Assimilation of GPS radio occultation measurements at the Met Office

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Talk outline

1. Met Office assimilation system / observation operator
2. Status of RO in operations
3. Recent impact studies
4. Future developments
Met Office system: brief summary

- NWP model is the Unified forecast model (UM):
  - Non-hydrostatic equations
  - Height as the vertical co-ordinate.
  - Charney-Philips grid-staggering in the vertical.
  - Terrain-following near the surface.

- Variational data assimilation system (VAR):
  - Incremental 4D-Var.
    - Uses perturbation forecast (PF) model to map background error info to the time of the observations
    - PF has simplified linearised physics, rather than direct tangent linear/adjoint of non-linear UM.
RO assimilation method within VAR:

• Given state vector $x_1$ on the $1^{\text{st}}$ iteration:
  • Forward model $N$ using non-linear operator: $y_1 = H(x_1)$
  • Calculate local gradient i.e. jacobian, sometimes called $K$ matrix:
    $$\frac{\partial y_1}{\partial x_1} = \frac{\partial H(x_1)}{\partial x_1} = K$$

• Store $x_1$, $y_1$ and the $K$ matrix.

• On subsequent iterations given incremented state vector $x_n$:
  • apply the tangent-linear approximation to estimate $y(x_n)$:
    $$y_n = y_1 + K(x_n - x_1)$$
  • Use $y_n$ and $K^T$ matrix to calculate on $n^{\text{th}}$ iteration:
    • Observation cost function ($J_{\text{obs}}$):
      $$J_{\text{obs}}(y_n - y_{\text{obs}})^T R^{-1} (y_n - y_{\text{obs}})$$
    • Gradient of $J_{\text{obs}}$ wrt $x$:
      $$\frac{\partial (J_{\text{obs}})}{\partial x_n} = \left( \frac{\partial y_1}{\partial x_1} \right)^T R^{-1} (y_n - y_{\text{obs}}) = K^T R^{-1} (y_n - y_{\text{obs}})$$

• Total GPSRO $J_{\text{obs}}$ and gradient information used with contributions from other observation data in the minimisation problem to produce an updated $x$. 
1. Interpolate model column data to occ time and location: to give \( x \)

2. Interpolate Exner from \( \rho \) to \( \theta \) levels to get \( P \) on \( \theta \) levels

3. Calculate layer mean virtual temperature on \( \theta \) levels

4. Calculate layer mean temperature on \( \theta \) levels, using RH

5. \( N \) calculated on \( \theta \) levels using Smith-Weintraub formula

6. \( N \) interpolated to obs heights
1D refractivity operator
strengths/weaknesses

• Strengths:
  • Simple and quick.
  • No extrapolation above model top, as required for BA.

• Weaknesses:
  • A priori data introduced high up (>~25 km) from climatology in N data.
  • R matrix more complicated for N than BA?

• Future updates:
  • Use q instead of RH.
  • Adjust code for BA assimilation.
  • Met Office system not yet capable of incorporating 2D operators.
GPSRO used in global model

- **UM:**
  - Ran at N320L50 i.e. ~40 km mid lat horizontal resolution, 50 vertical levels, top ~ 0.1 hPa (~63 km).
  - Forecasts out to 6 days.

- **VAR:**
  - 6 hour assimilation window.
  - First iteration non-linear using N320 3, 6, 9 hour forecast background information.
  - Subsequent tangent-linear iterations use increments to model columns.
  - Non-linear iteration is ran on every 10th iteration.
  - Other significant data types assimilated: Sonde, IASI, AIRS, ATOVS, Aircraft, Satwind, Scatwind, Surface, SSMI, SSMIS
**Global model:** GPSRO specific

- Use $R$ matrix for low, middle and high latitudes.
  - Based on $(O-B)/B$ std dev using COSMIC.

![Graph showing models of $R$ matrix standard error](image)

- Assume an exponentially decaying vertical correlation model with a scale length of 3.3 km.

- QC of $N$ data based on output of a 1D-Var.

\[ R_{ij} = \sigma_i \sigma_j \exp \left( -\frac{|z_i - z_j|}{H} \right) \]
Global model operational status

- CHAMP+ GRACE-A (GFZ) switched on.
- CHAMP+ GRACE-A withdrawn - data problems.
- 4 COSMIC sats switched on, FM2,3,5 and 6.
- COSMIC withdrawn - model crash. Later shown unrelated to COSMIC.
- Increase to all COSMIC sats.
- COSMIC reinstated. Latitude varying R matrix.
- Increase vertical range of assim from 4-27 to 0-40 km.

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Number of $N$ profiles assimilated in global model

Update run to produce better background for next run

• Assimilated = COSMIC data
• Available = COSMIC + GRAS + GRACE - A + CHAMP
Impact studies: increasing vertical range

- Increasing the vertical range of assimilation from 4-27 km to 0-40 km gave a small benefit to:

  - Tropospheric relative humidity in extratropics.
  - Winds - highly valued by customers.
  - Stratosphere model bias.

- Routine verification against sondes and analyses is only up to 50 hPa (~21 km).
Forecast RMS % diff. against obs (mainly radiosondes)

Control = 4-27 km

Exp = 0-40 km
Jun 2007
Stratosphere global model bias compared to COSMIC

- BA $(O-B)/B$ stats show a distinct ‘S’ shape bias at > 50 hPa (~22km, around model level 35).

- ECMWF stats shown for comparison: has its own biases

See latest GRAS SAF monitoring: http://monitoring.grassaf.org
Impact on bias of RO up to 40 km

- Stratospheric bias reduced by $N$ assimilation up to 40 km.

- Plot uses BA before statistical optimisation.
Impact of using more RO data

• More data seen to increase magnitude of the impact:
  
  • Dec 2006, going from 4 to all 6 COSMIC sats.
  
  • Jun 2006, going from 4 COSMIC to (6 COSMIC +CHAMP+GRACE-A).
  
  • Jan 2008, GRACE-A and CHAMP (GFZ) on top of COSMIC. Small improvements in geopotential height.
  
• Would be interesting to run experiment using incrementally more data - how saturated with RO are we?
Forecast RMS % diff. against obs, Dec 2006 trials

Increase in no. of occultations:

6 COSMIC vs no GPSRO
Forecast RMS % diff. against obs, Jun 2007 trials

Increase in no. of occultations:

6 COSMIC +CHAMP+ GRACE vs no GPSRO
GPSRO in limited-area models

• Ob types implemented into the global model then go into limited-area models with relatively little testing.

• Concerns higher horizontal resolution - problems using 1D $N$ operator.

• Ran test of $N$ assimilation using 1D operator.
NAE (North Atlantic and European) area
NAE test setup

- 24 km resolution (half operational res. to reduce time).
- 38 vertical levels, ~40 km model top. 4D-Var.
- Typically around 20-30 occs assimilated per cycle. All COSMIC +CHAMP+GRACE-A, using 0-40 km vertical range.
- 20 day period of testing from 24/04/08 to 26/05/08 (with some gaps)
NAE test results

• Verified using limited area **NWP index**. A Met Office score system based on comparisons to observed fields useful in limited-area model forecasting:
  
  • Surface visibility, 6 hr precipitation accumulation, total cloud amount, cloud based height (3/8 Cover), surface temp. and surface wind.

• Saw a small **overall improvement**. Particularly in surface visibility.

• NAE area NWP index increased by +0.13 %, i.e. slightly positive. UK area NWP index +1.23%, although significance in question over limited area and short period.
Some GPSRO in NAE verification

Mean error

RMS error

68% error bars calculated using $S/(n-1)^{1/2}$
Future updates/plans

  - **Global model**: use of MetOp GRAS (10-30 km vertical range), CHAMP+GRACE-A (GFZ) on top of COSMIC.
  - **NAE model**: use of COSMIC, CHAMP and GRACE-A (0-40 km):

- **Further tuning** of system:
  - Obs errors and correlations.
  - Vertical ranges.

- **Experiment** with BA assimilation
Any questions?