Use of GPS radio occultation measurements at ECMWF

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Many thanks to NSPO for the invitation to this meeting.
Outline

• **NWP**
  - Assimilation of GPS-RO at ECMWF.
  - Overview of current impact of GPS-RO for the period **DJF 2017-2018**.
  - Surprising(?) impact on tropical upper-tropospheric/stratospheric winds.
  - Idea for improving the bending angle forward model.

• **GPS-RO is ESSENTIAL for climate reanalyses** because its an *anchor measurement*.
  - Consistency of climate temperature reanalyses in UTLS since FORMOSAT-3/COSMIC.
  - **Indirect impact on stratospheric humidity**? Point to interesting published work outside this community. *More work required here.*

• Summary.
SOPHISTICATED assimilation with the 2D forward model. Solving a set of ray path equations rather than the BA integral.

The outer loop uses 31 profiles to describe the 1200 km “occultation plane”.
Reminder: Assumed **global** error statistic model (**CRUDE**) 
Same model used for all GPS-RO (GRAS, COSMIC, GNOS).

Impact height

- 1.25 % at 0 km
- 20 % at 10 km
- 3 microradians at ~32 km

% bending angle uncertainty
Data assimilated

• GRAS data from Metop-a,b assimilated to the surface (~1200-1300 profiles).

• COSMIC 1,6 (~350).

• TSX+TND-X (~350).

• Since March 6, 2018 FY3-C GNOS (~400). We do not yet assimilate these data to the surface.

• Experiments shown here are from the GNOS testing period.
Recent GPS-RO experiments for DJF 2017-2018

• Look at the impact of GPS-RO in/out with current operational system, using all data assimilated operationally.

• In a 12 hour assimilation window we assimilate ~210,000 bending angles in total. **Compare with hi-res IR sounder radiance numbers.**
  – Two IASI instruments ~ 6.4 million radiances.
  – AIRS ~2.6 million radiances.
  – CRIS ~2.9 million radiances.

• Verification against ECMWF operations (medium-range) and against other observations (short-range).

• **Focus on changes to forecast error statistics.** Look at the fractional (or %) change in the standard deviation of the forecast errors.
  – \( \frac{(\text{RO}_{\text{sigma}}-\text{NoRO}_{\text{sigma}})}{\text{NoRO}_{\text{sigma}}} \) **(-VE is GOOD)**
Temperature errors statistics

Error bars 95% confidence interval

GOOD
Short-range forecast/analysis fit to radiosonde temperatures (tropics)

Instrument(s): TEMP–
From 00Z 23–Nov–2011

Instrument(s): TEMP–T
From 00Z 23–Nov–2017 to 12Z 5–Mar–2018

Area(s): Tropics

Pressure [hPa]

std. dev. [K]

94 96 98 100 102

Analysis std. dev. [%], normalised

FG std. dev. [%], normalised

GNOS_8km

NoRO

EUROPEAN
Relative humidity

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS

23-Nov-2017 to 4-Mar-2018 from 93 to 102 samples, Verified against 0001.
Confidence range 95% with AR(1) inflation and Sidak correction for 4 independent tests
Vector wind statistics
Vector wind statistics

Surprising (?) impact on winds in tropics. Can also see it in fit to radiosonde winds
This improvement in the winds is produced by the bending angles in +/- 20 degree latitude band. Bending angles above an impact height of 10 km seem most important.

But the mechanism is unclear (to me, at least!) at present (e.g., B matrix correlation, ...?)
An idea for forward model development

• Bending angle profiles normally have ~200 m separation in the vertical in the BUFR files.

• Wave optics processing provides bending angle profile on a much denser grid ~ 1 m, which is then *smoothed and thinned*. We can include this processing step in the forward model.

• Compute bending angles on finer grid, \( H(a_i) \), with the 2D operator (say ~25 m), then introduce a vertical averaging similar to the observation processing.

\[
\alpha(a) = \sum_i w_i H(a_i)
\]

• Where (*I’ve assumed – input from data providers please!*)

\[
w_i = C \exp \left( - \left( \frac{a - a_i}{10000(m)} \right)^2 \right)
\]
Some improvement in GPS-RO departure statistics

Instrument(s): METOP–AR, AS, BR, BS COSMIC–6S
Area(s): N.Hemis S.Hemis Tropics
From 00Z 1–Jun–2017 to 12Z 10–Jul–2017

Possibly invalid – numbers are different by 19%

More data through the QC
Reanalyses (input from Adrian Simmons)

• GPS-RO is now considered an essential measurement for climate reanalyses (e.g., ERA-5, ERA-Interim, JRA-55, MERRA, MERRA-2).
  – Anchor measurements: assimilated without bias correction.

• The consistency of different climate reanalyses in the lower/mid stratosphere has improved significantly since the assimilation of COSMIC/FM3 late 2006.

• Suggests the observation set prior to COSMIC was not sufficient to constrain the mean state.
Tropical tropopause temperature

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Tropical tropopause temperature

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Indirect stratospheric humidity impact?

They use reanalysis temperatures and winds to compute particle trajectories to estimate the humidity entering the stratosphere in the tropics.

They introduced a bias correction for ERA-Interim to account for temperature changes introduced by COSMIC.
An indirect impact of GPS-RO on stratospheric humidity in reanalyses?

The stratospheric humidity is set to 0 in the “classical” temperature retrieval:

\[ N = 10^6 (n - 1) \]
\[ = \frac{c_1 P}{T} + \frac{c_3 P}{T^2} \]

This is reasonable because the contribution to the refractivity in the stratosphere from humidity is negligible. The GPS-RO alone does not provide information about stratospheric humidity.

However, air enters the stratosphere primarily in the tropics (The Brewer-Dobson Circulation). The composition of the air is determined by the tropical tropopause layer (TTL).

The air passing through the TTL is dehydrated (“freeze-dried”) at the cold point tropopause, leading to the extreme dryness in the stratosphere. We alter the temperature in this layer!
Physical processes in the tropical tropopause layer and their roles in a changing climate

William J. Randel* and Eric J. Jensen

Near 83 hPa

Water vapour

Tropopause temperature

GPS-RO
COSMIC is active in ERA-Int in Dec 2006.

COSMIC warms the tropical tropopause.
⇒ Moister stratosphere.
⇒ Gradient $d(Q_s)/d(T_{cp}) \sim 0.5 \text{ ppmv/K}$
More work to do here but qualitatively by improving the tropical tropopause layer and reducing a cold bias in ERA-Interim, we should be increasing the stratospheric humidity.

Can we confirm the increase? Is it improving the stratospheric Q?

Note the SPARC community emphasise that reanalysis stratospheric humidity values should be used with caution, although ERA-Interim is described as “… surprisingly reasonable …”.
Courtesy Sean M Davis, NOAA
Summary

• Outlined the assimilation approach, and presented recent GPS-RO impact experiments for DJF 2017-2018.

• Impact on tropical winds requires more analysis.

• Still trying to improve the bending angle observation operator. Vertical averaging step looks promising.

• GPS-RO is an essential observation type in reanalyses because its an “anchor measurement”.
  – Convergence of UTLS temperatures since COSMIC.

• FM3/COSMIC has led to improved consistency between the various stratospheric reanalyses.
  – Indirect impact on stratospheric Q via the model dynamics should be investigated further.