ESSD-2021-217
Response to RC1 (Referee 1)

The authors thank referee 1 for a thoughtful review of the manuscript. We agree with many of the referee's points and have made the necessary changes. The responses for the referee's specific comments are as follows.

Overall comments:

The authors generated the East Asia Regional Reanalysis (EARR) using Weather Research and Forecasting (WRF, v3.7.1) during the ten-year period 2010-2019, based on the advanced hybrid gain data assimilation method (AdvHG). The new advanced hybrid gain (AdvHG) data assimilation method combining E3DVAR and ERA5 based on WRF model is newly proposed and investigated in this study. The manuscript verified the EARR for two-year period 2017-2018 by comparing EARR against ERA-Interim, ERA5 and observations.

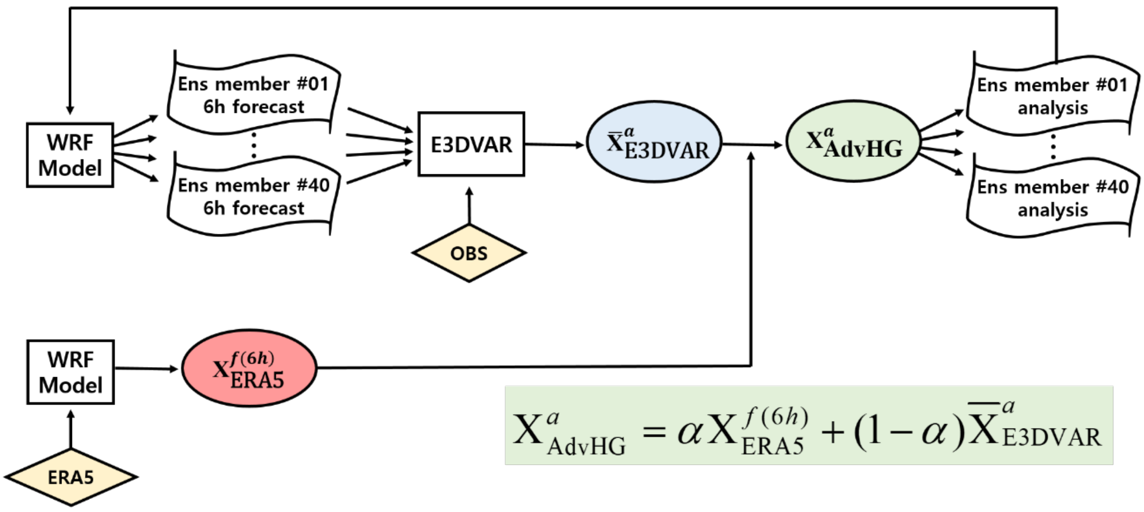
I think a lot of work behind this manuscript is worth publishing. However, there are some details and the underlying physics processes were not well discussed.

The detailed comments are listed as below.

Major comments:

1-A. It is not easy to understand the regional reanalysis method used in this paper. I'd suggest the authors use schematic diagram to clearly describe the regional reanalysis method.

Authors' response: Following the referee's suggestion, a schematic diagram for the advanced hybrid gain method is added to the revised manuscript as Fig. 2 (Figure_rev1. below).



Figure_rev1. The schematic diagram of the advanced hybrid gain data assimilation method in the East Asia regional reanalysis system.

1-B. What does "forecast fields are integrated up to 36h" mean? Is reinitialization used? What does "6h forecast of ERA5 reanalysis based on WRF model" mean? Does it mean WRF simulations using ERA5 as LBC forcing?

Authors' response: "Forecast fields are integrated up to 36 h" implies that forecast fields are produced using WRF model for 36 h. Thus, 24 and 36 h forecast fields are evaluated in this study (Figs. 4, 5, and 7 in the revised manuscript).

Reinitialization is not used in this study. For the experiments using data assimilation methods based on WRF model (E3DVAR, AdvHG), analysis fields are produced every 6 h (00, 06, 12, 18 UTC) via 6-h assimilation cycle, so forecast fields are generated from these cycled analysis fields used as initial conditions. For (WRF-based) ERA5 and ERA-I experiments, 36 h forecast fields are generated using WRF model with ERA5 and ERA-I reanalysis fields used as initial conditions, so reinitialization is not required in this study.

"6 h forecast of ERA5 reanalysis based on WRF model" means that 6 h forecast fields are produced using WRF model with ERA5 reanalysis as the initial condition. For WRF-based

ERA5 experiment, ERA5 is used as the lateral boundary condition as well as the initial condition in WRF model.

1-C. How many experiments are used in this manuscript? What experiments do "E3DVAR", "AdvHG", "WRF-ERA5" and "WRF-ERAIN" refer to respectively? These details should be more clarified.

Authors' response: In this study, E3DVAR and AdvHG imply analysis or forecast fields of experiments based on WRF model using E3DVAR and AdvHG data assimilation methods, respectively. Regarding reanalysis and (re)forecast fields of ECMWF, reanalysis fields (ERA5 and ERA-I) downloaded from ECMWF are evaluated (Figs. 3 and 6 in the revised manuscript). There are two different (re)forecast fields (e.g., ERA5_fromECMWF, WRF-based ERA5) used in this study, as mentioned in section 2.4. WRF-based ERA5 and ERA-I are forecast fields based on WRF model where ERA5 and ERA-I are used as initial conditions, respectively. In contrast, ERA5_fromECMWF and ERA-I_fromECMWF are reforecast fields based on ECMWF model not WRF model, and these reforecast fields are only evaluated for precipitation (Figs. 8 and 9 in the revised manuscript). Following the referee's suggestion, detailed information on each experiment is added to section 2.4 and Table 3 in the revised manuscript (L210-219) as follows (underlined).

<u>(L210-219) "In this study, (re)forecast as well as reanalysis fields need to be verified. Regarding reanalysis and (re)forecast fields of ECMWF, reanalysis fields (i.e., ERA5 and ERA-I) downloaded from ECMWF are evaluated (Figs. 3 and 6). There are two different (re)forecast fields (e.g., ERA5_fromECMWF, WRF-based ERA5) used in this study. WRF-based ERA5 and ERA-I are forecast fields based on WRF model with 12 km horizontal resolution where ERA5 and ERA-I are used as initial conditions, respectively. In contrast, ERA5_fromECMWF and ERA-I_fromECMWF are reforecast fields based on ECMWF model not WRF model, so the reforecast fields of ERA5 and ERA-I are provided and downloaded from ECMWF. These reforecast fields are only used for evaluation of precipitation (Figs. 8 and 9). The (re)analysis and (re)forecast fields and corresponding experiments are explained in Table 3"</u>

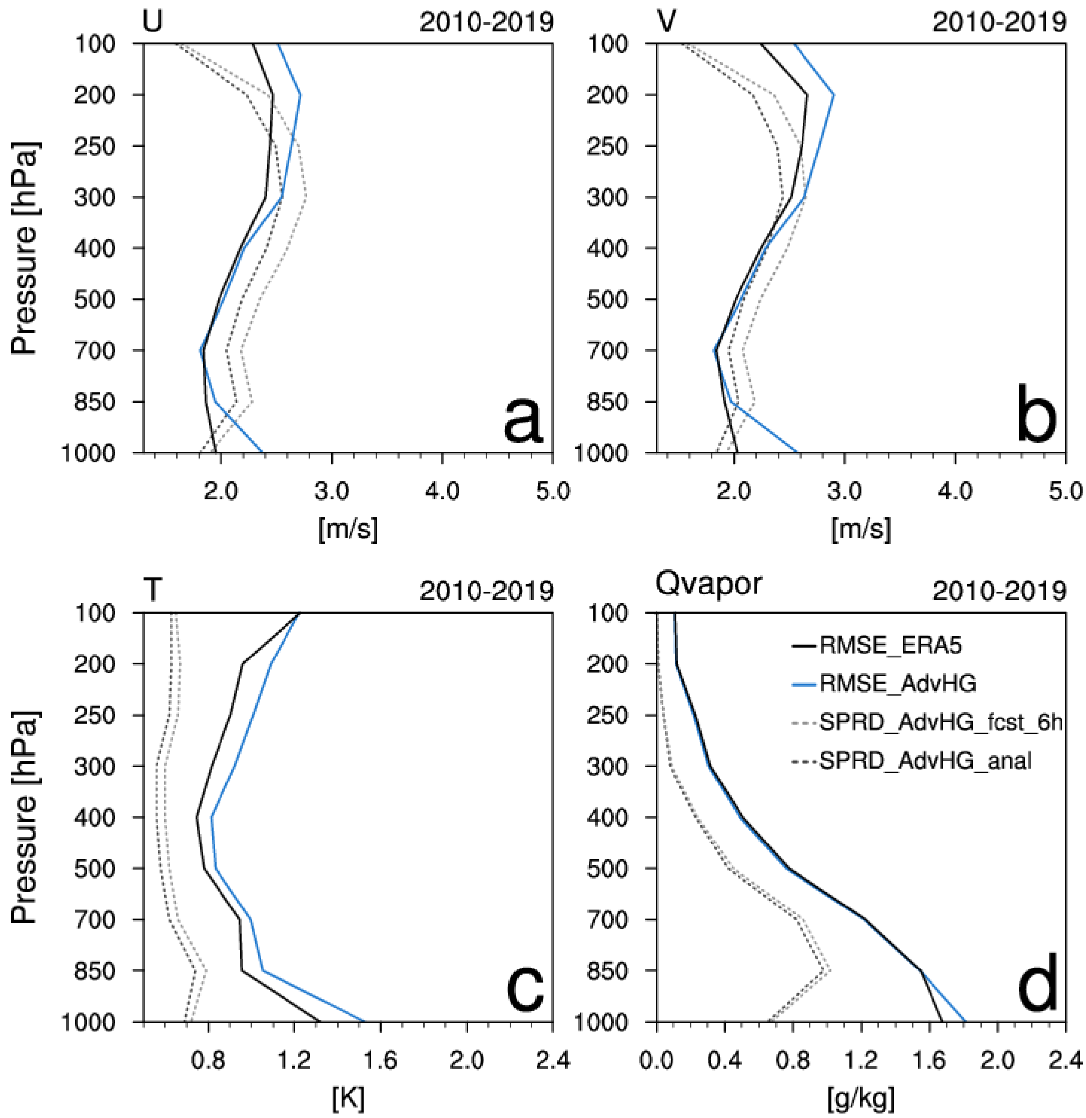
2. The newly advanced hybrid gain (AdvHG) data assimilation method uses 6h forecast ERA5 instead of deterministic analysis, and uses ERA5 instead of producing their own analysis fields from a variational DA method. The method is expected to save time and computing cost compared to traditional data assimilation framework. Why does the author use the 6h forecast of ERA5 reanalysis based on WRF instead of the deterministic analysis in AdvHG? Will the regional reanalysis be more accurate if using ERA5 deterministic analysis in AdvHG?

Authors' response: In this study, 6 h forecast of ERA5 based on WRF model is used instead of ERA5 reanalysis fields to maintain the consistency between different modeling systems as well as different resolutions. ERA5 reanalysis fields are generated based on the Integrated Forecasting System (IFS) of ECMWF with approximately 30 km horizontal resolution. If ERA5 reanalysis is directly used to combine with E3DVAR analysis based on WRF model whose horizontal resolution is 12 km, there could be some imbalance occurred in meteorological fields resulting from two different modeling systems. Thus, to reduce the imbalance and ensure the stability and consistency during analysis process, 6 h forecast of ERA5 is used instead of ERA5 deterministic reanalysis in Advanced Hybrid Gain method.

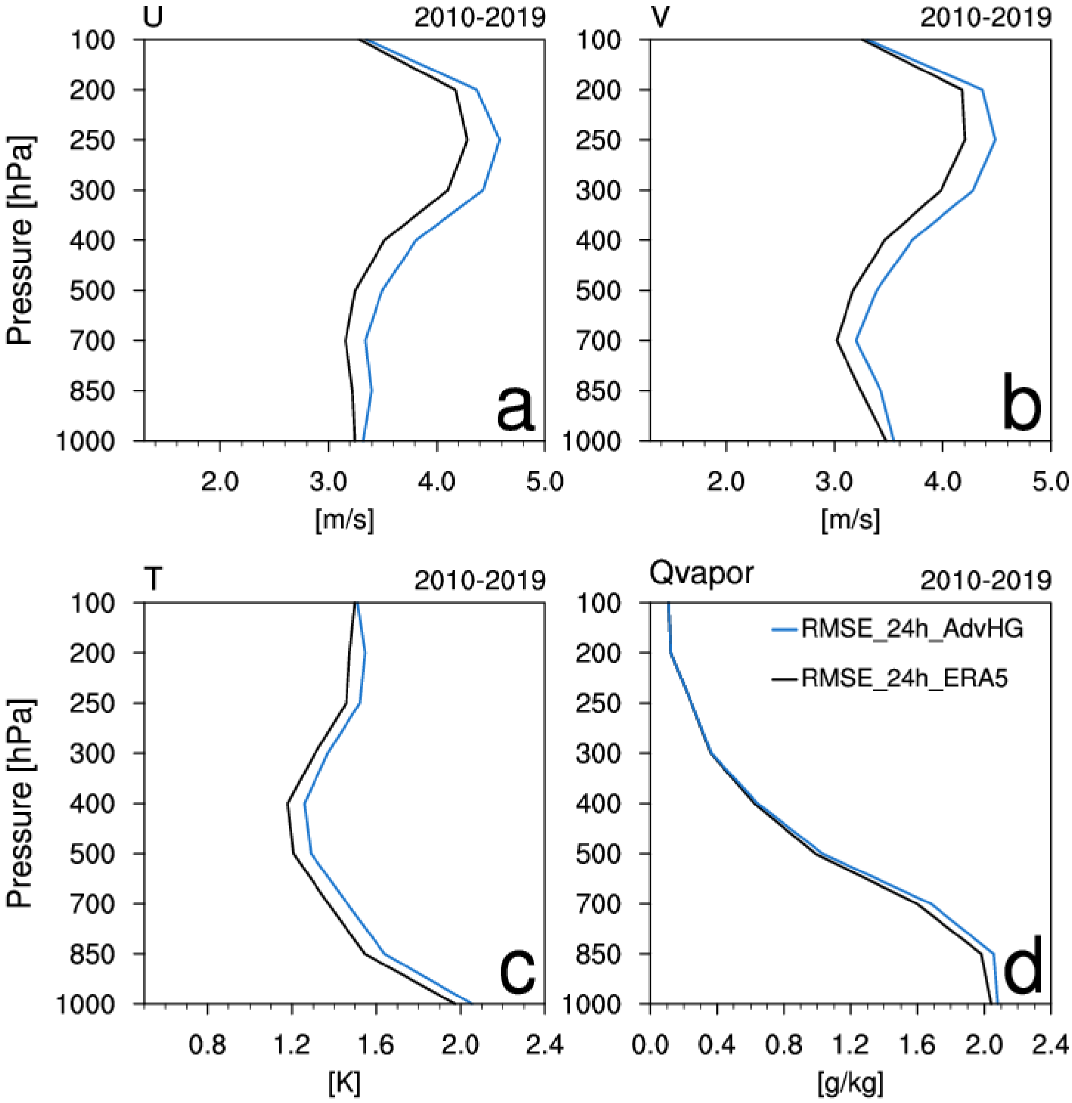
3. EARR is developed during the ten-year period 2010-2019, while in the manuscript, the authors only verified the product for two-year period 2017-2018. Why is this two-year period instead of the entire ten-year period chosen to be verified? I would like to see how the EARR product performs compared to the other two ECMWF global reanalysis in a longer time period, and whether EARR is suitable for application in long-term climatology research. If so, the influence of this product will be greatly increased.

Authors' response: One of the reasons for verifying only for two-year period in this study is that producing 36 h forecast fields of ERA5 using WRF model for 10-year period is too computationally expensive. In this study, (re)forecast as well as (re)analysis fields are verified. As mentioned in the section 2.4, for (re)forecast fields, two different forecast fields from ECMWF (i.e., forecast based on WRF model and reforecast based on ECMWF model) are used for comparison. In particular, 24 h forecast fields of ERA5 using WRF model are evaluated, as shown in Figs. 4 and 7 in the revised manuscript. While 24 h reforecast fields of EARR (AdvHG) for 10-year period have been generated during production process for the whole period, producing 24 h forecast for ERA5 is not necessary. Hence, two-year period was originally chosen for the purpose of evaluation. Furthermore, we consider it more valuable to make our dataset open to the public at the earliest possible time, so that it could benefit more people using this dataset. For these reasons, two-year period was originally verified in this study.

Nevertheless, as the referee pointed out, more investigation for longer-term period would be necessary. Therefore, as the referee proposed, we have evaluated longer-term datasets of EARR and ERA5 that are able to be verified for the whole 10-year period and replaced the results of two-year period with those of ten-year period (Figs. 6 and 7 in the revised manuscript) (Please see Figs_rev2 and rev3 below). Because the aim of our study is to investigate EARR (AdvHG) performance with ERA5, it is worth evaluating reanalysis and (re)forecast fields of EARR and ERA5 for 10-year period, as referee pointed out. However, it seems unfeasible to compare EARR performance with various experiments (e.g., E3DVAR, ERA-Interim) for the whole period due to the high computational costs producing those datasets, especially ensemble-based one (i.e. E3DVAR). The updated results for the period of 2010-2019 (Figs_rev2 and rev3) are almost the same as the previous results with two-year period, except for the water vapor mixing ratio (Qvapor). Although Qvapor RMSEs of reanalysis and (re)forecast of EARR and ERA5 for ten-year period are greater than those for two-year period, both of EARR and ERA5 Qvapor RMSEs increase and the RMSE differences between EARR and ERA5 for ten-year period are similar to those for two-year period. Thus, the longer-term evaluation reveals a large variability of atmospheric humidity and consequent predictability variability over East Asia for ten-year period of 2010-2019. We have revised the manuscript accordingly.



Figure_rev2. RMSEs of analysis of (a) zonal wind, (b) meridional wind, (c) temperature, and (d) Qvapor (water vapor mixing ratio) from ERA5 (black solid) and AdvHG (blue solid) and spreads of analysis (black dashed) and 6 h forecast (gray dashed) of AdvHG depending on pressure levels averaged over the ten-year period of 2010–2019.

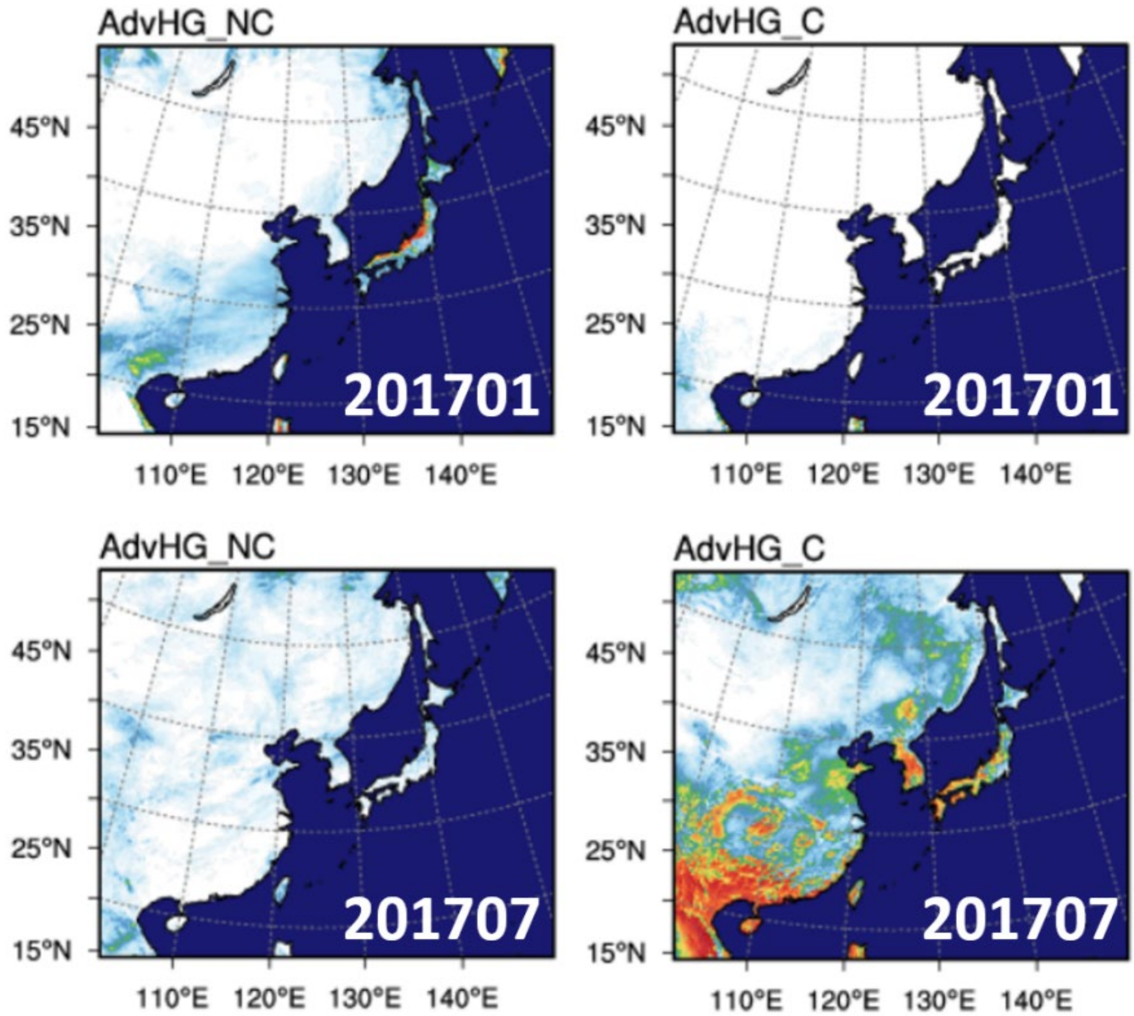


Figure_rev3. Same as Fig_rev2 except for RMSE of 24 h forecast.

4. The precipitation of AdvHG in winter (Juanuary) is the most accurate among other results, while E3DVAR (ERA5) performs better for weak (strong) thresholds in summer (July). The assimilation method tends to have positive effects on the simulated winter rainfall while brings limited improvement on summer rainfall. The possible underlying physics have not been well understood. Which physical process could be mostly possible affected leading to such positive effects?

Authors' response: As the referee pointed out, AdvHG shows the most accurate performance of precipitation in winter. In contrast, it shows limited improvement for summer. For summer season, ETS differences between the different results are not significant and the values of ETS are approximately 2 times smaller than those for the winter season (Fig. 8 in the revised manuscript). Hence, the overall predictability of precipitation for winter season for all results is higher than that for summer season.

To elucidate which physical process is responsible for more accurate simulation of precipitation, non-convective and convective precipitation fields of AdvHG are investigated respectively. The precipitation fields from microphysics (AdvHG_NC) and cumulus (AdvHG_C) parameterization schemes in WRF model for January and July 2017 are shown in Figure_rev4, and two seasons have different features in precipitation. While the majority of precipitation in January 2017 is represented by the large-scale (non-convective) precipitation, the simulation of precipitation in July 2017 depends mostly on the convective precipitation. Because convective scheme is more likely to have larger sub-grid variability, the predictability of precipitation in winter where large-scale precipitation can represent most of the total precipitation fields tends to be higher than that in summer.



Figure_rev4. The spatial distribution of the monthly accumulated precipitation of AdvHG from microphysics (AdvHG_NC) and cumulus (AdvHG_C) schemes for January and July 2017.

Furthermore, although large-scale variables of ERA5 forecast based on WRF (wind, temperature, specific humidity) have the lowest RMSEs among other results both for winter and summer seasons, the differences of forecast RMSEs between ERA5 and AdvHG for winter are much smaller than those for summer (Figs. 4 and 5 in the revised manuscript). The more accurate large-scale variables of AdvHG in winter could lead to higher AdvHG ETS in winter. Although AdvHG forecasts have less accurate large-scale variables than ERA5 forecasts, AdvHG ETS is higher than ERA ETS in winter implying that the precipitation could be a combination of small and large-scale processes in winter. In addition, it seems that producing analysis and forecast in the same system (WRF in AdvHG) could lead positive effects. Therefore, the consistency of modeling system for producing analysis and forecast could be fundamentally important.

5. Figure 2, it is clear that E3DVAR has the lowest RMSE for up-level variables, so what are the advantages of AdvHG? Does ERA5 in Fig. 2 mean WRF results forcing by ERA5?

Authors' response: As mentioned in the original manuscript L251-254 (in the revised manuscript L288-291), lower RMSEs of analysis fields do not guarantee the higher accuracy of analysis fields. Instead, RMSE of analysis indicates how much analysis fields are fitted to observations. Thus, not only those of analysis fields but also those of forecast fields need to be evaluated and compared to each other. As the referee pointed out in Fig. 2 in the original manuscript (Fig. 3 in the revised manuscript), the RMSEs of analysis fields of E3DVAR are lower than those of AdvHG. However, in Figs. 3 and 4 in the original manuscript (Figs 4 and 5 in the revised manuscript), RMSEs of 24 h and 36 h forecast fields of AdvHG are lower than those of E3DVAR. This is why AdvHG is used as a data assimilation method for East Asia Regional Reanalysis system in this study.

In addition, the ERA RMSEs in Fig. 2 in the original manuscript (Fig. 3 in the revised manuscript) are calculated based on ERA reanalysis fields downloaded from ECMWF. In contrast, ERA5 in Figs. 3, 4, and 6 in the original manuscript (Figs. 4, 5, and 7 in the revised manuscript) indicates forecast fields using WRF model, where ERA5 is used as the initial and lateral boundary conditions.

Minor comments:

1. The meaning of variables in Eq. (3)-(6) should be clarified.

Authors' response: Following the referee's suggestion, the explanation of variables in Eqs. (3)-(6) are added to the revised manuscript L141-143 as follows (underlined).

(L141-143) "<u>**H** is an observation operator mapping the model state vector to observation space and **R** is the observation error covariance matrix. The matrices $\mathbf{P}^f$ and **B** indicate the ensemble-based and the static climatological BEC, respectively.</u>"