The ECMWF 4D-Var Analysis in the Tropics: covariance **B**, dynamic and diabatic balance

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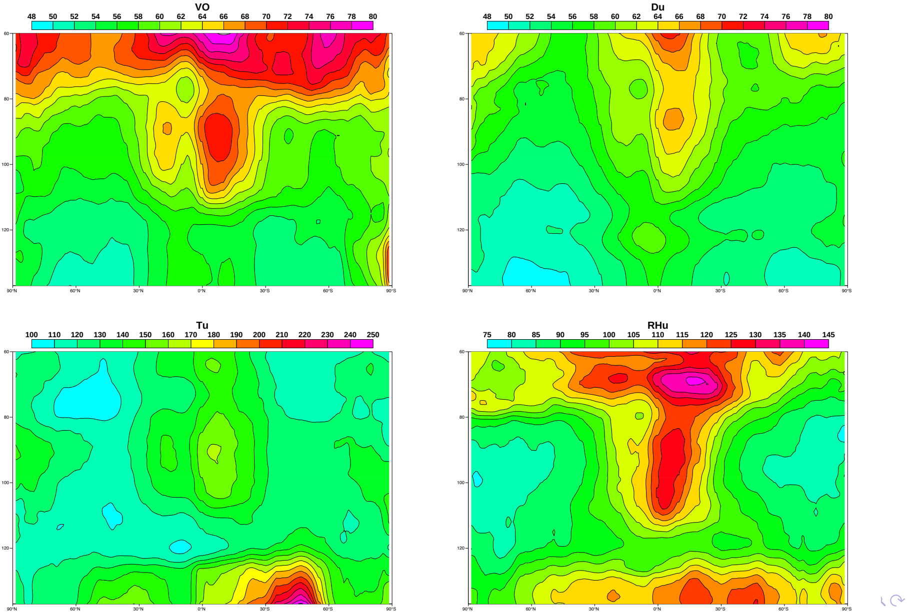
Background errors influence on the analysis

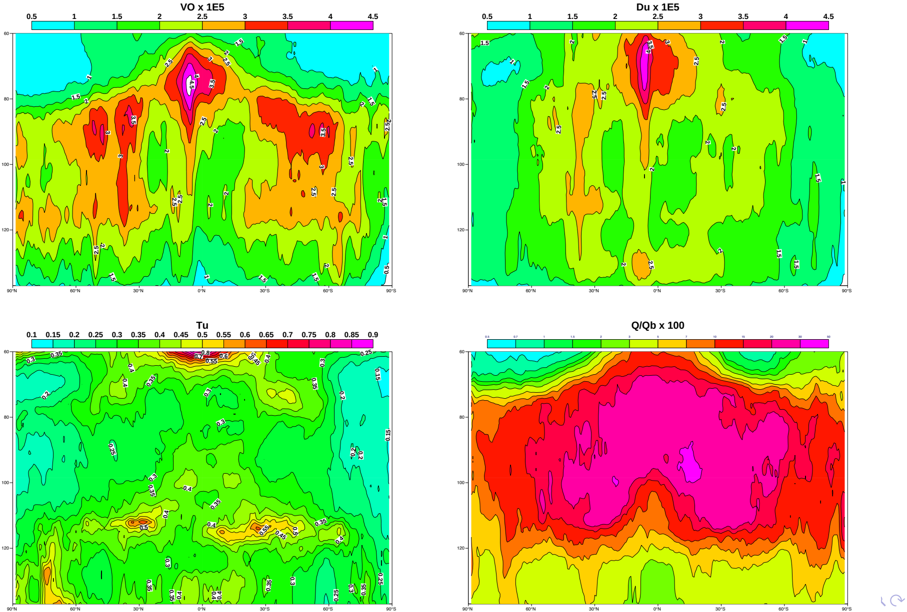
The Ensemble of Data Assimilation is input to update the background error covariance matrix **B** every analysis cycle;

- Standard deviations of all analysis variables are fully flow-dependent.
- Length-scales of the correlations are flow-dependent with climatological length-scales mixed in particularly for the low wavenumbers.
- The balance operator is a combination of analytical, flow-dependent functions and statistical climatological regressions.
- How does it look and what does it mean for the analysis?

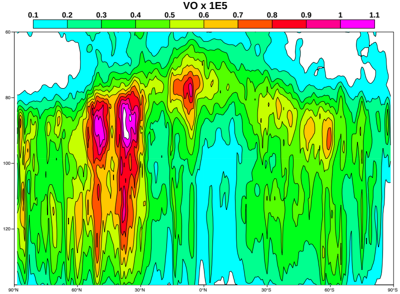
Lengthscales **B** [km], zonal ave

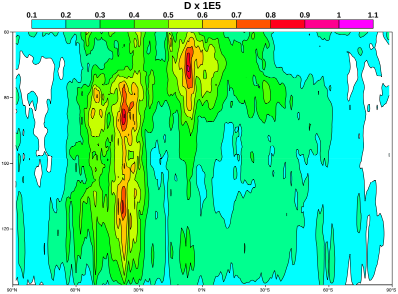


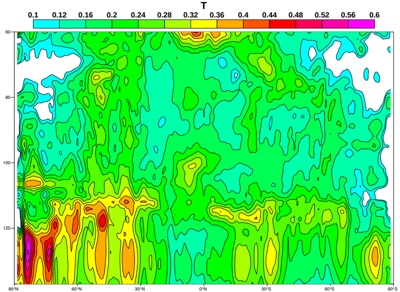
Standard deviations **B**, zonal ave

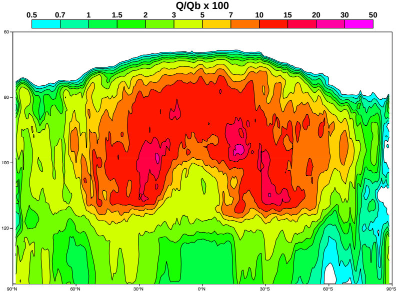


Analysis increments absolute values, zonal ave

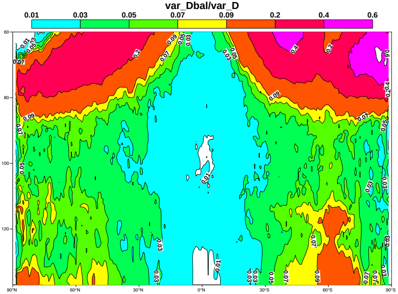


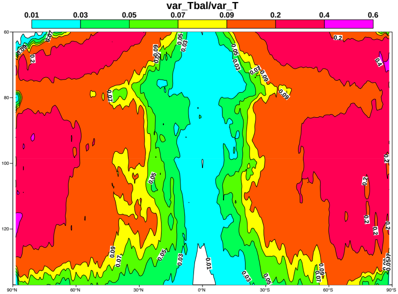


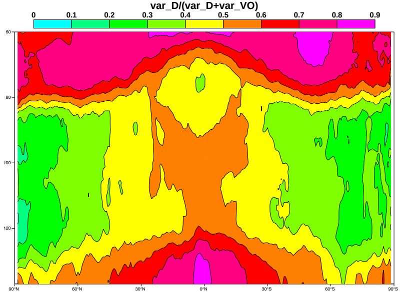




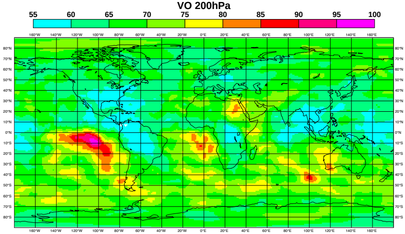
Variance of **B** explained by balance, zonal ave

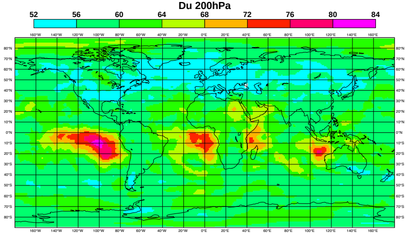


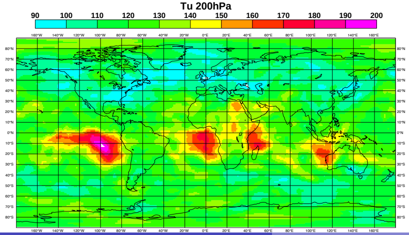


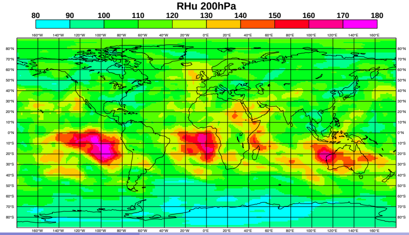


Lengthscales B [km], level 74 200hPa

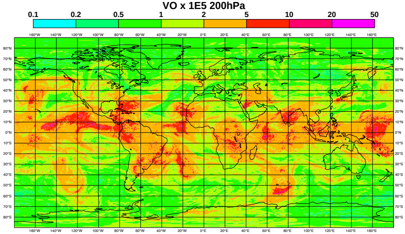


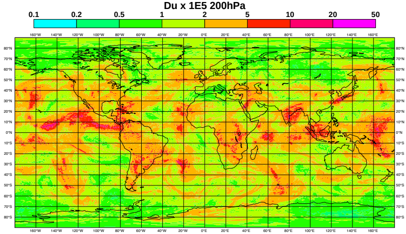


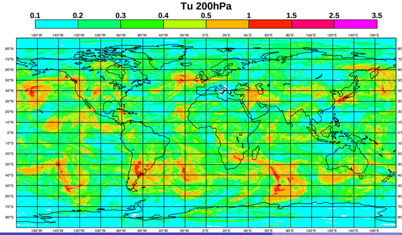


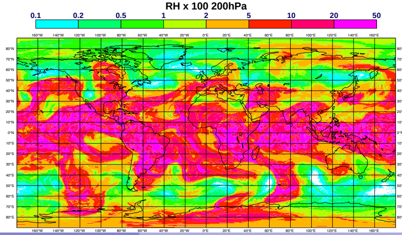


Standard deviations **B**, level 74 200hPa

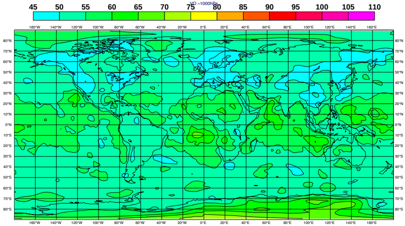


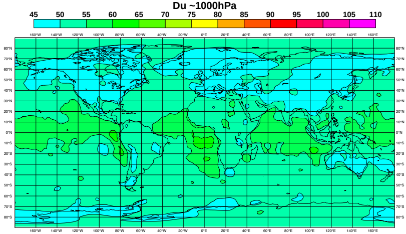


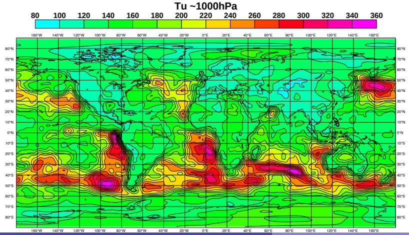


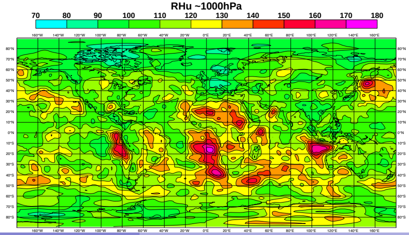


Lengthscales **B** [km], level 137 1000hPa

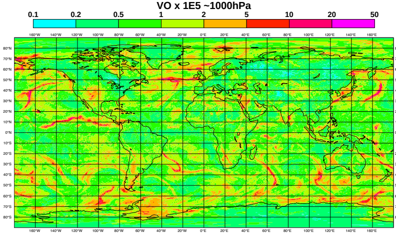


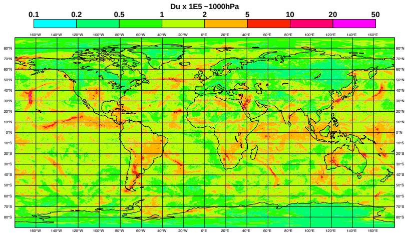


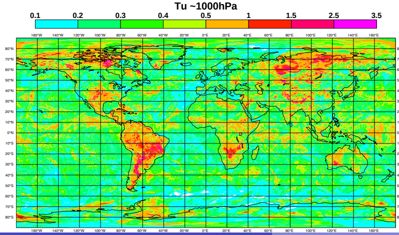


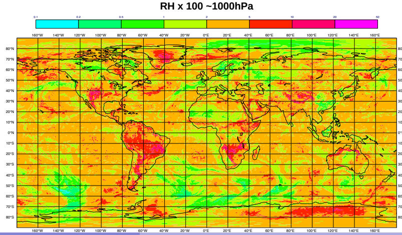


Standard deviations **B**, level 137 1000hPa

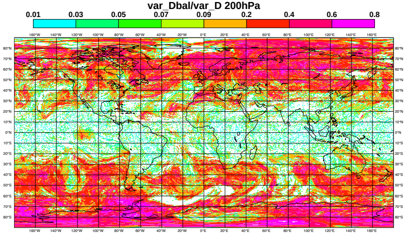


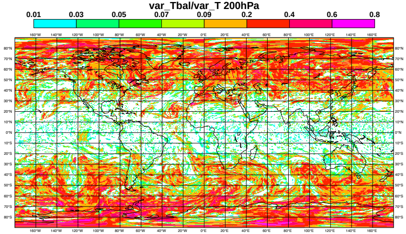


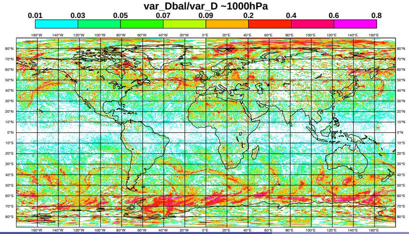


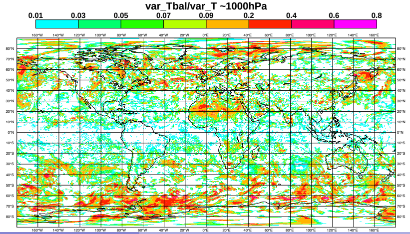


Variance of **B** explained by balance, 200hPa and 1000hPa

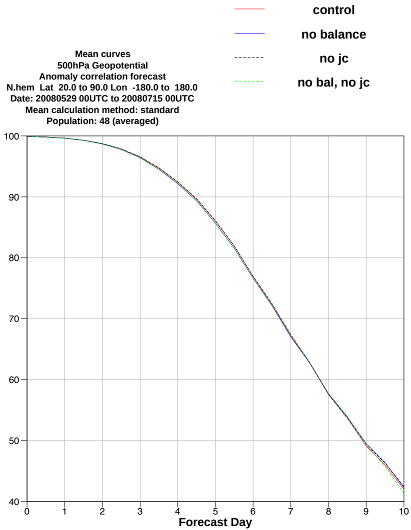








Does balance matter for forecast quality?



Does balance matter for forecast quality? Yes, but...

- The 4D-Var analysis manages without balance operator, creating negligible extra gravity wave noise.
- The current system is well observed with small analysis increments, enabling 4D-Var to infer balance from the temporal information in the observations.
- Tropospheric scores 1-2% worse without balance, so worth keeping on.

The dynamic balance operator

The balance operator consists of the dynamic horizontal simplified and linearized nonlinear balance (Fisher, 2003),
$\nabla^2 P_b = (f + \zeta) \times v_\psi + \frac{1}{2}\nabla(v_\psi \cdot v_\psi)$, combined with vertical balance operators (from statistical regression),

$$\begin{pmatrix} \delta\zeta \\ \delta\eta_n \\ \delta(T_n, p_s) \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ M & 1 & 0 \\ N & P & 1 \end{pmatrix} \begin{pmatrix} \delta\zeta \\ \delta\eta_u \\ \delta(T_u, p_{su}) \end{pmatrix}$$

and simplified and linearized version of quasi-geostropic ω-equation balance (Fisher, 2003), $\left(\sigma\nabla^2 + f_0^2 \frac{\partial^2}{\partial p^2}\right)\omega' = -2\nabla \cdot \mathbf{Q}$,

$$\begin{pmatrix} \delta\zeta \\ \delta\eta \\ \delta T \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ Q_2 & 1 & Q_1 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \delta\zeta \\ \delta\eta_n \\ \delta T \end{pmatrix}$$

Diabatic balance through linear saturation adjustment

Use linear saturation adjustment (based on Asai 1965 and Hólm et al., 2002),

$$\delta T = \delta T_n + C^b a \frac{L}{c_p}\left(\delta q_{vu} - \frac{L q_s(T^b)}{R_v (T^b)^2}\delta T_n\right)$$

$$\delta q_v = \delta q_{vu} - C^b a\left(\delta q_{vu} - \frac{L q_s(T^b)}{R_v (T^b)^2}\delta T_n\right)$$

$$\delta q_c = \delta q_{cu} + C^b a\left(\delta q_{vu} - \frac{L q_s(T^b)}{R_v (T^b)^2}\delta T_n\right)$$

In matrix from this becomes

$$\begin{pmatrix} \delta T \\ \delta q_v \\ \delta q_l \\ \delta q_i \end{pmatrix} = \begin{pmatrix} 1 - \frac{L}{c_p} C^b a\gamma & \frac{L}{c_p} C^b a & 0 & 0 \\ C^b a\gamma & 1 - C^b a & 0 & 0 \\ -\alpha C^b a\gamma & \alpha C^b a & 1 & 0 \\ -(1-\alpha) C^b a\gamma & (1-\alpha) C^b a & 0 & 1 \end{pmatrix} \begin{pmatrix} \delta T_n \\ \delta q_{vu} \\ \delta q_{lu} \\ \delta q_{iu} \end{pmatrix}$$

Details of linear saturation adjustment

- Increments δT_n and δq_{vu} assumed uniform over the gridcell.
- Saturation adjustment takes place in the in-cloud portion C^b of the gridcell, with C^b approximated by a regression formula as a function of rh^b and model level.
- $q^b = q_s(T^b)$ in the in-cloud part of the gridcell.
- Cloud condensate adjustment distributed by $\alpha(T^b)$ between δq_l and δq_i with $\alpha(T^b)$ varying between 0 and 1 according to mixed-phase formula.
- The adjustment conserves total water.
- The adjustment is unchanged for δT and δq_v whether δq_l and δq_i are included or not.
- Here $a = \frac{1}{1+\frac{L^2 q_s(T^b)}{c_p R_v \left(T^b\right)^2}}$ and $\gamma = \frac{L q_s(T^b)}{R_v \left(T^b\right)^2}$

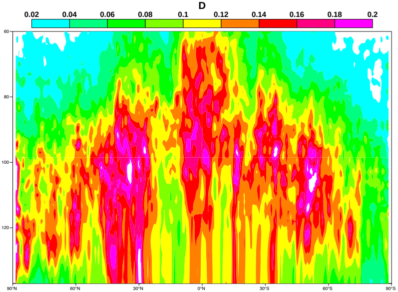
Apply ω-equation after saturation adjustment

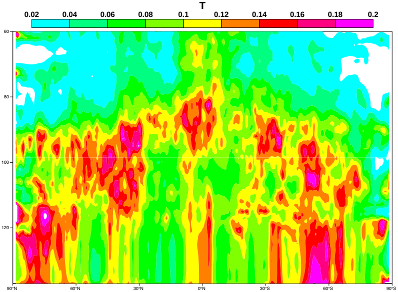
By applying the ω-equation balance after the saturation adjustment, the final divergence dynamically supports the water vapour and cloud condensate changes in an adaptive way without any special treatment:

$$\begin{pmatrix} \delta\zeta \\ \delta\eta \\ \delta T \\ \delta q_v \\ \delta q_c \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ Q_2 + M + Q_1 N(1 - \frac{L}{c_p} C^b a\gamma) & 1 + Q_1 P(1 - \frac{L}{c_p} C^b a\gamma) & Q_1(1 - \frac{L}{c_p} C^b a\gamma) & Q_1 \frac{L}{c_p} C^b a & 0 \\ N(1 - \frac{L}{c_p} C^b a\gamma) & P(1 - \frac{L}{c_p} C^b a\gamma) & 1 - \frac{L}{c_p} C^b a\gamma & \frac{L}{c_p} C^b a & 0 \\ N C^b a\gamma & P C^b a\gamma & C^b a\gamma & 1 - C^b a & 0 \\ -N C^b a\gamma & -P C^b a\gamma & -C^b a\gamma & C^b a & 1 \end{pmatrix} \begin{pmatrix} \delta\zeta \\ \delta\eta_u \\ \delta T_u \\ \delta q_{vu} \\ \delta q_{cu} \end{pmatrix}$$

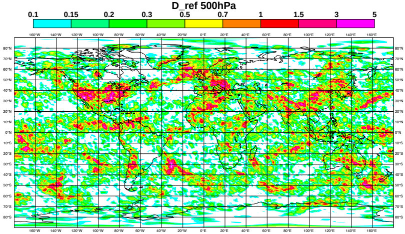
with $\delta q_c = \delta q_l + \delta q_i$ and $\delta T = \delta(T, p_s)$ and $\delta T_u = \delta(T, p_s)_u$.

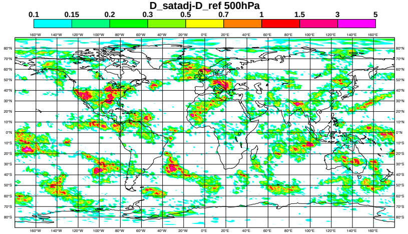
Increment ratio abs(SatAdj - Ref)/abs(Ref), zonal ave

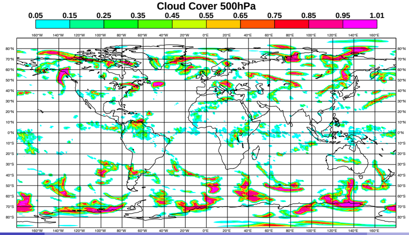




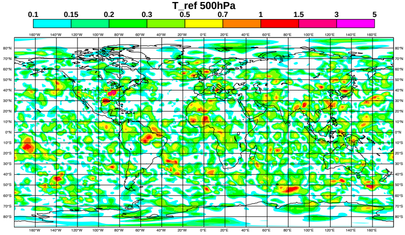
D 500hPa increments: abs(Ref), abs(SatAdj-Ref), cc

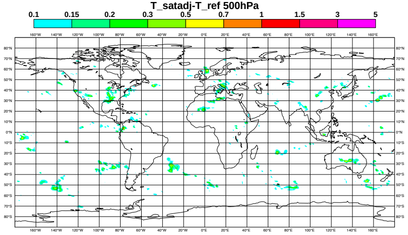


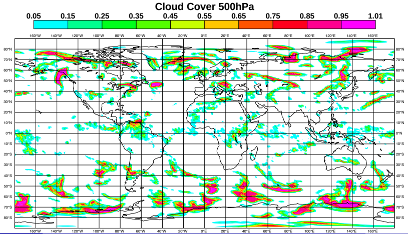




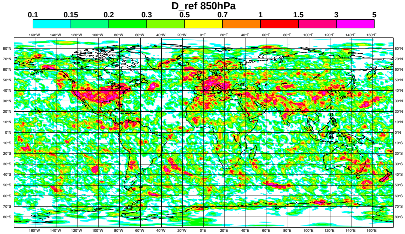
T 500hPa increments: abs(Ref), abs(SatAdj-Ref), cc

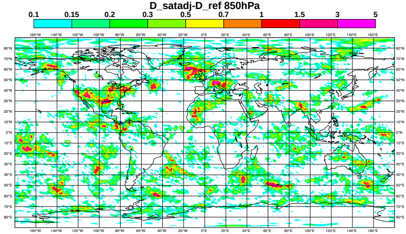


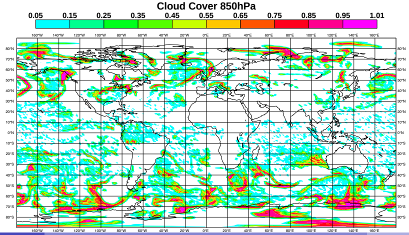




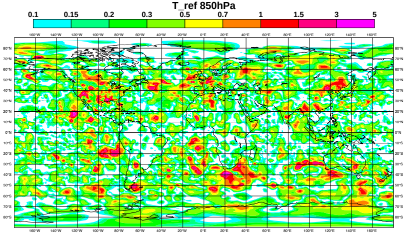
D 850hPa increments: abs(Ref), abs(SatAdj-Ref), cc

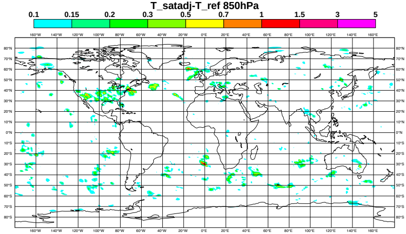


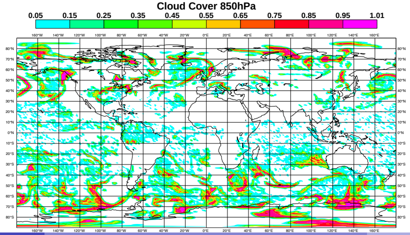




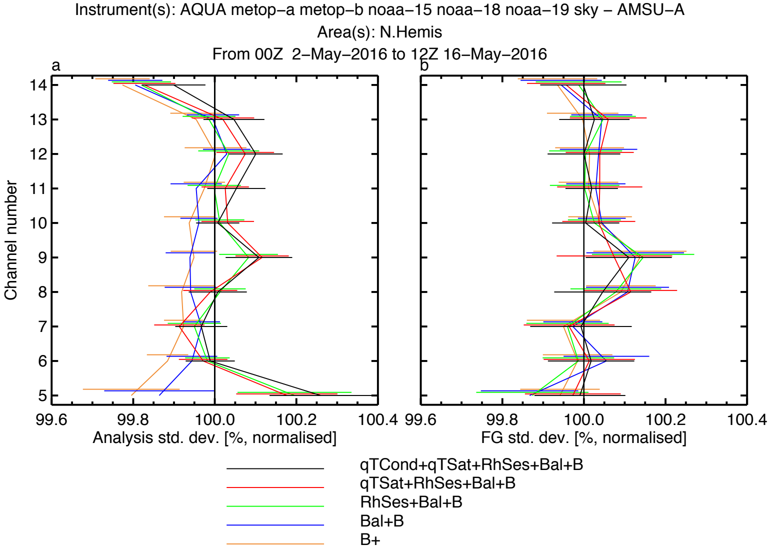
T 850hPa increments: abs(Ref), abs(SatAdj-Ref), cc



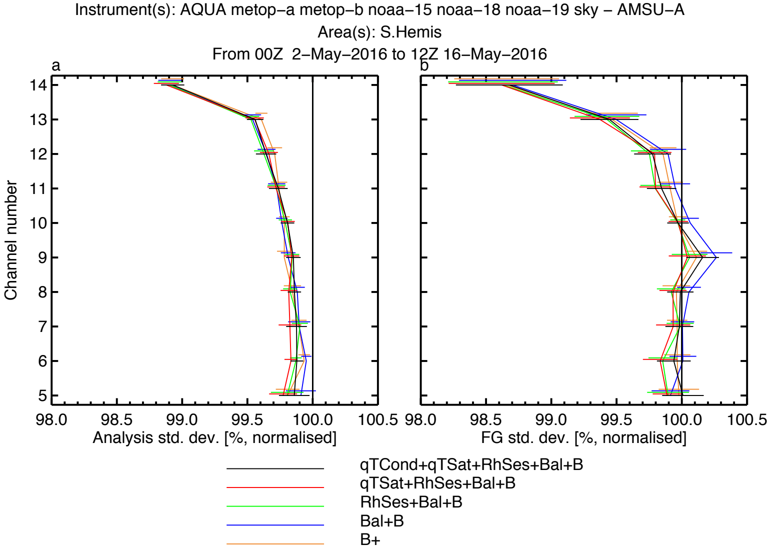




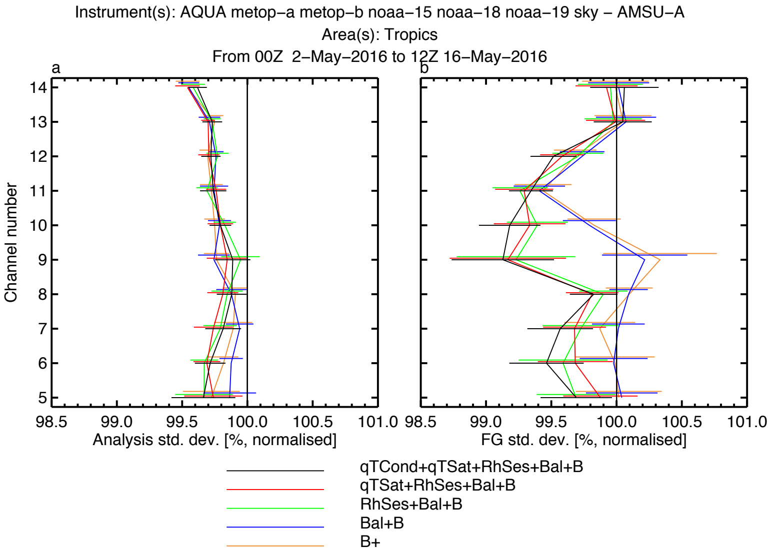
Results for AMSU-A (O-B) - NHem



Results for AMSU-A (O-B) - SHem



Results for AMSU-A (O-B) - Tropics



References

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- Hólm, E., E. Andersson, A. Beljaars, P. Lopez, J-F. Mahfouf, A.J. Simmons and J.N. Thpaut, (2002): *Assimilation and Modelling of the Hydrological Cycle: ECMWF's Status and Plans*. ECMWF Tech. Memorandum No. **383**, available from ECMWF, Shinfield Park, Reading RG2 9AX, UK.