Reply to Reviewer #2:

This contribution discusses observation processing for GPSRO observations in a pair of forecast systems. First, GPSRO observations are processed using the operational global model at KMA. The background error statistics of the prior estimates of GPSRO observations with and without the observation processing are compared. Second, the GPSRO observations are used in a pair of data denial experiments with an LETKF assimilation system with a low-resolution climate model, CAM-SE. A control assimilates only radiosonde observations and surface pressure while a second two-week experiment also assimilates GPSRO. The spread and adaptive inflation of the two cases are compared. In addition, the ensemble mean analyses are compared to an externally produced reanalysis product. The case that assimilates GPSRO is found to have reduced spread, especially in areas that have limited radiosonde coverage, and reduced differences from the reanalysis.

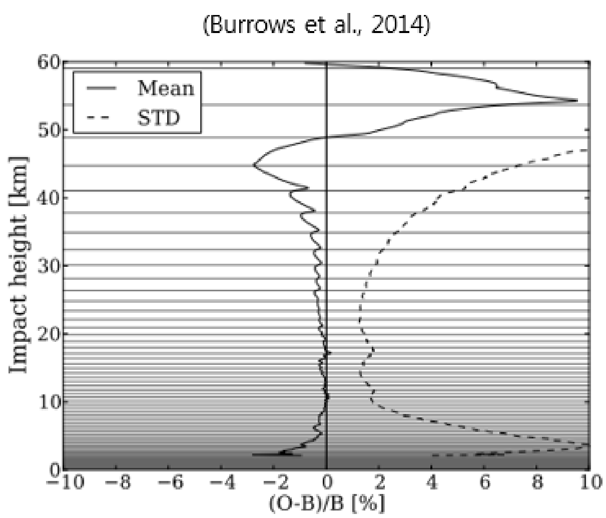
Thank you so much for your clear summary of our manuscript. We have done our best to answer your comments and to improve the manuscript as the reviewer suggested.

The results presented show that the observation preprocessing with the operational KMA system leads to the rejection of observations that disagree with the prior estimates. While this is a necessary condition for a reasonable preprocessing system, it is not possible to conclude much from the results. In particular, there is no evidence presented to support the conclusion that the observations being rejected by the background checks are fundamentally problematic. It is possible that good observations are being rejected in places where the model background is particularly inaccurate. A more careful analysis and comparison to other established operational quality control systems would be useful additional information to increase confidence that the background check is functioning appropriately.

Thank you for your constructive comments. We agree with your opinion that the observation being rejected by the background checks are not fundamentally problematic and it is possible that the good observation being rejected in places where the model background is particularly inaccurate. We did not conclude that the observations being rejected by the background checks are fundamentally problematic. We tried to shows that the implemented GPS-RO processing system in this study is working reasonably. We added explanation about the following comparison results of bending angle data processing from our and Met Office's systems in

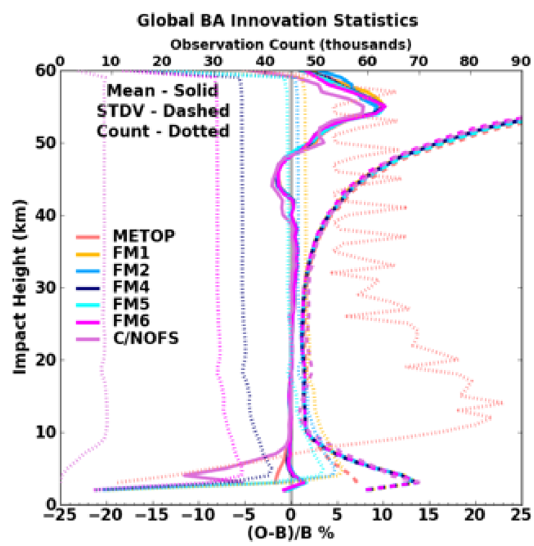
Section 2.4. Also, we added the description about the analysis results of number of observations before and after the quality control in Section 2.4.

We compared our results of bending angle departure (O-B) statistics to that from the established operational quality control system of the Met Office. The quality control of GPS-RO data in Met Office consists of a 1D-Var retrieval, with checks based on the size of the initial and final cost function, number of iterations and the difference between the observation and 1D-Var retrieval solution (Rennie, 2010). The initial cost function check is equivalent to a whole profile observation–minus-background check (Rennie, 2010). Following figures shows departure statistics of bending angle from the QC system of KIAPS and Met Office, respectively. The period (about one month) of data processing and types (satellites) of used observations are similar to each other even though the year and month of observation are different. Also, the UM is used for providing model background field in both processing.



(a) Bending angle innovations from 25 Met Office (6-hourly) model cycles, with observation data from all available RO instruments. The period started with the 00Z analysis on 1 January 2014.

(Met Office results)



(b) Global mean bending angle innovation and number of observations as a function of impact parameter before and after quality control for the month of November 2012. Statistics are calculated based on each satellite data and displayed with different colors.

(Our results)

In the comparison of bending angle departure statistics from our processing with Met office products, a reasonable consistency was shown in terms of global mean and standard deviation, except for the observation from the CORISS instrument in our data processing. Met office is shows the similar results of O-B statistics from CORISS instrument as well, so they do not use the GPS-RO observations under the height of 10 km for an operational data assimilation (2013, personal communication). We believe that this comparison results can support that the implemented GPS-RO processing system in this study is functioning reasonably. We also investigate the comparison results of bending angle statistics from the ECMWF processing system. Rennie, 2000 showed comparison results of bending angle statistics using both Met Office and ECMWF backgrounds. There are clear differences between the means of the ECMWF and Met Office departures for bending angle and they pointed out that there are biases unique to each model. Following figure shows the bending angle innovation statistics from the ECMWF model, using observations from all RO instruments over 30-day period (April 2013) (Burrows et al., 2014). Compared to the results from KIAPS and Met Office, O-B statistics from the ECMWF shows a different pattern depends on the impact height, but range of difference value is consistent with that from the KIAPS and Met Office within ± 4 % for under 50 km of impact height.

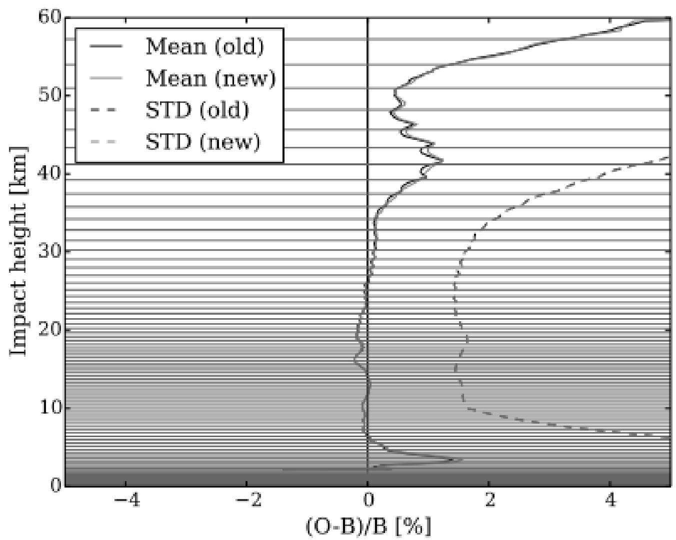


Figure 10. Bending angle innovation statistics from the 91-level ECMWF model, using observations from all RO instruments over a 30-day period (April 2013). Typical model level heights are overlaid. The statistics generated using the original "ROPP" operator are plotted in black, and the ECMWF implementation of the improved operator is plotted in grey (see Appendix A3 for full details).

The description of the observation processing system for the ensemble assimilation is not as clear as it could be. It does not seem that any information from the prior ensemble statistics is *used in the quality control although this is one of the great advantages of having an ensemble system. Instead of using some multiple of a specified observational error variance to determine if a prior is too far from the observation, ensemble systems can also incorporate information from the prior ensemble spread to determine the rejection threshold. If the system did use this type of quality control, it should be made clear.*

Thank you for your constructive and useful comment. We did not use any information from the prior ensemble statistics for the quality control in this study. Since this is our first version of GPS-RO data processing system for data assimilation, we adapted the popular way of defining observation error used in operational weather centers (Met Office and ECMWF). The forecast model used for the analysis in this study is the CAM-SE, which was developed for climate projection rather than weather prediction with a relatively coarse vertical (30 layers with the model top of 2.25 Pa) and horizontal resolution (~ 2.5 degree). After we switch to with optimal system (KIAPS-GM) in the near future, we will try to use the method you suggested for defining observation error for quality control of ensemble data assimilation. We added description about this research plan in Section 4. Thanks you so much for your constructive comment again.

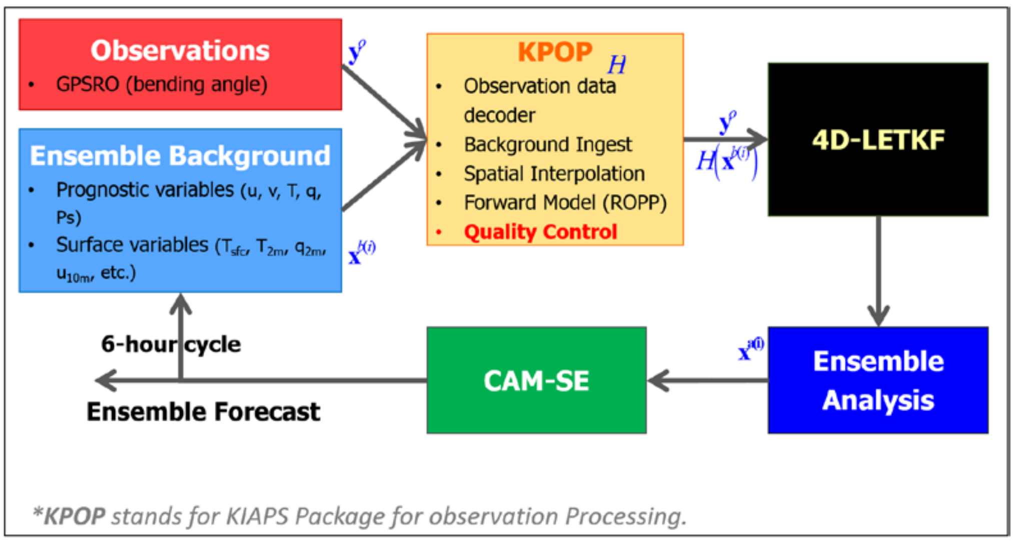
"Also, we will try to use the information from the prior ensemble statistics for the quality control of bending angle within the KPOP system."

We also added more explanation of the observation processing for the ensemble assimilation in Section 3.2.

"For the bending angle data assimilation within the KIAPS-LETKF system, we first processed the GPS-RO data with every-hour background ensembles from the CAM-SE forecast within KPOP system. All processing steps described in Section 2.3 are applied for the GPS-RO data processing with CAM-SE background."

Also unclear is exactly how the background check was implemented. The report states, ": : :whereas our CAM-SE background is the forecast from the analysis assimilating sonde and surface pressure station data only". This seems to indicate that the quality control was done only using the first LETKF case with no GPSRO assimilation. A more appropriate approach would be to do the data processing as an integral part of the GPSRO assimilation case as one would do with an operational system. Again, the authors should make sure to clarify exactly what they did and why.

Thank you for your careful comments and sorry to make you confused. The quality control for GPS-RO assimilation with KIAPS-LETKF system was done using every-hour background ensembles of the CAM-SE forecasts from every-six hour analysis for two weeks. Following figure shows the KIAPS-LETKF system coupled with KPOP and the cycle of assimilation experiment from ingests of observation and backgrounds to CAM-SE forecasts with ensemble analysis. This assimilation cycle including quality control process in KPOP is repeated for whole period of assimilation experiment similar with the case of the operational data assimilation system.



We modified our manuscript in section 3.2 as following,

"For the bending angle data assimilation within the KIAPS-LETKF system, we first processed the GPS-RO data with every-hour background ensembles from the CAM-SE forecast within KPOP system. All processing steps described in Section 2.3 are applied for the GPS-RO data processing with CAM-SE background. The data processing for ensemble data assimilation was done using each member of background ensembles of CAM-SE forecasts from every-six hour analysis for two weeks. The observations passed through the KPOP processing with all 30 ensemble backgrounds are used for the bending angle assimilation within the KIAPS-LETKF system. The background ensembles at the initial time of bending angle data assimilation cycles are the forecasts from the analysis assimilating sonde and surface pressure station data only. Since the EXP_RO cycle is initiated, the background ensembles used for the data processing are

CAM-SE forecasts starting from the analysis assimilating bending angle in addition to sonde and surface pressure data.”

“Another factor is that the KMA backgrounds already include the operational data assimilation effects of GPS-RO and many other observations on the analysis, whereas our CAM-SE background is the forecast from the analysis assimilating sonde, surface pressure station data and GPS-RO bending angle only.”

The first results shown comparing the two LETKF cases display differences in spread. The reduced spread in the case assimilating GPSRO is argued to be an indicator of a correct implementation. However, there is no attempt to validate the correctness of the spread in either system through, for instance, a spread/skill analysis or the use of tools like rank histograms. The spread decreases in places where there are few sondes, as one would expect, but again, this is only a necessary condition for a correctly functioning system.

We fully agree with Reviewer’s comment. Yes, it is a necessary condition for a correctly functioning system. Since this is our first trial of real GPS-RO bending angle data, we would like to check whether the system works okay in our new system. Therefore, we modified our manuscript, a part describing ensemble spread of Figure 8 as the reviewer pointed out.

“We found significant uncertainty reduction estimated over the areas where the analysis increments are shown in Figure 8. This illustrates that GPS-RO data are assimilated and reduce uncertainties of background and analysis over the areas with many data and relative inaccuracy of background states. Because we used the adaptive multiplicative inflation method (Miyoshi, 2011), which computes inflation parameters in a way that has large inflation where and when innovation is large, to avoid underestimation of background uncertainty, background/analysis tends to have greater inflation factors than unity. In contrast, the multiplicative inflation parameter is not adaptively estimated when there is no observation (no O-B information), and then a very small inflation factor (only 1% inflation) is set. Therefore, background states in EXP_RO tend to be inflated more than those in CTRL_SONDE. Despite greater inflation factors multiplied in EXP_RO than in CTRL_SONDE, resultant analysis of EXP_RO shows significant reduction of analysis spread as a result of assimilating additional data. . Before verifying our analysis, we just confirm that GPS-RO bending angle data are assimilated effectively for the first test with the KIAPS-LETKF system in a way to reduce analysis uncertainty where the data are expected to contribute."

The authors do provide a comparison of ensemble means to an independent reanalysis and this does show that, on average, errors are reduced using the GPSRO. However, the impacts are quite mixed in sign, even in the southern hemisphere, and appear to be negligible in the northern hemisphere. The impact appears to be quite small compared to similar published data denial experiments. I recommend that the authors compare their error change results to other published examples from the early years of GPSRO observations. Finally, it would be a good idea to compare the forecast fits to observations within the LETKF systems, rather than just comparing to an external reanalysis.

Thank you for your careful comment. First of all, we agree that the improvement in the Figures of our previous manuscript may not look encouraging, especially for the wind field, although temperature field shows obvious improvement in the Southern Hemisphere. We thought that it resulted from the characteristics of GPSRO data which has large sensitivity to the temperature rather than the wind field. The wind field should benefit from the improved temperature throughout the cycles of forecast-analysis though.

In this study, we have done only two-weeks analysis after adding GPSRO data so that the impact may not be shown well enough with such a short experiment period. Also, we should incorporate better model to expect more reasonable performance compared with other operational system as well as advance data assimilation method for better analysis of GPSRO data, which will be our next work. Here, we would like to check whether our observation processing and ensemble-based data assimilation system works appropriately and to discuss how we can improve the results in the future. The system may not be really ready to be comparable with other operational centers that have already experienced many cases with many data. Therefore, we'll mention remained work in our current system after adding two more Figures. The first additional figure shows vertical profiles of the impact of GPSRO data (Figure 11). Figure 11 indicates that the improvement of our resultant analysis becomes greater as altitude gets higher. Therefore, we added one more figure showing the improvement at the level where the error reduction looks more significant (Figure 12). Finally, we modified the last paragraph of the section 3, as following:

“We also took a look at the vertical profiles of analysis improvement in a comparison with ERA interim data in Figure 11. It shows significant error reduction introduced by adding GPS-RO bending angle data overall for two weeks of EXP_RO. There are considerable corrections of errors in upper level wind and temperature. In addition, we could apparently find positive impact of RO data even in the lower troposphere, especially over Polar region where there exists forecast imperfection due to inactivated sea-ice model. Figure 12 shows much greater improvement caused by GPS-RO bending angle data at the level of 20 hPa than the level of 100 hPa, and the global mean of error reduction looks remarkable for both variables of U and T. Those results are from the first version of GPS-RO bending angle data assimilation within the KIAPS-LETKF system coupled with KPOP. Thus, we want to prove our first achievement in this paper. In the meantime, we continue improving our current system (such as tuning parameters, replacing the forecast model by a better one, and so on) so that it could give comparable results with those of other centers (e.g. Cucurull et al., 2007, Anlauf et al., 2011) in the near future.**”**

Cucurull, L., J. C. Derber, R. Treadon, and R. J. Purser, 2007: Assimilation of Global Positioning System Radio Occultation Observations into NCEP's Global Data Assimilation System. Mon. Wea. Rev., 135, 3174-3193.

Anlauf, H., D. Pingel, and A. Rhodin, 2011: Assimilation of GPS radio occultation data at DWD. Atmos. Meas. Tech., 2, 1105-1113.

In summary, it’s difficult to use these results to assess much about the correctness of the implementation. Comparison to similar data denial activities in a well-tested system would provide much more information.

We hope that the revised version of our manuscript could convince the Reviewer #2. We would appreciate it if there are more suggestions.

The authors briefly discuss localization of GPSRO impact and suggest that they might limit it to only impacting T state variables. There is a lot of published work on localization including multivariate localization. This work supports the idea that different localizations for different types of state variables is often appropriate, but definitely does not suggest that completely eliminating impact on winds would be appropriate. If the authors do explore this, they should carefully evaluate the effects on the balance of model forecasts.

Yes, we agree with the Reviewer's comment and understand the Reviewer's concern. In EnKF, wind field still can benefit from the better temperature analysis through the ensemble forecast step. However, we'll keep in mind the reviewer's concern if we test it. Thank you so much.

Minor comment: Figures 3a,b, 4a, 5a, b: Can't see the dotted count in the figure.

We modified the figures. Thank you.