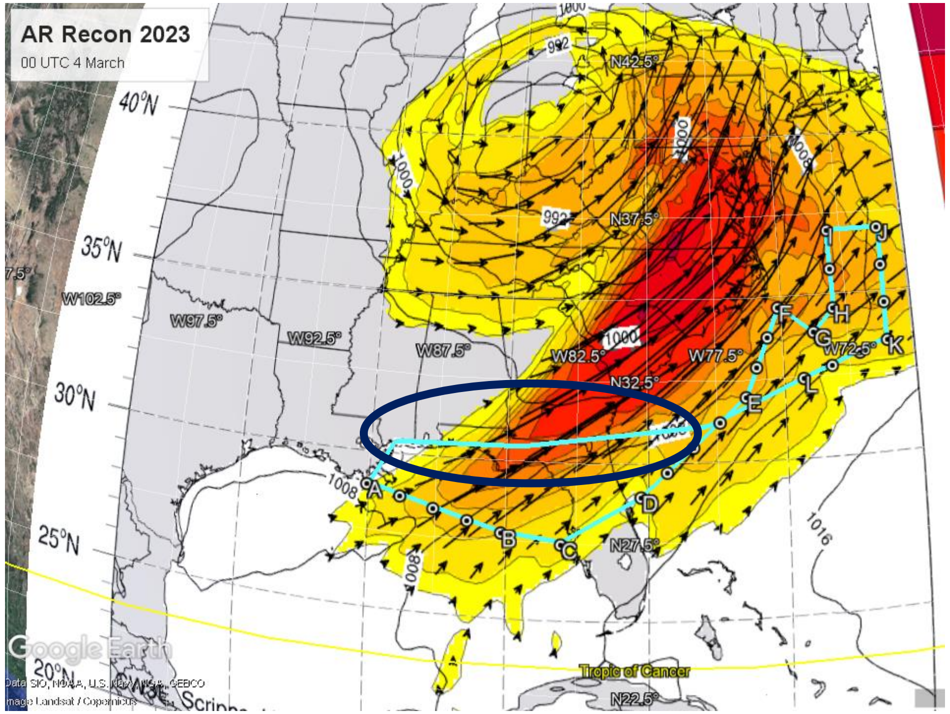
- ARO Team: Bing Cao, M.J. Murphy (now at NASA GMAO), P. Hordyniec, N. Do, I. Baños (now at NCAR), N. Contreras, P. Lee, K. Lord
- AF 403rd: C. Register, M. Gehl, R. Evans, R. Kober
- AF 53rd: Ryan Rickert, C. Dyke, K. McLaughlin
- NOAA AOC: A. Lundry, N. Underwood, G. Defao, S. Otero
- CW3E: F. Martin Ralph, Anna Wilson, Brian Kawzenuk, Minghua Zheng, Jay Cordeira, Luca Delle Monache, Colin Grudzien
- NCAR MPAS-JEDI team: Jake Liu, J.J. Guerrette

Extra Slides – Future Perspectives

ARO Working Group topics for discussion

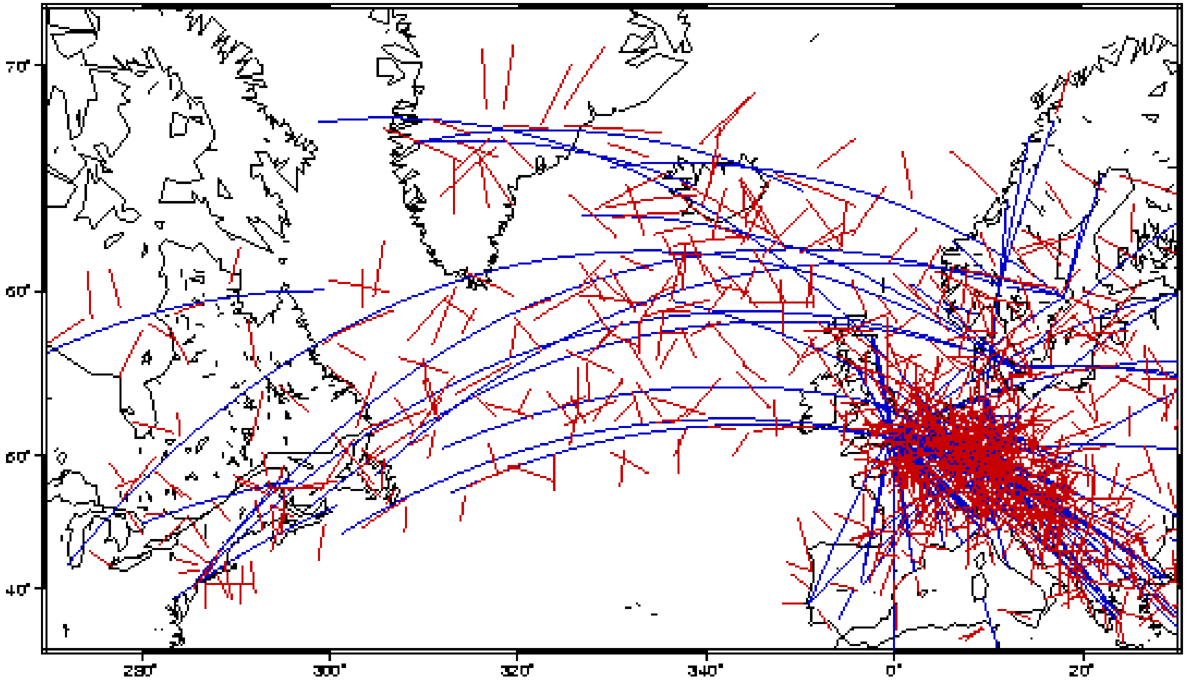
- AF C-130s equipped with ARO for the east coast winter storms
- Ferry back to station was planned to fly over AR features collecting ARO profiles



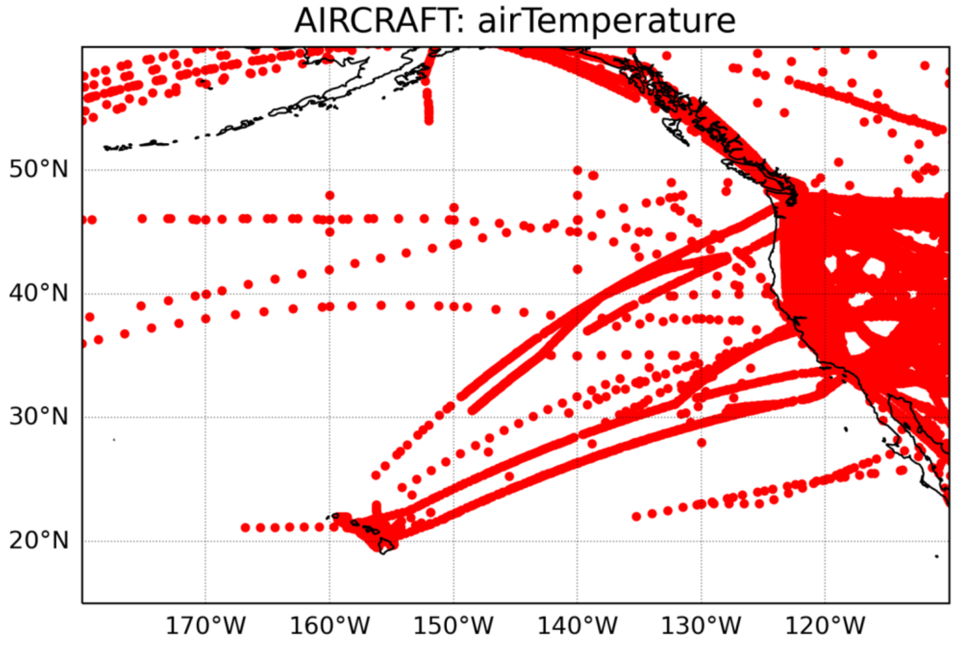


ARO Working Group topics for discussion

Potential for deployment on commercial aircraft:
14 transatlantic AMDAR flights in one day
~250 occultations (GPS only)
(Lesne et al., 2002; X-M. Chen Dissertation 2017)

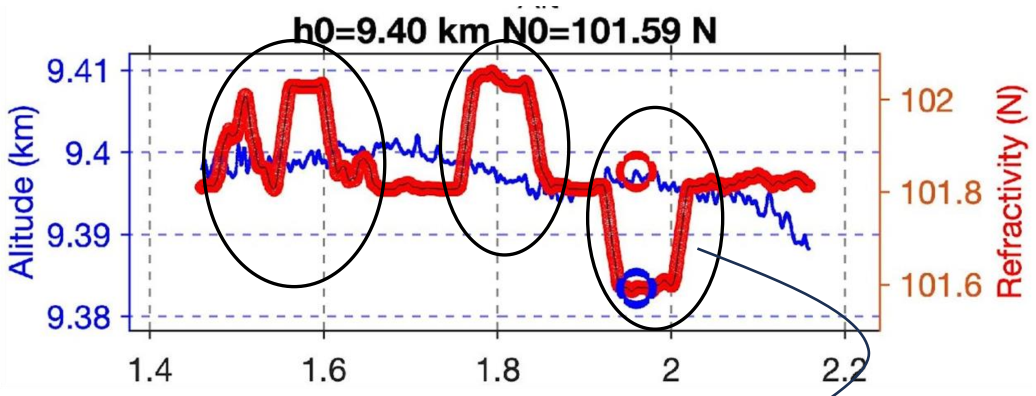


Example of commercial aircraft coverage
2023-01-06 18:00 UTC IOP07
13 flights across the east Pacific could provide
430 ARO profiles each 6 hours



Courtesy of I. Banos, see poster session

DA Working Group topics for discussion



Blue: flight altitude
Red: refractivity

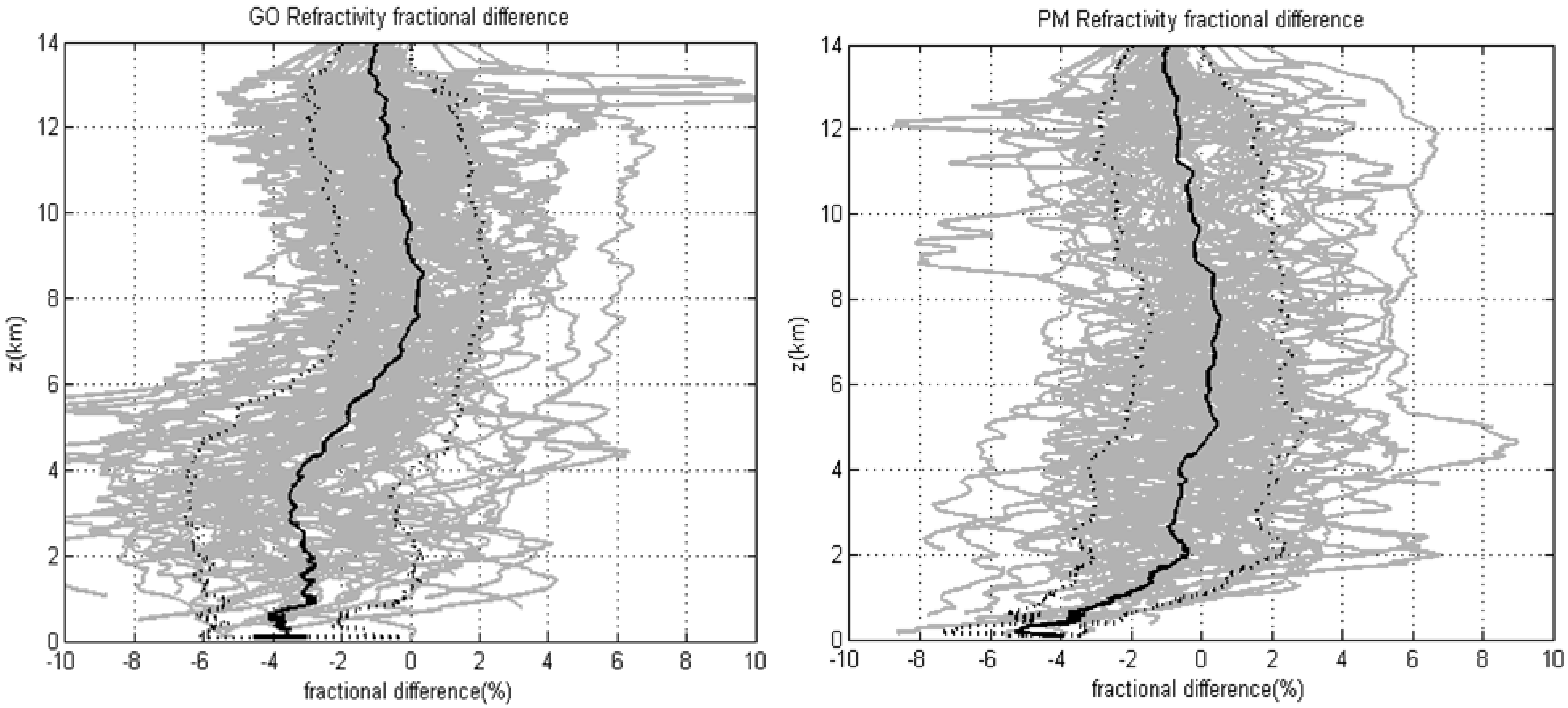
- **Coordinate flight level HDOBS data assimilation with ARO**
- Temperature recorded only to 0.5 K precision.
- ARO uses in-situ temperature in the retrieval.
- Inconsistencies can be detected by ARO.
- Potential for higher impact from flight level pressure given precise GNSS height.

Jumps due to 0.5 K precision temperature recordings

ARO improvements with OL tracking

- Conventional receiver tracking descends to ~4 km
- Open-loop software receiver retrieves data to the surface
- Climatological model increases SNR and accuracy of excess phase profile
- Phase Matching (Jensen et al., 2004; Wang et al., 2017) retrieval reduces bias in bending angle below 6 km.
- Refractivity retrievals from the Abel Inversion are improved
- Demonstrated with prototype GNSS signal recorder in 2010 Predict campaign
- New recorders are currently being tested in AR Recon

Penetration to the surface with OL tracking



Fractional refractivity difference with respect to ERA-Interim model for all 2010 hurricane Karl flights demonstrates tracking within .5 km of the surface, with reduced bias (Wang et al., JGR, 2017). Research on OL tracking from the GIV data has started. A new recording system is available for the C-130s starting for AR Recon 2024.