Assimilation of Transformed Retrievals from IASI radiances at the Met Office: current results and future prospects

Stefano Migliorini and Peter Levens

Introduction

The concept of Transformed Retrievals (TransRets) was introduced to simplify the process of assimilating satellite radiances in an operational NWP model, without invalidating the assumptions behind the procedures to minimise the data assimilation (DA) cost function (Migliorini, 2012). This simplification consists in splitting the satellite DA problem into two parts: a) a best estimate is found over a reduced state space defined by the portion of state on which the observation operator for a single field of view is dependent; the observation vector is then scaled and projected to define a “transformed retrieval” (TransRet); b) the TransRet components with signal-to-noise ratio above a chosen threshold are then assimilated in the full NWP model. The advantage of this framework is that the TransRet observation vector has trivial observation errors and has a linear observation operator, which simplifies the operational DA process, given the nonlinear problem is solved in a pre-processing step. This means there is no need to call the radiative transfer operator in the assimilation, as the observation operator is read in from an input file, the size of which depends on how many observation components are retained.

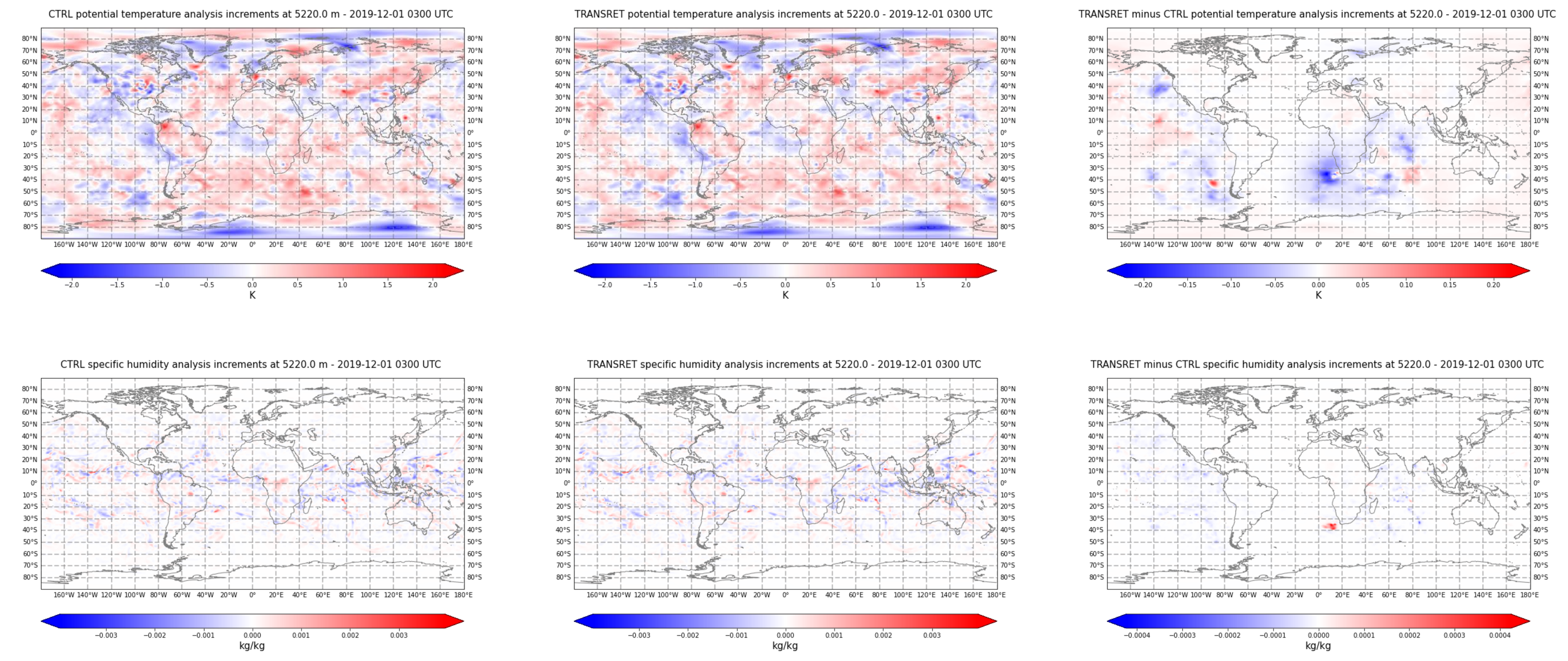

Figure 1 Potential temperature (top row) and specific humidity (bottom row) analysis increments for the first DA cycle. Left panels: increments from CTRL trial; mid panels: increments from TRANSRET trial; right panels: difference between increments from TRANSRET and CTRL trials

Assimilation of IASI radiances and TransRets

A three-month trial from 1st December 2019 to 28th February 2020 that assimilates the same observations as those used in the Met Office operational DA scheme – both in-situ or ground based, satellite products and satellite radiances – was performed using hybrid 4D-Var with midlatitude spatial resolution of 90 km and 40 km and forecast model midlatitude spatial resolution of 10 km using a six-hour DA window. This trial, denoted as CTRL, considers IASI radiances over 175 channels in band 1 and 2 as input for 1D-Var, which is used to retrieve atmospheric temperature and specific humidity profiles over 70 model levels, temperature and specific humidity at 2 m, skin temperature, surface pressure, cloud-top pressure, effective cloud fraction and the 12 most significant principal components of surface emissivity (over land only). All IASI channels are rejected when the radiances are deemed to be affected by rain (based on a scattering index threshold) or are over sea ice or land higher than 1000 m. Some lower-peaking channels over land are also rejected. Also, radiances are rejected from channels with fraction of temperature jacobian below cloud top greater than 10% To simplify the comparison with TransRet, here satellite radiances only have a static bias correction that is not updated using VarBC. For this reason, observations from SSMIS and MWRI, requiring orbital bias corrections, were excluded from the trial.

The following trials were also run with the same observations as in CTRL except for IASI, where TransRets were assimilated in the place of radiances: TRANSRET (where all y'_{ret} components $\lambda_i > 0$ were assimilated) and TRANSRET_L0p1 (where only y'_{ret} with $\lambda_i > 0.1$ were assimilated). Note that y'_{ret} and $\mathbf{H}'_{\mathrm{ret}}$ were computed using the same $\mathbf{B}$ matrix used in 1D-Var and the same $\mathbf{R}$ matrix used to assimilate IASI radiances.

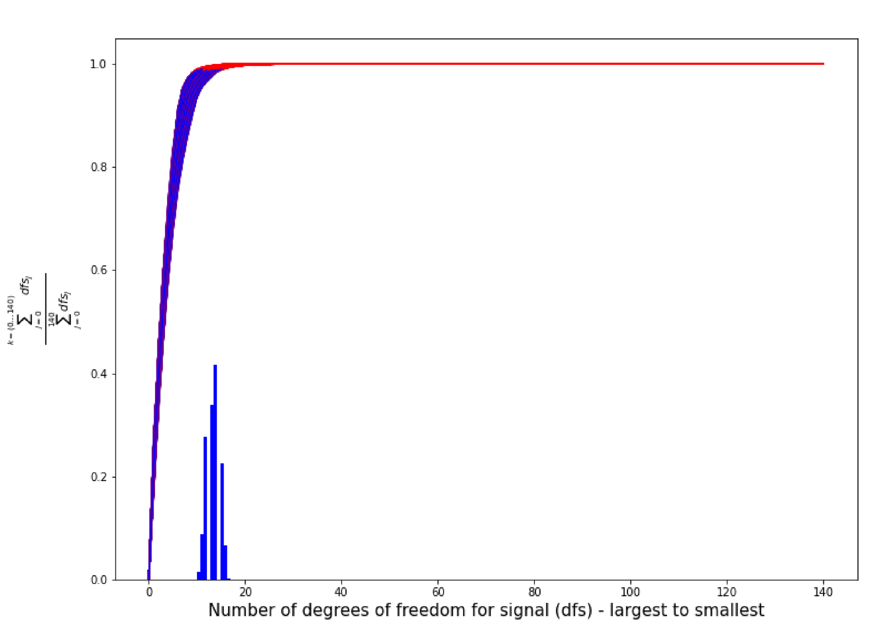

Figure 3 Cumulative distribution function of degrees of freedom for signal (dfs) of the IASI measurements, used in the first DA cycle of the trials, with maximum number of dfs

Theory

The relationship between a satellite observation $\boldsymbol{y}^o_{\mathrm{rad}}$ over *m* channels and the *n*-component true state vector $\boldsymbol{x}^t$ can be written as $\boldsymbol{y}^o_{\mathrm{rad}} = H(\boldsymbol{x}^t) + \boldsymbol{\varepsilon}^o_{\mathrm{rad}}$, where $H(\boldsymbol{x}^t)$ is the nonlinear observation operator and $\boldsymbol{\varepsilon}^o_{\mathrm{rad}}$ is the observation error vector, with $\mathrm{cov}(\boldsymbol{\varepsilon}^o_{\mathrm{rad}}) = \mathbf{R}$. We can write $\hat{\boldsymbol{y}}'_{\mathrm{rad}} \cong \mathbf{R}^{-\frac{1}{2}}\hat{\mathbf{H}}_{\mathrm{rad}}\boldsymbol{x}^t + \mathbf{R}^{-\frac{1}{2}}\boldsymbol{\varepsilon}^o_{\mathrm{rad}} \equiv \hat{\mathbf{H}}'_{\mathrm{rad}}\,\boldsymbol{x}^t + \boldsymbol{\varepsilon}'_{\mathrm{rad}}$ where $\hat{\mathbf{H}}_{\mathrm{rad}}$ is the jacobian of $H(\boldsymbol{x}^t)$ calculated at the 1D-Var analysis $\hat{\boldsymbol{x}}$. Let us define $\mathbf{S} = \hat{\mathbf{H}}_{\mathrm{rad}}\mathbf{B}^{1/2} \equiv \mathbf{U}_r\boldsymbol{\Lambda}_r\mathbf{V}_r^T$ the signal-to-noise matrix with rank $r \leq \min(m,n)$, where $\mathbf{U}_r \in \mathbb{R}^{m\times r}$ and $\mathbf{V}_r \in \mathbb{R}^{n\times r}$ are matrices whose columns are the left and right singular vectors of $\mathbf{S}$ corresponding to the positive singular values of $\mathbf{S}$ and $\boldsymbol{\Lambda}_r \in \mathbb{R}^{r\times r}$ is a diagonal matrix that contains the r positive nondimensional singular values λ_i of $\mathbf{S}$ on its diagonal. If we define $\boldsymbol{y}'_{\mathrm{ret}} \equiv \mathbf{U}_r^T\hat{\boldsymbol{y}}'_{\mathrm{rad}} \in \mathbb{R}^r$ and $\mathbf{H}'_{\mathrm{ret}} \equiv \mathbf{U}_r^T\,\hat{\mathbf{H}}'_{\mathrm{rad}} \in \mathbb{R}^{r\times n}$ we can write $\boldsymbol{y}'_{\mathrm{ret}} = \mathbf{H}'_{\mathrm{ret}}\boldsymbol{x}^t + \boldsymbol{\varepsilon}'_{\mathrm{ret}}$ where $\mathrm{cov}(\boldsymbol{\varepsilon}'_{\mathrm{ret}}) = \mathbf{I}_r$. We can now assimilate the $\boldsymbol{y}'_{\mathrm{ret}}$ TransRets using the linearised observation operator $\mathbf{H}'_{\mathrm{ret}}$ in the place of $\boldsymbol{y}^o_{\mathrm{rad}}$ and $H(\boldsymbol{x}^t)$. When the restriction of the global true state given as input to $H(\boldsymbol{x}^t)$ has the same prior pdf of the state used in 1D-Var, it is possible to show (Migliorini, 2012) that the analyses resulting from the assimilation of radiances and of all TransRets are equivalent, i.e. they contain the same information content. Also, it is possible to reduce significantly the number of TransRets to be assimilated while retaining most of the information content of the measurements (Prates et al., 2016).

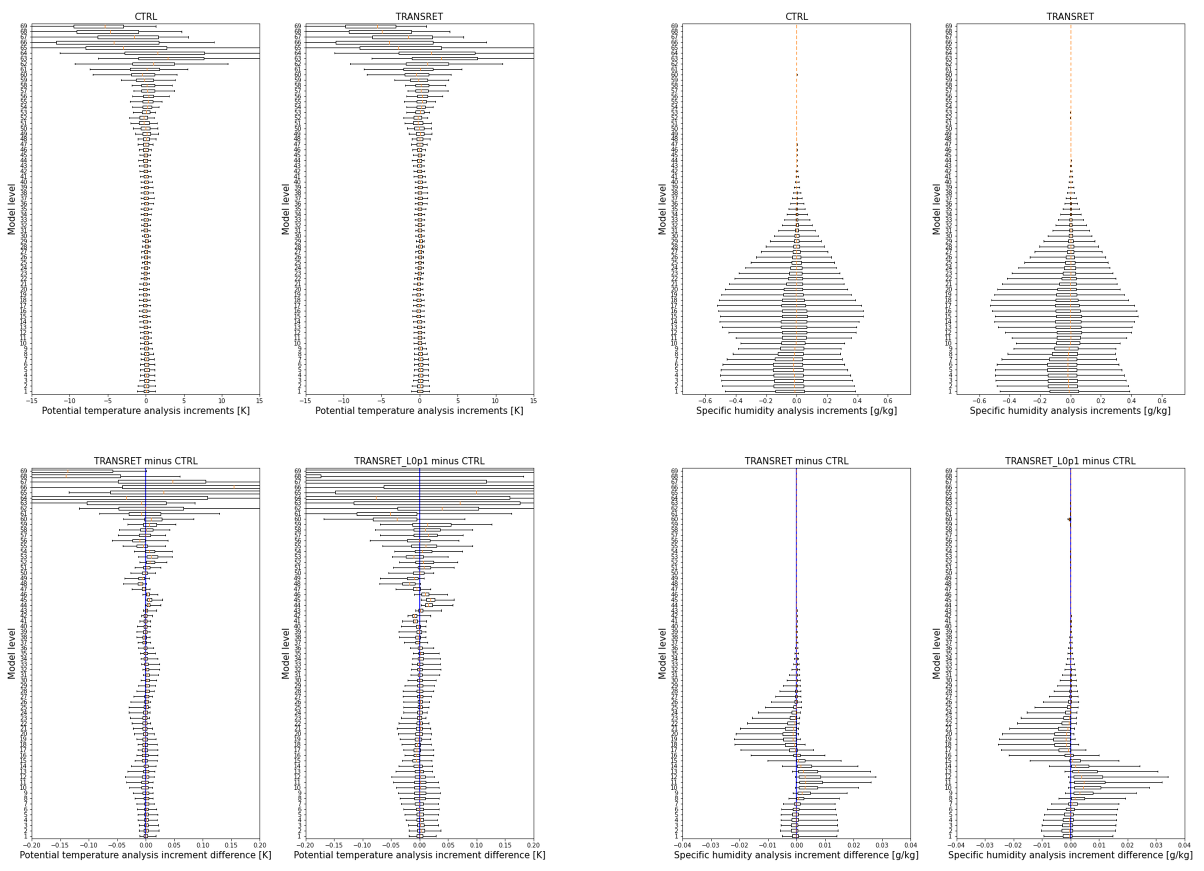

Figure 2 Statistical distribution of potential temperature (left panels) and specific humidity (right panels) analysis increments for CTRL and TRANSRET trials and of the difference between TRANSRET, TRANSRET_0p1 and CTRL trials. At each model level, the width of the box represents the interquartile range and the whiskers delimit the 5th and 95th percentile the of the distribution.

Results and discussion

The analysis increments for the first DA cycle at model level 27 (5220 m above mean sea level) are shown in Figure 1. The figure shows that the maximum absolute difference between TRANSRET and CTRL potential temperature (specific humidity) increments is less than 10.3% (10.8%) the maximum absolute CTRL increments. Figure 2 shows that the statistical distributions of TRANSRET and TRANSRET_L0p1 increments at all model levels are not significantly different from that of CTRL. In Figure 3 the cumulative distribution function of the degrees of freedom for signal (*dfs*) of the 3344 out of 13061 IASI observations having S with maximum rank $r = r_{\mathrm{max}} = n = 140$ and the histogram of the number of *dfs* with $\lambda_i > 0.1$ are shown. From Figure 3 it follows that no more than 17 TransRet components with largest λ_i are required to express from 97.9% up to 99.3% of the total number of *dfs* of each observation. This means that almost all information from up to 175 IASI channels can be represented by no more than 17 TransRet components. Finally, Figure 4 shows the scorecards with the relative RMSE differences between CTRL and TRANSRET or TRANSRET_L0p1 trials for a range of fields over the northern and southern hemispheres and the Tropics, and verified against observations or ECMWF analyses. Both TRANSRET and TRANSRET_L0p1 show no significant forecast skill difference from CTRL.

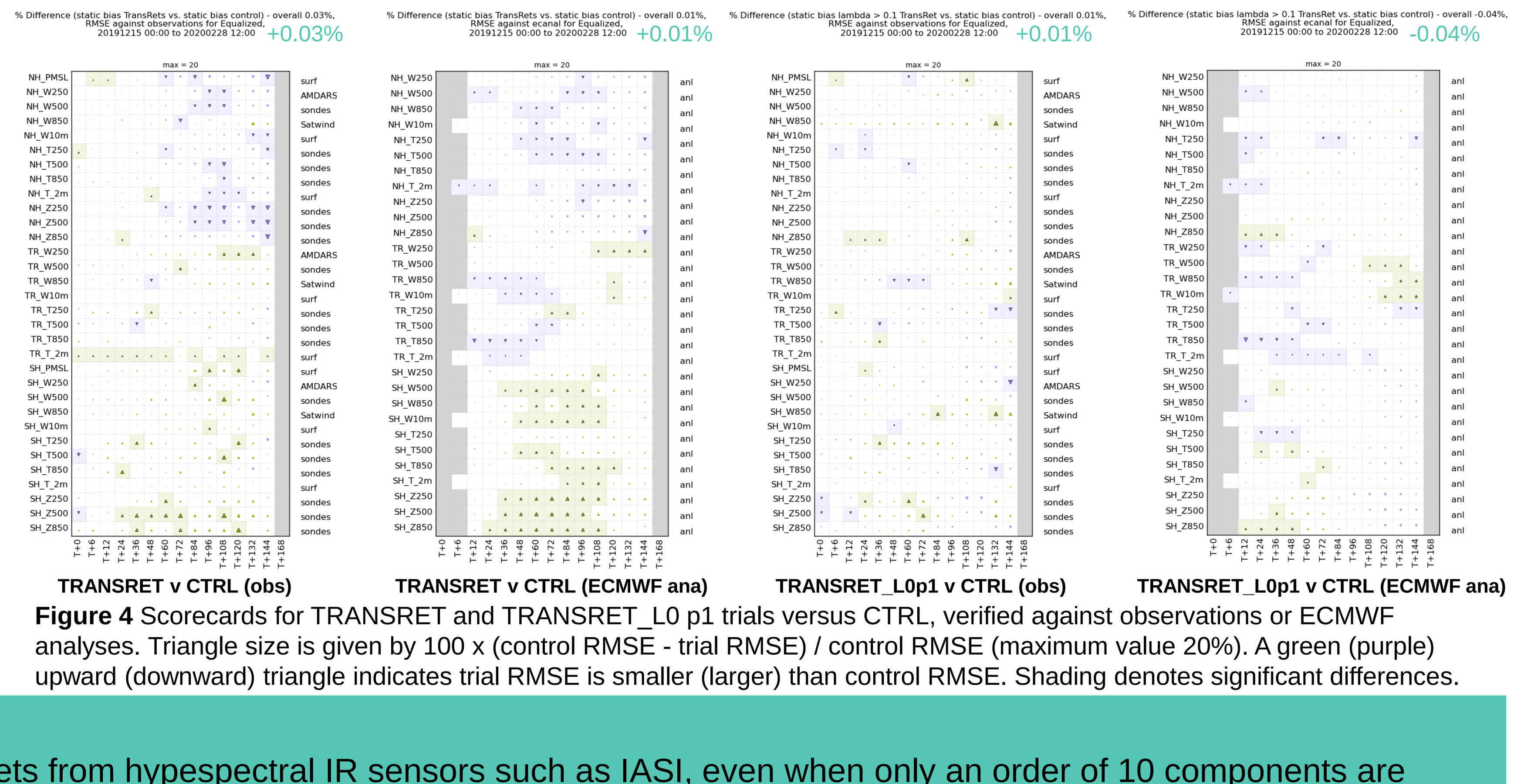

Figure 4 Scorecards for TRANSRET and TRANSRET_L0 p1 trials versus CTRL, verified against observations or ECMWF analyses. Triangle size is given by 100 x (control RMSE - trial RMSE) / control RMSE (maximum value 20%). A green (purple) upward (downward) triangle indicates trial RMSE is smaller (larger) than control RMSE. Shading denotes significant differences.

Conclusions

- The results of the TRANSRET and TRANSRET_L0p1 trials show that the assimilation of TransRets from hypespectral IR sensors such as IASI, even when only an order of 10 components are retained, achieves forecast skill results in the Met Office operational DA system that are equivalent to those obtained when the radiances from the IASI channels selected for operational assimilation are assimilated directly as from standard practice.
- This is the first time such statistical equivalence has been proven using real IASI data in an operational DA system.
- These results pave the way to a more aggressive use of the information from hyperspectral IR sounders and open the possibility of increasing the number of IR channels for assimilation by an order of magnitude.

References

Migliorini, S., 2012: On the Equivalence between Radiance and Retrieval Assimilation. Mon. Wea. Rev., 140, 258–265

Prates, C., Migliorini, S., Stewart, L. and Eyre, J. (2016), Assimilation of transformed retrievals obtained from clear-sky IASI measurements. Q.J.R. Meteorol. Soc., 142: 1697-1712.

Met Office FitzRoy Road, Exeter, Devon, EX1 3PB United Kingdom
Tel: +44 1392 885680 Fax: +44 1392 885681
Email: stefano.migliorini@metoffice.gov.uk