Stratospheric Data Assimilation at ECMWF

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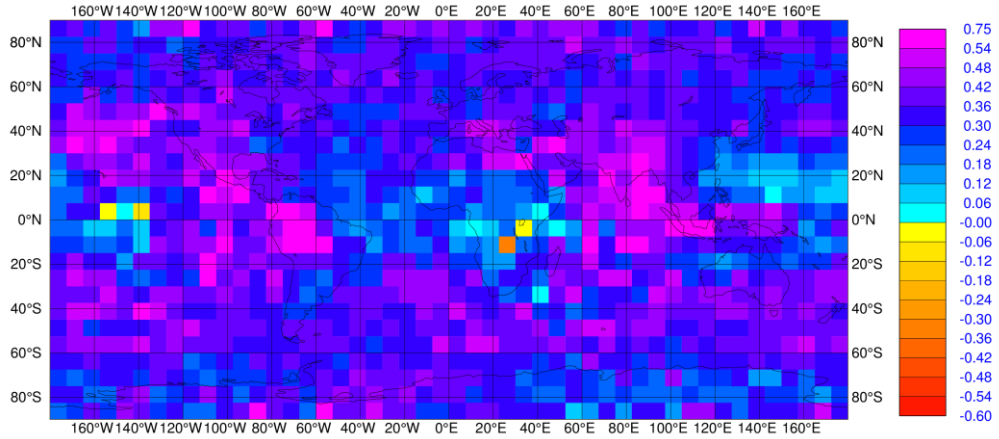
- The stratosphere presents several challenges to the assimilation system, including:
  - Systematic biases in models and observations.
  - Gravity wave dynamics affecting the balance of the analysis.
  - Limited amount of humidity observations.
- Recent developments have made it possible to address some of these challenges more directly, leading to improvements in the stratospheric analysis.

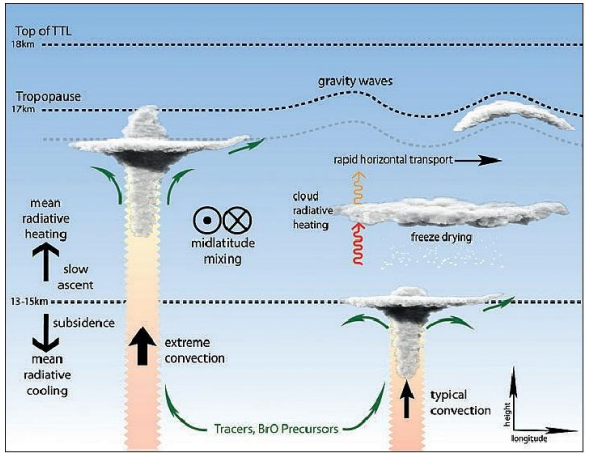
Temperature Bias in the Operational IFS Model

GPS-RO temperature retrievals provide a global coverage which allows the study of spatial patterns of model error



Temperature first-guess departure with respect to GPS-RO (~70hPa, January 2017)

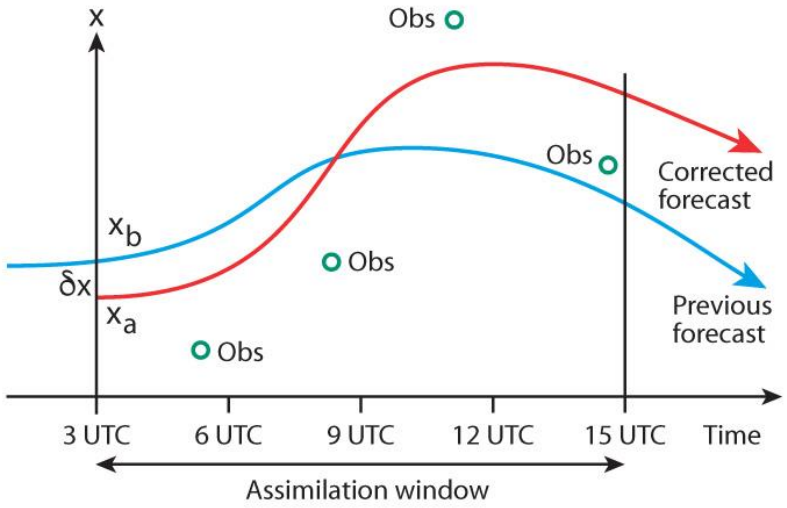
→ model error is large scale and presents specific features



The bias is due to

- discretization errors in the vertical advection (dynamical core)
- inadequate representation of gravity waves in the vertical direction

4D-Var Strong-Constraint Formulation



If the model is assumed to be perfect

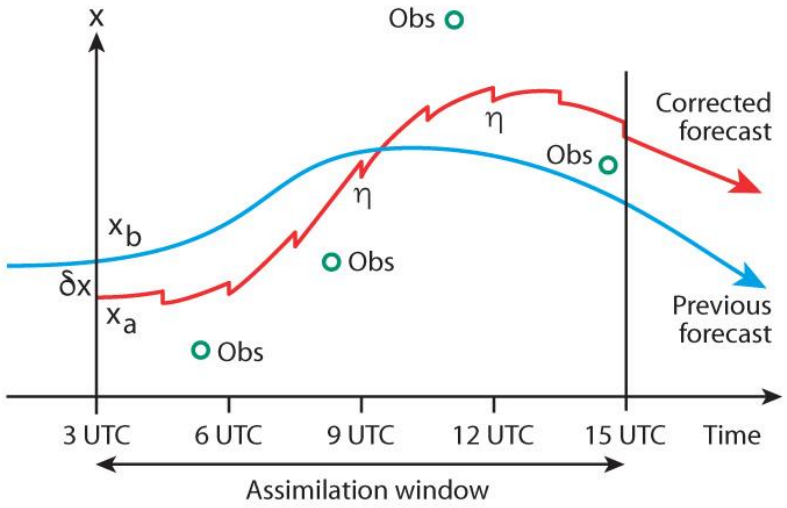
$$\mathbf{x}_k = \mathcal{M}_{k,k-1}(\mathbf{x}_{k-1}) \qquad \text{for} \qquad k = 1, \ldots, N$$

Cost function depends only on the state at the beginning of the assimilation window

$$J(\mathbf{x}_0) = \frac{1}{2}\left(\mathbf{x}_0 - \mathbf{x}_0^b\right)^{\mathrm{T}} \mathbf{B}^{-1}\left(\mathbf{x}_0 - \mathbf{x}_0^b\right) + \frac{1}{2}\sum_{k=0}^{N}\left(\mathcal{H}_k\mathcal{M}_{k,0}(\mathbf{x}_0) - \mathbf{y}_k\right)^{\mathrm{T}} \mathbf{R}_k^{-1}\left(\mathcal{H}_k\mathcal{M}_{k,0}(\mathbf{x}_0) - \mathbf{y}_k\right)$$

4D-Var assumes **random zero-mean errors** for all sources of information, but the IFS model has biases

4D-Var Weak-Constraint Formulation



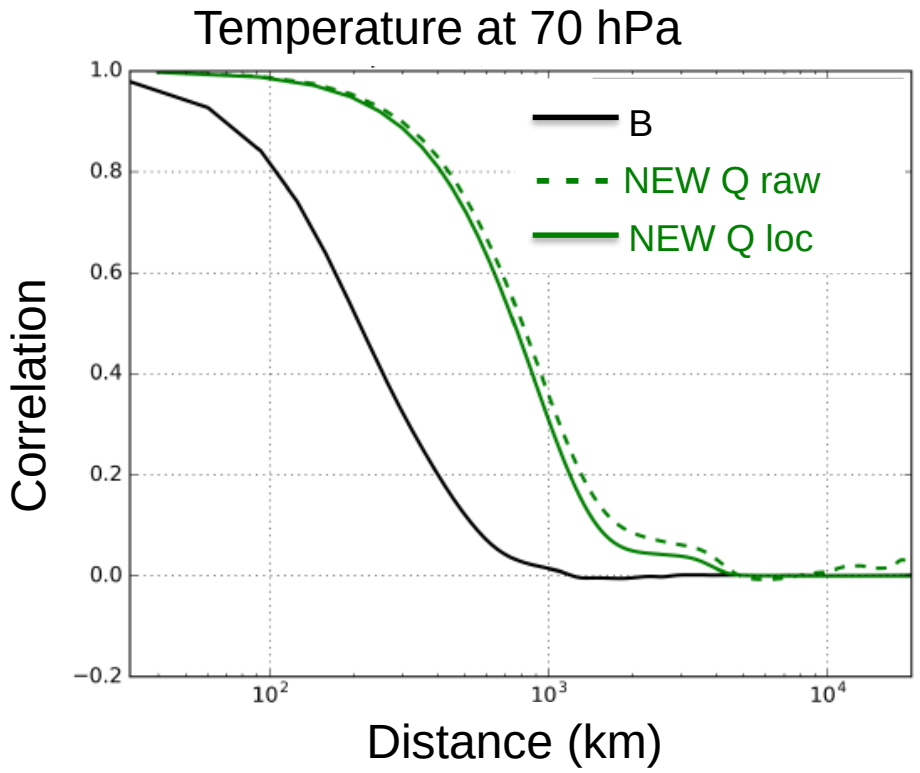
Unknown forcing is introduced (additive, Gaussian, constant within the assimilation window, no cross-correlation with the background error).

$$\mathbf{x}_k = \mathcal{M}_{k,k-1}(\mathbf{x}_{k-1}) + \eta \qquad \text{for} \qquad k = 1, \ldots, N.$$

Cost function depends on the initial state and the model forcing

$$\begin{aligned} J(\mathbf{x}_0, \boldsymbol{\eta}) = & \frac{1}{2} \left(\mathbf{x}_0 - \mathbf{x}_0^b\right)^{\mathrm{T}} \mathbf{B}^{-1} \left(\mathbf{x}_0 - \mathbf{x}_0^b\right) \\ & + \frac{1}{2} \left(\boldsymbol{\eta} - \boldsymbol{\eta}^b\right)^{\mathrm{T}} \mathbf{Q}^{-1} \left(\boldsymbol{\eta} - \boldsymbol{\eta}^b\right) \\ & + \frac{1}{2} \sum_{k=0}^{N} \left(\mathcal{H}_k(\mathbf{x}_k) - \mathbf{y}_k\right)^{\mathrm{T}} \mathbf{R}_k^{-1} \left(\mathcal{H}_k(\mathbf{x}_k) - \mathbf{y}_k\right) \end{aligned}$$

New Model Error Specification in Weak-Constraint 4D-Var



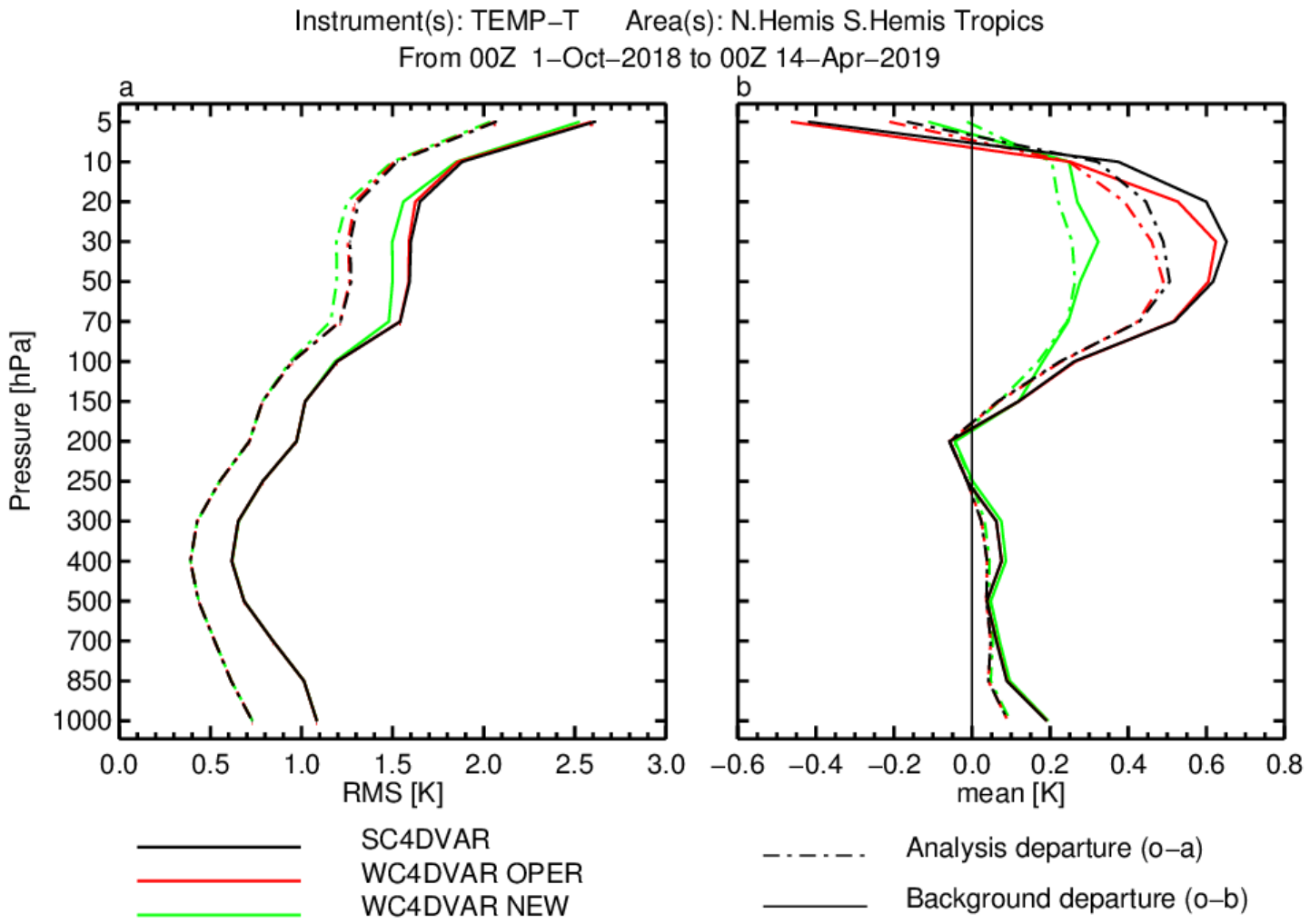
Horizontal correlation in the covariance matrices

→ **B** corrects the small scales

→ **Q** corrects the large scale

Scale separation between model and background errors

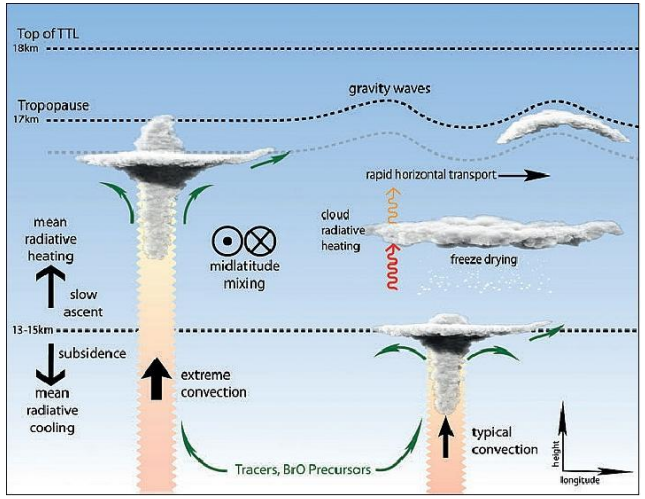
Weak-Constraint 4D-Var with Scale Separation



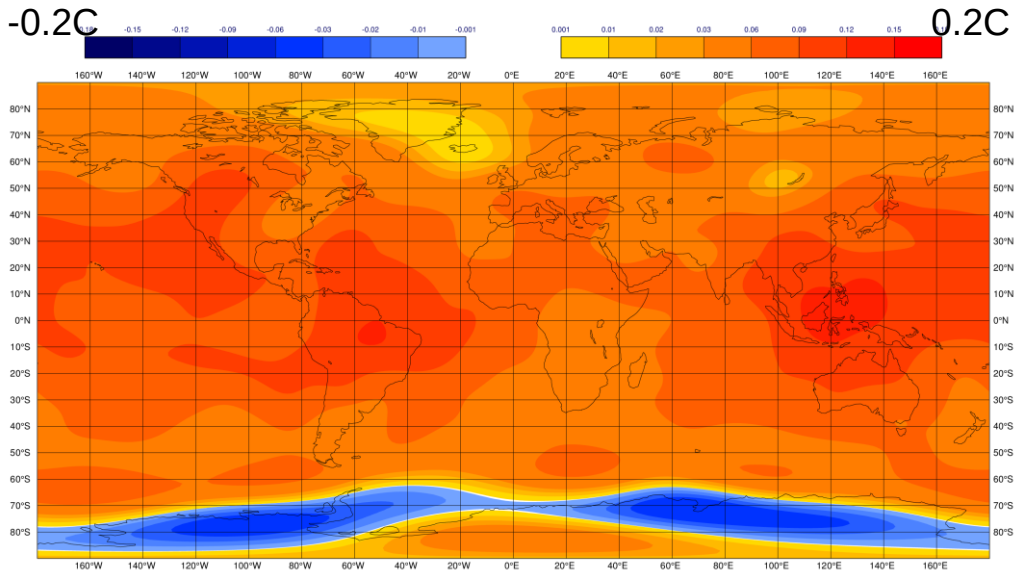
→ temperature bias is reduced up to 50% with respect to radiosondes and GPS-RO (RMSE is reduced up to 6%)

→ implemented in CY47R1 above 100hPa where the model bias is significant

Weak-Constraint 4D-Var with Scale Separation



Cold biases in the lower/middle stratosphere over strong convective regions

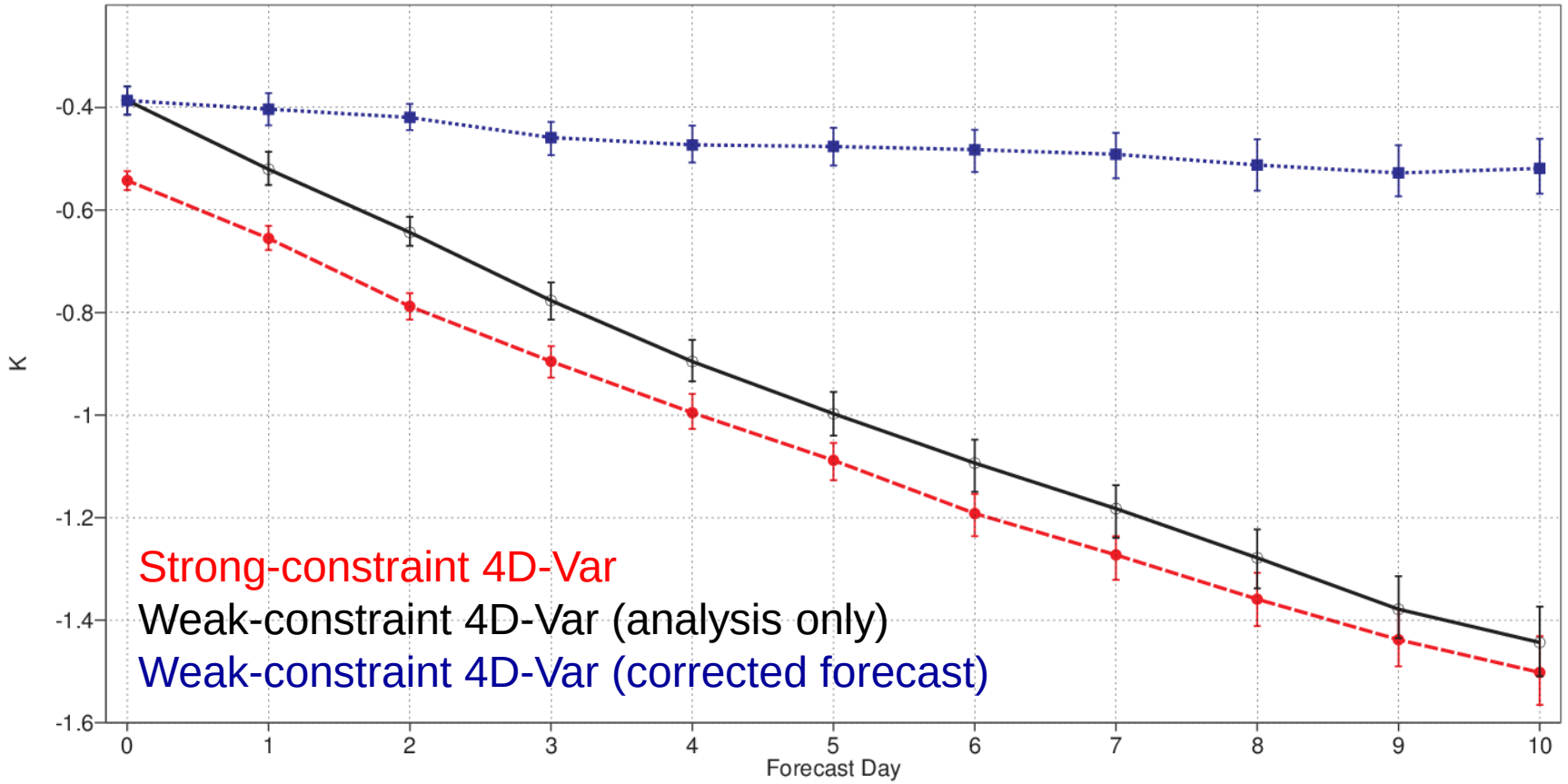


Model error forcing from WC4DVAR NEW at 70 hPa

→ correcting the bias from the missing gravity waves

Use Weak-Constraint 4D-Var Forcing in the Forecast?

Mean forecast error against radiosonde temperature (70hPa)



Forecast lead time (day)

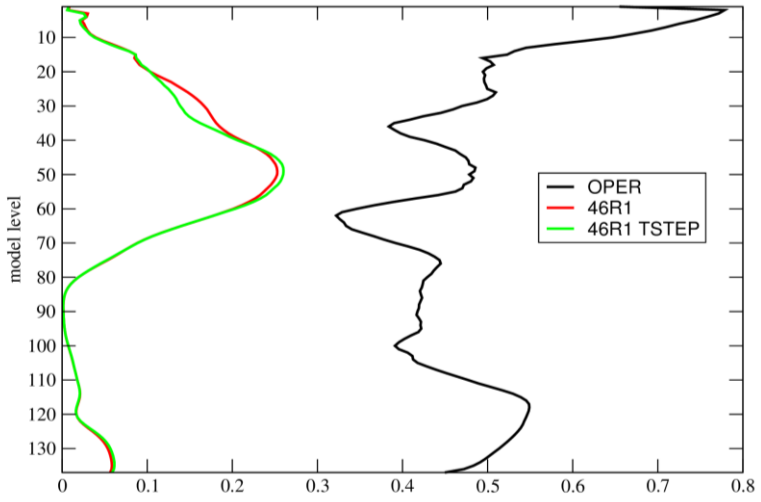
WHAT IF the model error estimation η is applied as a constant model forcing over 10 days?

→ the forecast model is not biased anymore and mean error does not increase

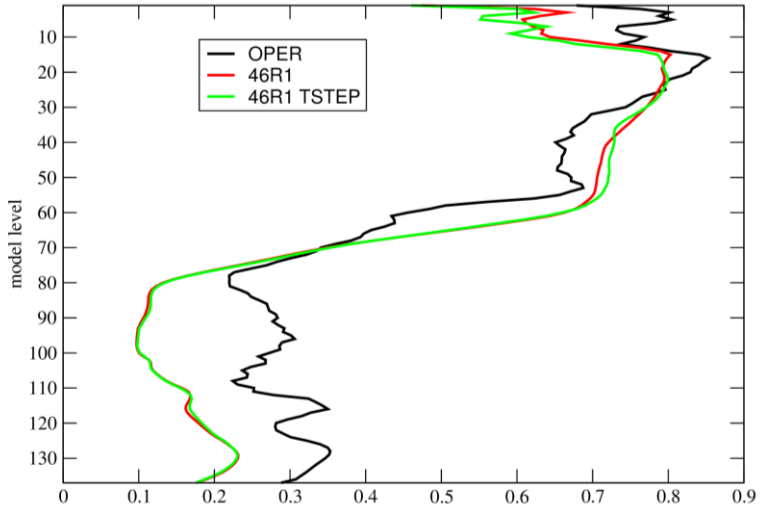
Stratospheric Gravity Waves: Balance off in Stratosphere

- Problem 1: Stratospheric gravity waves cause noise when the analysis uses the normal balance operator (nonlinear balance and omega equation) in assimilating mainly temperature observations in the stratosphere. But in principle, the model and analysis should be able to handle gravity waves, they are reasonably predictable outside Tropics.
- "Solution": Balance operator tapered off starting from 50hPa, completely above 20hPa.
- However, balance diagnostics show that the mass-wind balance still explains ~20% of the divergent wind increment in the stratosphere and ~70% of the rotational increment:

Explained divergence

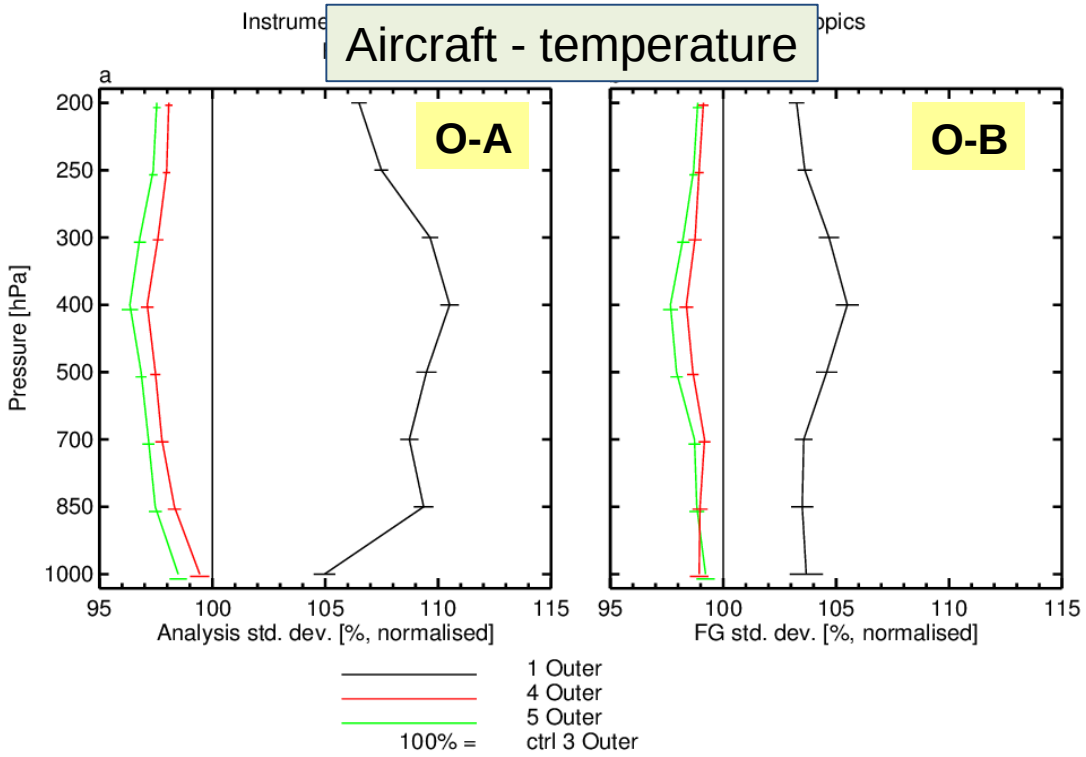


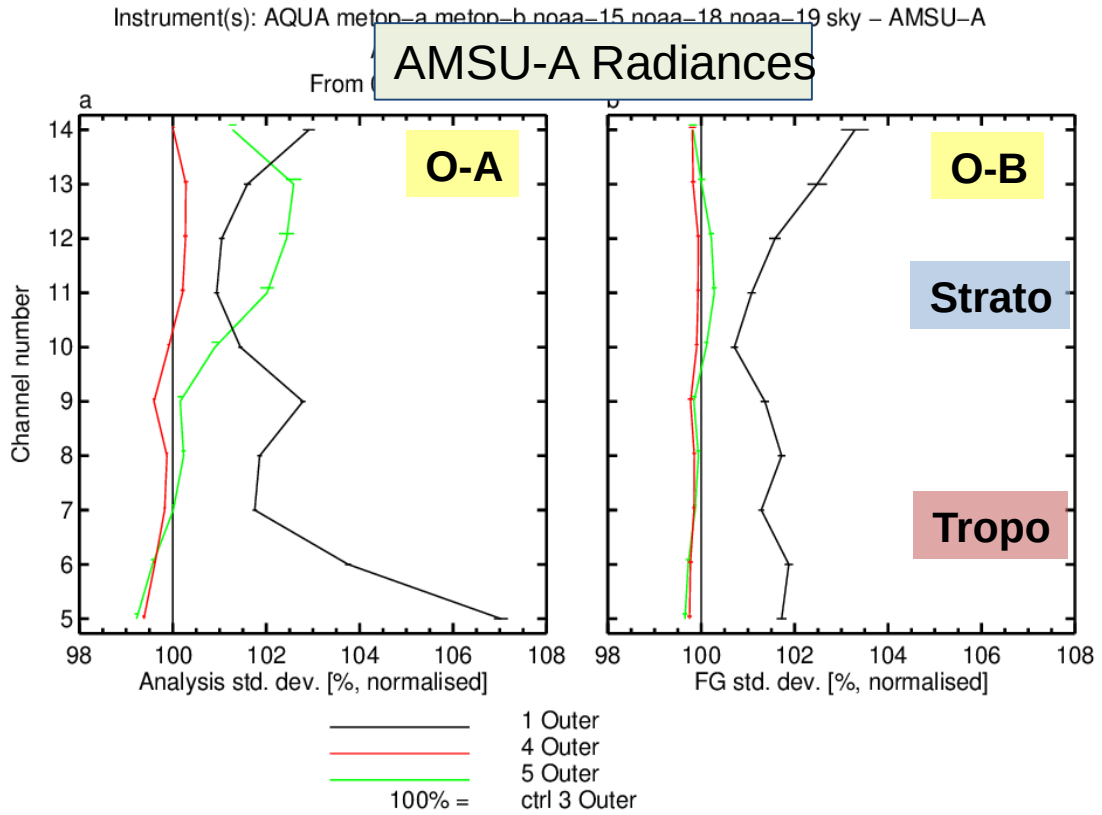
Explained vorticity



Stratospheric Gravity Waves in the Analysis

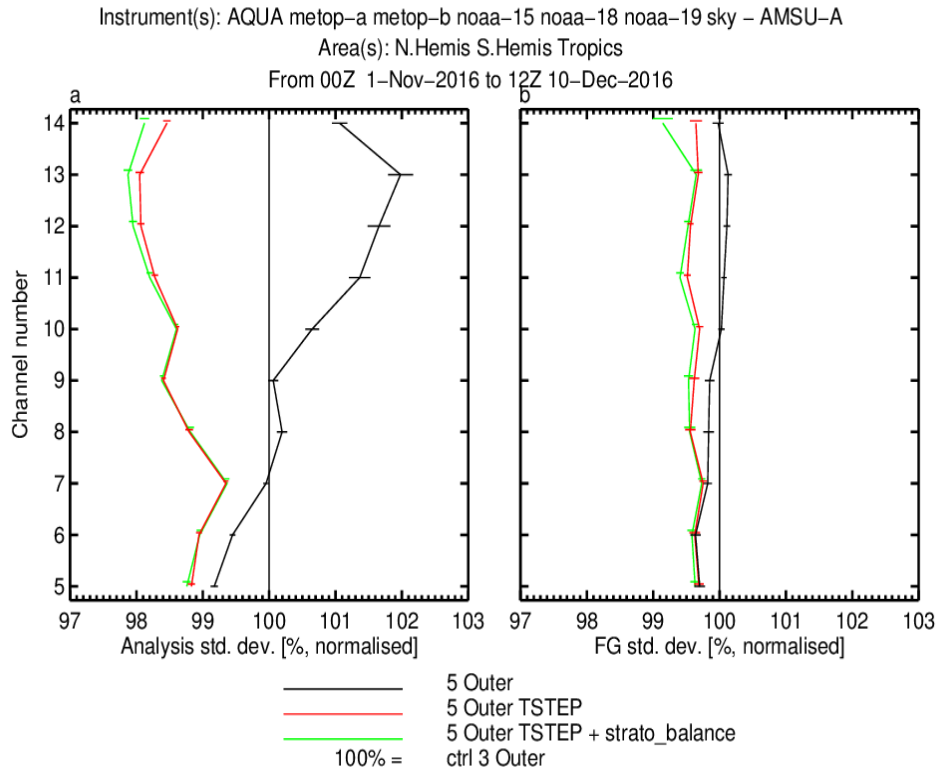
Problem 2: Experiments with ECMWF 4D-Var showed that increasing the number of outer loop re-linearisations beyond three is beneficial in the troposphere, but lead to degraded O-A and O-B statistics in the stratosphere. More outer loops possible by Continuous Data Assimilation, “Cont-DA”, developments that moves work out of the time-critical path for operations.





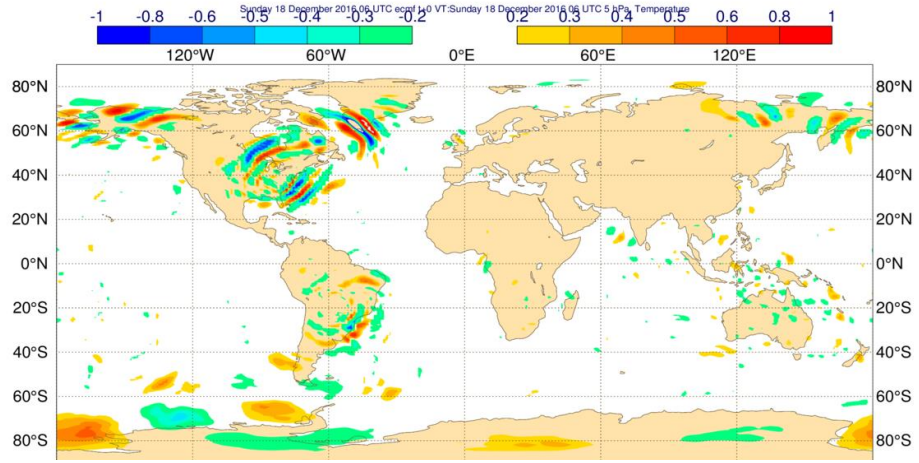
Solution: Matching Timestep in Final Minimisation

- Why? Numerical gravity wave propagation speed is mostly sensitive to timestep, and not resolution
- Solution: **Matching timesteps** in 4D-Var outer/inner loops which are at different resolution. Knew this earlier, but more outer loops make it more important + recent Cont-DA developments make it affordable.
- Improved O-B statistics in the stratosphere, even with stratospheric balance (using new statistics).

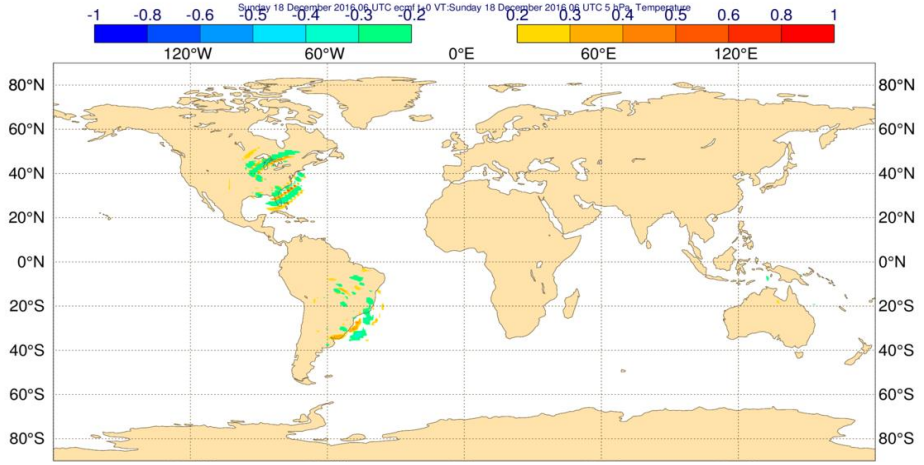


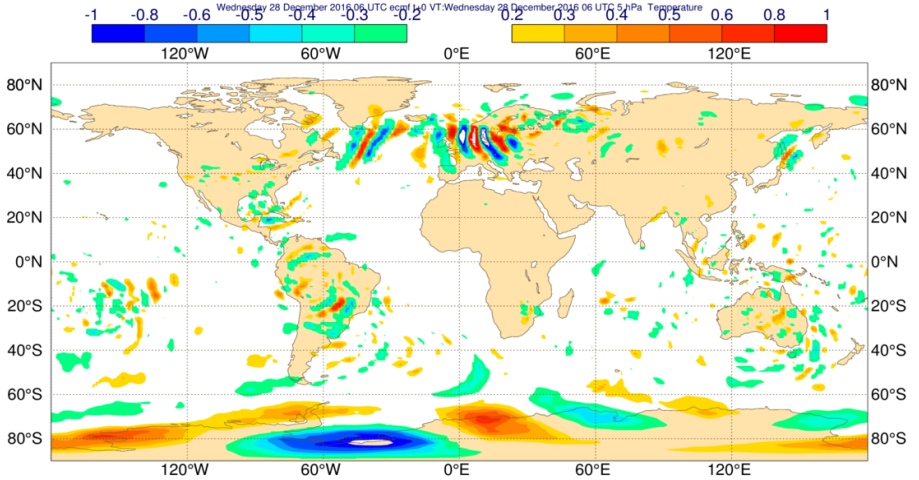
AMSUA Radiances

Nonlinear - linearised model analysis increments 9 hours into the assimilation window (**temperature ~5 hPa**).



20181218





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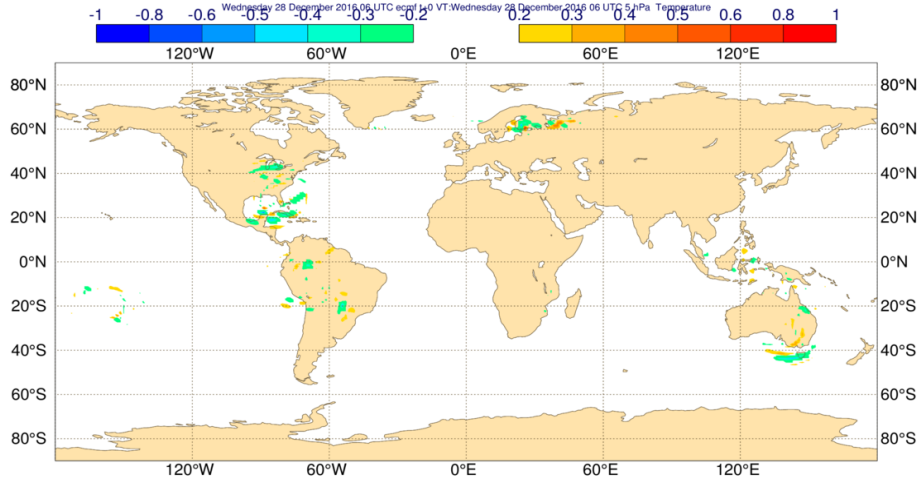


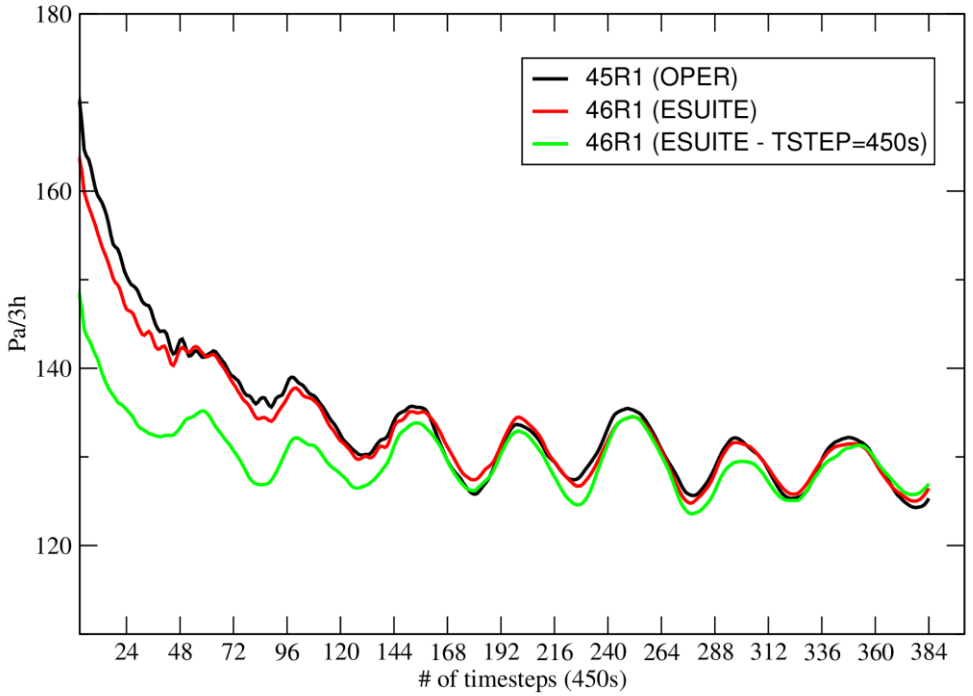
Nonlinear Model tstep=450s; Linearised Model tstep=900s

Nonlinear Model tstep=450s; Linearised Model tstep=450s

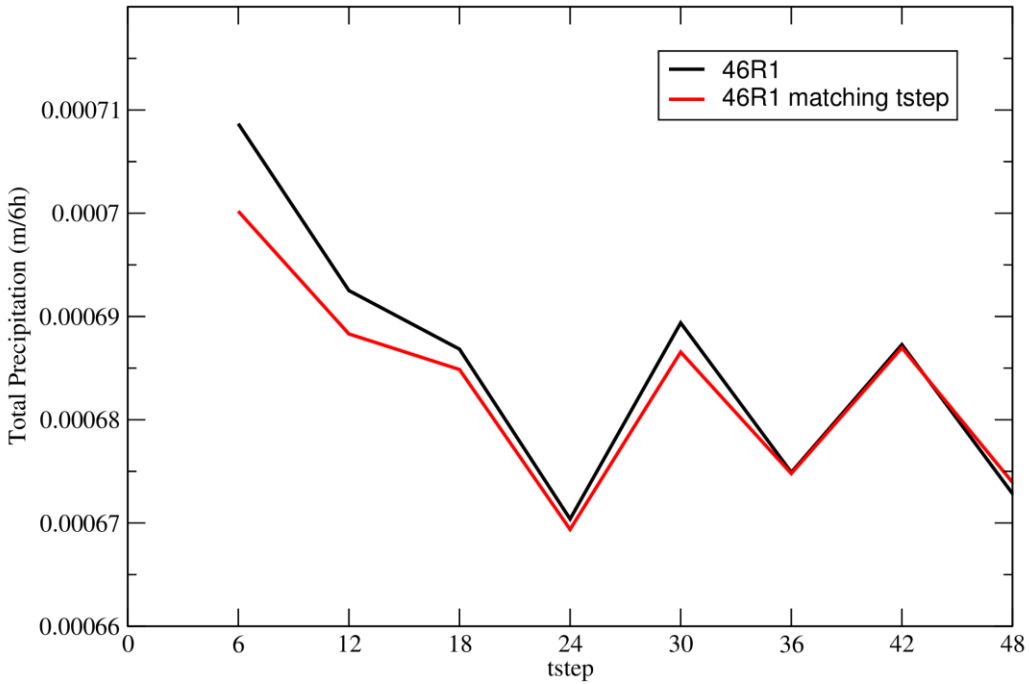
Matching Timestep: Reduced Spindown

Abs(dps/dt), global average

$$\left| \int_0^1 \nabla \cdot \left(\mathbf{v} \frac{\partial p}{\partial \eta} \right) d\eta \right|$$

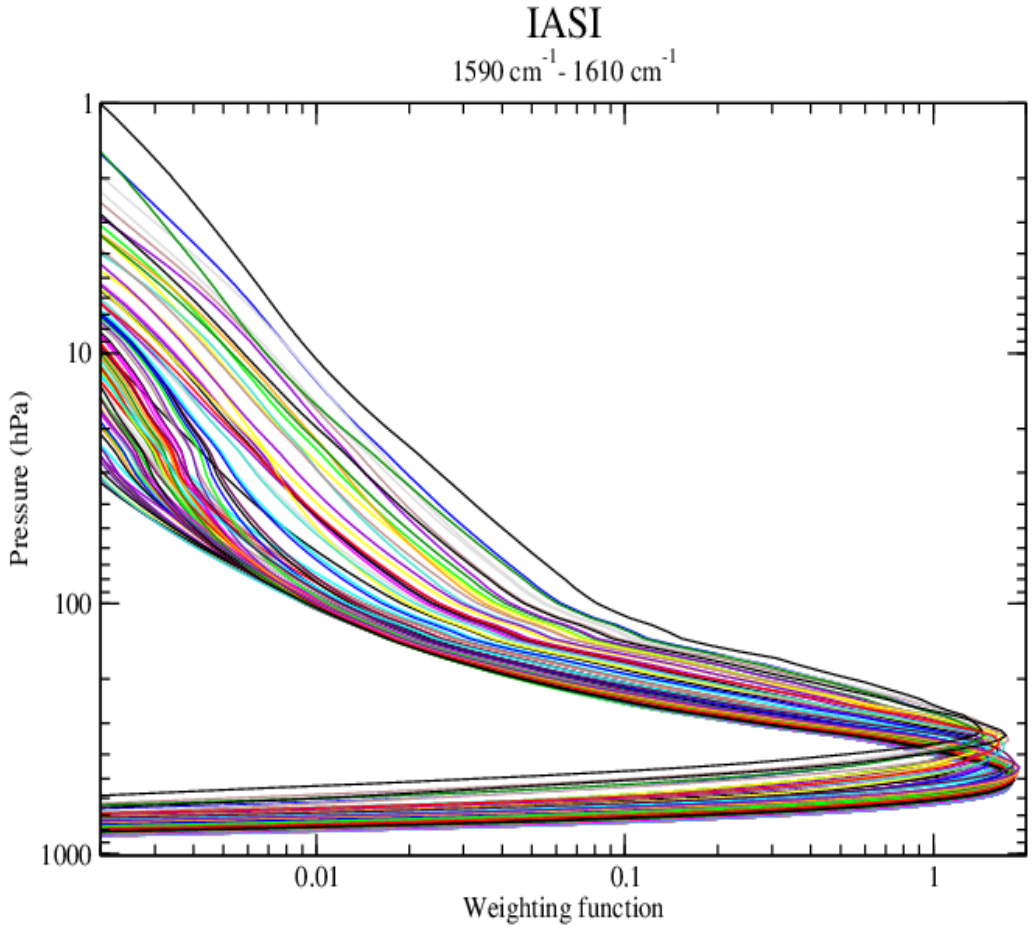


Total precip. - 6h accumulation

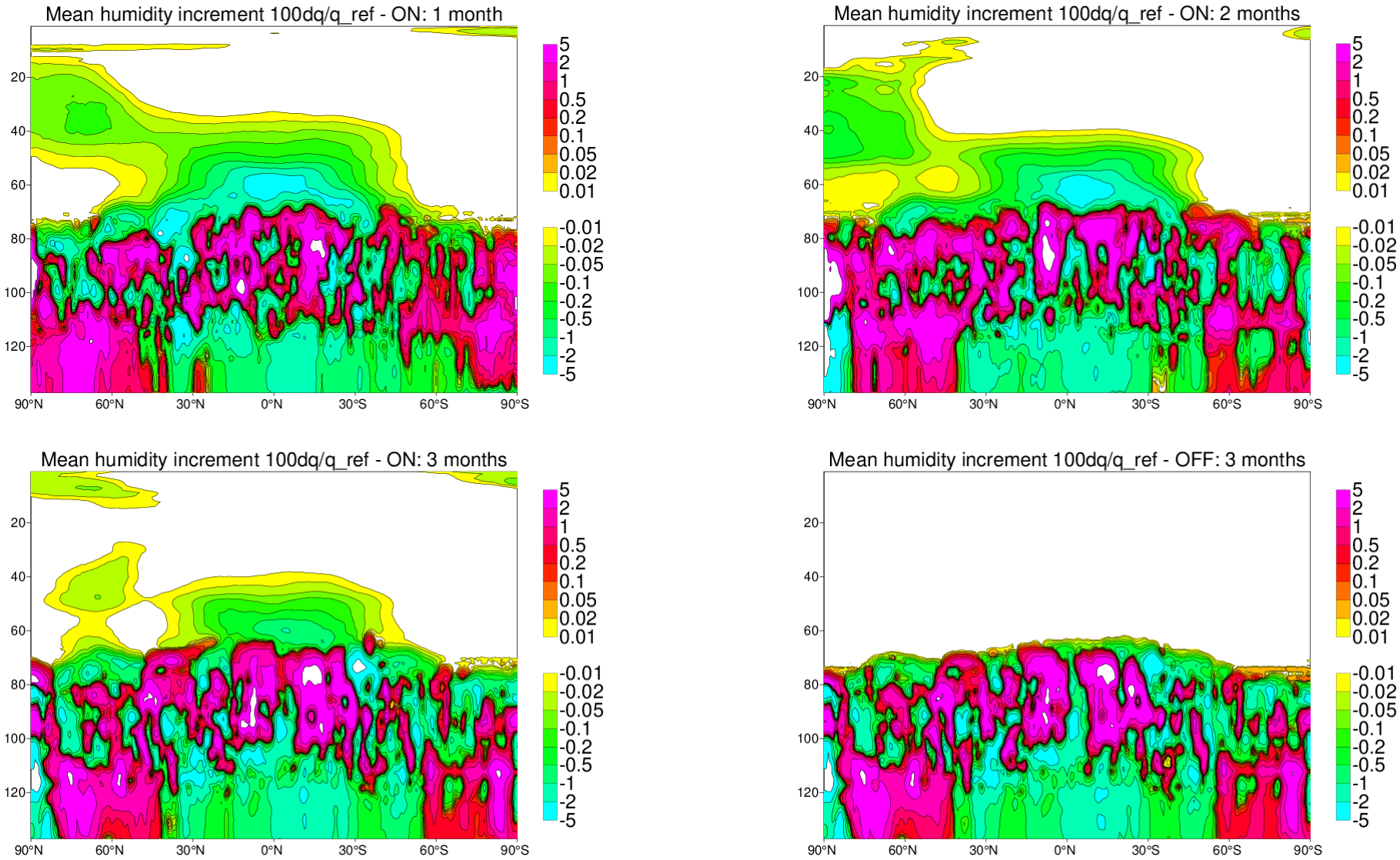


Stratospheric Humidity Analysis: Currently OFF

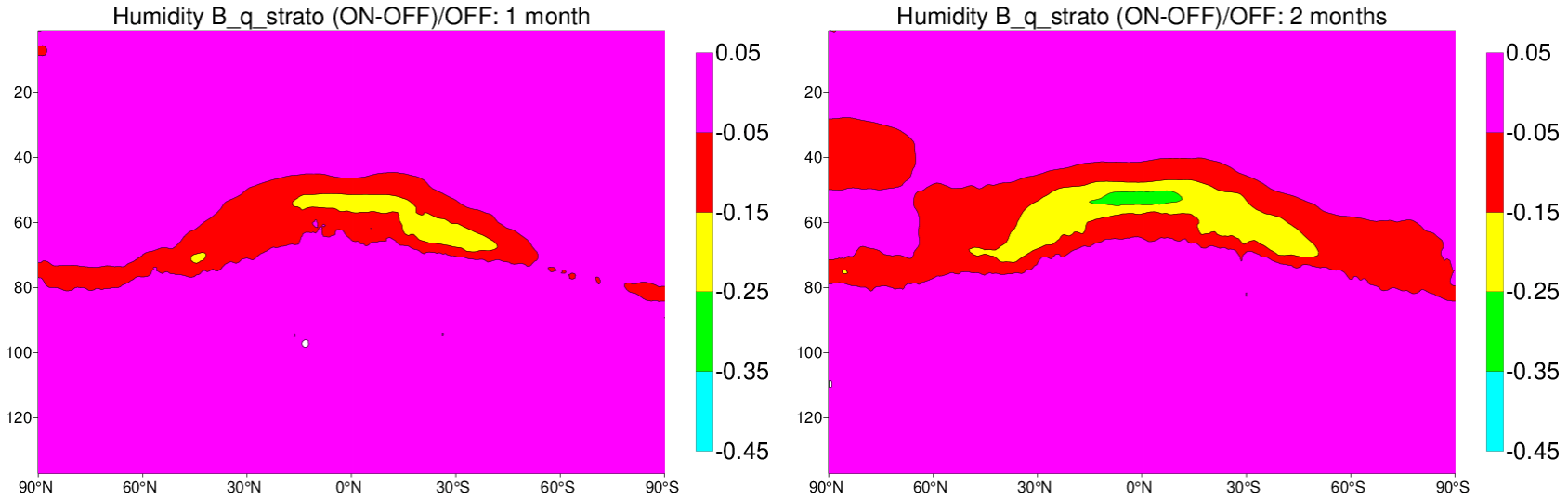
- Problem: Drift (months-year) of lower stratospheric (LS) humidity in the analysis.
  - Humidity sensitive satellite channels with peak sensitivity in upper troposphere (UT) often have long tail of sensitivity in the stratosphere, up to 1hPa but are bias-corrected mainly against the upper tropospheric model column.
  - This leaves relatively small errors in UT to significantly affect humidity in LS, where values are two orders of magnitude lower.
  - No other observations assimilated that can control LS humidity.
- "Current solution": Humidity background errors tapered to low values above the hygropause diagnosed in each analysis.
- "Experiment": Allow humidity increments in the stratosphere – what happens?



Stratospheric Humidity Analysis Increments $\delta q/q_{OFF}$



Stratospheric Humidity Analysis (q_{ON} - q_{OFF})/q_{OFF}



- Humidity still evolving after 3 months analysis, -40%.
- Going in right direction, but no control and could override what model does right, could go too low or increase again.
- Options: Assimilate MLS-AURA H2O or use weak stratospheric forcing based on MLS-AURA.