GNSS RO Data Processing for Climate Applications at JPL

Chi O. Ao, Anthony J. Mannucci, and
Olga P. Verkhoglyadova

Jet Propulsion Laboratory
California Institute of Technology, Pasadena, CA, USA

IROWG-4, Melbourne, Australia
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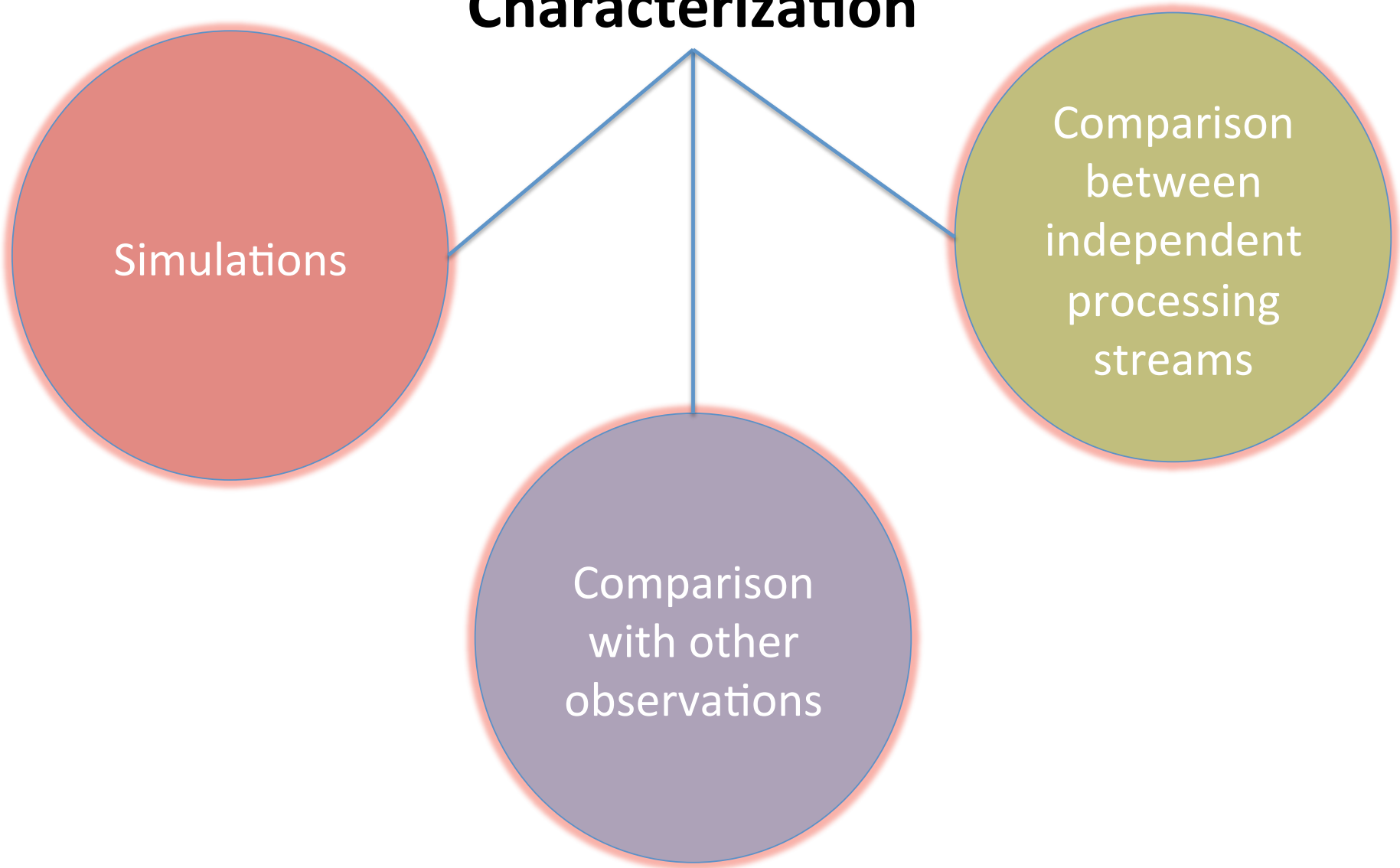
Special thanks to representatives from all processing centers that participated in the ROTrends/RO-Clim inter-center comparison studies.

RO as Climate Benchmark

- NWP data assimilation has demonstrated the value of RO data as an anchor dataset for bias correction of other data.
- Recognition of RO as a unique reference dataset for anchoring other climate observations, e.g.,
  - MSU/AMSU calibration
  - Synergy with GRUAN and GSICS (3G workshop in May 2014)
  - NPROVS from NOAA STAR
  - CLARREO NRC decadal survey mission
- Growing community interests in using RO for climate model comparisons
  - obs4MIPs for CMIP5/6.
- **Reduction/characterization of systematic bias is crucial.**

Uncertainty Characterization



Outline

- Structural uncertainty analysis
  - Continuation of inter-center comparison
  - Effects of vertical smoothing
- Climate data analysis
  - Obtaining gridded monthly averages
  - Comparing geopotential heights with CMIP5 simulations

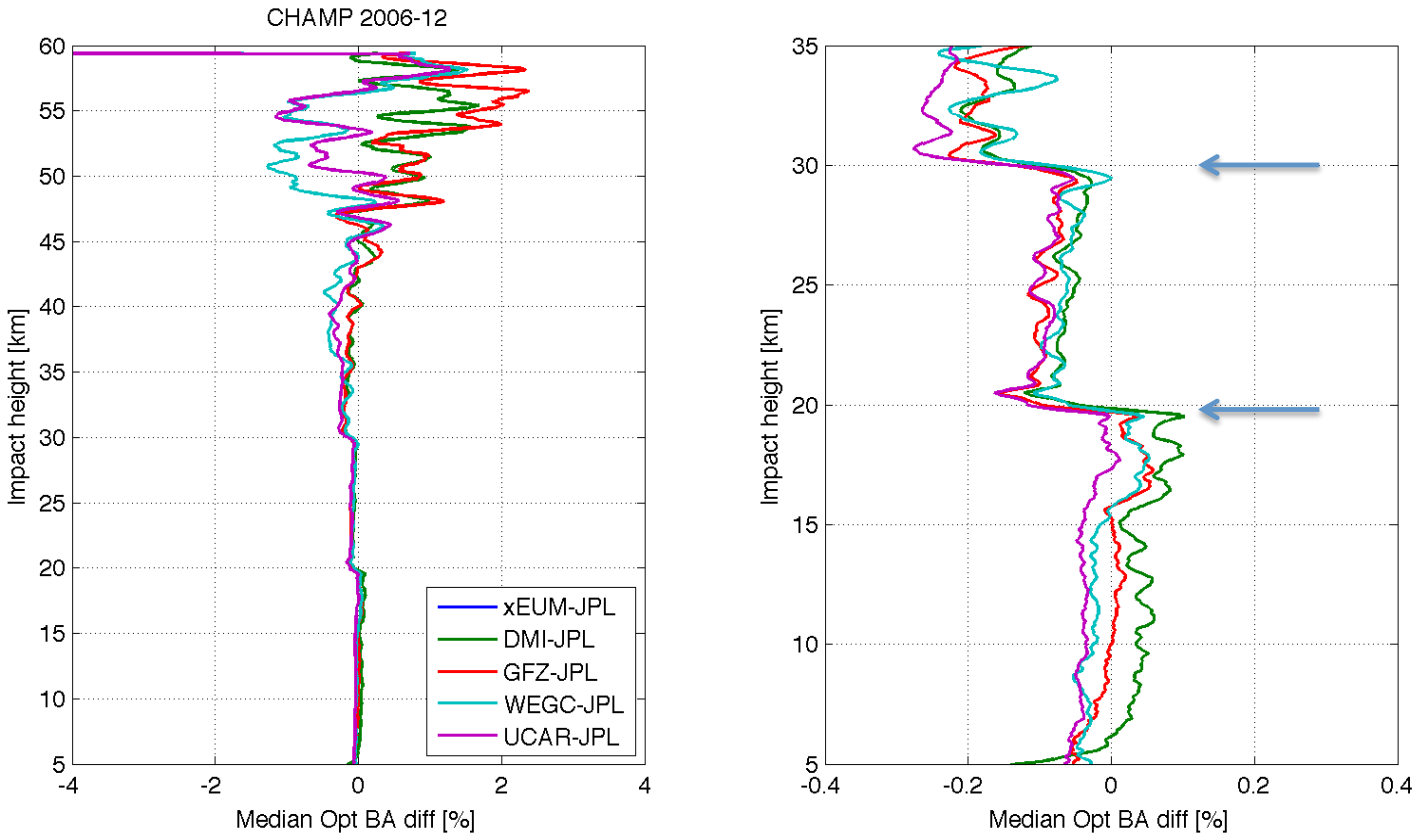
RO Intercomparison Studies

- Joint effort from multiple GPS-RO processing centers (EUM, DMI, GFZ, JPL, UCAR, WEGC)
  - "ROTrends" -> "RO-Clim" (SCOPE-CM project)
- Comparisons of retrievals based on multi-year CHAMP data quantified structural uncertainty in RO retrievals [Ho et al. 2009, Ho et al. 2012, Steiner et al. 2013].
  - Follow on studies
    1. **Understand where the reported CHAMP differences, especially in the stratosphere, originate [led by JPL]**
    2. Differences across different RO missions [led by WEGC]
    3. Differences in quality controls [led by UCAR]

“Extended” CHAMP Analysis

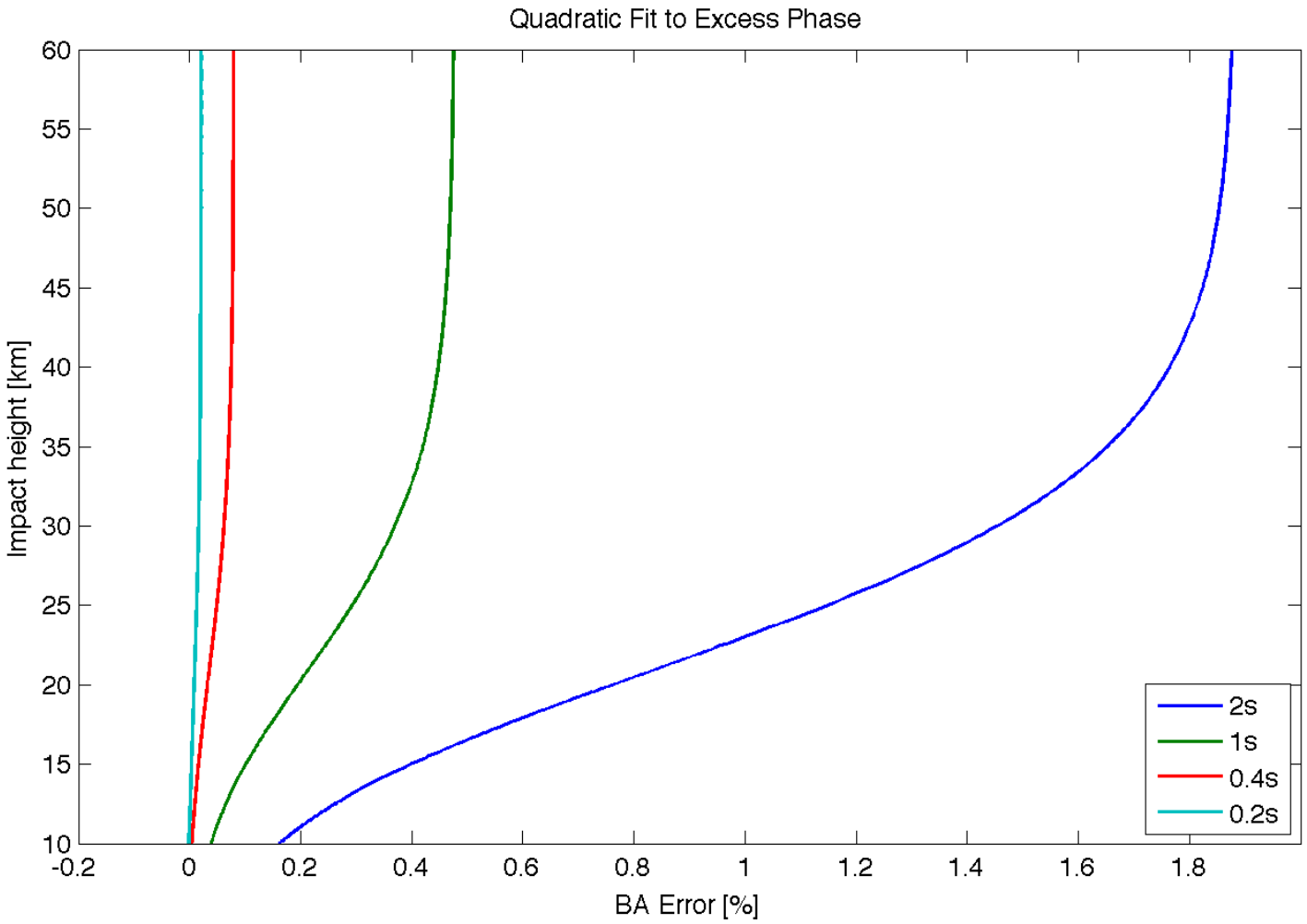
- Two months of CHAMP data were chosen (Dec 2006 & July 2008).
- Extended altitudes and data types (L1, L2, Raw and “Optimized” BA) were requested.
- Unfortunately not all centers stored all data types and to altitudes > 60 km.
- Results shown here based on profiles that pass QC for all processing centers (~ 3000 profiles per month).
- Results presented in median fractional difference relative to JPL.

Neutral BA (“Optimized”)



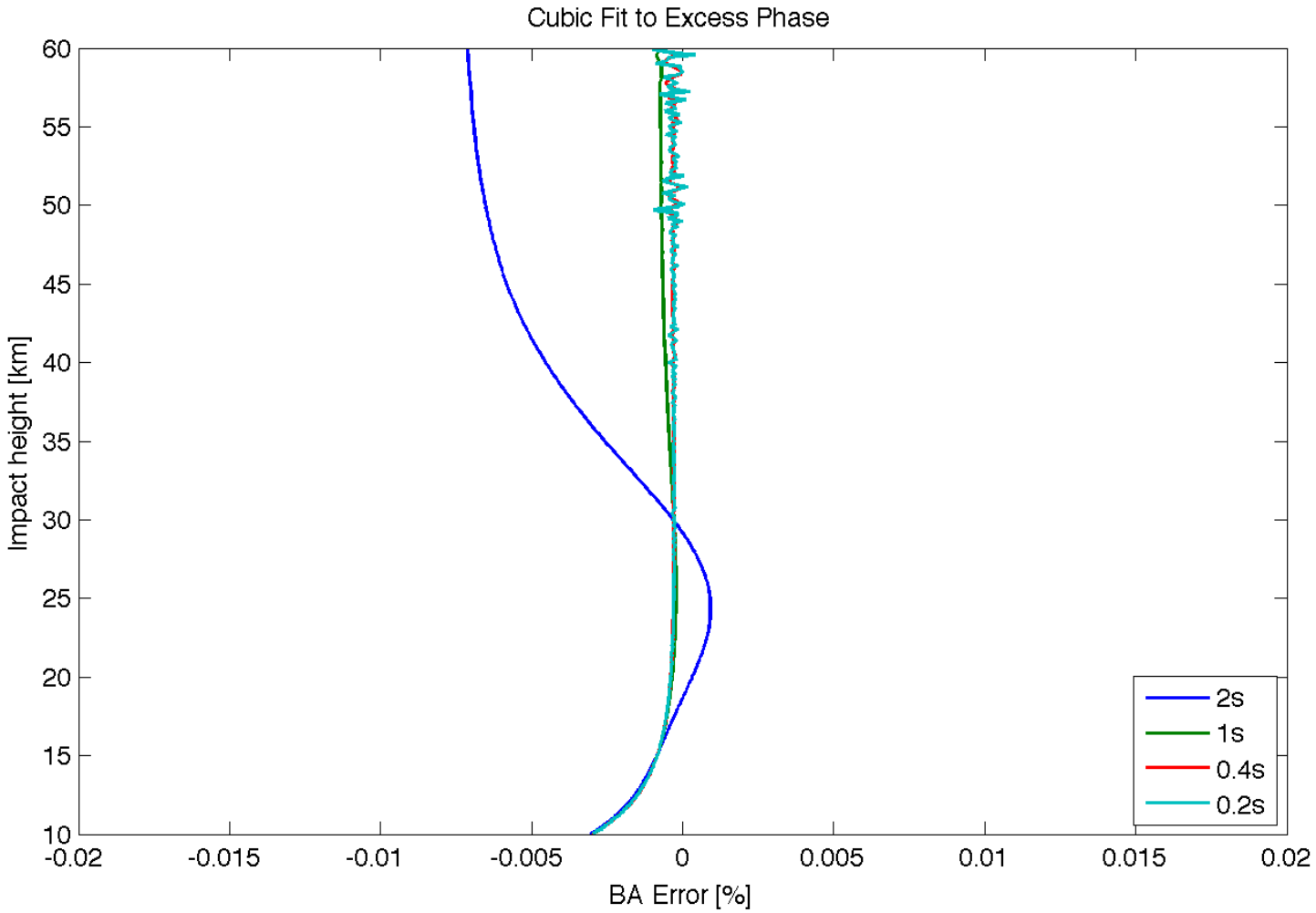
The abrupt jumps at 20 and 30 km occur where JPL changes its vertical smoothing intervals, suggesting that JPL smoothing algorithms might have introduced systematic biases.

Vertical Smoothing (Sim/GO): Quadratic

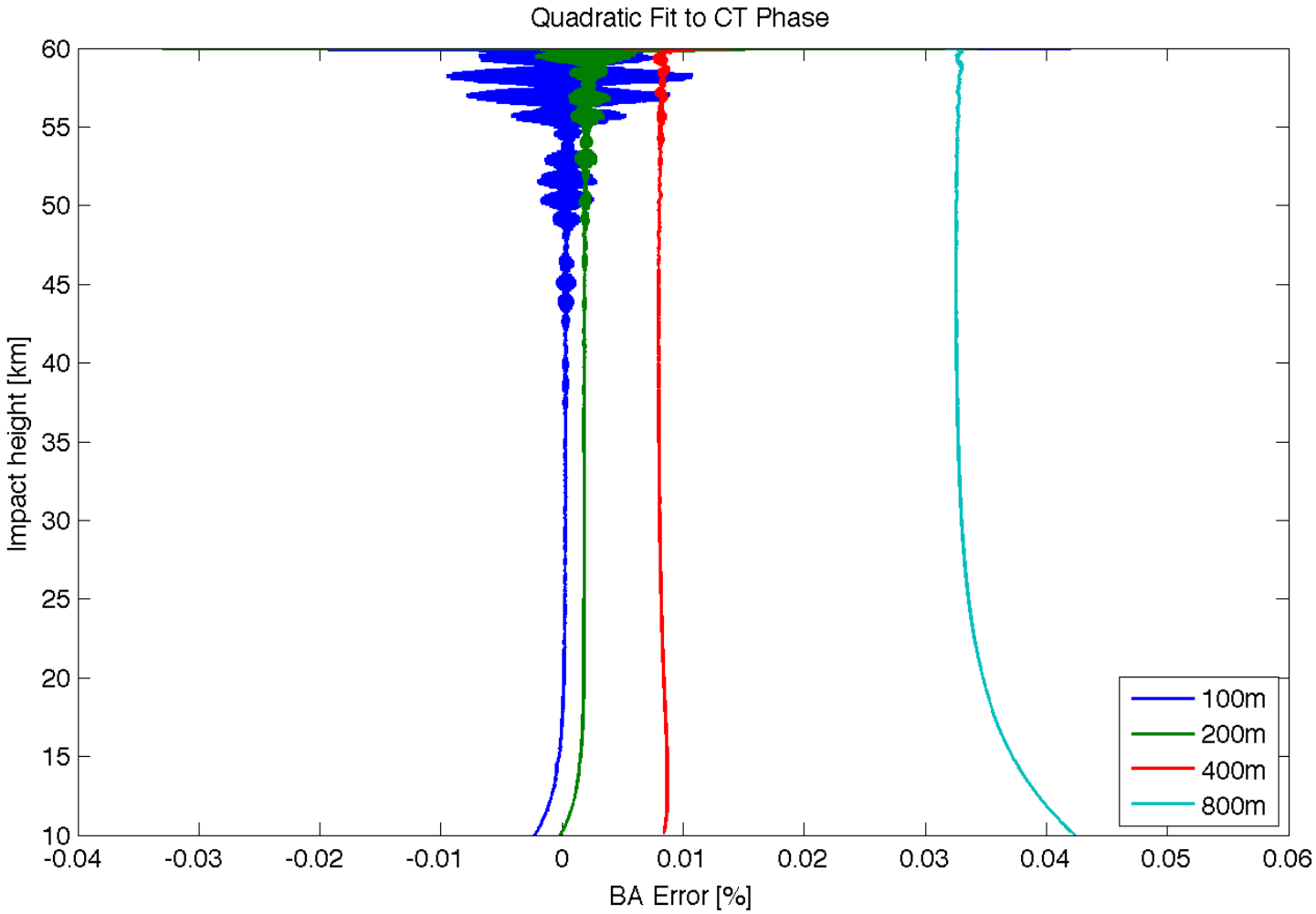


2 s = 6 km
1 s = 3 km
0.4 s = 1.2 km
0.2 s = 0. 6 km

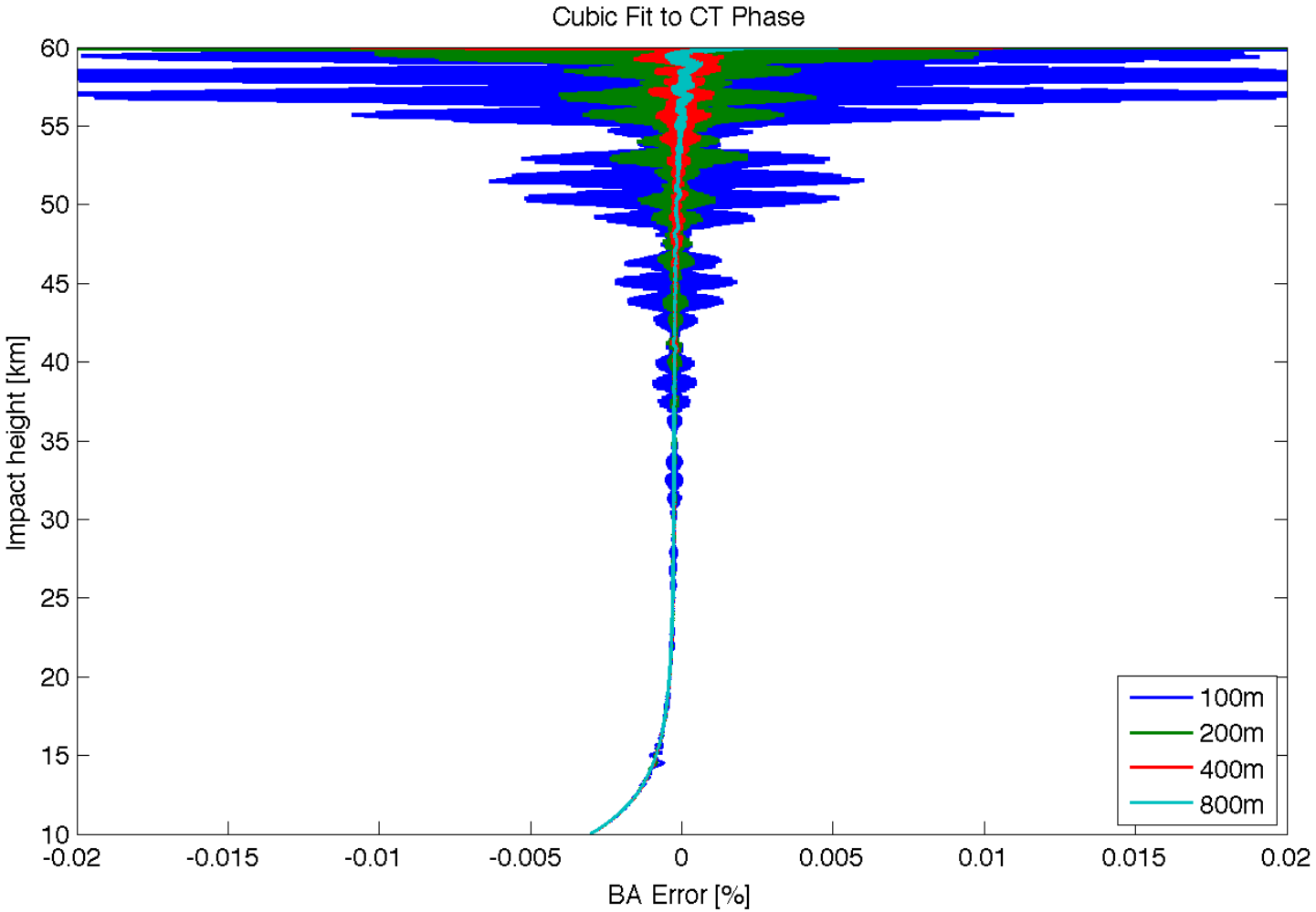
Vertical Smoothing (Sim/GO): Cubic



Vertical Smoothing (Sim/CT): Quadratic



Vertical Smoothing (Sim/CT): Cubic

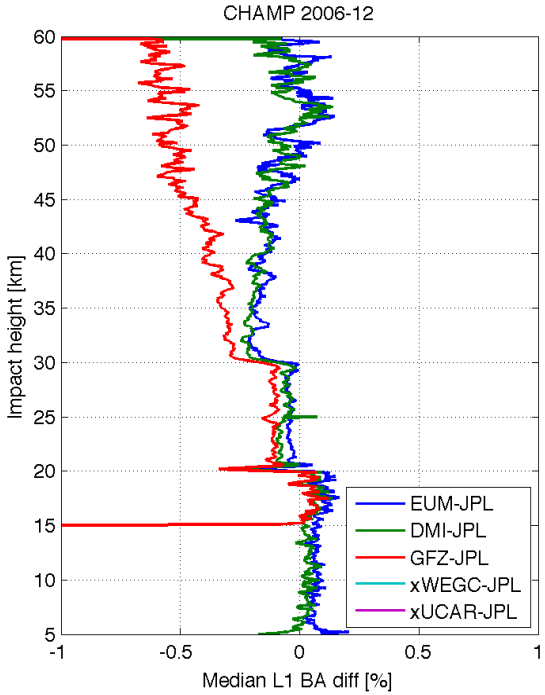


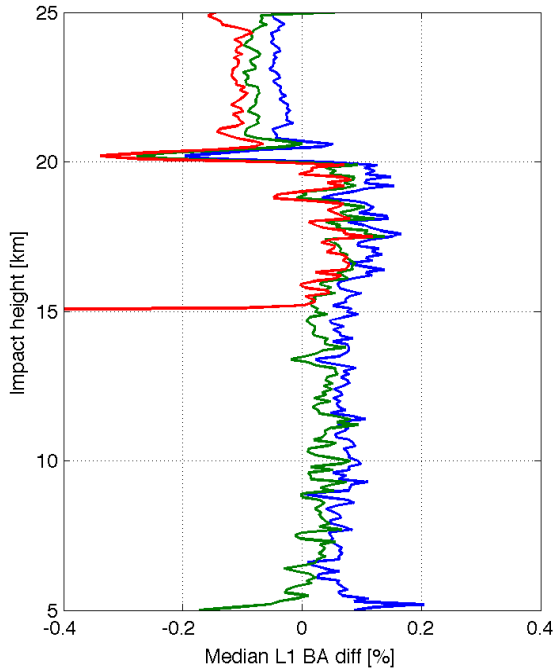
Changes in JPL Smoothing

Impact height	Before	After
h < 20 km	L1: CT, 200 m (quad) L1-L2: GO, 2sec (quad)	L1: CT, 200 m (quad) L1-L2: GO, 2sec (cubic)
20 km < h < 30 km	L1, CT, 1 km (quad) L1-L2: GO, 2sec (quad)	
h > 30 km	L1: GO, 1sec (quad) L1-L2: GO, 2sec (quad)	L1: GO, 1sec (cubic) L1-L2: GO, 2sec (cubic)

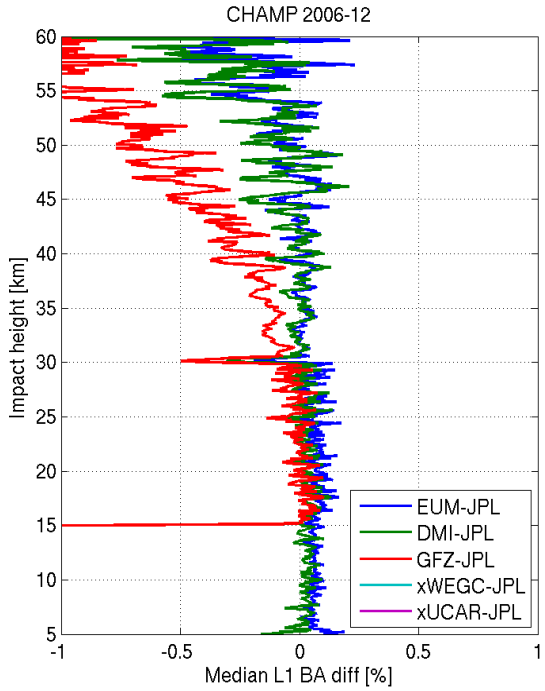
L1 BA Dec 2006

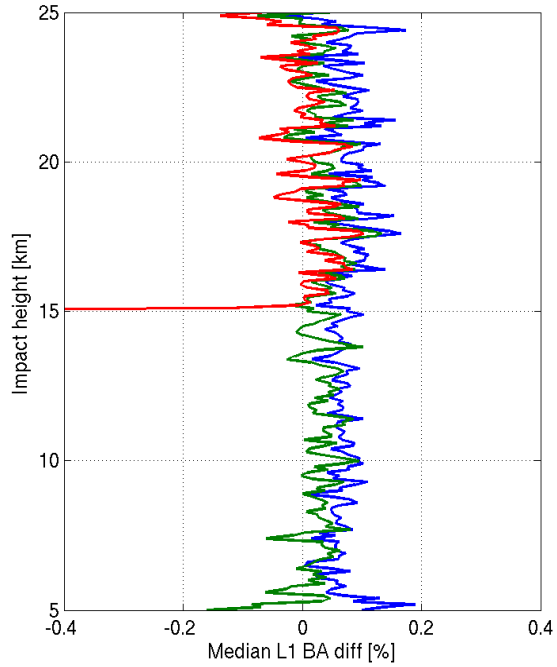
Before





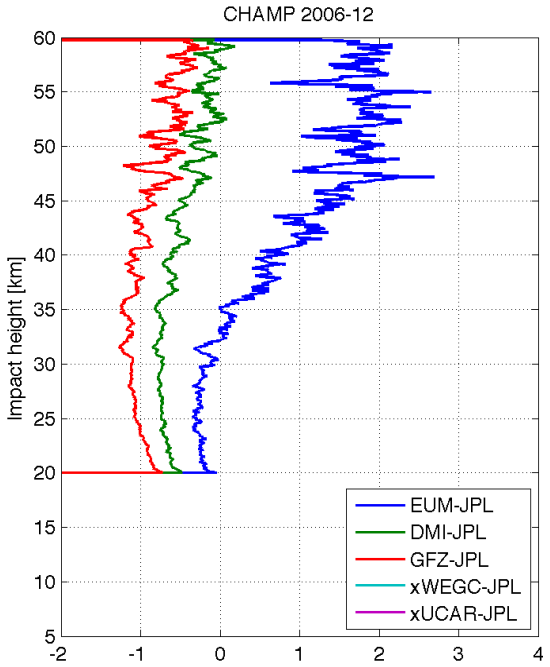
After

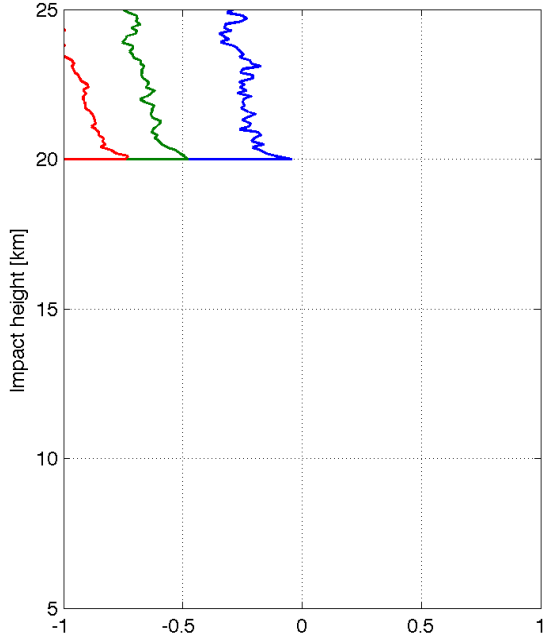




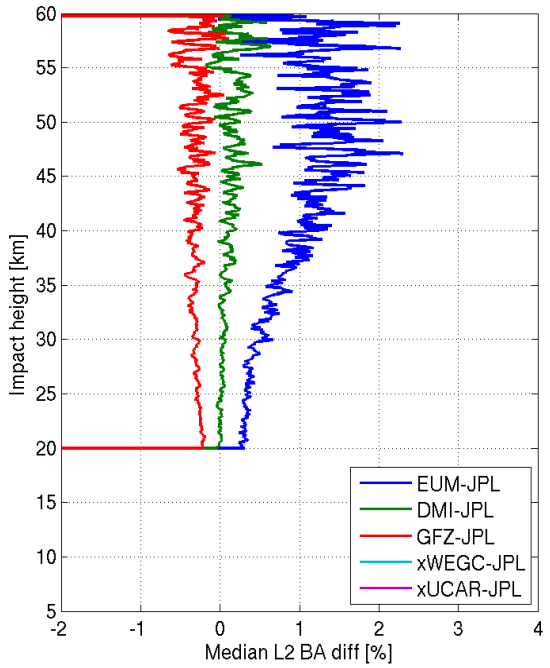
L2 BA Dec 2006

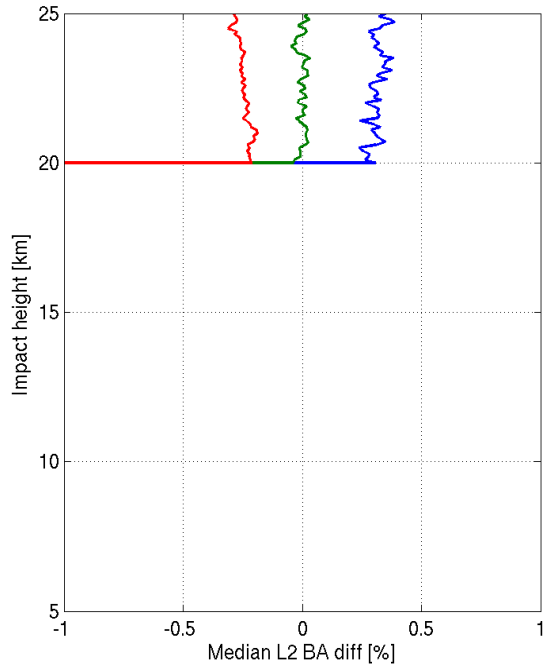
Before





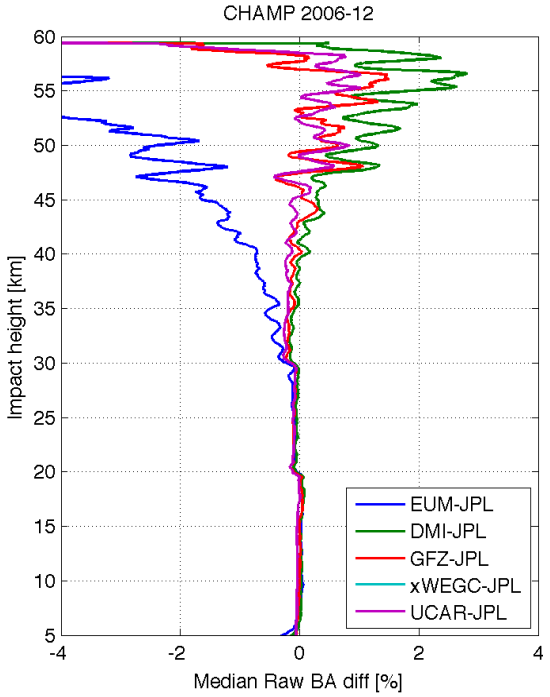
After

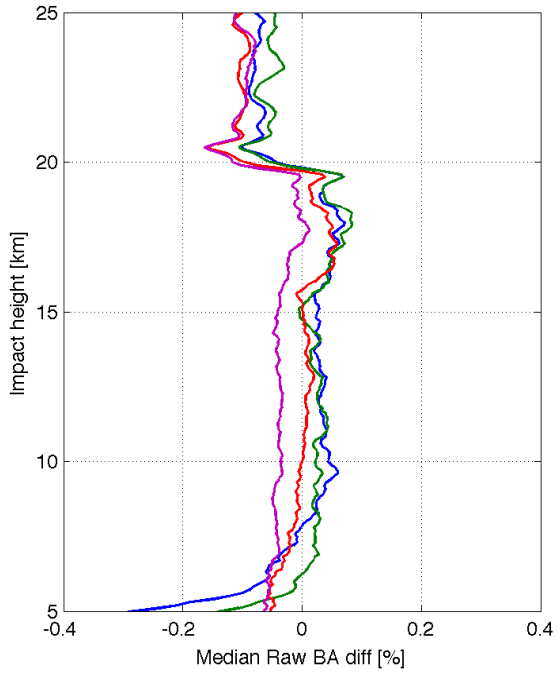




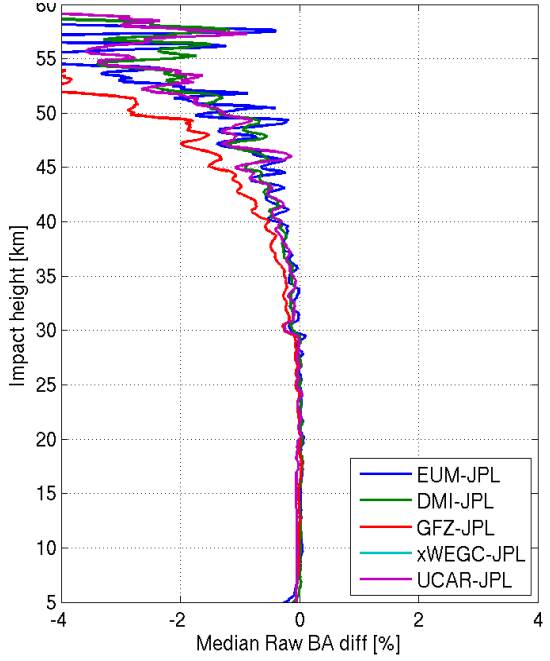
Neutral BA Dec 2006

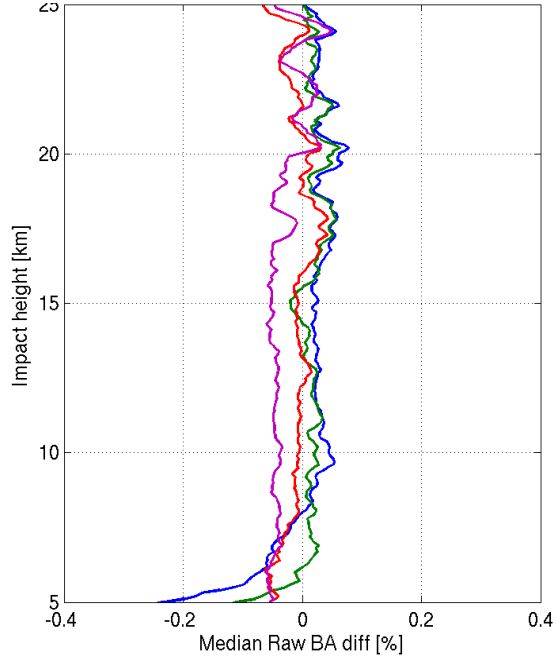
Before





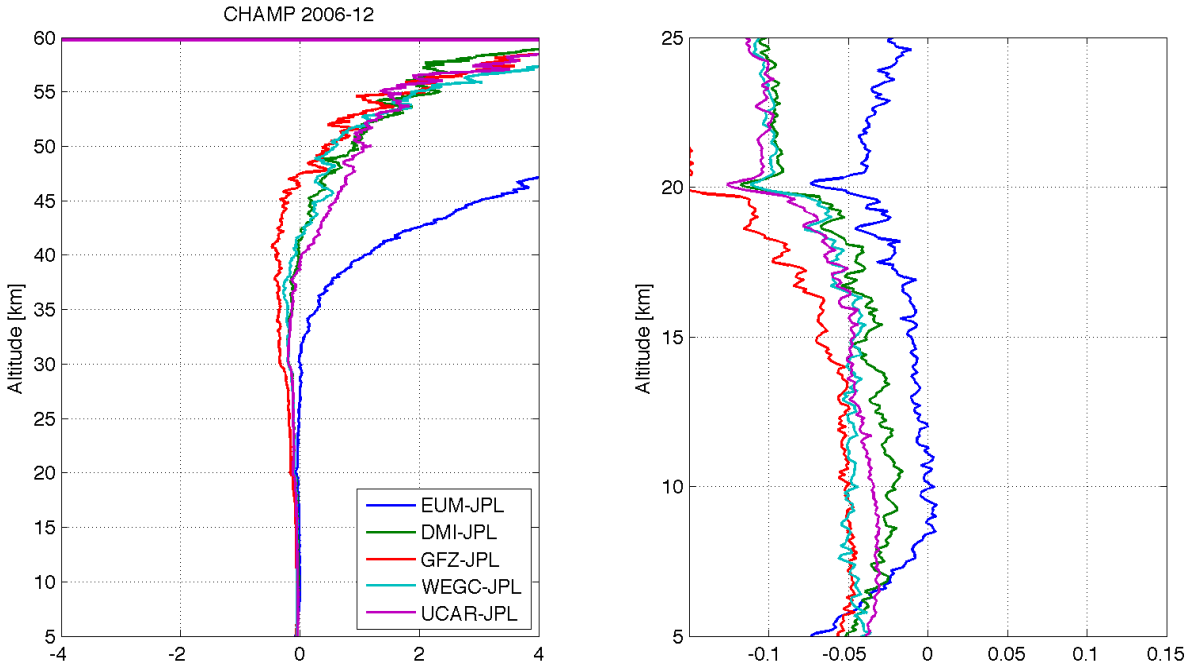
After



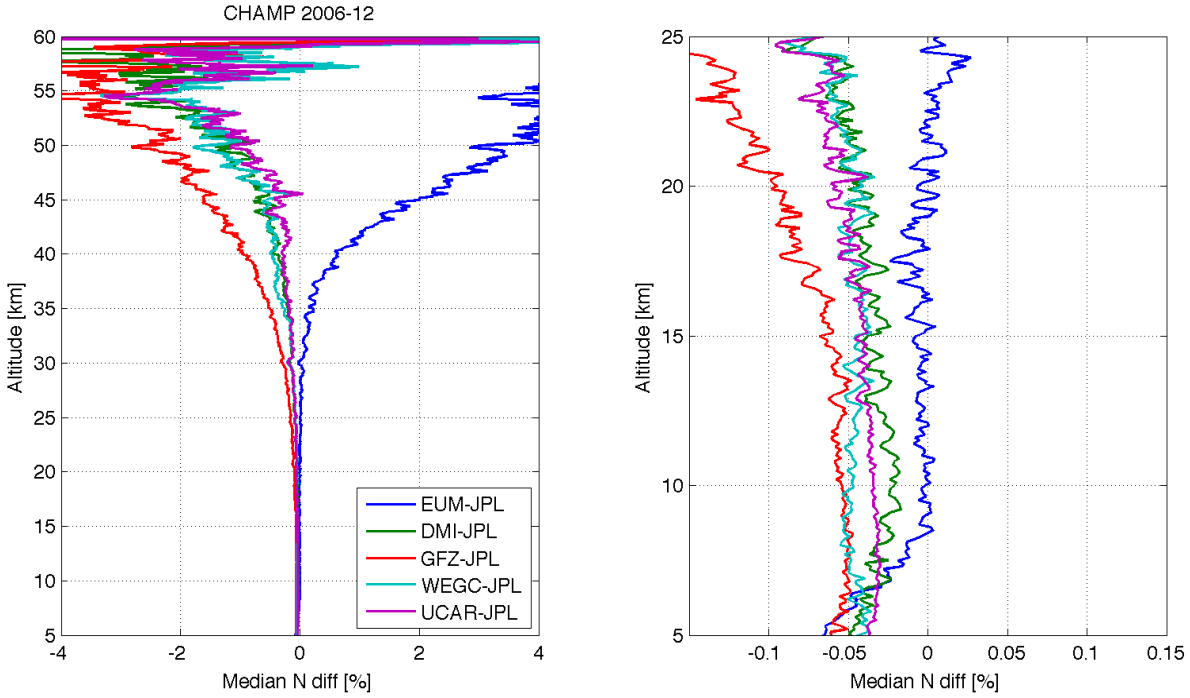


Refractivity Dec 2006

Before

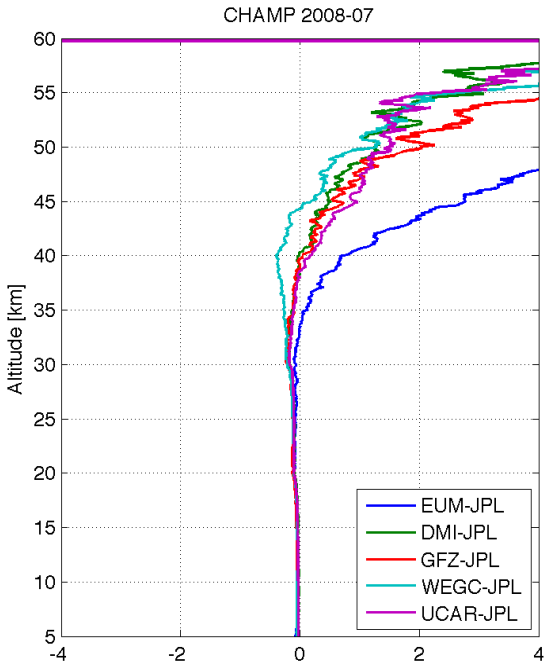


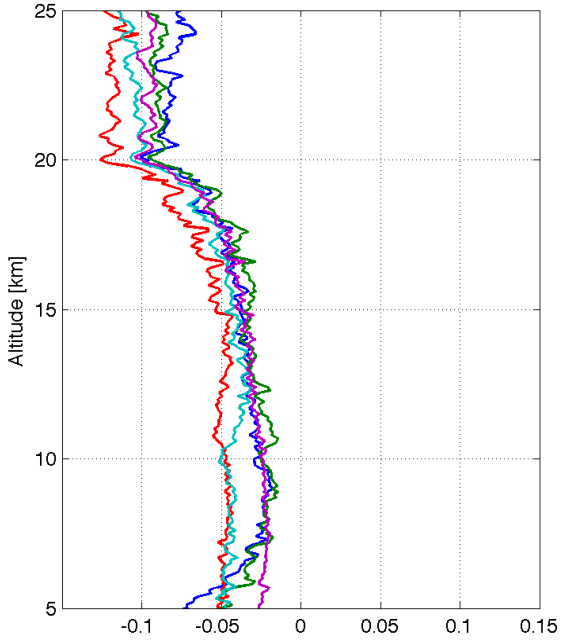
After



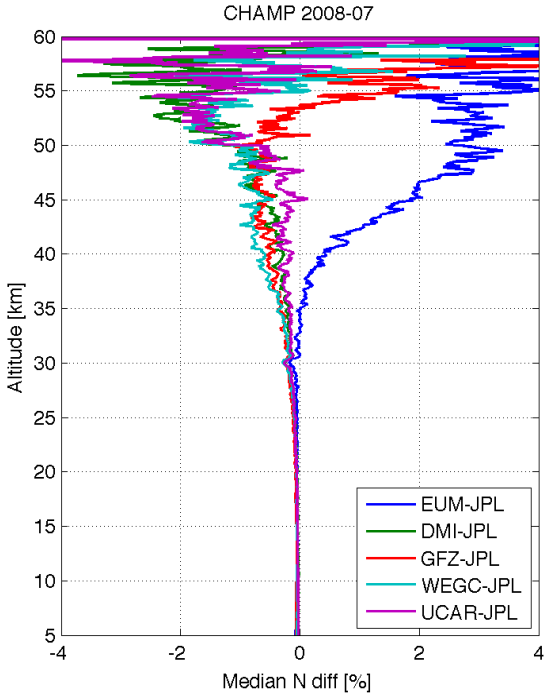
Refractivity Jul 2008

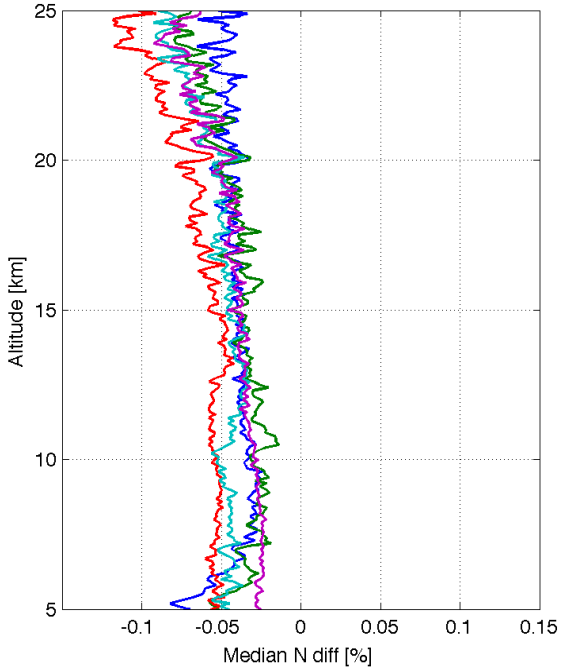
Before





After





Discussion

- Vertical smoothing can introduce systematic bias if not done correctly.
- Cubic smoothing of excess/CT phase gives a big improvement over quadratic smoothing. Going to quartic yields little benefits in reducing systematic error.
- Retrieval differences among centers not fully understood, especially relating to implementations of ionospheric correction.
- Another puzzle relates to the refractivity differences (geoid differences account for < 0.01%). Implementation of Abel inversion?

Gridded Data & CMIP5 Comparisons

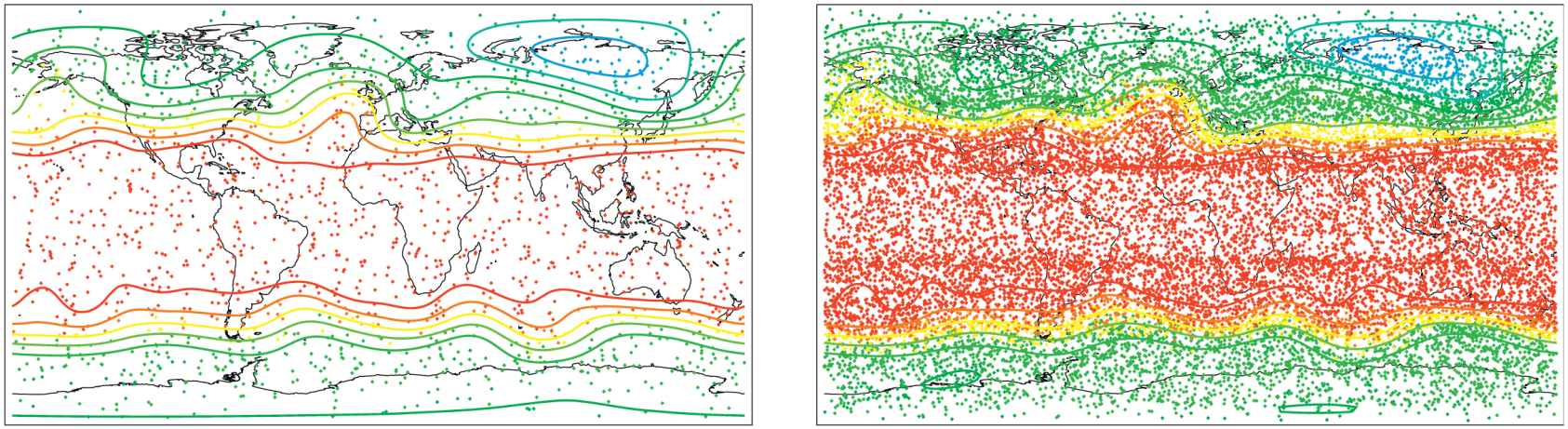
- Recent effort at JPL to generate monthly gridded data for climate model evaluation & other applications ("obs4MIPs").
- Initial focus on upper-tropo/lower-strato temperature, geopotential height, and geostrophic wind.
- Includes estimates of retrieval and sampling errors.

Bayesian Mapping of RO Data

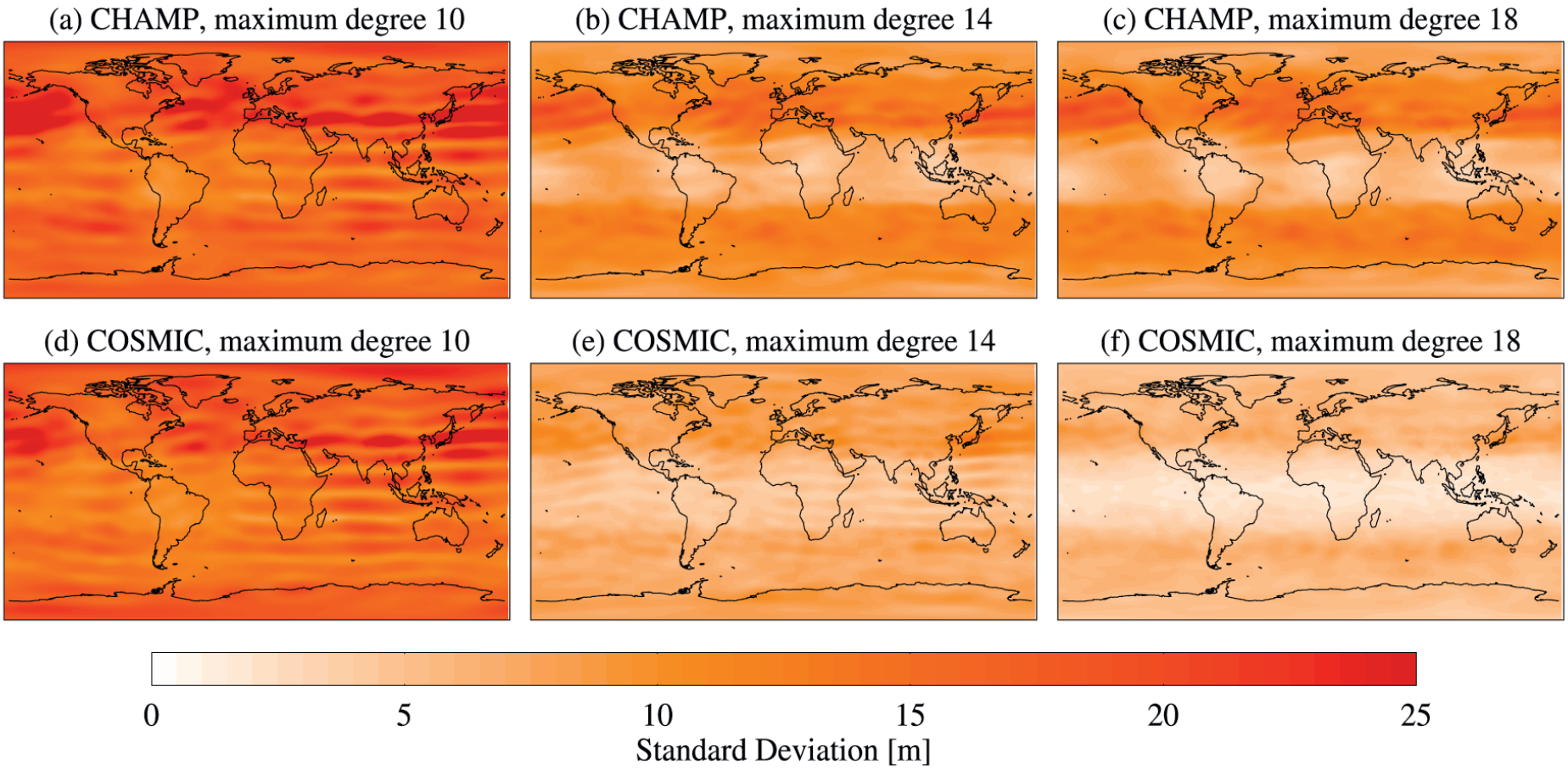
- GPS RO soundings are quasi-randomly though non-uniformly distributed. Simple "binning and averaging" method for gridding could lead to systematic sampling bias.

1. Fit data at each vertical level over sub-monthly bins (~ 2–5 days) using Bayesian interpolation method with spherical harmonics basis functions.
2. Obtain gridded data (5 deg x 5 deg) over sub-monthly bins.
3. Obtain monthly average by averaging sub-monthly gridded data.

Leroy, Ao, & Verkhoglyadov, Mapping GPS radio occultation data by Bayesian interpolation, J. Atmos. Oceanic Tech., 2012.



Sampling Uncertainty



From Leroy, Ao, & Verkhoglyadov, 2012.

T and Zg Uncertainty Estimates

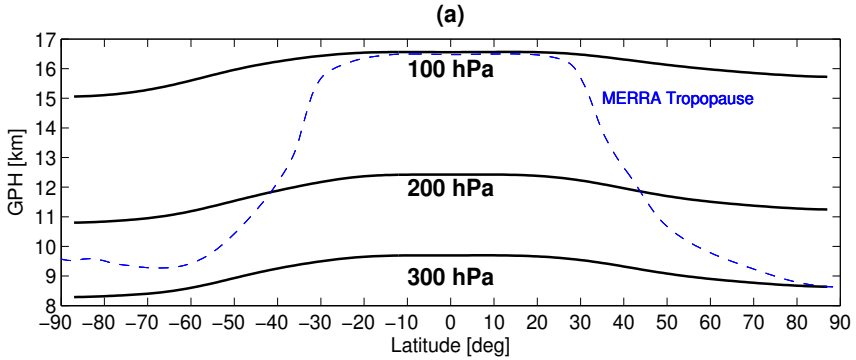
100–300 hPa

	T [K]	Zg [m]
Systematic Error (solar max daytime)	0.2	5
Random Error (along track horizontal)	0.4	10
Sampling Error (Monthly mean, upper bound)	0.5 (*)	13
COSMIC, Tropics COSMIC, mid-Lat CHAMP, Tropics CHAMP, mid-Lat	0.1 (*) 0.25 (*) 0.25 (*) 0.5 (*)	2 6 6 13

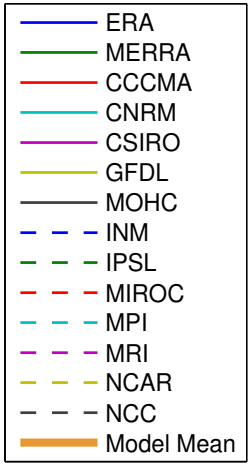
(*) scaled from Zg sampling uncertainties

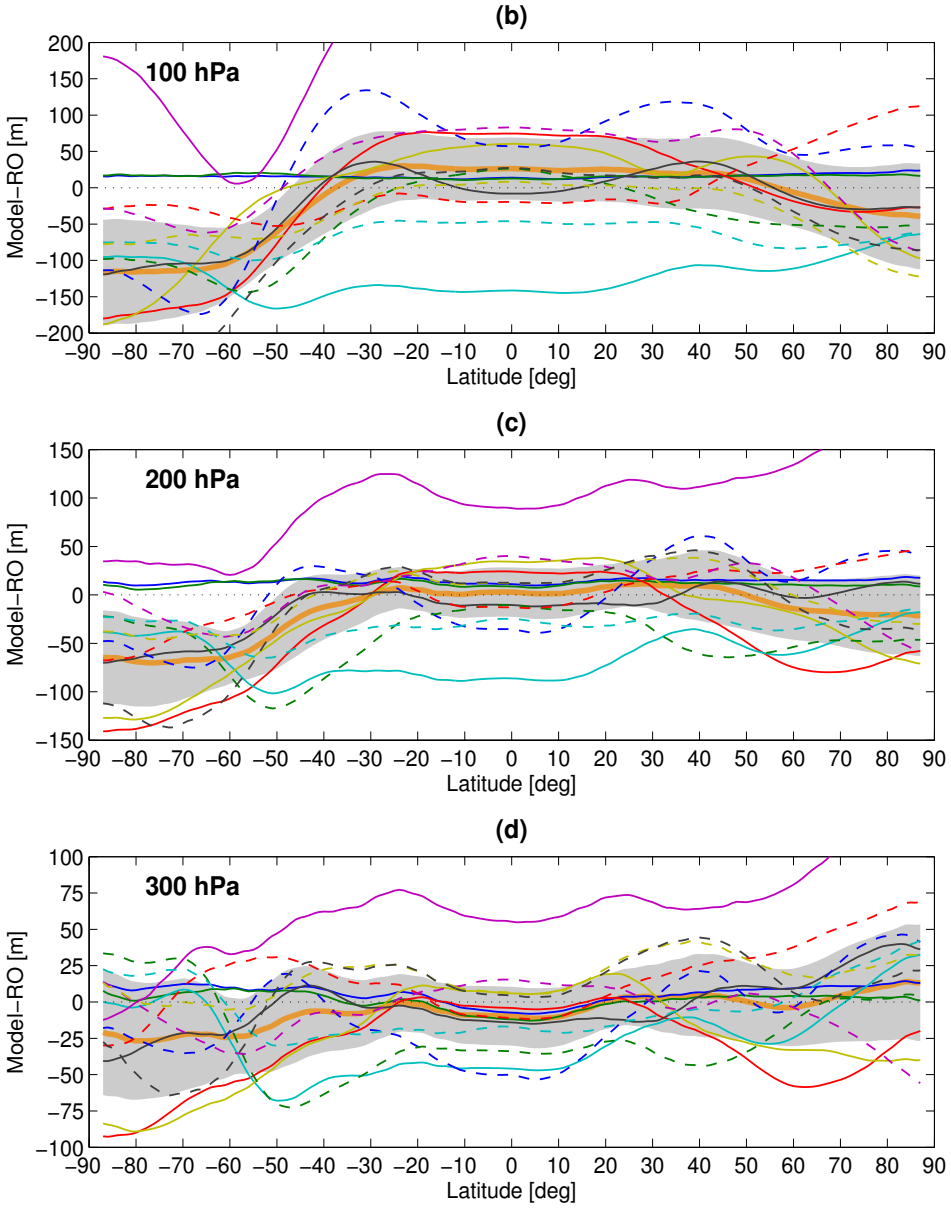
Zg Comparison with CMIP5 (AMIP)

2002–2008 Annual Zonal Mean



- **Best agreement with RO in tropics at 200 hPa.**
- **Largest inter-model spread (shaded area) at high latitudes.**
- **Negative bias in SH mid-to-high latitudes.**
- **Reanalyses are ~ 10 m larger than RO.**

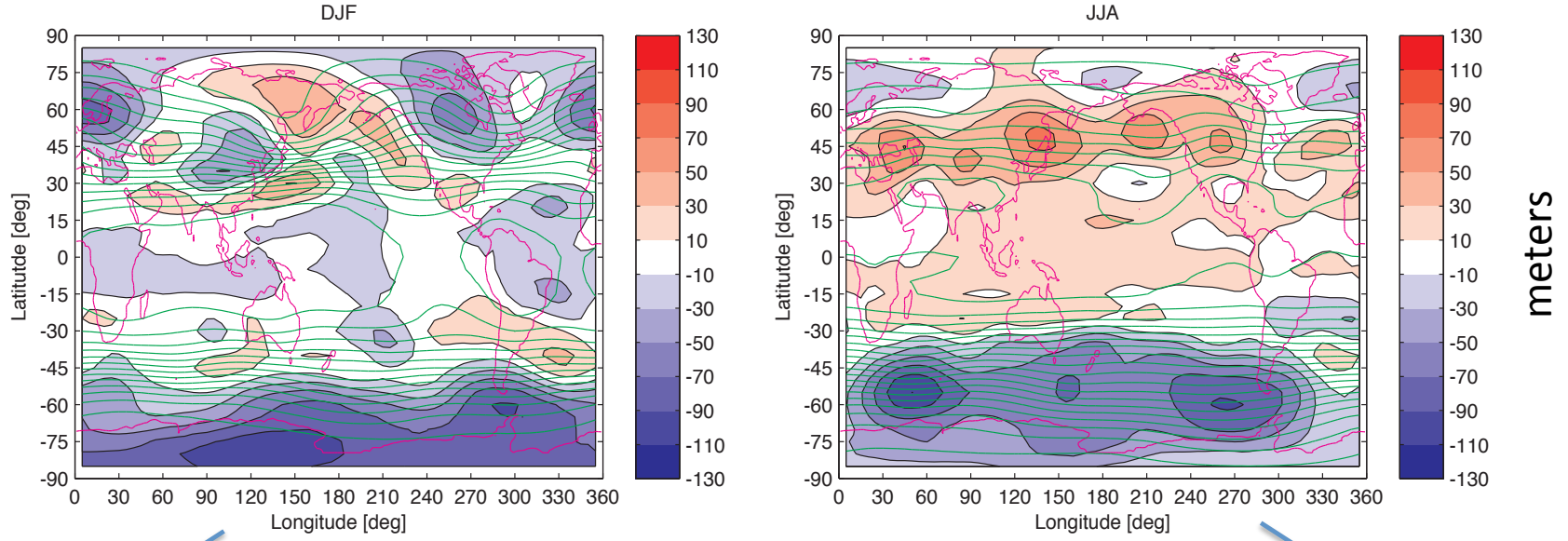




Ao et al., *JGR*, 2015.

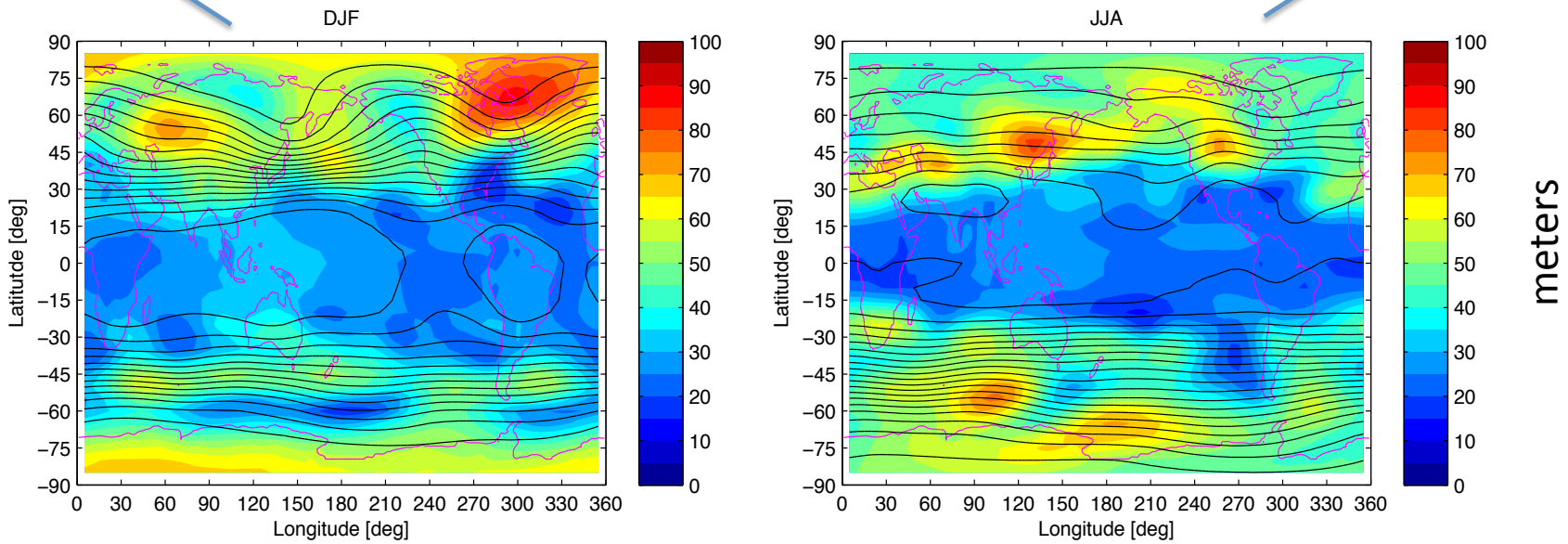
2002–2008 Seasonal Mean 200 hPa Zg

Multi-model mean – RO



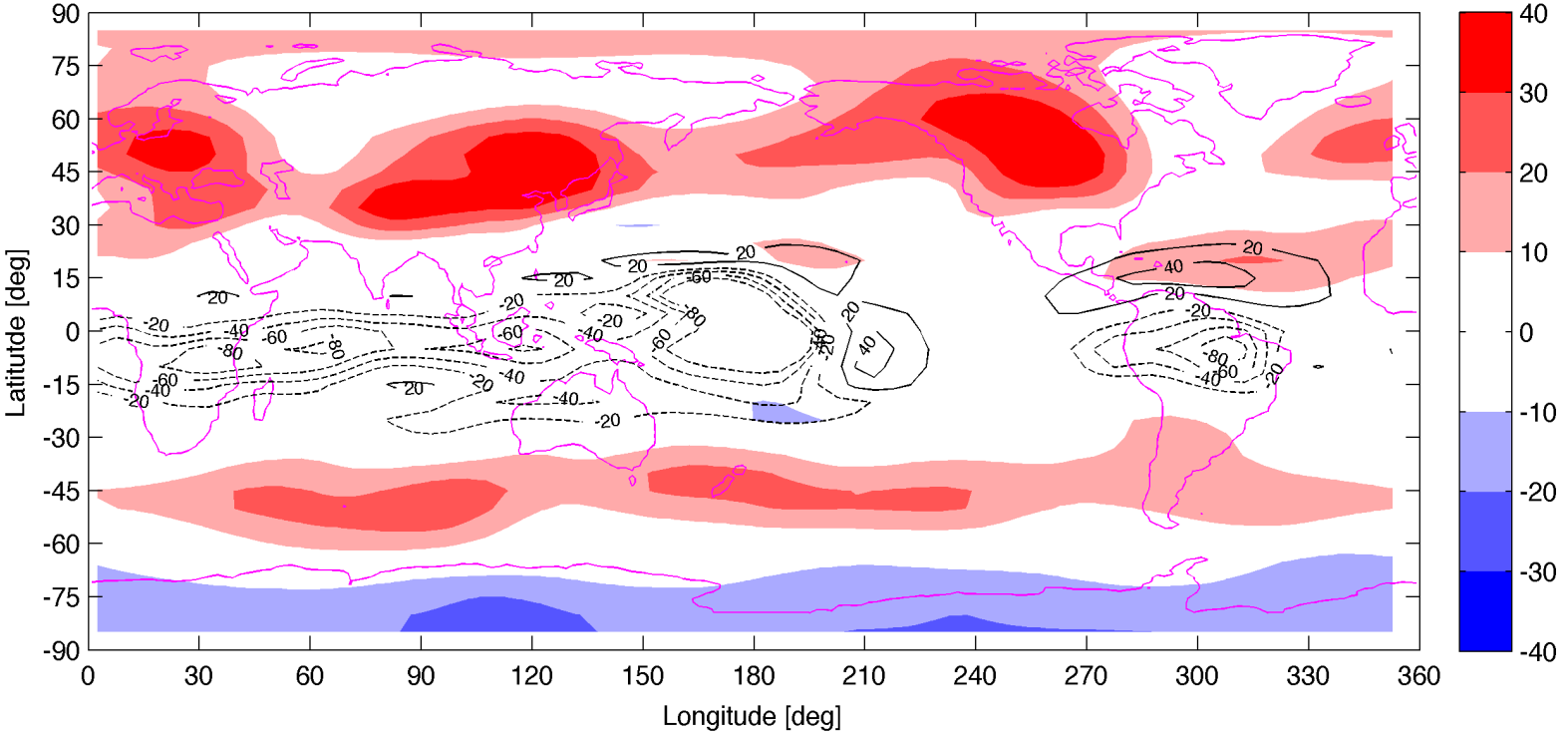
DJF **JJA**

Inter-model spread



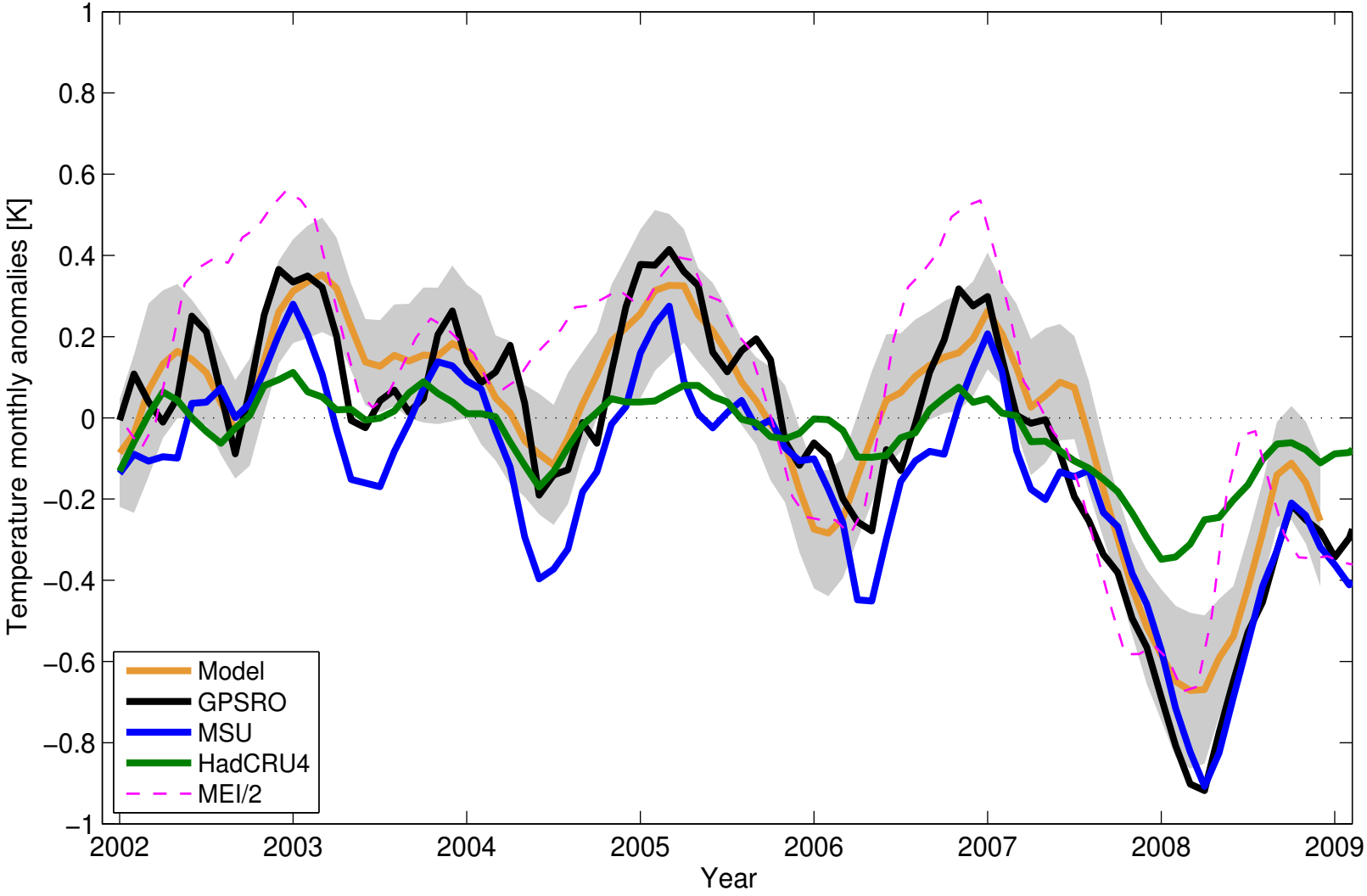
Seasonal Variability 200 hPa Zg

Color = absolute differences in meters
B/W = fractional differences in %



- **Models show excessive seasonal amplitudes in mid-latitudes (esp. NH land).**
- **In the tropics, models underestimate seasonal amplitudes esp. over Central Pacific.**

Troposphere Temperature (10S-10N)



Conclusions

- 20 years of RO record going back to GPS/MET: valuable for studying climate variability, recent trend, and evaluating climate models and other observations.
- Continued retrieval improvement and uncertainty characterization that focuses on systematic bias.
  - Better understanding of inter-center differences.
  - Implementation of data-based quality control and the use of averaged RO bending angles for upper altitude initialization [Scherllin-Pirscher et al. AMT, 2015].