Responses to Anonymous Referee #1:

General Comment:

Data fusion across satellite and gauge precipitation data has been widely concerned around the world in the last decade and also has been investigated by many studies in China. In this study, the authors aim to develop a fusion framework to improve the precipitation estimation in mountainous areas. The framework is then applied to the Nu river basin, a place with high altitude and complex topography and also with distinctive climate. From this perspective this study is meaningful. I would suggest that this paper be accepted with a few minor revisions.

Response: We highly appreciate the reviewer's positive feedback. Our detailed responses are given after each comment (italics) below.

Specific Comments:

1) *Page-7, line 158, "59 gauges are available", which are not consistent with the number of stations in Figure 2.*

Response: We thank the reviewer for pointing out the inconsistency between the original Fig. 2 and text. We now have corrected Fig.2 with all the 59 gauges displayed, which is reproduced as follows:

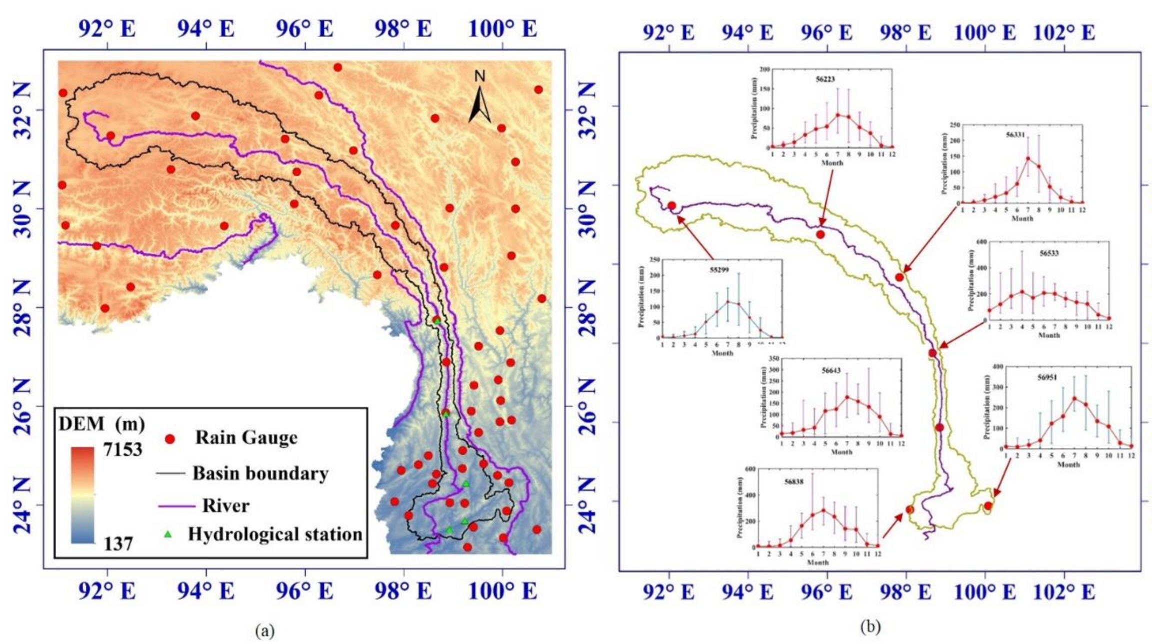

Figure 2 (a) Terrain map of the study area (the Nu-Salween basin and its adjacent areas), (b) The distribution of precipitation during the year across the Nu River.

2) *Page-7, line 164, it is suggested that a sentence be given to describe the temporal and spatial resolution of MOD13A3 and MYD13A3 vegetation products*

Response: The temporal and spatial resolutions of the MOD13A3 and MYD13A3 products are 1 month and 1 km, respectively. This description will be inserted into the revised manuscript in line 165, page 7.

3) *Page-8-9, line 208-209, "It is also noted that R2 values of RMIs for drier years are less than wetter years. . .. . . ". Time-lag effects of vegetation responses to precipitation can be considered to explain this phenomenon.*

Response: We thank the reviewer for the valuable suggestion. Although several studies indicate that vegetation responses to precipitation with a time lag varying from several days to 3 months according to different vegetation types, climates and latitudes (Wang et al., 2003; Bao et al., 2007; Long et al., 2010; Wu et al., 2015; Lin et al., 2015), such time-lag effects are not apparently observed in the monthly NDVI data we used in the Nu River application.

By comparing the annual NDVI with that of 1 month time lag (Fig. R1a), we see minimal difference between them with over 75% of the samples showing less than 1% difference (Fig. R1b). As such, we think that the time-lag effects of vegetation responses to precipitation are not capable of explaining smaller R^2 values of drier years than wetter years.

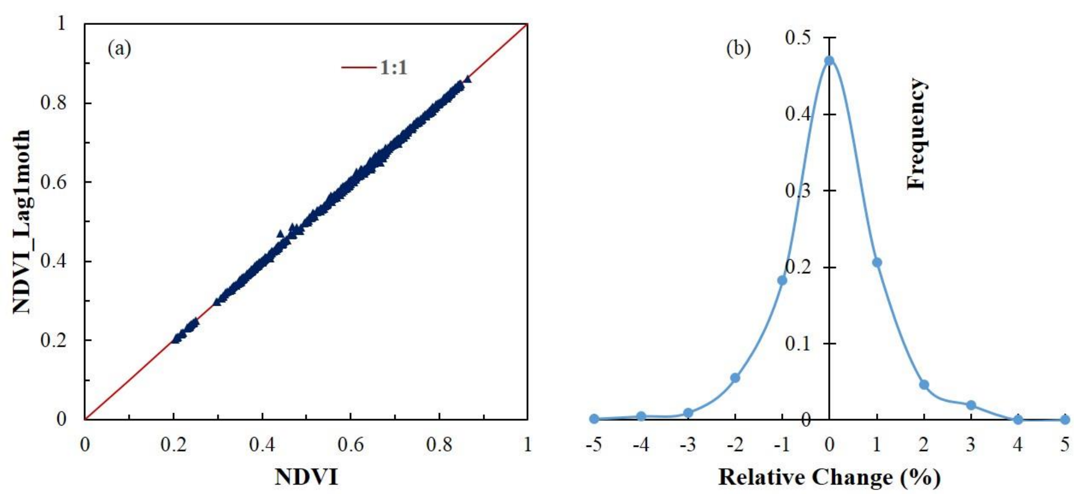

Figure R1 (a) Comparison between yearly mean NDVI and yearly mean NDVI with 1 month lag, (b) frequency distribution of 1 month lag NDVI's relative change to NDVI without time lag

4) *Page-12, line 299, "the negative regression coefficient of temperature in RME+T indicates that precipitation decrease as the temperature increase". I don't agree that your explanation of negative*

regression coefficient of temperature shows that that precipitation decreases as the temperature increase.

Response: We thank the reviewer for pointing out the careless wording in this statement. Such statement was directly inferred from the negative regression coefficient of temperature to precipitation, with the aim to show the inconsistent trends of precipitation with temperature and elevation. We have reworded the statement in the revised manuscript as follows:

> "The negative regression coefficient of temperature in RME+T indicates inconsistent trends between precipitation and temperature."

5) *Some detailed should be paid more attention. For example, line 191, correct website should be given; In Figure 2, legend of DEM should not be 0 in this region.*

Response: These details have been corrected/explained as follows:

1) The correct website address is added as: http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_MUL_DAY_V3.0/keywords/v3.0.html.
2) In Figure 2, the bottom left corner is located in the Bay of Bengal where several few pixels have altitude value of zero.

References:

Bao, Y., Song, G., Li, Z., Gao, J., Lü, H., Wang, H., Cheng, Y. and Xu, T.: Study on the spatial differences and its time lag effect on climatic factors of the vegetation in the Longitudinal Range-Gorge Region, Chin. Sci. Bull., 52(2), 42–49, doi:10.1007/s11434-007-7005-5, 2007.

Brunsdon, C., McClatchey, J. and Unwin, D. J.: Spatial variations in the average rainfall-altitude relationship in Great Britain: an approach using geographically weighted regression, Int. J. Climatol., 21, 455–466, doi:10.1002/joc.614, 2001.

Lin, Y., Xin, X., Zhang, H. and Wang, X.: The implications of serial correlation and time-lag effects for the impact study of climate change on vegetation dynamics – a case study with Hulunber meadow steppe, Inner Mongolia, Int. J. Remote Sens., 36(19–20), 5031–5044, doi:10.1080/01431161.2015.1093196, 2015.

Long, H., Li, X., Bao, Y., Huang, L. and Li, Z.: Time lag analysis between vegetation and climate change in Inner Mongolia, in 2010 IEEE International Geoscience and Remote Sensing Symposium, pp. 1513–1516., 2010.

Wang, J., Rich, P. M. and Price, K. P.: Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA, Int. J. Remote Sens., 24(11), 2345–2364, doi:10.1080/01431160210154812, 2003.

Wu, D., Zhao, X., Liang, S., Zhou, T., Huang, K., Tang, B. and Zhao, W.: Time-lag effects of global vegetation responses to climate change, Glob. Change Biol., 21(9), 3520–3531, doi:10.1111/gcb.12945, 2015.

Responses to Anonymous Referee #2:

General Comment:

This is a very interesting and clearly written paper on precipitation distribution in a mountainous river basin. Mountains, in particular high mountains in Asia, are the source of freshwater for many people, but the observation of precipitation is far from enough. For example, the first item of Scientific Questions of GEWEX under WCRP is the observation of precipitation. As such, the topic of this paper is within the scope of HESS, and is a hot topic in hydrology. As already described above, the paper is very clearly written, thus easy to follow. Therefore, I basically want to recommend this paper toward publication in HESS. Nevertheless, I would also mention that there are concerns, comments, or suggestions as written below.

Response: We greatly appreciate the reviewer's positive feedback. Our detailed responses are given after each comment (*italics*) below.

Specific Comments:

1) *In the title, abstract and also in any other part of this paper, the authors should clearly mention that the target of this research is annual mean or climatological mean precipitation amount. The authors compared their product with IDW (of gauge-based precipitation) and a TRMM-based product. I can accept this product is better for annual mean and climatological mean. However, IDW and TRMM*

can provide us short timescale data, such as daily data. This is a major difference between these products against the product which the authors try to show in this paper.

Response: We thank the reviewer for the valuable suggestion. We change the title as “Remapping annual precipitation in mountainous area based on vegetation pattern: a case study in Nu river” to emphasize the target of this research, and modify the corresponding parts in the manuscript.

2) *It is also recommended to clearly describe that this study is a case study for a specific area, in the title, abstract, and also in other places of this paper. Why I recommend so is described in the following. As shown in Figure 2 and Figure 6, in this target area, precipitation amount is larger for areas of lower elevation. In areas of lower elevation, it is usually expected that air temperature is warmer. It means, in the areas of lower elevation in this study, both precipitation and temperature are better, favorable, for NDVI. I suspect, this the reason why the authors can get a clear positive relationship between precipitation and NDVI. But, this is specific to this particular area. Of course, there could be other similar areas in the world. However, there must also be areas with different characteristics between NDVI and precipitation. Thus, the authors are requested to explicitly describe in the title and the abstract and also in relevant places of the main text that this study is a case study with such characteristics shown in Figures 2 and 6.*

Response: We thank the reviewer for the suggestion. We change the title as “Remapping annual precipitation in mountainous area based on vegetation pattern: a case study in Nu river” to emphasize the specific area of this research, and make it clear in the conclusion that comparison study is needed in other regions.

3) *This comment is a comment following the above comment. Very in general, precipitation is larger if elevation is higher. This is in contrast with what is seen in Figures 2 and 6. But, I need to add to “precipitation is larger if elevation is higher”. Such a general tendency is probably true to 2000m or 3000m in elevation. In this regard, “we note that for simplicity, the extra determinants are assumed to have linear relationship with precipitation” is somewhat suspicious because this area has elevation up to 7000m. Is it possible to make a figure in which horizontal axis is elevation and vertical axis is precipitation (and NDVI) using observed precipitation data and NDVI data. There might be a positive relationship between elevation and precipitation up to 2000 or 3000m in elevation, and a negative or flat relationship between elevation and precipitation after it. Also, because NDVI favors large precipitation and warmer temperature (= lower elevation), the response of NDVI is different up to 2000 or 3000m and after it. NDVI-precipitation relation may depend on elevation bands such as lower than 3000m and higher than 3000m (of course, I do not know it would be 3000m or not which changes*

the relationship), but such an analysis was not done in this study as far as I can see. I think the authors can easily analyze.

Response: The suggested analysis is conducted in two stages: 1) we examine the relationship between annual precipitation and elevation within different elevation ranges; and 2) we examine the relationship between annual precipitation and NDVI within corresponding elevation ranges as in stage 1, whose results are presented as follows:

1) the relationship between annual precipitation and elevation:

An overall negative relationship is found between precipitation and elevation for the whole elevation range 0–5000 m with a R^2 value of 0.62 (Fig. R2a), whereas there is only unapparent/weak relationship at different elevation bands (Fig. R2b-f). Given the spatial heterogeneity of orographic effects on precipitation (Brunsdon et al., 2001; Daly et al., 2008) and insufficient data of this study, a more thorough investigation of the relationship between precipitation and elevation needs to be conducted with more information that might be available in the future.

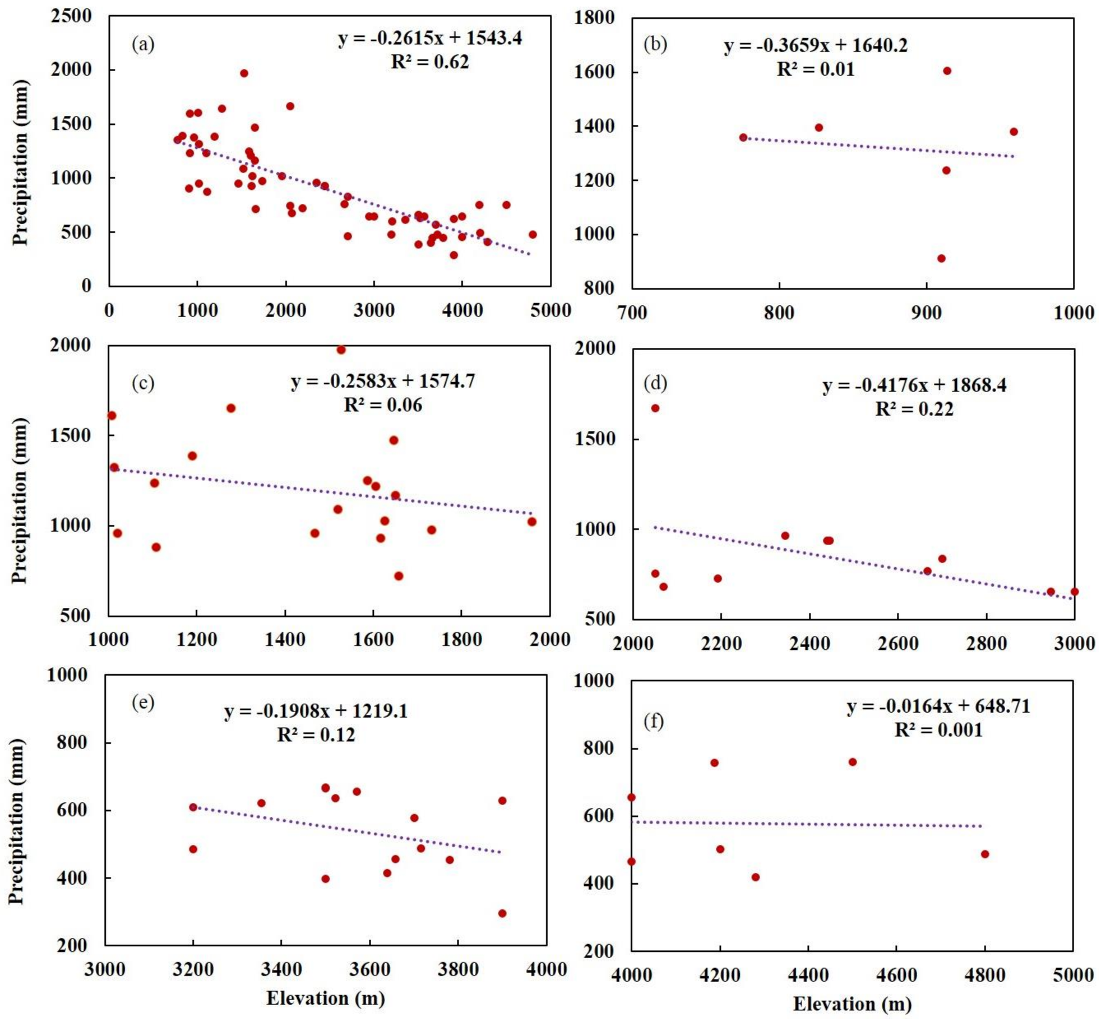

Figure R1 The relationship between mean annual precipitation and elevation at different elevation bands, (a) whole elevation bands; (b) elevation band :<1000 m; (c) band:1000~2000 m; (d) band: 2000~3000 m; (e) band :3000~4000 m; (f) band: >4000 m.

2) the relationship between annual precipitation and NDVI:

Positive precipitation-NDVI relationships are found at different elevation bands (Fig. R3) with the best and worst fitness observed at elevation band 2000~3500 m with a R^2 value of 0.94 and at elevation band 0~2000 m with a R^2 value of 0.62, respectively. By comparing the three regressions at different bands with the global regression, we notice that more significant overestimates of precipitation are observed with the range of lower NDVI values (<0.4) at band 0–2000 m than other three regressions whereas regression at band >3500 m has an significant overestimation of precipitation than other three regressions for higher NDVI values(>0.5).

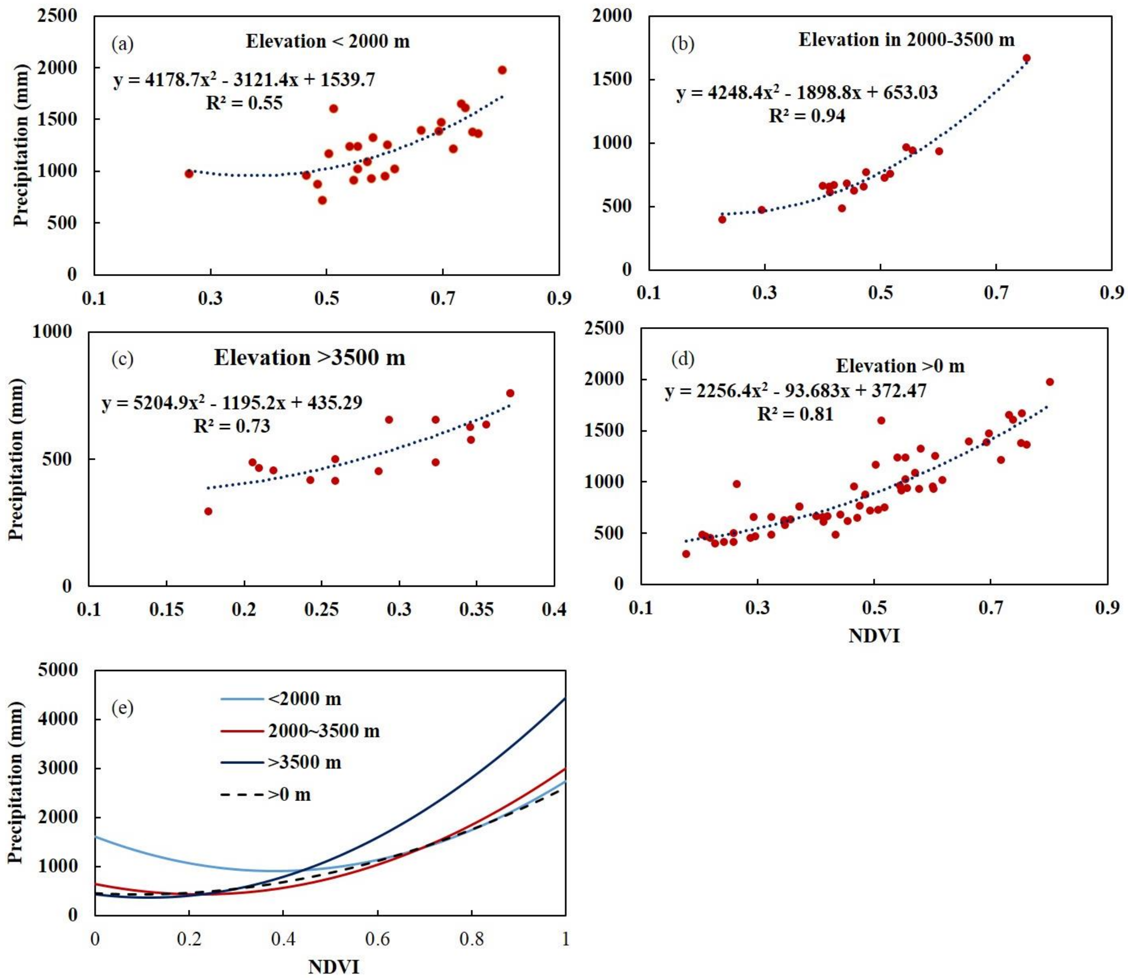

Figure R2 The relationship between mean annual precipitation and NDVI at different elevation bands, (a) elevation band : <200m; (b) band: 2000~3500 m; (c) band: >3500 m; (d) whole bands; (e) comparison of precipitation-NDVI relationship for different bands .

To summarize, an overall negative relationship is found between precipitation and elevation across different elevations in the study region and the NDVI and precipitation demonstrates positive correlations at different elevation bands.

4) *Although target temporal and spatial scales are different, a recent study submitted to HESSD (Beck et al., 2016) provides a globally distributed precipitation data (called MSWEP) in which mountainous precipitation is corrected for gauge under-catch and also orographic effect was introduced by inferring catchment-average P from stream-flow (Q) observations at 13762 stations across the globe. I found mountainous precipitation is somehow well represented in the product by Beck after*

downloading the data from http://www.gloh2o.org and by making figures of the data by myself. Thus, it is recommended to have discussion in terms of Beck et al. (2016).

Response: We thank the reviewer for the suggestion and present the comparison between MSWEP product and our product as follows:

Comparison in mean annual precipitation between the gauged measurements and predictions by the MSWEP (Multi-Source Weighted-Ensemble Precipitation, Beck et al. 2016) and TRMM product (Fig. R4) shows that TRMM and MSWEP predicted the precipitation well with an overall overestimation while RME product shows no obvious systematic deviation. The RMSE values for MSWEP, TRMM and RME are 241, 196 and 174 mm, respectively. The possible reason why MSWEP shows no superiority over TRMM in predicting annual precipitation is that few gauge data is available in this region which limited the efficiency of MSWEP method. However, the method in MSWEP does provide insights into the production of high temporal resolution (3-hourly) precipitation, which we believe will be helpful to our future work.

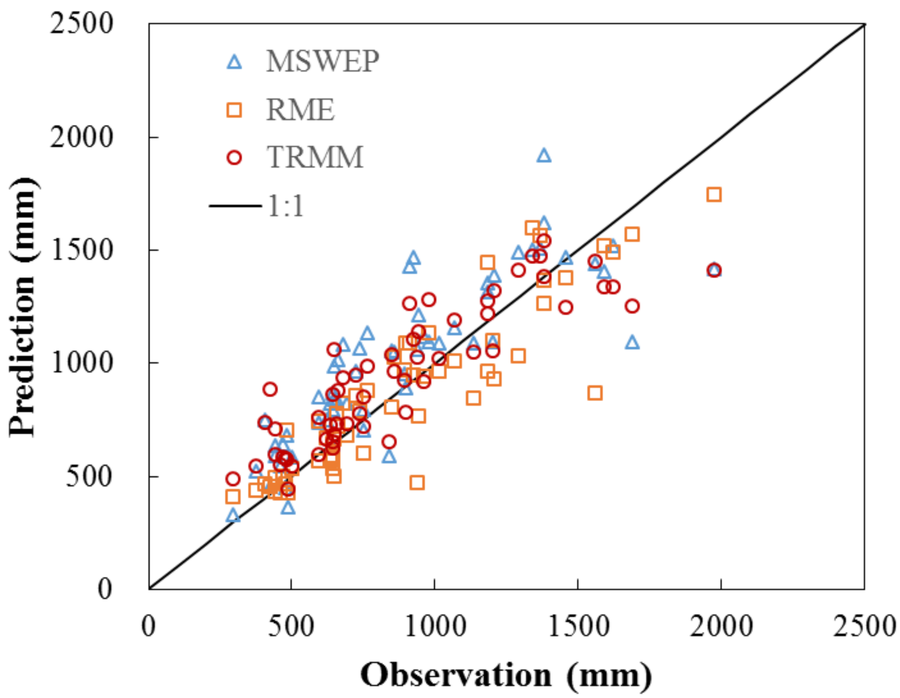

Figure R4 Comparison in mean annual precipitation between the gauged measurements and predictions by the MSWEP, RMM and RME.

5) - A map of sub-basins is better to be provided (for Figure 10).

Response: Added as suggested (Fig. R5).

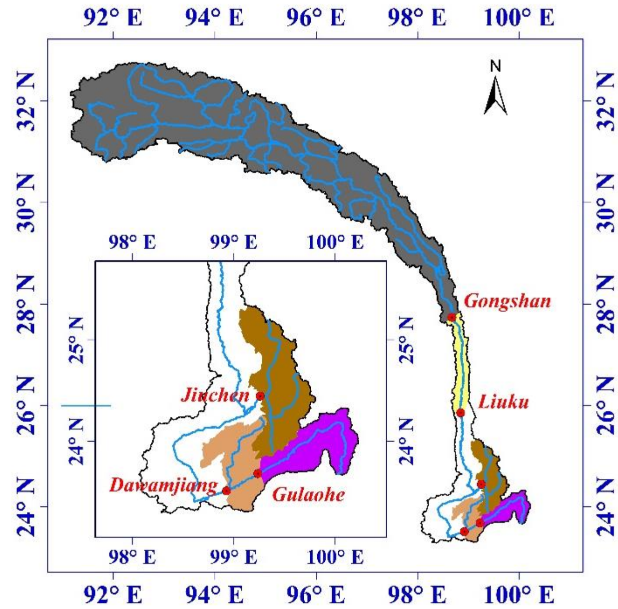

Figure R5 Sub-basins based on hydrologic stations

6) *- I do not think Figure 7 is good to show. I can understand if the authors show the difference between Figure 8 and Figure 6. At least, I would say Figure 7 is awkward.*

Response: Removed as suggested.

7) *- I also suspect that all the areas in Figures 6, 7, 8 are appropriate to show. I mean, there is almost no observation station in the left lower quarter of Figure 2. Then, I suspect whether the values of precipitation amount shown in Figure 6, 7, 8 for the left lower quarter of those figures are enough valid, particularly for the main product of this study and the IDW-based output.*

Response: We agree with that the values of precipitation shown in Figure 6, 7, 8 for the left lower quarter are doubtful because no observation station located in this region. Both RME and TRMM product show this region has large precipitation (>1800mm) and RME gives smaller values than TRMM. As discussed in our manuscript (Line 202-204), the regression model tends to underestimate precipitation as annual precipitation exceeds a certain threshold. We emphasized this conclusion in our manuscript and modified relevant figures.

8) *Very finally, this is probably out of scope of this paper, but I am interested in whether major precipitation season is the same over this particular region. I mean, summer precipitation and winter precipitation (particularly solid precipitation like snow) may have different responses.*

Response: According to our previous study, the distributions of precipitation during the year varies significantly across this region. Fig. R6 shows the distributions of precipitation during the year for 7 stations located in the up, middle and downstream of Nu River. The upstream and downstream have similar distribution of precipitation with major precipitation occurs in summer and little occurs in winter while the middle of Nu River has relatively large precipitation in winter and spring. The solid precipitation mainly occurs in upstream during winter and the amount is small.

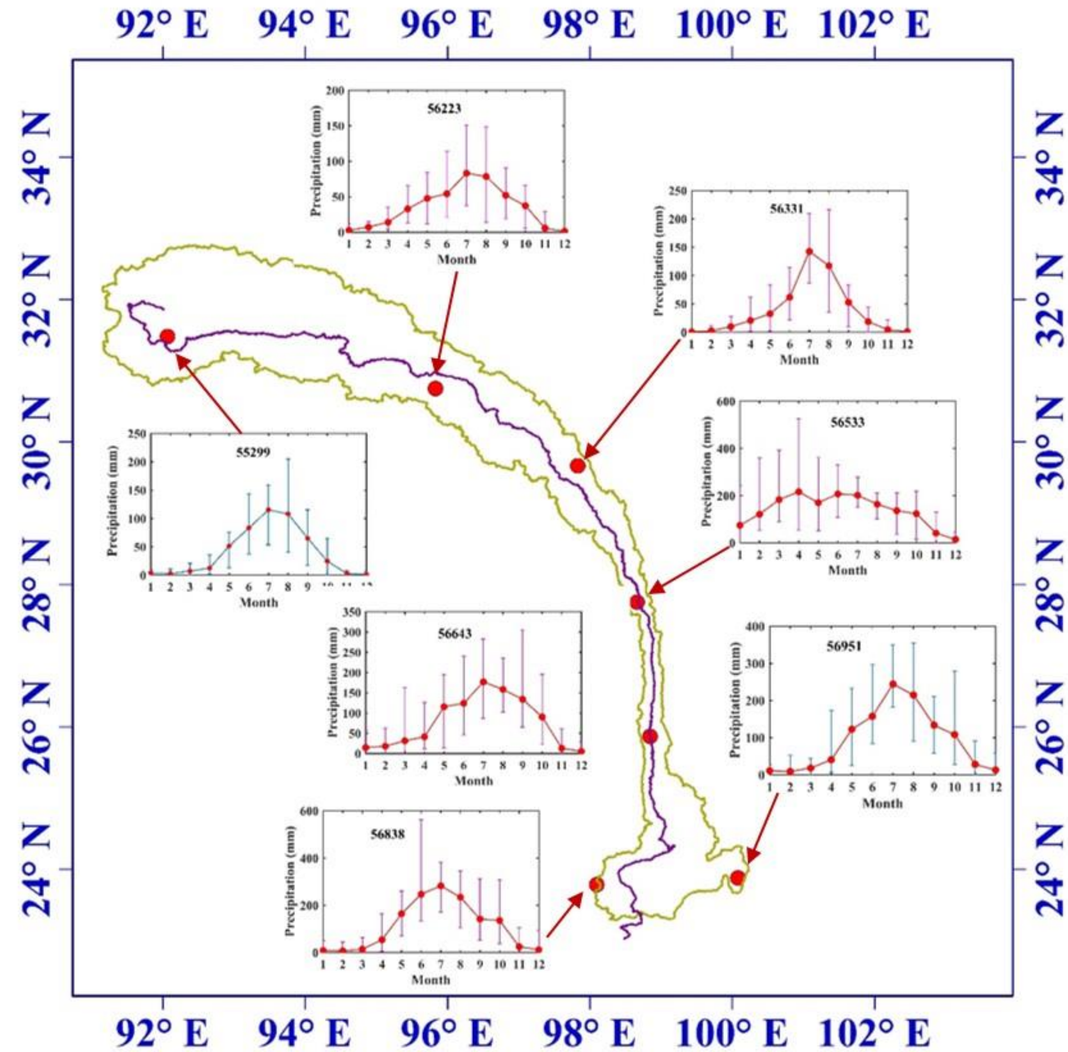

Figure R6 The distribution of precipitation during the year across the Nu River

References :

Brunsdon, C., McClatchey, J. and Unwin, D. J.: Spatial variations in the average rainfall-altitude relationship in Great Britain: an approach using geographically weighted regression, Int. J. Climatol., 21, 455–466, doi:10.1002/joc.614, 2001.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J. and Pasteris, P. P.: Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States, Int. J. Climatol., 28, 2031–2064, doi:10.1002/joc.1688, 2008.

Beck, H.E., A.I.J.M. van Dijk, V. Levizzani, J. Schellekens, D.G. Miralles, B. Martens, A. de Roo (2016): MSWEP: 3-hourly 0.25° global gridded precipitation (1979–2015) by merging gauge, satellite, and reanalysis data, Hydrology and Earth System Sciences Discussions, doi:10.5194/hess-2016–236.

Responses to Anonymous Referee #3:

General Comments:

Gridded precipitation data are very useful for hydrological application and others and ground-observation-based ones have been developed for many regions. This study investigated a methodology to develop gridded precipitation data for the Nu River basin based on the ground-observed precipitation combined with vegetation indices. As an interpolation method, the data fusion may be a strong tool especially for a sparse observation area. Its application to the Nu River with sparse observations may contribute to expanding a hydrological knowledge. This paper requires some more analyses to make readers more convinced of the effectiveness. Therefore, I recommend to revise this manuscript based on comments below before publication.

Response: We thank the reviewer for the positive feedback. Our detailed responses are given after each comment (*italics*) below.

Major comments:

1) *The regression for RME uses all the data at the gauge stations and for the entire years. Such regression provide the climatological mean relationship between precipitation and NDVI. This regression cannot be applied for individual year as seen Table 1 where the coefficients distinct vary with year. Authors must mention the limitation of the proposed method in an appropriate paragraph.*

Response: We agree with the reviewer that the limitation in applying the RME regression to each year's data needs to be appreciated, which has been added in Section 5 of the revised manuscript as follows:

> In addition, although the RME model can utilize the full knowledge of precipitation in the entire study period compared with RMI models, the difference in the coefficients suggests apparent inter-annual variability of precipitation that should be considered when applying these models. Given the duration

of study period and purpose, we suggest the RME model be used for long-term climatology identification while RMI models for inter-annual variability examination.

2) *Judging from Figure 6, climatological mean annual precipitation seems to depend on elevation. The dependence of precipitation on elevation is a well-known fact. In order to clarify the effectiveness of your method, it is better to compare the geographical distributions of climatological mean precipitation between your methods and a method by a regression between precipitation and elevation. A figure of the difference between the two may provide an important suggestion about strong points of your method.*

Response: We thank the reviewer for the insightful suggestion. In the revised manuscript, we compare our method (i.e., RME) with the precipitation-elevation regression (DEMP) model and present the difference of their precipitation estimates as the new Figure 9, which is reproduced as follows:

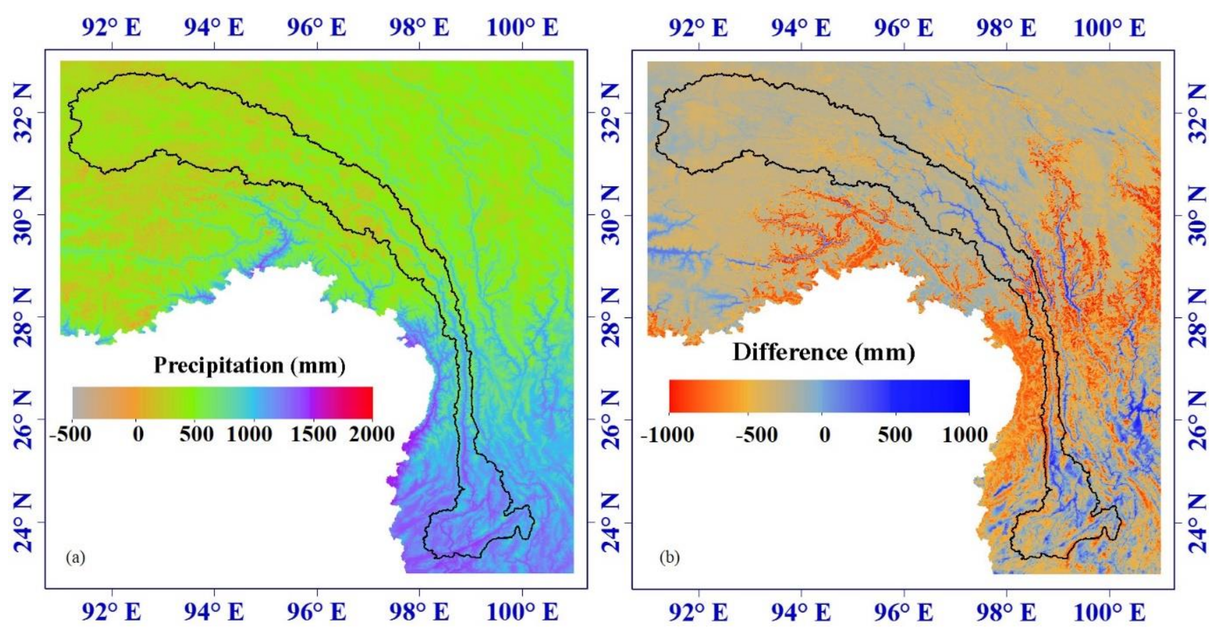

Figure 9 (a) The map of precipitation estimates of DEMP; (b) difference in precipitation estimates between RME and DEMP.

Specific Comments:

3) *L66: The objective of this study should be more specified in terms of spatio-temporal scale: climatological annual mean and 1 km.*

Response: Added in the abstract and introduction as suggested.

4) *L103: The center of a certain box is not used in computing the averaged value of the grid box? If so, please provide a reason.*

Response: We thank the reviewer for pointing out incorrect statement. The center of a certain box is used in calculating the averaged value of the grid box. Related statement is corrected in the revised manuscript.

5) *L157: The number of rain gauge stations in the Nu River basin seems smaller than 13 as long as it is judged from Figure 2.*

6) *L158: Moreover, the 59 stations are not plotted on Figure 2.*

Response: We thank the reviewer for pointing out the inconsistency between the original Fig. 2 and text. We now have corrected Fig.2 with all the 59 gauges displayed, which is reproduced as follows:

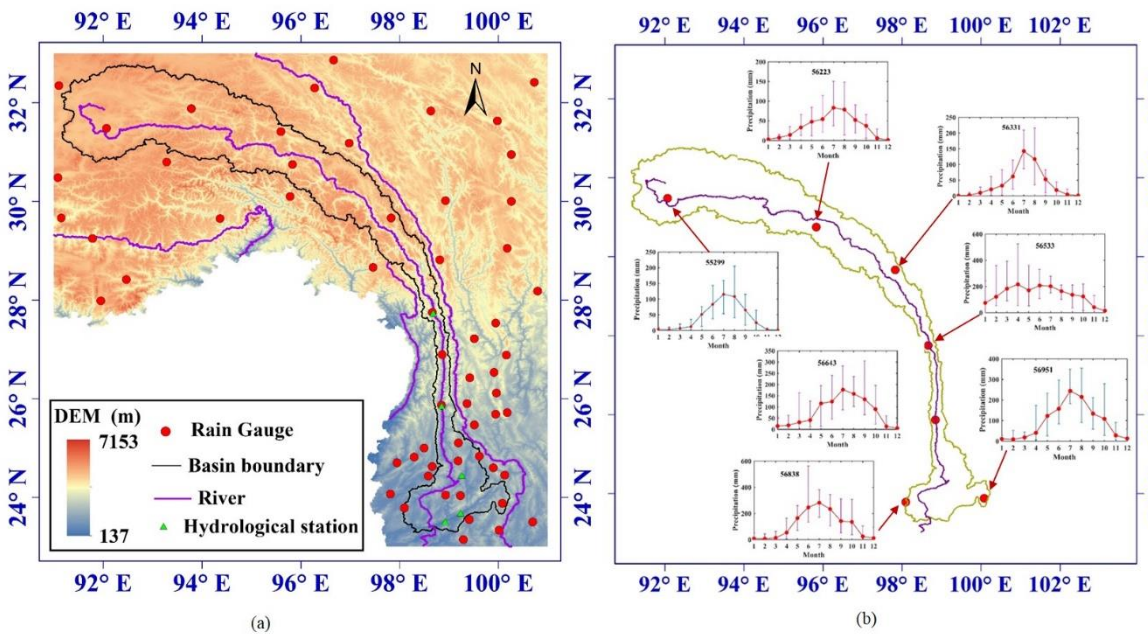

Figure 2 (a) Terrain map of the study area (the Nu-Salween basin and its adjacent areas). (b) The distribution of precipitation during the year across the Nu River.

7) *L159: Please explain what you mean by "climatic and topographic conditions are consistent with the Nu River basin."*

Response: We mean the enlarged area has similar climatic and topographic conditions as the Nu River basin: both regions are characterized as mountainous areas under the subtropical climate influenced by southeast and southwest monsoons. Such explanation has been added in the revised manuscript.

8) *L162: You use three terminologies: uncertainty, reliability, and accuracy in the 3.2.1 subsubsection. Please provide short definitions if you distinguish them in this manuscript.*

Response: We are sorry about bringing up the confusion due to the inconsistency in our terminology. We now only use “reliability” across Section 3.2.1 in the revised manuscript.

9) *L163: In this paragraph, please provide the spatio-temporal resolution of the MODIS dataset.*

Response: The temporal and spatial resolutions of the MOD13A3 and MYD13A3 data we used are 1 month and 1 km, respectively. This information has been added in the revised manuscript.

10) *L176: “m” in “merged” should be in standard font.*

Response: Corrected as suggested.

11) *L185: How do you classify an upscaled 1 km pixel when it is composed of two forest and two cropland pixels? You do not consider the mixed pixel? If so, please provide this information.*

Response: If any of the four 500 m pixels in MCD12Q1 classified as water, urban, snow or ice and cropland, the upscaled 1 km pixel will be classified as abnormal pixel (or non-natural vegetation) and assigned with a missing value (i.e. -9999), otherwise will be classified as normal pixel (or natural vegetation) and assigned with a 1 value.

12) *L196: Readers may know the rationale about the selection of the regression form. Not by “not shown here” but “judging from Figure 3” is better.*

Response: We thank the reviewer for the suggestion. Figure 3 is modified to include the comparison of the four regression forms and updated in the revised manuscript.

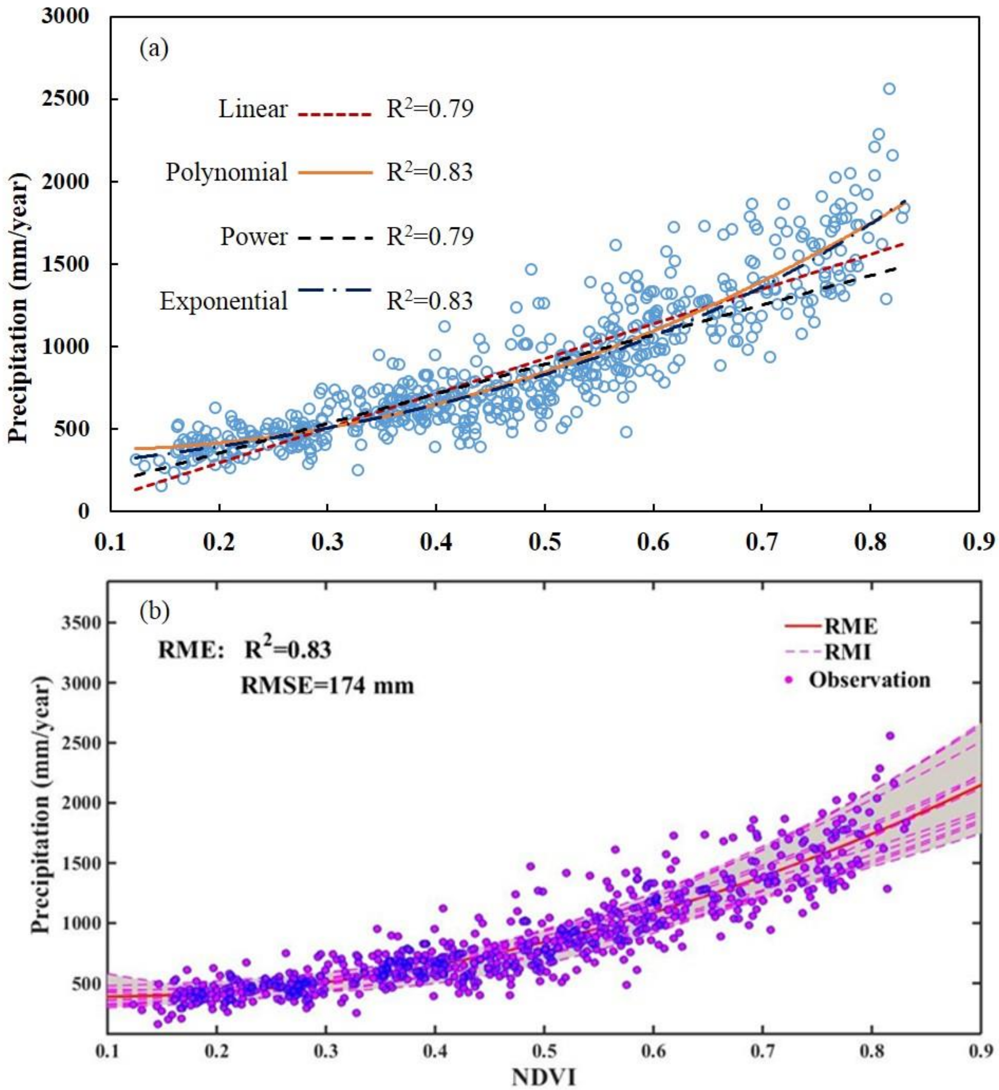

Figure 3 (a) Different regression forms for precipitation–NDVI relationship; (b) The precipitation-NDVI relationships for RME and RMI

13) *L202: Did you use these results when you draw Figure 6? If not, why don't you use these important information?*

Response: We did use these results in making the original Figure 6 (now Figure 8 in the revised manuscript). However, we didn't make any correction to the pixels out of the range from 400 mm to 1500 mm because there is no justifiable methods for such correction. Given the limited fraction of invalid pixels (10% in the whole study area and 7% in the Nu River basin), we still have them plotted in the Figure 8 to demonstrate a full picture of the spatial precipitation pattern in the study area, but we note those pixels are of large uncertainties and should be interpreted with caution.

14) L220: Two spaces exist between of and regression.

Response: The redundant space is removed.

15) L222: Scenario should be Scenarios.

Response: Corrected as suggested.

16) L242: Please provide rationale about the use of the IDW method here.

Response: IDW is one of the most popular methods for spatial interpolation of precipitation due to its easy implementation and flexibility in incorporating other auxiliary information (e.g., elevation).Such statement has been added in the revised manuscript.

17) L264: Precipitation by the RME method often the largest among the three in Figure 10 is reasonable? Can you validate this precipitation estimates larger than the other two by sub-basin water balance such as observed river discharge = P – E. In other words, large amount of precipitation is better than small one in order to explain the observed river discharges.

Response: We thank the reviewer for this suggestion. However, we deem that it would still be difficult to justify the magnitude order of estimates by the three methods even if the observed river discharge of a certain sub-basin is provided: the ***observed*** river discharge implies the response of a basin to the only ***realistic*** precipitation rather than different ***estimates***. In other words, it is difficult to infer the impacts of different inputs (i.e., precipitation estimates by different methods) based on a single output (i.e., river discharge observation).

To evaluate the accuracy of different precipitation estimates, we utilize MODIS evapotranspiration products MOD16 to calculate the water balance based precipitation (i.e. ET+R). Then we compare it with 5 precipitation products and the results are presented in Fig. R2. DEMP represents precipitation based on precipitation-elevation relationship, BandP represents precipitation based on precipitation-NDVI relationship with consideration of elevation band. It can be found that RME and BandP produce closer estimation to water balance based precipitation, implying that the precipitation mapping result based on precipitation-NDVI relationship is reasonable.

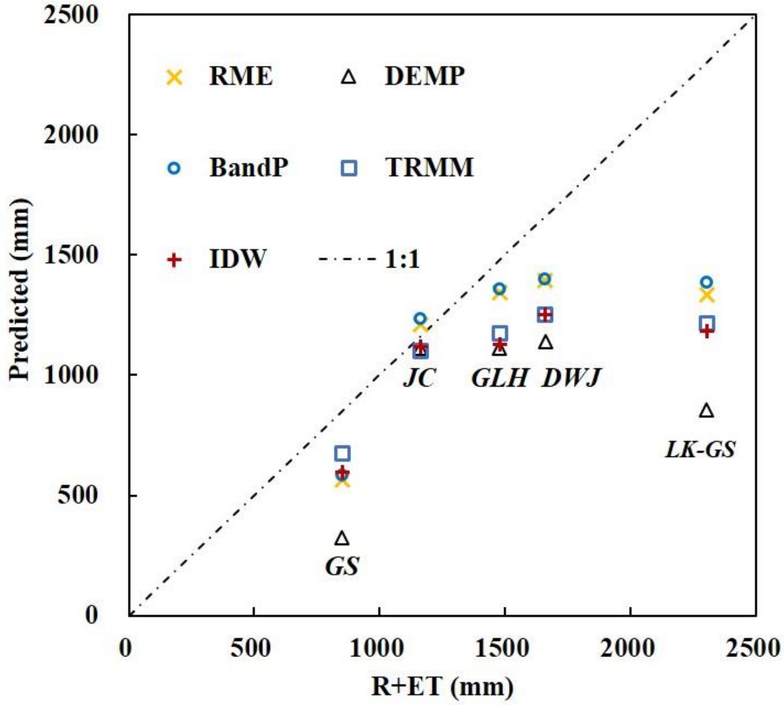

Figure R2 Comparison between water balance based precipitations (R+ET) and 5 precipitation products: DEMP (P-elevation relationship), BandP (P-NDVI relationship with consideration of elevation band), RME, TRMM and IDW. Here GS, JC, GLH, DWJ and LK-GS stand for Gongshan, Jiuchen, Gulaohe, Dawanjing and Liuku-Gongshan, respectively.

18) *L295: As mentioned above, in addition to RME+T and RME+H, how the regression of T or H onto precipitation works for producing climatological mean annual precipitation like Figure 6.*

Response: Our intention of using RME+T and RME+H was to demonstrate the inconsistent trends of precipitation with temperature and elevation. According to Table 5 and Fig. 15, the differences in performance metrics and the regression coefficients between RME+T, RME+H and RME are minimal. Therefore, we think that the influence of including H and T on the regression results is limited.

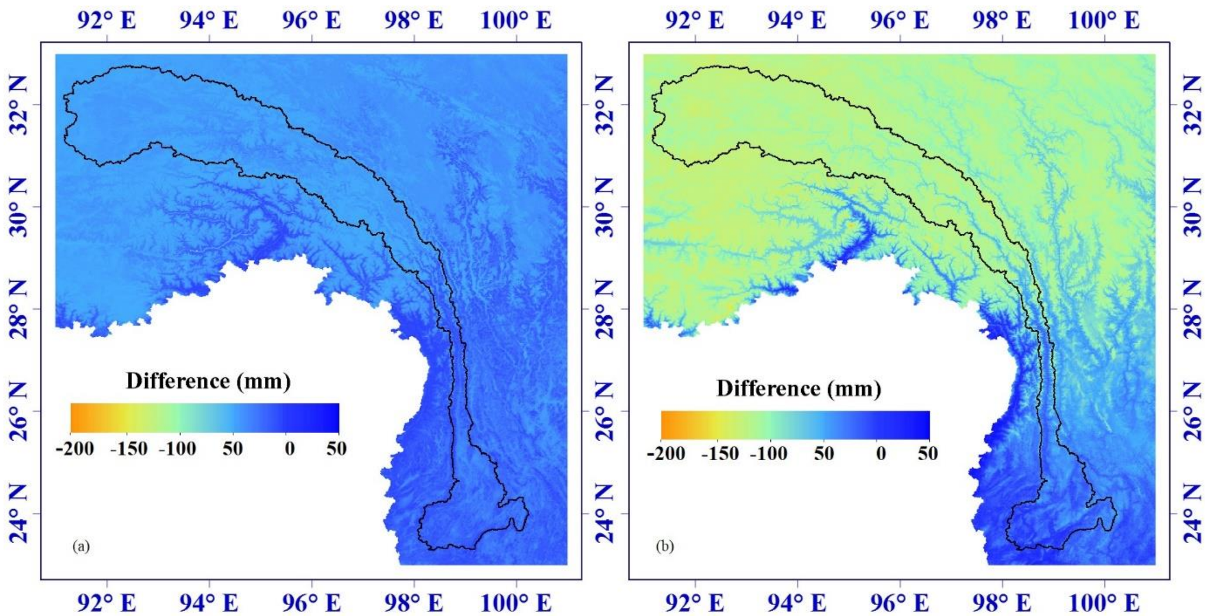

Figure 15 Spatial precipitation difference between RME and (a) RME+H; (b) RME+T

19) *Figures 1: Font color should be the same as in outline color of boxes.*
20) *Figures 2, 6, 7, 8, and A2: Minutes and seconds should be removed from the annotations of the coordinates. Font size should be enlarged so as to see them easily.*

Response: Modified as suggested.

21) *Figure 4: Please provide explanations about two symbols in the figure caption.*

Response: We thank the reviewer for this suggestion .The triangle markers denote the values (R, R^2 and RMSE) of RME model. The plus markers represent the outliers that are out of the range from (Q1-1.5IQR) to (Q3+1.5IQR). Q1 and Q3 are the 25th and 75th percentiles, and IQR (=Q3-Q1) is the interquartile range. Such explanation has been added in the revised manuscript.