Response to Reviewer 1

The authors would like to thank the reviewer for his/her careful review and constructive comments, which we believe will help improve the content of the manuscript. Below, under each bullet point, we provide a point by point response to each comment/question. The author responses are given in blue, and textual changes are italicised.

General comments

- "precipitation and most dense clouds" I think the hydrometeor size is an important factor.

  Reply: We agree that the hydrometeor size is an important aspect, but when it comes to an overview of the cloud contamination at 183 GHz, precipitating clouds and clouds with large optical thickness have the strongest effect, and a dense cloud could be composed of hydrometeors of different shapes and sizes.

- L66: "only using measurements (no background data involved)" My understanding is that the method is in theory model-free, but for the demonstration in this study, simulations (e.g. background simulated at MWHS2 frequency) are used. Am I correct? Maybe this should be stressed here. Why not try with real MWHS2 observation for the all sky dataset?

  Reply: Yes, the demonstration of the entire concept is based on simulations. We do not try with the real MWHS-2 observations as the validation of the training process could only be performed against clear-sy simulations. To stress on the fact that only background MWHS-2 observations are used, we have added the following text to Sect. 2.1.1:
  Pg 4, line 104: "*For the demonstration of the study, MWHS-2 simulations from the ECMWF model background are used. Actual measurements are not taken into account. The requisite data was obtained from ECMWF. More details are described in Sect.2.1.1.*"

- L137 "Simulations for all three sensors are noise free, so to incorporate the measurement uncertainties, whenever needed, Gaussian noise is added according to the channel NEDT (Table 1 - Table 3)." Are the errors arising from the radiative transfer calculation accounted for?

  Reply: The most important errors arising from radiative transfer calculations, are related to representing the cloud microphysics. In this study, for ICI and SMS, we consider only one particle size distribution (PSD) and habit and this could underestimate the true cloud variability. Underestimation of scattering at higher frequencies can lead to some imperfections in mapping the cloud information from sub-mm and 183 GHz. Other factors affecting the accuracy of simulations, but not considered due to brevity include neglected antenna pattern and limitations associated with input data, both Cloudsat and ERAInterim. For

example, the simulations could have tendency to be biased towards the Cloudsat geographical sampling. The actual background departures and the corresponding bias correction shall only be revealed when data from ICI is available in future.
We have added a short description these radiative transfer errors that could affect the simulations in Sect. 2.2.

- L159: "for all selected quantile fractions " by quantile fraction, do you mean the n th amongst the 7 selected (from 0.2 to 99.8%)? Also, 16, 50 and 85% are not symmetric (rounding?)

  Reply: Yes, the selected quantiles are the seven percentiles mentioned. We re-phrase some sentences here to make it more clear. 85% is a typo, it should be 84%. It has been corrected.

- L163: Pfreundschuh uses an indicator function I (=1 or 0) in the CRPS, the authors here use y, can they explain the difference?

  Reply: The CRPS in the manuscript is incorrect. We thank the reviewer for highlighting it. We have corrected the equation in the revised manuscript.

- L173: " The input data is all-sky brightness temperature" the simulated one, even for MWHS2, right?

  Reply: Yes, even for MWHS-2 we use simulated all-sky brightness temperatures.

- L301: "0.15 K" should be -0.15

  Reply: The correction is made.

- L453: "Among these four channels, 150 GHz has the highest peaking function around 4 C2km (Chen and Bennartz, 2020)" Could you please clarify what you mean here, 150GHz is neither the highest nor the lowest peaking channel nor it peaks at 4km. Channel 89, 118+/-1.1, 118+/-2.5, and 150 GHz peak at 0.1, 9.6, 2.9, 1km, respectively (according to Chen and Bennartz, 2020), this can also be seen in Lawrence et al. (2018) Fig. 1 through the Jacobians of channels 6 and 7.

  Reply: The reviewer is correct. It was wrongly mentioned that 150 GHz is the highest peaking channel, at 4 km. We have corrected the text and it now reads as:
  Pg 25, line 465: "*The channels, 150 GHz and 118.75±2.5 peak between surface and 4 km. These channels can only provide coverage to the humidity channels in the lower and mid troposphere. However, the 183 GHz channels are sensitive to hydrometeor content up to 10 km. The channel 118.75±1.1 peaks around 10 km, but such information is only partly relevant for the higher peaking channels of 183 GHz.*"

- L460: "but such information would be not be completely orthogonal" duplicate "be"

Reply: The duplicate word is removed.

- Table 1: NEDT are constructor specifications, the real noise is lower, see Fig 5 Guo, Y., J. Y. He, S. Y. Gu, and N. M. Lu, 2019: Calibration and validation of Feng Yun-3-D microwave humidity sounder II.
IEEE Geoscience and Remote Sensing Letters, doi:10.1109/LGRS.2019.2957403. Tab 5 Carminati, F., Atkinson, N., Candy, B., Lu, Q.: Insights into the Microwave Instruments Onboard the Feng-Yun 3D Satellite: Data Quality and Assimilation in the Met Office NWP System. Adv. Atmos. Sci. (2020). https://doi.org/10.1007/s00376-020-0010-1

  Reply: The reviewer rightly mentions that the real noise is lower, however we add the sensor noise according to the pre-launch specifications. This can be viewed as a conservative estimate of the sensor noise to include other sources of error not accounted for in NEDT. For example in the study by Carminati et al. (2020) the authors describe radiation leak affecting the higher frequency channels.
  We clarify in the manuscript that pre-launch specification values are used.

Questions

- Is this method applicable to IR e.g. to an ATOVS system?

  Reply: Yes, the method could potentially be applied to IR. The operation and performance of the cloud correction approach is based on the fact that different frequencies have varying sensitivity to cloud signatures in the same field of view. For IR, infact this feature is regularly used to flag out cloud contamination. Most cloud flagging schemes for IR are based on brightness temperature thresholds.
  In the manuscript, without going into the details, we mention that "*The scheme could also be potentially extended to cloud correction at infra-red frequencies*"

- The authors explain that it could benefit the all-sky assimilation systems indirectly for the analysis increment. Instead (or in addition) could it be used to model the variable observation error (when and by how much to be inflated)? This would be, in my view, the most valuable.

  Reply: The reviewer has a very good point. At ECMWF, the observational errors for MHS and MWHS-2 are defined as quadratic functions of symmetric cloud indicator (Geer et al., 2014). The observational errors are higher in regions for cloud and vice-versa. Thus it could be potentially feasible to use the QRNN identified cloud impact to formulate the observational errors. This could probably be the best use of the QRNN technique for all-sky. Of course using QRNN to develop a full observational model, would require to characterize the performance of the scheme over upper latitudes, land and ocean.
  We have included the following text in the manuscript:
  Pg 29, Line 577: "*Also, it could be feasible to use the QRNN identified cloud impact to formulate the observational errors. This may be the best use of the QRNN technique when it comes to all-sky assimilation.*"

- Could the uncertainty use for weak constraint 4dvar?

  Reply: Although, the uncertainties obtained from QRNN do not have a direct application to weak constraint 4dvar, but they could still be considered as a diagnostic to help evaluate the weak constraint in the troposphere. For example, undiagnosed cirrus contamination in the upper troposphere might be associated with apparent model biases that are actually caused by systematic forward model errors.

- What is the resource cost of this method (is this fast enough to be used in 1-h regional nwp with 30min window)?

  Reply: The method is probably computationally more complex than other methods based on, for example, a scattering index, we consider it unlikely that the computational cost of the scheme would be an issue in an operational context.
  The only demanding part of the scheme is the training process, but it is performed offline. Evaluating the network during operational processing would require only a forward pass through the network. In the study, we employ a simple, fully-connected network architecture so that the complexity of a forward pass is dominated by a low number of matrix-vector multiplications (one for each layer the network). The matrix-vector multiplications are typically combined into matrix-matrix multiplications to evaluate the network for multiple observations in parallel. Due to the recent popularity of neural networks, highly optimized implementations of these methods are available for all common computing architectures. We have included the following information in the Conclusions section.
  Pg 29, Line 591: "*Due to its low computational cost, implementation of this scheme should be feasible in NWP models given their computational constraints. Although the method is probably computationally more complex than existing cloud clearing methods, the demanding part of the scheme, the training, is performed offline. The operational processing only requires a forward pass through the neural network, for which highly-optimized implementations are readily available on all common computing platforms.*"

References

Carminati, F., Atkinson, N., and Candy, B.: Insights into the Microwave Instruments Onboard the Feng-Yun 3D Satellite: Data Quality and Assimilation in the Met Office NWP System., Adv. Atmos. Sci., https://doi.org/https://doi.org/10.1007/s00376-020-0010-1, 2020.

Geer, A. J., Baordo, F., Bormann, N., and English, S.: All-sky assimilation of microwave humidity sounders, Tech. Rep. 741, ECMWF, https://doi.org/10.21957/obosmx154, URL `https://www.ecmwf.int/node/9507`, last access: :29 October 2020, 2014.