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Developments on the interpretation and assimilation of GPSRO data at Environment Canada

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Outline

- Considerations around unbiased observations
- Realization of GPSRO as a calibrated source
  - Quality of our knowledge
  - Air compressibility
  - Expression of refractivity
- Exploration of calibration's forecast value
  - Direct value
  - Indirect value through radiance bias correction

The Numerical Weather Prediction (NWP) Objective

- To track the atmosphere numerically:
  - Atmospheric field (AF, external)
  - Numerical field (NF, we control it)
- Tools
  - Correction of the numerical field (=**assimilation** of measurements)
  - Time propagator of the numerical field (=**forecast** model)
- Therefore:
  - We have established a link **AF→NF**
    - Actually (AF → Obs → NF)
  - We want this link to be as **strong** as possible

2 kinds of Observations

Absolute:

- We can state the accuracy of their calibration with high degree of confidence (more than our system)
  - Eg. Radiosondes, GPSRO, some aircraft and surface data
  - We tell the **system to trust the observations (Obs → NF)**
  - Strengthens coupling **(AF → Obs → NF)**

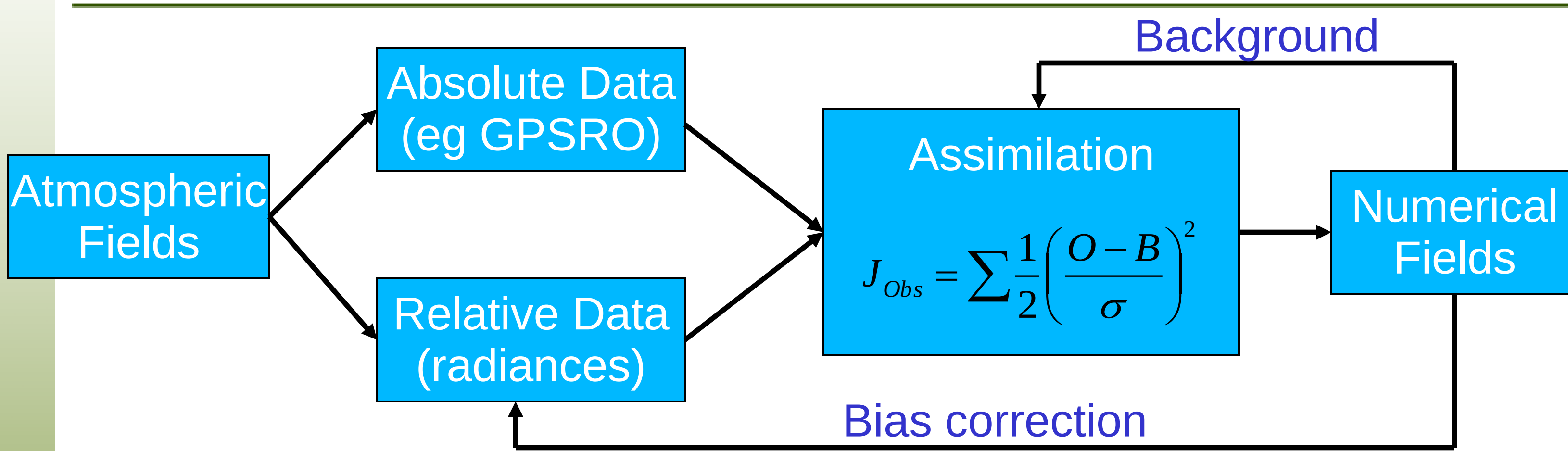
Relative:

- The calibration is less known (less than our system)
  - Notably, radiances (vast amount of data)
  - We establish a bias-correction procedure.
  - We tell **observations to trust the system (NF → Obs)**

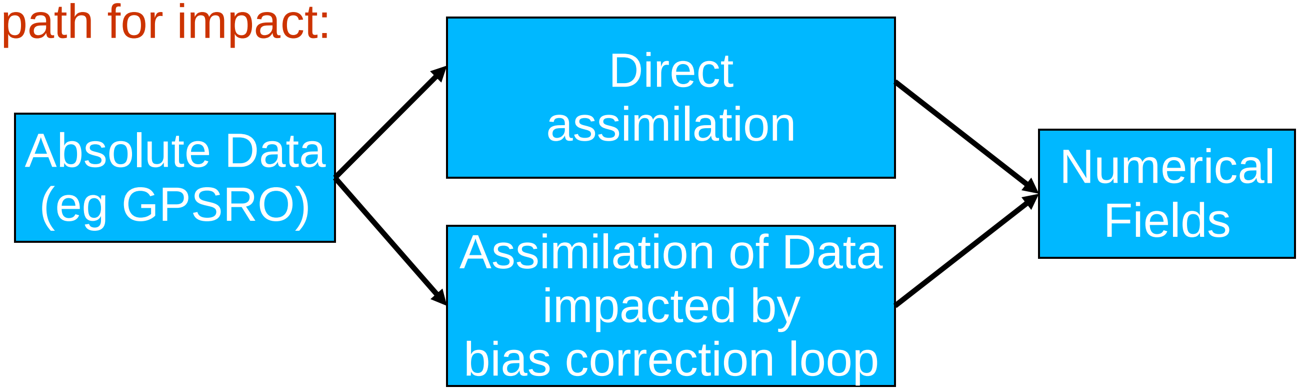
Then:

- Radiances and numerical field end **strongly coupled**
  - Bidirectional coupling **(Obs → NF)** and **(NF → Obs)**
- But actual objective (Numerical Field and Atmosphere) more **weakly coupled**
  - Coupled by **physics** and **absolute observations**

Information flow from data



Double path for impact:



Absolute observations

Impact the numerical field directly

- **numerical field should trust absolute observations**
- (AF → **absObs** → **NF**)

Also impact indirectly:

- relative **observations should trust the field**
- (AF → **absObs** → **NF** → **relObs** → **NF**)
- Feedback loop

Then

- Absolute observations have
  - Larger **impact**
  - Higher **responsibility**

The tolerance to bias (in NWP) : 1

Standard view within the GPSRO community:

- "GPSRO is self-calibrating, unbiased"

But:

- 1: Is it true?
- 2: Is it verifiable?
- 3: Does it require a careful procedure? (to realize the accuracy)

Most measurements in NWP (radiances) are more biased (10x-100x)

- But nobody is claiming that they are not
- They don't receive the responsibility to calibrate other data

The tolerance to bias (in NWP) : 2

- From an **NWP user** perspective, the no-bias claim means:

  "Sufficiently unbiased to avoid degrading forecast performance"

- Window of optimum forecast quality is very narrow
  - Verified in different ways at EC, ECMWF, NCEP.
  - Width of this window about 0.05% (O-B)/B

- Not so surprising:
  - GPSRO injects information at fractional levels around 0.5% (O-B)/B, leaving little room to accept a bias

Traceability of GPSRO

- Chain of measurements related through physically understood relationships, to within a given accuracy, linked to a fundamental property.

- For GPSRO:

TAI – GPS Ground segment – GPS clocks – Receivers – Refractivity – Atmosphere

1 2 3 4 5

-Links 1-2 : outside GPSRO community
-Link 3 : a hardware issue
-Links 4-5 : fall within the retrieval/user community
-Link 5 : (Refractivity-Atmosphere) is the weakest

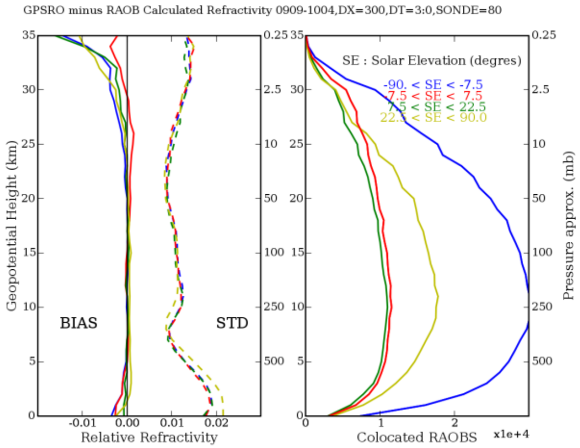
- GPSRO is very precise

enough to be limited by systematic biases in the links

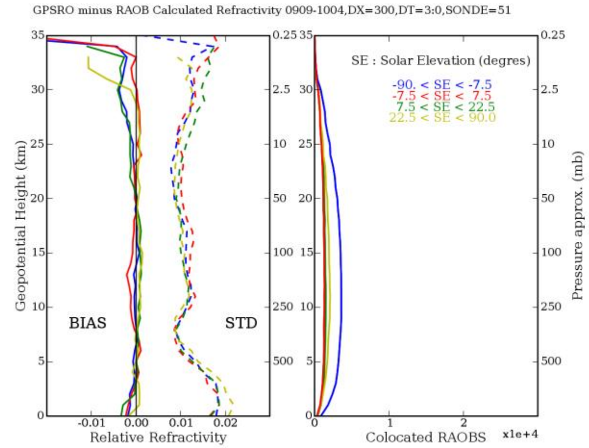
Agreement of several « anchors »

Coincident (>10^4) GPSRO vs several RS types, at several sun elevations

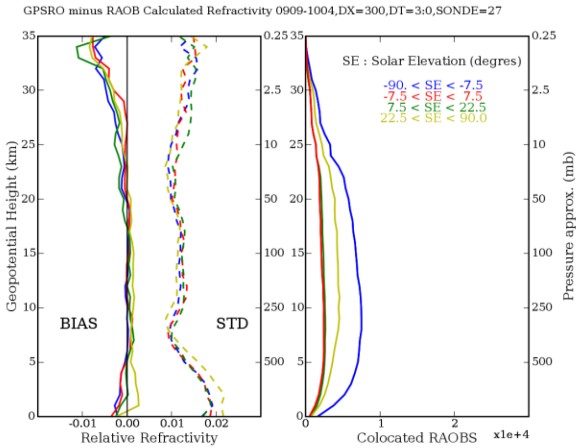
Vaisala RS92



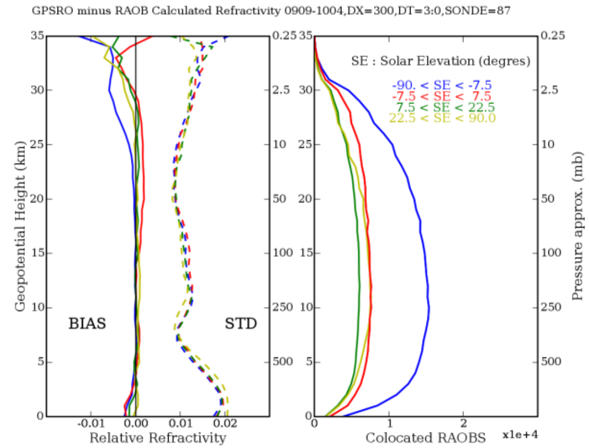
VIZ-B2



AVK-MRZ



Sippican Mark IIA



The Refractivity-Atmosphere link

- Measurement is $N(\vec{x})$
  - Or equivalent $N(h)$, $\alpha(a)$ or other
- Interpreted as field of (P,T,q)
- Required
  - Refractivity expression $N \leftrightarrow (P,T,q)$

    Local relationship (thermodynamic)
  - Structure of the atmosphere $\vec{x} \leftrightarrow (P,T,q)$

    Nonlocal (hydrostatic eqn, etc)

Note: NWP Obs operators must include **<u>both relationships</u>**

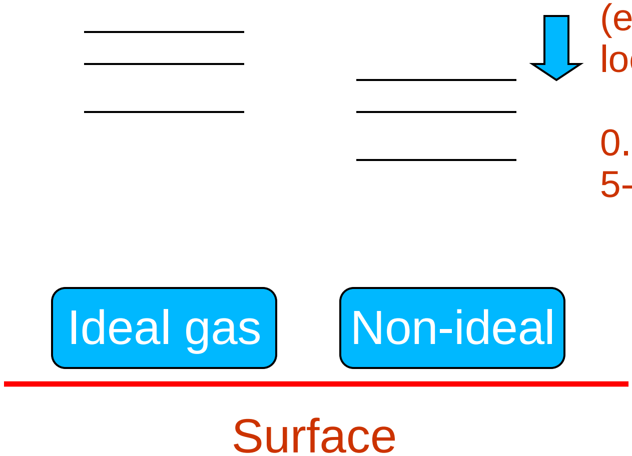
1: Structure of the atmosphere

- Essentially, the hydrostatic equation
- We need there the equation of state (EOS)
- Already found that the deviation of EOS from ideal is non-negligible
- **<u>Non-local</u>**

- 0.05% relevant for NWP if **<u>systematic</u>** (affects the anchor of radiances)

$$\nabla P = -\vec{g}(\vec{x})\rho$$

$$P(\rho, T, x_w)$$



2: Refractivity expression

- Local N(P,T,x)
- Band of expressions within 0.1%
  - We already know that systematic biases of [0.01%-0.1%] do not simply translate to small fcst bias but **affect fcst precision**

    (long term accuracy, tested with GPSRO by EC, ECMWF, NCEP)

Suspected (ECMWF, NCEP) that the classical expression requires recalibration

$$N = k_1 P_d / T + k_2 P_w / T + k_3 P_w / T^2$$

- We undertook this recalibration with
  - Theoretical modeling (microscopic/macroscopic relationships)
  - Selection of high precision data (broad range of measurements)

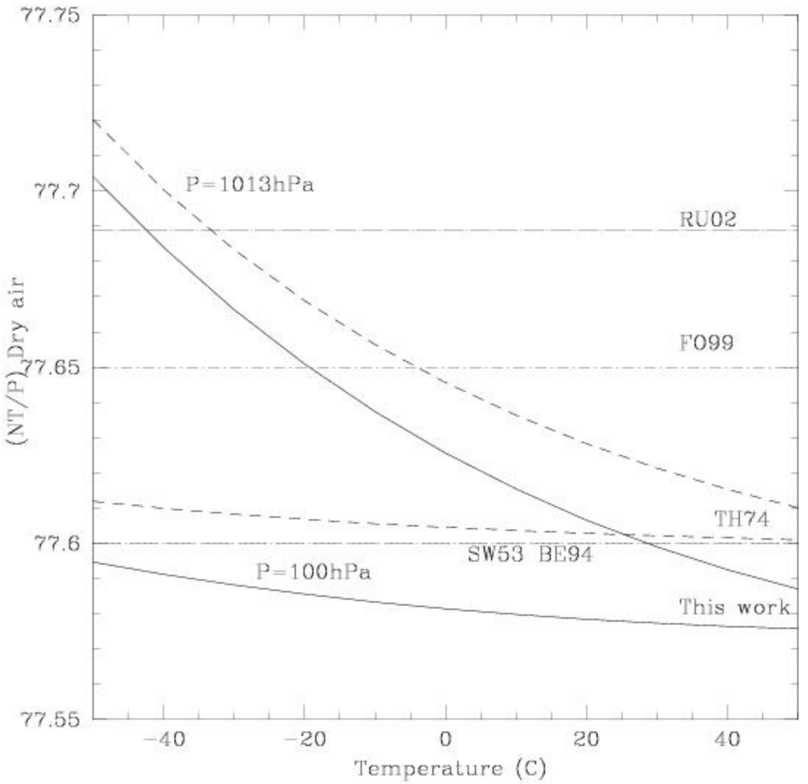
Dry air refractivity

What is normally called k1 (NT/P for dry air)

Not a constant

<u>No constant would fit</u> to better than 0.1% rms

(max err up to 0.2%)



Higher at

- low T
- high P

WV refractivity

WV Partial pressures **not even well-defined** in a non-ideal gas

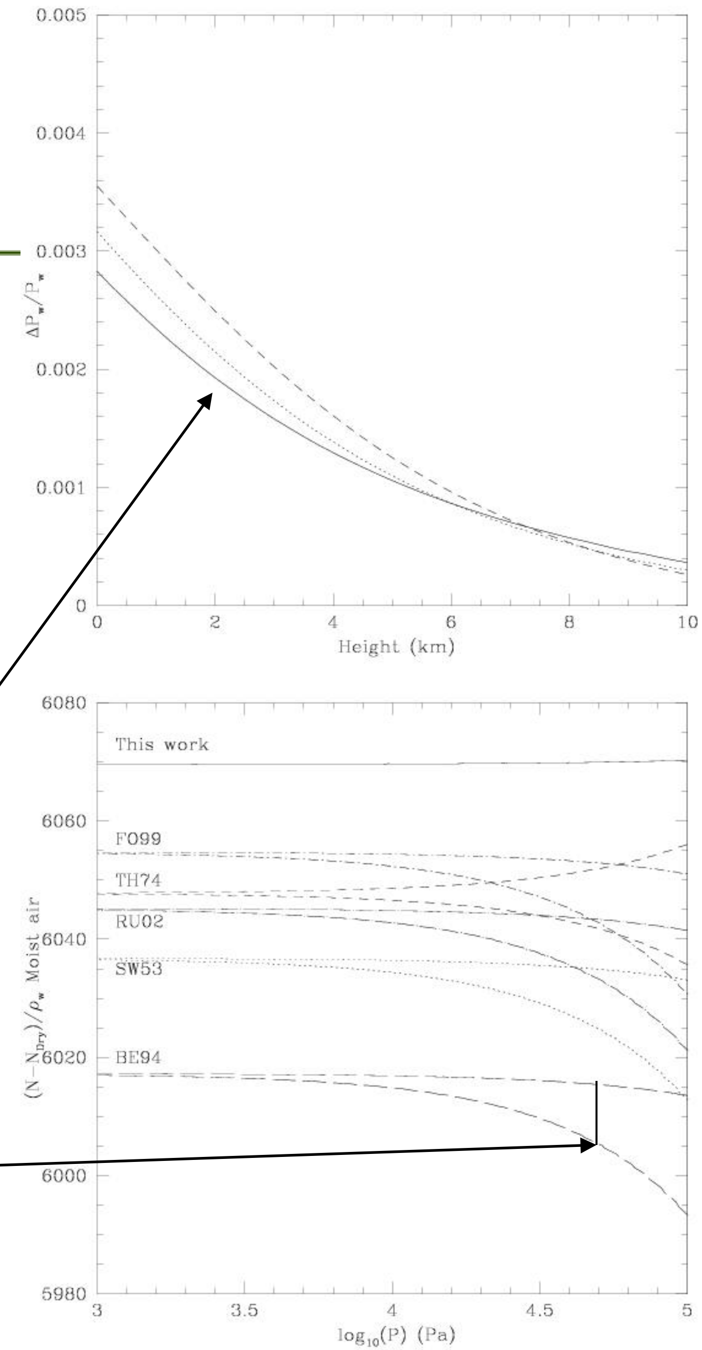
Is it:

$$P_w = x_w P$$

or

$$P_w = P - P_{dehydrated}$$

Or even another?



Proposed setup

Hydrostatic equation

- Should consider $g(\lambda, h)$
- EOS should include compressibility $\rho(P, T, x_w)$

Refractivity expression

- Calibration should have included compressibility
- Expressions of the form $N = k_1 P_d / T + k_2 P_w / T + k_3 P_w / T^2$

  cannot attain stated accuracy (for any set of coefficients)
- By theory or experiment should consider
  - Air composition
  - Molecular polarizability
  - Electric dipoles (H2O)
  - Magnetic (O2) dipoles
  - Dielectric enhancement
  - Univocal meaning

$$\mathrm{Pr}\,oposal:$$

$$N = N_0(1 + N_0 \cdot 10^{-6} / 6)$$

$$N_0 = (222.682 + 0.069 \cdot \tau) \cdot \rho_d +$$

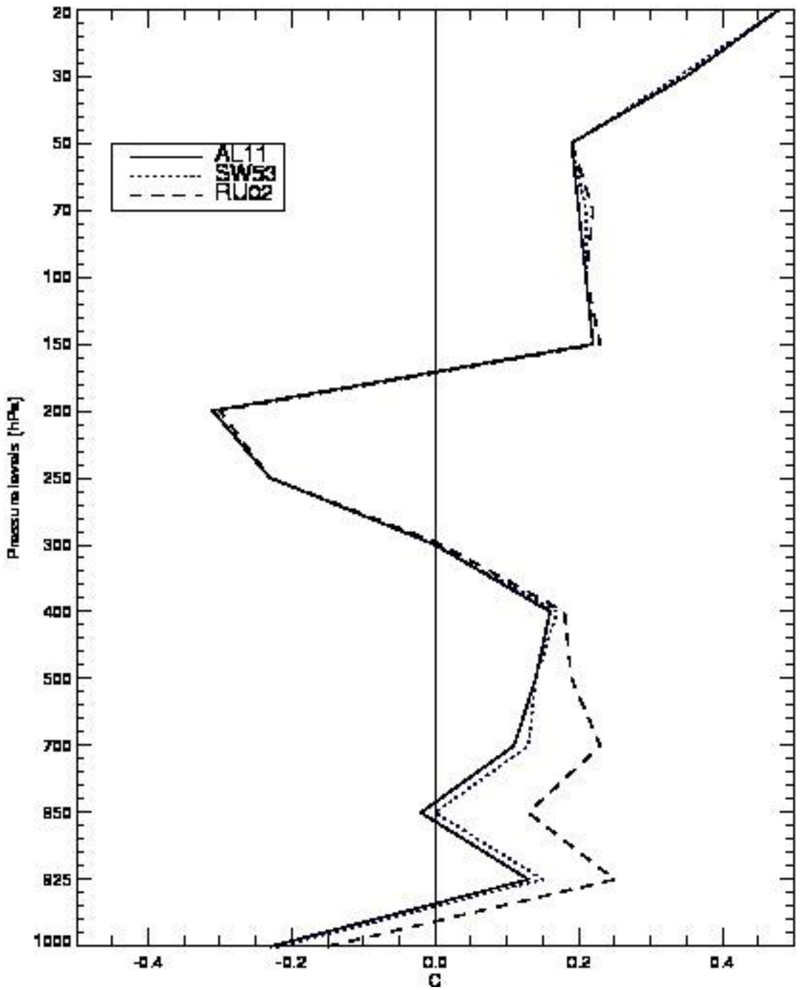
$$(6701.605 + 6385.886 \cdot \tau) \cdot \rho_w$$

$$\tau = 273.15 / T - 1$$

Forecast impact of the calibration I

- Different implementations of GPSRO calibration
  - Our first (RU02)
  - Our refined (see former viewgraphs, AL11)
  - Other tests (SW53)
- Good tropospheric temperatures at stake

RS Temperatures (World AVG)



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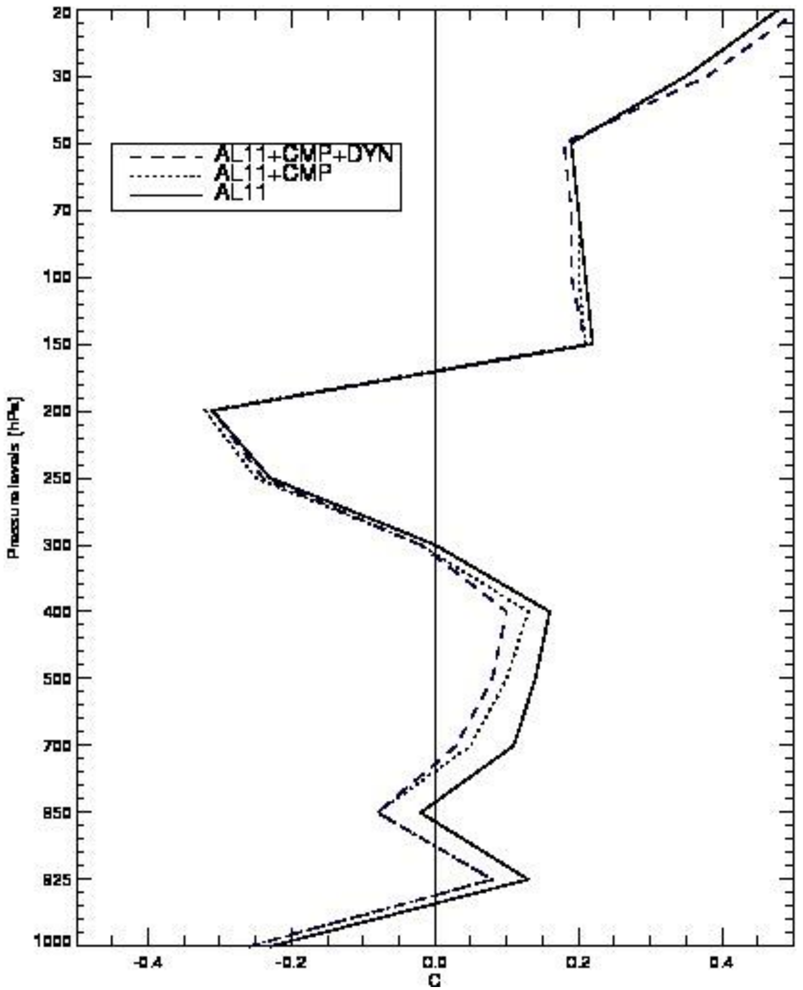
Forecast impact of the calibration II

RS Temperatures (World AVG)

- Bias correction
  - Each RO implementation blocked/allowed to calibrate radiances
- Blocking/allowing (DYN) bias correction feedback loop between implementations
- Impact smaller, but comparable to differences between calibrations
- Indirect impact of RO assimilation comparable to direct impact



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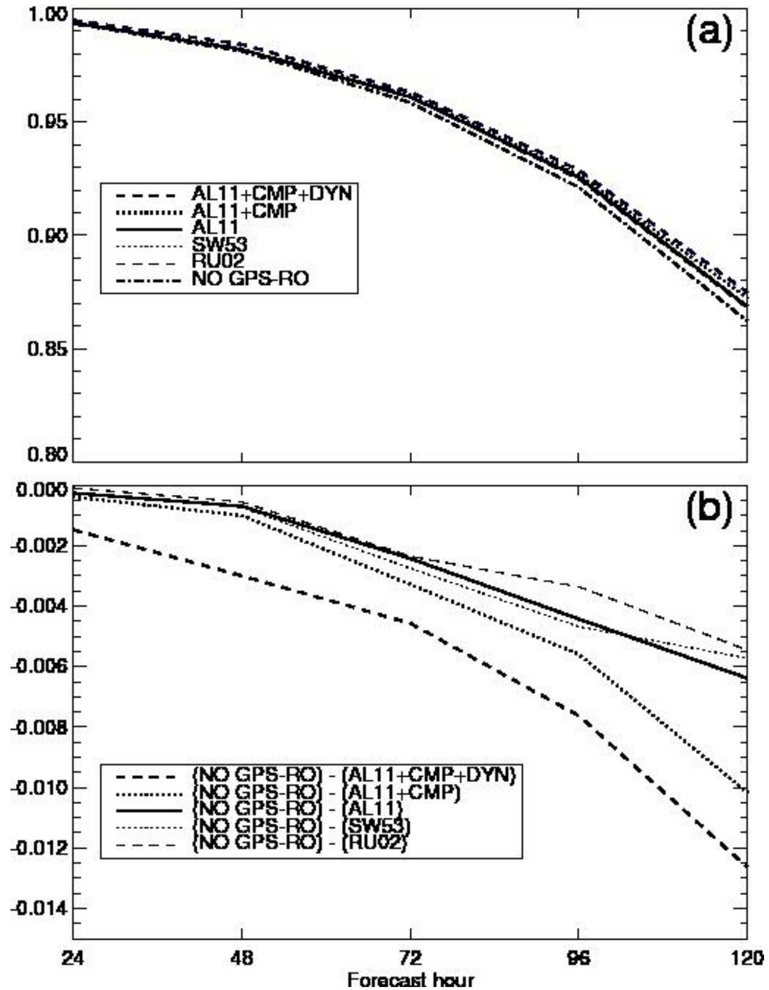
Forecast impact of the calibration III

- We use NO-GPSRO as reference
- Blocking/allowing (DYN) bias correction feedback loop between implementations
- Impact comparable to differences between calibrations
- Indirect impact of RO assimilation comparable to direct impact

Anom CORR GZ 500



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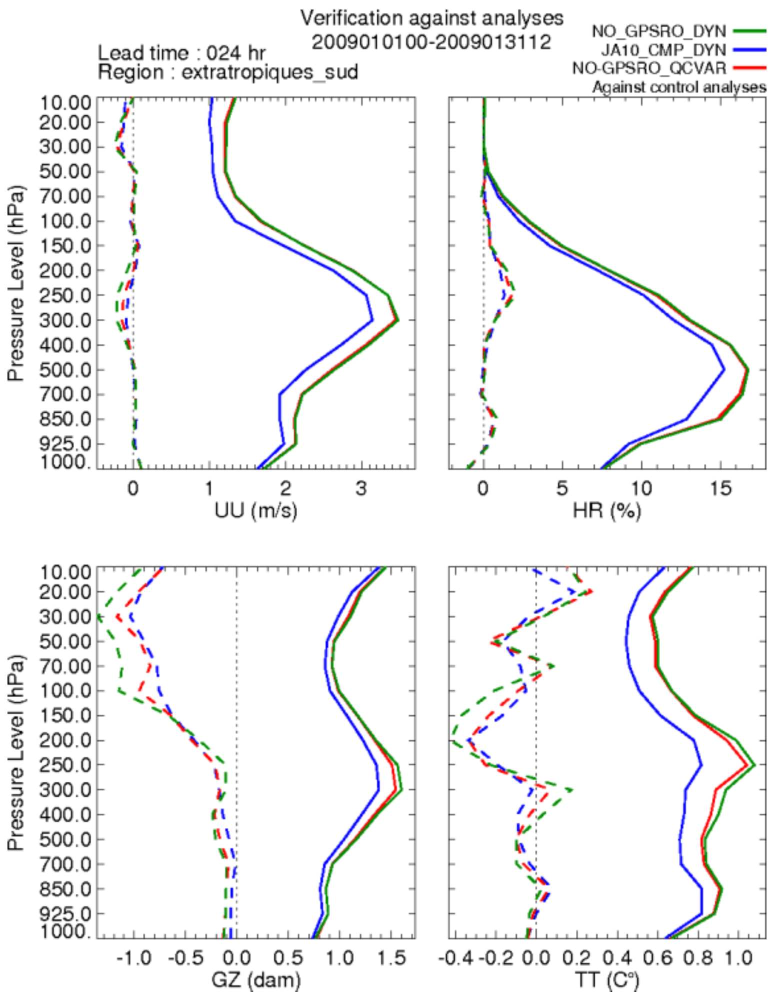
GPSRO denial test

- Cycles
  – Best estimate, with its own bias correction
  – No GPSRO assimilation, but bias correction from best estimate retained
  – No GPSRO assimilation, and bias correction recalculated



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Conclusion

- As calibrated data, GPSRO has
  - Direct impact (entered in the cost function)
  - Indirect impact (anchors radiance bias correction)

- Both impact paths have forecast value

- Different calibrations lead to different fcst performance

- Indirect impact smaller than direct, but comparable

For both reasons:

- A careful revision of intercalibration recommended for optimal results

Thank you!