Assessing the benefits of assimilating GPS RO profiles into Global Numerical Weather Prediction Models

L. Cucurull, J. C. Derber, and W. Lapenta
NOAA/NWS/NCEP/EMC

WMO workshop, Sedona, Arizona, 22-25 May 2012

Born on April 30 at 8 pm!!

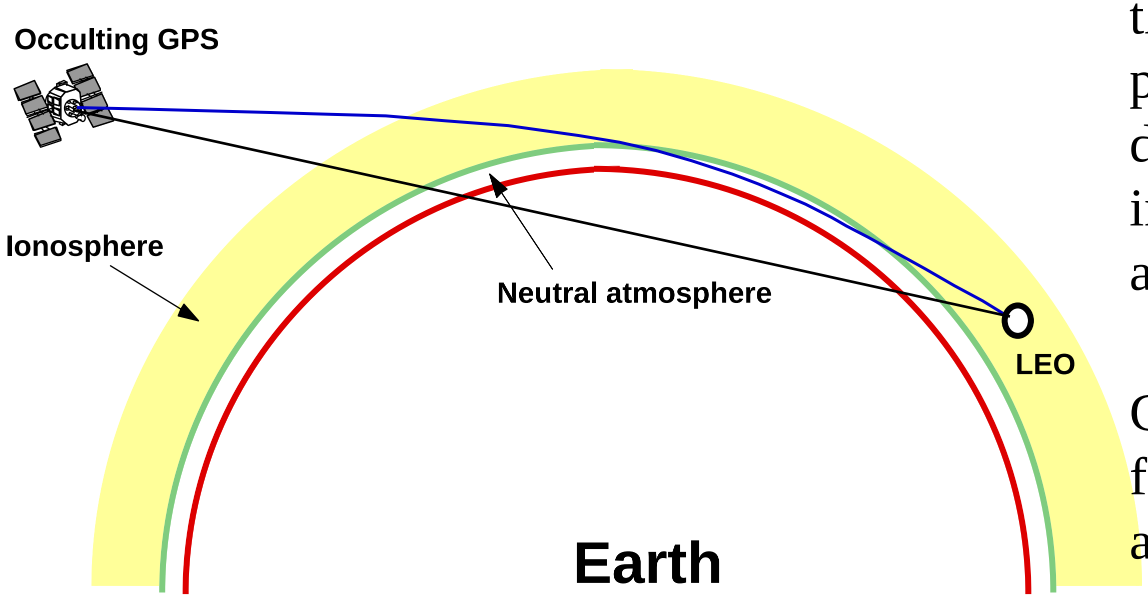
Laia Cucurull Ector is here!

Outline

- Introduction to GPS RO
- Use of GPS RO observations at NCEP
- Assimilation approaches and impact on dynamic forecast skill
  - Refractivity
  - Bending angle – NBAM (NCEP's Bending Angle Model) forward operator, implemented operationally at NCEP today!!!
- Impact at NASA/GMAO with the adjoint technique
- GPS RO and satellite radiance bias correction
- Summary

Radio Occultation concept

- An occultation occurs when a GPS (GNSS) satellite rises or sets across the limb wrt to a LEO satellite
- A ray passing through the atmosphere is refracted due to the vertical gradient of refractivity (density)
- During an occultation (~ 3min) the ray path slices through the atmosphere



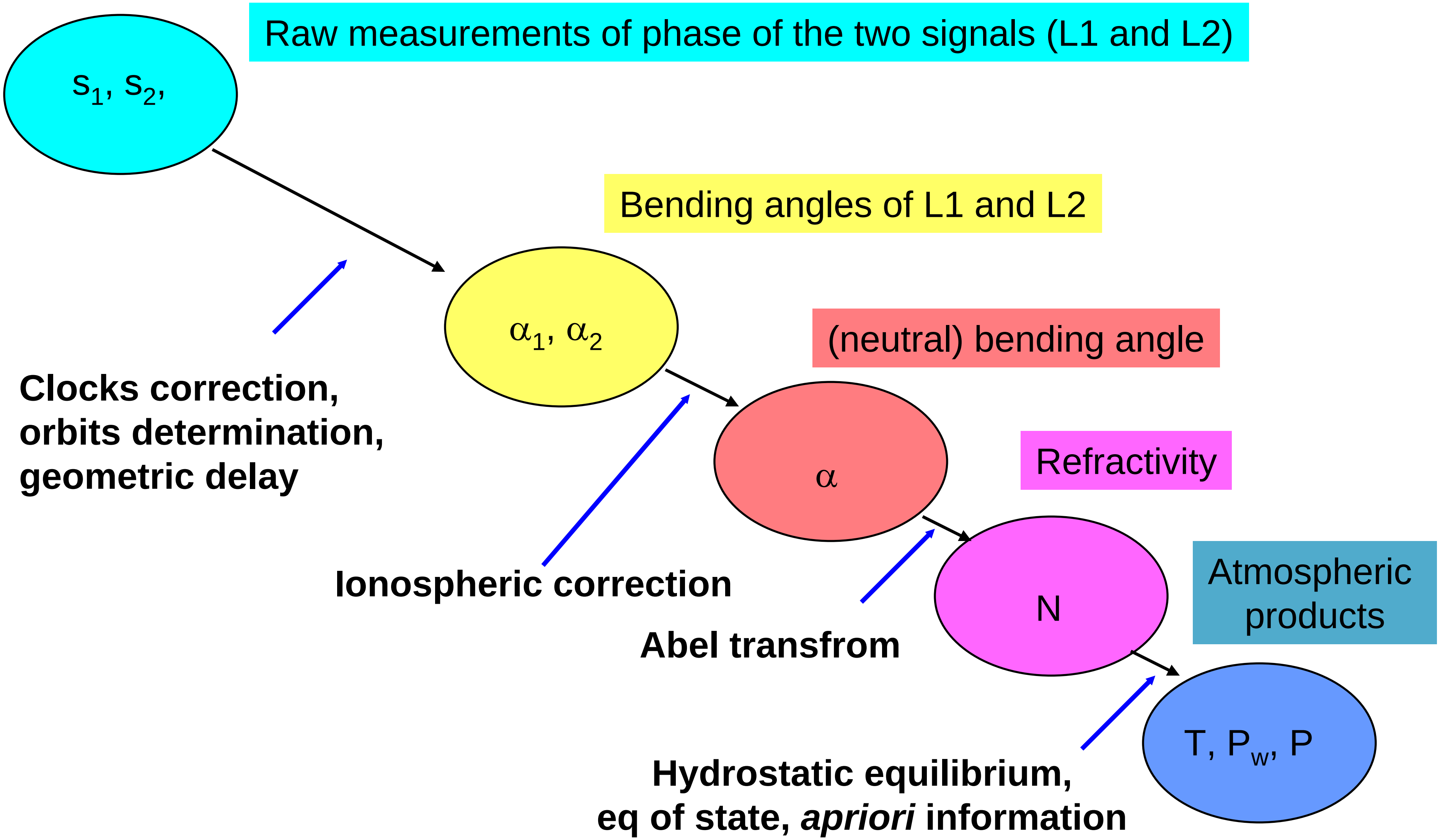
<u>Raw measurement</u>: change of the delay (phase) of the signal path between the GPS and LEO during the occultation. (It includes the effect of the atmosphere)

GPS transmits at two different frequencies: ~1.6 GHz (L1) and ~1.3 GHz (L2).

Radio Occultation features

- Limb sounding geometry complementary to ground and space nadir viewing instruments
  - High vertical resolution (~100 m)
  - Lower ‘along-track’ resolution (~200 km)
- All weather-minimally affected by aerosols, clouds or precipitation
- High accuracy (equivalent to ~ 0.1 Kelvin from ~12-25 km)
- Equivalent accuracy over ocean than over land
- No instrument drift, no need for calibration
- Global coverage distribution
- No satellite-to-satellite measurement bias
- No need for bias correction in NWP

choice of ‘observations’



Raw measurements of phase of the two signals (L1 and L2)

$s_1, s_2,$

Clocks correction, orbits determination, geometric delay

Bending angles of L1 and L2

α_1, α_2

Ionospheric correction

(neutral) bending angle

α

Abel transfrom

Refractivity

N

Atmospheric products

T, P_w, P

Hydrostatic equilibrium,
eq of state, *apriori* information

Choice of observation operators

Complexity

L1, L2 phase

L1, L2 bending angle

Not practical

Neutral atmosphere bending angle (ray-tracing)

Possible choices

Linearized nonlocal observation operator (distribution around TP)

Local refractivity, Local bending angle (single value at TP)

Retrieved T, q, and P

Not good enough

Use of GPS RO in NWP

- GPS RO observations from several missions are being assimilated at most operational NWP centers
- Profiles of refractivity or bending angle are used
- **All NWP centers have found significant positive impact with the use of GPS RO in their data assimilation system –** regardless of the type of observation being chosen
- Quite impressive - the number of GPS RO observations is much lower than radiances (the cost is also much lower)
- NWP centers assimilate GPS RO observations without bias correction – they can be used to ‘anchor’ the model, avoiding a drift to its own climatology

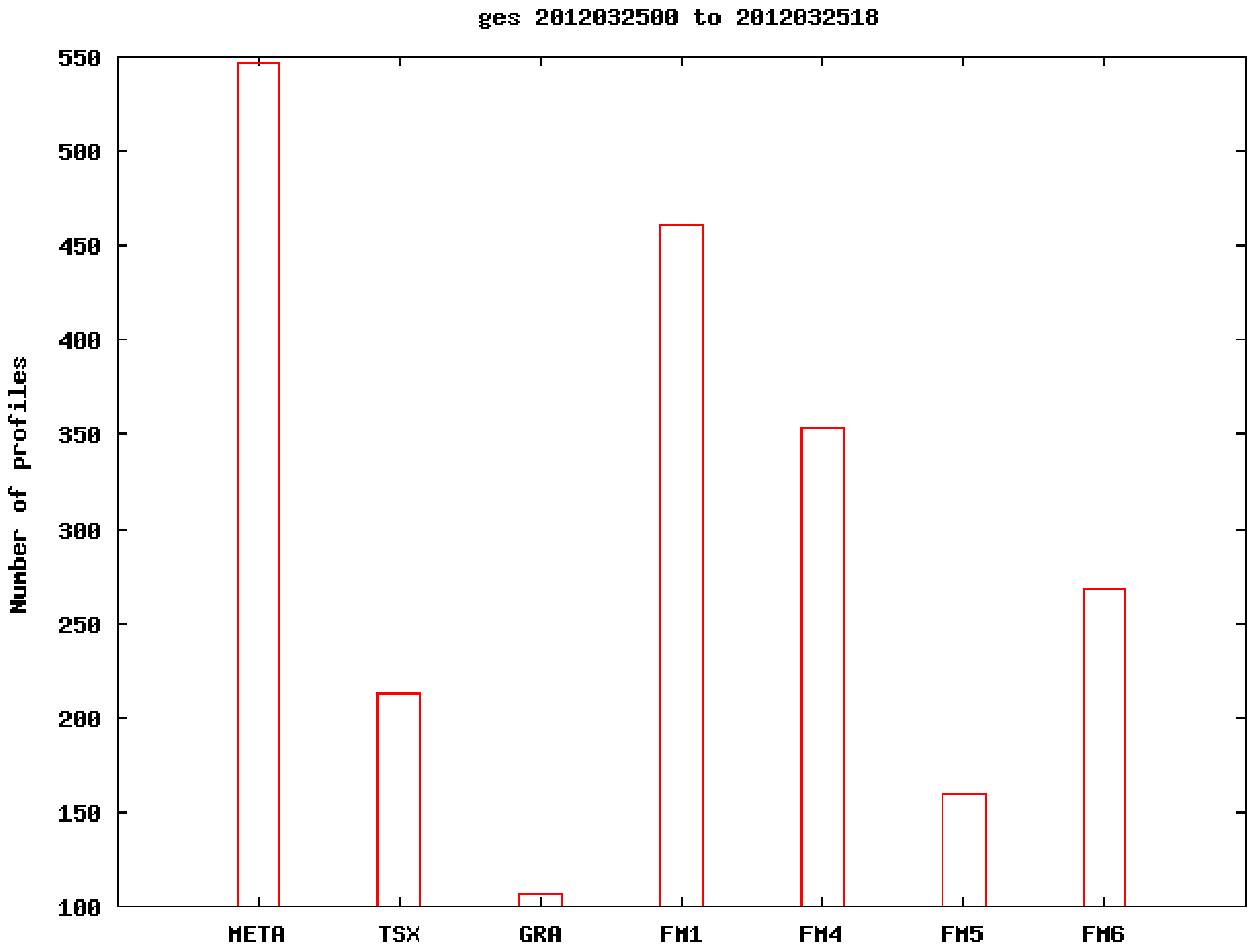
GPS RO sensors

- NCEP Global Data Assimilation System (GDAS) assimilates operationally the following RO instruments for total daily soundings of ~ 2,000:
  - **COSMIC 1-6** (since May 2007)
  - **Metop/GRAS** (since February 2010)
  - **GRACE-A** (since February 2010)
  - **SAC-C** (since May 2011)
  - **C/NOFS** (since May 2011)
  - **TerraSAR-X** (since May 2011)

- Near-operational monitoring of the systems above can be found in:

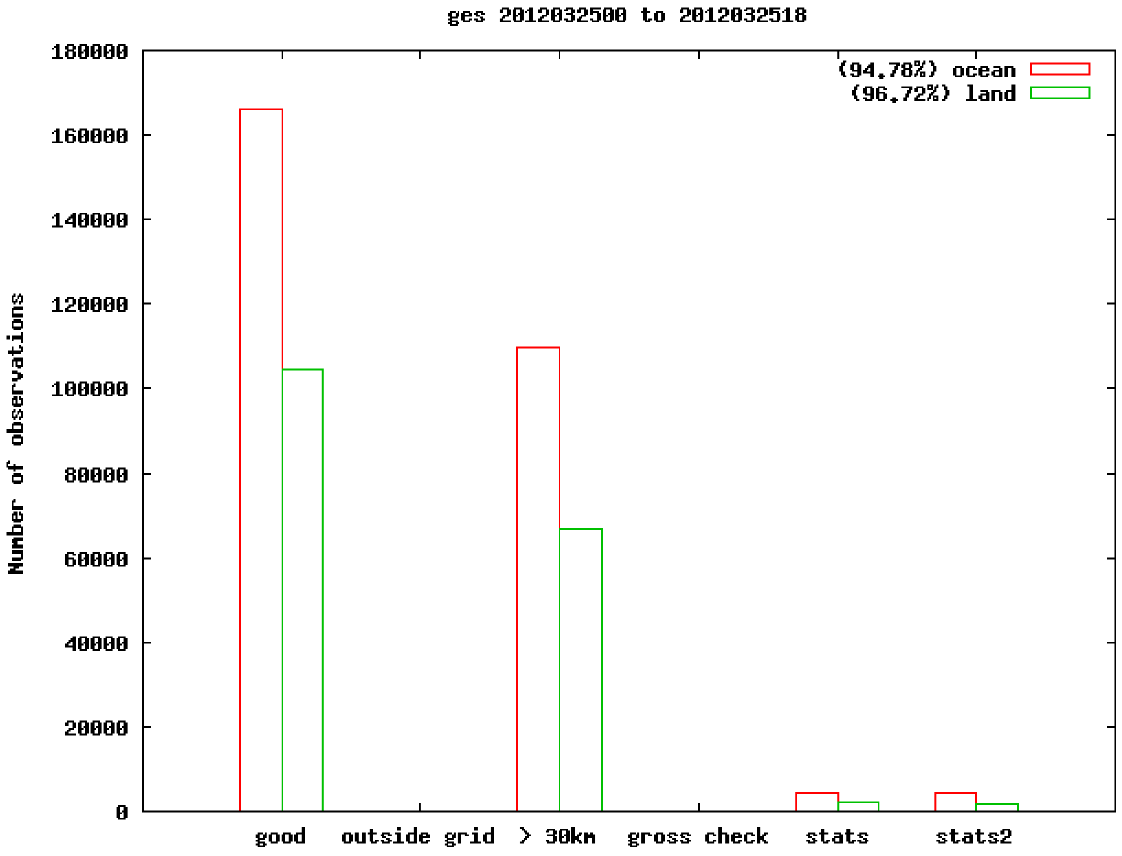
http://www.emc.ncep.noaa.gov/gmb/gdas/ under “GPSRO Monitoring”

Number of profiles 25 March 2012



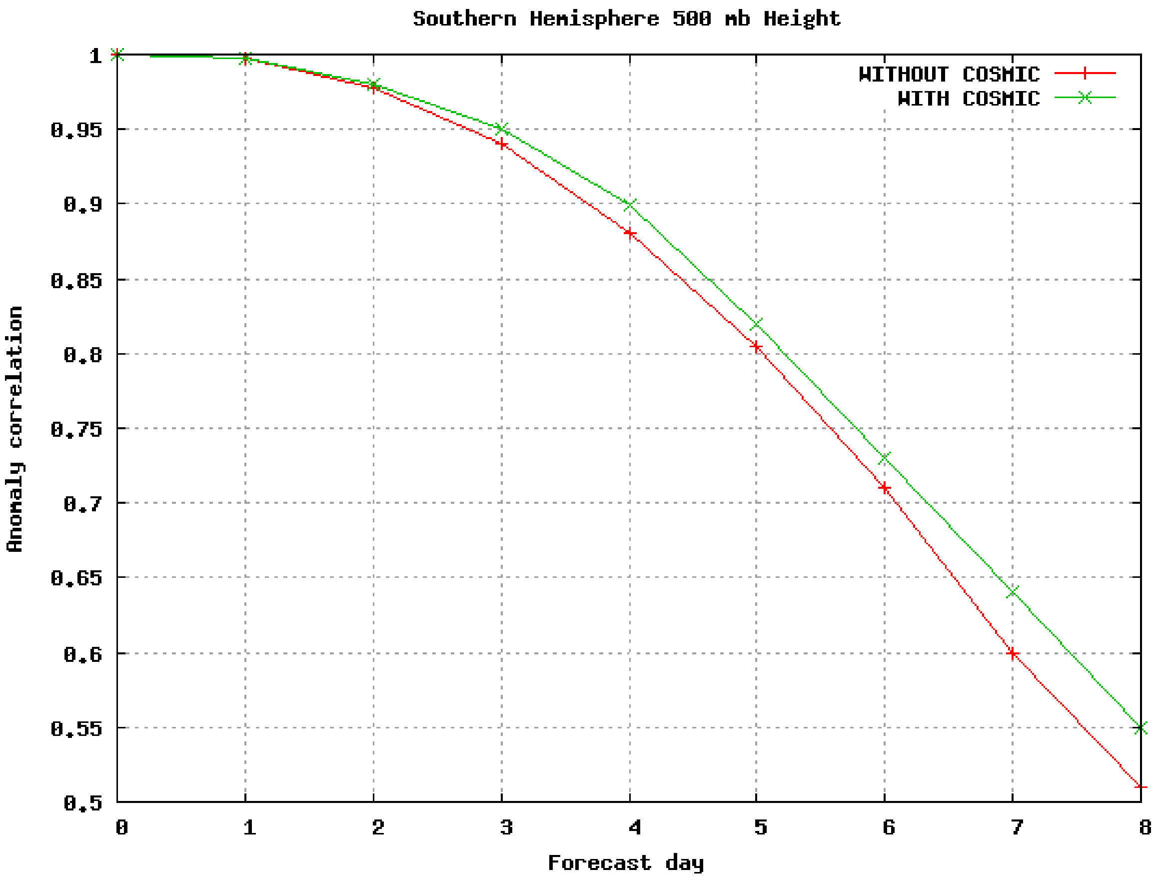
Quality control

- We assimilate 95-96 % of the observations that we “can” assimilate. These numbers do not consider observations:
  - outside the model vertical grid
  - above 30 km (maximum height being assimilated)



GPS RO impact at NCEP

- AC scores (the higher the better) as a function of the forecast day for the 500 mb gph in Southern Hemisphere



Cucurull 2010 (WAF)

COSMIC provides 8 hours of gain in model forecast skill starting at day 4 and 15 hours at day 7 !!!

Assimilation algorithms

- Operational GDAS assimilates **refractivity** observations up to 30 km (*Cucurull 2010*, *WAF*, **25**,2,769-787).

$$N = 77.60\frac{P_d}{T} + 70.4\frac{P_w}{T} + 3.739\times 10^5\frac{P_w}{T^2}$$

- Relatively *easy* to implement (interpolation of modeled pressure, water vapor and temperature values from the model grid points to the location of the observation).
- However, the resulting modeled refractivity would only match the *observed* refractivity (assuming perfect model and retrieved refractivities) if the atmosphere were strictly spherically symmetric.
- Ignores the existence of horizontal gradients of refractivity in the atmosphere (global spherical symmetry approximation).
- Some climatology or auxiliary information is necessary to retrieve refractivities from bending angle profiles.
- Under super-refraction conditions, conversion of bending angles to refractivities formally results in a negative bias below the height where super-refraction occurs.

Bending angle observations

- Make use of approximation of local, rather than global, spherical symmetry around the ray path tangent height.
- Not weighted with climatology information.
- Do not suffer from the formal negative bias in the lower troposphere caused by super-refraction conditions.
- Measurement errors are less correlated than refractivity profiles because there is no use of an Abel transform.
- Retrieved earlier than refractivity in the processing of the GPS RO observations, which makes it more attractive from a data assimilation point of view.
- However, their use in data assimilation algorithms is more challenging due to the large variability of the vertical gradients of refractivity.
  - Lower vertical resolution of NWP models compared to the GPS RO observations.
  - Ionospheric-residual noise in the mid-upper stratosphere due to the ionospheric compensation.

Bending angle observations (cont'd)

- A forward operator to assimilate bending angle observations has been developed, implemented and tested at NCEP (NBAM operator). Quality control procedures and observation error characterization have been tuned accordingly.
- An earlier version of this forward operator was available at NCEP in 2006 (*Cucurull et al. 2007*). The updated bending angle code has many improvements over the earlier version.

$$\alpha(a) = -2a\int_a^{\infty} \frac{d\ln n / dx}{(x^2 - a^2)^{1/2}}\, dx$$

$$(x = nr)$$

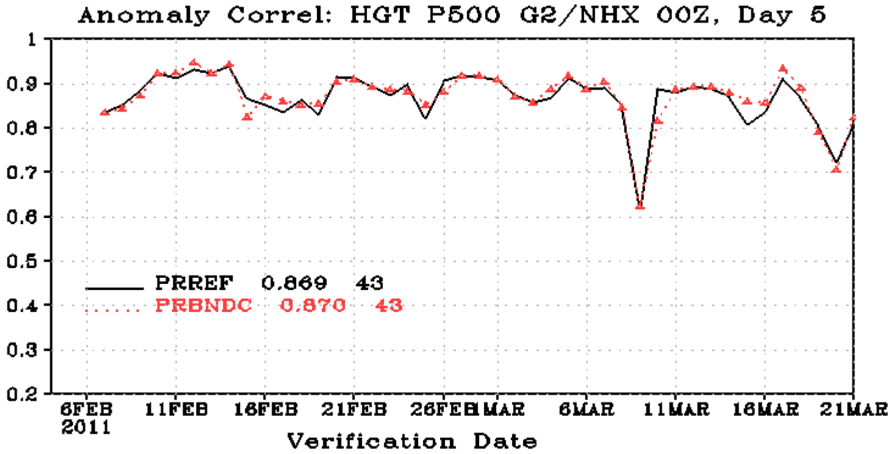
NBAM characteristics

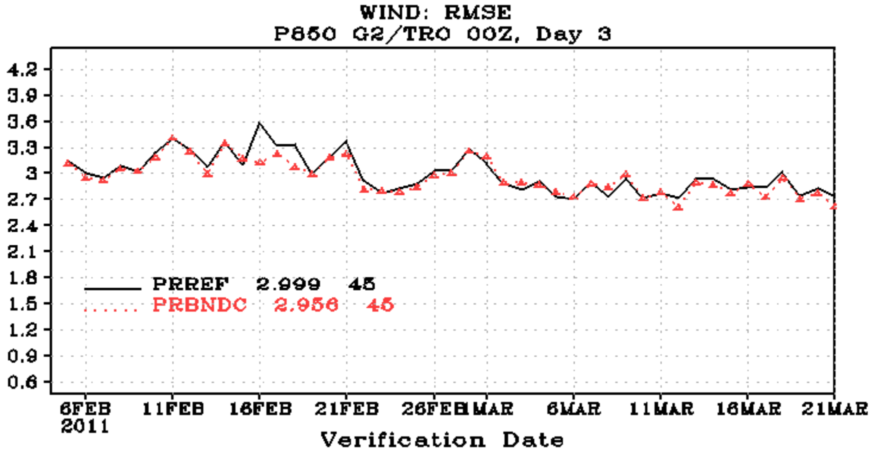
- Enables the assimilation of GPS RO observations up to 50 km – QC procedures and observation error structures have been tuned up to this height.
- Algorithms to include the compressibility factors in the computation of the geopotential heights have been implemented to compute a more accurate forward operator for GPS RO (following *Aparicio et al. 2009*).
- Both refractivity and bending angle codes have the option to use the compressibility factors.
- When the compressibility factors are used, the GPS RO forward operators use a more accurate set of refractive indices (Rüeger coefficients).
- The use of compressibility factors will affect the assimilation of GPS RO observations as well as all the observations that use geopotential heights. In fact, any subroutine within the assimilation code that makes use of the geopotential heights will be affected by the changes.
- Details on the design and implementation of NBAM can be found in *Cucurull et al. 2012, submitted to JGR.*
- <u>Since NBAM reverses the procedure of assimilating refractivities, it still suffers from errors induced by deviations from spherical symmetry.</u>

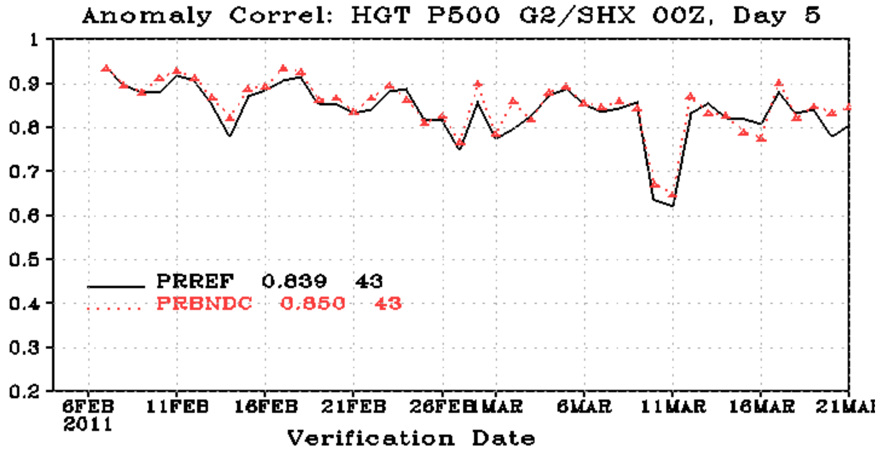
NBAM: Parallel testing

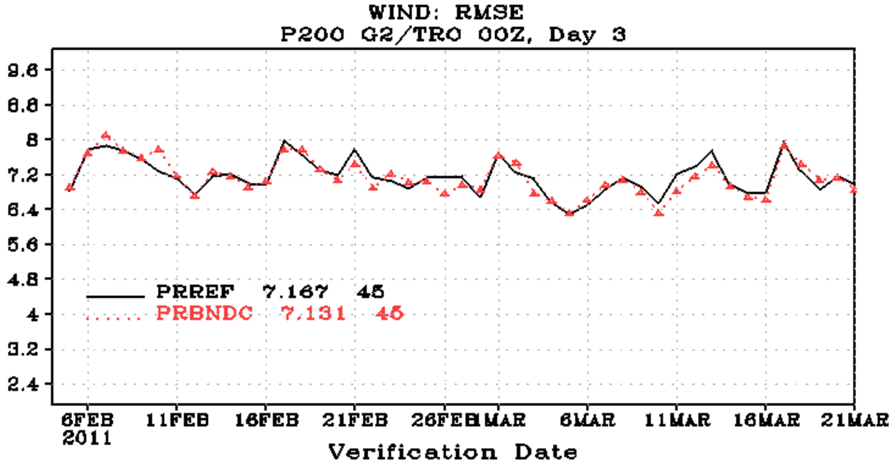
- Period: 2 February 2011 – 22 March 2011.
- **PRREF**: assimilation of refractivities up to 30 km.
- **PRBNDC (NBAM)**: assimilation of bending angles up to 50 km & use of compressibility factors & updated refractive indices.
- Both experiments use the operational GFS model, GSI T382L64.
- Results are averaged over the entire campaign.

Dynamic forecast skill


Anomaly Correl: HGT P500 G2/NHX 00Z, Day 5


WIND: RMSE
P850 G2/TRO 00Z, Day 3


Anomaly Correl: HGT P500 G2/SHX 00Z, Day 5


WIND: RMSE
P200 G2/TRO 00Z, Day 3

NASA/ GAMO (GSI analysis)

Courtesy of
R. Gelaro
(NASA/GMAO)

❑ 01 Sep – 31 Dec 2010 (mostly time averaged)

❑ ~2.4 million obs/6-h assimilated, includes

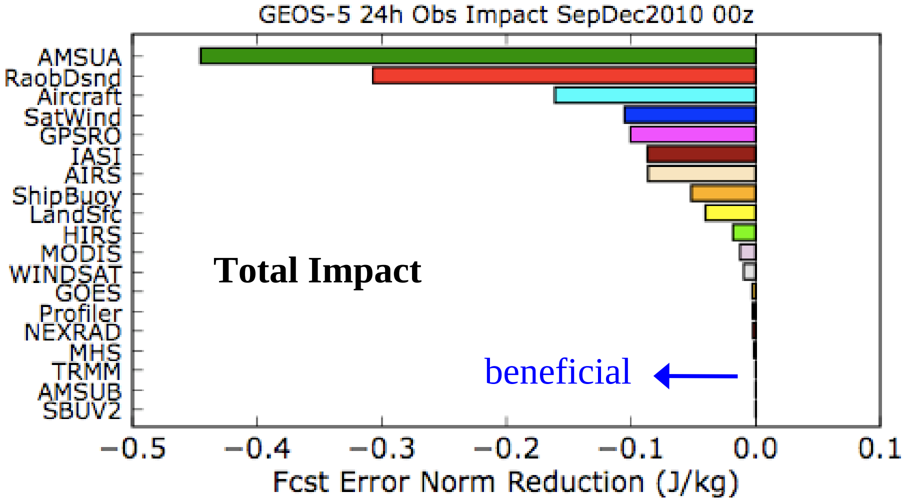
- 5 AMSU-A
- 5 HIRS-3/4
- AIRS
- IASI
- 5-7 GPSRO
- Satellite Winds (AMVs)
- Conventional

❑ Observation Impact

- **Global 24-h forecast error measure, sfc-150 hPa**
- **Dry total energy norm** (u, v, T, $p_s \rightarrow$ J/kg)
- **Dry adjoint model physics**

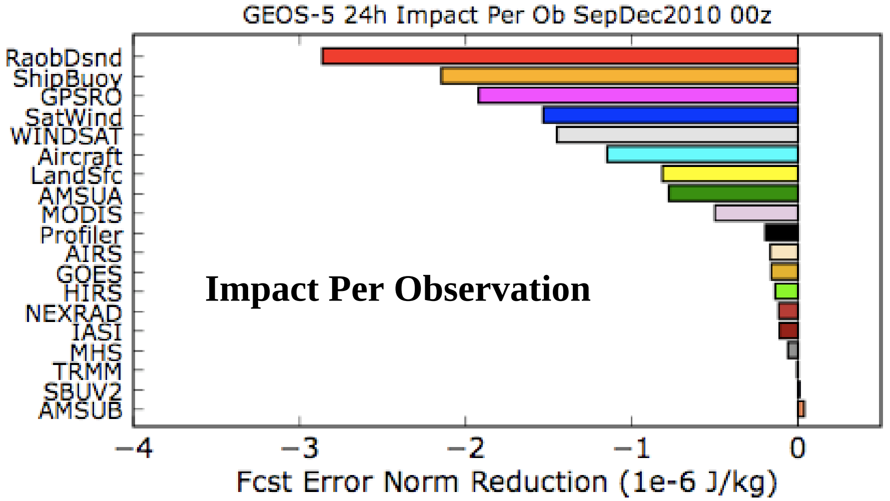
Daily Average of Impacts of Various Observing Systems in GEOS-5

01 Sep – 31 Dec 2010 00z

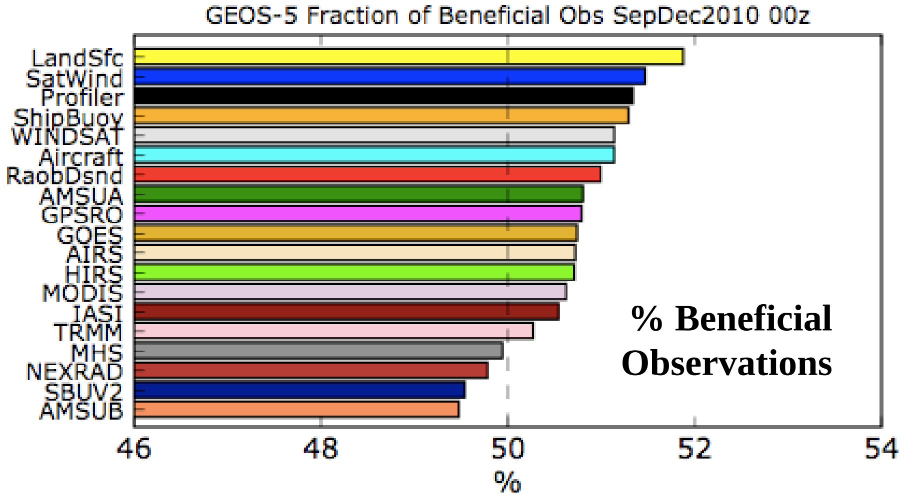

GEOS-5 24h Obs Impact SepDec2010 00z

Total Impact

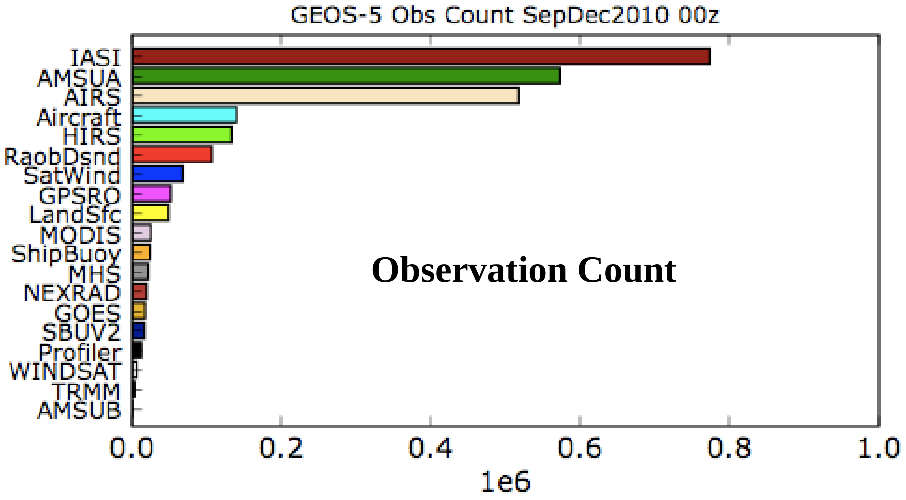
beneficial ←


GEOS-5 24h Impact Per Ob SepDec2010 00z

Impact Per Observation


GEOS-5 Fraction of Beneficial Obs SepDec2010 00z

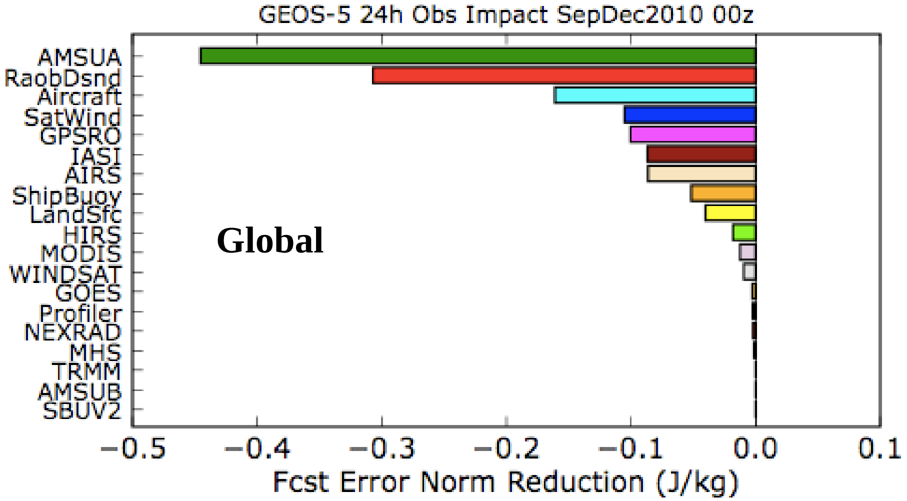
% Beneficial Observations

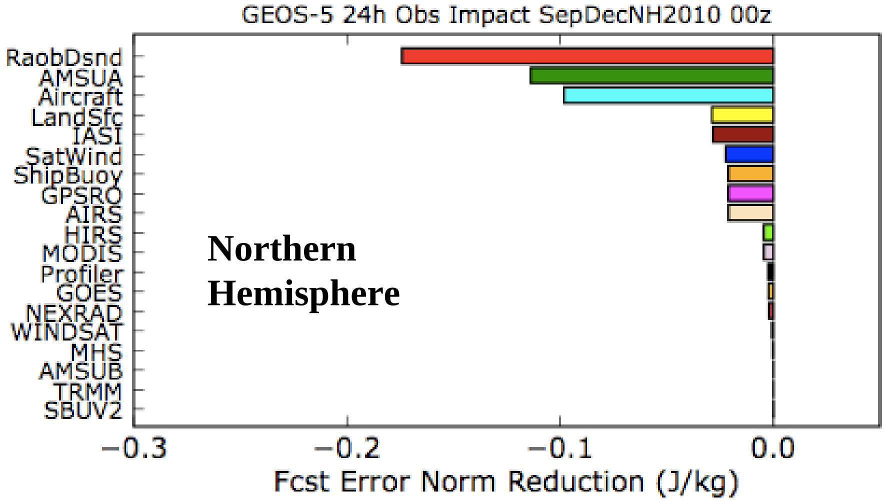

GEOS-5 Obs Count SepDec2010 00z

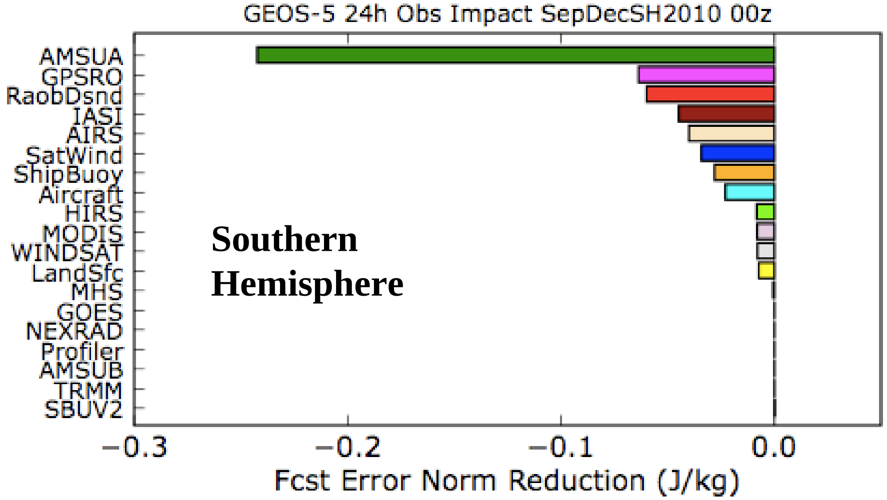
Observation Count

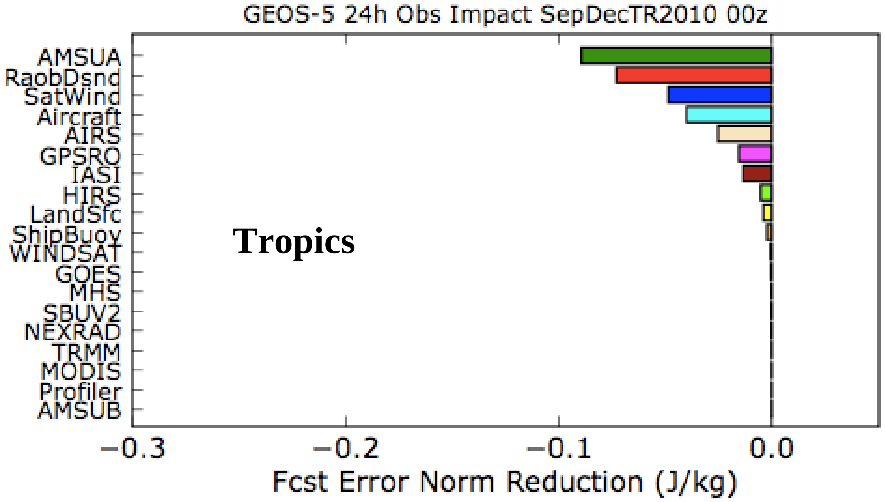
Impact of Various Observing Systems **by Region**

01 Sep – 31 Dec 2010 00z


GEOS-5 24h Obs Impact SepDec2010 00z


GEOS-5 24h Obs Impact SepDecNH2010 00z


GEOS-5 24h Obs Impact SepDecSH2010 00z


GEOS-5 24h Obs Impact SepDecTR2010 00z

Satellite radiance assimilation

- Radiance observations contain biases
  - Observations
  - Instruments
  - Forward model
  - Background

Bias = $Y_{obs} - H(X_b)$

Y_{obs}: observation

H: Forward model

X_b: background

- Satellite radiances are bias corrected in NWP, which requires some measurements to be assimilated without bias correction to 'anchor' the model.
- GPS RO is an <u>anchor measurement</u> (unbiased measurement)

Parallel run: 20071201 00Z – 20080229 12Z

Work done by Ling-Ling Tsao (CWB, Taiwan)

Models:

Resolution: T382L64

GFS	00Z - 192hr forecast
GDAS (GSI)	00Z, 06Z, 12Z, 18Z

R12014, updated to trunk on 2 Feb. 2011

Experiments:

gps	using all satellite data with GPS RO
nogps	using all satellite data without GPS RO

Radiance satellite data usage:

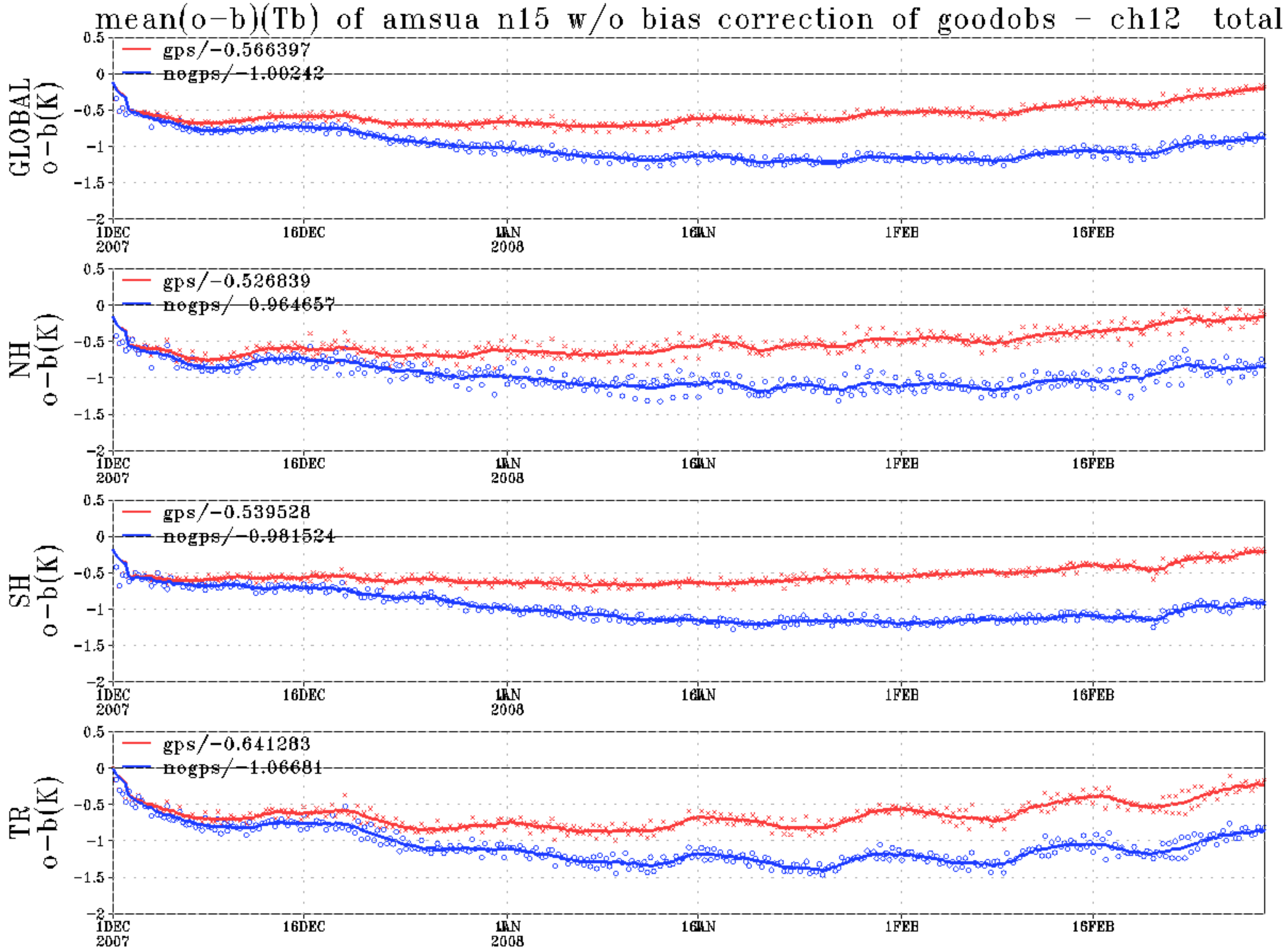
AMSU-A	
NOAA-15	Channels 1-10, 12-13, 15
NOAA-18	Channels 1-8, 10-13, 15
METOP	Channels 1-13, 15
AQUA	Channels 6, 8-13
AMSU-B	
NOAA-15	Channels 1-3, 5
NOAA-16	Channels 1-5
NOAA-17	Channels 1-5

MHS	
NOAA-18	Channels 1-5
METOP	Channels 1-5
HIRS-3/4	
NOAA-17	Channels 2-15
METOP	Channels 2-15
AIRS	
AQUA	120 Channels

SNDRD1-4	
GOES 11, 12	Channels 1-15

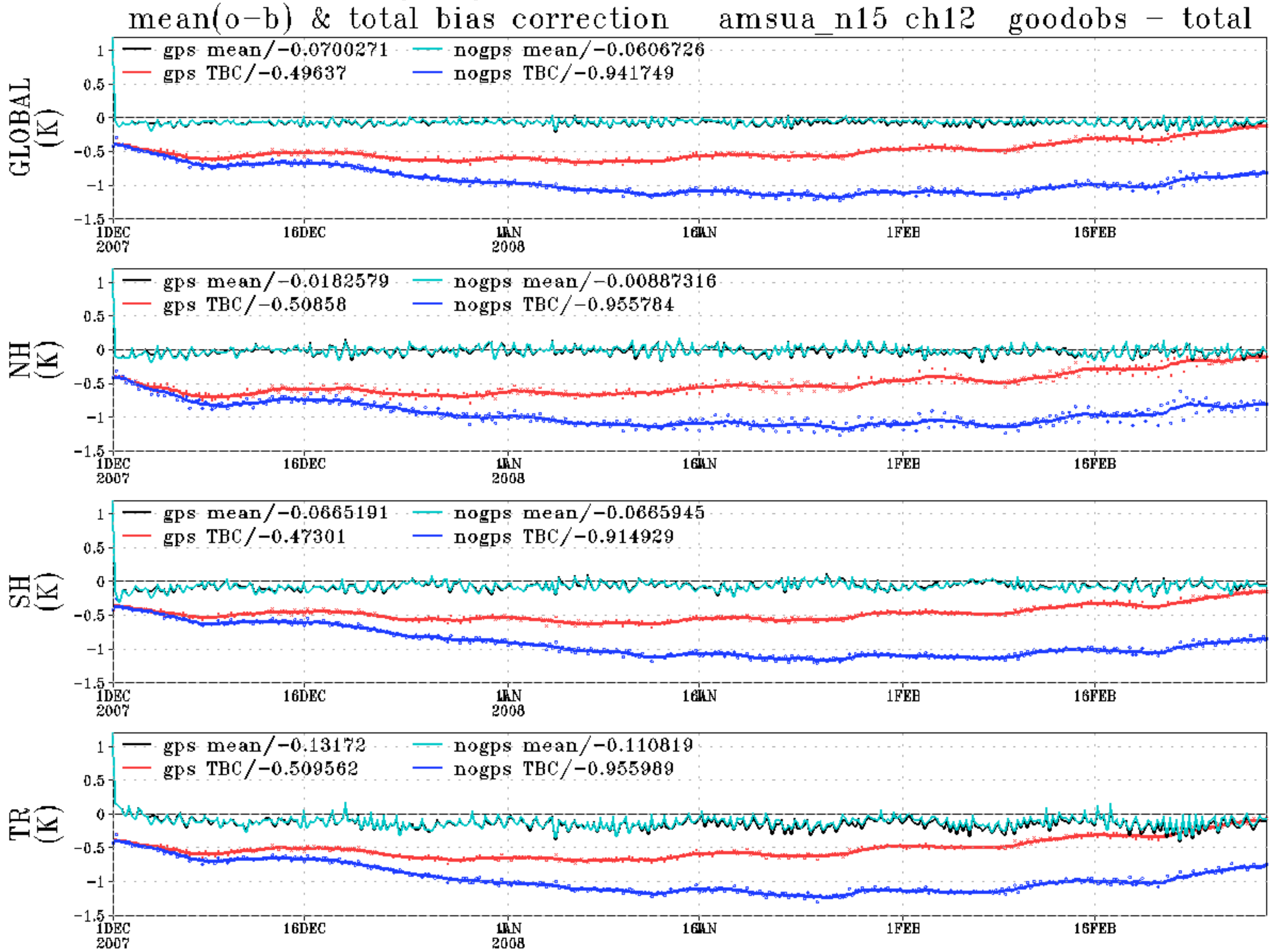
AMSU-A NOAA-15
Channel 12 - Weighting function peak: 10 hPa

Temporal evolution of mean(o-b) without bias correction



AMSU-A NOAA-15
Channel 12 - Weighting function peak: 10 hPa

Temporal evolution of mean(o-b) with bias correction and Total bias correction



Bias correction in the model

- The experiment with GPS RO produced better forecast skill for all fields and pressure levels.
- If one believes that radiance data is good and the model has less bias, radiance observations will be consequently bias-corrected less.
- More information will be extracted from the observations.
- Better use of radiance observations in NWP centers.
- Improvement in weather prediction skill.

Summary

- GPS RO has been shown to provide significant benefits in operational NWP weather forecasting.
  - Impact from the direct assimilation of GPS RO observations
  - Indirect impact on the assimilation of satellite radiances by improving the bias correction
  - Saturation of information with the current GPS RO sensors has not been reached

- **GPS RO has proven itself to be one of the key sensors for NWP**