Responses to Reviewer #2

We would like to thank Anonymous Referee #2 for his/her comments which helped the manuscript to be clearer and stronger. Please note that the italic paragraphs are part of the revised manuscript.

i) Comment: The paper does attempt to tackle a rather complex, difficult, and often insurmountable problem. This in itself should be carefully approached: while some issues can be resolved, others can only be partially resolved, and attempts to provide 'an answer' often only address 'findings' for particularly cases studied.

Responses:

We understand that bias adjustment is a very complex process, particularly for rainfall estimates from different sensors. That in mind, we are partially solving the problem of biases in satellite Quantitative Precipitation Estimation (QPE) by matching with that of the radar-gauges. Matching bias from radar and satelllite QPE serves to mitigate the discrepancies between the satellite and radar-gauge rainfall products. The current work is aimed at producing a satellite QPE with similar bias features with the radar-gauge QPE so that they can seamlessly be blended together. This is, in fact, more relevant to many operational settings where radar and satellite QPEs being merged (to produce multi-source QPEs) can differ sharply in terms of bias even though both undergo gauge-based bias adjustments before merging. In addition, the purpose is to produce a satellite QPE with bias consistent with radar-gauge QPE so that it can be used in lieu of radar-gauge stage-IV (ST-IV) data (mountainous regions, radar outages etc).

To address this concern, based on the Reviewer's comment, the title of the paper is revised as: *"Bias adjustment of satellite rainfall estimates using a radar-gauge product- a case study in the Oklahoma region (USA)"*

ii) Comment: The assumption that 'radar is good' is a bad idea. While there is no doubt that radar has very nice spatial coverage and provides information in the gaps between the gauges, radar does have some serious issues (clutter, range, bright-

band) which are not really mentioned by the authors. This can be problematic since even with gauge- correction, these radar artefacts are likely to be present in the final product in one form or other. Ultimately, bias-correcting on a pixel-pixel basis will perpetuate the errors from one field into another field.

<u>Responses:</u>

We would like to break down this comment into three parts:

1. "The assumptions that ……. in one form or other"

We are aware that radar-based rainfall, by itself, is not a good product. However, the Stage IV (ST-IV) data that we used in this study is a gauge-radar mosaick rather than a radar-only product. Radar-only QPEs under go considerable bias correction before they are quilted with the rain-gauge measurements. Besides, quality controlled ST-IV is the best possible high resolution (4km, hourly) rainfall product that we could find. (more details are included in Appendix A).

2. While there is no doubt that radar has very nice spatial coverage and provides information in the gaps between the gauges, radar does have some serious issues (clutter, range, bright-band) which are not really mentioned by the authors.

One reason for selecting Stage-IV rainfall product is being aware that radar-only products suffer heavily from issues such as calibration, anomalous beam propagation, clutter, range dependent bias and bright-band contamination (Krajewski and Smith, 2002, Fulton et al., 1998). Stage-IV product is adjusted for some of the above mentioned error sources by implementing Radar Product Generator (RPG) adjustment algorithm, using hybrid scan construction, and more. It is a manual quality controled product too. (please see the attached Appendix A for details)

3. "Ultimately, bias-correcting … into another field."

There will always be a possibility that errors can perpetuate from one source to another in the process of bias adjustment using any method. The best we can do is, match the bias of satellites (which is assumed to be worse than radar-gauge) to radar-gauge. The other existing methods (mean field bias and maximum ratio) fail to address the correlation coefficient issues. The impacts of perpetuating error from one field ino another field, also, may be reduced by correcting local bias using rain-gauges first and then performing pixel to pixel bias adjustment.

iii) <u>Comment:</u> the portrayal of the satellite-based observations is basic. I would say that satellites estimates are much more than 'approximations': the nuances of the English language can be subtle at times, but the satellite-derived precipitation estimates are 'estimates'. In addition, the sentence that states that "IR products are the only sources of rainfall observations in mountainous regions" is wrong. We have passive microwave products, combined products, satellite-borne precipitation radar etc.

<u>Responses:</u>

Your comment is appreciated, and the statement on P8915 L8-11 has been mofied as follows: "*In general, since satellite-based rainfall products are estimates from indirect observations (e.g., IR cloud-top temperature) they are prone to errors greater than the ones for radar-based rainfall measurements. NESDIS rainfall retrieval algorithm, Hydro-Estimator, using GOES-IR as input, has been selected in this study for bias adjustment due to characteristics of GOES-IR imagery. GOES IR-based rainfall products can be used in developing operational real-time flood forecasting and hydrological prediction models after correcting errors, due to the following reasons. First, high temporal (15 minutes) and spatial (4 km × 4 km) resolutions that required for severe storm and flood nowcasting, in comparison with microwave data from polar-orbiting satellites. Second, satellite IR products are available for any location regardless of topography and land type, in comparison with radar coverage. Hence , satellite is the major source of available observations, in comparison with radar network blockage, over mountainous regions where orographic effects cause heavier precipitation consequently results in severe flash floods.*"

iv) <u>Comment:</u> There has to be a greater appreciation of the precipitation characteristics and measurement techniques. In particular, all gauges really produce and accumulation of precipitation at a point (i.e. time integral & point) whereas radar and satellites provide point-in-time, areal estimates (i.e.

instantaneous & spatially integrated). This fundamental factor seems to be have been neglected in the radar : the hourly radar data is not really an accumulation, but a summation of a number of samples; the satellite estimate likewise. The gauge data although at a point, if measured over 1 hour, posses a time-integral factor inherent in all precipitation studies. Moreover, the intensity distribution of the rainfall data is heavily skewed towards zero: this in itself is enough to make most 'models' inappropriate – yet alone the statists associated with any calibration/validation.

Responses:

The above reviewer's comment is a very important issue on analysis of error for estimating and/or validating of rainfall produced from radar, satellite, and gauge observations. The impacts of using different approaches used in existing algorithms to obtain accumulated rainfall for any specific period of time for different rainfall retrieval algorithms need to be studied also. But it cannot be included in the present study since the objective of this research is to develop a technique to estimate and adjust rainfall bias of existing satellite-based products with respect to radar-gauge Stage-IV not developing a new algorithm to produce another rainfall product.

Appendix B is included in the revised version to provide a more detailed information about the rainfall products.

v) Comment: care need to taken when 'selecting' representative cases. Representative rainfall cases are essentially all no-rain cases! In particular, when matching up data sets (as in this case) care needs to taken in what data is excluded: zero is a valid rainfall value. For example, although satellite rain: radar rain pixels are okay, and you might exclude satellite no-rain: radar no-rain, but what do you do with the no-rain:rain and the rain:no- rain?

Responses:

To select rainfall cases, we tried our best to pick the heavy rainy hours form the selected long term storm, listed in Table 1. We have also made the maximum effort to pick cases with a wide and large range of correlation between the original radar-gauge and satellite rainfall estimates to show the performance of the proposed technique for a range of correlation coefficients.

For the question " **but what do you do with the no-rain:rain and the rain:no- rain?**" Basically, radar-gauge no-rain:satellite rain is a false alarm (under the assumption that radar-gauge is the better product), and hence, these pixels cannot be used for bias field generation. Radar-gauge rain:satellite no-rain gives mathemathically undefind pixel bias factors.

Based on the Reviewer's recommendation, the following paragraph in italic has been added on P8920, L18 to improve the manuscript:
From Eq. (2), bias factors can be 0 (if the radar pixel is not rainy and the corresponding satellite pixel is rainy), positive real number (if both corresponding pixels from radar-gauge and satellite are rainy), infinity (if the radar-gauge pixel is raining and the corresponding satellite pixel is not rainy (0)) or undefined (if both pixels from ST-IV and HE are not raining). To avoid any mathematical inconveniency, bias factors with positive values were considered for evaluation.

vi) <u>Comment:</u> Ultimately, the problem here is whether the mathematically-formulated framework can adequately work on the full gamut of gauge/radar/satellite data sets and under all meteorological conditions. One thing that is strikingly obvious when expanding techniques to the full range of events is that although it might seem to work in a number of situations, that overall it rarely works in all.

<u>Response:</u>
In general, the algorithms, which run for time and/or space dependent variables, need to be evaluated and modified regularly for different time periods and locations. Regarding to our developed approach, we expect that the proposed methodology can be applied for bias adjustment of satellite-based rainfall products against calibrated radar-gauge products, but the optimized model parameters need to be tested and adapted seasonally, regionally, and for any rainfall product. The developed model parameters, which are adaptable as presented in this manuscript, will be examined and adjusted, if needed, due

to seasonal, regional, and type variability of storms and for any satellite-based rainfall retrieval algorithm because of using different model inputs and methodologies.

Appendix A

Problems in radars have continuously been addressed in different studies. The original WSR-88D algorithm have considered quality control for correction for isolated targets and ground clutter, tilt test and anomalous propagation, and partial beam correction (Fulton et al., 1998). Other independent studies, range dependent bias correction algorithm (Seo et al., 2000), ground clutter removal using the Radar Echo Classifier (REC) (Kessinger et al., 2000), Vertical Profile of Reflectivity (VPR) variability (Vignal et al., 2001) and Convective-Stratiform Separation Algorithm (CSSA) (Seo et al., 2002) have been pivotal in addressing such difficulties (see the respective references and therein for details). At the NWS, the REC algorithm was implemented a few years ago. The VPR and range-dependent bias correction are not yet implemented. The CSSA is not implemented, but the dual-polariation Hydrometeor Classifier Algorithm scheduled for deployment serves the same purpose (personal communication with David Kitzmiller at the NWS).

Through a thorough understanding of radar problems and their solutions, in the US, radar based QPEs have risen to operational and validation importance, besides they are arguably the best remotely sensed rainfall products. For instance, Vicente et al., 1998 used collocated radar rainfall pixels to develop a relationship between Auto-Estimator (AE) (Vicente et al., 1998) rain-rate and cloud Brightness Temperature (Tb (10.7 micron)). Rozumalski (2000) used radar Stage-III to validate the satellite product AE. Bias in radar Stage-III is better than AE (McCollum et al., 2002). McCollum et al., 2002 used gauge adjusted radar rainfall product to evaluate biases in different satellite rainfall products. Ebert et al., 2007 utilized daily accumulated radar precipitation to validate 12 different satellite QPEs (HE is one of them) over the northwestwen Europe.

To summarize why ST-IV can be an appropriate choice to adjust HE:

a. NOAA's ST-IV radar-gauge data, which is a mosaic of 159 radar and more than 3000 gauge networks over the continental US, undergoes through manual quality control at 12 River Forecast Centers (RFC) in the US. Range correction, clutter adjustment and bright band exclusion are done using the methods explained in the above paragraph.
b. Theoretically, a bias free output can be obtained by collocating all the satellite pixels with rain-gauges. Unfortunately, rain-gauges are sparse and limited in number. Besides, bias validation with limited number of rain-gauges has always issues with quality control and sampling (McCollum et al., 2002).
c. Radar estimates are more direct than satellite products which can be argued that they are better than satellite products.
d. It is a gauge-radar mosaic rather than radar-only.
e. Most of the existing bias corrections are based on rain-gauges. This work is also intended to take bias correction to another dimension, using a radar-gauge product.
f. We believe that a continuous effort on radar uncertainties will further enhance a more accurate rainfall estimation in the near future.

Appendix B

P8918 L8-17 is modified as:
The two GOES (East and West) provide five channels of information every 15 minutes at a spatial resolution of 4 km in the visible and Infrared spectral regions over the continental US. The visible and infrared data have been pivotal in developing high resolution (hourly) satellite based rainfall estimation algorithms (eg. AE, GMSRA, SCaMPR and HE). Interested readers can refer the respective references for further details.

One of the approaches, HE (Scofield and Kuligowski, 2003) uses GOES Infrared window channel-4 (10.7 µm wavelength) as the main input data to estimate the rate of surface rainfall. HE was developed as an improvement to the original AE which was developed for deep, moist convective systems *(http://satepsanone.nesdis.noaa.gov/PS/PCPN/HE.html). The HE algorithm identifies raining clouds based on both pixel brightness temperature (Tb) in GOES channel-4 and its value relative to its surroundings—pixels that are colder than their neighbors are presumed to be regions with updrafts and rainfall, and pixels warmer than the prescribed surrounding averages are associated with lower clouds with light or no-rain. Rainfall rate is estimated as a function of pixel Tb, its surrounding values, precipitable water, relative humidity, convective equilibrium level, and lower-tropospheric winds interfaced with terrain to diagnose regions of terrain-induced updrafts and downdrafts. At the (NOAA)/National Environmental, Data, and Information Service (NESDIS), HE has been one of the operational satellite-based rainfall product since 2002, and has been available for use at a spatial scale of 4 km by 4 km and time scale of 1 h for the US (CONUS) since 2004.*

Since satellite rainfall estimations are not direct, they are usually liable to systematic errors. HE is one of the data sets chosen to be corrected for systematic error in this study. For our study, hourly products at a spatial scale of 4 km by 4 km for the year 2006 have been used.

P8919 L-9 is modified as:

Radar based estimations are known to have significant problems including isolated targets and ground clutter, anomalous propagation, and partial beam in mountainous regions (Fulton et al., 1998). It also mainly suffers from range dependent attenuation (Young et al., 1999). However, composite products, such as ST-IV from National Centers for Environmental Prediction (NCEP) is manually quality controlled and corrected for these problems. In this work, it is assumed that a quality controlled radar-gauge product, ST-IV can be used as a reference precipitation estimation source to adjust biases in satellite rainfall estimations.

At NWS, there are four stages of radar based rainfall products. References such as Fulton et al., 1998, http://www.emc.ncep.noaa.gov/mmb/ylin/pcpanl/QandA/#STAGEX and, Lin and Mitchell 1999 contain details of how the different stages of radar products are produced; only a brief explanation is included in here. Stage-I radar rainfall product *is produced for each radar scan at each radar site using the Z-R relationship. Hourly Stage-I products are then generated by summing up the scan-wise accumulations. In the next step, the Stage-I products are adjusted for mean field bias using all the available rain-gauges to produce bias-adjusted Stage-II. The bias adjusted Stage-II products are further optimally merged with point rain-gauges. For detailed bias correction of radar rainfall and Stage-II products, readers can refer (Smith and Krajewski, 1991, Fulton et al., 1998, Seo et al., 1999). In Stage-III, at each NWS's River Forecast Centers (RFC), the Stage-II (radar-gauge) products from multiple radars are stitched together to cover a larger area in the respective RFCs. At this stage, overlapping Stage-II products are optimized using the technique explained in* http://www.nws.noaa.gov/oh/hrl/dmip/stageiii_info.htm*. In addition, at each RFC, regional Stage-III products undergo routine manual quality control to make sure that products are free from any notable error (Fulton et al., 1998). The regional Stage-III products obtained from the 12 RFCs are further moisacked to a national 4 km stereographic NWS's Hydrologic Rainfall Analysis Project (HRAP) grid at NCEP to produce ST-IV products. The final ST-IV is a mosaicked product generated by merging more than 3000 automated hourly rain-gauge observations and WSR-88D radar based digital precipitation arrays (DPA) (Fulton et al., 1998). The product is available for use since 2001.*

Hourly radar ST-IV, a mosaicked product over the CONUS with a spatial resolution of 4 x 4 km for the year 2006 has been used in this study.

References:

1. Ebert, E. E., Janowiak, J. E., and Kidd, C.: Comparison of near-real-time precipitation estimates from satellite observations and numerical models, Bull. Amer. Meteor. Soc., 88, 47-64, 2007.
2. Fulton, R. A., Breidenbach, J. P., Seo, D. J., Miller, D. A., and O'Bannon, T.: The wsr-88d rainfall algorithm, Wea. Forecast, 13, 377-395, 1998.
3. McCollum, J. R., Krajewski, W. F., Ferraro, R. R., and Ba, M. B.: Evaluation of biases of satellite rainfall estimation algorithms over the continental united states, J. App. Meteorol., 41, 1065-1080, 2002.

4. Rozumalski, R. A.: A quantitative assessment of the nesdis auto-estimator, Wea. Forecasting, 15, 397-408, 2000.
5. Seo, D.-J., Ding, F., and Fulton, R.: Final report interagency mou among the nexrad program, the wsr-88d radar operations center, and the nws office of hydrologic development, Office of Hydrologic Development, National Weather Service, Silver Spring, MD, 2002.
6. Stellman, K. M., Fuelberg, H. E., Garza, R., and Mullusky, M.: An examination of radar and rain gauge–derived mean areal precipitation over georgia watersheds, Wea. Forecasting, 16, 133-144, 2001.
7. Vicente, G. A., Scofield, R. A., and Menzel, W. P.: The operational goes infrared rainfall estimation technique, Bull. Amer. Meteor. Soc. , 79, 1883-1898, 1998.
8. Vignal, B., and Krajewski, W. F.: Large-sample evaluation of two methods to correct range-dependent error for wsr-88d rainfall estimates, J. Hydrometeor., 2, 490–504, 2001.
9. Young, C. B., Nelson, B. R., Bradley, A. A., Smith, J. A., C.D., P.-L., Kruger, A., and Baeck, M. L.: An evaluation of nexrad precipitation estimates in complex terrain, Journal of Geophysical Research- Atmospheres 104, 19691-19703, 1999.