Can COSMIC-2 Bending Angle Assimilation Improve HWRF Tropical Cyclone Forecasts?
A Preliminary Evaluation Using Six Cases from the 2020 Atlantic Hurricane Season

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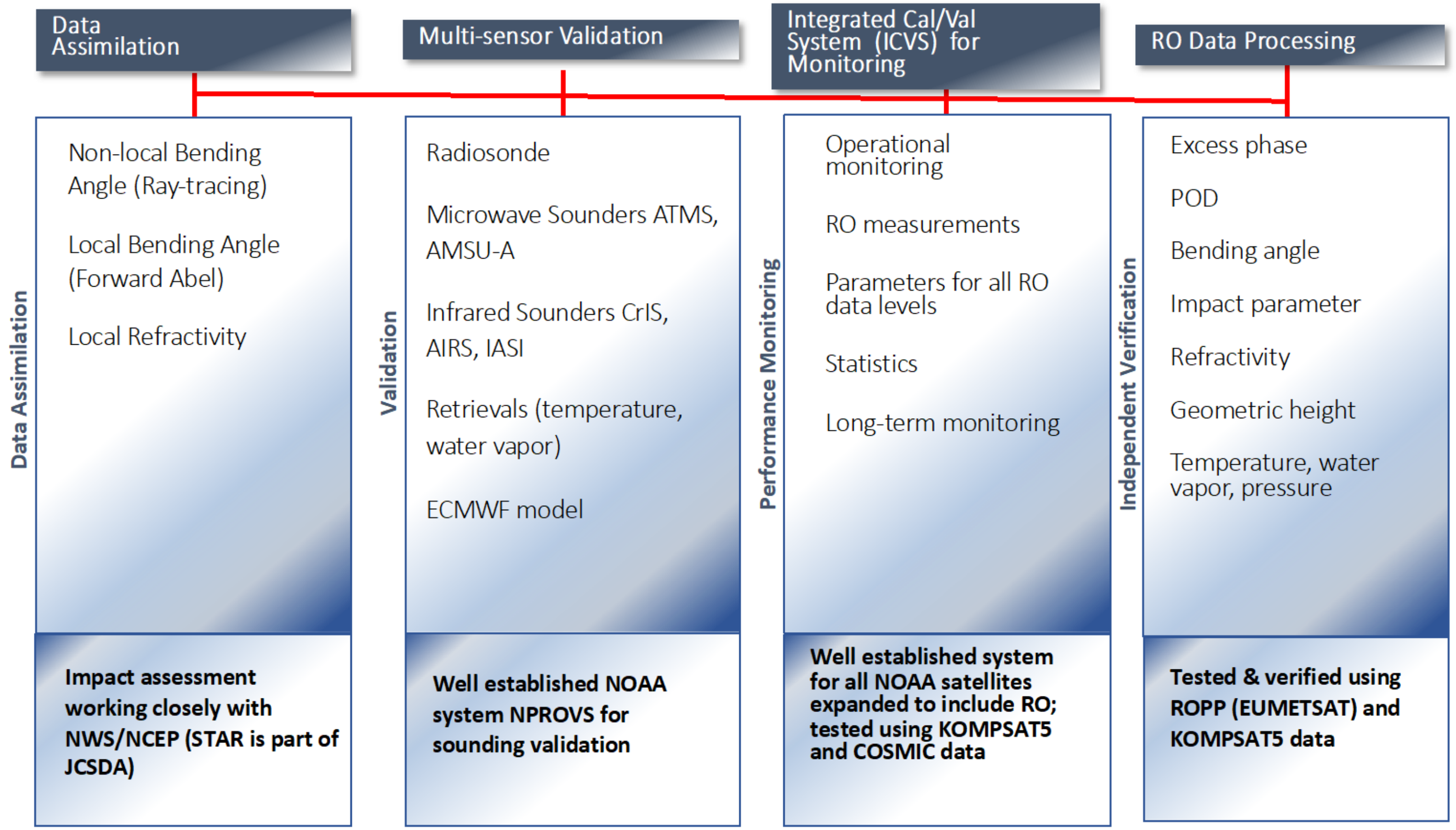
2. NOAA STAR GNSS RO processing and validation System



https://www.star.nesdis.noaa.gov/smcd/GNSSRO/RO/index.php

To better quantify how the observation uncertainty from clock error and geometry measurements may propagate to bending angle and refractivity profiles, STAR has developed the GNSS RO Data Processing and Validation System.

Ho et al., (2022), NESDIS STAR GNSS RO Processing, Validation, and Monitoring System: Initial Validation of the STAR COSMIC-2 Data, COSMIC-2 special issue, TAO (submitted).

Objectives

- **Can COSMIC-2 RO bending angle assimilation improve tropical cyclone (TC) intensity forecast error statistics** in a regional NWP model that already assimilates satellite radiances?

  → RO bending angle yields information about the atmospheric p, T, q_v profile above the RO ray tangent height

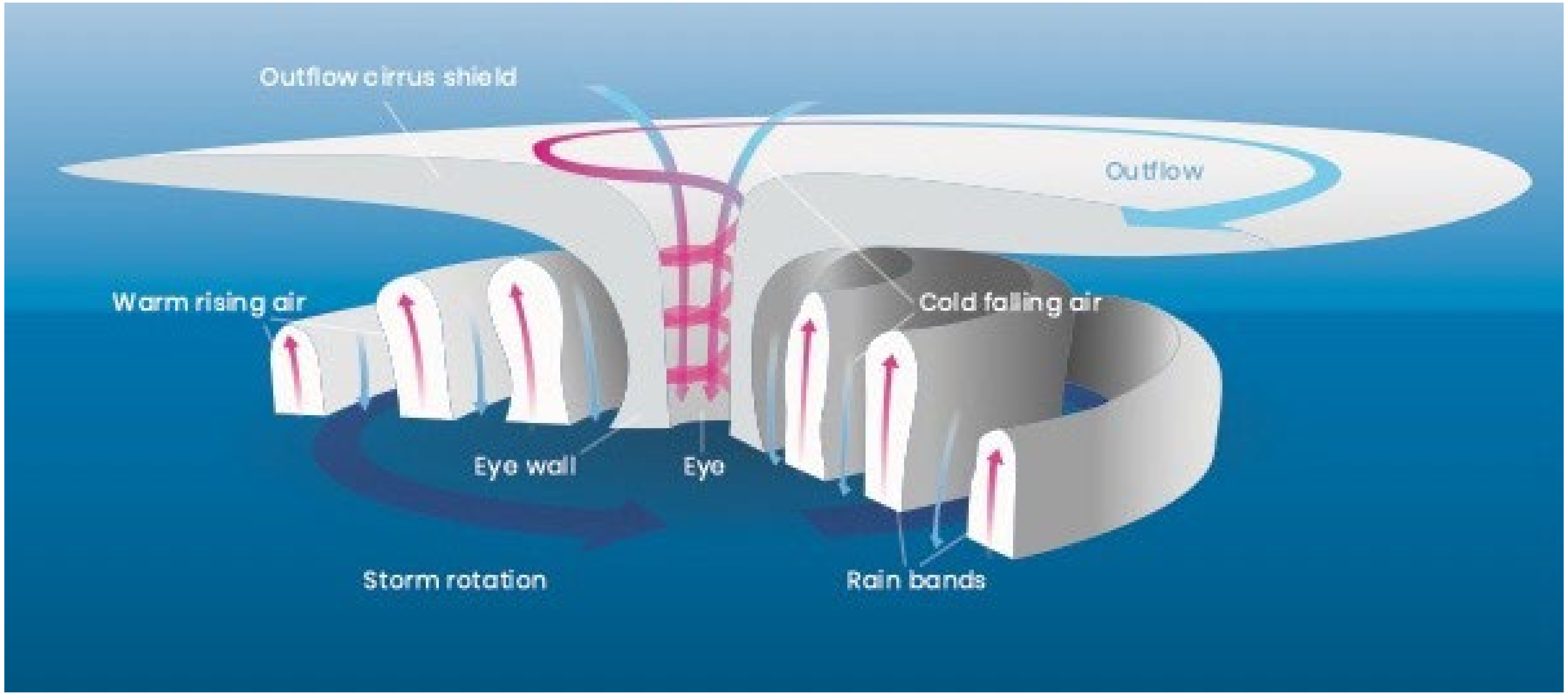
- **If so, through what physical pathways** can this TC intensity forecast improvement be achieved?

  → investigate using case studies

Hurricane Development and Intensification Can Depend Strongly on Low-to-middle Tropospheric Water Vapor

- Latent heat release in eyewall updrafts helps drive low-level inflow that advects higher-AAM (~ rv_t) air and moisture from outer regions

- Subsaturated low-to-middle tropospheric air penetrating into the inner core can suppress eyewall convection:
  - entrainment
  - enhanced downdrafts cooling the boundary layer



- 700-850 hPa layer-mean RH in the tropical cyclone (TC) environment is an intensity predictor in the SHIPS model

DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). *Wea. Forecasting*, **20**, 531-543.

- Model simulations of developing TCs have shown strong sensitivity to inner-core water vapor

Nolan, D. S., 2007: What is the trigger for tropical cyclogenesis? *Aust. Meteor. Mag.*, **56 ,** 241–266.

Sippel, J. A., and F. Zhang, 2008: A probabilistic analysis of the dynamics and predictability of tropical cyclogenesis. *J. Atmos. Sci.,* **65**, 3440-3459.

Part I

Model Configuration, Methodology, and TC Case Summary

Model Configuration and Experiment Design

- Use the Hurricane Weather Research and Forecasting (HWRF) model v4.0a

 - 13.5/4.5/**1.5 km** Δx triply nested grid

 - 75 vertical levels

 - 10 hPa model top **extended to 0.26 hPa in analysis**

- GSI hybrid ensemble-3DVAR DA

 - only for ghost d02 and ghost d03
 - uses 80-member GDAS ensemble covariances
 - assimilated observations include:

 conventional

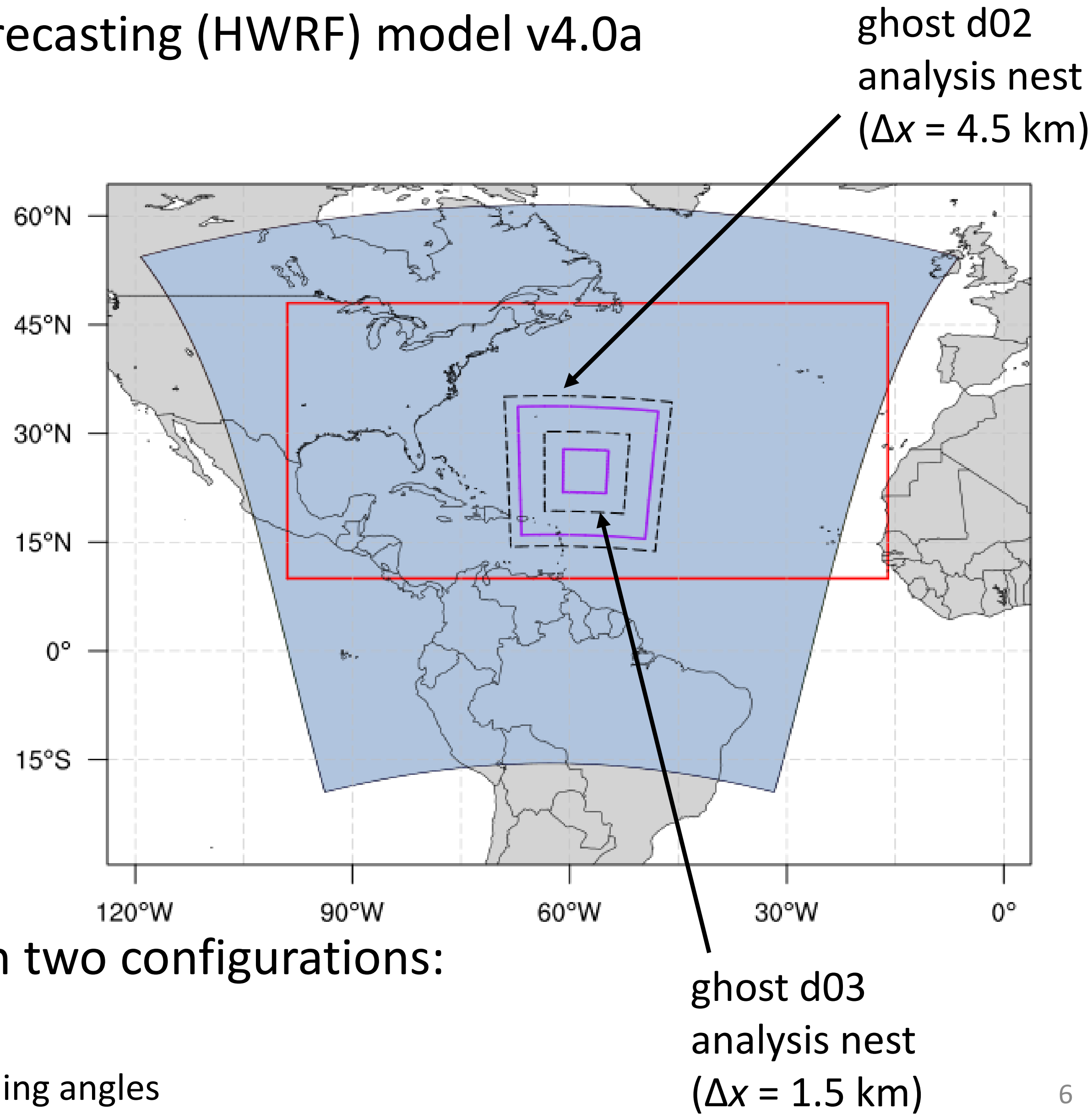
 GPSRO bending angle

 aircraft recon data (flight-level data, dropsondes, TDR)

 satellite radiances:

 microwave (AMSU-A, MHS, ATMS, SSMIS)

 infrared (HIRS, AIRS, IASI, CrIS)



- Run 6-h cycled HWRF forecast experiments in two configurations:

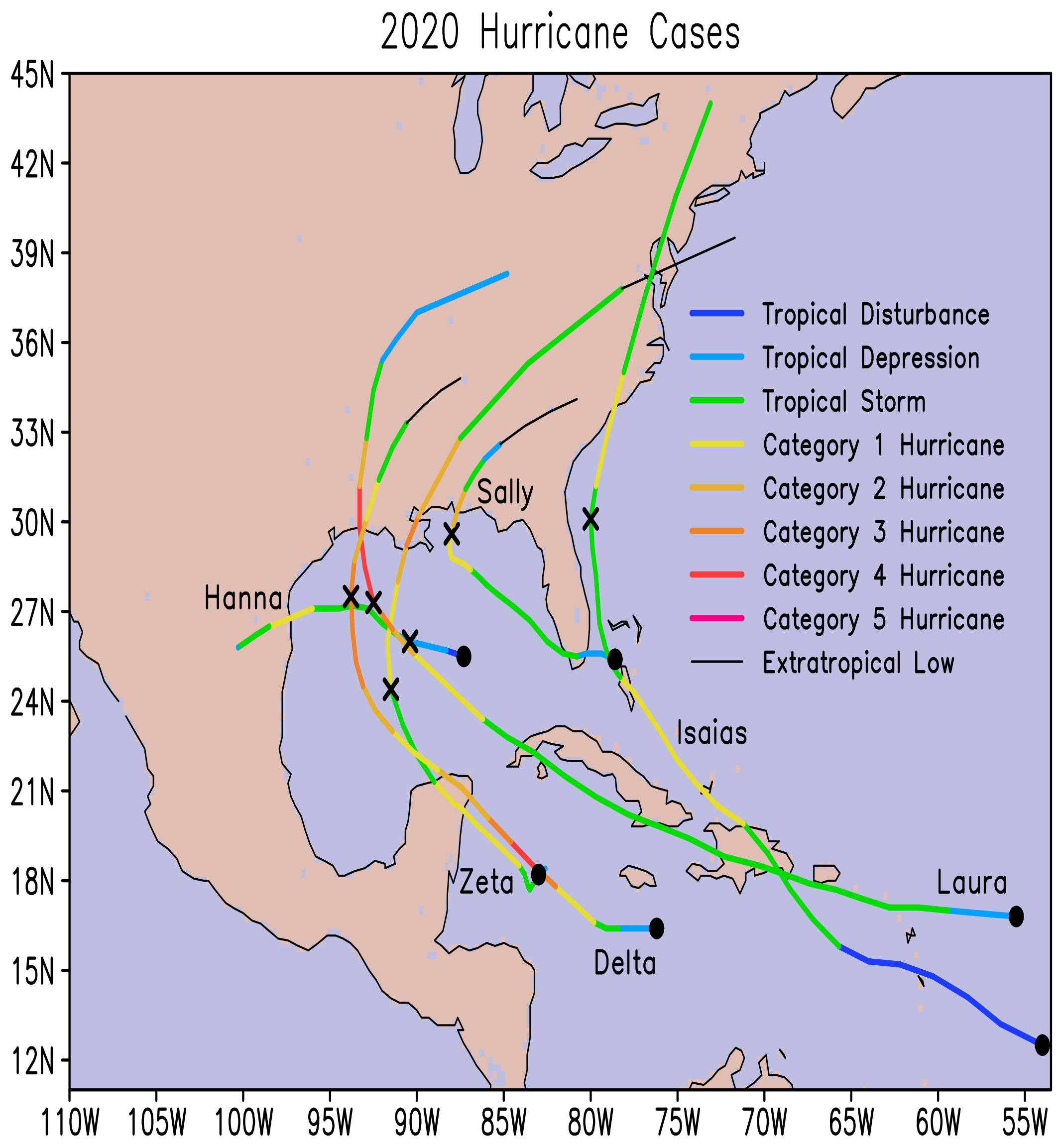
 - Control: COSMIC-2 RO bending angles withheld

 - C2: same as Control, but also assimilating COSMIC-2 RO bending angles

Summary of HWRF-Simulated 2020 Atlantic Hurricane Cases

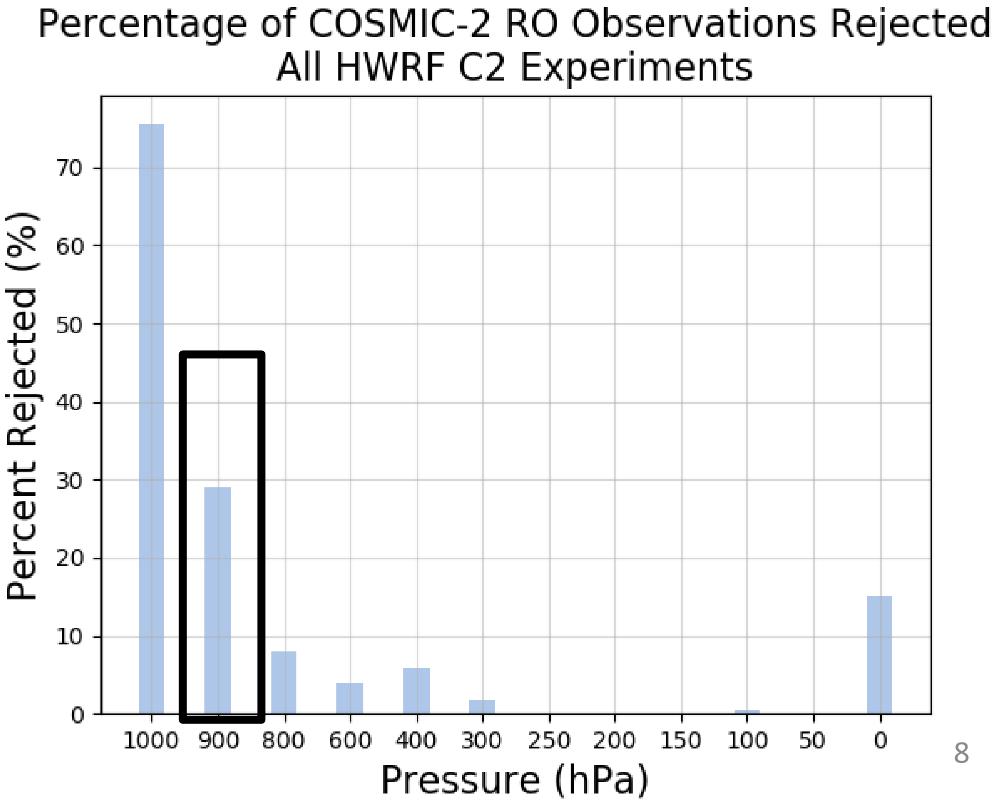
Name	Saffir-Simpson Category at Peak Intensity	# of HWRF DA Cycles
Hanna	1	6
Zeta	3	15
Laura	4	24
Sally	2	18
Delta	4	20
Isaias	1	25

- Initialize HWRF "cold start" around time that the system is declared a Tropical Depression
- Each cycle on average assimilates ~ 3 COSMIC-2 profiles into the ghost d03 nest, although the number varies between 0 and 6



HWRF-GSI COSMIC-2 Bending Angle Assimilation Settings

- local forward operator (1D sounding; neglects horizontal water vapor gradients along ray path)
- representiveness error depends on:
  - processing protocol (CDAAC or UKMET)
  - whether or not the observation is inside the +/- 40° lat band
  - piecewise function of impact height; coefficients determined using Desroziers et al. (2005) method applied to COSMIC data in the GFS
- ~ 30% of COSMIC-2 obs rejected below 850 hPa
  → primarily due to
  - SR-likely condition detected in the background
  - (O-B)/O exceeding a threshold empirically determined from COSMIC data in the GFS



Cucurull, L., J. C. Derber, and R. J. Purser, 2013: A bending angle forward operator for global positioning system radio occultation measurements. *JGR Atmos.,* **118,** 14-28.

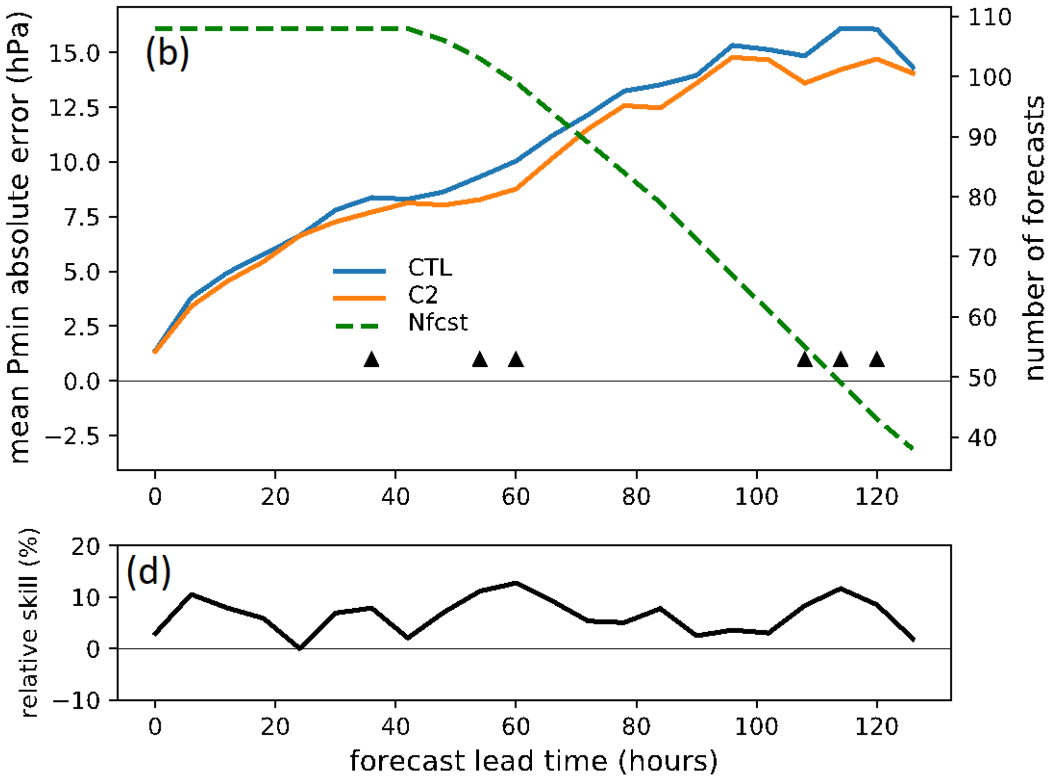
Desroziers, G., L. Berre, B. Chapnik, and P. Poli (2005), Diagnosis of observation, background and analysis-error statistics in observation space, *Q. J. R. Meteorol. Soc.,* **131,** 3385–3396.

Part II

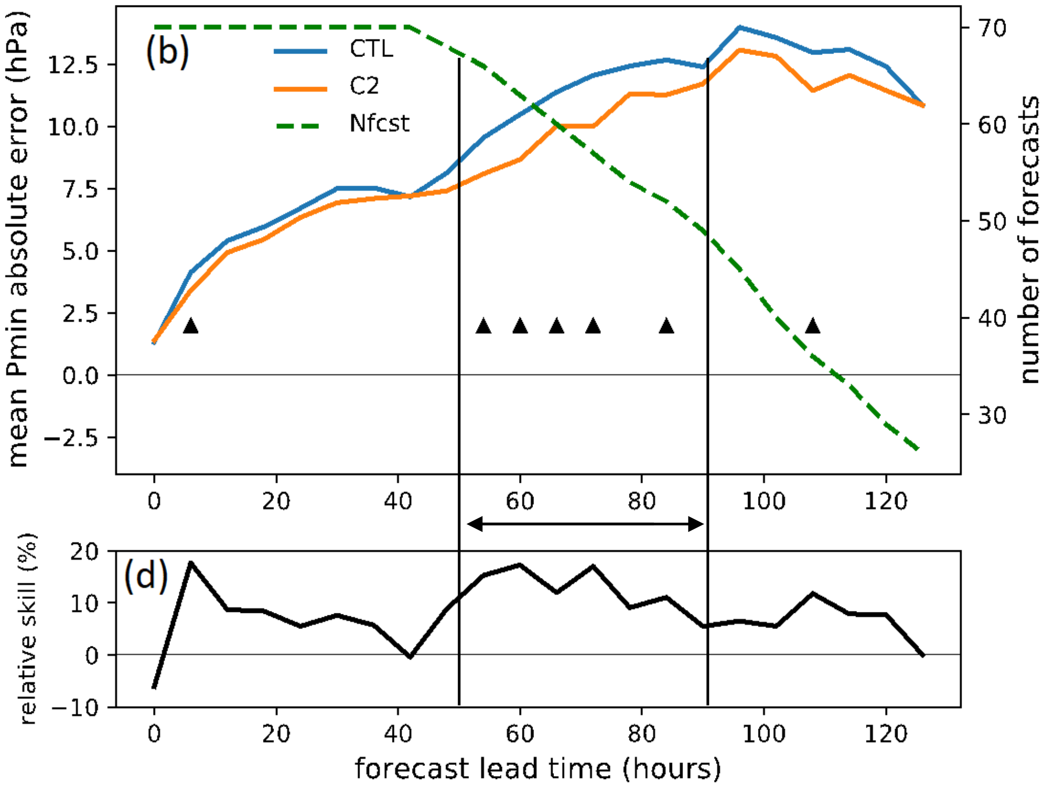
HWRF Forecast Error Statistics

HWRF Mean Forecast Intensity Errors

All forecasts from the six Atlantic TC cases



Only forecasts from intensifying storms [V_{MAX} increase > 10 kt (12 h^{-1})]



- COSMIC-2 **DA improves mean P_{MIN} intensity forecast relative skill for all lead times**, although the improvement is generally a modest ~ 5-10 %
- When considering only the subset of 70 forecast initializations from **intensifying storms, COSMIC-2 DA improves mean P_{MIN} intensity relative skill by a more substantial ~ 10-15%** over the *t* = 48-90 h period

HWRF Forecast t = 24 h q RMSD Profile

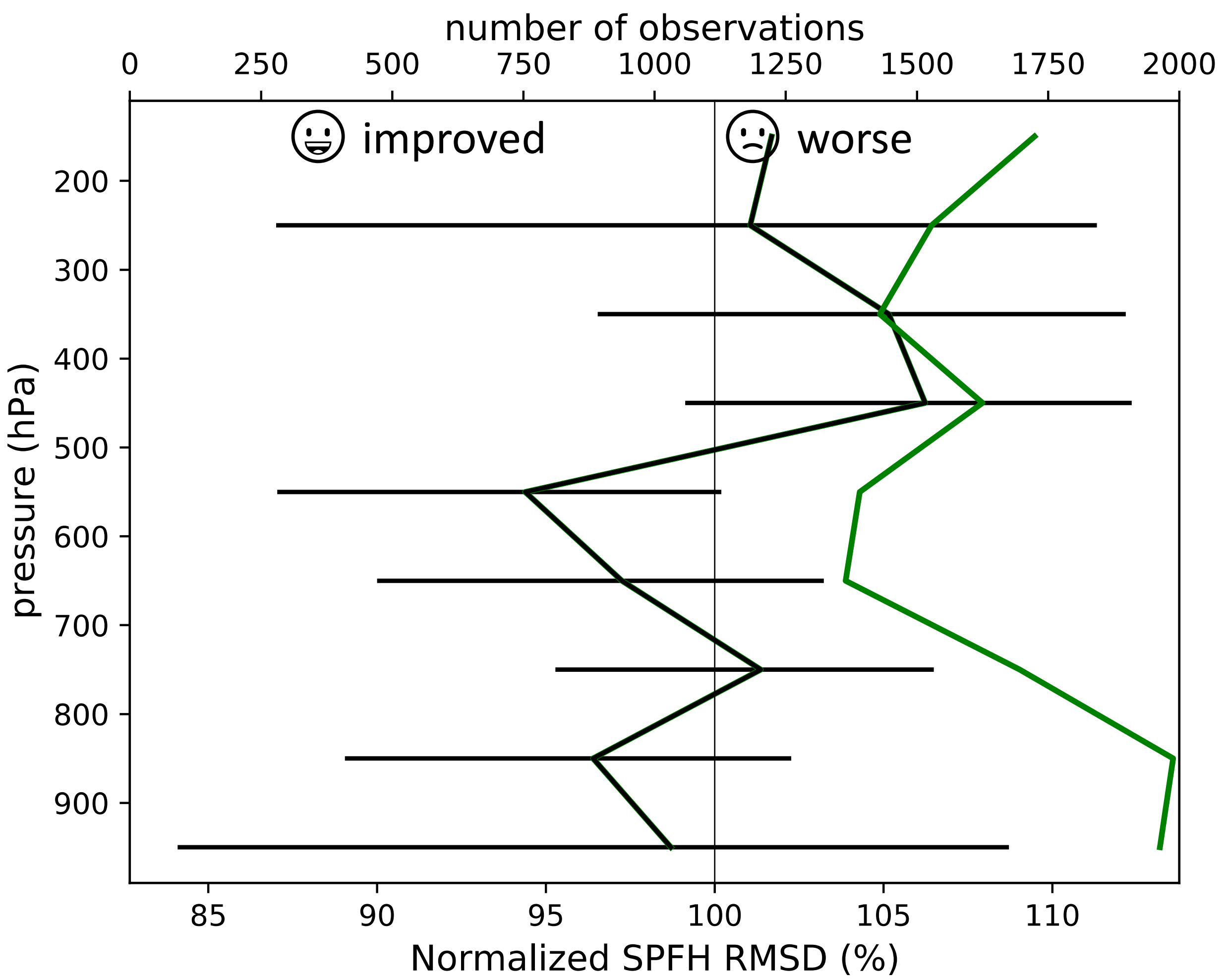
- Computed with respect to synoptic radiosondes and aircraft reconnaissance mission dropsondes within 500 km of the TC center

  → position corrected to match observed storm-relative locations

- **COSMIC-2 DA impacts on t = 24 h HWRF specific humidity forecasts are most beneficial in the mid-troposphere** 500-600 hPa layer where the RMSD is reduced by ~ 5%

  - these improvements are not statistically significant at the 95% level, but it's close

- C2 improvement below 800 hPa does not hold for some other forecast verification times (not shown)



$RMSD_{C2}$ / $RMSD_{Control}$ with 95% confidence interval (black line)
Number of observations per vertical bin (green line)

Part III

Case Studies:

Hurricane Hanna (2020) and Hurricane Zeta (2020)

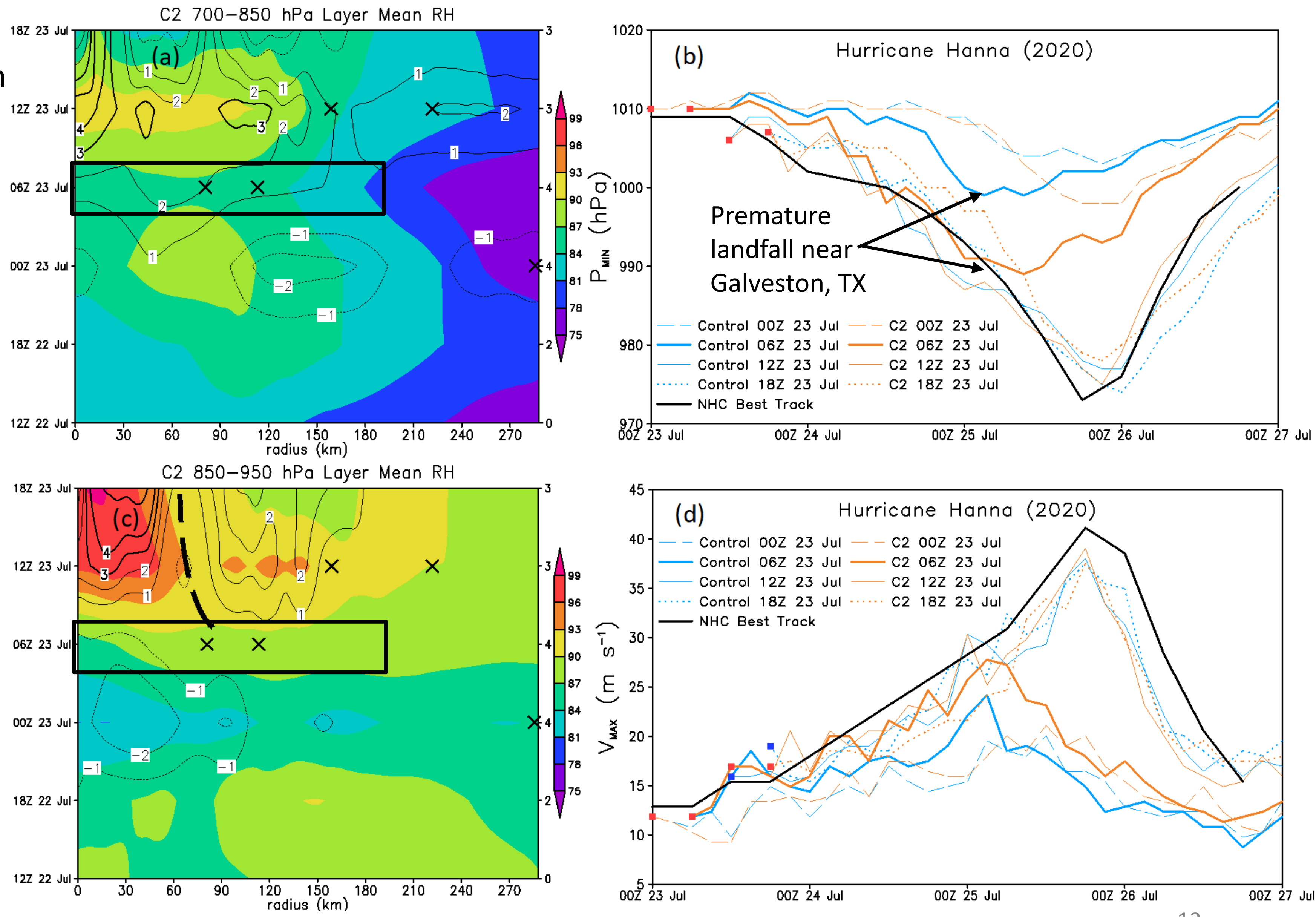
Hurricane Hanna (2020) Control vs. C2 Cycled Analysis Comparison

- For the 700-850 hPa layer, C2 azimuthal mean RH is > 1% higher than Control starting with the 0600 UTC 23 Jul cycle

  → these differences persist through t = 18h in the 0600 UTC 23 Jul forecast (not shown)

- This cycle assimilates two COSMIC-2 profiles ~ 100 km from developing TC Hanna's center

- **COSMIC-2 assimilation helps correct Control's severe low-intensity bias** in the 0600 UTC 23 Jul forecast (compare solid blue and orange lines in panels b & d)



Left column: Hovmöller radius vs. time plots of layer-averaged, azimuthally-averaged C2 RH (%) with difference from Control contoured

Right column: selected free forecasts initialized from cycled analyses

Hurricane Hanna (2020) 0600 UTC 23 Jul Analysis

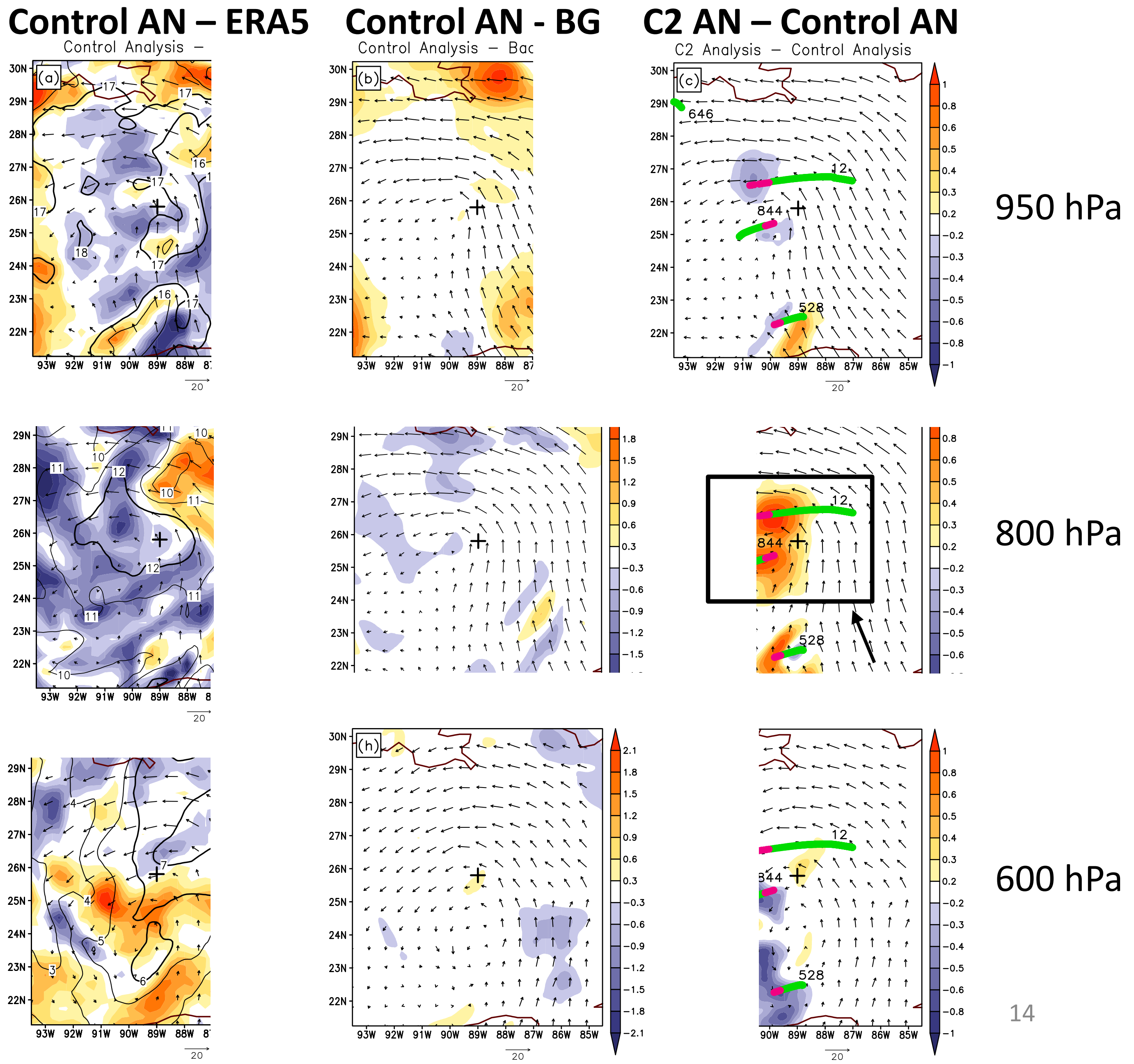
- At 0600 UTC 23 Jul Hanna is a tropical depression in the central Gulf of Mexico
- Control and C2 both assimilate observations into the GDAS 6-h background

  → analysis differences should result from the 4 assimilated COSMIC-2 profiles

- Background forecast vortex NW, SW and SE quadrants have a lower tropospheric dry bias in *q* (0.3 – 1.5 g kg^{-1}; panels a,d)

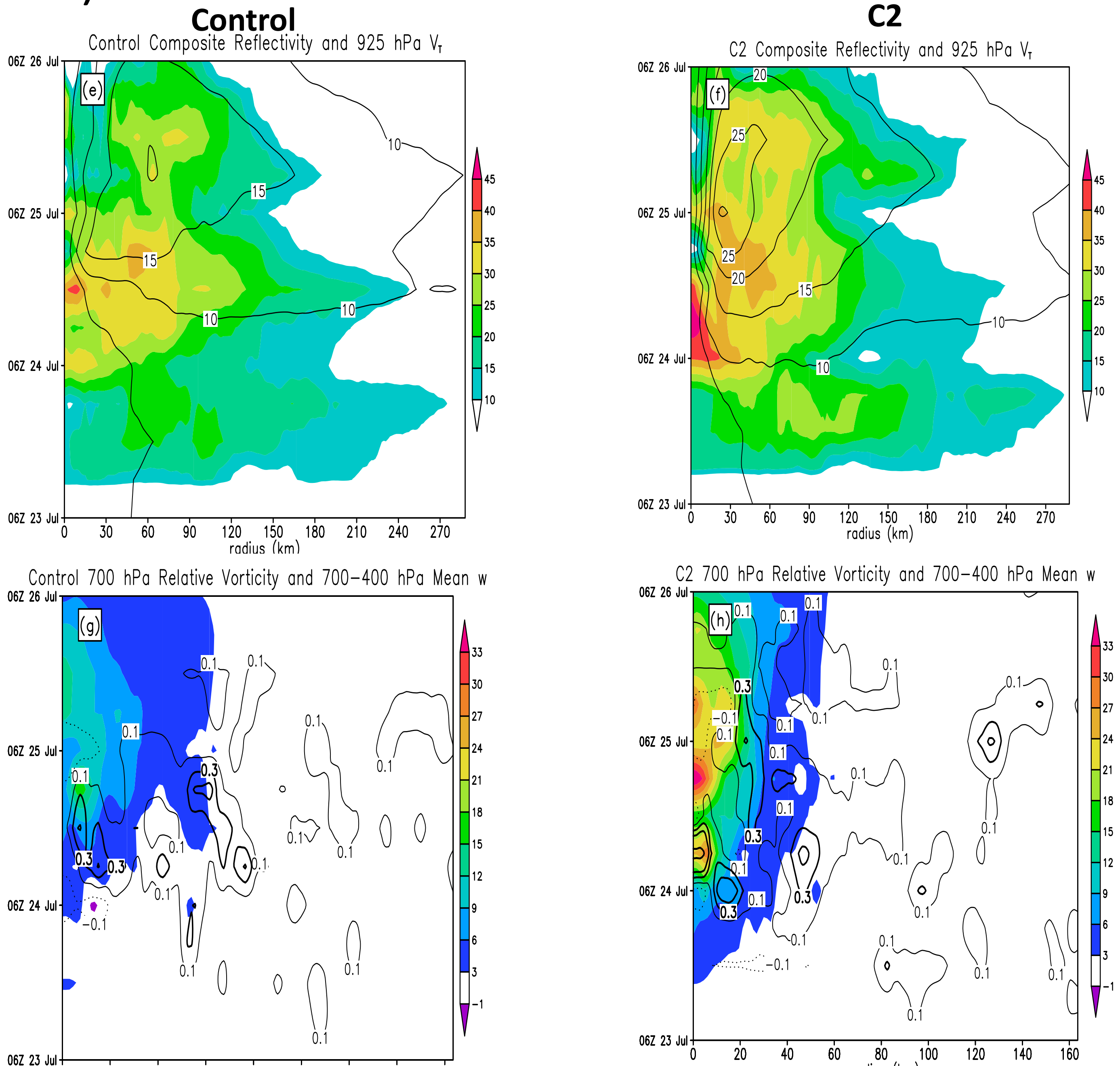
- **Two COSMIC-2 profiles assimilated near Hanna's center increase 800 hPa *q* by 0.3 – 1.0 g kg^{-1} locally (panel f)**

q differences (shaded; g kg^{-1}) and ERA5 *q* (contoured; g kg^{-1}) →



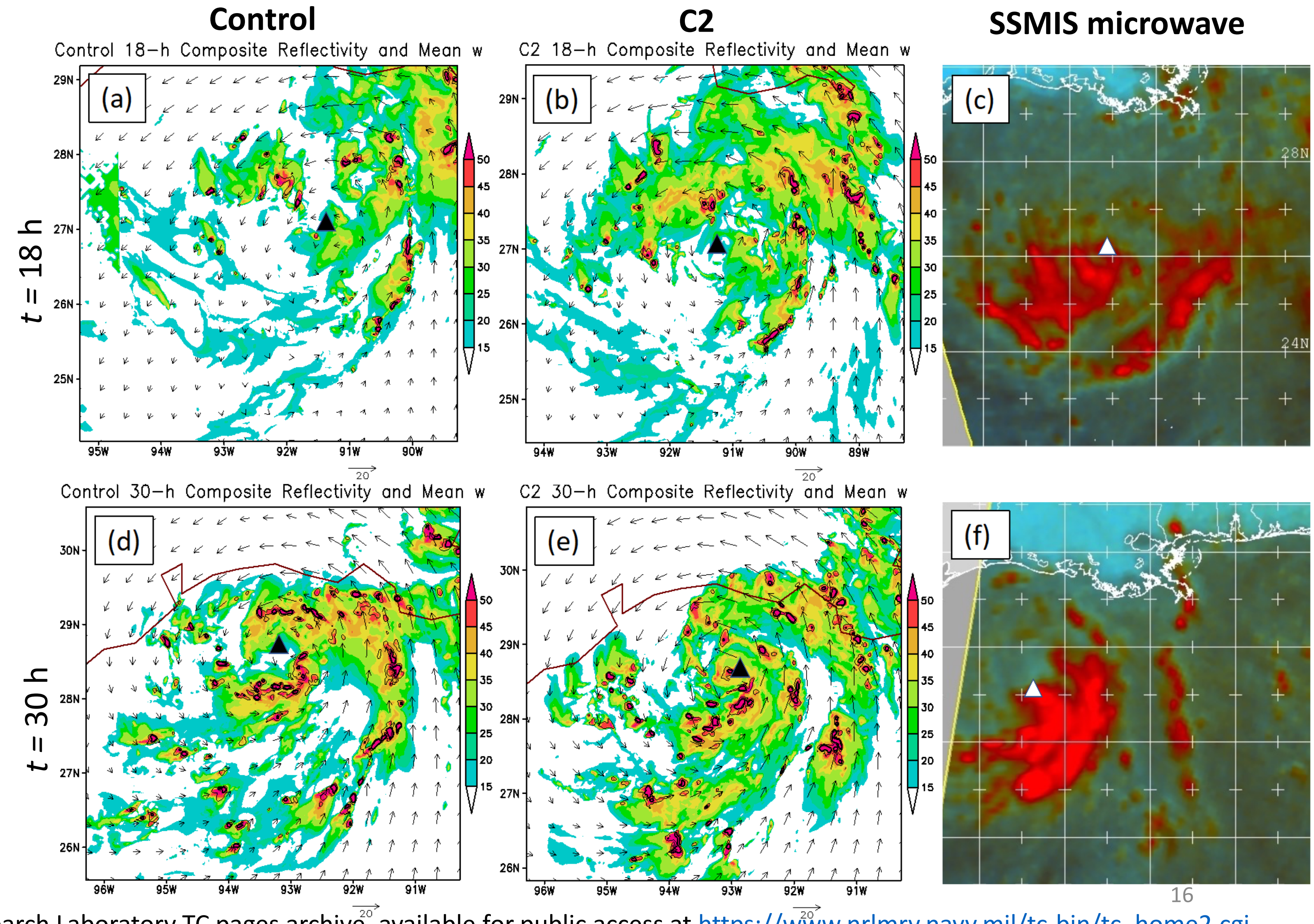
Hurricane Hanna (2020) 0600 UTC 23 Jul-initialized Forecast

- **Around *t* = 24 h C2 develops a vigorous outbreak of deep convection close to the TC center**; this feature persists for the next 12 h
- Control also develops deep convection near the TC center, but this happens 12 h later and the feature is weaker and more transient
- **It is possible that C2's higher inner-core low-to-middle troposphere RH facilitated its earlier and more persistent convective outbreak**
- C2 convective updrafts focused inside RMW where latent heat is more efficiently converted to cyclonic wind kinetic energy
  -> consistent with C2 eyewall development and near-surface wind intensification soon afterward



Hurricane Hanna (2020) 0600 UTC 23 Jul-initialized Forecast

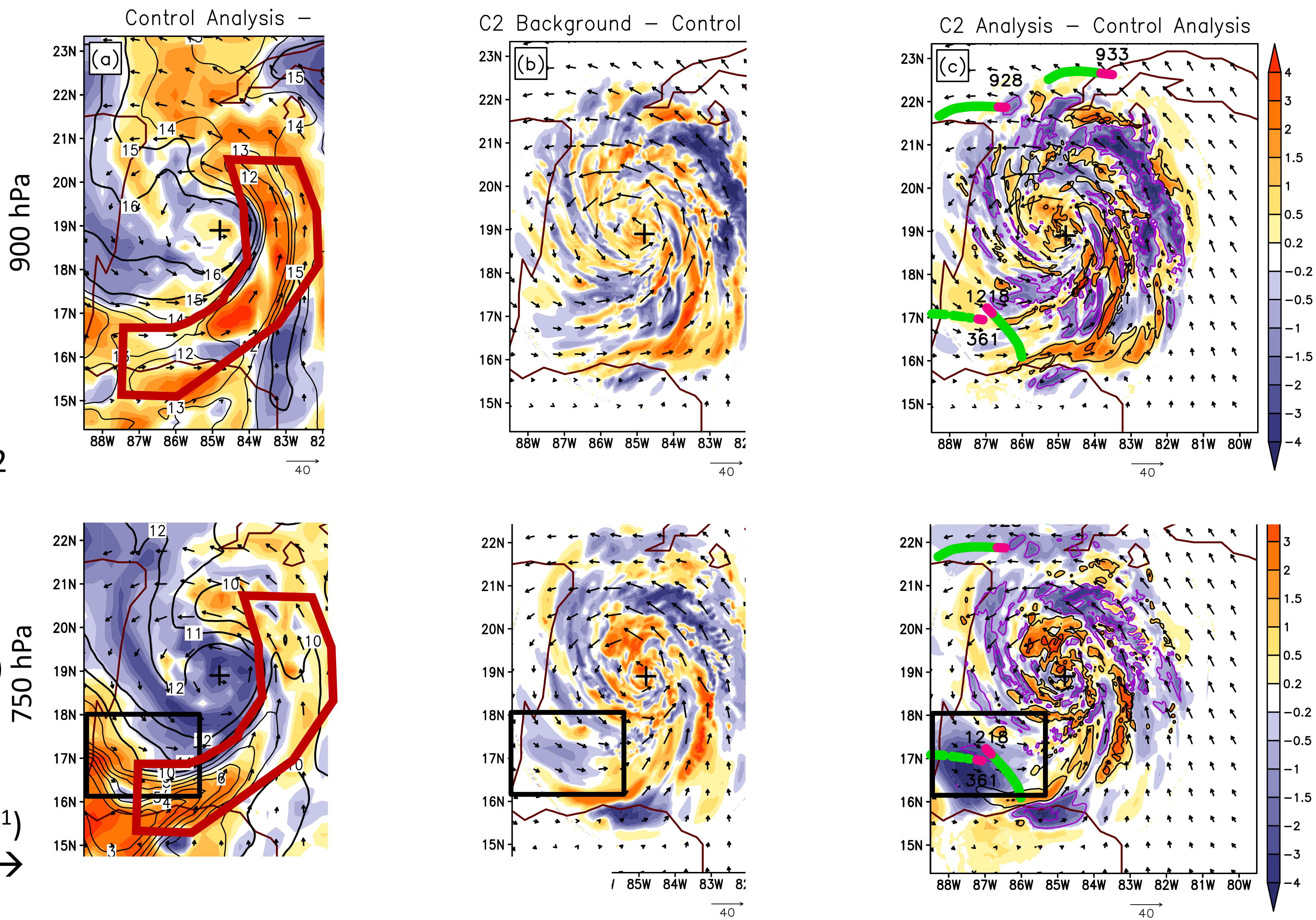
- **At t = 18 h (top), C2 has more widespread inner-core deep convection**
- **At t = 30 h (bottom)**, inner-core convection coverage has substantially increased in Control; however, **C2 convection is closer to the center and C2 has a tighter, stronger 925-hPa wind circulation**



Panels c & f: Images from the Naval Research Laboratory TC pages archive, available for public access at https://www.nrlmry.navy.mil/tc-bin/tc_home2.cgi.

Hurricane Zeta (2020) 1200 UTC 26 Oct Analysis

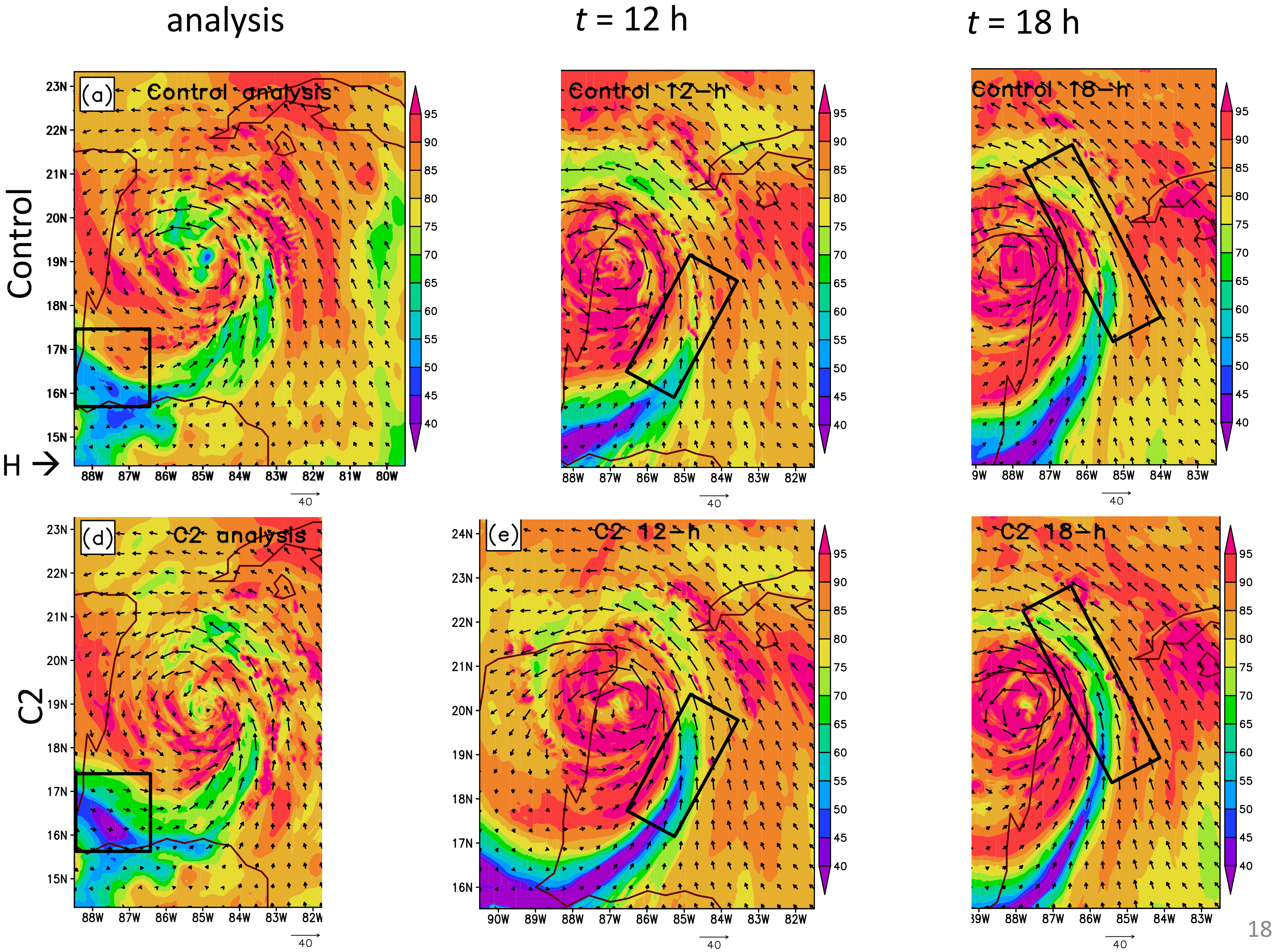
- ERA5 shows a dry tongue at 900 and 750 hPa wrapping cyclonically into the eastern side of Zeta's circulation from Central America (a,d)
- Control analysis does not capture this dry tongue well (a,d)
- Assimilation of two COSMIC-2 profiles in Zeta's southwestern circulation (near dry tongue source region) appears to have a drying impact at 750 hPa (e,f)



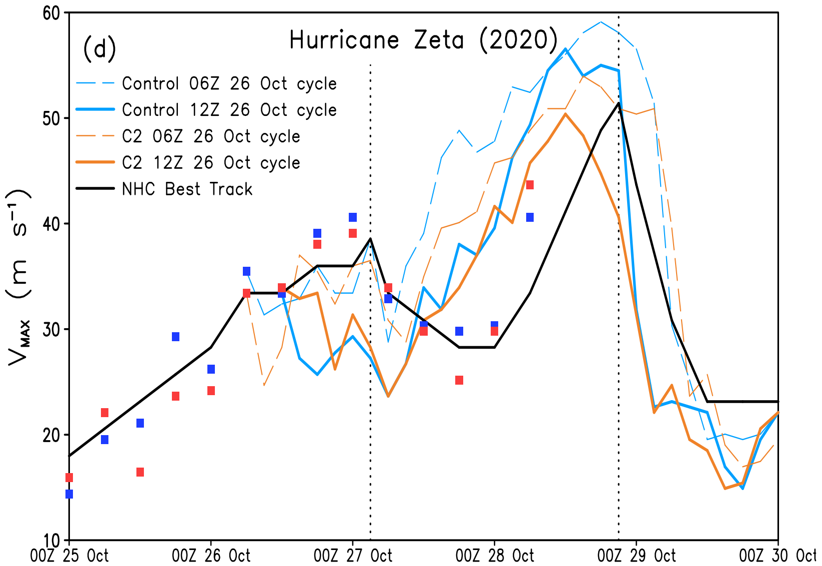
q differences (shaded; g kg^{-1}) and ERA5 *q* (contoured; g kg^{-1}) →

Hurricane Zeta (2020) 1200 UTC 26 Oct-initialized Forecast

- 700-850 hPa layer dry tongue wrapping into east side of Zeta's circulation over first 18 hours is more robust in C2 compared to Control
- Although Zeta's inner-core remains moist and "protected" for both Control and C2, it is possible that the C2 core's closer proximity to drier air helps account for its slower intensification after re-emerging over water in the Gulf of Mexico



700-850 hPa layer-averaged RH →



Summary

- COSMIC-2 assimilation impacts on HWRF forecasts evaluated for six 2020 Atlantic TC cases:

  - **modest 5-10% P_{MIN} forecast relative skill improvement for most lead times**

  - more substantial 10-20% P_{MIN} forecast relative skill improvement for intensifying storms (t = 48-90 h lead times)

- Case studies:

  - Hurricane Hanna (2020) 06 UTC 23 Sep cycle: assimilating two COSMIC-2 profiles ~ 100 km from the developing TC center increases 800 hPa q_V up to 1 g kg^{-1} locally

    → C2 storm develops more persistent, robust inner core convection 24 h later

    → **C2 forecast has a significantly reduced weak bias compared to Control**

  - Hurricane Zeta (2020) 12 UTC 26 Oct cycle: assimilating two COSMIC-2 profiles in the southwestern outer circulation helps to correct Control's moist 750 hPa bias there

    → Compared to Control, the C2 forecast storm has a stronger 700-850 hPa dry air intrusion wrapping from this southwestern region into the eastern circulation

    → **C2 forecast has a reduced over-intensification bias compared to Control**

Questions?

Disclaimer: The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect those of NOAA or the Department of Commerce

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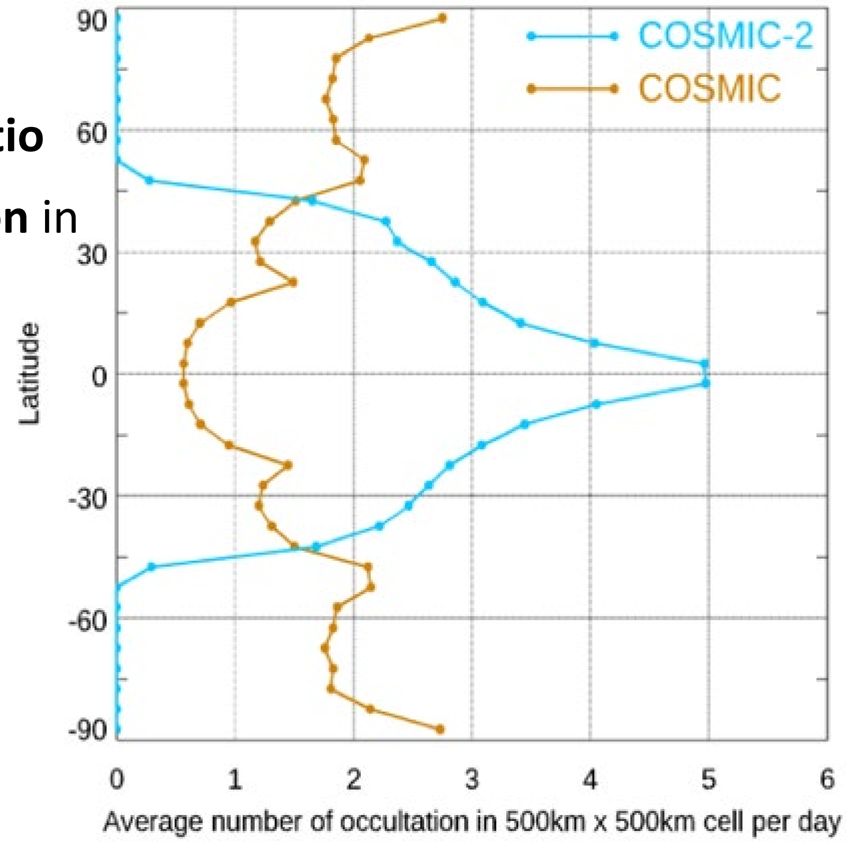
Supplementary Slides

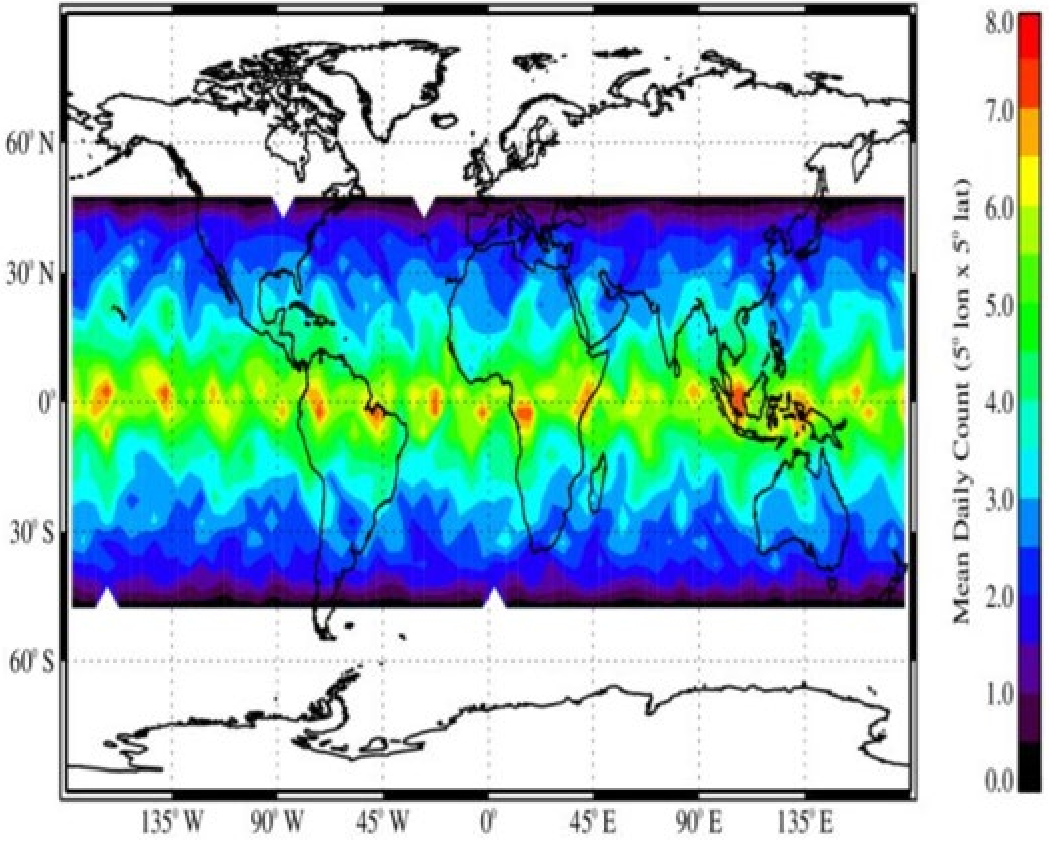
COSMIC-2 RO Bending Angle Assimilation Diagnostics

COSMIC-2 RO Receiver Satellite Mission

- COSMIC-2 Global Navigation Satellite System (GNSS) radio occultation (RO) receiver satellite mission was launched in June 2019 as a successor to the COSMIC mission (April 2006 - May 2020)
- Compared to COSMIC, COSMIC-2 has

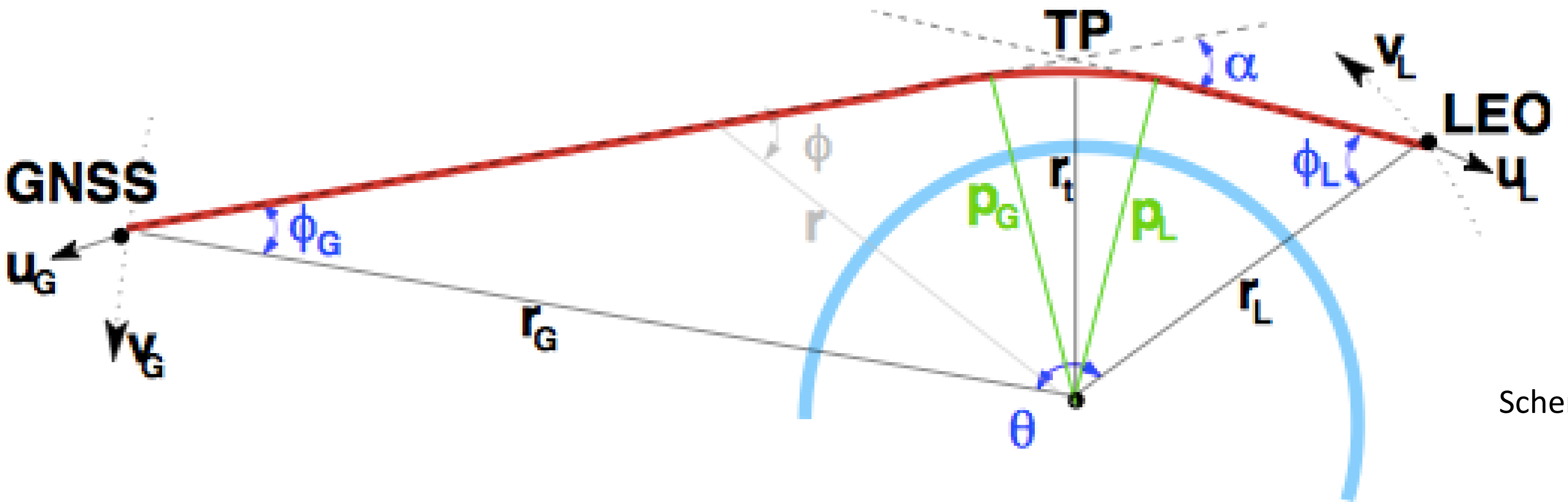
- **denser spatial coverage** in the tropics and subtropics
- **higher signal to noise ratio**
- **deeper signal penetration** in the lower troposphere





Ho, S.-P., and Coauthors, 2020: Initial Assessment of the COSMIC-2/FORMOSAT-7 Neutral Atmosphere Data Quality in NESDIS/STAR using in-situ and satellite data. *Remote Sens.*, **12,** 4099.

HWRF-GSI RO Bending Angle Forward Operator



Schematic provided by EUMETSAT ROM SAF

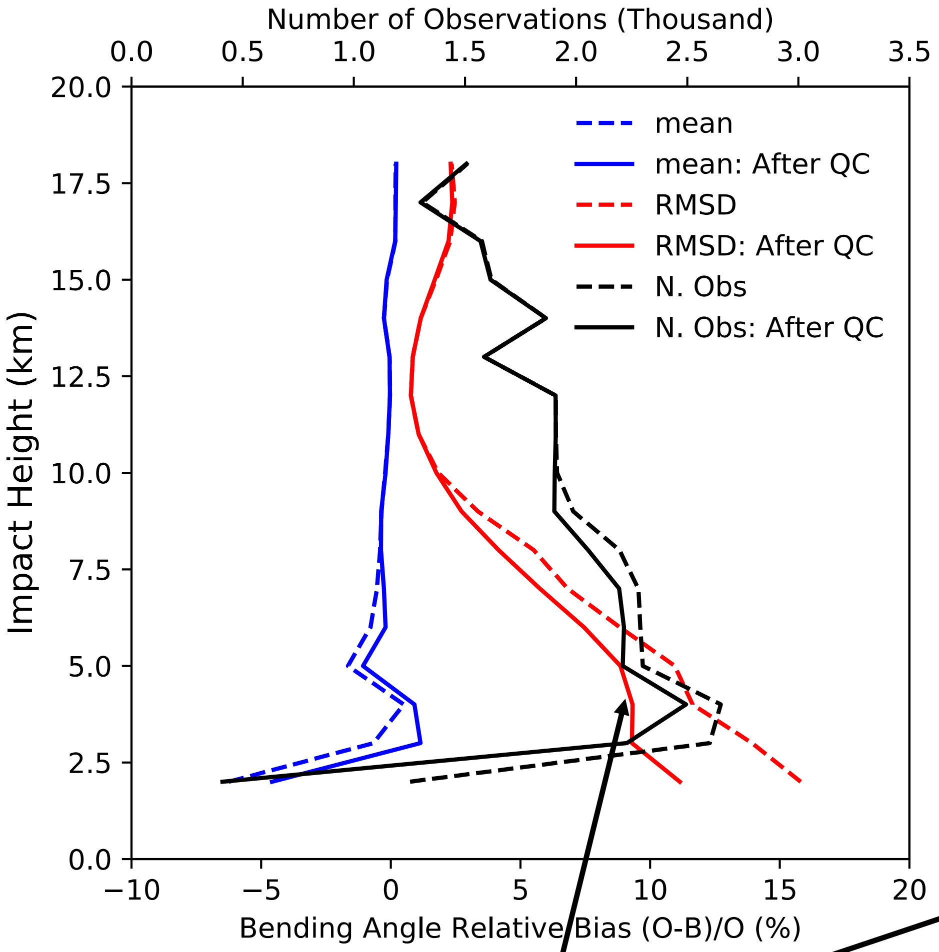
- Index of refraction n can be approximated as a function of atmospheric pressure, temperature, and water vapor
- NBAM local forward operator computes the bending angle (α) from the background state using:

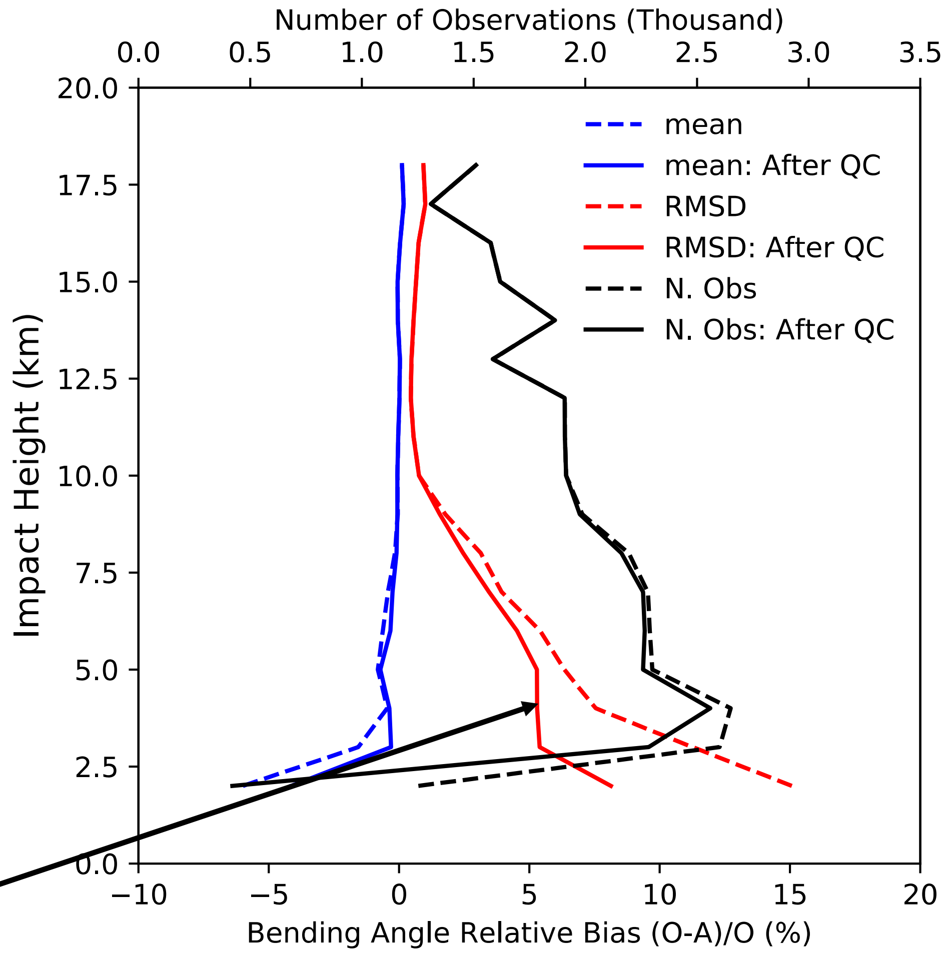
  - observation's impact parameter $a = r_t n$ where n is evaluated at the ray tangent point (TP)
  - vertical n profile above the observed α location
  - neglects horizontal n gradients (assumes local spherical symmetry)

$$\alpha(a) = -2a \int_a^{\infty} \frac{d \ln n / dx}{\sqrt{x^2 - a^2}} dx, \quad x = n\, r$$

Cucurull, L., J. C. Derber, and R. J. Purser, 2013: A bending angle forward operator for global positioning system radio occultation measurements. *JGR Atmos.*, **118,** 14-28.

COSMIC-2 O-B/O and O-B/A Mean Bias and RMSD Profiles





- COSMIC-2 DA reduces the (O-B)/O RMSD by ~ 40%
- COSMIC-2 (O-B)/O RMSD largest in lower troposphere, likely due in part to
  - greater forward operator uncertainty (e.g., SR events, spherical symmetry approximation being less valid)
  - model forecast errors

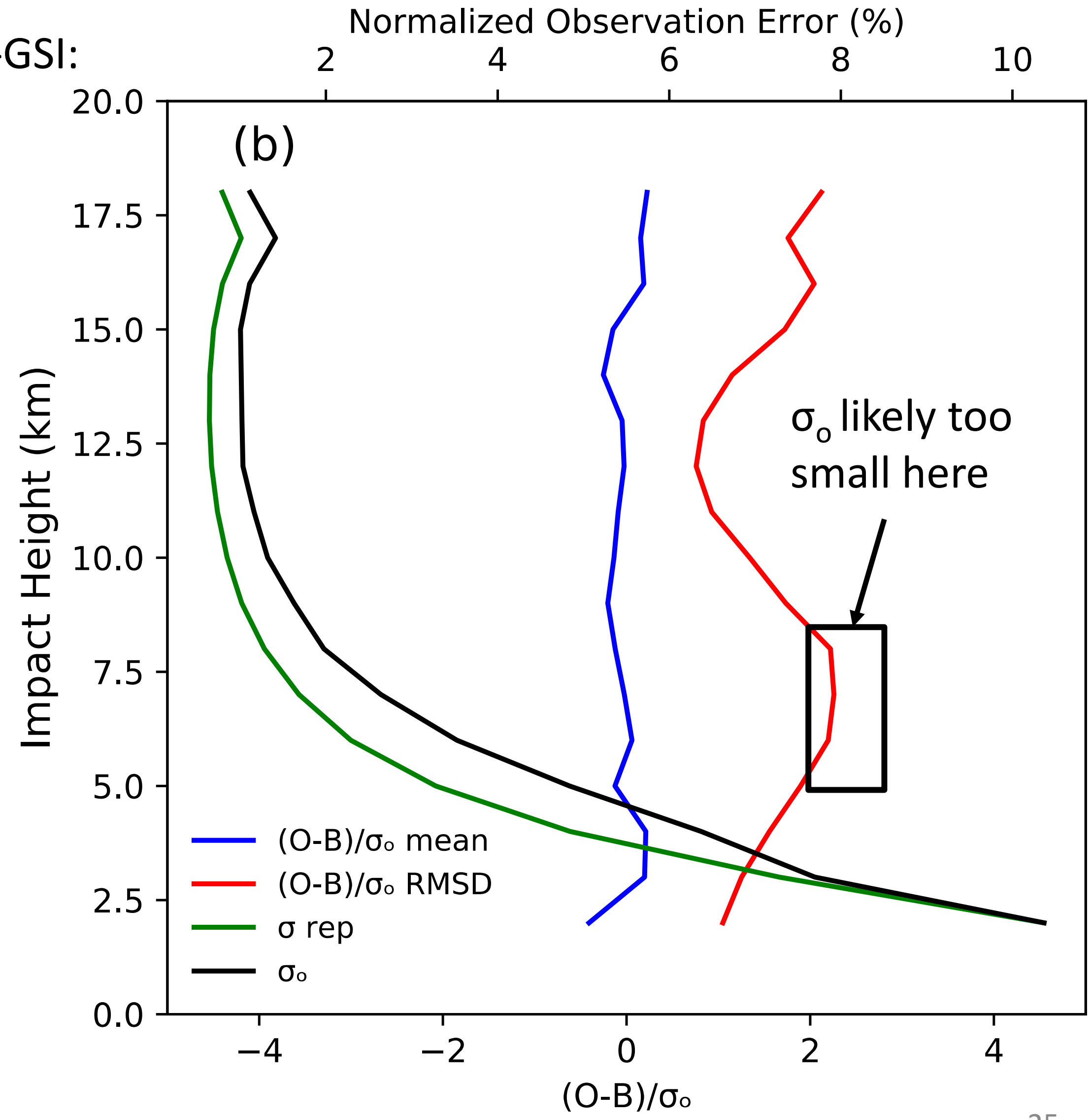
COSMIC-2 RO Bending Angle Observation Errors

- Three contributors to RO final observation errors (σ_o) in HWRF-GSI:
  - instrument error (from processing center)
  - representiveness error for forward operator uncertainty
  - “superobs factor” for spatial correlations in σ_o

both assigned in GSI

- Use settings tuned for FS3/COSMIC bending angles in GFS

- representiveness error depends on:
  - processing protocol (CDAAC or UKMET)
  - whether or not the observation is inside the +/- 40° lat band
  - piecewise function of impact height; coefficients determined using Desroziers et al. (2005) method

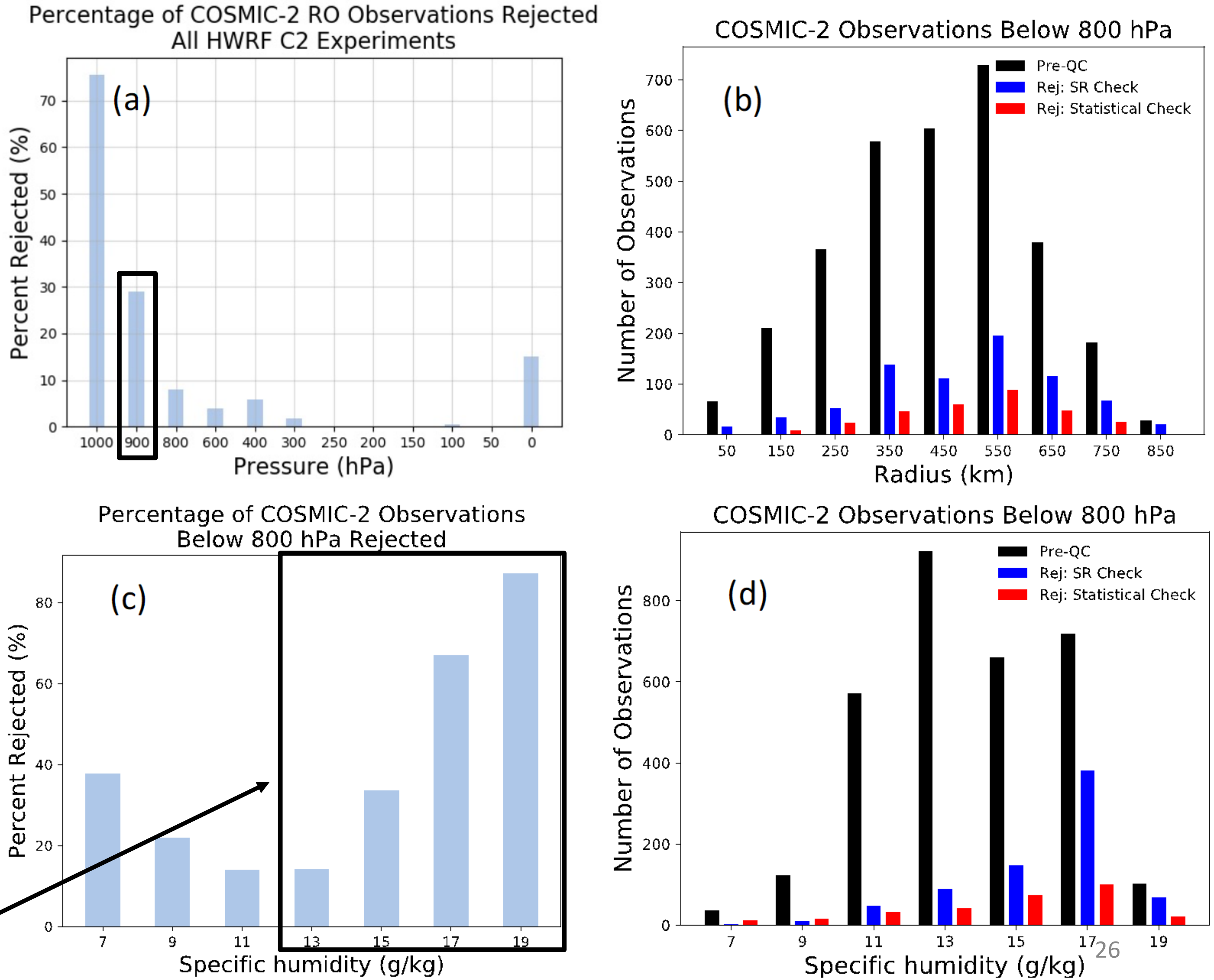


Desroziers, G., L. Berre, B. Chapnik, and P. Poli (2005), Diagnosis of observation, background and analysis-error statistics in observation space, *Q. J. R. Meteorol. Soc.*, **131,** 3385–3396.

HWRF-GSI COSMIC-2 Quality Control Statistics

- About 30% of COSMIC-2 bending angles are rejected from the 850-950 hPa layer

- are too many "good" observations being thrown out?

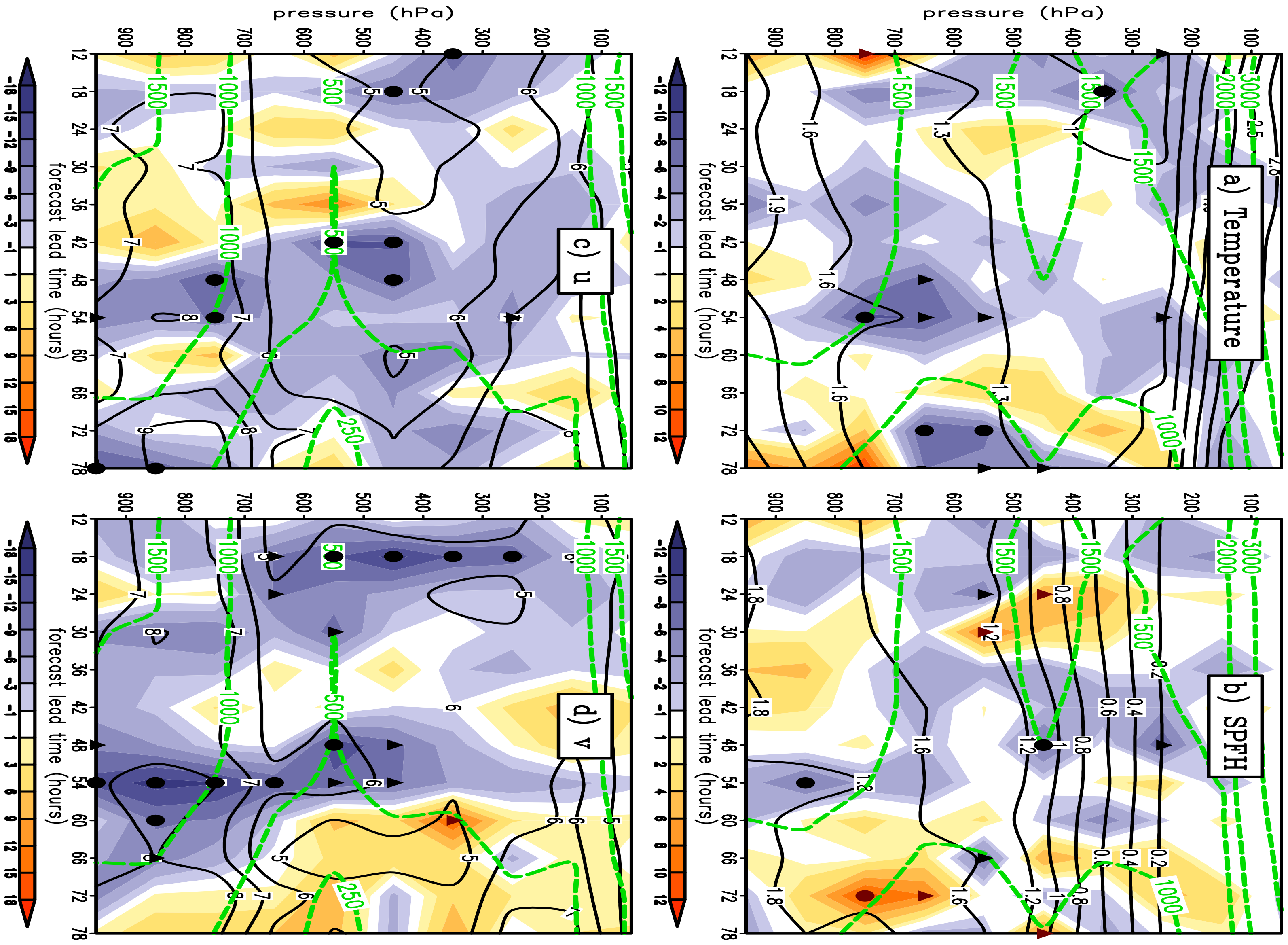


- Lower troposphere COSMIC-2 rejections come almost entirely from either:

  - Super-refractivity (SR) check triggered by the background refractivity (N) vertical gradient exceeding a limit
  - |O-B|/O exceeding an empirically tuned cutoff value that depends on height, latitude, and temperature

- Lower troposphere COSMIC-2 rejection rate increases with background *q* for moist regions

HWRF C2/Control Fractional RMSE Change



Hurricane Zeta (2020) Control vs. C2 Cycled Analysis Comparison

- TC vortex region: COSMIC-2 DA impacts on analysis low-to-middle troposphere water vapor field can persist for several cycles

- Cycled COSMIC-2 DA generally has a drying impact on the low-to-middle troposphere azimuthally-averaged RH outside of *r* = 150 km

- 0600 and 1200 UTC 26 Oct initializations: C2 forecast reduces a Control over-intensification bias