Responses to the Reviewer's Comments

Reviewer #2:

We sincerely thank you for the comments that help to improve our paper. The responses to the comments are as follow.

Comment:

The authors suggest tweaking the measured values of Z, Zdr, and Kdp to match the average expected dependencies of Zdr and Kdp on Z or the bivariate distributions obtained from the disdrometer-based simulations. The "reference" dependencies are specified in Eqs 1 and 2. The major problem with such approach is that there are no universal reference dependencies valid for all rain types. For example, the Z –Zdr average dependency for tropical rain generated by a warm rain process is quite different from the one for continental rain which mostly originates from the ice aloft. For a given Z, Zdr in tropical rain is significantly lower than in continental rain, particularly at higher rain rates. A similar rule holds for the Z – Kdp dependency. In fact, using the suggested methodology, the authors deny the impact of the DSD variability on the performance of radar rainfall algorithms. I guess that the improvement in the QPE performance caused by the recommended adjustment is mainly due to mitigation of the measurement biases in Z and Zdr. The description of the adjustment routine in section 3.2 is very brief and insufficient for understanding or reproducing the methodology. The adjustment of Zdr or Kdp for a given Z looks straightforward but the procedure for Z adjustment is totally unclear. Obvious underestimation of rainfall, say, by using the R(Z) relation illustrated in Fig. 6a could be caused by either negative bias in the Z measurements or by the very nature of the observed rain (e.g., tropical) for which a power-law R(Z) relation with higher intercept is required. How to distinguish between these two sources of error? A range of needed adjustment (likely attributed to negative Z bias) between 3 and 10 dB shown in Table 5 is quite disturbing because it may point to a serious problem with radar calibration. The magnitude of such bias is too high for operational weather radars. Moreover, the magnitude of the Z adjustment for a single rain event can vary by as much as 3 dB depending on the algorithm choice. To me this is an indication that both Z bias and the DSD variability (which differently affects the performance of various rainfall relations) may come into play. The English usage has to be improved dramatically since even the meaning of several sentences is "lost in translation". There is inaccurate *statement regarding the methodology of Seliga and Bringi for DSD retrieval and rainfall estimation (first paragraph in Introduction). It is not a single Zdr but the combination of Z and Zdr which was proposed to address these problems.*

Response:

Due to the introduction of dual-pol. radars, additional polarimetric variables are used for various applications in meteorological field, e.g. hydrometeor classification, detection and correction of bright band, removal of non-precipitation echo, etc. In hydrology, it is important to quantitatively estimate radar rainfall using those variables, because the radar rainfall is one of the most important input data for rainfall-runoff analysis. It is, however, more complicated to estimate rainfall of dual-pol. radar, because multivariate analysis (Z, ZDR and KDP) have to be considered. Naturally, if dual-pol radars can provide polarimetric variables without errors (bias and random error), there will be no problem at all to estimate radar rainfall. The variables, however, are affected by calibration of radar hardware, environmental interferences and rainfall events and so on. Also, errors in variables exist inevitably. For this reason, some researchers suggested methods to solve the problem such as self-consistency and ZDR calibration. Nevertheless, those methods were not able to satisfy the need of quantitatively estimating radar rainfall. We thought the empirical method in this study can contribute to solve the problem for QPE of radar.

The polarimetric variables were adjusted by using Z - ZDR relation and Z - KDP relation regardless of precipitation types. We agree with your comment that the relations will be different with various rain types. Also the reviewer commented poor calibration of the radar used in this study because of large bias in the reflectivity observed by the YIT radar. The YIT Radar was installed in August 2015 and is still in the process of calibrating and optimizing to produce more reliable data. Although the YIT radar has shown lower values for the reflectivity, the correlation coefficient compared to the gauge rainfall was greater than 0.8 even without adjustment suggested in this study. In addition atmospheric phenomena, such as bright band, are also well observed as illustrated for the Event 1 in the ‘Supplementary information for the four events’ later on this response. Therefore we would like to say that the YIT radar is not poorly calibrated but work in progress.

The empirical method in this study is designed not only to improve radar QPE but also to find errors in the polarimetric variables compared to raingauge measurement. The most advantage of the empirical method might be able to generalize or quantify errors including bias and random errors, which were observed or existed on radar data over long periods. It is also very important to removing bias of the polarimetric variables in order to improve the accuracy of radar QPE. However random biases or errors are not easy to remove, rather they are inevitable. Nevertheless it will be very useful to quantify the errors particularly for the better QPE, because the errors in the polarimetric variables can propagate biases in the radar rainfall estimation throughout the processes of radar QPE. Therefore the provisional aims of the empirical method are quantifying errors in radar data and improving QPE. In order to achieve these aims, we need a reference such as the relation between the polarimetric variables, Z - ZDR relation and Z - KDP relation. Of course the relations will be different depending on rain types. As a preliminary study, we apply the relations regardless of the rain types, although random errors will be inevitably occurred. It was planned to quantify random errors later when more radar data are available. At this point the section, Methodology, could was inadequate to give clear idea on the empirical method for readers; we will enhance the section in our revised manuscript.

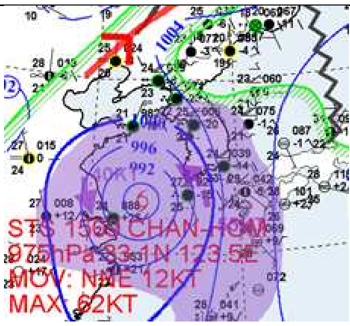
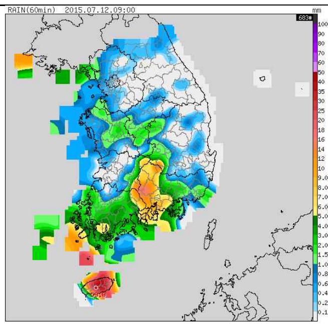
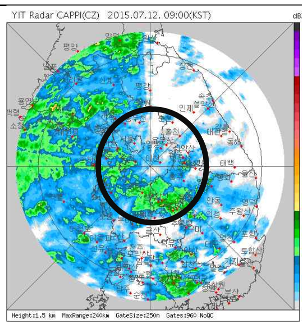
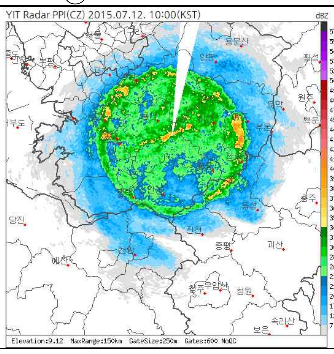
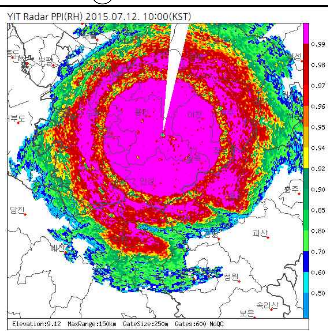
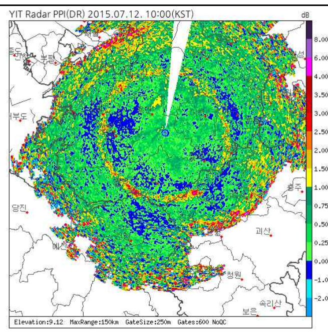
All the authors are well aware of that our manuscript is required professional English review, and our revised manuscript will be getting a professional English correction before it will be submitted. Hope this process will improve our manuscript to reach high standard of English requirement for the journal. Also we will correct the sentence about the reference in introduction, Seliga and Bringi.

(In addition we put ‘Supplementary information for the four events’ to show the data used for this study, which would be helpful to relieve your concern on our radar calibration and poor quality of observation).

Supplementary information for the four events:

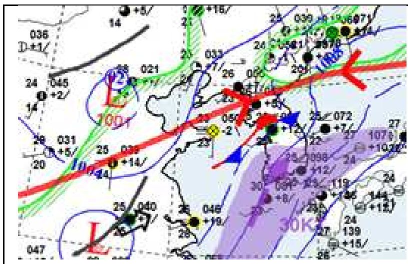
Event 1:

Event 1 was related to the Typhoon Chan-Hom, which was developed near the Equator, traveled through West Sea of Korea and finally hit mainland China (Fig. A). Korea had light or moderate rain over the most part of the country and rain was lasted over 24 hours since late 11th July 2015(Fig. B). Observed hourly maximum rainfall was 18mm at 201507120900KST during the event. Fig. C is shown CAPPI reflectivity image composed at 1.5 km in height using data observed by the YIT radar at 9am on 12th July 2015. Black circle is represented 100km in horizontal distance from the YIT radar and only inner circled areas are used for this study. The precipitation type was mainly stratiform rain with very clearly observed bright band as supportive evidences of Fig. D(Z), E(. ρ_{hv}) and F(ZDR) observed by the YIT radar at 9.12^{o} . Bright band was developed about 4.5km in height, therefore the used CAPPI image composed at 1.5km was not influenced by bright band. The YIT radar has been purposely set a beam blockage area around 0~10degree to prevent intervenes by neighboring telecommunication radar.

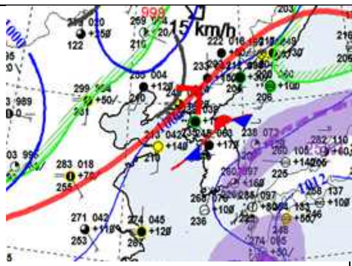
		
A. Weather surface chart @201507120900KST	B. AWS- 60min accumulated rainfall @ 201507120900KST	C. YIT CAPPI (1.5km) CZ@ 201507120900 KST
		
D. CZ@ 201507120900 KST	E. ρ_{hv} at 201507121000KST	E. ZDR@ 201507120900 KST

Event 2:

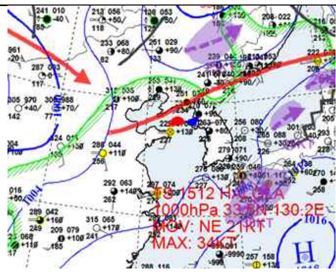
During this Event 2(23~26 July 2016), southern cold front was faced with warm front from the North in middle of Korea Peninsula and stayed over 72 hours as presented in Figure A, B and C. As strong frontal precipitation developed, the maximum hourly rainfall was recorded with 57.5mm at 2am on 25th July 2015 as shown Fig.D. Leading convective cells were lined from the South-West to the North-East with stratiform rain developed surrounded area.



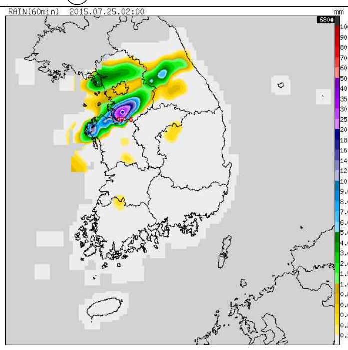
A. Weather surface chart @201507232100KST



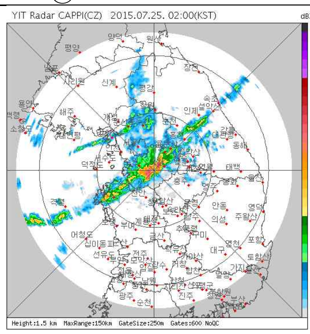
B. Weather surface chart @201507252500KST



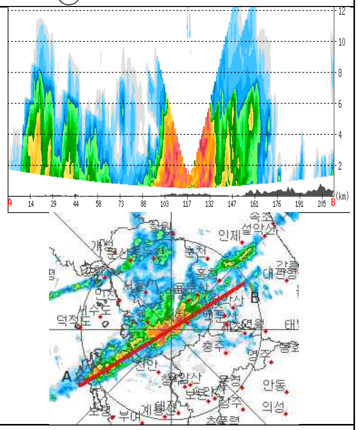
C. Weather surface chart @201507262100KST



D. Max hourly rainfall 57.5mm @ 201507250200 KST



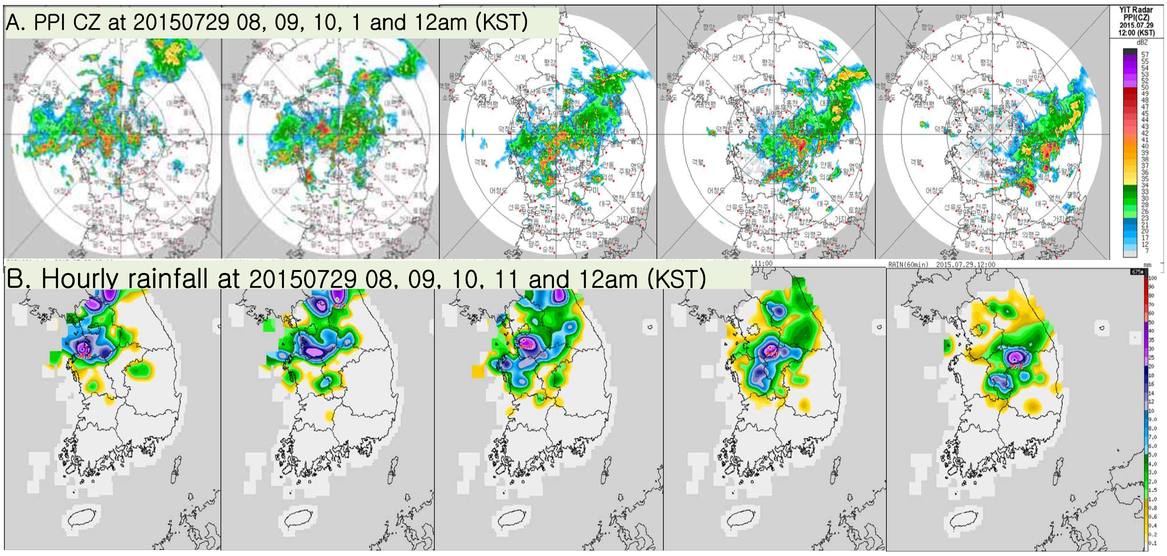
E. CAPPI CZ at 201507250200 KST



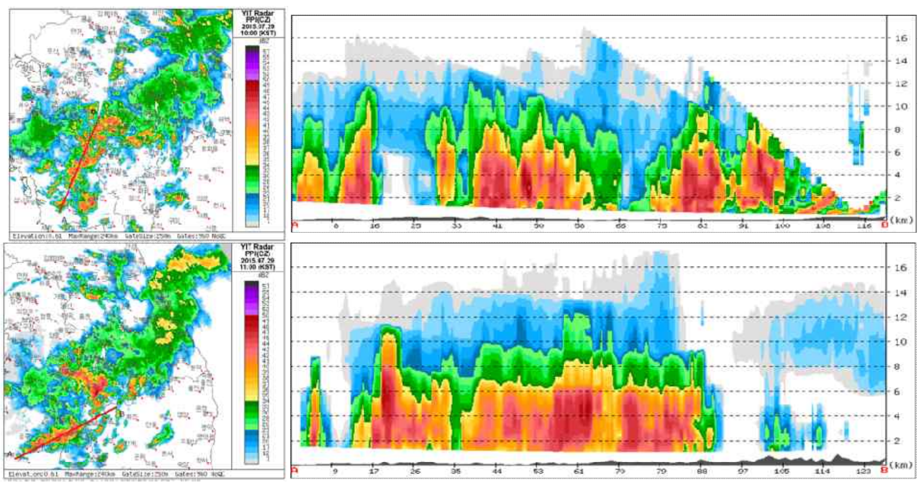
E. Vertical profile of CZ at 201507250200 KST

Event 3:

This event (201507290000~2300KST) was occurred during the Asian summer monsoon. Frontal precipitation band was developed midland in South Korea. Multi super cell storms were traveled from the West Sea and passed mainland, and light or moderate stratiform echoes were largely developed (Fig. A). Naturally heavy rain was led by storms; hourly maximum rainfall was recorded 46mm at 10am on 29th July 2015.

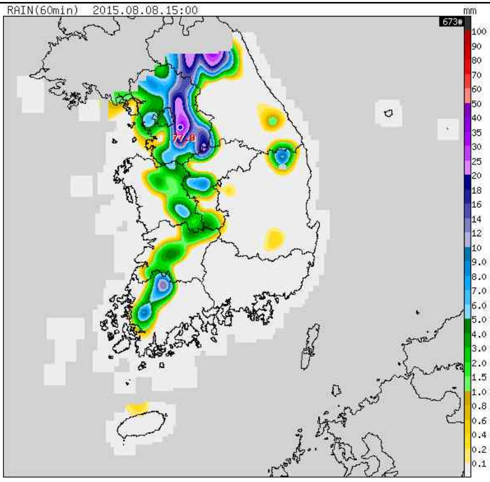
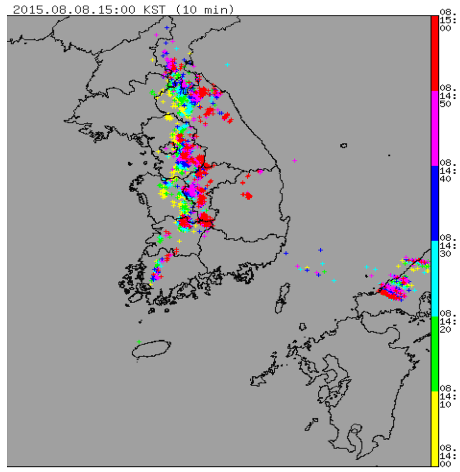
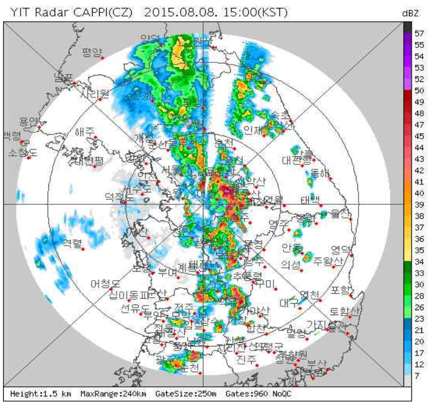
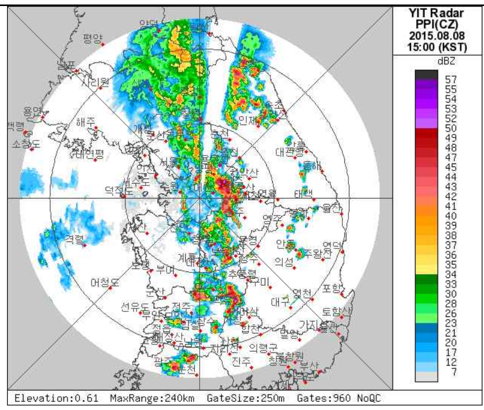


The strong cells were activated from 8am to 11 am on the day and it was light rain rest of the period at the event. With the figure below, the processes of strong, invigorate, deep and rotating updraft are well presented on a scale of (1 ~ 20km) with trailing large stratiform at 8am on 29th July 2015. Thus this event can be categorized as a mixture of super cell storms and very light stratiform rain.



Event 4:

The Event 4 is typical mid-latitude squall line system accompanied by strong lightning as presented in Fig. A and B. The linear convective cells were developed particularly from non to 19pm on 8th August 2015. During this time, persistent thunderstorms and contiguous precipitation areas were produced. The strongest reflectivity was appeared around 55dBZ, which is surrounded by 45~50dBZ. Maximum hourly rainfall was 77mm at 201508081500KST.

	
A. 60min accumulated rainfall in mm at 201508081500KST	B. Lightning hit number for 10min at 201508081500KST
	
C. Used CAPPI reflectivity at 201508081500KST	D. Observed PPI reflectivity at 201508081500KST