Environment Canada Environnement Canada

Canada

The assimilation of Radio Occultation Data

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General Presentation
Dorval
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Limb observations & Refraction

- Sunrise, sunset, moonrise, moonset…
- Atmospheric refraction distorts objects
- From satellite, the effect is larger (twice the airmass)

Moonrise from Skylab (1973)

An Occultation (an optical case)

- From a Low Earth Satellite, ~1 minute
- Refraction angle
  - ~ 1 degree at horizon
  - Roughly proportional to P with altitude
  - Potential for remote sensing
- It turns out that this concept is more precise in radio frequency

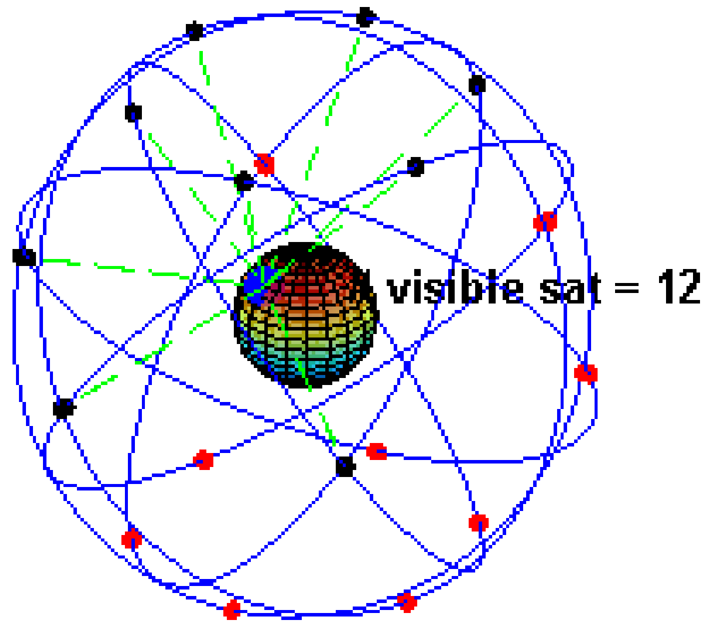
Moonset from ISS (2003)

Accurate measures

- For centuries, the most accurate measurements were angles
  - Time as angle of the sun, meridian passage of stars
  - Latitude as angle of the polar star
  - Position by triangulation
  - Distance by parallax
  - Weight with scales
- After atomic clocks, the most accurate is time
  - Distance as light travel time
  - Position by trilateration
  - Weight by vibration/acceleration/inertia
  - Temperature through the vibration frequency of a crystal

Global Navigation Satellite Systems (GNSS)

- Orbiting atomic clocks, which broadcast time signals (precision ~10^{-12} s)
- Put in place for Positioning, Navigation, Timing, but has many other applications
- Distance to Earth ~20000 km (propagation ~0.06 s)
- Refraction by atmosphere: delay by ~2m-2km (10^{-8}-10^{-5} s)
- Weather signature in the atmospheric refraction: (10^{-10}-10^{-7} s)
- Quasi-vertical geometry: Ground-based GNSS-Meteorology
- Quasi-horizontal geometry: **Satellite-based GNSS-Meteorology**

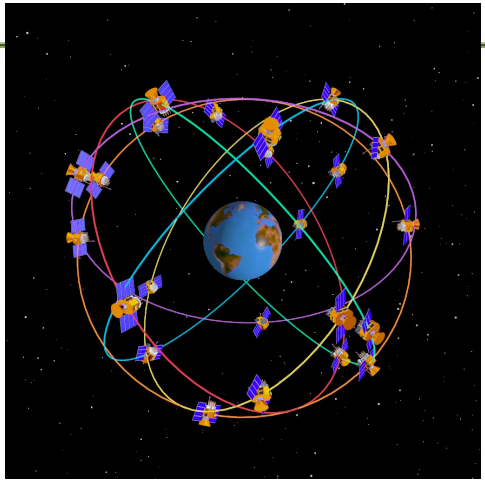


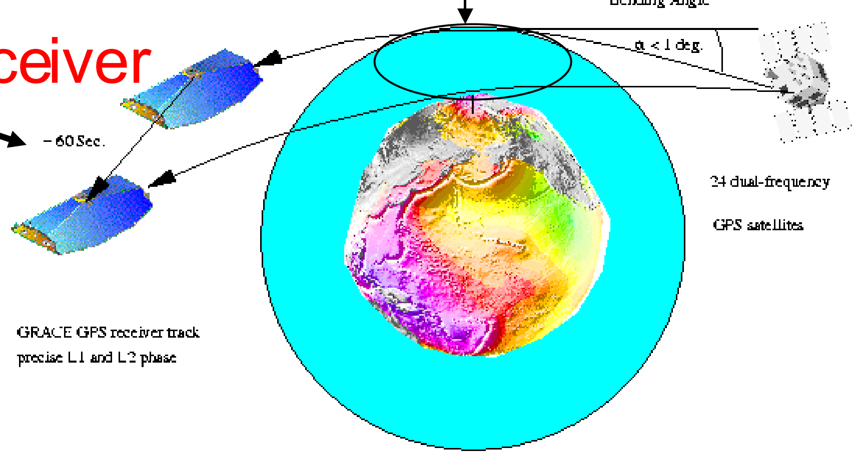
Satellite Radionavigation Systems

- Global systems:
  - GPS: US DoD, since 1978 (~32 satellites)
  - GLONASS: Russia, since 1995 (~24 satellites)
  - GALILEO: European Union (operational by 2012 ?)
  - Compass: China (still not operational, ~35 sats)
- Regional systems:
  - WAAS: North America
  - EGNOS: Europe
  - Beidou: China
  - MSAS, QZSS: Japan
  - IRNSS: India
- Due to long term stability of GPS, nearly all GNSS applications are based on GPS
- Large growth potential due to the still unused GNSS systems

Radio Occultations

- Satellite to satellite propagation
- Signal Source: A radionavigation satellite
  - GPS (they form a sphere of ~30 emitters around Earth)
- Receiver: a polar low Earth orbiter (LEO)
- Geometry comparable to sunrise/sunset





Observables I

- Reception delay of the signals by the atomic clock
- Light has been slowed, its path bent (=bending angle)
- It is possible to reconstruct the profile of refraction index (assume spherical symmetry)
  - 1.000000 in vacuum
  - 1.000270 near the surface, dry airmass
  - 1.000340 near the surface, wet airmass
- Excess (air-vacuum) known as refractivity

Elasticity of electron clouds in atoms

$$N = 10^6 (n_{Air} - 1) = 77.6890 \frac{P_d}{T} + 71.2952 \frac{P_w}{T} + 375463 \frac{P_w}{T^2}$$

Induction of molecular rotation

- Water observable nearly only as vapor (the third term is negligible in a liquid/solid
- Each water vapor molecule ~15 times more refractive than a nitrogen/oxygen molecule

Observables II

From travel time to refraction index

- EM signal received by LEO: $\varphi(t)$
- Doppler $\dot{\varphi}(t)$
- From GPS itself, we know the orbit of the receiver (that's the primary application of GPS!) $x(t), \dot{x}(t)$
- Which is the incoming angle of the signal?
  - Derived from $\dot{\varphi}(t), \dot{x}(t)$
  - From which incoming direction comes this signal if it shows this Doppler?
  - As it turns out, not from the straight line from the emitter.
  - We can find that the signal was bent by the atmosphere.
  - Bending angle as a function of the impact parameter $\alpha(a)$
- Bending angle and refraction index are related by

$$\ln(n(a)) = \frac{1}{\pi}\int_a^\infty \frac{\alpha(a')da'}{\sqrt{\left(a'^2 - a^2\right)}}$$

Observables III

- There is a direct chain of physical connections between GPSRO measurements and fundamental definitions of the second, meter, etc
- A large part of the chain is maintained by the GPS system itself (we do not need to calibrate it)

- Our part of the chain includes the **postprocessing** and the **observation operator**
- The simplifications made are well known, the largest being local spherical symmetry of the atmosphere
- Spherical asymmetry will be addressed in future operators

- These data are said “unbiased” because
  - the chain is known
  - the assumptions introduce errors smaller than our tolerance

Observation operator

- We receive an array (H_i,N_i) (Height,Refractivity)
- We transform to (GZ_i,N_i) (Geop, Refractivity)
- The background provides (TT,LQ,PS)
- Refractivity at each bgck level N
- Geopotential at each bgck level GZ

- Find each GZ_i within GZ
- Interpolate N to GZ_i (better interpolate log N)

Some properties of radio occultations

- Raw observed property: refraction-induced propagation delay
- Obs have direct link to SI standards: **Nearly unbiased**
- When obtained from a polar orbiting LEO, occultations are **worldwide distributed, very homogeneously**
- Vertical scan of atmosphere with ~500m resolution
- ~500 occultations/polar LEO/day
  - But may be smaller (150-300) in non-optimized missions (GPS receiver as secondary instrument)

GPS Radio Occultation Missions

- Initial tests for meteorology (1994)
  - GPS/MET (US, proof of concept, very sparse data)
- Data now available continuously since late 2001 (offline)
  - CHAMP (Germany, ~180 profiles/day)
  - SAC-C (Argentina/US, ~180 profiles/day)
- We are receiving NRT data in large volume since July 2006
  - CHAMP (Germany, ~180 profiles/day)
  - GRACE (Germany, ~180 profiles/day)
  - COSMIC (Taiwan-US, 1000-1600 profiles/day)
- Near future:
  - METOP (EUMETSAT, ~300 profiles/day), launched, not yet commissioned
  - TERRASAR (Germany, ~150 profiles/day), launched, not yet commissioned
  - CHAMP: approaching end of life.
  - SAC-C: May become NRT.
- Long term:
  - COSMIC II: 3000 profiles/day (not yet approved, in search for funding)
  - CHINOOK: 300 profiles/day (CSA)
- Other proposals around:
  - Constellations of 24-100 microsats (~10000-100000 occultations/day)
  - Technology allows <$5M/satellite lifetime (~5yrs) if done in volume
  - Active radio occultations (we produce the signal, instead of reusing a preexisting one)
    - Could control frequency, optimize for signature of O_3, H_2O
  - Radio occultations in Mars
  - Sea reflections during the occultation

Assimilation of GPS RO NRT data at Environment Canada (EC)

- Project started in Oct 2003 with funding from the Canadian Space Agency (CSA)
- Satellites: CHAMP, GRACE, COSMIC
- Data received NRT & monitored
- Offline tests show positive impact. Will be proposed for parallel implementation within the next few weeks.

Current Assimilation Tests of GPS RO

- Project started in Oct 2003 with funding from the Canadian Space Agency (CSA)
- Satellites: CHAMP, GRACE, COSMIC
- Present assimilation tests done in 4D-Var for periods:

  20 December 2006 0000 UTC to 3 February 2007 0000 UTC

  15 June 2006 0000 UTC to 17 July 2006 0000 UTC

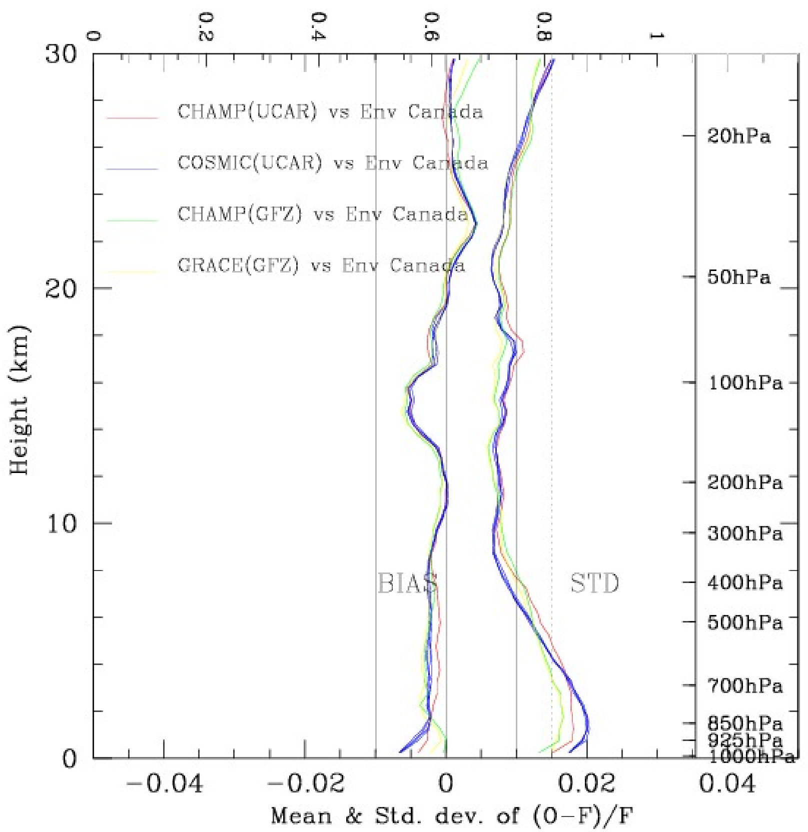
- The summer period includes the COSMIC comissioning phase (was launched April 15th .Declared commisioned July 13th. Thus less data in the summer period.
- Important:
  - All instruments are of the same type
  - There is no instrument-dependent calibration
  - Only postprocessing & operator can introduce bias (although should be very small)
  - All data used was postprocessed by the same software (UCAR)

EC analysis and forecast system

- GEM Global Environmental Multi-scale Model
  - Global grid 800x600 or ~ 33 km resolution
  - 58 vertical levels
  - Model Lid at 10 hPa (~ 30 km)
- 4D-Var Incremental data assimilation system, with options to use
  - 3DVar
  - 3DVar with First Guess at Appropriate Time (FGAT)
- Early tests in 3DVar-FGAT, Final in 4DVar
- Data also assimilated:
  - Radiosondes, aircrafts, surface, AMV,…
  - ATOVS (8 AMSU-A, 7 AMSU-B channels) –RTTOV8.7
  - GOES (1 channel -6.7 microns)
  - SSM/I (7 channels)
  - AIRS
  - QuikScat
- Dynamic (15 day sliding window) bias correction for radiances

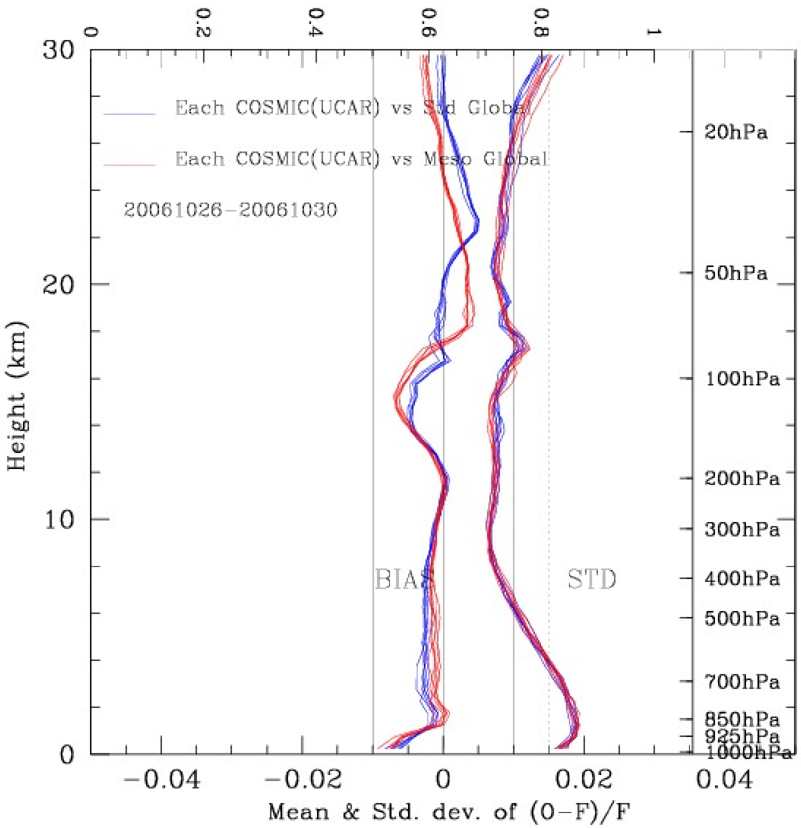
The data I

- The different sources (satellites) of data are extremely similar (even if sampling is different)
- Differences between postprocessors are noticeable but small
- Shown all data in 2006.221-243 (last 3 weeks of Aug 2006) versus EC-Operational



The data II

- Differences between models dominate the features (here, operational EC-400x200 and EC-Meso, then parallel)
- Each curve is shows data from one of the 6 LEO in COSMIC
- So
  - All LEO behave identically
  - All postprocessors are nearly identical
  - Features are dominated by model biases
  - Only low tropo bias suspected to be real data bias



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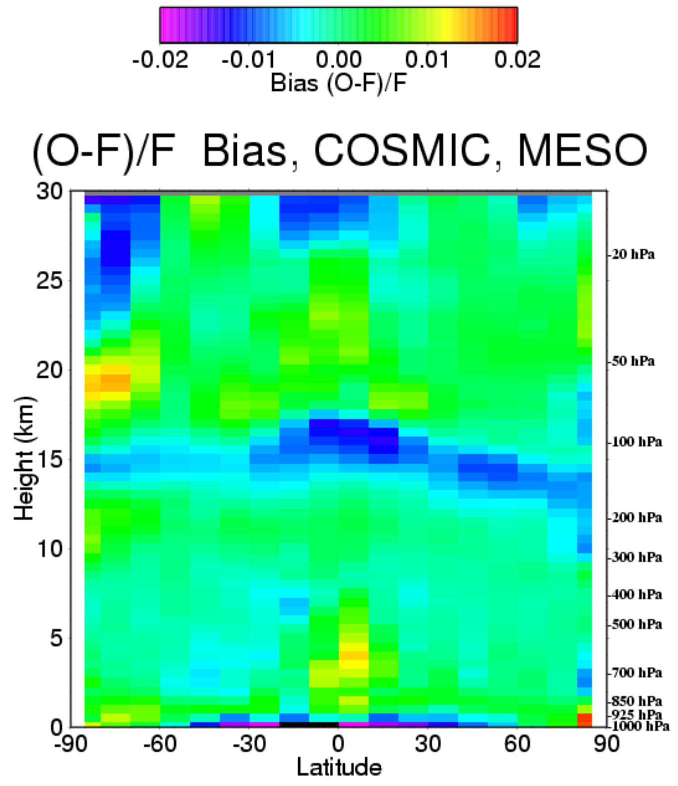
The data III

- The observed bias (suspected to be largely model bias) is dominated by a tropopause feature.
- All models show this (ECMWF, UKMet, NCEP, EC-400x200) but in EC-Meso is significantly more pronounced
- A minor feature here will reappear later: areas of small negative bias in midlat tropo
- Shown: Jan 2007 vs EC-Operational



GPS RO data processing at EC (I)

- Refractivity profiles versus MSL height (Level 2)
- Data thinning:
  - No more than 1 profile within 45 minutes and 300 km.
  - No more than 1 observation/vertical km (approximately 1 datum out of every 5, as profiles are usually received with 200m resolution)
- Vertical Clipping: Use data
  - above 4 km
  - at least 1 km above background model surface
  - below background model lid (10 hPa, ~30 km)
- Background Error Check

  $-0.05 < (O-F6h)/F6h < 0.05$ in all the profile (after clipping)

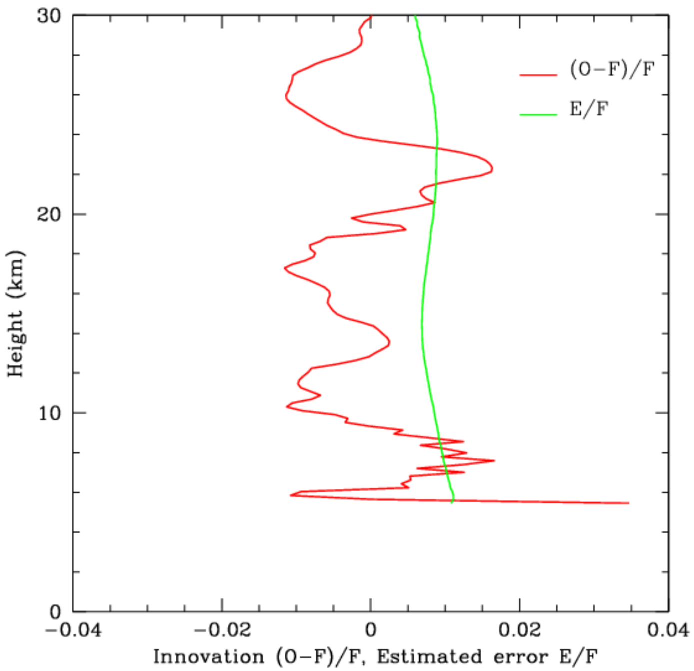
GPS RO data processing at EC (II)

- Observation bias expected to be very small (no bias correction, data used as anchor)
- Observation error: ~0.5-1.5%, known to vary with horizontal gradients (mostly with water content)
- Definition of observation error E_i: **dynamical**
  - O-F6h used online to estimate observation error
    - Within each profile:

      Weighted RMS of O-F6h

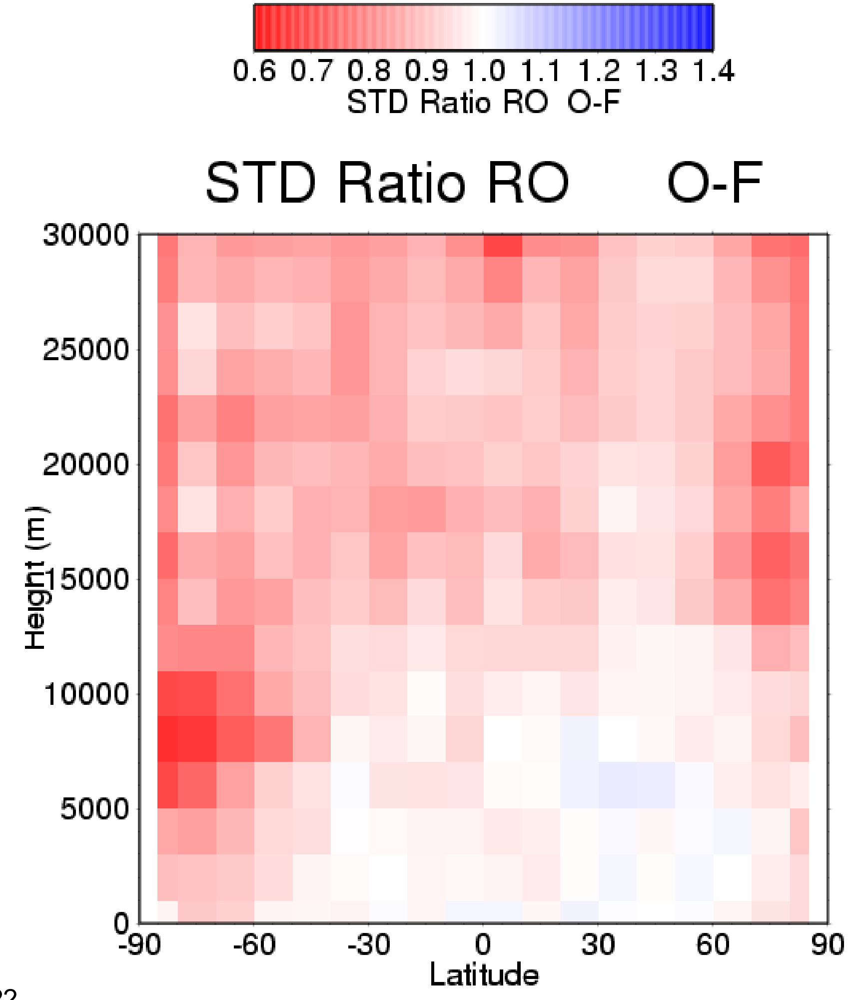
      Weighting: Gaussian, D=5km
  - This allows dynamical optimization
    - Automatic adjustment of data weight
    - Error tightens as cycle progresses (larger RO data weight ***if accuracy improves***)
    - Data weight automatically reduced if forecasts are less accurate

$$\left(\frac{E_i}{F_i}\right)^2 = \frac{\sum_j e^{-\left(\frac{h_i - h_j}{D}\right)^2} \cdot \left(\frac{O_j - F_j}{F_j}\right)^2}{\sum_j e^{-\left(\frac{h_i - h_j}{D}\right)^2}}$$



GPS RO Impact on 6h forecasts

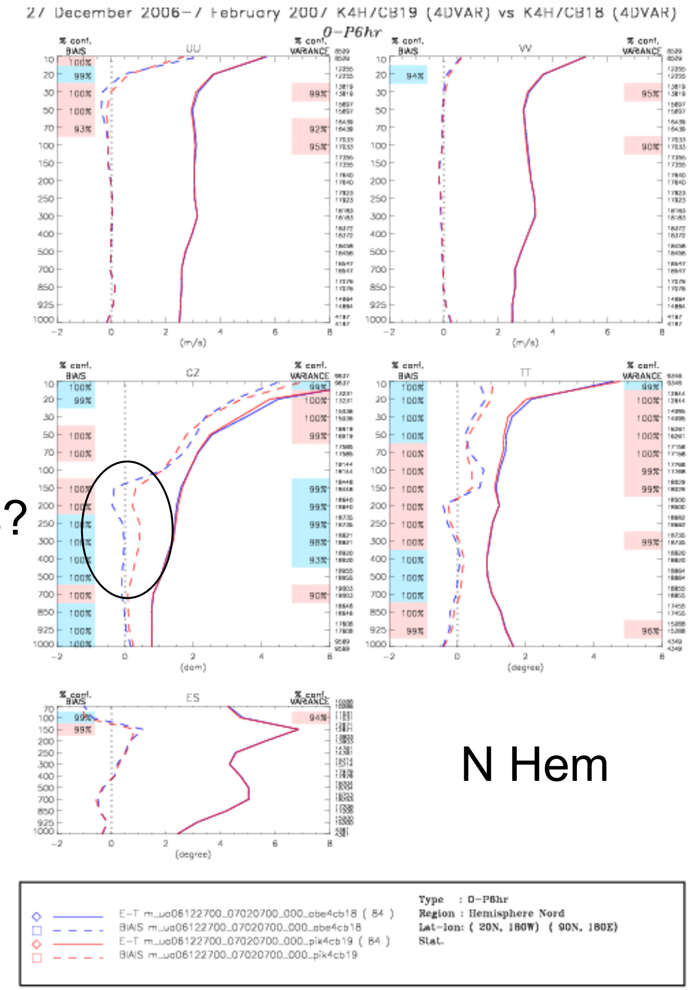
- ***TRUTH=GPS RO***
- Shown: ratio of refractivity forecast STD with/without assimilation of GPSRO
- Error in forecasting GPSRO observations reduced by 5-40% after assimilating RO.
- Red areas: improves with RO
- Blue areas: degrades with RO
- Similar in summer & winter



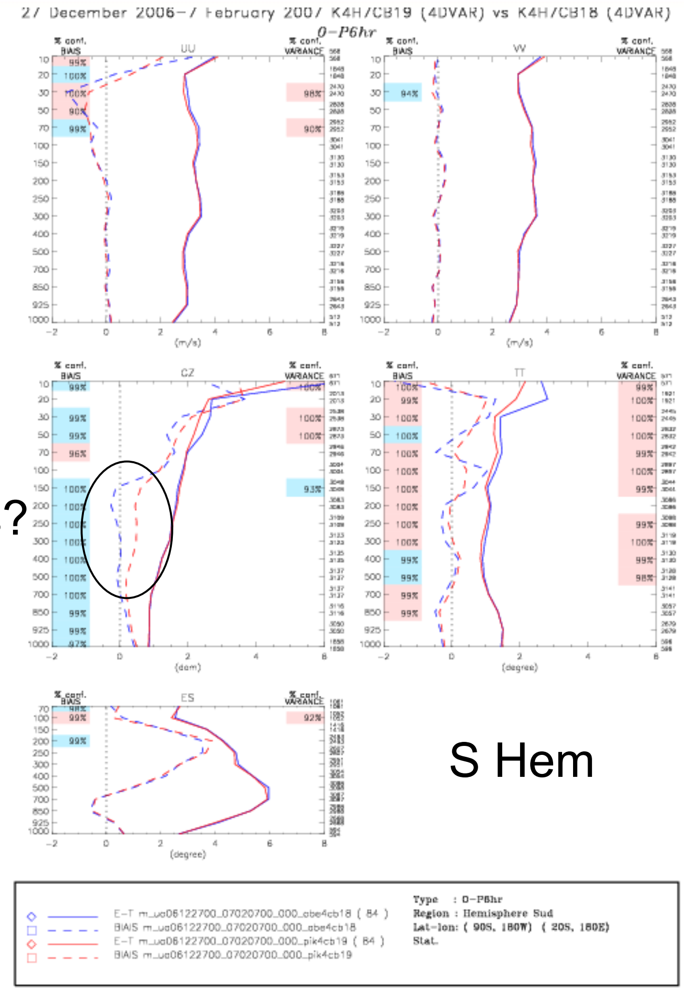
GPS RO Impact on 6h forecasts Radiosondes (winter)

WITH GPS
WITHOUT GPS

GZ Bias?



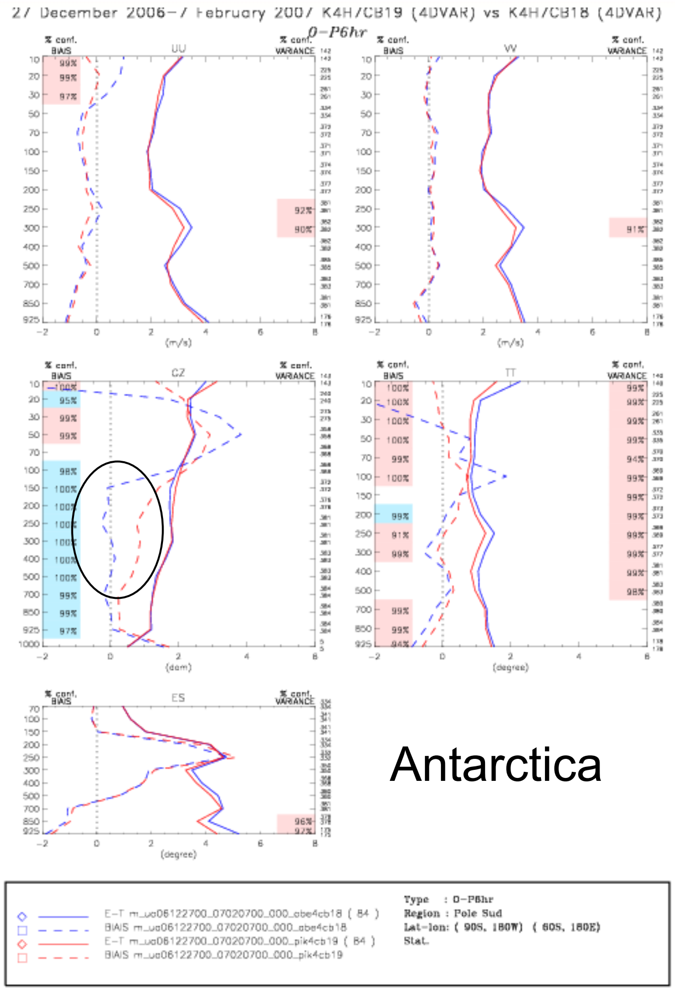
GZ Bias?



GPS RO Impact on 6h forecasts Radiosondes (winter)

WITH GPS
WITHOUT GPS

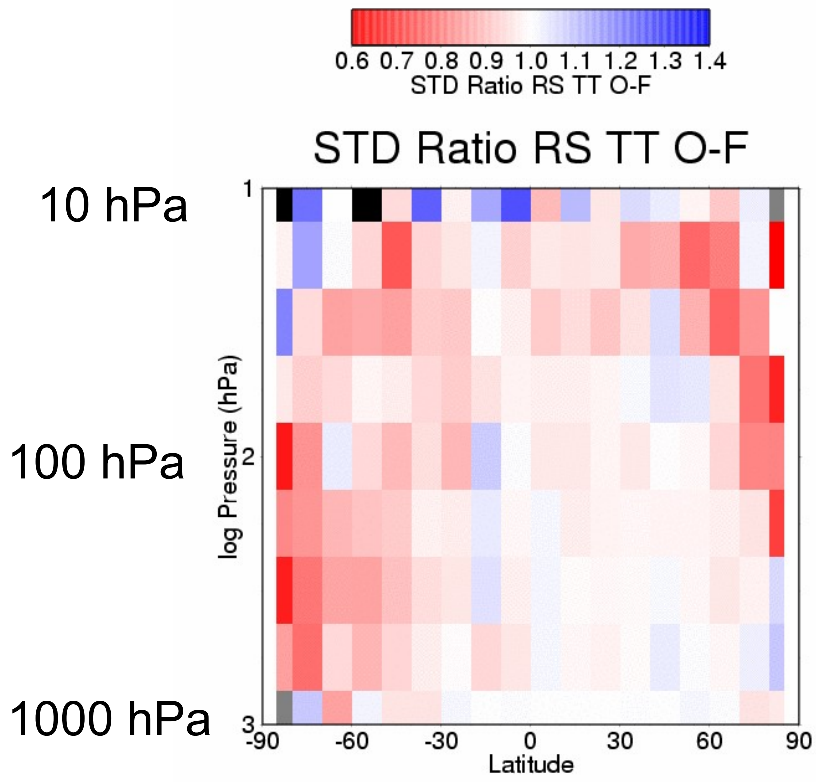
- Very important impact in the Antarctica
- GZ Bias even bigger
- However, TT Bias and TT STD are improved
- Something is wrong with altitudes
- Even so, the effect is small (3-10m at 15 km) i.e. in the range 0.02%-0.1%



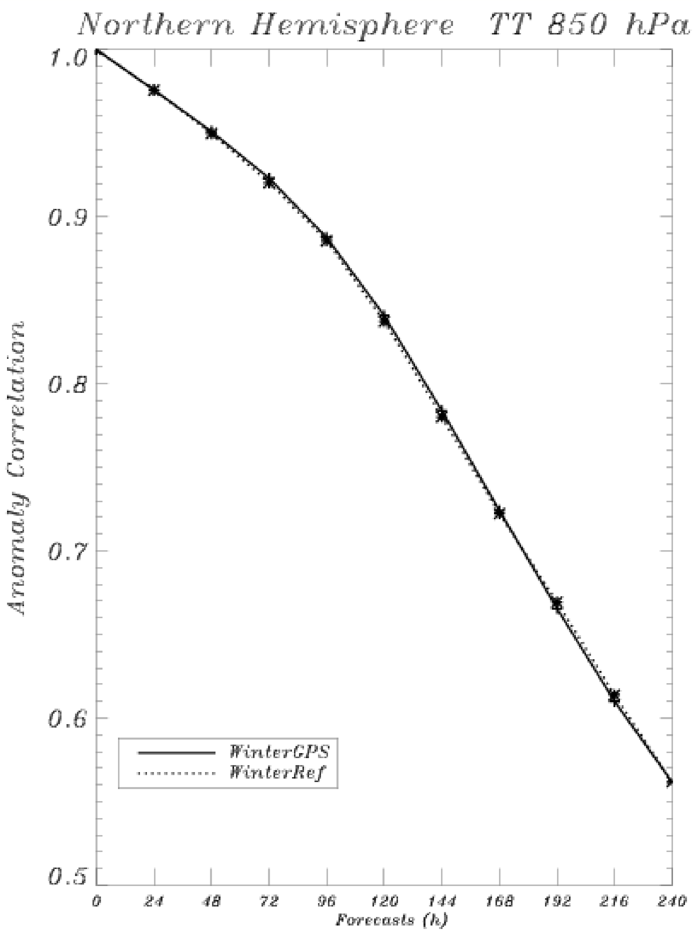
Antarctica

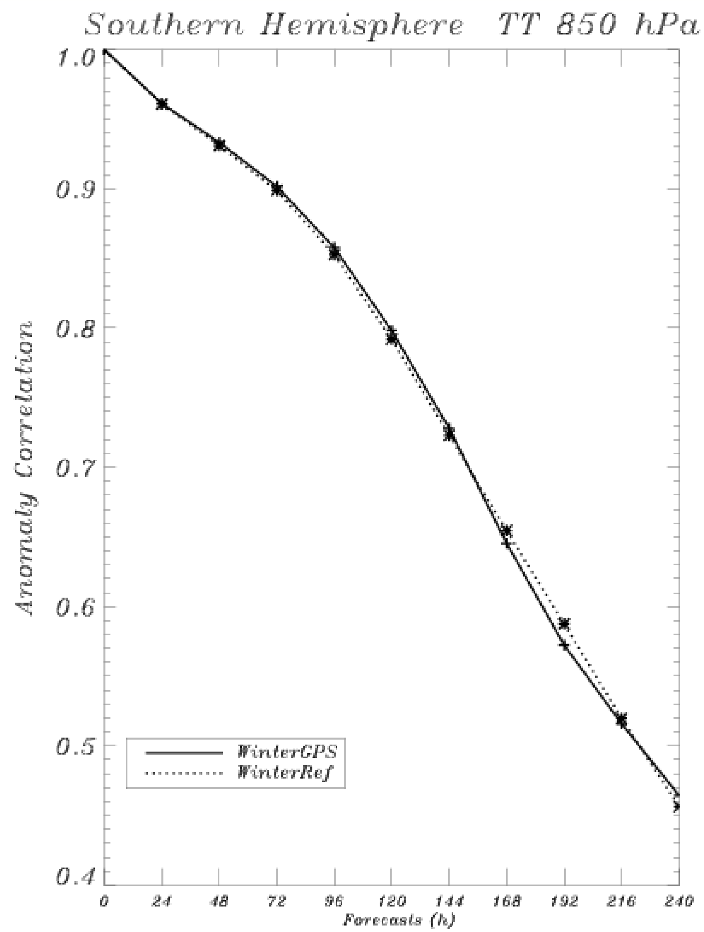
GPS RO Impact on 6h forecasts Radiosondes

- ***TRUTH=Radiosonde Temperature***
- Error forecasting radiosonde temperature observations reduced on average by 5-10% after assimilating RO.
- Red areas: improves with RO
- Blue areas: degrades with RO

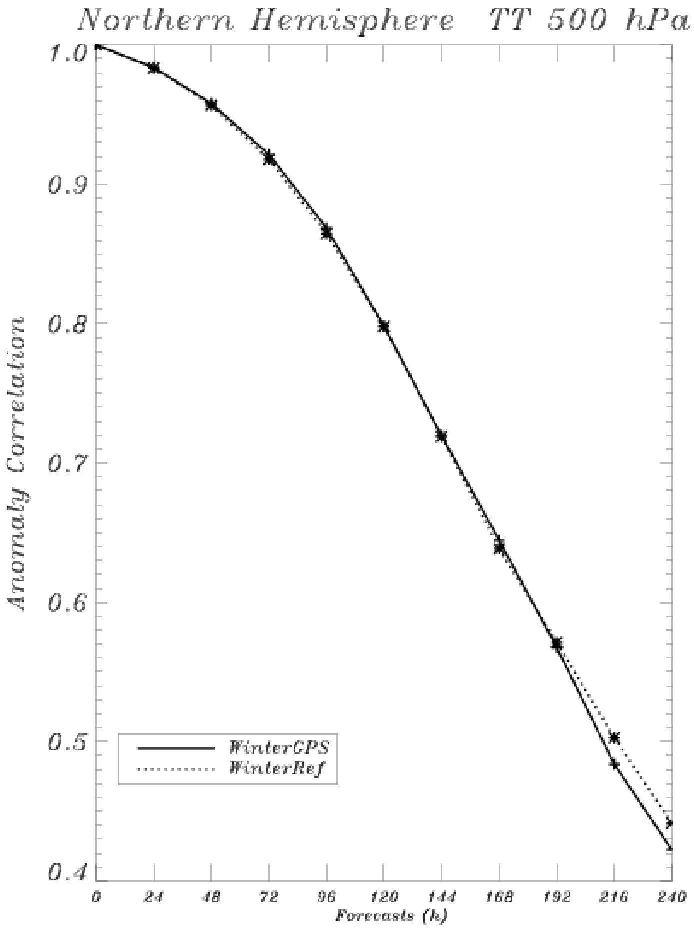


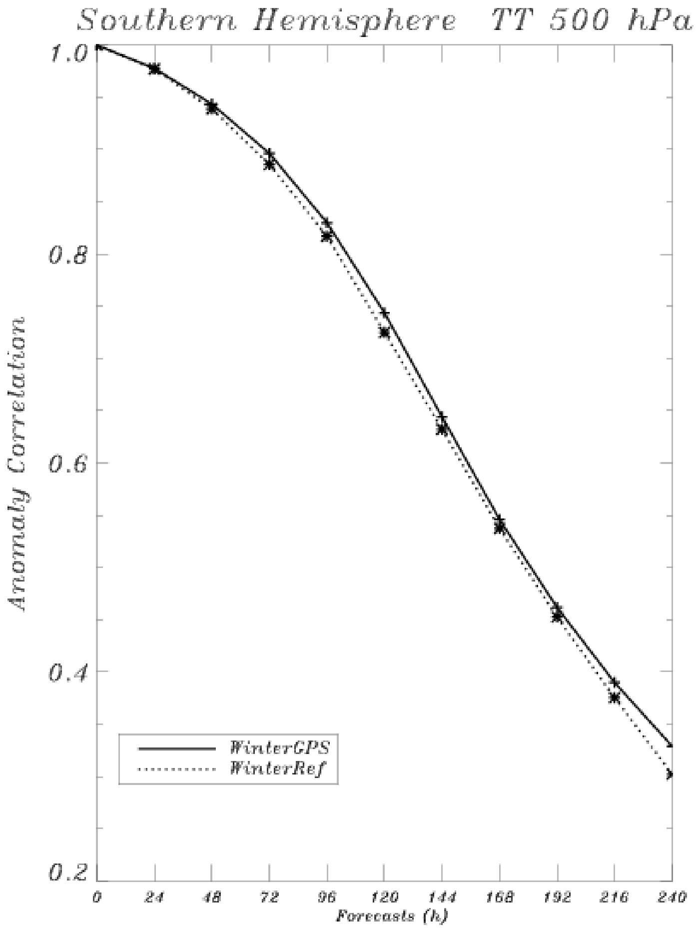
GPSRO Impact on 0-10 day forecasts Anomaly Correlation: T at 850 hPa Winter



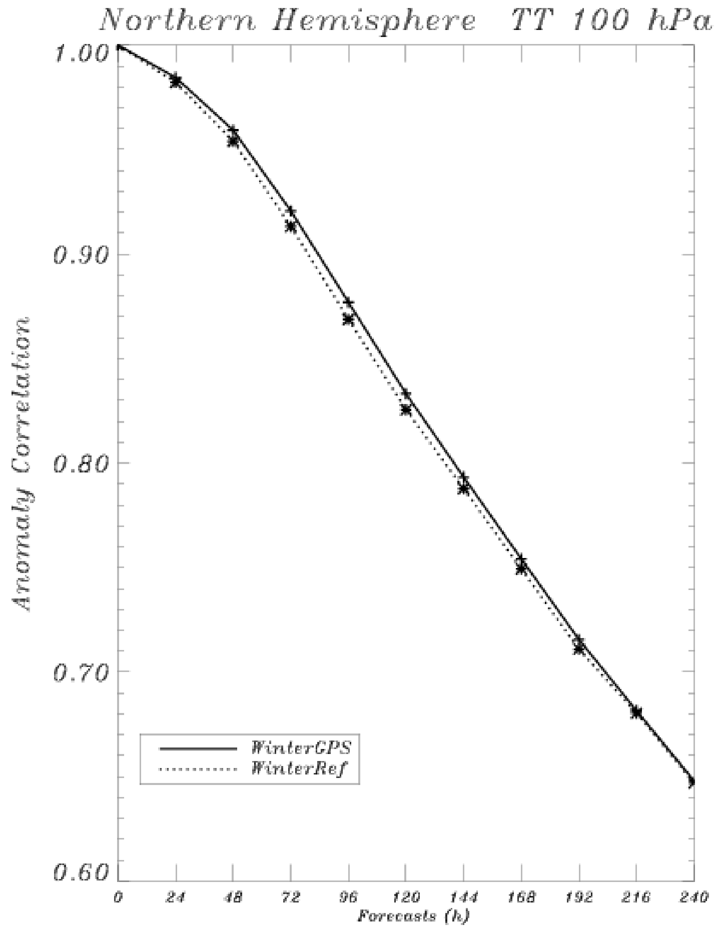


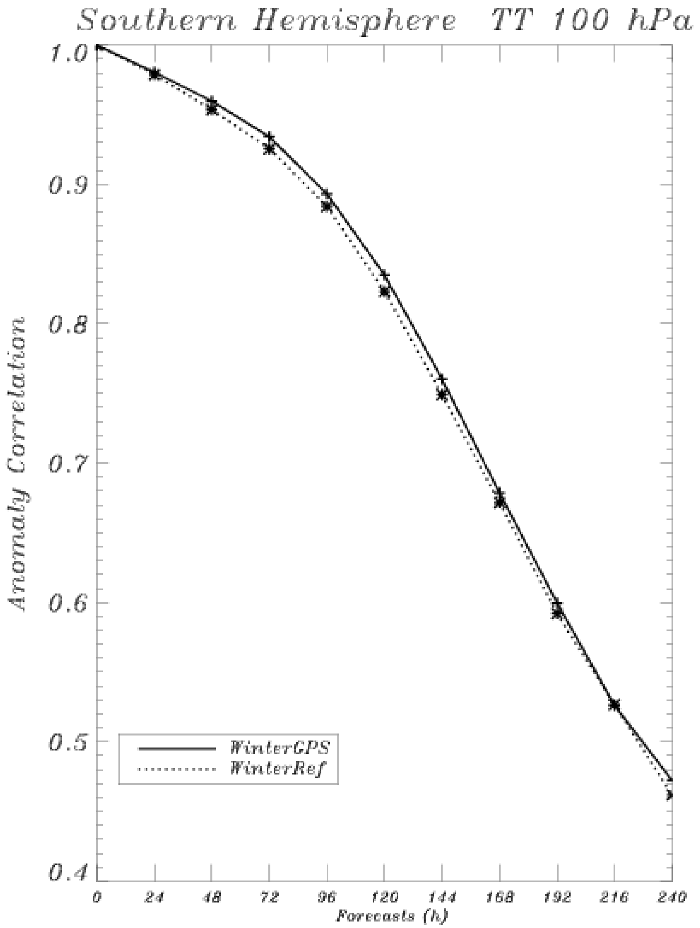
GPSRO Impact on 0-10 day forecasts Anomaly Correlation: T at 500 hPa Winter



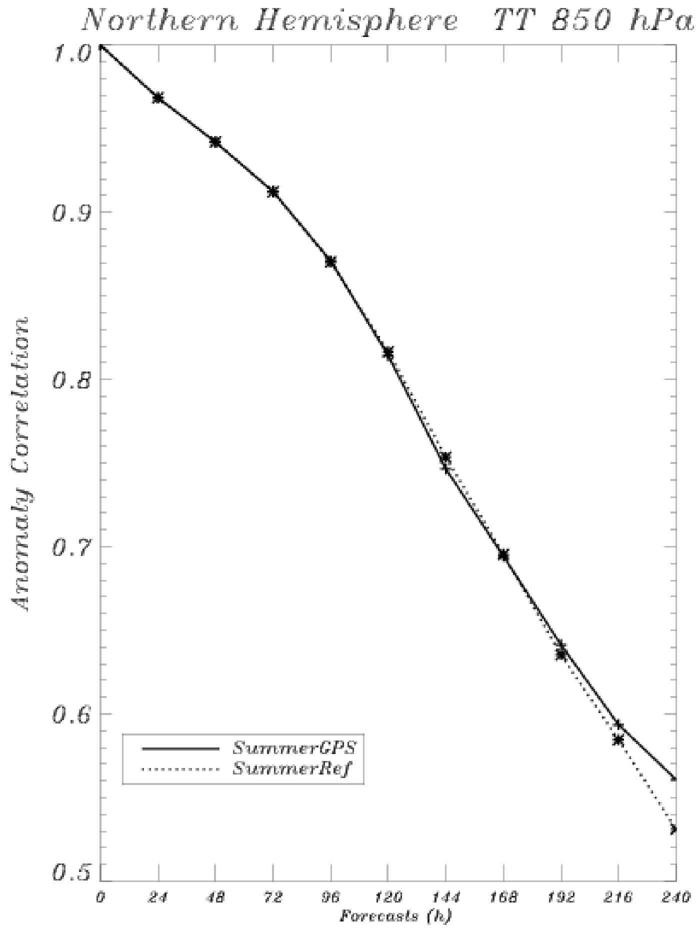


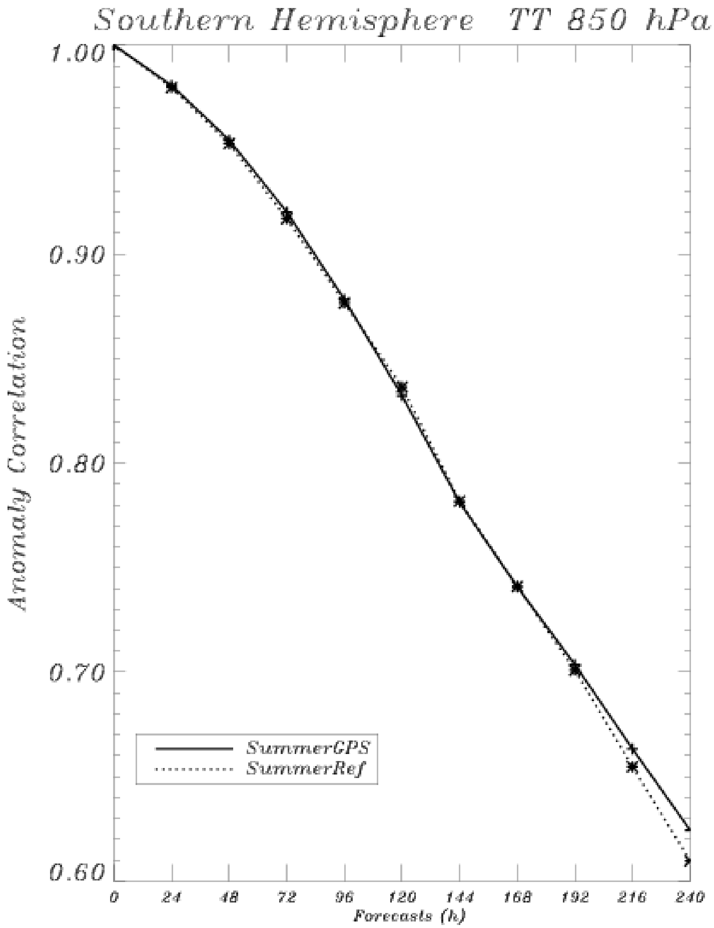
GPSRO Impact on 0-10 day forecasts Anomaly Correlation: T at 100 hPa Winter



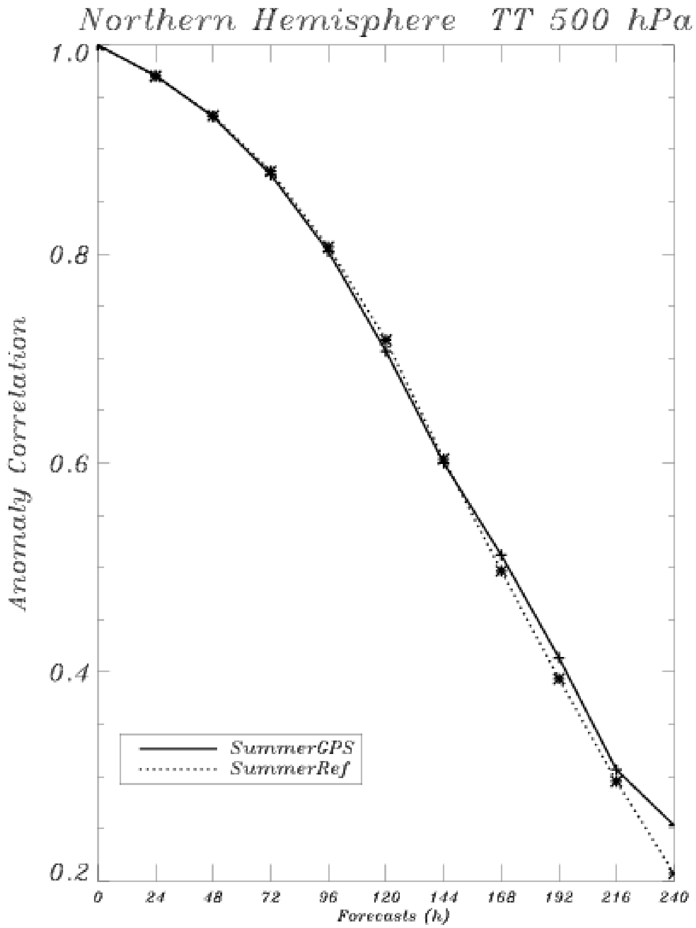


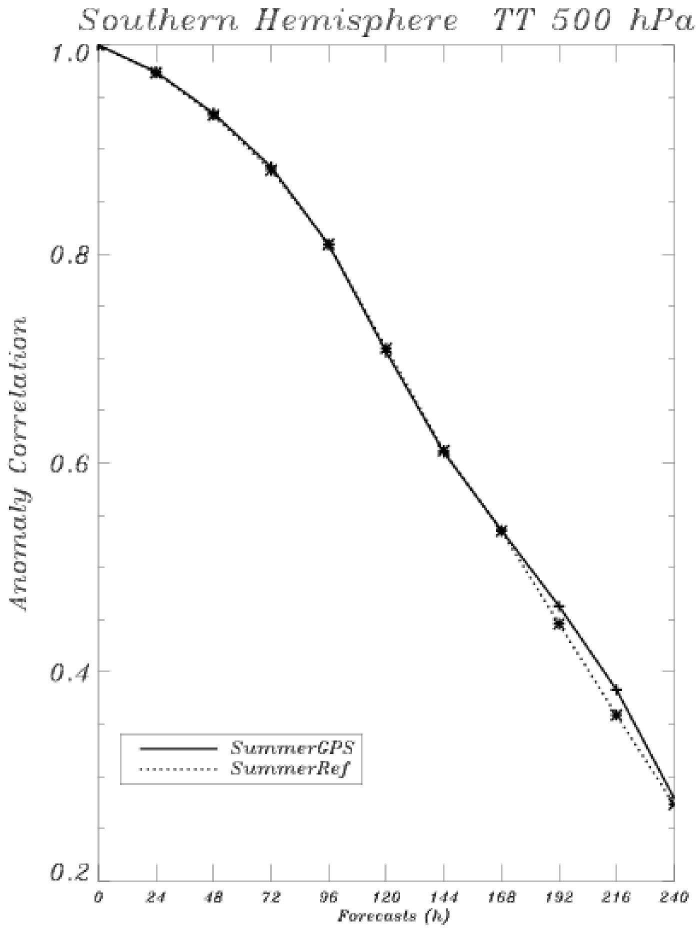
GPSRO Impact on 0-10 day forecasts Anomaly Correlation: T at 850 hPa Summer



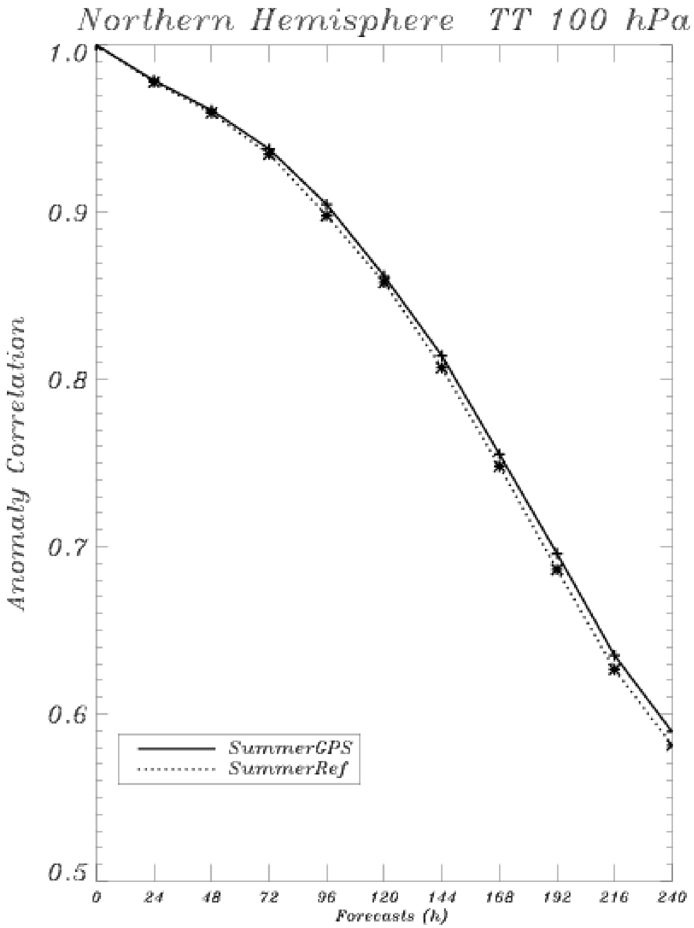


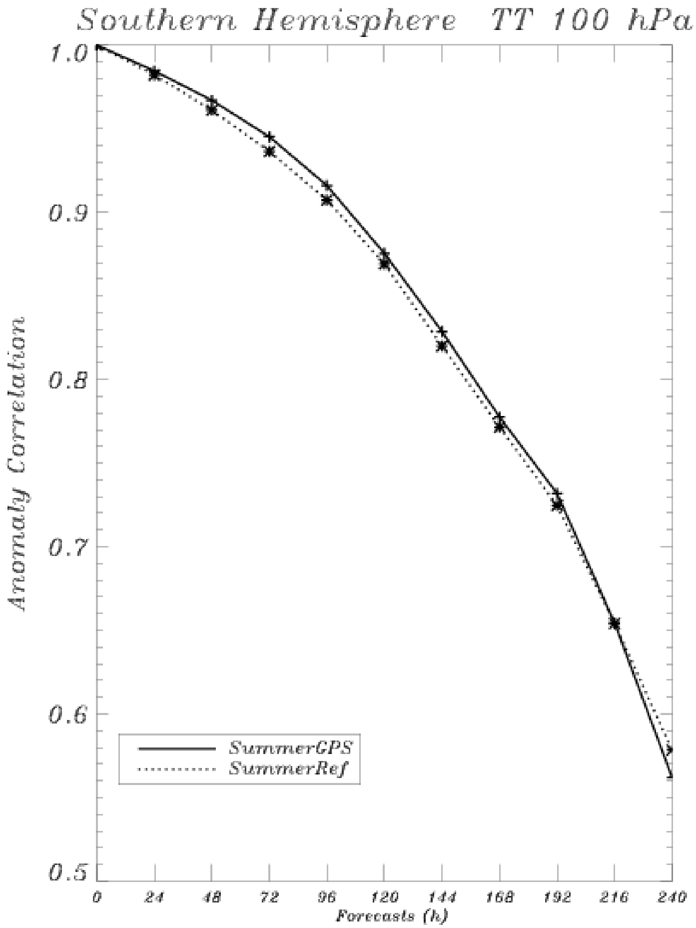
GPSRO Impact on 0-10 day forecasts Anomaly Correlation: T at 500 hPa Summer





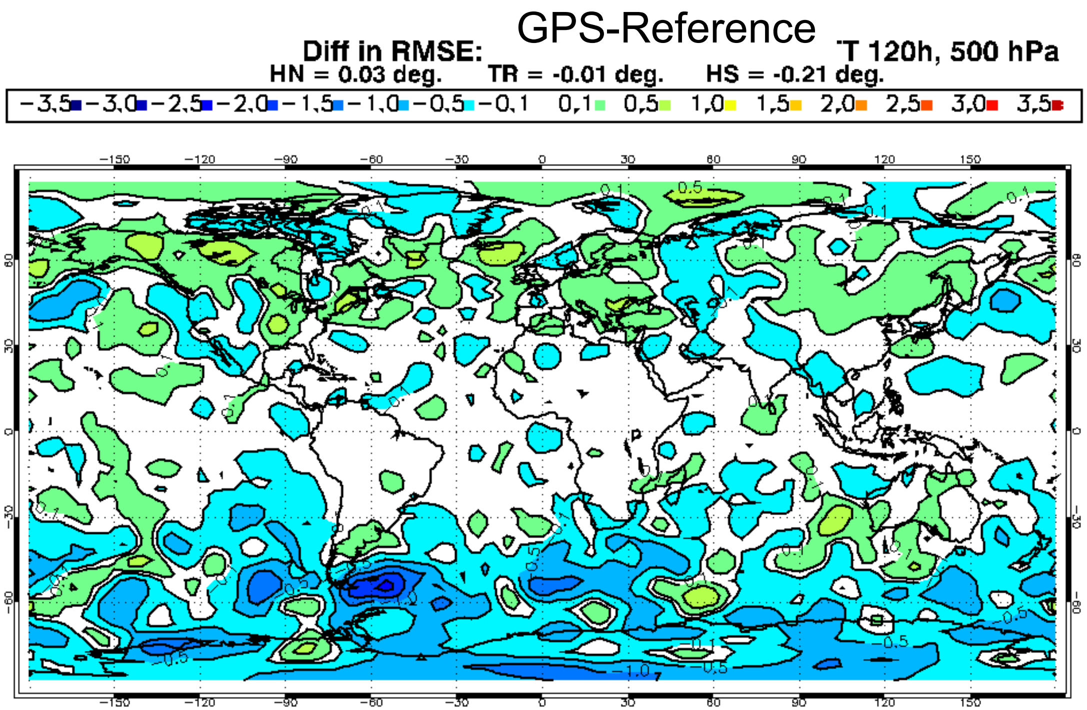
GPSRO Impact on 0-10 day forecasts Anomaly Correlation: T at 100 hPa Summer





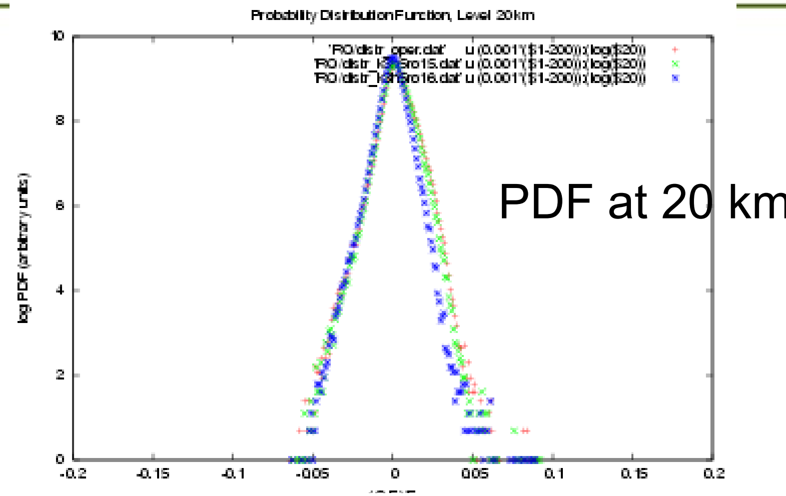
GPS RO Impact on day 5 forecast
Difference in RMS
Temperature at 500 hPa

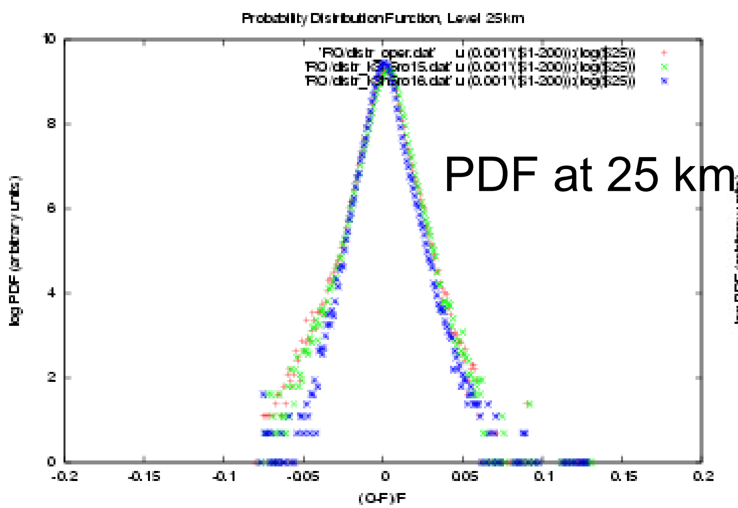
- ***TRUTH=Analysis***
- Blue areas: improves with RO

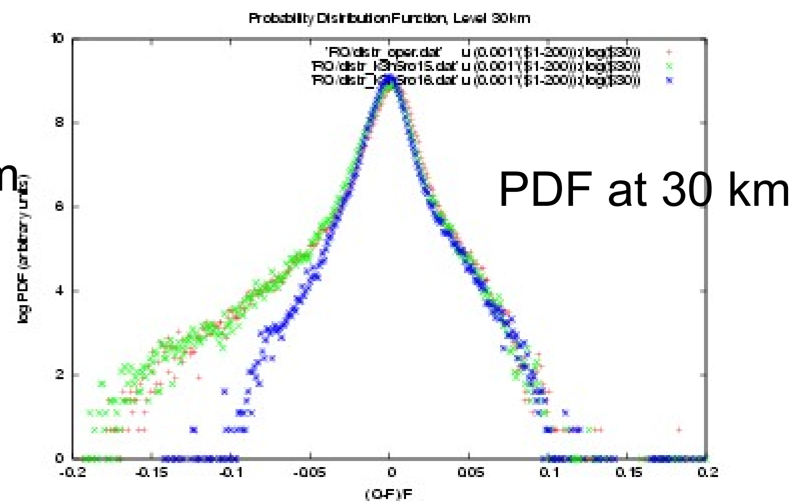


GPS RO impact on extreme deviations

- GPSRO reduces the probability of extreme deviations
- Shown are Probability Distribution Functions (log) in stratosphere
- Red: EC Operational
- Green: Control (no GPSRO)
- Blue: GPSRO







Conclusions so far

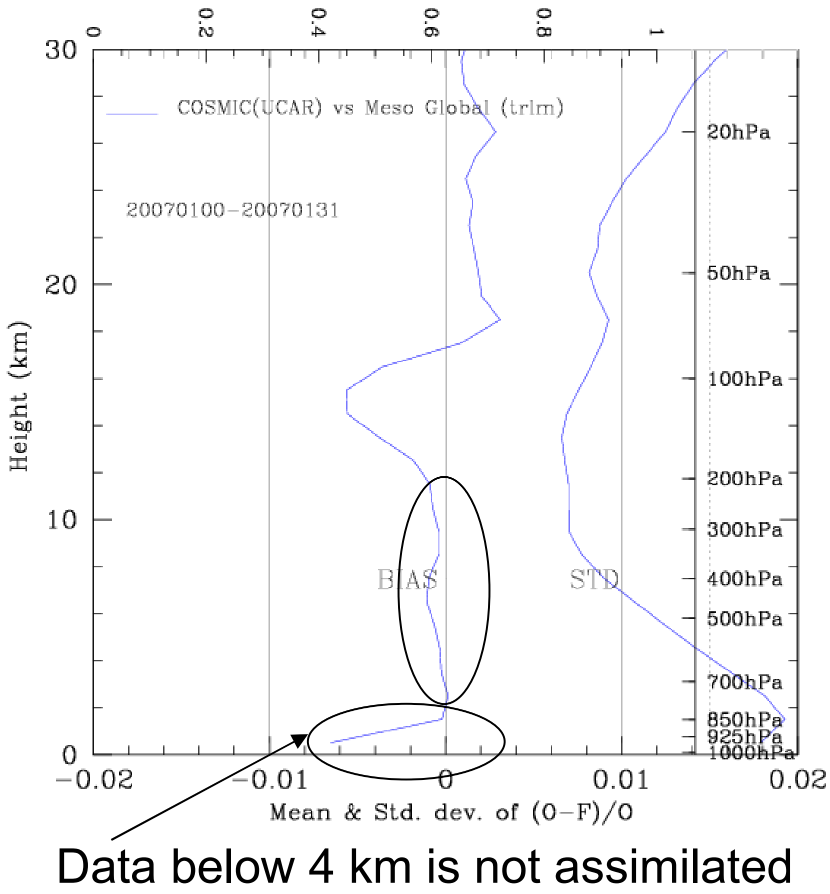
- Data arrives in NRT. Quality is good.
- Assimilation of these data is in general positive
- Better temperatures, winds
- We expected more impact in tropics and moisture fields, but impact is small there (although not negative)
- Substantial impact in Antarctica (major data source)
- If everything is so nice… why does GZ degrade?

The altitude mismatch

- RS indicates that there is an altitude mismatch of 0.02%-0.1% after GPSRO assimilation
- GPSRO indeed uses a different vertical scale:
  - Nearly all measurements are vertically located in pressure (P)
  - GPSRO is located in geometric altitude (H)
  - A mismatch P vs H of ~5e-4 can lead to this GZ bias
  - Many things were in fact not designed with that accuracy

The bias in observation space

- The source of the GZ bias is a small bias in refractivity. The forward model, when applied to the background field systematically forecasts a refractivity too big by ~5e-4 in the troposphere
- Effect is not noticeable in stratosphere, as there are other errors of bigger magnitude



The origin of the O-F bias

- The P vs H relationship is based on the hydrostatic equation

$$\frac{dp}{dH} = -\rho(H) \cdot \gamma(\lambda, H)$$

- And the ideal gas equation of state

$$p = \rho \cdot R_d \cdot T_v$$

- So (WMO standard)

$$dH = \frac{-1}{\gamma(\lambda, H)} \cdot R_d \cdot T_v \cdot d[\ln p]$$

$$dGZ = \frac{-1}{\gamma_0} \cdot R_d \cdot T_v \cdot d[\ln p]$$

- But a real gas is not ideal (small attraction/repulsion between molecules)

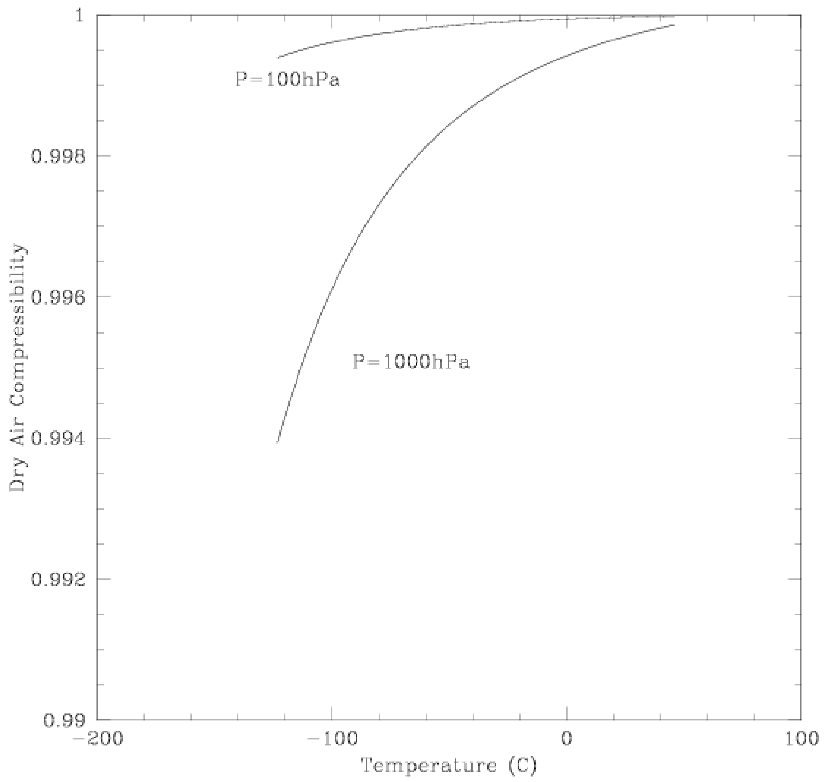
$$p = \rho \cdot R_d \cdot T_v \cdot Z$$

Should be added

Z~0.9990-0.9998 for air

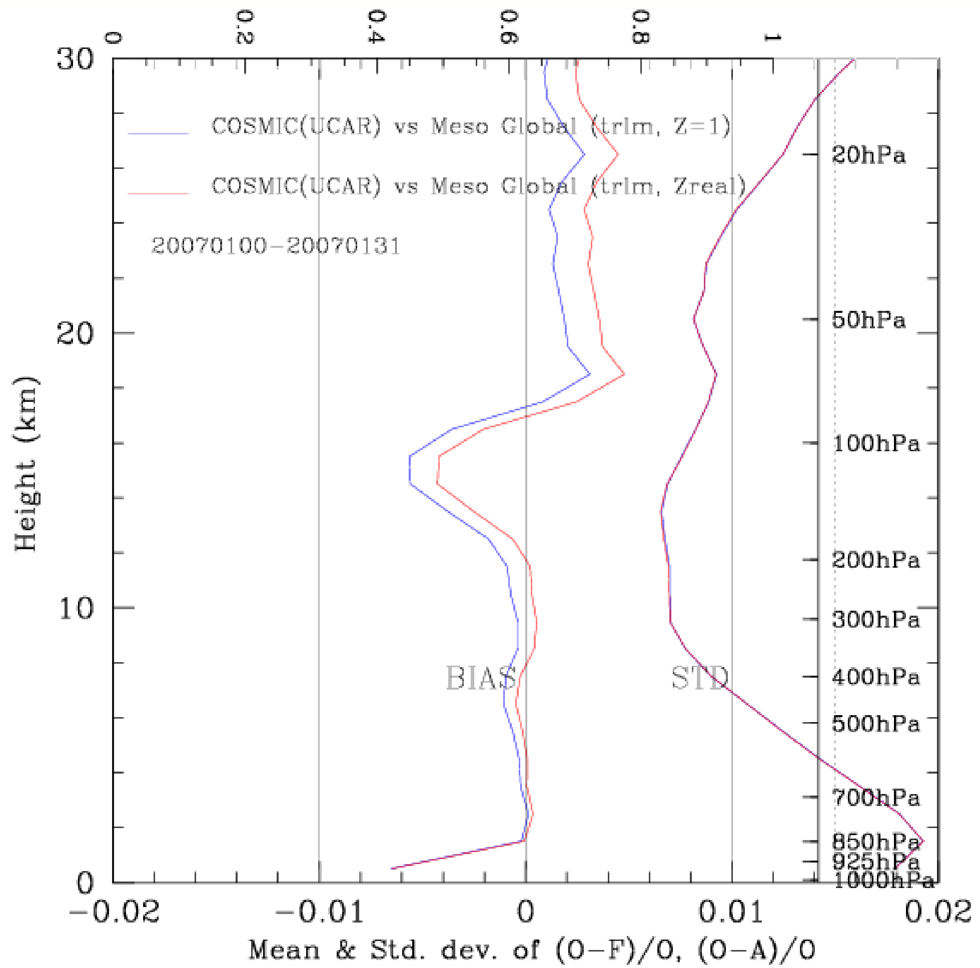
Order of magnitude of the compressibility (Atmosphere)

- For dry air, Z=0 around 77C
- <1 at normal atmospheric conditions
- Smaller with low temperature
- ~ proportional to pressure
- Z(T) explains why GZ bias was larger in polar regions
- Effect never larger than 0.1% for atmospheric P,T

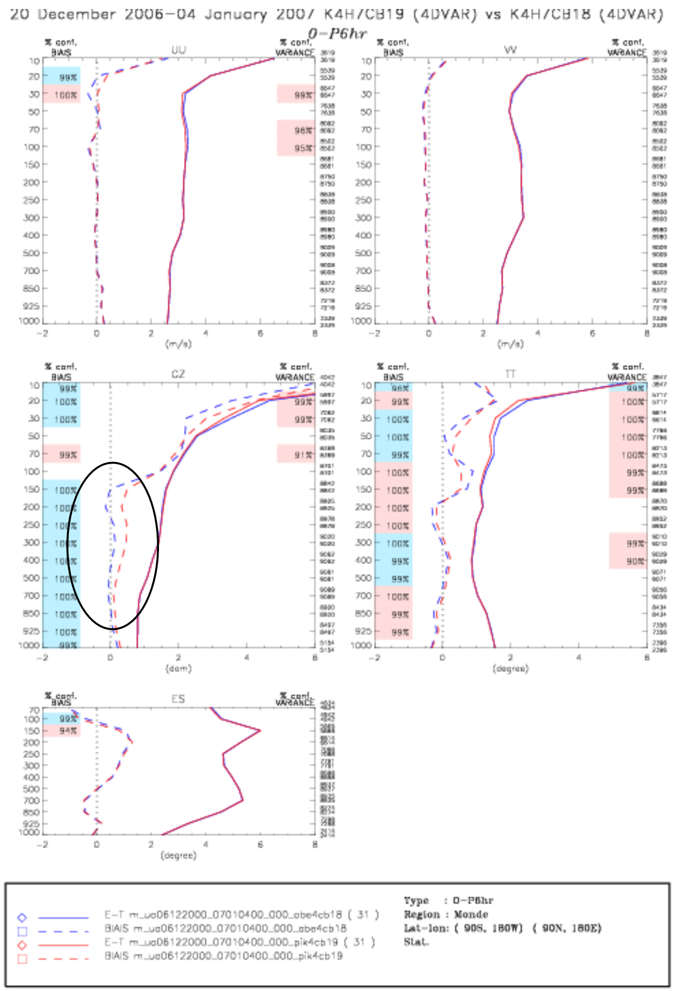


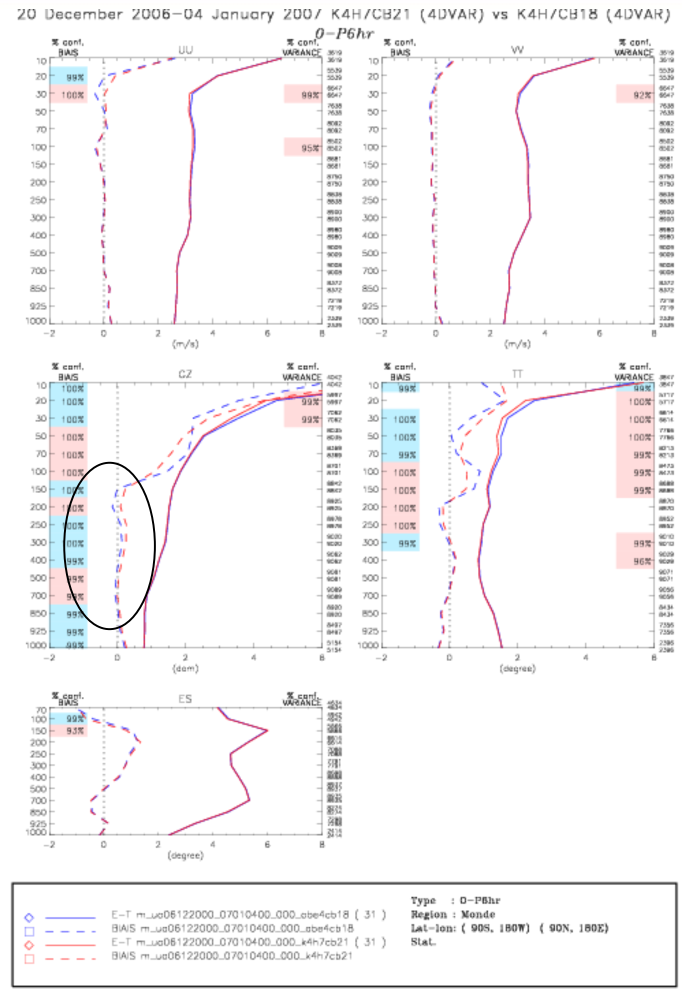
Bias in observation space II

Once included the compressibility Z the bias is very small



RS statistics after accounting for the compressibility (Winter, World)





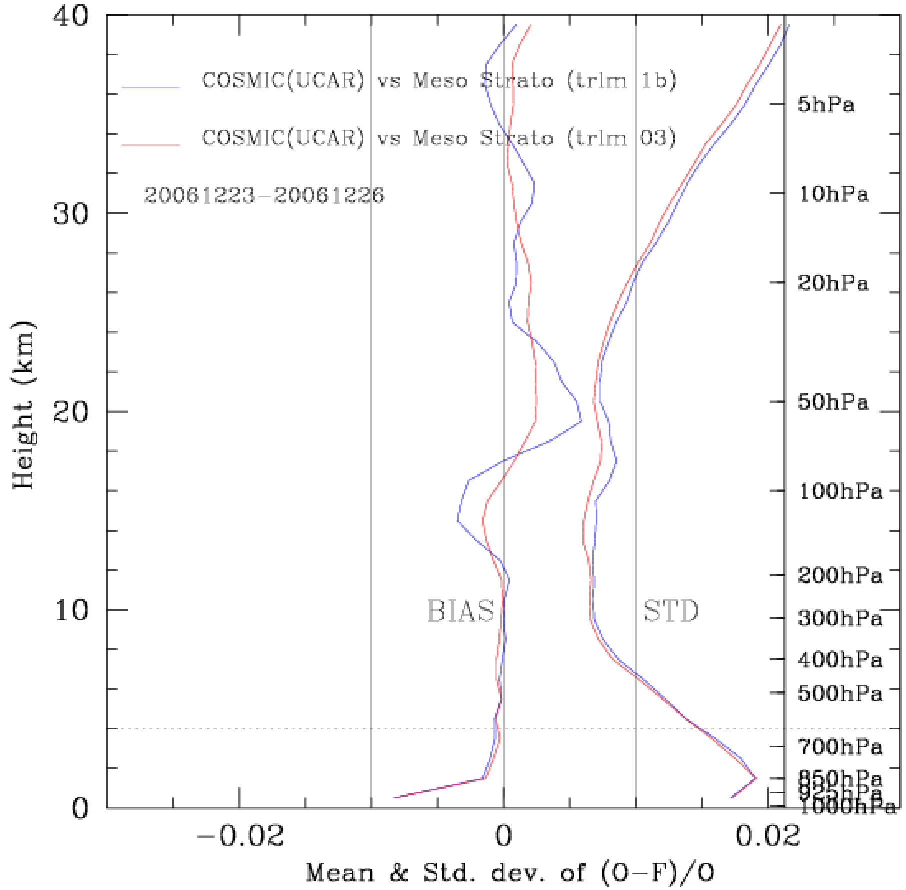
Summary

- Impact of GPSRO data positive in general, especially in the stratosphere.
  - Verified against GPS RO:
    - Generally positive. Very positive in high troposphere & stratosphere.
    - Moderately in tropics.
  - Verified against Radiosondes:
    - Weak impact in N Hemisphere
    - Very positive in S Hemisphere, especially high latitudes
  - Verified against analysis (e.g. anomaly correlations):
    - Weak impact in N Hemisphere
      - Neutral in troposphere
      - Moderately positive in stratosphere
    - Very positive in S Hemisphere, especially high latitudes
- No regions with degradation
- Tropical troposphere has been the most challenging
- Implemented dynamic weighting of GPSRO observations.
- Compressibility of air found not to be negligible. A GZ bias appears if it is not accounted for.

Postscriptum: Meso-Strato

- First results of assimilation in Meso-Strato (with M. Roch)
- Winter 2007
- Only 6 days of cycle so far
- Bias & STD improved when measured against **GPSRO truth**
- Order of magnitude rule of thumb:
  - 0.01 corresponds to ~2.5K
- Blue no GPS assim
- Red with GPS assim

O-F6h for GPSRO data



Thank you!