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Atmospheric
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Discussions

Interactive comment on "Using reference radiosondes to characterise NWP model uncertainty for improved satellite calibration and validation" *by* Fabien Carminati et al.

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We are grateful to the referee for his/her comments that helped clarify certain points of our study and gave us some insight for future work on e.g. the impact of observation error applied to radiosondes. Each of the four questions is addressed in order below and manuscript changes are documented accordingly.

Referee:
In the paragraph from line 404 to 419, it is explained that to compute Tb+ and Tb-, a one-sigma error is added (resp. removed) to all input variables. But in many cases, even for a single variable like humidity or temperature, Jacobians of the radiative transfer model do change of sign in the vertical which mean that adding a one-sigma error on the whole vertical profile does not maximize the difference between Tb and Tb+ or Tb-. So there are not only 8 possibilities as mentioned in the text, the combination to find out the maximum error is likely to be more complex than that.

Authors:
The referee is right in pointing out that the approach does not cover the full range of possible uncertainty propagations in radiance space due to the complex modulations of the temperature, humidity, and pressure Jacobians on the vertical. This is precluded by the assumption of full vertical correlation and we acknowledge that a different approach such as the Monte Carlo method (that would randomly perturb on the vertical the profiles within their uncorrelated uncertainty range) may provide, given an ensemble of sufficient size, a better approximation of GRUAN uncertainty in radiance space. This solution however, cannot be implemented with the current version of the GRUAN product that, as described in the text (lines 427-434), does not discriminate properly correlated and uncorrelated uncertainty.
Our simplified approach is nonetheless complemented by the more realistic propagation using the Jacobians as detailed in section 5 eq. (26) but noting that even the propagation via the Jacobians remains suboptimal as long as error covariance matrices are not derived for the GRUAN products.
The text has been revised as to make clear that the resulting uncertainty is the best approximation that this simplified approach can yield, noting that other technics exists and are discussed later in this paper.
Future versions of the GRUAN Processor may potentially be upgraded in order to estimate GRUAN uncertainty in radiance space using either the Monte Carlo method if the next generation GRUAN products allows it or the propagation via Jacobians, although there is no such plan at this moment.

Manuscript change:
Line 416 – 424:
Note that the eight combinations of sign that this approach can allow have been tried during the test phase. The resulting uncertainty was not found significantly different from that obtained with Tb+ and Tb-, but the processing time significantly increased. Tb+ and Tb- were therefore retained as the best compromise.
It should be noted that the simplified nature of this approach, which applies a perturbation of constant sign in the vertical, ignores the complicated fluctuations that the propagation of uncertainty via a multiplication by the Jacobians would induce (see section 5). Here, we assume that the GRUAN profiles of uncertainty used to perturb the atmospheric profiles are fully correlated at all levels. This assumption differs from the truth in that GRUAN total uncertainty consists of a root sum square of correlated and uncorrelated components (Dirksen et al., 2014). Nevertheless, assuming a fully correlated perturbation enables the estimation of the total GRUAN uncertainty upper bound in radiance space allowed by this approach.

Referee:
In the paragraphs from line 519 to line 532, it is underlined that the ECMWF model is not always find within GRUAN uncertainty but the UK Met Office is. Could it be a matter of observation errors difference used in both models? For instance, if in the UK Met Office data assimilation system, these radiosondes are assimilated with a smaller observation error, it is then more likely that it compares better than the ECMWF model.

Authors:
There is a small difference in the observation errors used at the Met Office, that vary on the vertical from 5 to 14% in humidity and 0.55 to 2K in temperature, and those used at ECMWF, that vary from 7 to 10% in humidity and 0.9 to 2.6K in temperature. Note that, in addition, the Met Office and ECMWF do not treat radiosondes in the

exact same way. This is further described in the response to referee 1 comment 3.
One way to evaluate if the difference in observation error could explain the larger ΔTb found for ECMWF would be to conduct an experiment at the Met Office with radiosonde observation error equal to that of ECMWF. Such experiment would be however demanding both in term of time and resources. Instead, we can compare the data from a denial experiment that has been conducted at the Met Office during the development phase of the GRUAN Processor for testing purposes. In this experiment, all radiosondes launched from Lindenberg in 2016 were removed from assimilation. The model used is a low resolution (N320, ∼40km at mid-latitudes) version of the full Met Office global system (as of 2016) with 4D-VAR uncoupled hybrid assimilation.
Model background fields from the experiment and its control have been extracted and processed with the GRUAN Processor. The comparison of the resulting ΔTb (i.e. $MetOffice_{denial} - GRUAN$ and $MetOffice_{control} - GRUAN$) shows that the differences between control and experiment are smaller than 0.03K (figure R1). Based on that result, we could argue that since the complete removal of a radiosonde launch site from the system does not impact significantly the model background, it is unlikely that a change in observation error (or the different radiosonde treatments) can explain the ∼0.2K difference seen on Fig.s 4 and 5 between ΔTb_{ECMWF} and $\Delta Tb_{MetOffice}$ in high peaking temperature channels.
Arguably, the low resolution used in the denial experiment potentially attenuate the impact of the radiosondes on the short range forecasts. But although this could result in an underestimation of the impact on humidity that varies on small scales, it is not expected to strongly affect temperature that varies at scales captured by the model.
On the contrary, as pointed out in the paper, the somewhat large ΔTb in high peaking temperature channels can be related to the 0.5K cold stratospheric bias observed in the ECMWF dataset. The lower stratospheric cold bias in the ECMWF analyses is a known feature observed by e.g. Ingleby (2017) using various type of radiosondes or Shepherd et al. (2018) in ERA5, noting that ERA5 reanalysis are being produced using IFS cycle 41r2 (the cycle used for operational forecasting in 2016). Shepherd et

al. (2018) also show that ERA5 is 0.25K biased in radiance space compared to ERAi at frequencies equivalent to those of ATMS temperature channels. It is suggested that an excess of water vapour entering IFS lower stratosphere lead to a cold bias by radiative cooling. This excess may come from too intense overshooting convection in ERA5 according to the authors.
At the Met Office, an imposed cap on water vapour transport at the tropopause reduce the moistening effect of the lower stratosphere.

Manuscript change:
Line 492:
In Fig.s 4 and 5, the main feature for ECMWF is a 0.5K cold bias in the stratosphere (100-10hPa), observed both day and night. This bias has also been detected by Shepherd et al. (2018) in the ERA5 reanalysis that are based on IFS cycle 41r2, the operational model in 2016. It is attributed to an excess of moisture transported into the lower stratosphere, which lead to a cold bias by radiative cooling.

Line 916:
Gobiet, A., Foelsche, U. , Steiner, A. K., Borsche, M., Kirchengast, G. and Wickert J.: Climatological validation of stratospheric temperatures in ECMWF operational analyses with CHAMP radio occultation data, Geophys. Res. Lett., 32, L12806, doi: 10.1029/2005GL022617, 2005.

Line 984:
Shepherd, T.G., Polichtchouk, I., Hogan, R.J., Simmons, A.J.: Report on Stratosphere Task Force, ECMWF Technical Memorandum, 824, https://www.ecmwf.int/en/elibrary/18259-report-stratosphere-task-force, 2018.

Referee:
Line 346, "Fig. 3 shows a the changes from...” Please remove "a".

Authors:
Changed according the referee suggestion.

Referee:
Line 519:
the authors discuss the differences for channels 8 to 12 and then mention the red shading of Figure 5 but these channels are not present on Figure 5. Please add them on the Figure or change the text.

Authors:
For readability, the horizontal axis on figures 4 and 5 only shows odd channel numbers but all 22 ATMS channels are plotted. The caption has been revised for more clarity.

Manuscript change:
Line 538:
the difference in simulated brightness temperatures for the 22 ATMS channels is expressed in K (bottom)

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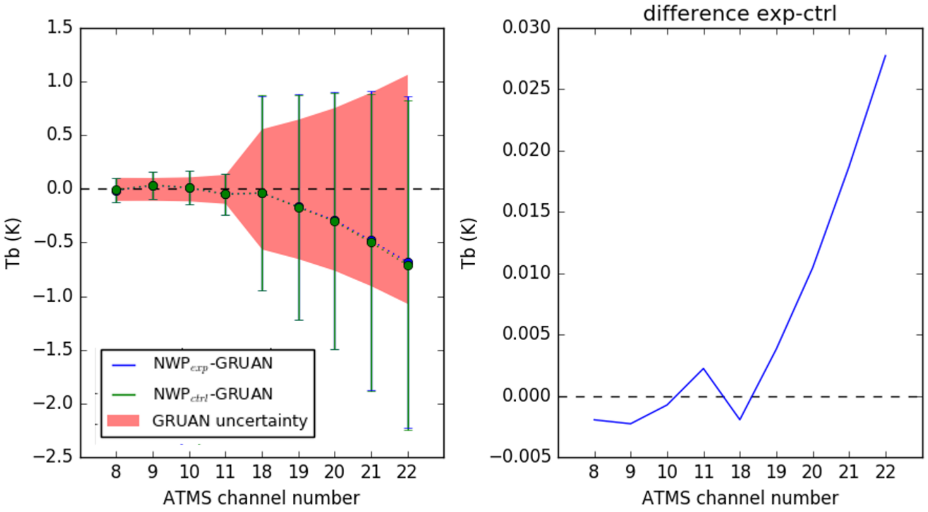

Fig. 1. Figure R1: (left) NWP-GRUAN simulated Tb at ATMS freq. using the MetOffice denial exp. (blue) and from control (green). (Right) difference between exp. and control.