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Impact of 2D ROPP Forward Operators and Airborne Radio Occultation Assimilation on Global Numerical Weather Prediction

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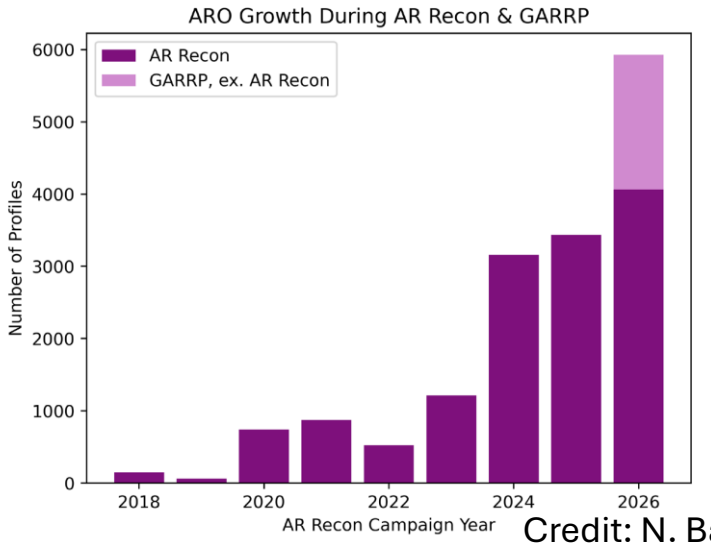
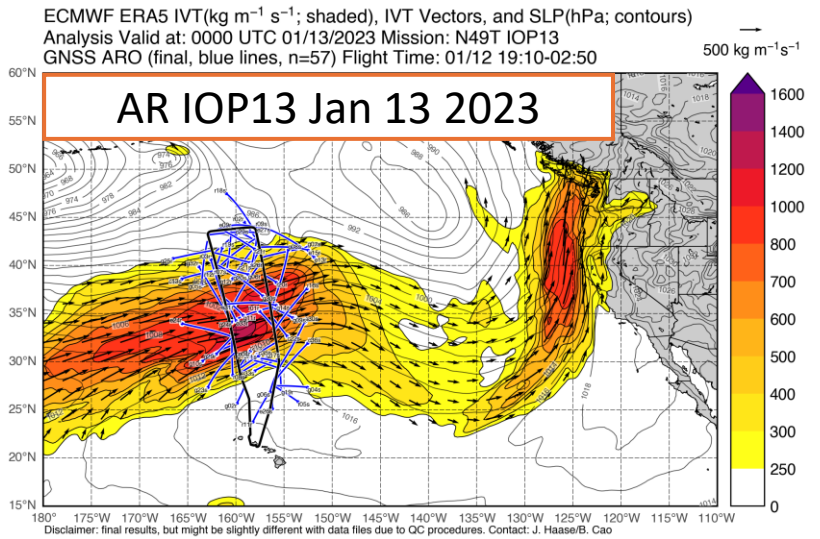
Motivation

- Decent increase of GNSS Airborne Radio Occultation (**ARO**) profiles recently (Hasse et al. 2014; 2021)
- ARO profiles provide critical thermodynamic information aloft over the open ocean, filling observational gap
- Assimilation of ARO refractivity profiles into a **regional** NWP model has been shown to improve the representation of moisture and temperature fields (Hasse et al. 2021)
- Assimilation of ARO bending angle profiles in a global model improved precipitation forecasts (Do et al. 2025)
- Most ARO data in this study were collected during Atmospheric River RECON missions (Zheng et al. 2026)



Credit: N. Barton



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

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Status and Objective

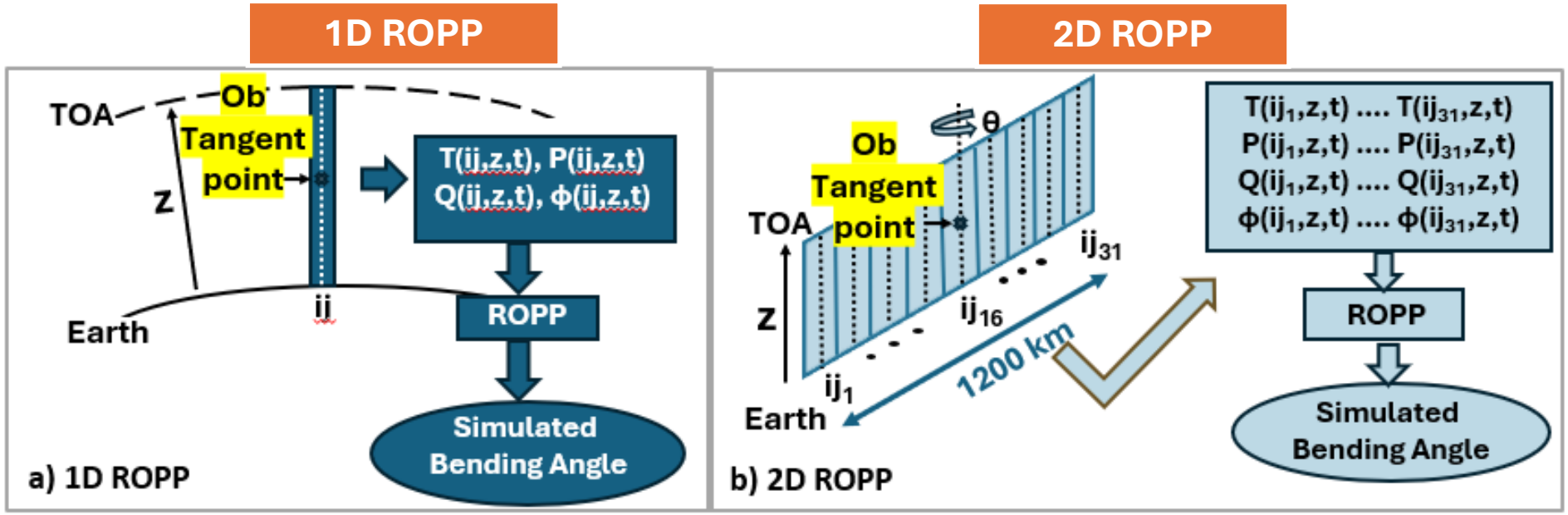
- Current global data assimilation (DA) ingests GNSS space-borne RO bending angles with 1D **Radio Occultation Processing Package** (**ROPP**) (Culverwell et al., 2015; Ruston and Healy, 2020)
- 2D foreword operator (FO) represents more accurately the signal ray path than 1D FO (Healy et al. 2007)
- 2D forward operator and its tangent linear and adjoint model for ARO assimilation is ready for ops integration (Hordyniec et al. 2025)

Objective

- Upgrade GNSS RO forward operator from 1D to 2D in the global model
- Assess whether using 2D forward operator for spaceborne RO leads to better global NWP forecasts
- Develop ARO assimilation capability within the global model
- Evaluate Airborne RO assimilation impact on NWP forecasts, particularly for Atmospheric River prediction

Spaceborne RO Forward Operator

- Quality control and observation error specifications are in Ruston and Healy (2021)
- Tangent-point drift correction is applied
- Substantial effort was required to rewrite the original 1D RO assimilation code to support the 2D upgrades
- The 2D ROPP forward operator is applied up to 10 km altitude; above 10 km, the 1D ROPP forward operator is used.



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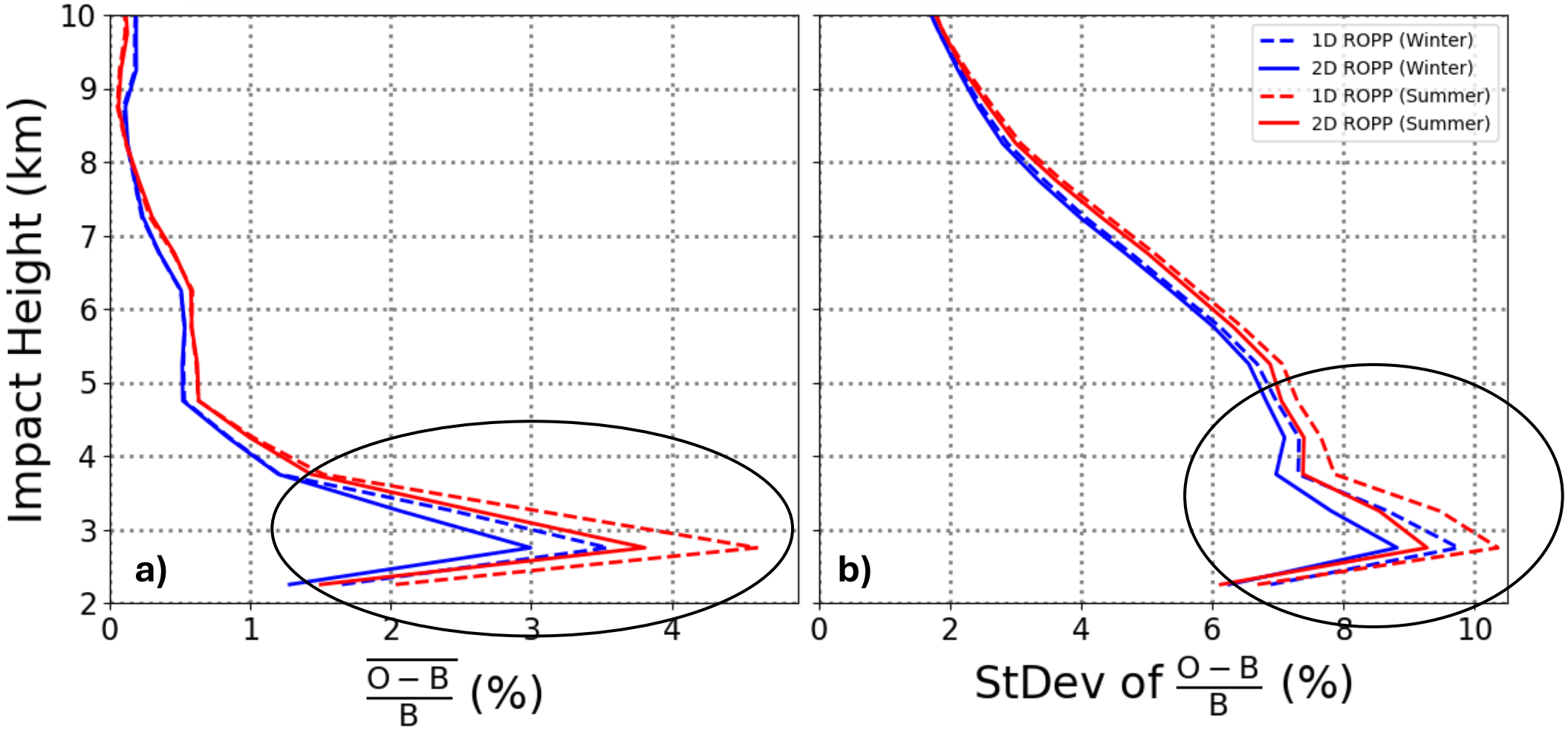
2D ROPP
Observing system experiments (OSEs)

Experiment Name	Duration	Radio Occultation Obs Assimilated
1D ROPP (Summer)	1 July 2023 → 30 Sep 2023	GNSS RO with 1D Forward Operator (FO)
2D ROPP (Summer)		GNSS RO with 2D FO
1D ROPP (Winter)	8 Dec 2022 → 8 Mar 2023	GNSS RO with 1D FO
2D ROPP (Winter)		GNSS RO with 2D FO

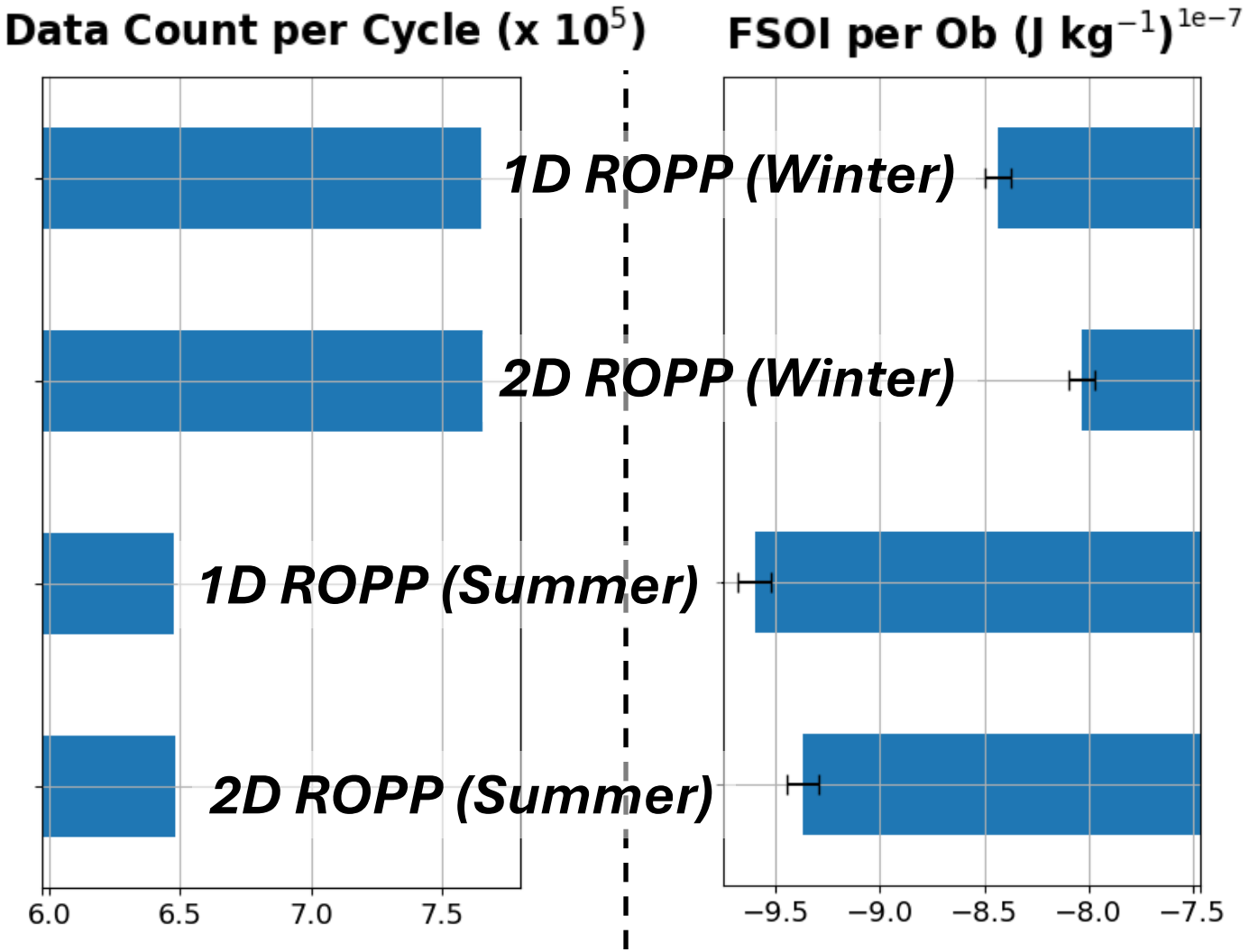
Global model: T681L60 (~19km horiz. res. with a model top at 0.04 hPa) (Hogan et al .2014)
DA system: 4DVar Hybrid (Kuhl et al. 2013)
Baseline dataset includes all observations routinely assimilated in ops

Bending Angle Background Departure Stats (1D ROPP vs. 2D ROPP)

Bending angle background departure stats decreased in low- to mid-levels by 2D forward operator.



FSOI of GNSS Spaceborne RO (1D ROPP vs. 2D ROPP)

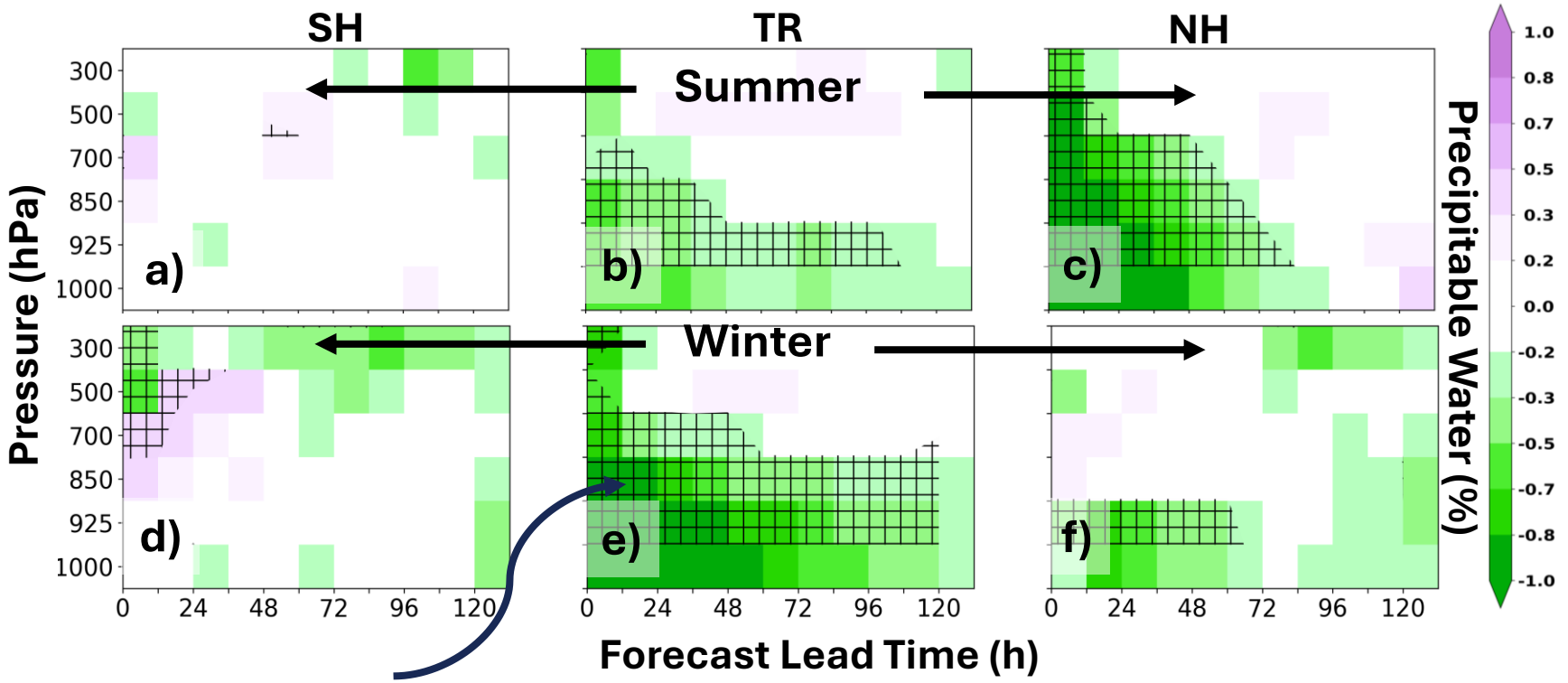


FSOI: forecast sensitivity to observation impact (Langland and Baker 2004)
Moist energy norm

Based on FSOI, the 2D forward operator was not more beneficial than the 1D forward operator when assimilating GNSS Spaceborne observations.

Relative Impact on Moisture Forecasts (1D ROPP vs. 2D ROPP)

Verification Against ECMWF Analyses



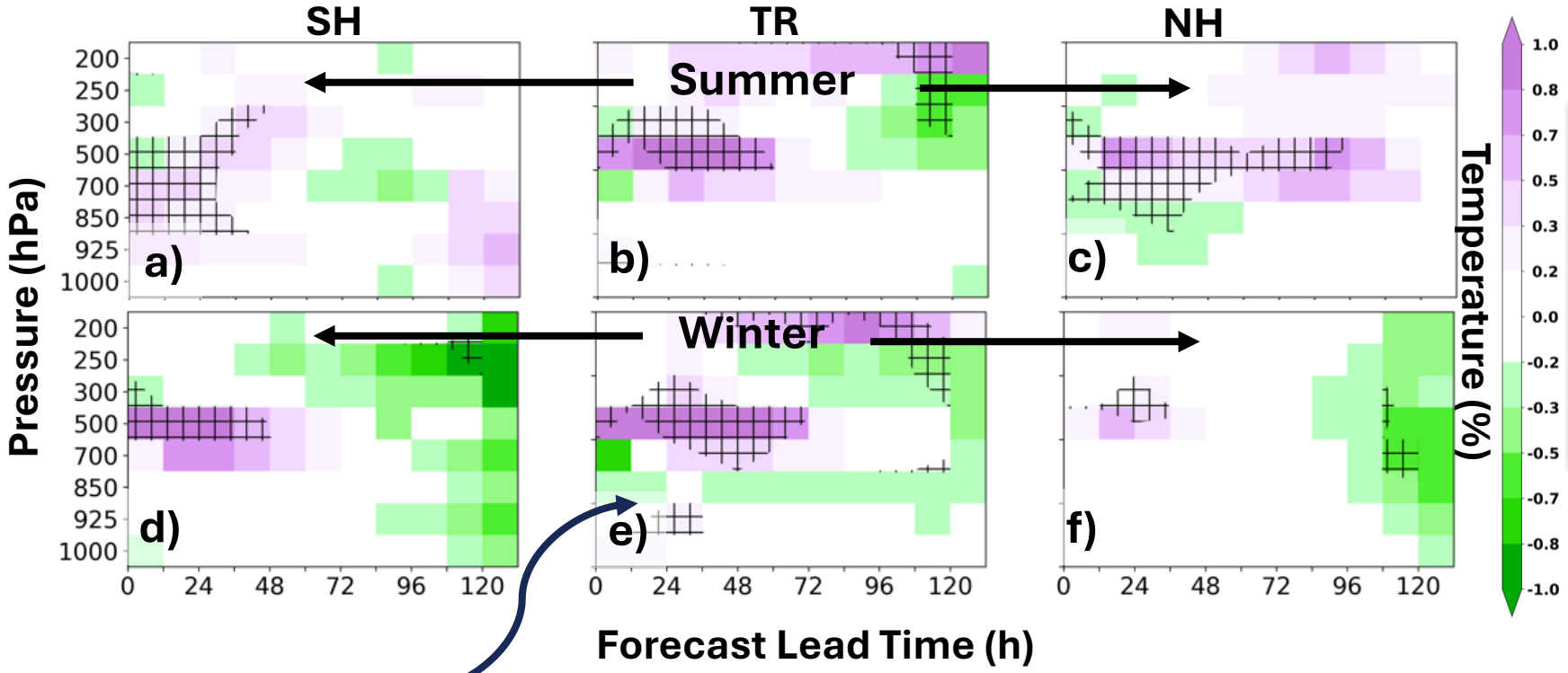
Global forecasts of precipitable water, particularly in TR and NH, improved in low- to mid-levels by 2D forward operator.

≥ 95% statistical confidence

$$100 \times \frac{\mathrm{RMSD}_{\mathrm{2D\ ROPP}} - \mathrm{RMSD}_{\mathrm{1D\ ROPP}}}{\mathrm{RMSD}_{\mathrm{1D\ ROPP}}}$$

Relative Impact on Temperature Forecasts (1D ROPP vs. 2D ROPP)

Verification Against ECMWF Analyses



Global forecasts of temperature slightly degraded in low- to mid-levels by 2D forward operator.

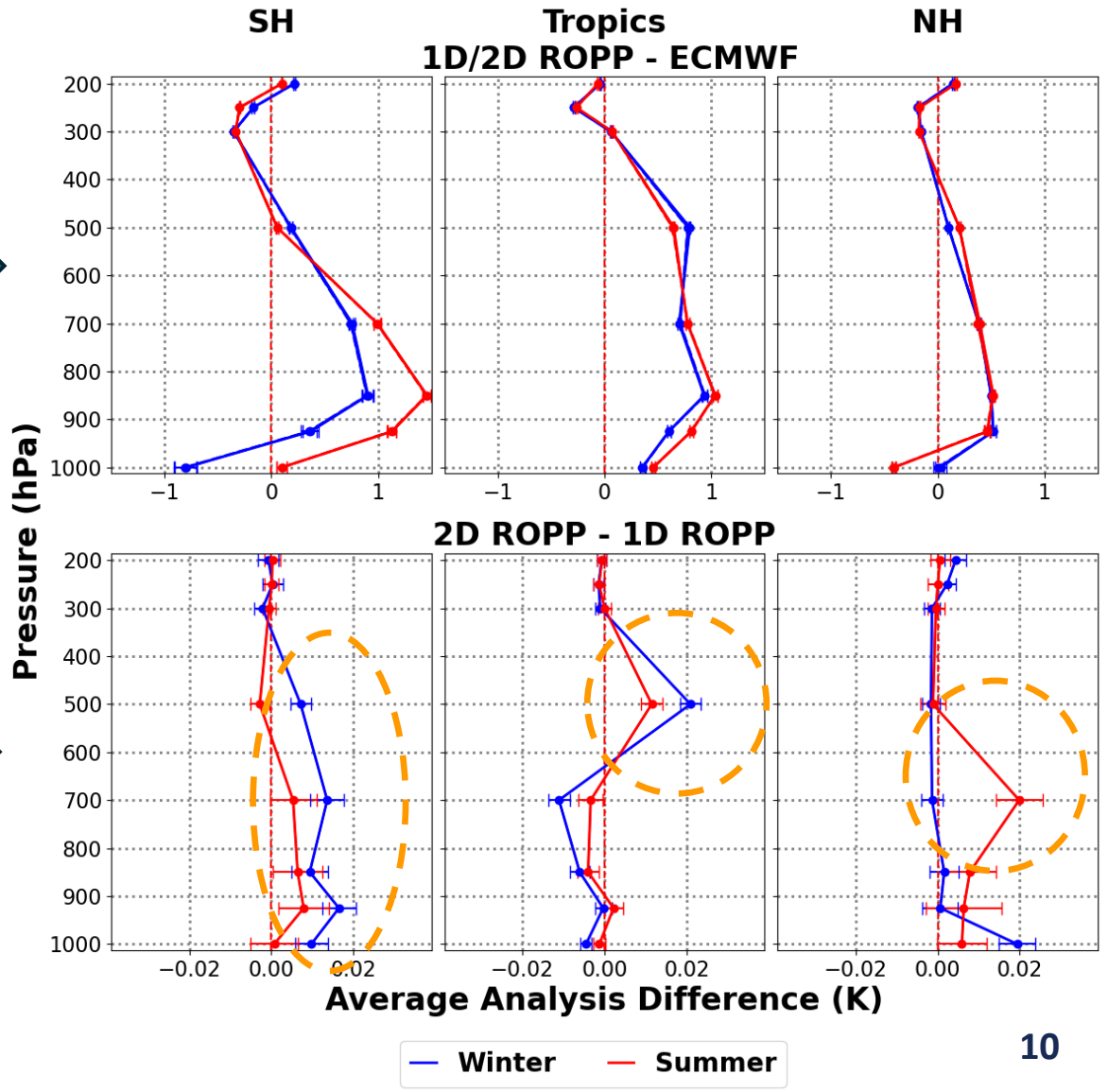
≥ 95% statistical confidence

$$100 \times \frac{\mathrm{RMSD}_{\mathrm{2D\ ROPP}} - \mathrm{RMSD}_{\mathrm{1D\ ROPP}}}{\mathrm{RMSD}_{\mathrm{1D\ ROPP}}}$$

Temperature Analysis Biases (1D ROPP vs. 2D ROPP)

Both 1D & 2D ROPP analyses have positive temperature biases relative to ECMWF above the lowest levels.

2D ROPP temperature analysis bias is larger than 1D ROPP at many levels.



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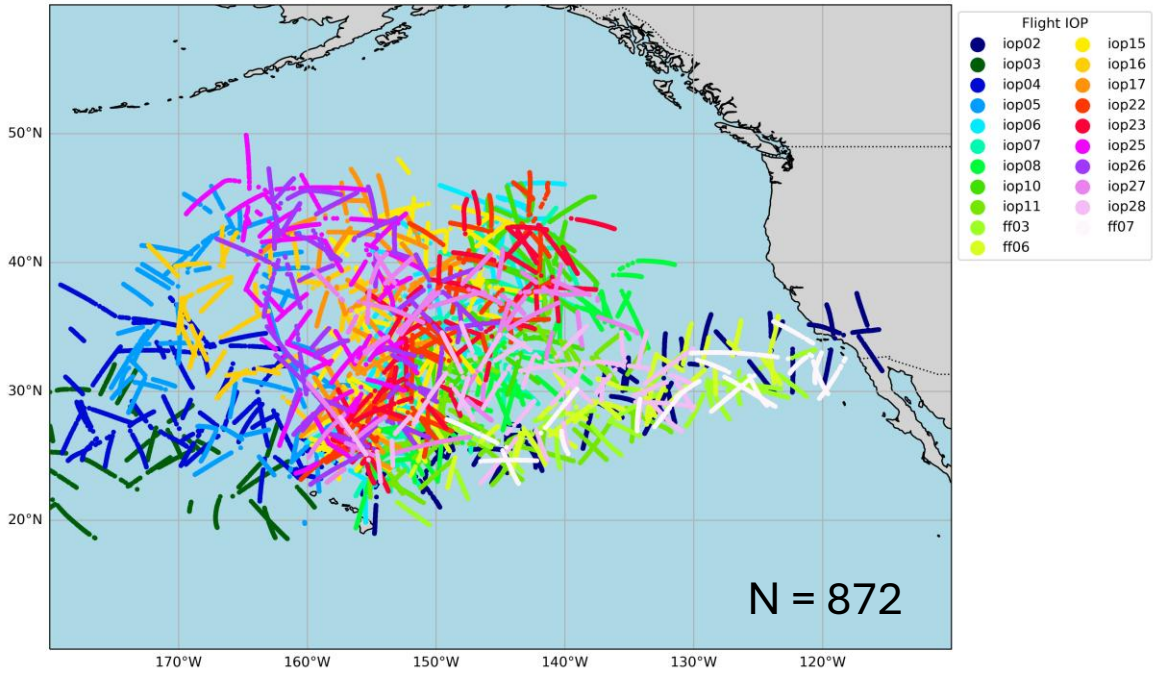
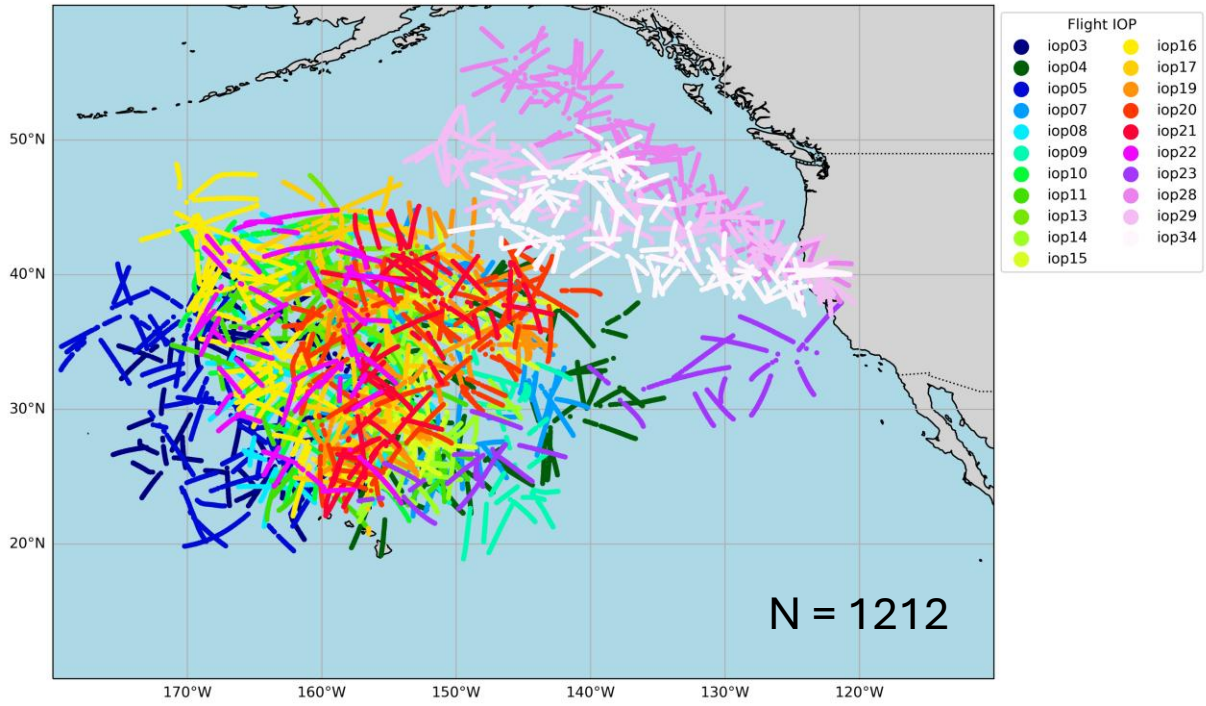
ARO Observation Availability

AR Recon Season 2021



AR Recon Season 2023



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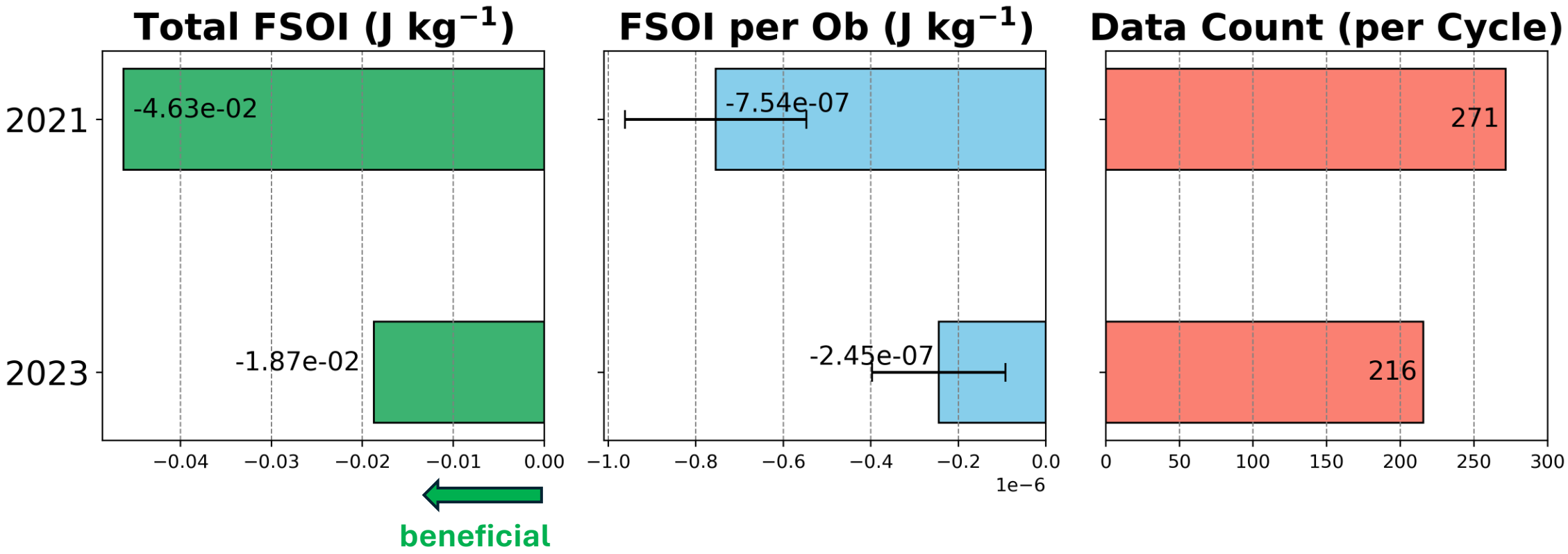
ARO OSEs

Experiment Name	Duration	Radio Occultations Assimilated
Control 2021	18 Jan 2021 → 18 Mar 2021	GNSS RO
ARO 2021		GNSS RO and ARO
Control 2023	8 Dec 2022 → 8 Mar 2023	GNSS RO
ARO 2023		GNSS RO and ARO

GNSS RO and ARO bending angles are both assimilated with 2D forward operator

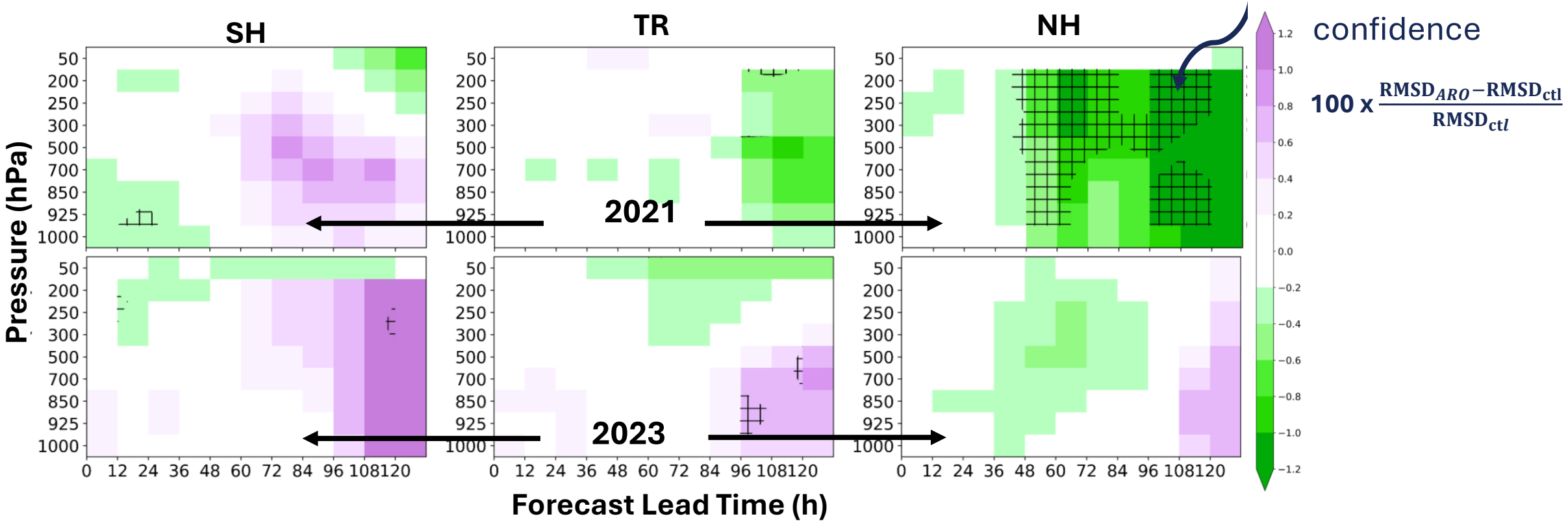
ARO FSOI

- *Despite sparse in quantity, ARO data are beneficial*
- *ARO total FSOI or FSOI per obs in 2021 appears to be larger than in 2023*



Relative Impact on Geopotential Height Forecasts (control vs. ARO)

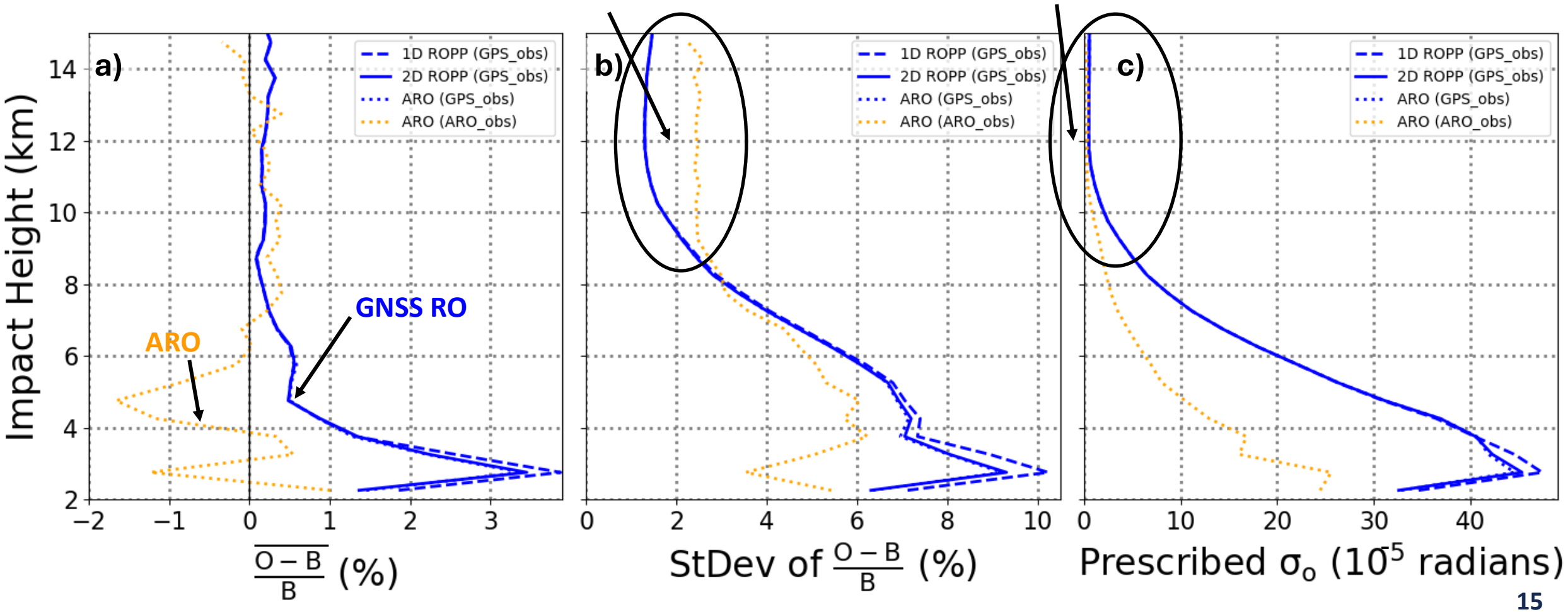
Verification Against ECMWF Analyses



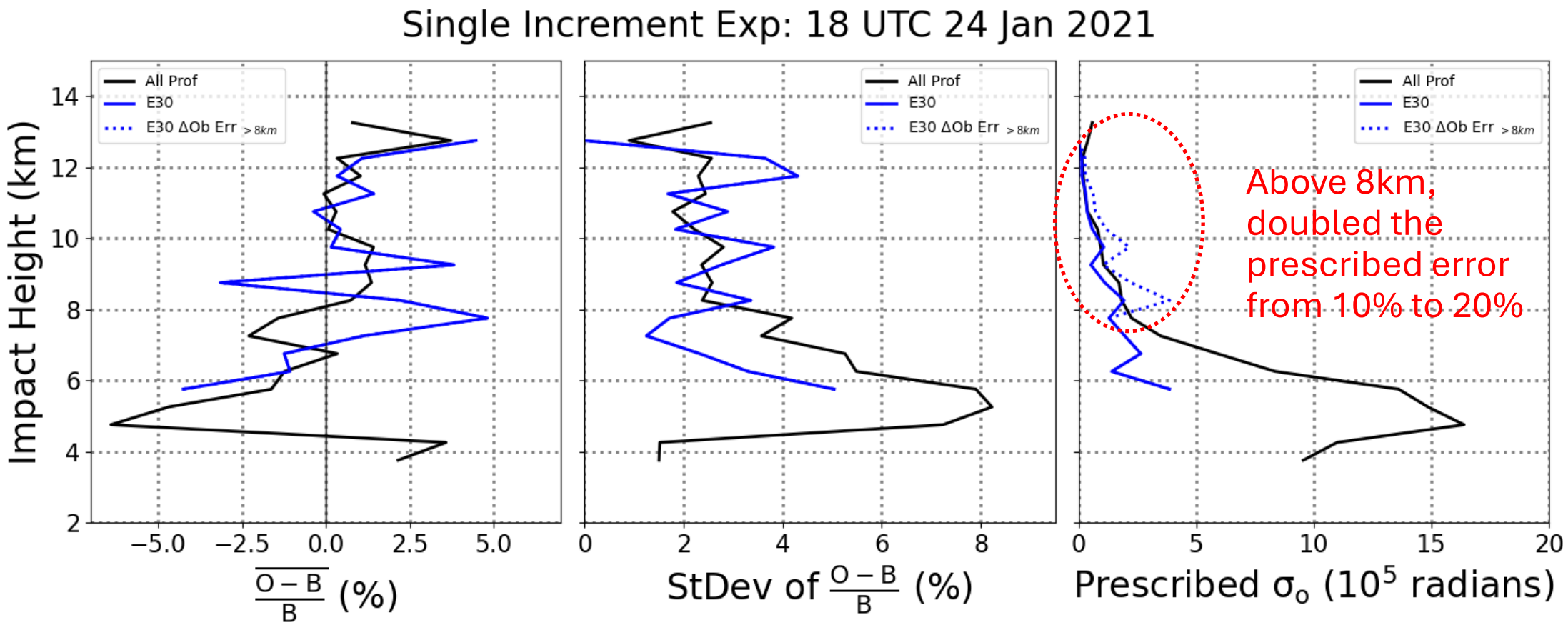
ARO assimilation improved global forecasts of NH geopotential heights, with a greater impact in 2021 AR Recon cases than in 2023

Bending Angle Background Departure Stats (7 – 17 Jan 2023)

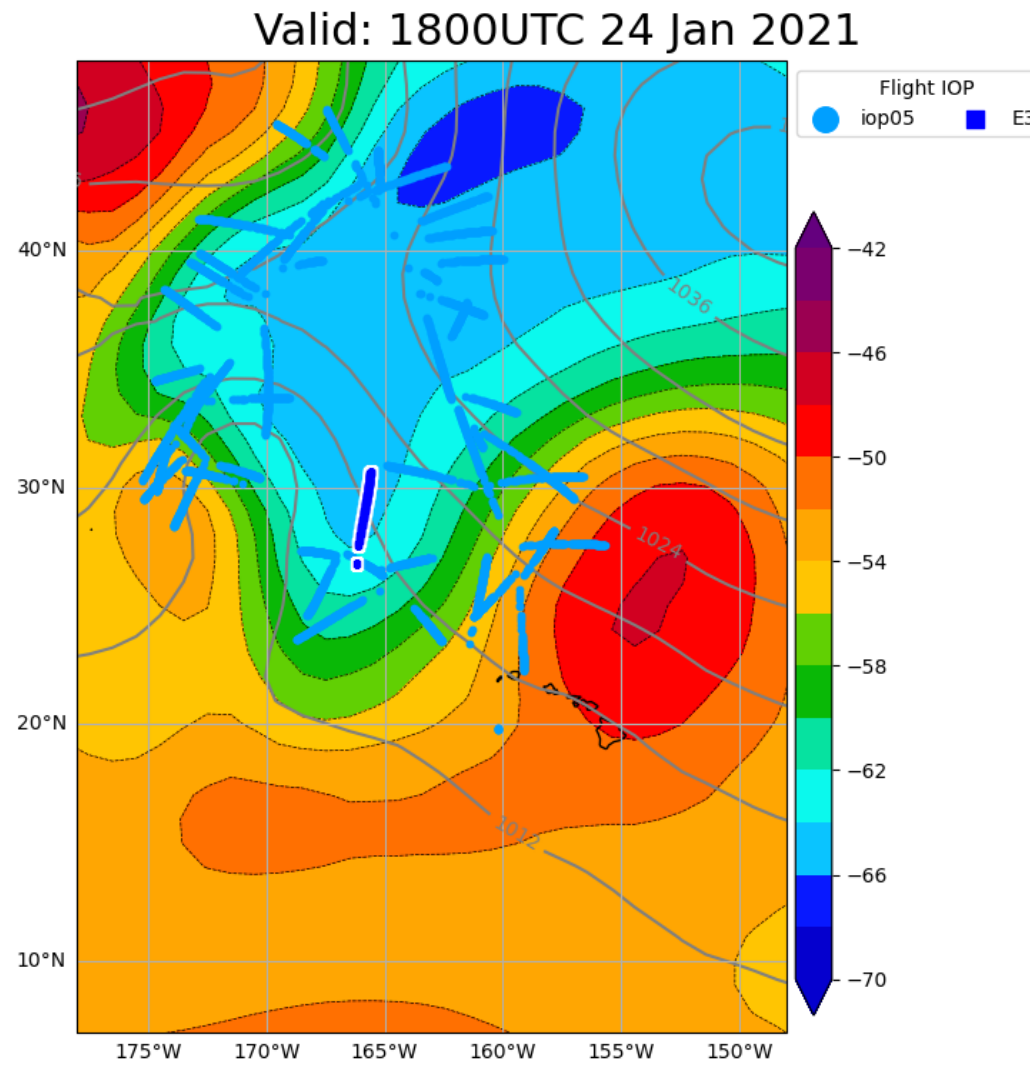
Prescribed error for ARO obs above ~ 8 km might be too low.



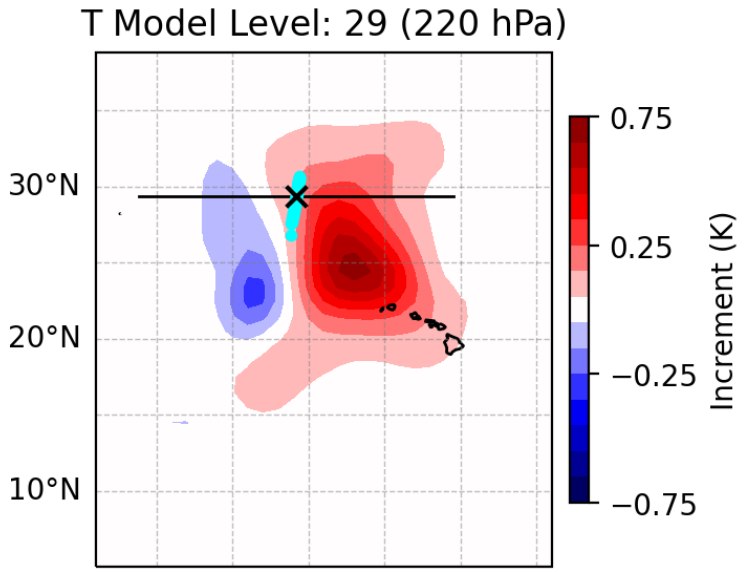
Single ARO Observation Error Sensitivity Departure Stats



Single ARO Observation Error Sensitivity Temperature Analysis Increment

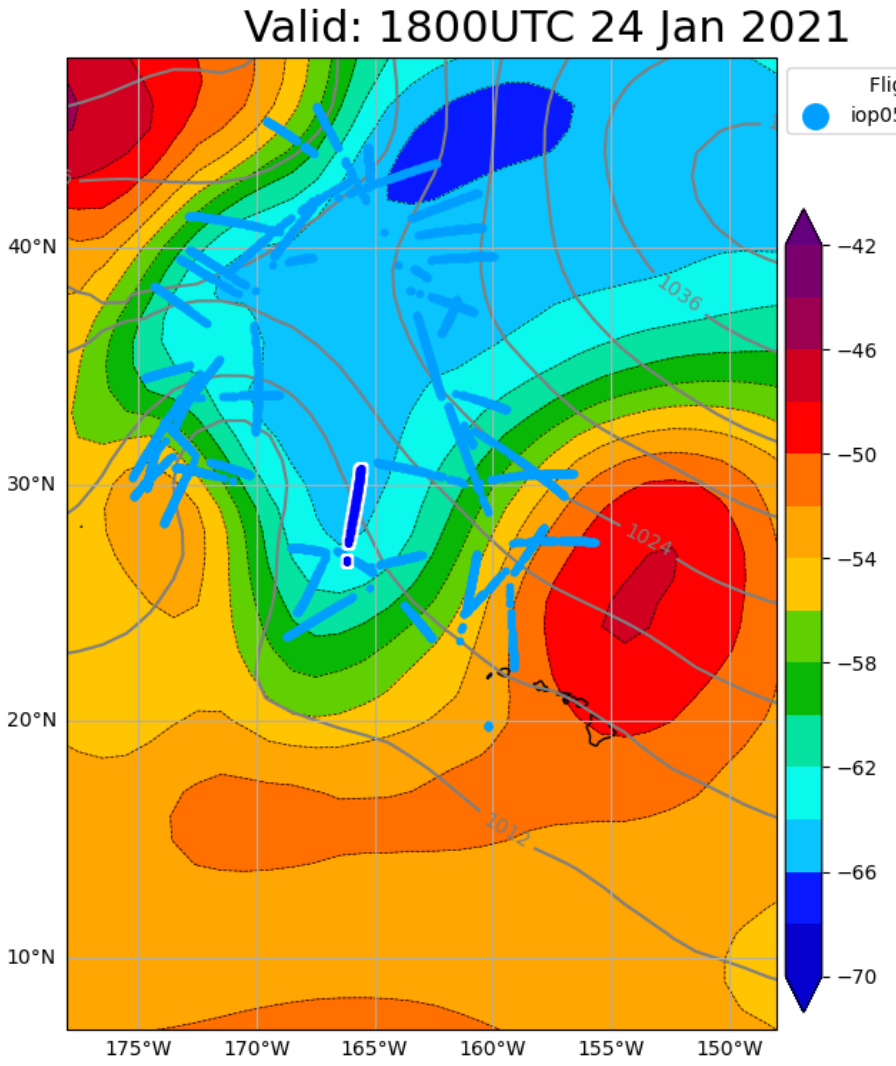


200 hPa Temperature (shaded) and SLP

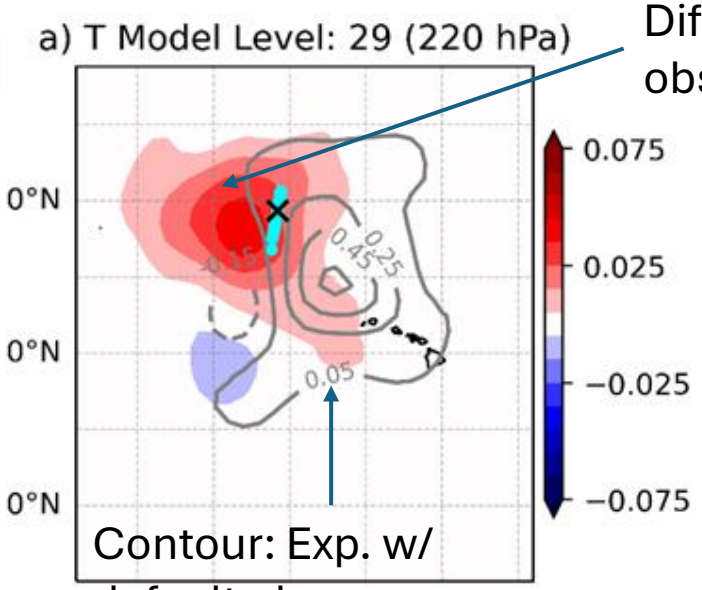


Increased temperature on the right side of the trough

Single ARO Observation Error Sensitivity Temperature Analysis Increment Difference



200 hPa Temperature (shaded) and SLP



Diff between Exp. w/ increased obs error and control

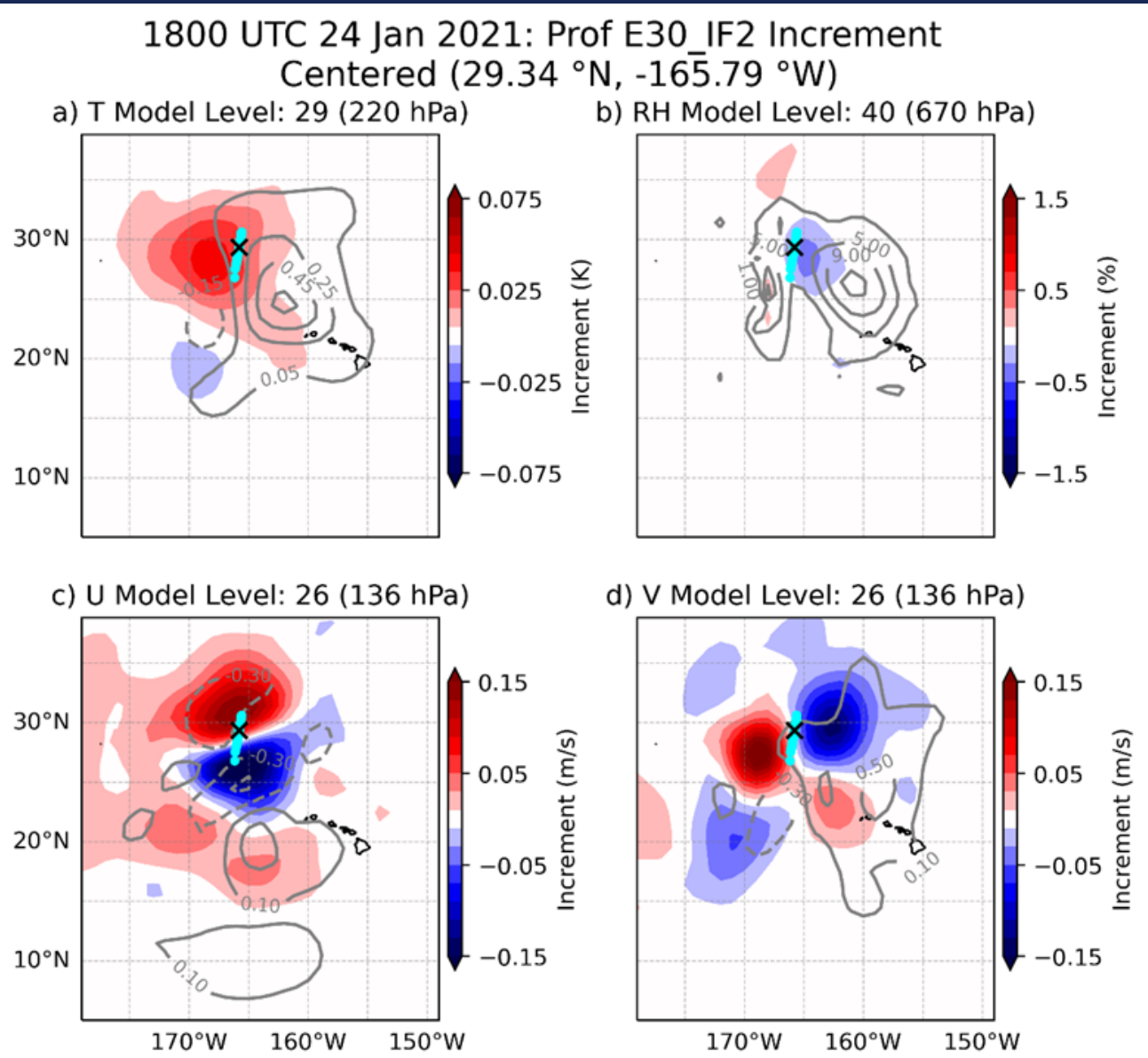
Contour: Exp. w/ default obs error

Temperature increment dampens after increasing obs error

Single ARO Observation Error Sensitivity Analysis Increment Differences (T, RH, u, v)

- The difference fields for temperature, RH, U and V winds (shading) increments are opposite in sign to the original control increments
- The initial warming, moistening, and wind adjustments that strengthened the trough's cyclonic vorticity were all substantially reduced in the sensitivity test (by increasing slightly obs error above 8 km)

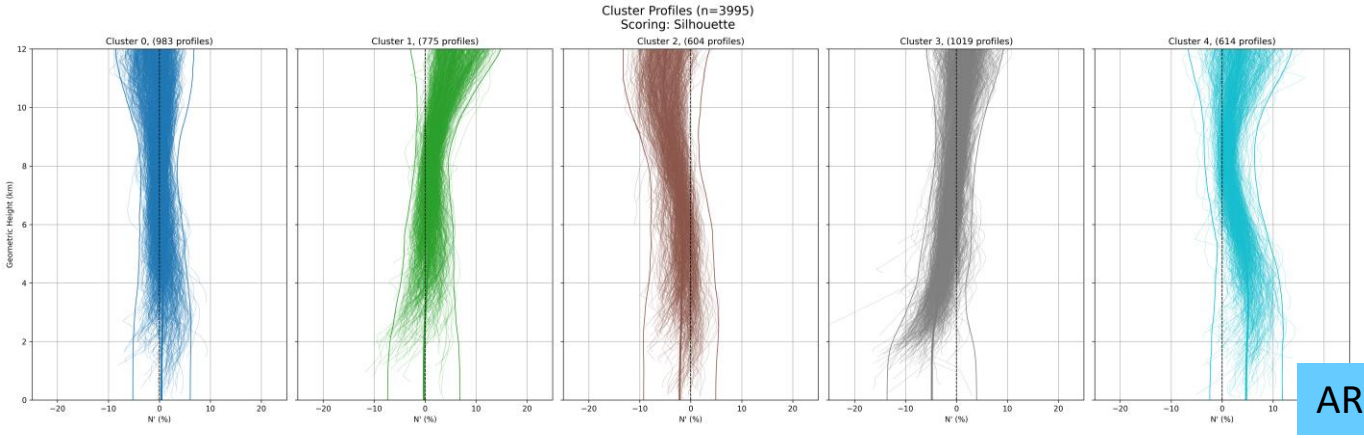
Analysis increment sensitive to prescribed observation uncertainty

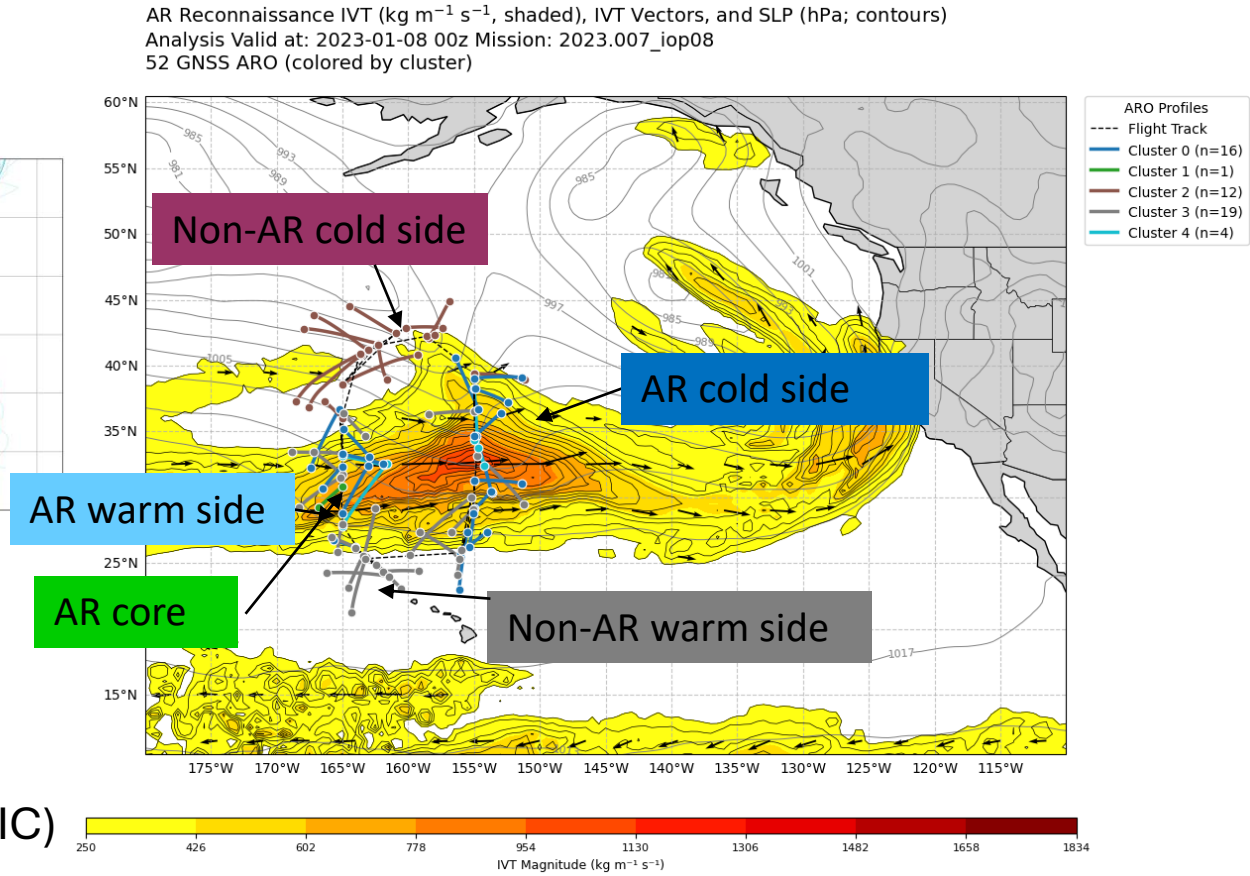


Clustering on ARO Refractivity
ARO data (2018-2025)

Can we use machine learning techniques (e.g., k-means clustering) to estimate the prescribed errors of airborne RO obs based on their thermodynamic environment to improve atmospheric river events?

ARO data (2018-2025)





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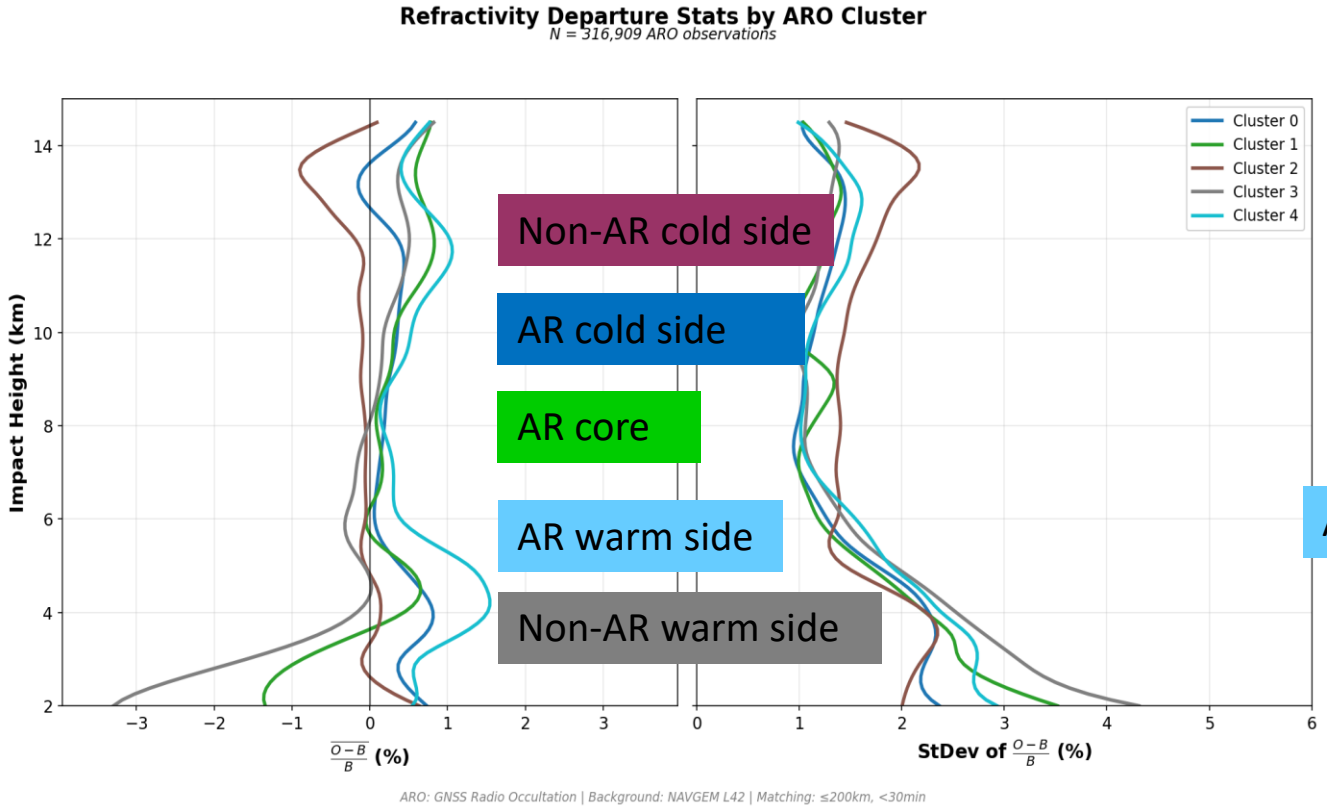
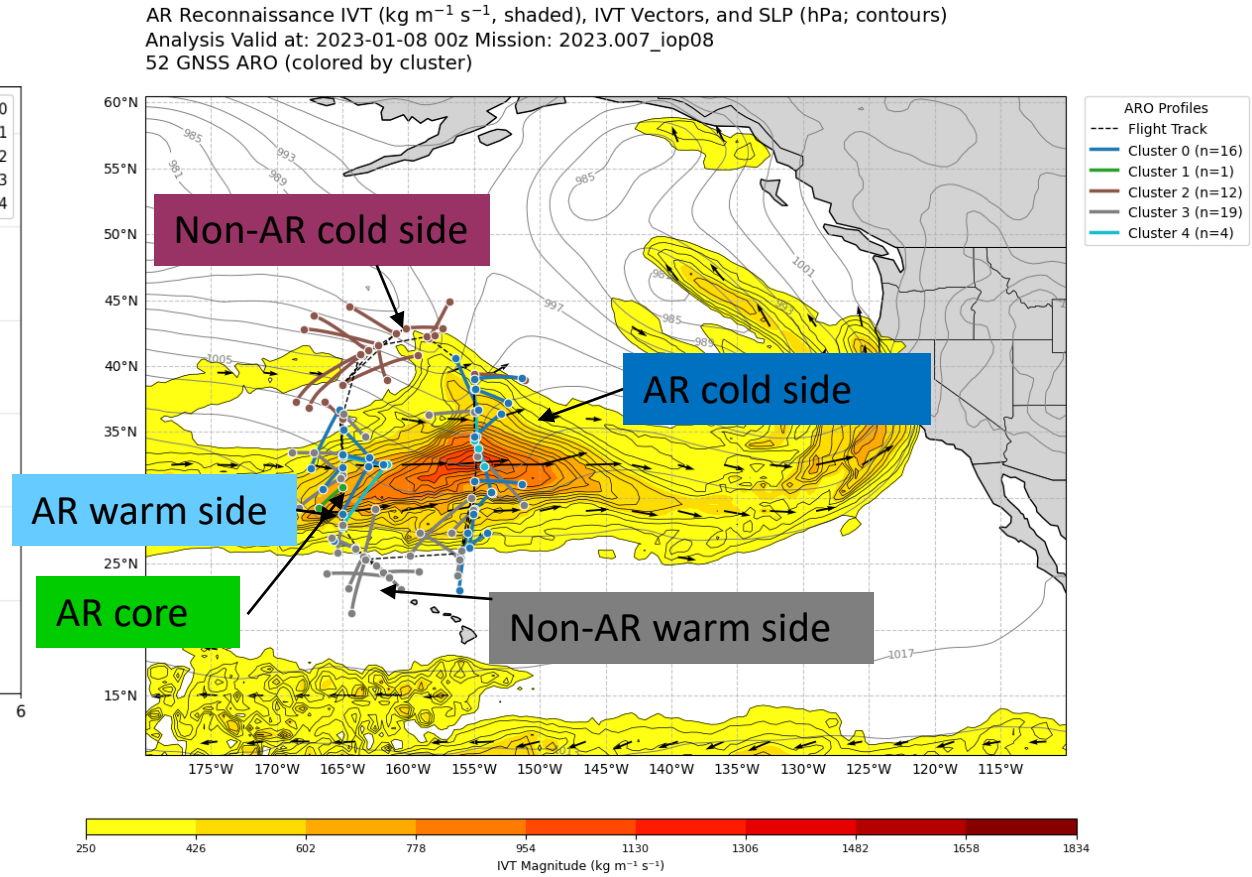
ARO Refractivity Background Departure Stats ARO data (2018-2025)

AR different sectors appear to have different refractivity error characteristics





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Summary and Future Work

- Assimilating GNSS RO obs with a 2D forward operator (2D ROPP):
  - Yields statistically significant improvements in global forecasts of low- to mid-level moisture
  - Produces small but statistically significant degradations in global forecasts of low- to mid-level temperature
    - Amplified existing large temperature bias relative to ECMWF analyses
- ARO assimilation improved global forecasts of NH geopotential heights, with a greater impact during 2021 AR Recon campaign than in 2023
- Single-profile ARO sensitivity tests show that analysis increments are sensitive to the prescribed observation uncertainty
- Clustering based on ARO refractivity identifies five atmospheric river sectors with distinct error characteristics, which can be used to guide future experiment design

Future Work:

- Understand why 2D ROPP amplifies existing known model bias
- Integrate cluster-aware error model for ARO assimilation

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Acknowledgement

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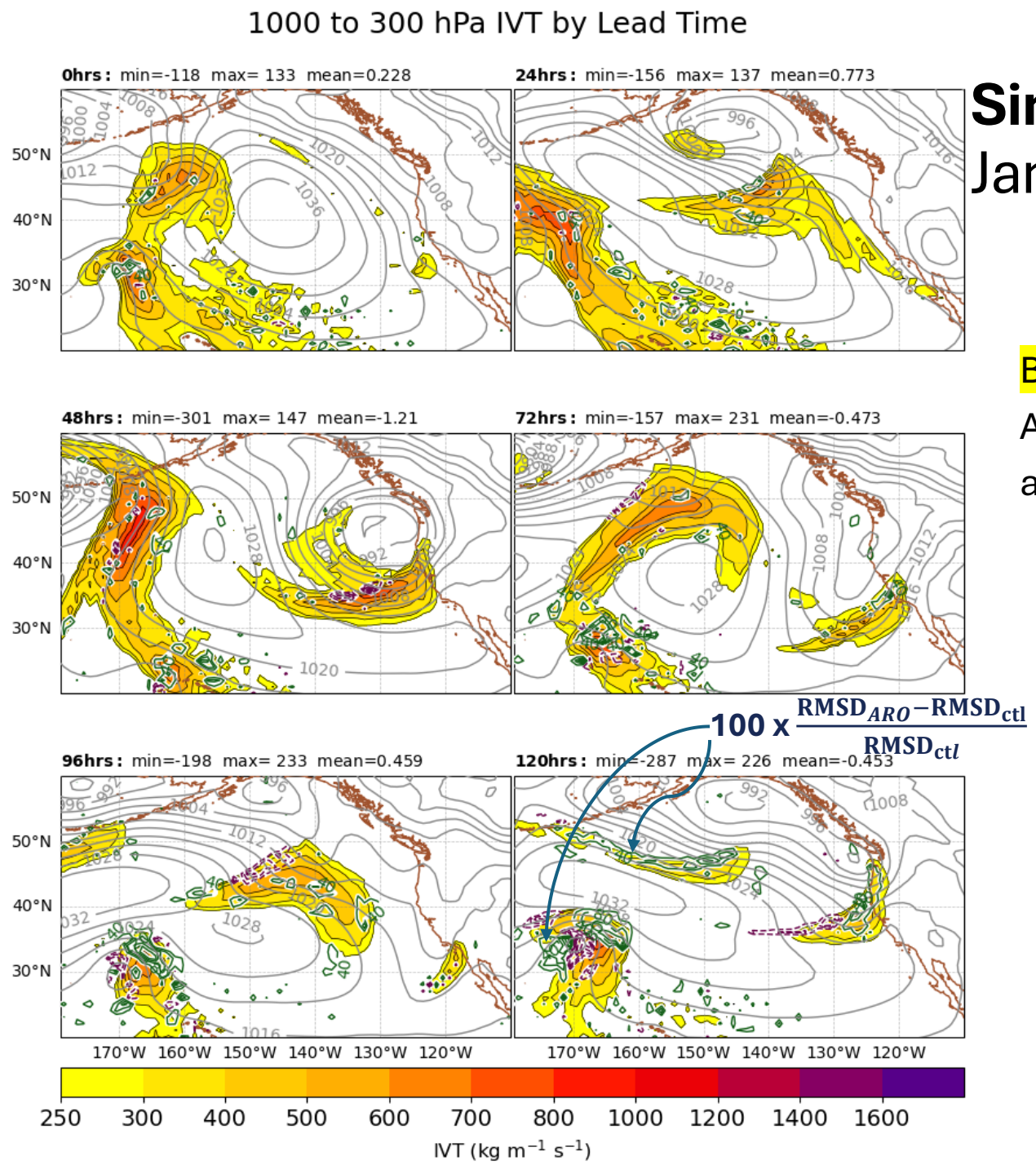
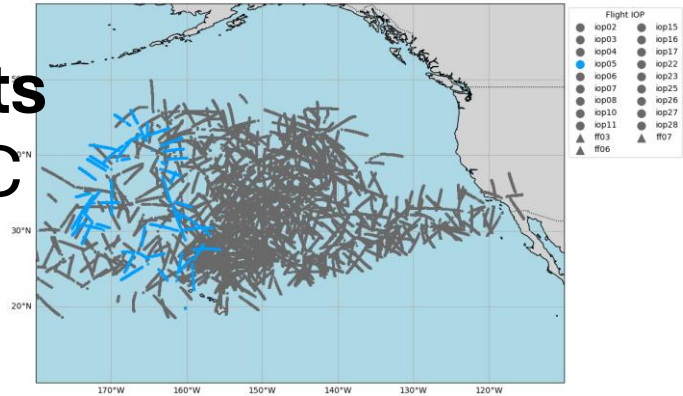
Supplemental Slides



Single Case Forecasts

Jan 25 2021 0000 UTC



Background ECMWF IVT (shading) and SLP (contours)

ARO impact (**green->positive**; **purple->negative**; ECMWF analysis as a reference)

ARO on average has a positive impact on forecast, especially following the upstream portion of the AR

- Some positional differences with the control and experiment compared to ECMWF analysis
- The ARO experiment shifts the high band of IVT south of Alaska farther south, closer to the analysis at 120 h

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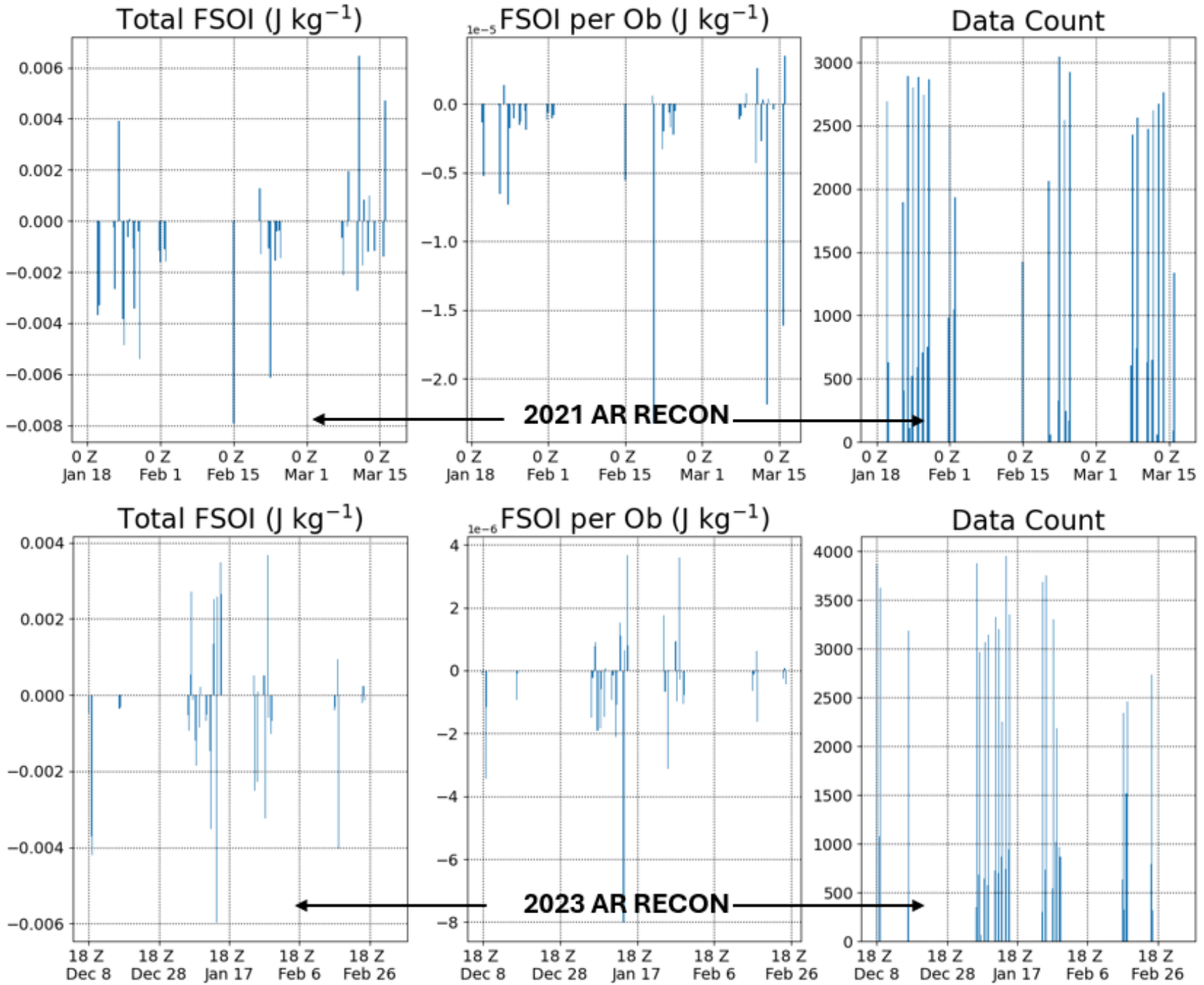
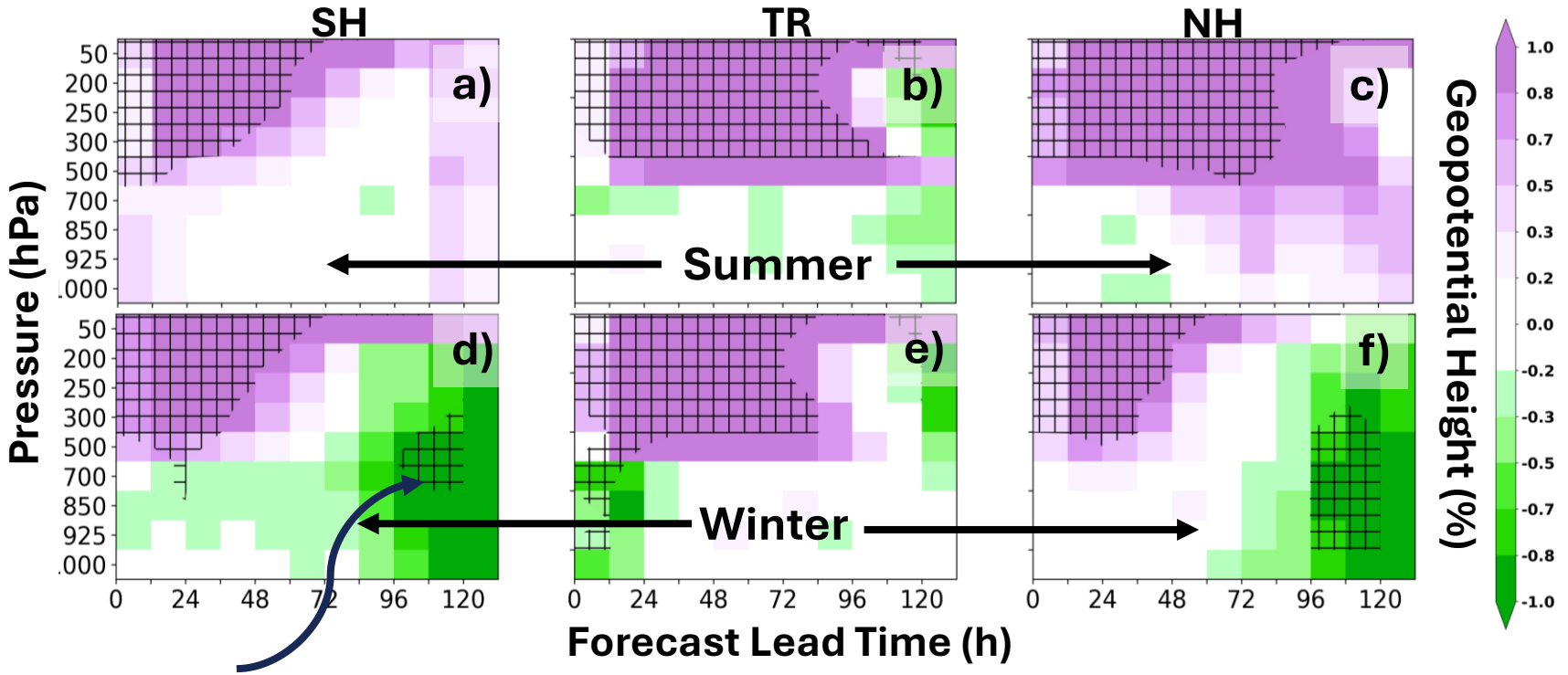


Relative Impact on Geopotential Height Forecasts (Full 3 Months; 1D ROPP vs. 2D ROPP)

Verification Against ECMWF Analyses



≥ 95% statistical confidence

Global forecasts of geopotential height degraded in mid- to upper-levels by 2D forward operator

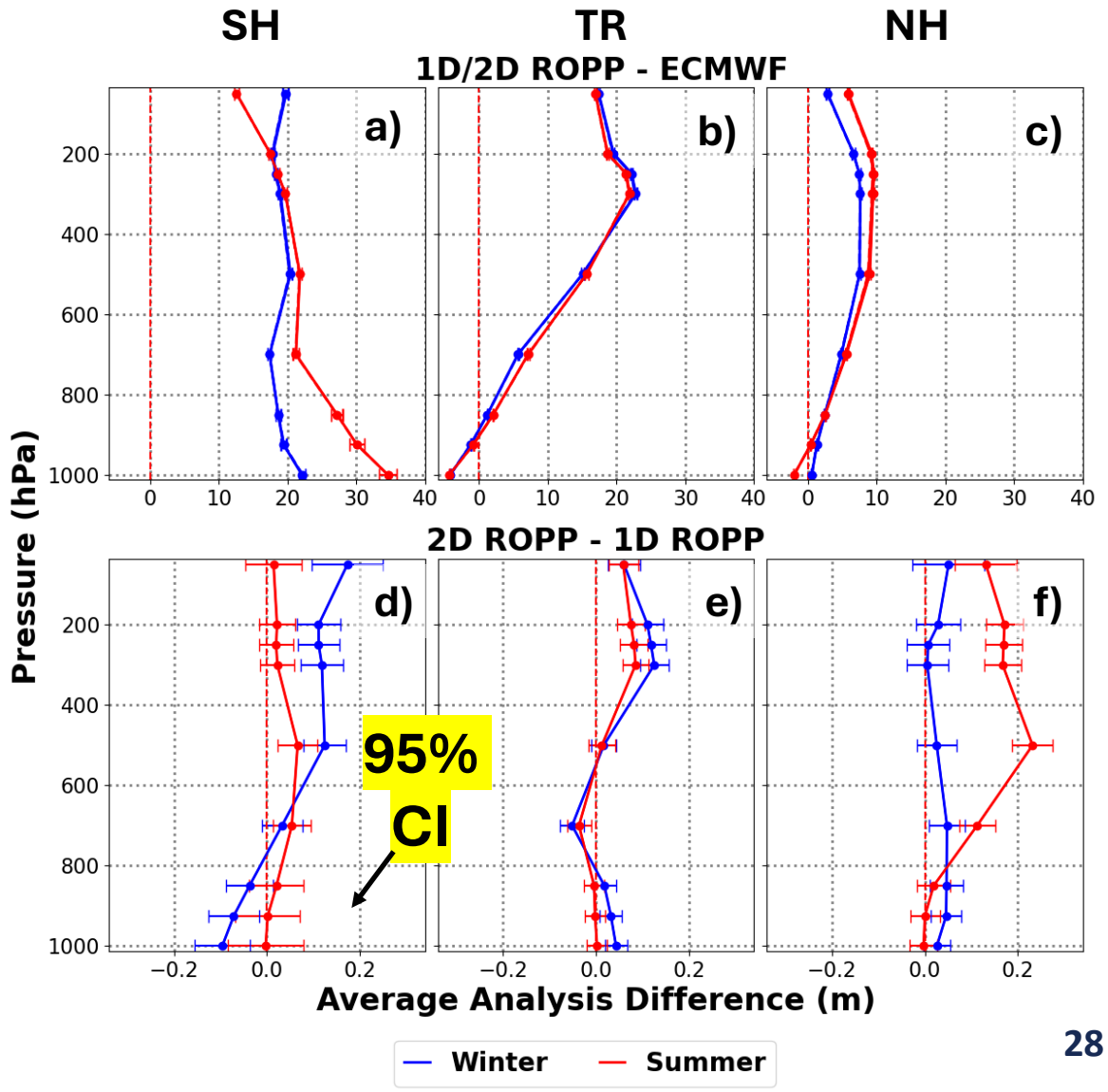
(some low-level improvements in winter experiment).

$$100 \times \frac{\mathrm{RMSD}_{\text{1D ROPP}} - \mathrm{RMSD}_{\text{2D ROPP}}}{\mathrm{RMSD}_{\text{1D ROPP}}}$$

Geopotential Height Analysis Biases (Full 3 Months; 1D ROPP vs. 2D ROPP)

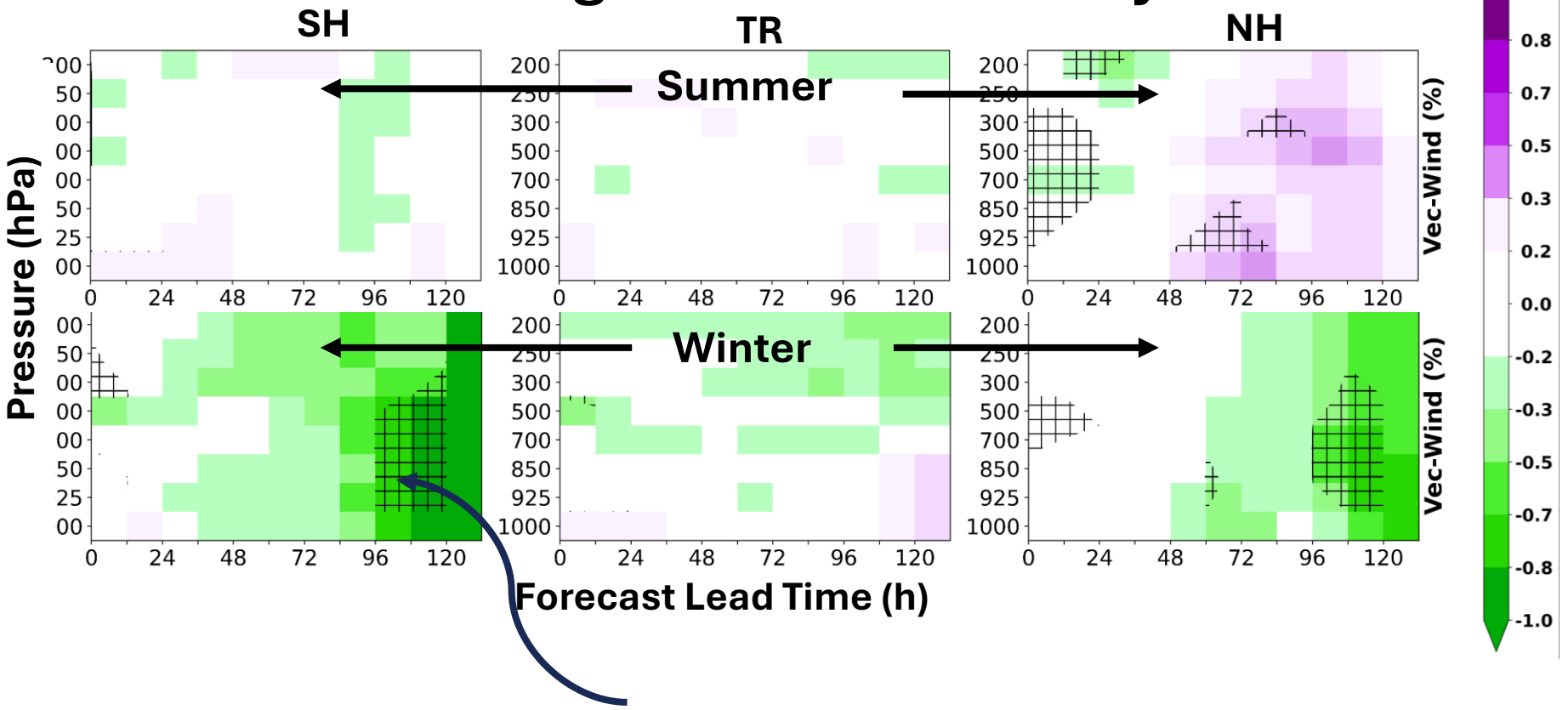
Both 1D & 2D ROPP analyses have large positive geopotential biases relative to ECMWF at mid- to upper-levels.

2D ROPP geopotential analysis bias is larger than 1D ROPP at mid- to upper-levels.



Relative Impact on Wind Speed Forecasts (Full 3 Months; 1D ROPP vs. 2D ROPP)

Verification Against ECMWF Analyses



2D forward operator had larger impact in the winter period than the summer period, particular at longer lead time

≥ 95% statistical confidence

$$100 \times \frac{\mathrm{RMSD}_{\text{2D ROPP}} - \mathrm{RMSD}_{\text{1D ROPP}}}{\mathrm{RMSD}_{\text{1D ROPP}}}$$

Wind Speed Analysis Biases (Full 3 Months; 1D ROPP vs. 2D ROPP)

Both 1D & 2D ROPP analyses have low wind speed biases relative to ECMWF above the lowest levels.

2D ROPP reduces the negative temperature bias in SH; no real pattern outside SH.