Estimated GNSS RO NWP Impact by the Numbers (+ its future cousin, ATOMMS)

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Outline

- Motivation & Harnisch et al. Report (HHB)
- Extracting error variances & weighting from HHB
- Impact on analysis T, ZG, Winds & RH
- Error variance power law exponents
- Impact Scaling of DFS% & potential “bang for the buck”
- ATOMMS update

Questions

- How does the NWP impact scale with number of occultations?
- How does RO contribute to the analysis information content as the occ numbers increase?
- What is the GNSS RO impact in the troposphere vs. stratosphere?
- How does the RO compare to JPSS and other observing systems?
- What is the NWP impact vs. number of GNSS RO satellites vs. $?

Harnisch et al. 2012, 2013 Overview

- Examined impact of 2K – 128K occultations per day
- Ensemble Data Assimilation (EDA) approach
- Error reduction is relative to the NWP system assimilating observations other than GNSS RO
- EDA generates realistic results for current # of occ particularly in Northern & Southern Hemispheres
- HHB results are likely an *underestimate* of GNSS impact because of suboptimal combining of the background and simulated GNSS observations
  - EDA spread was smaller than assumed error covariance

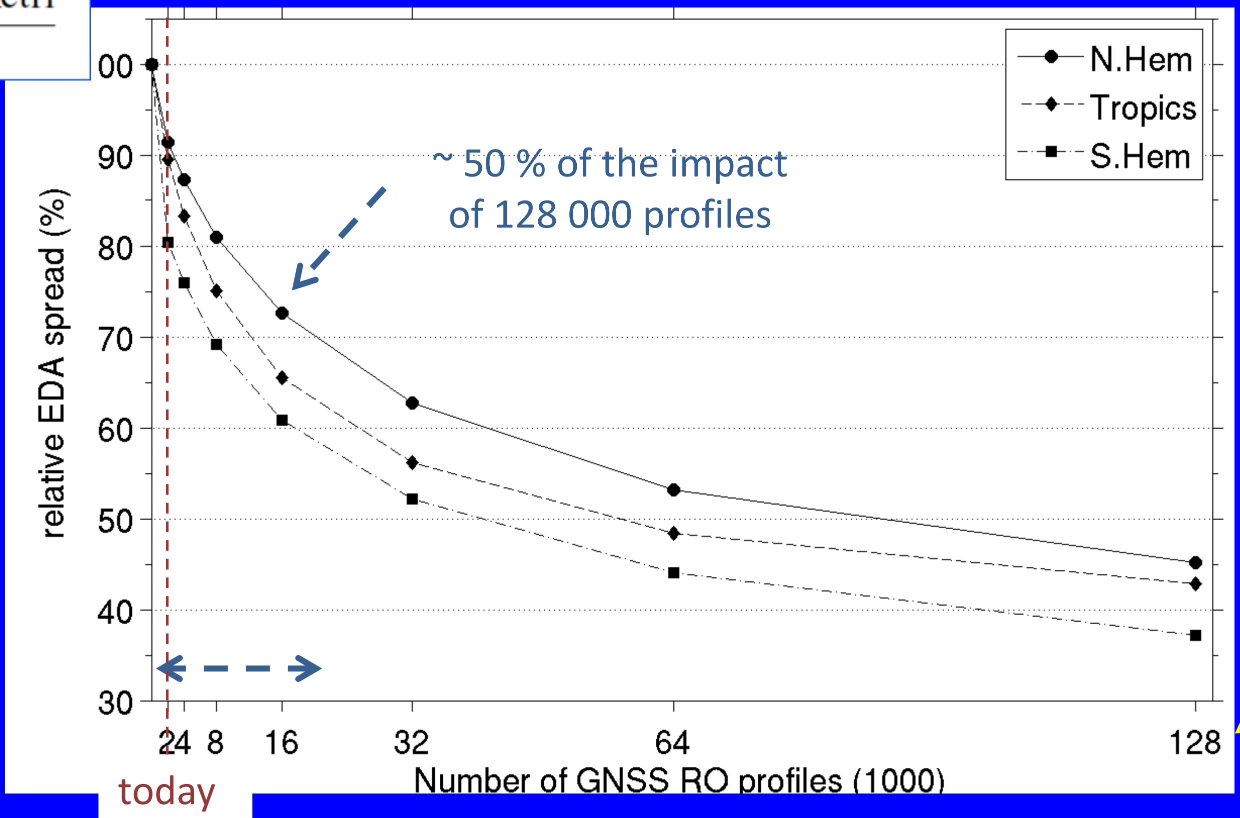
Harnisch et al. Study Overview

- Period of simulations: July 1 to August 15, 2008
  - NH summer (warm wet), SH winter (colder drier)
- Results examined here are HHB Error Reductions relative to the control or background error
  - Analysis and 24 hr forecast results
- **4 variables:** Temperature, Geopotential Height, Winds and Relative Humidity
- **14 pressure levels:** 10, 50, 70, 100, 150, 200, 250, 300, 400, 500, 700, 850, 925, 1000 hPa
- **3 regions:** Northern Hemisphere, Tropics & Southern Hemisphere
- **# occ/day:** 2k, 4k, 8k, 16k, 32k, 64k, 128k => 256k

Scaling of GNSS RO impact (F. Harnisch)

$$\frac{\text{EDA\_}n - \text{EDA\_ctrl}}{\text{EDA\_ctrl}}$$

Temperature analysis at 100 hPa



~ 25 million bending angles per day

Large improvements up to 16 000 profiles per day

Even with 32 000 – 128 000 profiles still improvements possible

→ no evidence of saturated impact up to 128 000 profiles (although the additional impact per observation is decreasing)

Impact via Least Squares

- Analysis is a combination of a Background or Control (= forecast plus observations other than GPS) and the GNSS RO observations
- Assuming the Background or Control & GPS errors are independent, then the **least squares solution** that combines the background and GNSS information has a variance given by

$$\sigma_A^2 = [\sigma_C^{-2} + \sigma_G^{-2}]^{-1}$$

- The variances here represent regional averages at a given pressure level
  - for one of the 4 variables (*T*, *ZG*, *U* & *RH*),
  - for the NH, SH or Tropics,
  - for a given number of occultations/day.

Extracting the GPS Error Variance

HHB provide one relative error reduction number.

- For each data type (*T*, *ZG*, *U* & *RH*),
  - At each pressure level,
    - In NH, SH or Tropics,
      - For a given # of occultations,

$$\varepsilon_{Hr} = \frac{\sigma_A - \sigma_C}{\sigma_C} = \sigma_{Ar} - 1$$

where σ_C is the control EDA spread w/o GNSS RO

σ_A is the analysis EDA spread w/ GNSS RO

$\sigma_{Ar} = \sigma_A / \sigma_C$

Extracting the GNSS RO Error Variances

- Variance of Analysis normalized to Background

$$\sigma_{Ar}^2 = \sigma_A^2 / \sigma_C^2 = [1 + \sigma_{Gr}^{-2}]^{-1}$$

  - where $\sigma_{Gr} = \sigma_G / \sigma_C$

- Determine relative GNSS error variance as

$$\sigma_{Gr}^2 = [\sigma_{Ar}^{-2} - 1]^{-1}$$

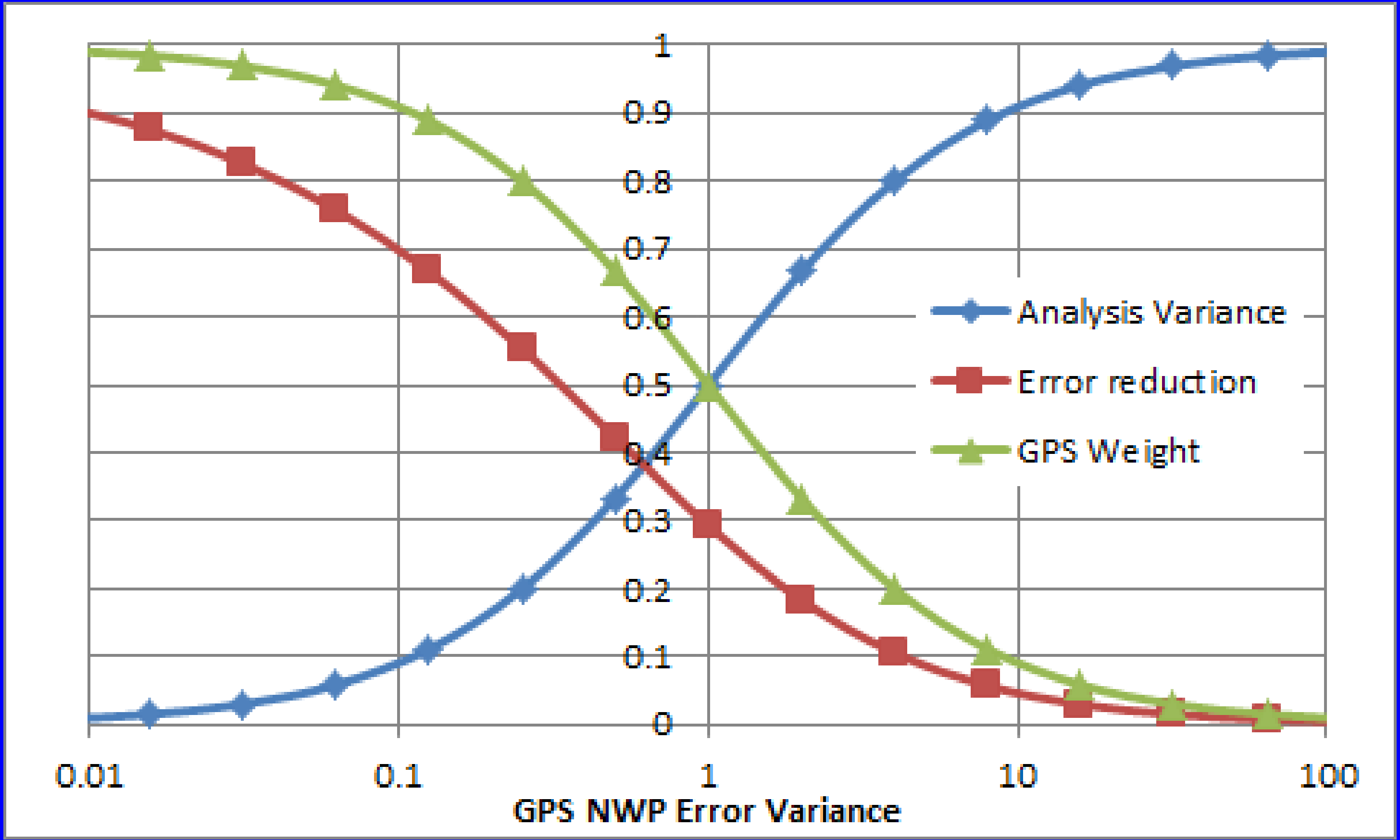
  - to see how the GNSS error, σ_{Gr}, is scaling with the number of occultations

- Least squares optimized GNSS weight

$$W_G = [1 + \sigma_{Gr}^2]^{-1}$$

  - closely related to Degrees of Freedom constrained by GNSS RO observations
  - Create impact bar charts from this

σ_{Gr} and these relationships help in interpreting and understanding the HHB results and scaling of the NWP impact and information content of large increases in the # of GNSS RO observations

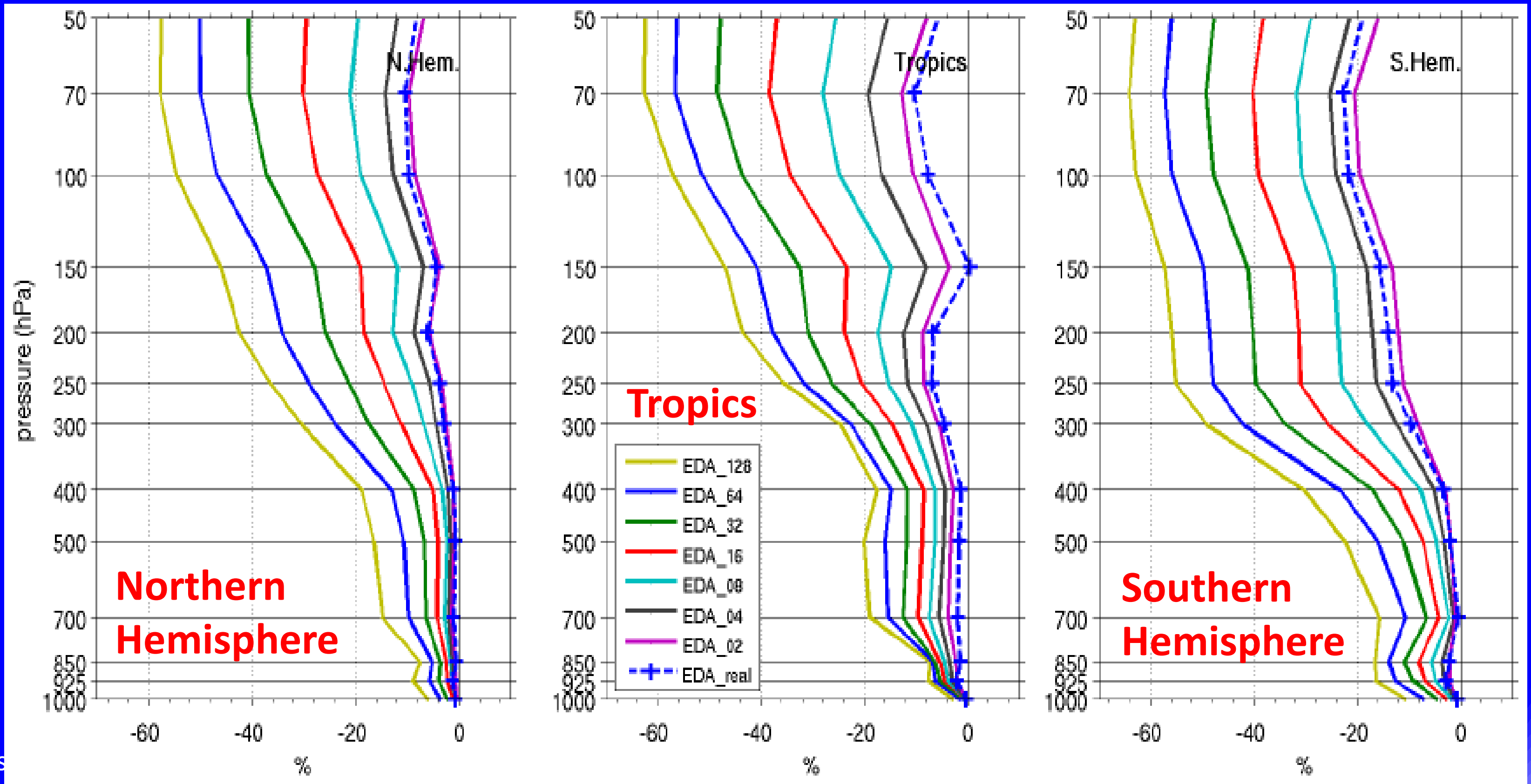


Impact & Information Content

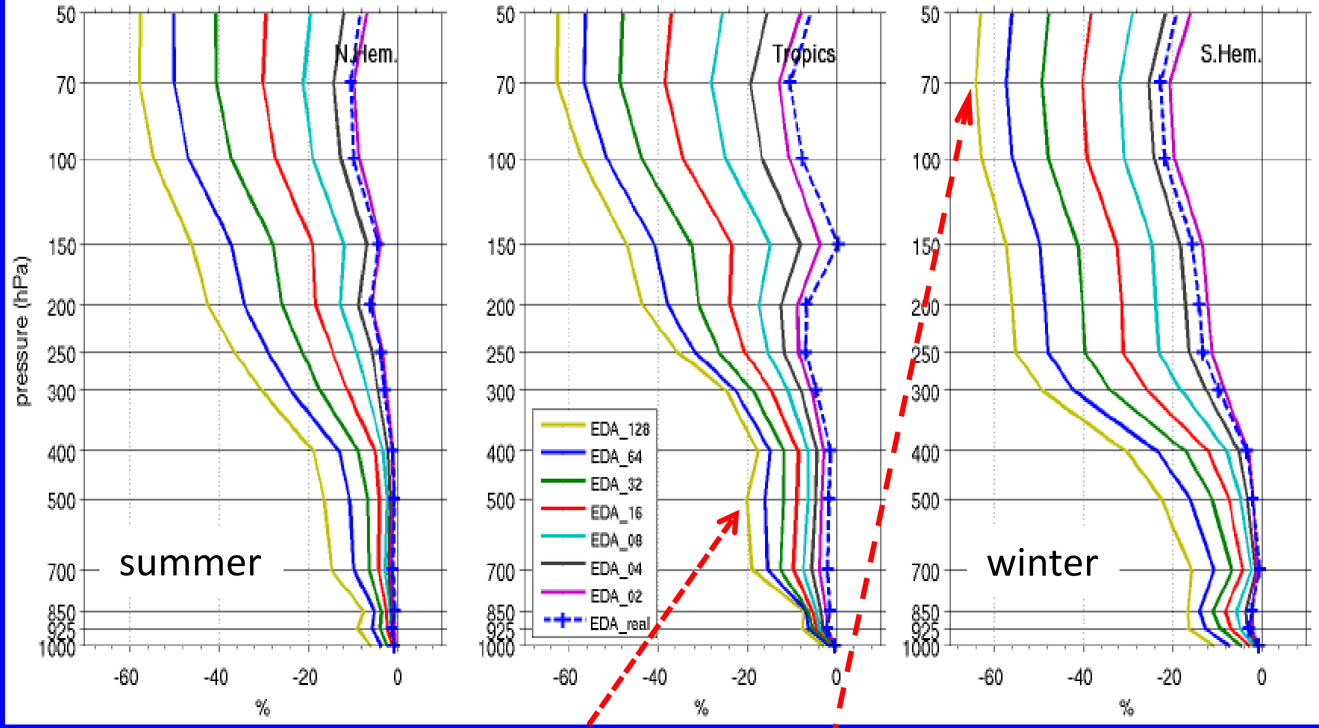
- Present analyses are ~80% forecast and ~20% observations.
  - Presently, RO contributes ~10% of the 20% ~ 2% of analysis content
- The observational impact on and contribution to the information content in the analyses can be greatly increased by greatly increasing the number of occultations

HHB EDA Error Reduction Results

- Example: Normalized impact results on **Temperature**
- Believability: Simulated 2000 occ close to observed impact
- Colors correspond to particular number of occultations
- X-axis is fractional reduction in error due to GNSS RO



GNSS RO Impact on Temperature Analyses

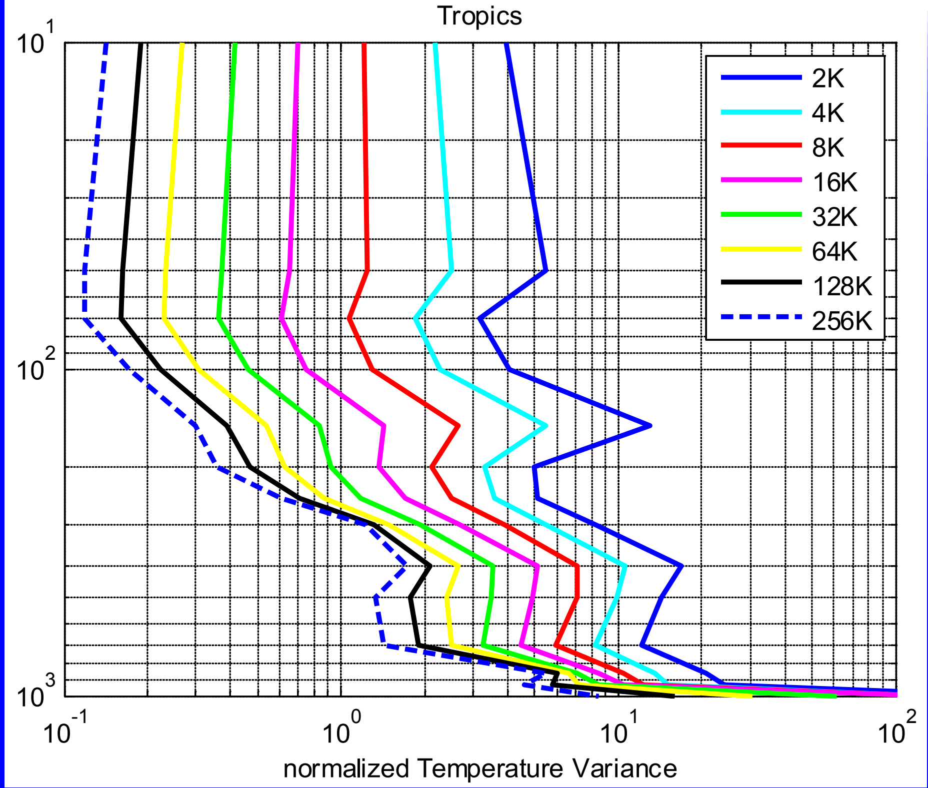


For 128K occ/day

- GPS T σ_{GrT}^2 at 500 hPa in Tropics: **1.76**
  - $\Rightarrow$ **36%** of temperature information from GNSS RO
  - $\Rightarrow$ 64% of information from background & rest of GOS
- Minimum GPS T σ_{GrT}^2 at 70 hPa in SH: **0.15**
  - $\Rightarrow$ **87%** of temperature information from GNSS
  - $\Rightarrow$ 13% of information from background & rest of GOS

Extrapolate Temperature Error Variance

128K => 256K occ/day



- **T (500 hPa)** in Tropics: 1.76 x 2^-0.45 = 1.29
  - ⇒ **44%** of temperature analysis information from GNSS RO
  - ⇒ 56% of information is from background & GOS
- **T (50-100 hPa)** in SH & Tropics: 0.16 x 2^-0.6 = 0.11
  - ⇒ **90%** of temperature analysis information from GNSS RO
  - ⇒ 10% of information is from background & GOS

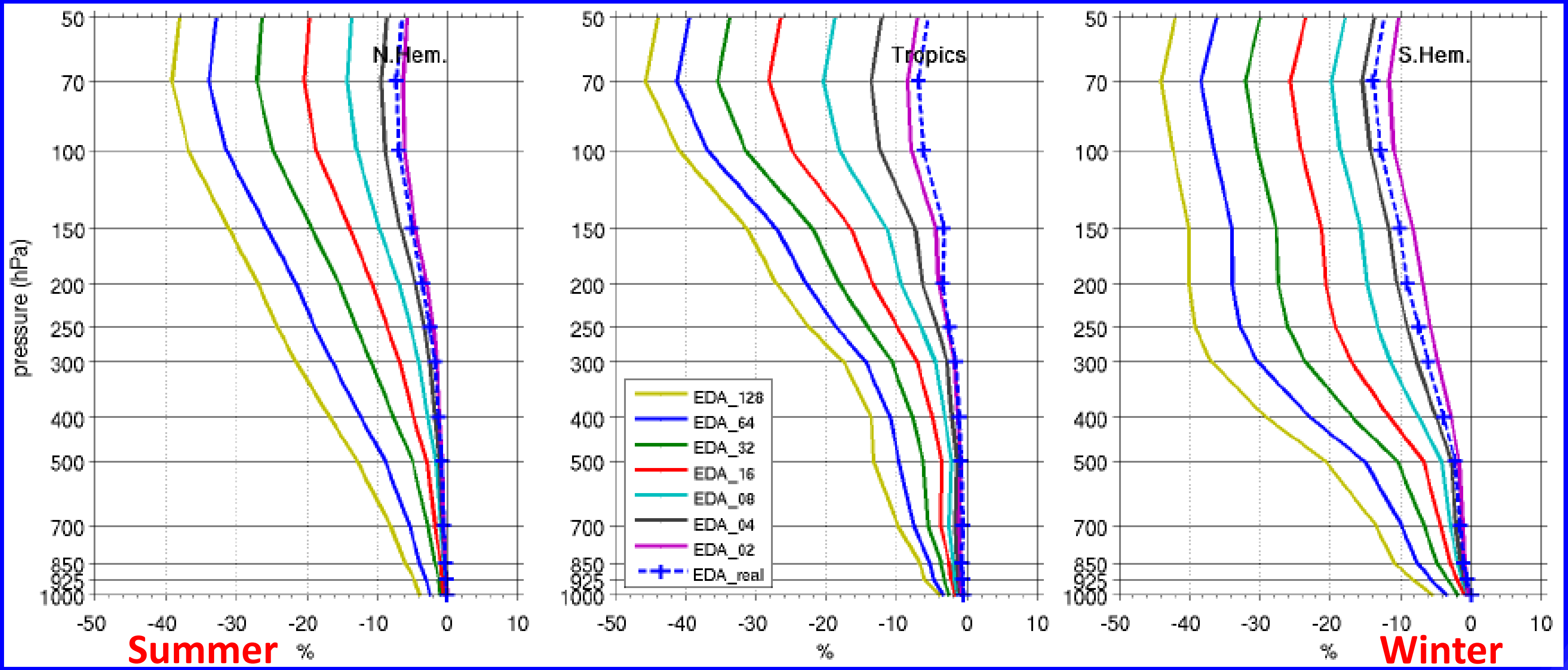
Temperature Impact Summary

	σ_{GrT}^2 (2K)	2K Info	σ_{GrT}^2 (32K)	32K Info	σ_{GrT}^2 (128K)	128K Info	σ_{GrT}^2 (256K)	256K Info
70 SH	1.71	37%	0.35	74%	0.15	87%	0.11	90%
500 NH Summer	49	2%	6.7	13%	2.3	30%	1.36	42%
500 Tropics	14.4	**6.5%**	3.5	**22%**	1.76	36%	1.29	44%
500 SH Winter	23.7	4%	3.8	21%	1.5	**40%**	0.95	**51%**

- Strongest variance scaling is in NH,
  - Exponent: -0.72

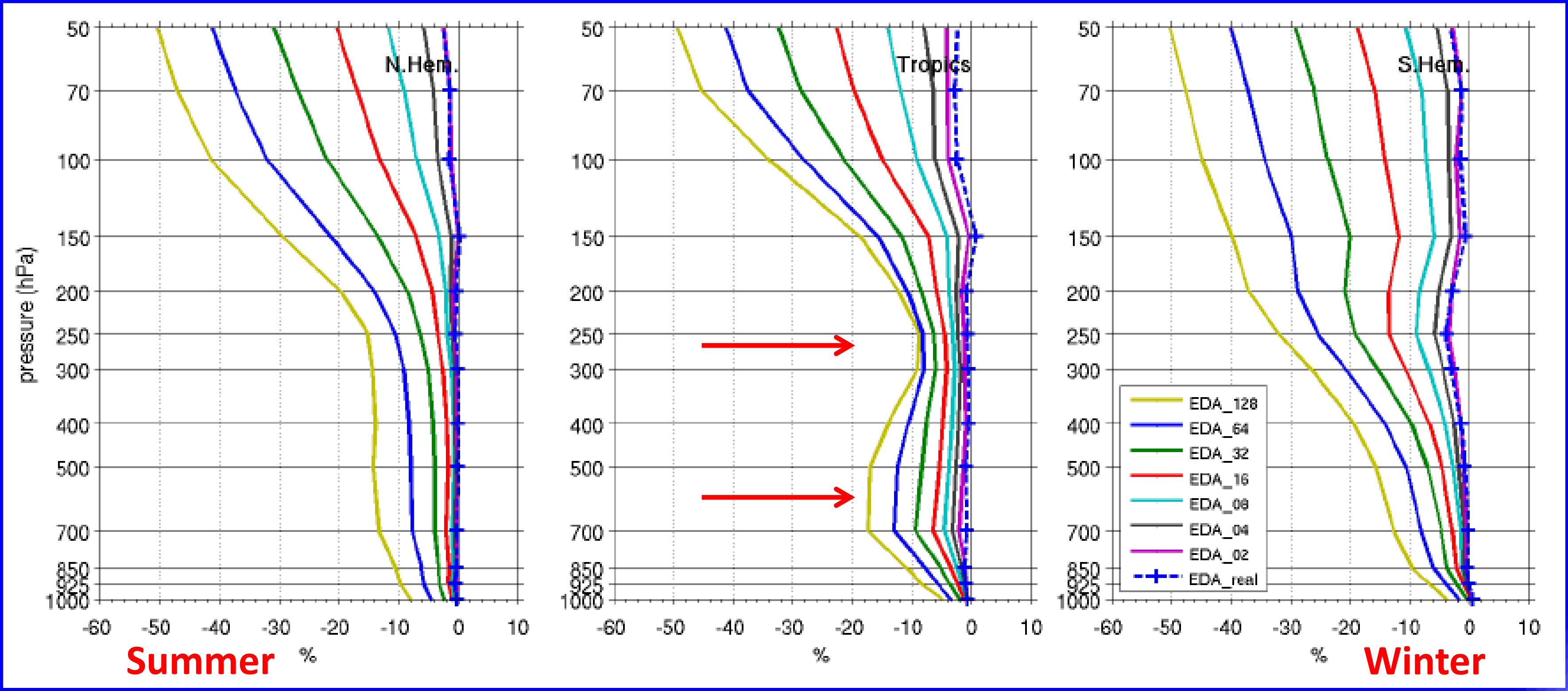
Geopotential

- Geopotential shows similar overall impact pattern
- Peak impact: **40%** error reduction (smaller than Temperature)



Impact on Wind Analyses

- Impact on winds shows similar overall pattern
- Peak impact in LS of **50%** error reduction for 128K occ lies between Temperature & Geopotential peak impacts



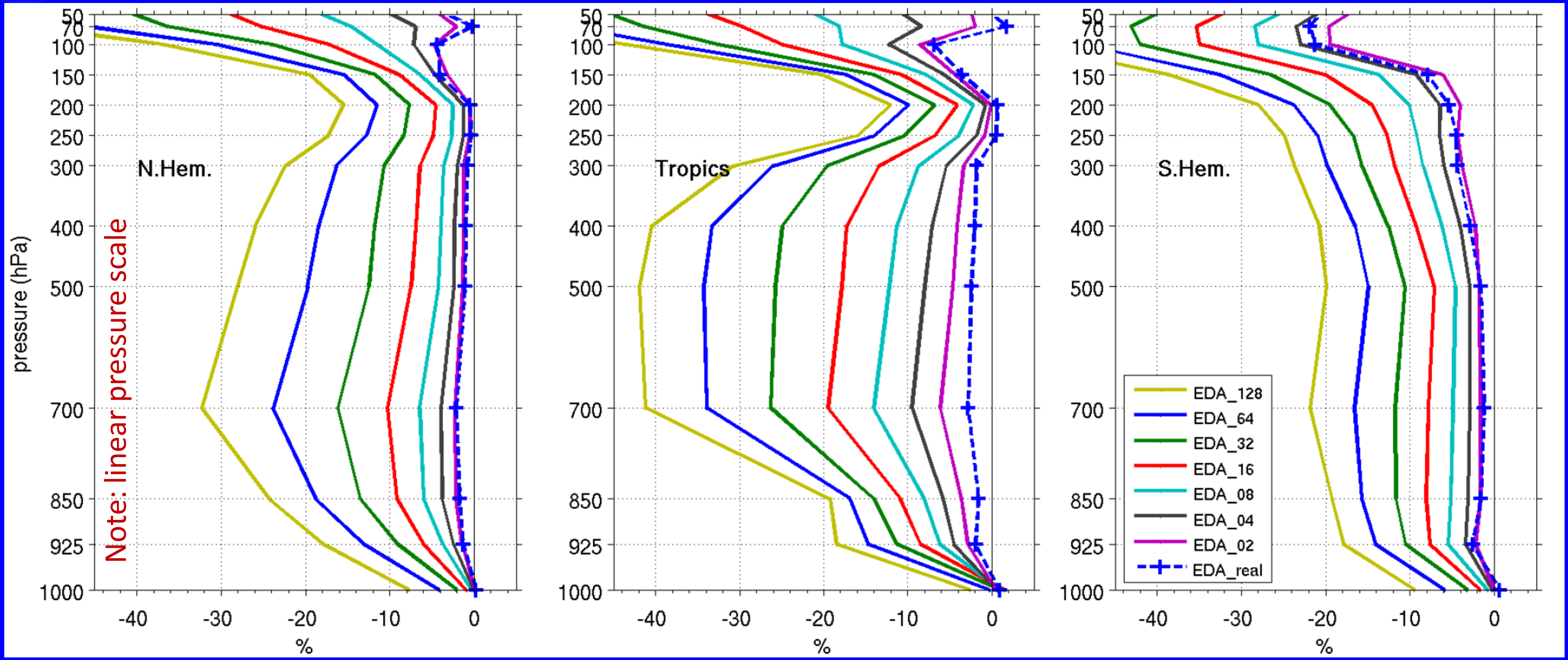
GPS RO Impact on NWP Moisture

GPS RO provides unique information on tropospheric water vapor

- Most useful in warm tropospheric regions
  - For measuring variability: up to ~240K level in troposphere
- High precision in lower into upper trop: σ_q ~ 0.2 g/kg
- |Bias| < 0.03 g/kg
- Unique high vertical resolution (~200 m) with global sampling
- All-weather, unbiased sampling

- Need to solve super-refraction problem to routinely probe low latitude boundary layer

EDA Spread Reduction (%) for Relative Humidity Analysis

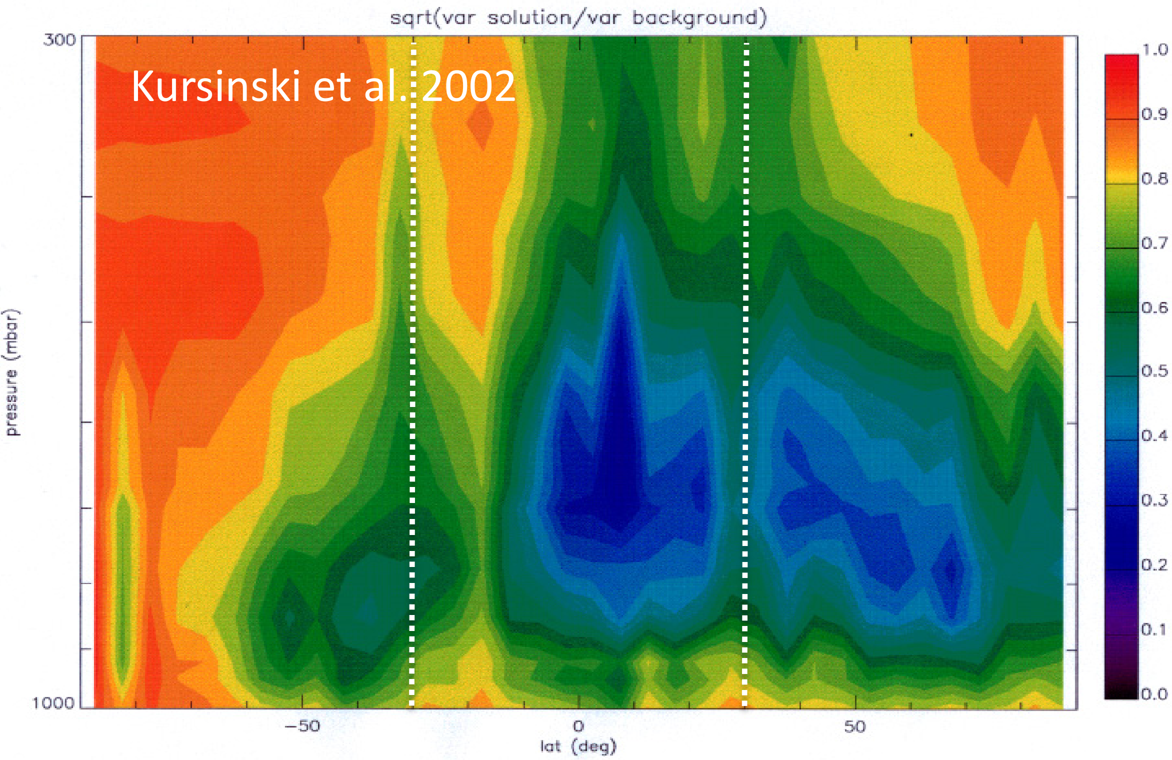


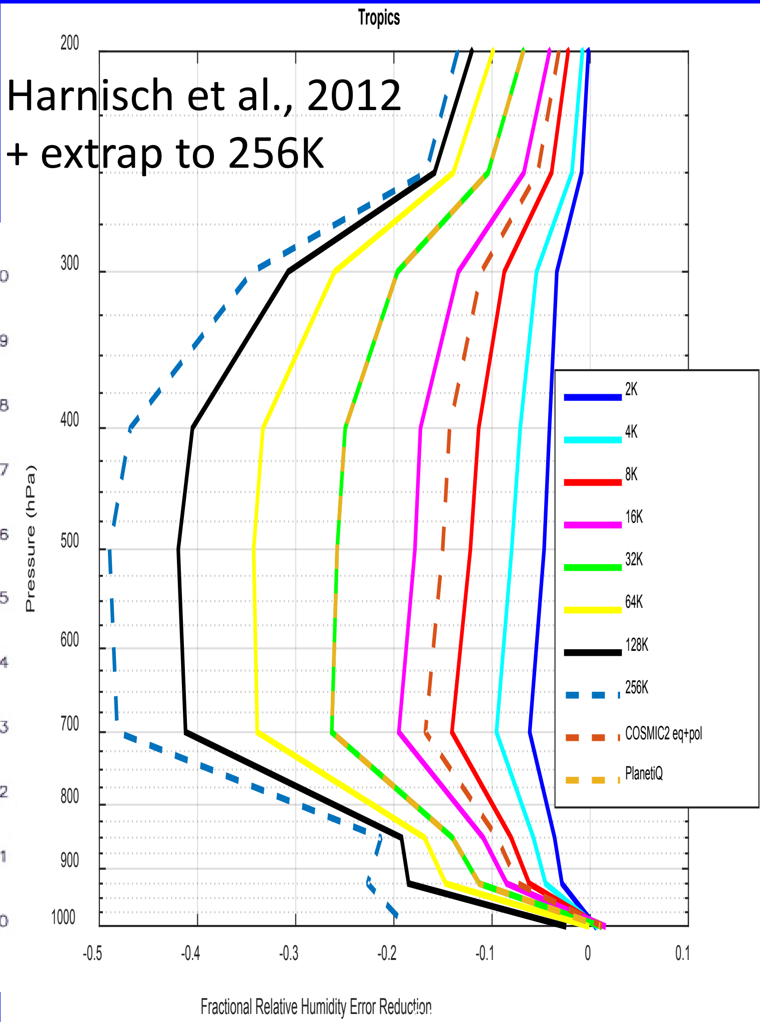
- Impact at high altitudes due to temperature, not moisture
- Absolute humidity impact at altitudes below ~300 hPa level
- Largest humidity impact on tropical troposphere (850 – 300 hPa)
- Relative minimum of impact at 100 – 300 hPa

Predicted Impact on Moisture Analyses

- Local 1DVar estimate based on GPS-MET
- Harnich et al. EDA estimate up to 128Kocc/day
- Background covariances differ

Left Panel Right Panel
(0.3 - 1 = -0.7)



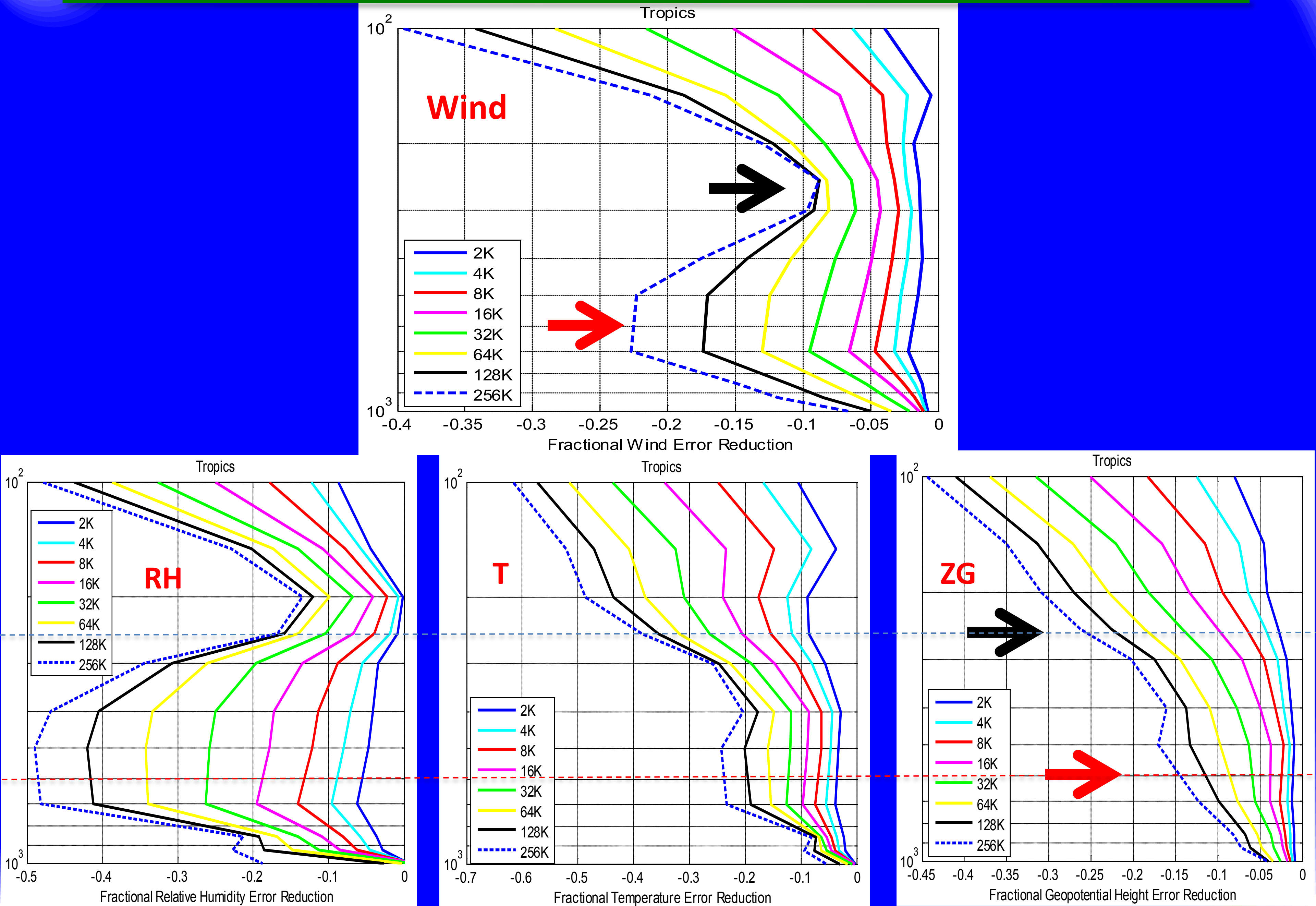


Maximum of Humidity Impact

- Max humidity impact: **Tropics 400 to 700 hPa**
- 128K daily occ: GNSS relative error variance ~ 0.5
  - ⇒ **~2/3** of analysis WV information from GNSS RO at these levels in the tropics.
- 256K daily occ: GNSS relative error variance ~ 0.37
  - ⇒ **3/4** of analysis WV information from GNSS RO
  - ⇒ Observational constraints are important for climate research

⇒ Lack of RO impact on humidity to date apparently because of too few occultations

Surprise: Impact on Tropical Troposphere Winds



Where is RO Impact on Tropical Mid-Troposphere Winds Coming From?

- Little impact of RO on tropical wind 200 & 300 hPa
  - Despite relatively small T & ZG errors there
  - Indicates wind information is not coming from T & ZG

- Moisture at 700-400 hPa tightly constrained by RO

  ⇒ Suggests constraint is via **advection of moisture** in the 4DVar system

  - Clear sky satellite water vapor channels are used to constrain mid-troposphere winds (Bormann et al., 2012)

500 hPa Wind Impact Summary

Pressure level & region	σ_{GrU}^2 2K	2K Info	σ_{GrU}^2 32K	32K Info	σ_{GrU}^2 128K	128K Info	σ_{GrU}^2 256K	256K Info
500 NH summer	241	0.4%	11.7	7.9%	2.8	**26%**	1.53	**40%**
500 Tropics	33	**2.9%**	5.2	**16%**	2.2	**31%**	1.58	**39%**
500 SH winter	45	2%	6.4	13.5%	2.5	**29%**	1.52	**40%**

- Strongest scaling in NH from 2K to 128K,
  - Exponent: **-1.07**
  - Due to tight correlations in background??
- *Could orbiting lidar could provide this level of NWP analysis impact (given its sparse coverage)?*

Power law scaling of error variances

- HHB figures suggest power law dependence for GNSS error variance scaling based on the :

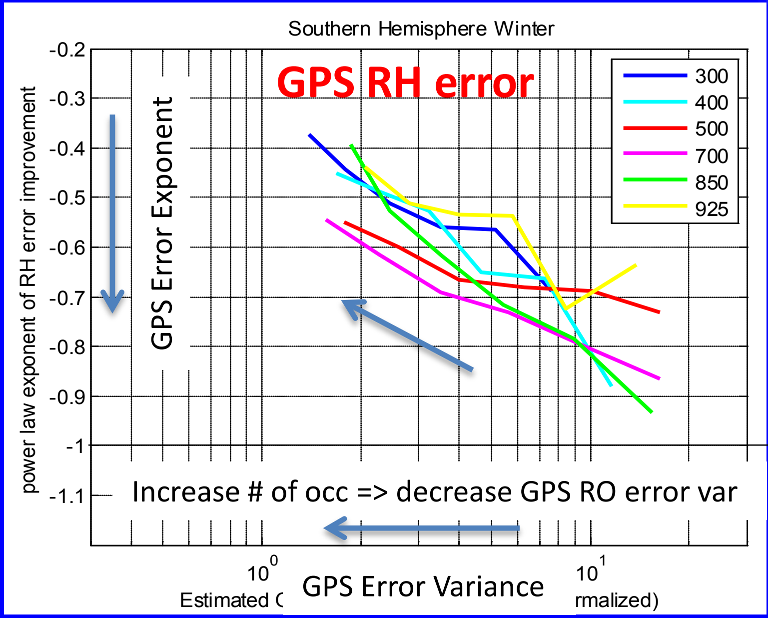
$$\sigma_{Gr}^2(N_i) = \sigma_{Gr}^2(N_j) * (N_i/N_j)^P$$

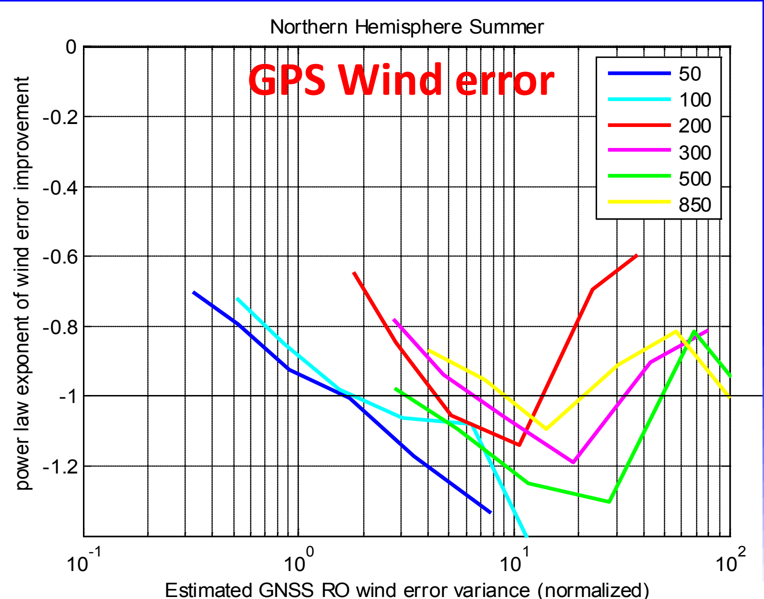
where N is the number of occultations per day and $P < 0$.

- Determine P from the HHB results
- The exponent, P, determines how quickly the error variance decreases as the number of occultations increases.
  - Large negative value means more impact per occultation
  - Simple argument about adding independent constraints to a 2D grid of variables: $P = -1$.

What do Error Variance Power Law Exponents tell us

- Exponent magnitudes are generally less than 1
- But exponent magnitudes for GPS wind errors can be > 1
- Gradual decrease in impact per occultation as the number of occultations increases (gradual saturation)
- Exponents tend to be larger in Northern Hemisphere





Exponent Behavior

- GNSS wind error variances tend to have largest exponent magnitude
  - ⇒ Change in impact for Doubling # occ is larger
  - ⇒ Guess: adding single new geopotential height profile yields pressure gradients with multiple nearby points
    - ⇒ constrains winds in multiple directions from that single point
- GNSS error variances in the Northern Hemisphere tend to have lower impact for small # of occultations but largest error variance exponent magnitudes, winds in particular
  - ⇒ Increase in impact for Doubling # occ is larger in NH
  - – Tighter background error & correlations in NH due to in-situ obs?

Wind Impact Summary

Pressure level & region	σ_{GrU}^2 2K	2K Info	σ_{GrU}^2 32K	32K Info	σ_{GrU}^2 128K	128K Info	σ_{GrU}^2 256K	256K Info
500 NH summer	241	**0.4%**	11.7	7.9%	2.8	**26%**	1.53	**40%**
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- Strongest scaling in NH from 2K to 128K,
  - Exponent: **-1.07**
  - Due to tight correlations in background??
- Suggests ability to infer impacts of large amount of occ from present impact may be limited

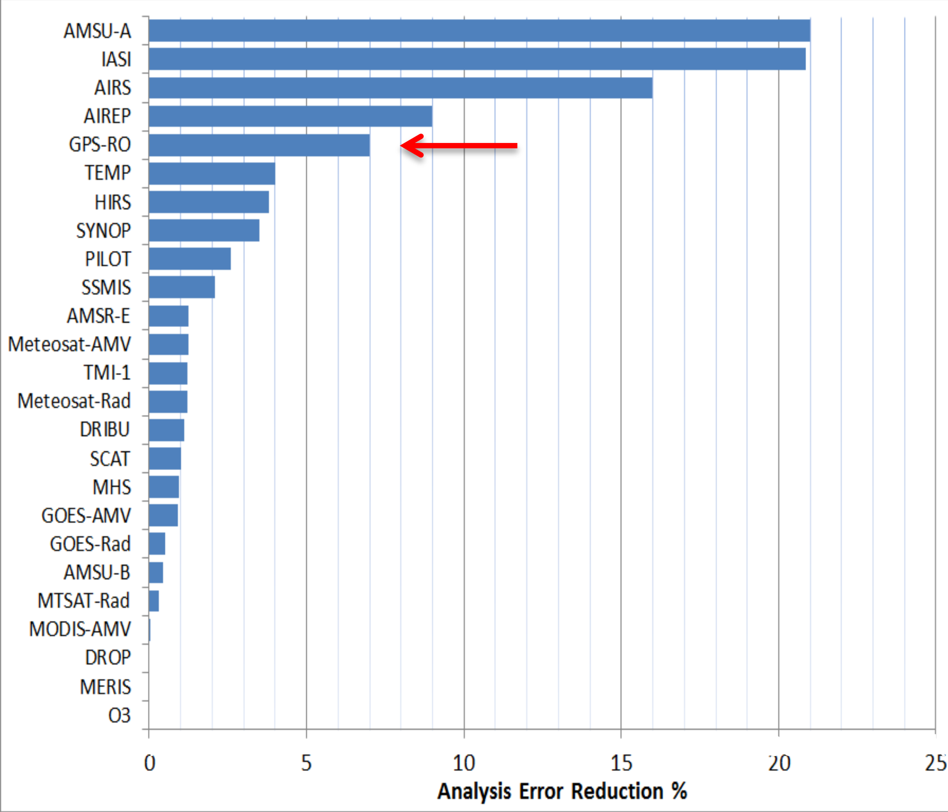
Scaling GNSS RO Impact in Terms of DFS

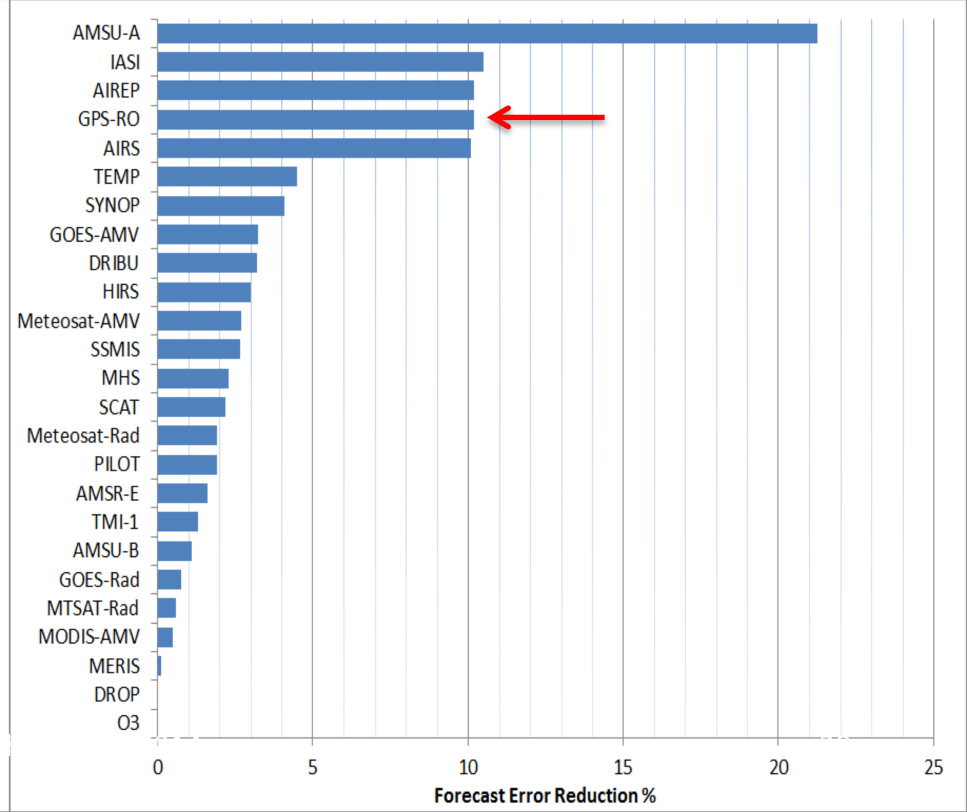
- HHB results are in terms of analysis error reduction
- DFS% is used to compare impact of different observing systems
- Conversion from HHB results to extrapolate present GPS RO DFS results to higher densities

$$Err_{HHB} \Rightarrow Var_{GPS} \Rightarrow Weight_{GPS} \sim DoF$$

Observational Impacts at ECMWF 2010

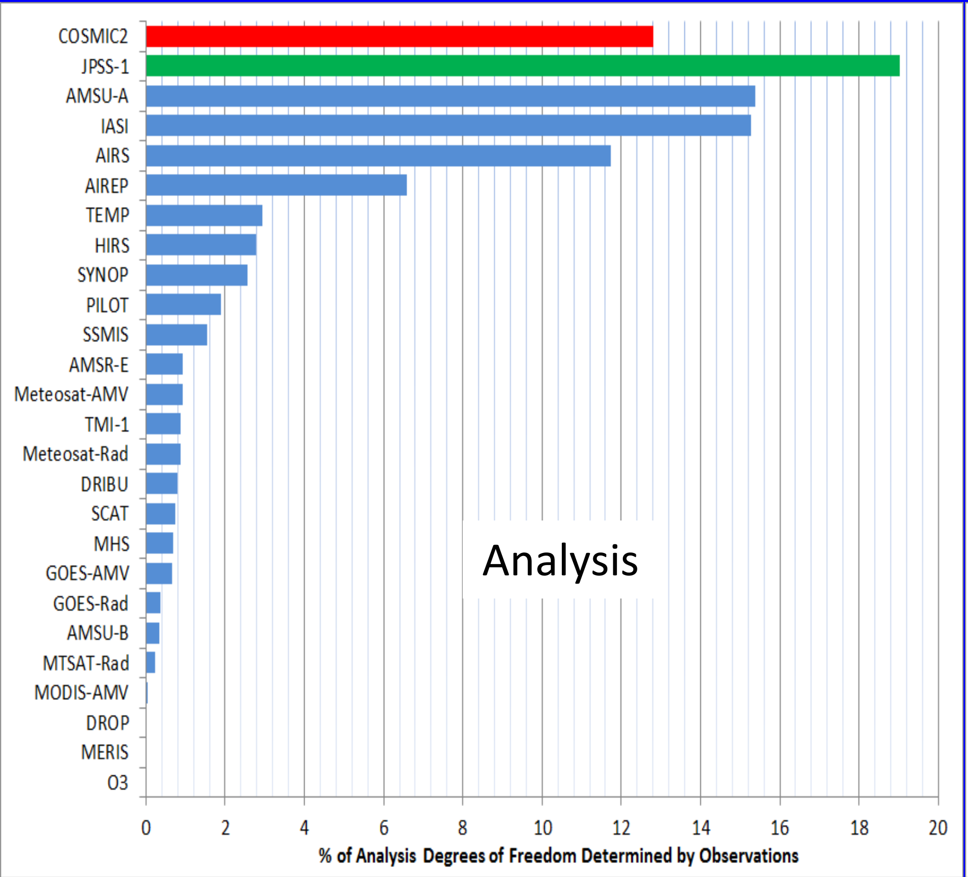
Cardinali & Healy (2013)	DFS (DF total)	FER
• ~2500 GPS occ/day	7% (1.4%),	10%
• 6 AMSU-A	21% (4.2%),	21%
• IASI/AIRS	16-21% (3.2-4.2%)	10%

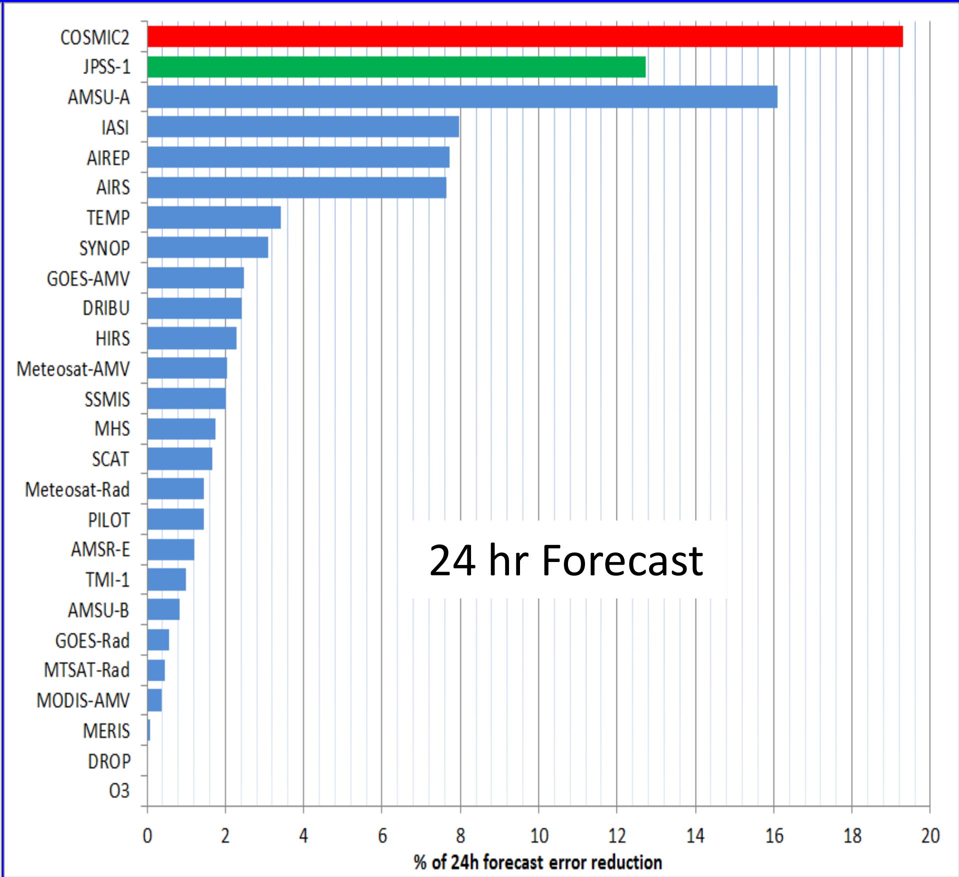




GPS RO Impact Extrapolated to COSMIC2

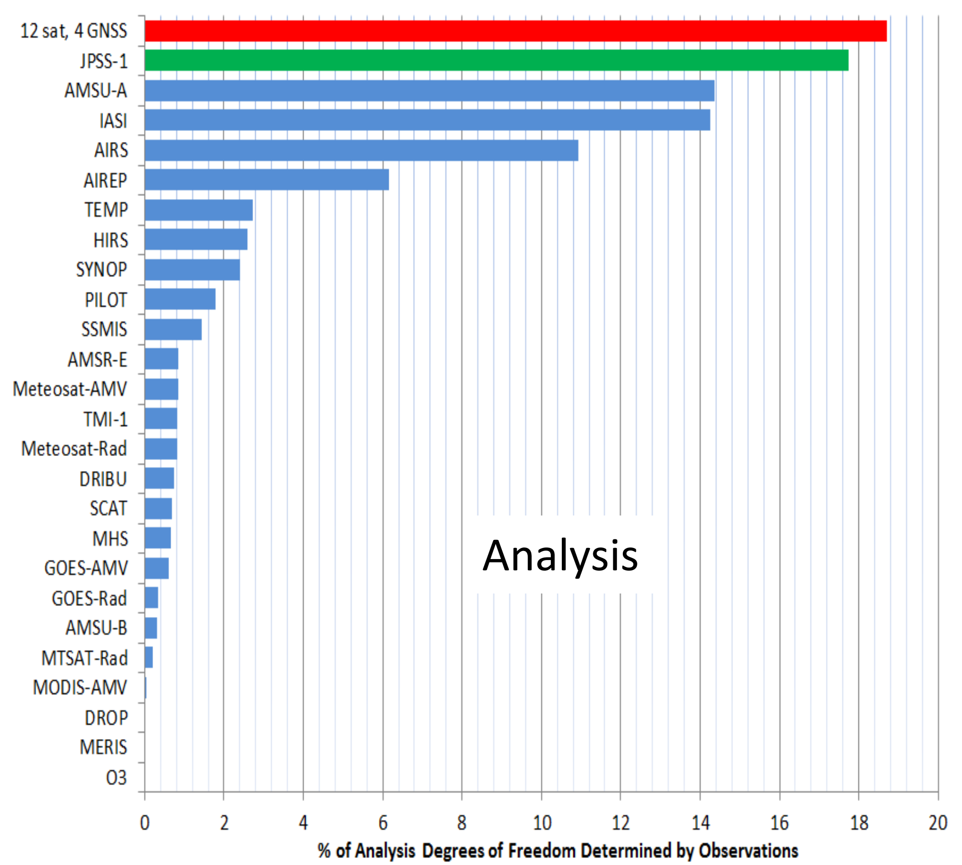
- Cardinali & Healy 2013 DFS & FER results in **blue** (re-normalized)
- JPSS (**green**) = linear sum of IASI, AMSU-A, MHS & Meteosat AMV (1 each)
- Extrapolation to 12 COSMIC2 satellites (in **red**) based on Harnisch et al. (2012, 2013) results at ECMWF, Power law exponent of variance scaling: **0.58**

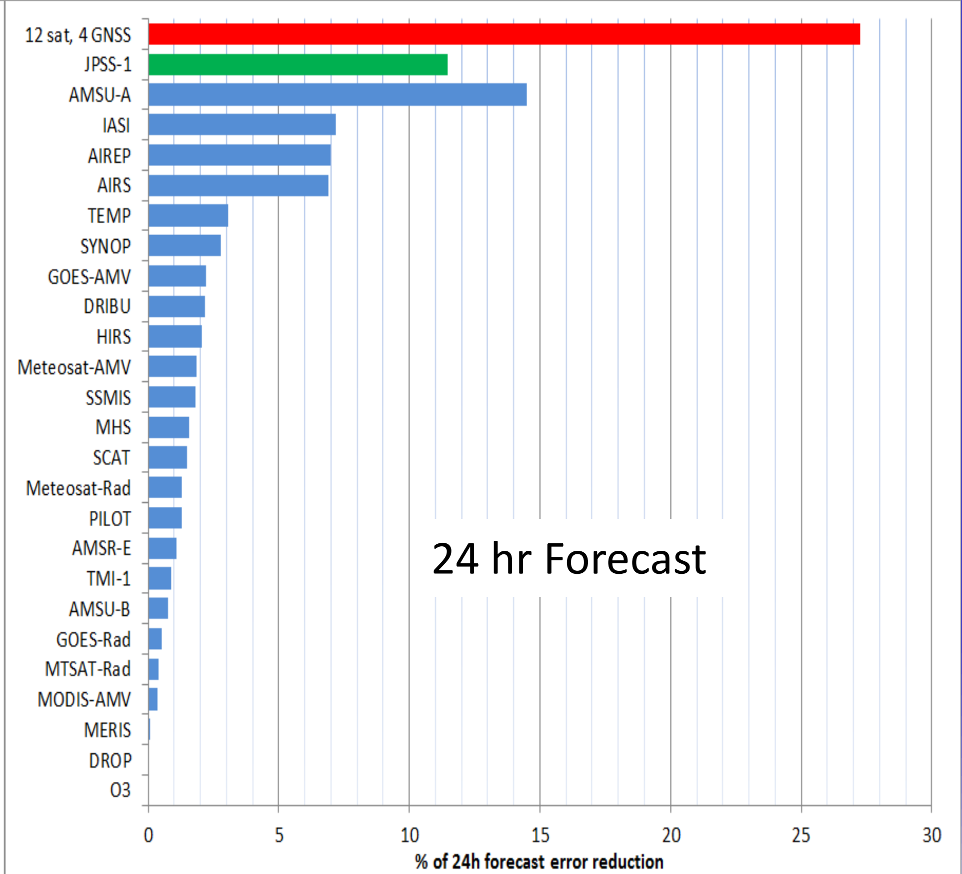




GPS RO Impact Extrapolated to 12 satellites 4 GNSS

- Cardinali & Healy 2013 DFS & FER results in **blue** (re-normalized)
- JPSS (**green**) = linear sum of IASI, AMSU-A, MHS & Meteosat AMV (1 each)
- Extrapolation to PiQ 12 satellites (in **red**) based on Harnisch et al. (2012, 2013) results at ECMWF, Power law exponent of variance scaling : **0.53**

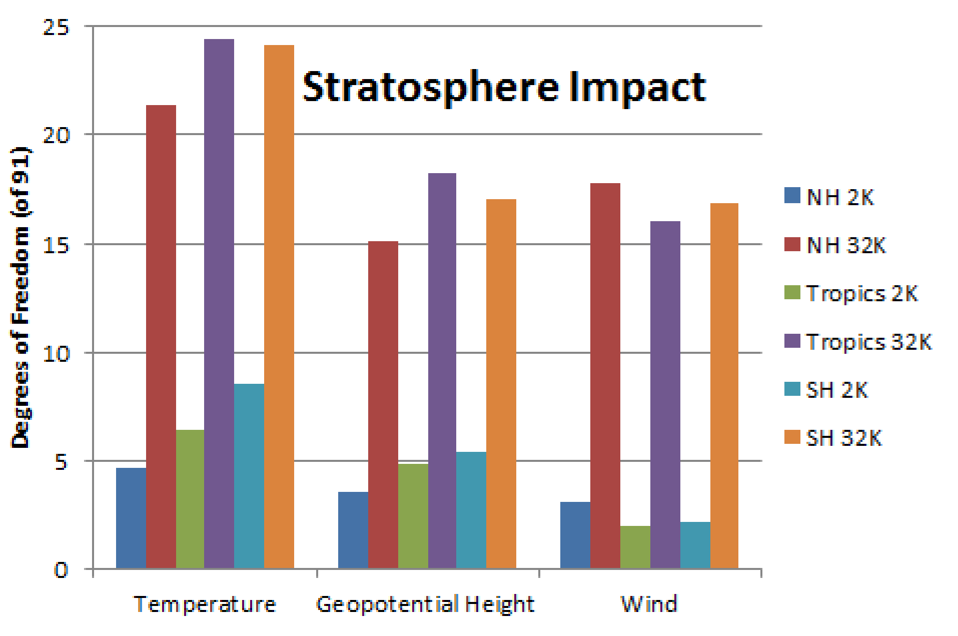


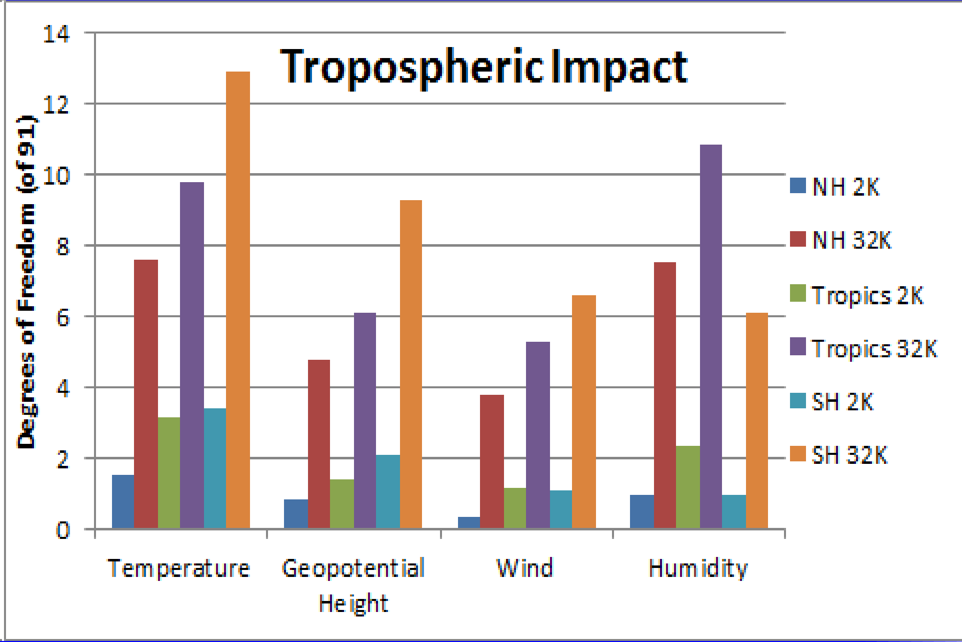


Impact in Troposphere v. Stratosphere

Based on Weighting estimated from HHB results…

- Roughly 2/3 of analysis **DFS** impact is in stratosphere and 1/3 is in troposphere





FER Bang for the Buck

	kOcc/ day	Cost ($B)	24 hr FER (2010)	FER/cost (%/$B)
JPSS-1 (CrIS, ATMS, VIIRS,OMPS)		**5**	1 (=16.8%)	3.4
6 sat, 1 GNSS	2.5	0.15?	0.6	**68**
6 sat, 2 GNSS	6	0.25?	**1.1**	**70**
12 sat, 2 GNSS	12	0.46 US:0.23?	**1.5**	**55 (110)**
12 sat, 4 GNSS	32	<0.25	**2.4**	**>160**
96 sat, 4 GNSS	272	<0.8	**6.3**	**>130**

- Some apples vs. oranges here
- GNSS RO impact can be much larger than JPSS
- And a bargain in comparison

What could you do if you were to design an RO system from scratch?

Answer:

- Build an RO system that probes the 22 & 183 GHz water vapor absorption lines

$\Rightarrow$Active Temperature Ozone and Moisture Microwave Spectrometer (ATOMMS)

$\Rightarrow$ ***Open air spectrometer***

$\Rightarrow$ Approaching sonde profiling from orbit (but more accurate)

22 & 183 GHz RO Active Spectrometer

- Profiles speed of light (like GPS RO) & attenuation of light (unlike GPS RO)

⇒Profiles H_2O vapor, temperature & pressure versus height **simultaneously**, unlike GPS RO

in clear & cloudy air,   over land & water

⇒ Also cloud LWC, O_3, NO_2, water isotopes, LoS winds above 10 mb & turbulence

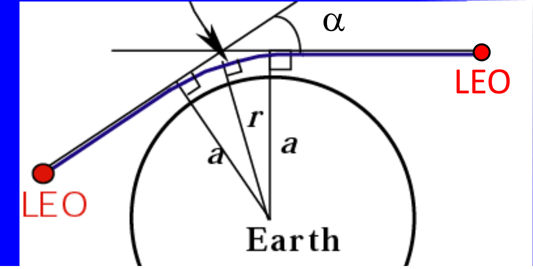
RO: Self calibrating, **no drift**

Resolution: ~100 m vertical, ~50 km horiz.

H_2O vapor: < 3% precision, < 1% accuracy

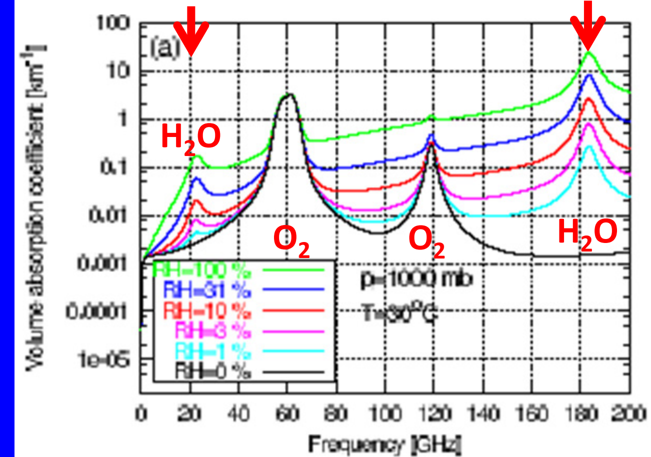
Temperature: 0.4K precision, < 0.05 K accuracy

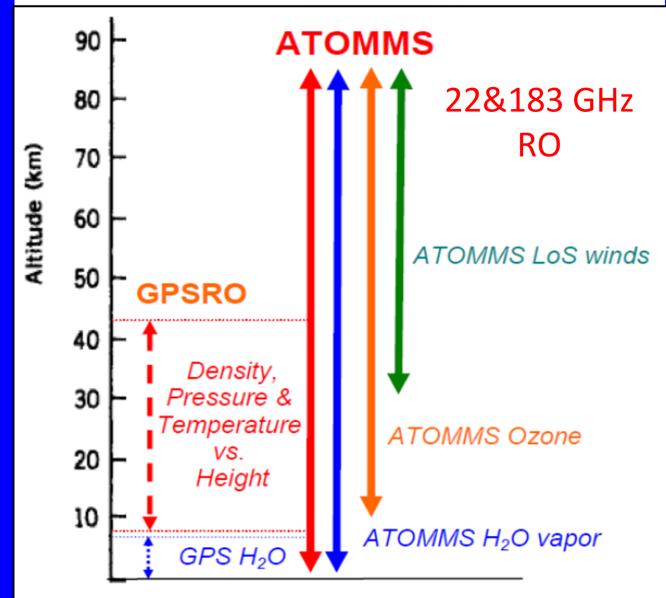
- Will provide unique constraints on **turbulent surface fluxes** from orbit



RO geometry: Transmit & Receive

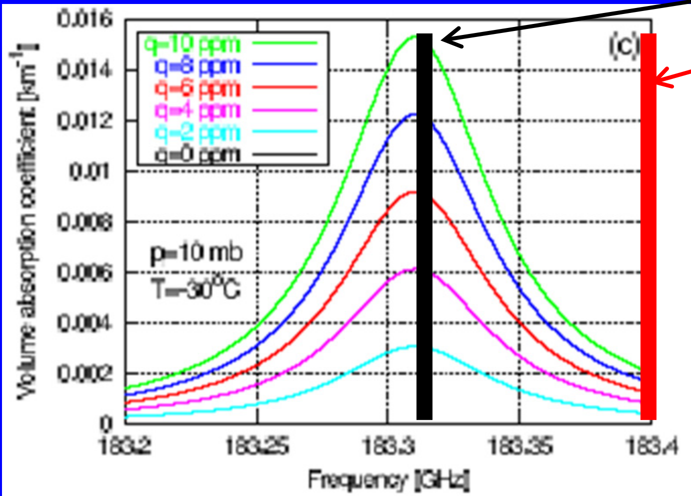
22 GHz & 183 GHz





Differential Absorption to Profile in Clouds

Differential Absorption: 2 tones



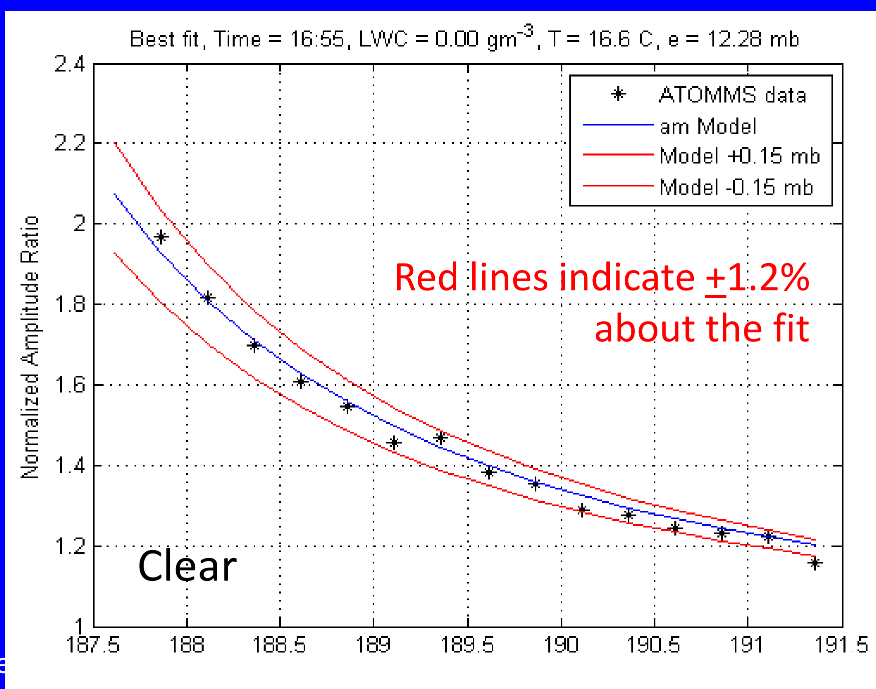
- 1st tone on absorption line
- 2nd calibration tone off the line

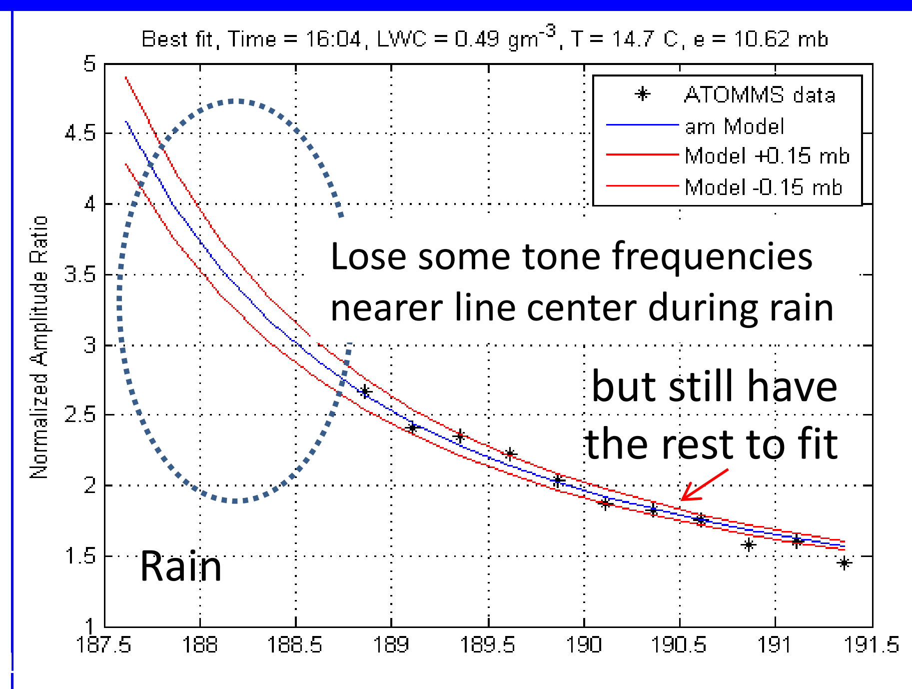
2 tone amplitude ratio eliminates common mode noise

⇒ Enables profiling in clouds & rain

⇒ Enables profiling of cloud LWC

Mountaintop demonstration results





ATOMMS Mountaintop Geometry

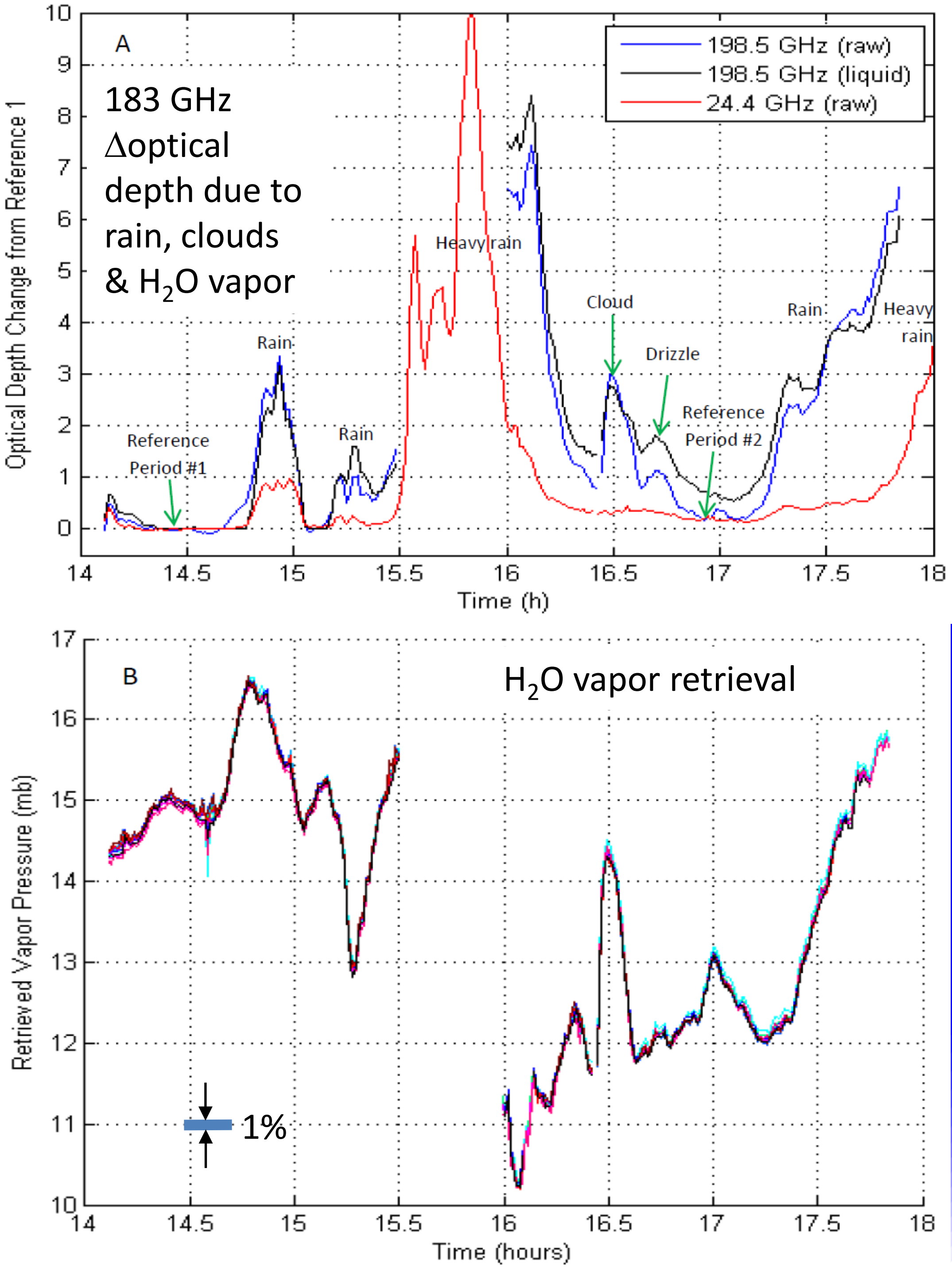
ATOMMS Latest Results

Mtn-top retrievals

- In cloud & rain
- Retrievals up to optical depth = 17

Water vapor retrievals

- Extremely little ambiguity
- Stdev < 1%
- Ward et al. (2015) submitted to GRL



IR - GPS RO - ATOMMS Comparison

Hyperspectral IR

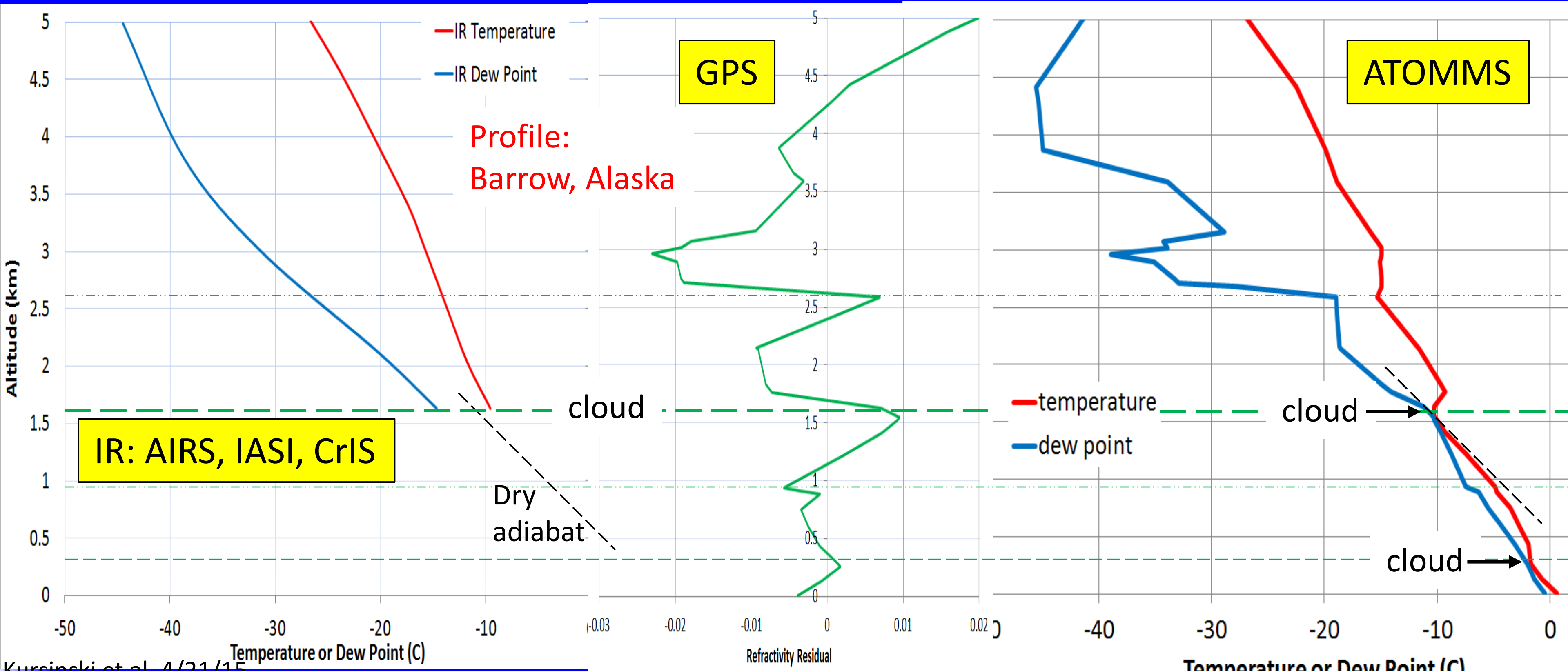
- Smooth temperature & water vapor profiles, limited to above the top cloud

GPS

- Vertical resolution much higher than IR
- Ambiguity => can't directly separate wet & dry contributions. Also can't identify clouds.

ATOMMS

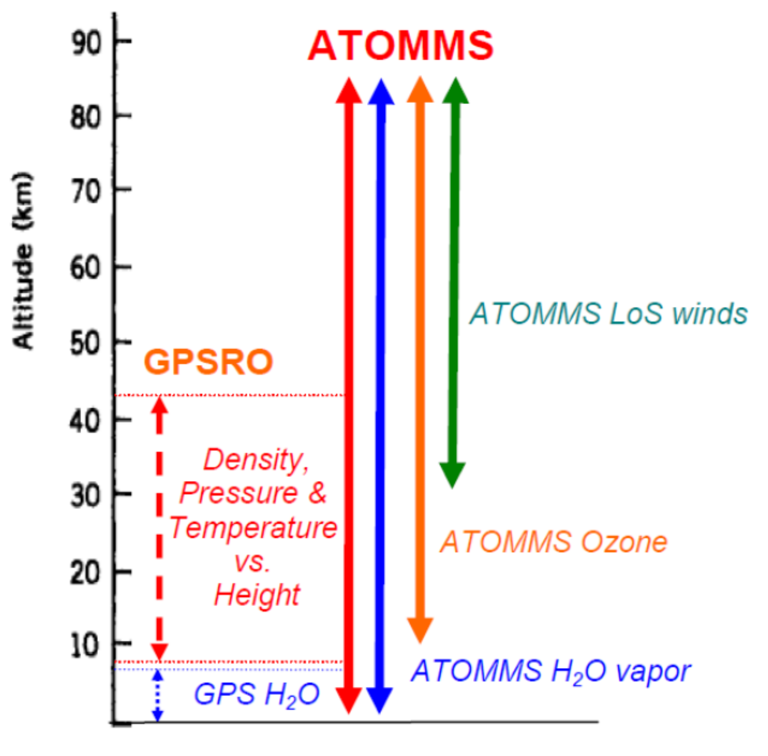
- Profiles water vapor & temperature in clear & cloudy air with 100 m vertical resolution
- Sees the clouds, at both levels. Also sees thru the clouds
- Measures ***stability*** which is critical to dynamics. (It sees the dry adiabat)



Kursinski et al. 4/21/15

Extrapolate to ATOMMS for NWP

- RO system probing near the 22 & 183 GHz H_2O lines and 195 GHz O_3 line
- Simultaneously profiles temperature, geopotential and H_2O vapor as well as O_3, cloud liquid water, cloud ice, rain, line of sight winds, turbulence
- Requires its own set of transmitters & receivers
- Designed for climate
- Big impact on NWP with sufficiently large number of occultations
  - ~40K occ/day w/ 50 sat.



Overview of Key Results

- Strong impact on temperature, geopotential height and winds in UTLS as number of occultation increases
  - GNSS RO has strongest impact on Temperature
- Strong Tropical mid-troposphere water vapor impact
  - Similar to prediction of Kursinski, Healy & Romans (2000)
- Surprising impact on Tropical mid-tropospheric winds
- ~1/3 of DFS impact in Troposphere
- No "saturation" but gradual decrease in impact per occultation as # of occultations increases.
  - Particularly large power law exponents in Northern Hemisphere and for wind impact

Overview of Key Results

- GNSS RO large impact/$ in general
- Very large total impact as # of occ increases

Suggestion:

- When discussing the impact of GPS RO on the forecasts, state that this is the impact for the current sampling densities
- Otherwise, the impression is this is the level of GPS RO now (correct) and in the future (which is incorrect)

- ATOMMS has tremendous potential if we can get it into orbit