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Evaluation of gridded multi-satellite precipitation (TRMM-3B42-V7) estimation performance in the Upper Indus Basin (UIB)

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Abstract: The present study aims to evaluate the capability of the TRMM-3B42-(V7) precipitation product to estimate appropriate precipitation rates in the Upper Indus basin (UIB) and the analysis of the dependency of the estimates' accuracies on the time scale. To that avail statistical analyses and comparison of the TMPA- products with gauge measurements in the UIB are carried out. The dependency of the TMPA estimates' quality on the time scale is analysed by comparisons of daily, monthly, seasonal and annual sums for the UIB. The results show considerable biases in the TMPA-(TRMM) precipitation estimates for the UIB, as well as high false alarms and miss ratios. The correlation of the TMPA- estimates with ground-based gauge data increases considerably and almost in a linear fashion with increasing temporal aggregation, i.e. time scale. The BIAS is mostly positive for the summer season, while for the winter season it is predominantly negative, thereby showing a slight over-estimation of the precipitation in summer and under-estimation in winter. The results of the study suggest that, in spite of these discrepancies between TMPA- estimates and gauge data, the use of the former in hydrological watershed modelling, endeavoured presently by the authors, may be a valuable alternative in data- scarce regions, like the UIB, but still must be taken with a grain of salt.

Keywords: Precipitation; Tropical Rainfall Measurement Mission (TRMM); Multi-satellite Precipitation Analysis (TMPA); Upper Indus basin (UIB).

1. Introduction

The continued improvements in computation capabilities and the subsequent increase in the development of spatially explicit and distributed models for expressing environmental phenomena has necessitated the provision of more intensive and improved data for environmental variables both in space and time. Two major issues, especially, in hydro-meteorological studies, are the possible sparsity of data sampling points (gauge stations), and the discontinuities in the data and in the quality of the temporal records. These issues are more frequent in mountainous regions with high altitudes which are immensely challenging environments for measurements of precipitation, either through remote-sensing or the traditional ground based methods, because of the difficult topography and the highly variable weather and climatic conditions [1, 2]. Similarly, these and other reasons have restricted many developing countries to have consistent spatial and temporal coverage for ground-based precipitation measurements [2, 3] and make it difficult for them to achieve an effective spatial coverage of rainfall [4, 5]. The consequent lack of good quality precipitation data, then turns out to be a big hurdle for properly assessing impacts of climate change on water resources in these regions [1].

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As data with an acceptable gridded resolution of daily climatic variables are critical for hydrological and water resources modeling [6, 7], managing the gaps in the data appropriately is then the first stage of most climatological, environmental and hydrological studies [2]. This step is also necessary to improve the spatial resolution for sparse gauge station data set, before using it as an input for spatially-distributed rainfall-runoff models, because the gauge-based interpolation methods, commonly used in hydrologic models, usually do not cover the spatial heterogeneity of the variability of climatic variables in the catchment. These errors in the interpolated data field have then the potential to significantly bias model calibrations and water balance calculations [6].

Fortunately, the continued scientific development is also showing new prospects in addressing these issues. . For example, the advancements in the gathering and deriving climate data through satellite remote sensing could provide a possible opportunity to mend some of the issues with regard to the spatial coverage of climate data. That is why the use of satellite-based precipitation products, individually, or in combination with land-based gauge data, has been increasingly recognized as a very promising alternative to address the aforementioned problems [5]. Such precipitation products prove to be of great value, especially, in developing countries with remote and high-altitude locations, where conventional rain gauge- or weather data are of bad quality or have low coverage [8][8].

There are numerous satellite-based precipitation products currently available with varying degrees of accuracy. These include the Climate Prediction Center (CPC) morphing algorithm (CMORPH) [9], the Global Satellite Mapping of Precipitation [10–12], the Naval Research Laboratory Global Blended Statistical Precipitation Analysis [13] and the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA) [14, 15] and a few others. Since their inception, most of these gridded datasets have been evaluated for their suitability and usability for a specific regions or intended uses. In general such investigations are specifically for mountainous regions, and even less for the Hindukush, Karakurm and Himalays (HKH) region. In the HKH and the Upper Indus Basin (UIB) region, most of the reported work related to evaluation of gridded precipitation products, are suggestive of considerable biases in the gridded products in comparison to the gauge records [16–19].

Additionally the quality, coverage or reprentetiveness of the available observed gauge records have also been questioned and sometimes regarded below par [20–22] with considerable under estimation of regional precipitation amounts especially at higher altitudes (Khan and Koch unpublished).(the spatial distribution of estimated real precipitation by khan and Koch (unpublished) over study are is given in the supplementary materials – Appendix-I while the Vertical meteorological and cryspheric regimes in UIB (modified from Hewitt 2007) is given in Appendix-II)

While, in most cases, these gridded global precipitation data sets are some interpolated version of point measurements, (most often through geo-statistical procedures), they may only be useful for regions where dense network of rain gauges are available, because otherwise, in absence of a dense enough networks or over regions of complex topographies, the interpolated precipitation present a very generalized destitution, not able to reflect on the prevalent orographic, surface or atmospheric processes [19].

In comparison with the sparse gauge observations or the gridded data products, based on them, satellite-based precipitation products, such as "Tropical Rainfall Measurement Mission" (TRMM) "Multi-satellite Precipitation Analysis" (TMPA) (TRMM-3B42-(V7) have an inherent advantage, due to their higher spatial coverage. However, they also have certain limitations, because they are indirect estimates of rainfall, which depend on the cloud height and the properties of the cloud's surfaces (IR-algorithms) and on the integrated sparse and multi-source hydro-meteorological content (passive microwave algorithms) [23, 15, 24]. Before such satellite-based data can be used with confidence, it is therefore important to evaluate its accuracy or error characteristics by comparing it with data from ground-based observations.

The current study was therefore aimed at assessing the skill of the TRMM precipitation dataset in matching the magnitudes and occurrences, at different temporal scales, at all the points of the

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observational network available, to evaluate its further processing and correction requirements or suitability for subsequent use in hydrological modelling.

2. Materials and Methods

2.1. Study Area: "The Upper Indus River Basin (UIB)

The Indus River, one of the largest rivers in Asia with a total length of about 2880 km, has a drainage area of about 912,000 km^2 which extends across portions of India, China, Pakistan and Afghanistan. The portion of the Indus that comprises the upper Indus river basin (UIB), with a logical lower boundary at Tarbela Dam, is about 1125 km long and drains an area of about 170,000 km^2 [25] .

Being a high-mountain region, the UIB contains the largest area of perennial glacial ice cover (22 000 km^2) outside the polar regions of the earth, and which extends even further during the winter season [26]. The altitude within the UIB ranges from as low as 455 m to a height of 8611 m and, as a result, the climate varies greatly within the basin [27].

The summer monsoon has no significant effect on the basin, as almost 90% of its area lies in the rain shadow of the Himalayan belt [28][20]. Except for the south-facing foothills, the intrusion of the Indian-ocean monsoon is limited by the mountains, so that its influence weakens northwestward. Subsequently, the climatic controls in the UIB are quite different from that in the Himalayas on the eastern side. In fact, over the extent of the UIB, most of the annual precipitation originates in the west and falls in winter and spring, whereas occasional rains are brought by the monsoonal incursions to the trans-Himalayan areas, but so that even during the summer months the trans-Himalayan areas do not obtain all their precipitation from the monsoons [29–32].

Climatic variables are usually strongly influenced by topographic altitude. Several studies have pointed out that precipitation in the HKH region exhibits large changes over short distances and has a considerable vertical gradient [33–36, 30, 29]. Thus the northern valley floors of the UIB are arid, with annual precipitation of only 100-200 mm, but these totals increase with elevation and reach upto 600 mm at 4400 m, and even reach to an annual glacier accumulation rates of 1500 to 2000 mm at 5500 m altitude, according to some glaciological studies [29]. The average snow cover area in the Upper Indus River Basin fluctuate between ~10% to 70%. Snow cover in the area is at a maximum of 70–80% in the winter- (December to February) snow accumulation period and at a minimum 10–15% in the summer- (June to September) snow melt period [27]. Stream flow is generated by the combination of the storm runoff in the lower parts of the upper Indus basin and the snow- and glacier runoff from the higher parts of the UIB [37, 25].

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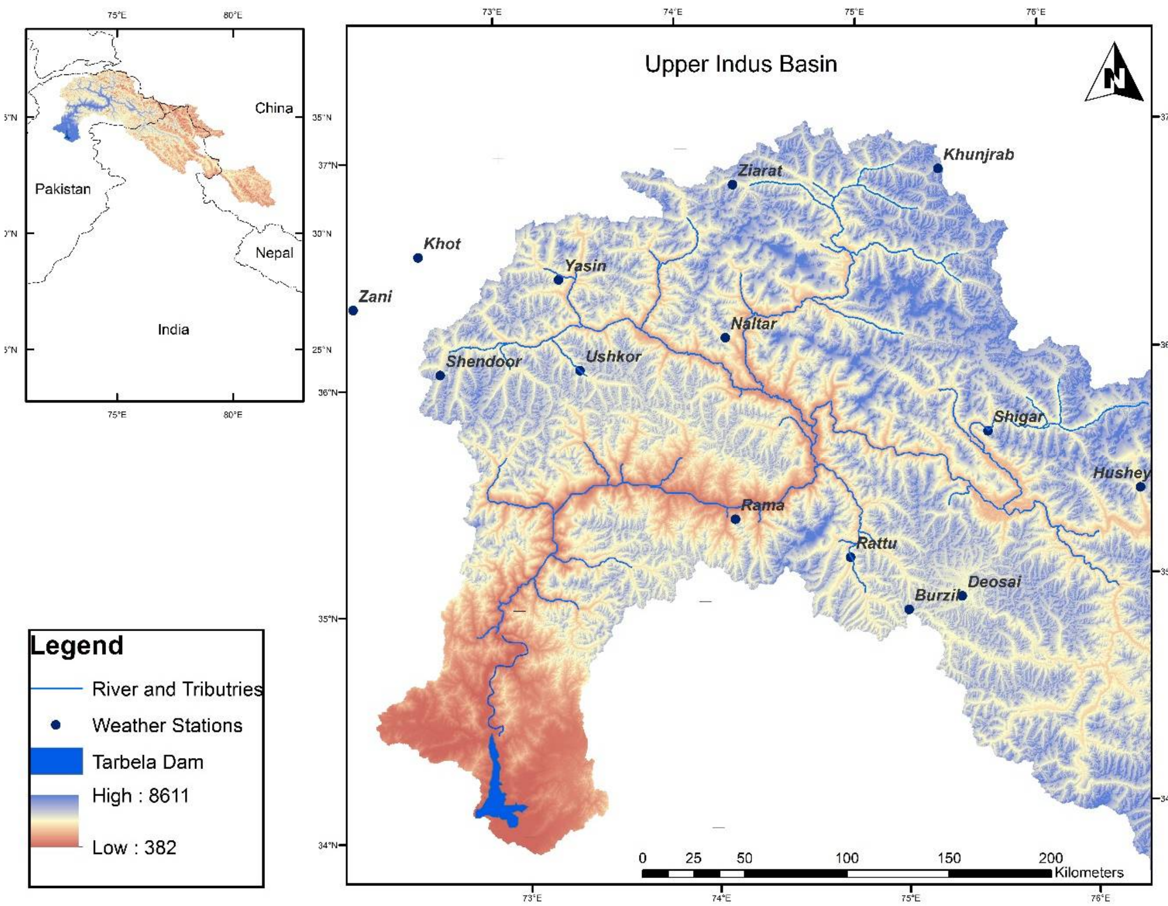

Figure 1: Upper Indus Basin with hydro-climatological stations

2.1.1. TMPA Data (TRMM 3B42 V7)

In this study the TRMM 3B42 (V7) precipitation product is used. This product is basically a calibration-based combination scheme for precipitation estimates from multiple satellites and space-borne sensors, including infrared, microwave, radar data and gauge measurements. Though the dataset has very good spatio-temporal resolution (0.25° × 0.25° grid, 3-hourly) and good global coverage (latitude band 50°N to 50°S) and is available since 1998 to the recent past [15, 1] it also has certain uncertainties, because the inputs on which they are based are indirect estimates of rainfall, depending on the cloud height and the properties of the cloud surface (IR algorithms) and on the integrated sparse and multi-source hydro-meteorological content (passive microwave algorithms) [15, 24, 14].

During the current study, 3-hourly data from January 1, 1998 to December 31, 2008, were summed to daily accumulated precipitation for each of the 0.25° X 0.25° grid box, which have a gauge station, and evaluated for match with the corresponding gauge station's observed daily accumulated precipitation. As the observational network is scant, no TRMM grid box had more than one in situ gauge station located in it.

2.1.2. Observed gauge data

In HKH region of Pakistan, observed in situ data are limited, and operated by different organizations, mainly the Pakistan Meteorological Department (PMD) and Water and Power Development Authority (WAPDA). The stations operated by PMD have daily time step climate data available for longer periods (1947 to date) but with huge gaps and missing data in the record and with only monthly data available freely for research purposes. Furthermore, all the PMD stations are valley-based, at elevations below than 3000 m a.s.l. altitude, and therefore hardly represent the frequency and amount of precipitation in the high-altitude areas. The climate stations, operated by

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WAPDA, are fairly new and have considerably consistent, data over the time period, coinciding with the TRMM product. These gauge stations are distributed almost evenly across the UIB inside Pakistan and cover a wide range of elevations. During the current study, daily precipitation records of 14 meteorological stations operated by WAPDA were utilized for evaluation of TRMM estimates. Their geographical attributes are given in Table 1. The evaluation limited to the duration of 1998 to 2008, as the observed precipitation data could not be acquired for the period beyond 2008.

Table 1; Geographical attributes of the Precipitation gauge Network

	S. No.	**Station name**	**Latitude (◦)**	**Longitude (◦)**	**Altitude (m)**
High Altitude (2367–4440 ma.s.l.) stations operated by Water and Power Development Authority, Pakistan (WAPDA)	1	Burzil	34.906	75.902	4030
	2	Deosai	35.09	75.54	4149
	3	Hushey	35.42	76.37	3075
	4	Khot	36.517	72.583	3505
	5	Khunjrab	36.84	75.42	4440
	6	Naltar	36.17	74.18	2898
	7	Rama	35.36	74.81	3179
	8	Rattu	35.15	74.8	2718
	9	Shendoor	36.09	72.55	3712
	10	Shigar	35.63	75.53	2367
	11	Ushkor	36.05	73.39	3051
	12	Yasin	36.454	73.3	3350
	13	Zani	36.334	72.167	3895
	14	Ziarat	36.77	74.46	3020

2.2. *Methods*

The quantitative comparison of the TRMM-estimates with ground rain-gauge station observations is done by employing various widely used statistical indicators. These include the correlation coefficient (*R*), the mean relative bias error (*rBIAS*), the mean bias error (*MBE*); mean absolute error (*MAE*), and the root mean square error (*RMSE*). The *R*, *rBAIS*, *MBE*, *MAE* and *RMSE* are defined in the following equations:

$$R = \frac{\sum_{i=1}^{n}(T_i - \overline{T})(G_i - \overline{G})}{\sqrt{\sum_{i=1}^{n}(T_i - \overline{T})^2} \sqrt{\sum_{i=1}^{n}(G_i - \overline{G})^2}} \qquad (1)$$

$$rBIAS = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{T_i - G_i}{\frac{1}{n}\sum_{i=n}^{n} G_i}\right) \qquad (2)$$

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$$MAE = \frac{1}{n}\sum_{i=1}^{n} |T_i - G_i|) \qquad (3)$$

$$MBE = \frac{1}{n}\sum_{i=1}^{n} T_i - G_i) \qquad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(T_i - G_i)^2} \qquad (5)$$

where n is the number of samples, T_i are satellite-based precipitation, G_i are gauge-based precipitation, and $\bar{T}$ and $\bar{G}$ are the corresponding means. Among these statistical indices, R shows the degree of linear correlation between TRMM precipitation estimates and gauge observations; *MBE*, *MAE* and *rBIAS* are used to assess the systematic bias, i.e. the deviation of the satellite precipitation from the gauge observations, and the *RMSE* gives the magnitude of the average error in relative terms.

Table 2. Contingency table 2X2

		OBSERVED VALUES (GAUGE DATA)		TOTAL
		YES	NO	
ESTIMATED VALUES (TRMM-ESTIMATES)	YES	**-a- Hits**	**-b- False Alarms**	*Total-Yes Estimated*
	NO	**-c- Misses**	**-d- Correct negative**	*Total-No Estimated*
TOTAL		*Total-Yes Observed*	*Total-No Observed*	**TOTAL** *a+b+c+d*

In addition, evaluations were also made for the daily TRMM estimates and gauge data, based on a 2×2 contingency table (Table 2), by detecting rain events, no events, misses by TRMM and false-alarms by the TRMM, over the Indus river basin.

We used a threshold of 0.3 mm/d, to differentiate precipitation and no precipitation events since lower precipitation values may be the result of noise, as indicated by [30, 38] etc.

Based on these four indicators, orders as shown the table, several categorical statistical indices are derived, including, accuracy (Ac), bias score or frequency bias index (FBI), probability of detection (POD), false alarm ratio (FAR, critical success index (CSI) and true skill statistics (TSS) [39, 40] . These are defined in the following equations:

$$Ac = \frac{a + d}{Total} \qquad (6)$$

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$$FBI = \frac{a+b}{a+c} \tag{7}$$

$$POD = \frac{a}{a+c} \tag{8}$$

$$FAR = \frac{b}{a+b} \tag{9}$$

$$CSI = \frac{a}{a+b+c} \tag{10}$$

$$TSS = \frac{a}{a+b} - \frac{b}{c+d} = \frac{ad-bc}{(a+b)(c+d)} \tag{11}$$

where a represents the number of rainfall events that have been successfully estimated by TRMM data (hits), b is the number of events incorrectly predicted as rain events by TRMM (false alarms). c is the number actual events, that are missed by TRMM (Misses), while d is the number of dry days or no-rainfall events identified successfully by the TRMM dataset. For each day, depending on how the estimated and observed precipitation behave, any events above the given threshold (0.1 mm), is scored either as hit, miss, false-alarm or correct-negative.so that the rainfall is a hit if both, TRMM and observed, reach the threshold, False-alarm if if only the TRMM estimate reach the threshold, miss if only the observed precipitation reaches it, and correct-negative if both are below the threshold. The number of hits, fals-alarms, misses and correct-negatives ar used in eq-5 to 10, to calculate the above mentioned statistical indices

Each of these indices provides a specific information of the two data sets compared. Thus *Ac* indicates the fraction of estimates which is correct (range: 0 to 1. perfect score: 1); *FBI* indicates whether the estimated dataset have a tendency to underestimate (FBI < 1) or to overestimate (FBI > 1) rain events, *POD* quantifies the fraction of rain occurrences that is estimated correctly (range: 0 to 1. perfect score: 1); *FAR* measures the fraction of false alarms in the satellite rain estimates (perfect score of 0 and a range from 0 to 1. *CSI* measures the fraction of estimated events that are correctly predicted (perfect score: 1) and a range from 0 to 1. Unlike all the aforementioned indices, *TSS* does not depend on the frequency of climatological event and uses all elements in the contingency table (Table 2). Thus *TSS* provides a measure of the accuracy of the estimates in terms of the probability of correct detection of events or no events. In this case the range is form -1 to 1. Perfect score is 1, with 0 showing no skills and a negative score means that the estimates are worse than a random forecast.

3. Results and discussion

The assessment of the reliability of the TRMM estimates and their comparisons with the rain data from gauge station presented in this section has been done by three different methodologies, i.e. (1) a *statistical analysis*, based on R, BIAS, MAE and RMSE for monthly, annual and seasonal data aggregates, (2) *categorical statistics* daily data by computing Ac, FBI, POD, FAR, CSI and TSS, and (3) *visual comparison* for monthly, annual and seasonal data.

3.1. Statistical analysis

The results of the TRMM-assessment based on the statistical measures *R*, *rBIAS*, *MBE*, *MAE* and *RMSE*, are given for daily data aggregation in **Table 3**, for monthly and annual data aggregation in Table 4, and for seasonal aggregation in Table 5. The summer season include months of April, May, June, July, August and September, while the remaining 6 months: October, November, December, January, February and March are aggregated to represent Winter season.

It is evident from a first glance at the two tables that the TRMM performs overall rather poorly for estimating the observed rain amounts for the study region at all resolutions, as the average *R*

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values are only 0.16, 0.22, 0.22 and 0.20 for monthly, annual, and seasonal (summer and winter) aggregation, respectively. Further specific results are discussed in the subsequent sub-sections

3.1.1. Skill Statistics for TRMM precipitation estimates (Daily aggregates)

The daily aggregates of TRMM precipitation estimates showed poor skill in matching observed precipitation, with an average R of 0.16. Our comparison of the observed and TRMM daily rainfall data shows highly variable MAE across the UIB, with a range ≥ 23 mm/day (**Table-3**). Values of MAE were high throughout most of compared locations in UIB, with MAE ≤ 13 mm for the all stations averaged rainfall, across the UIB. The North-Western parts of the UIB showed the highest and the most variable MAE. The results showed that the TRMM data have huge under-estimation across most of the UIB (average MBE of -3.53 mm), while the MBE values also showed a distinct spatial pattern across the study area, with distinct under-estimation by TRMM estimates for all the studied locations in the Eastern and Northern UIB; for the Southern UIB, TRMM estimates showed a high under-estimation at all locations except one; while the stations located in the North-western UIB had a mixed trend, where TRMM data showed moderate to high, under or over estimation at half (three) of the locations each. The mean relative bias (rBIAS) at the different gauge location also followed an similar pattern with huge veriations and ranging from a (-)tive 0.42 to as high as 5.27 (Table 3), while at certain locations the relative bias was very high and at one location i.e. "Yasin" the *rBais* was even more than 5 times the observed values. The RMSE for the daily time series were also very high and showed large variations, ranging from and 8.08 to as high as 46.57 mm/day, with averages RSME of 20.88 for all locations averaged rainfall.

These results are in agreement with previous studies () as most of them have reported TRMM product to underestimate rainfall amounts over the HKH region in general and even higher over the western parts of HKH.

Table 3. Statistical analysis based on monthly and annual data aggregation.

	STATION	DAILY R	rBIAS	MBE (mm)	MAE (mm)	RMSE (mm)
Southern UIB	***Burzil***	0.22	-0.42	-11.77	16.20	20.76
	Deosai	0.10	0.99	4.41	14.53	26.33
	Rama	0.23	-0.22	-16.20	18.31	27.44
	Rattu	0.14	0.69	-7.90	18.12	29.24
Eastern UIB	***Shigar***	0.08	1.31	-3.99	10.24	17.81
	Hushey	0.14	-0.07	-5.73	10.79	14.73
North-Western UIB	***Khot***	0.19	0.70	0.49	4.93	8.08
	Naltar	0.25	0.24	-11.94	15.39	21.10
	Shendoor	0.16	1.48	1.22	9.46	15.67
	Ushkor	0.21	0.70	-0.51	8.16	12.74
	Yasin	0.10	5.27	24.24	28.68	46.57
	Zani	0.13	-0.14	-15.23	19.16	26.96
Northern UIB	***Khunjrab***	0.15	-0.27	-5.50	10.52	15.40
	Ziarat	0.14	0.71	-0.94	6.05	9.48
Average (all stations in UIB)		0.16	0.78	-3.53	13.61	20.88
Maximum		0.25	5.27	24.24	28.68	46.57
Minimum		0.08	-0.42	-16.20	4.93	8.08

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3.1.2. Skill Statistics for TRMM precipitation estimates (Monthly and annual aggregates)

The monthly and annual aggregated TRMM precipitation estimates also showed poor skill in matching observed precipitation, but with considerably improved values for the Pearson correlation coefficient R for all the studied locations and with an R of 0. 61 and 0.57 for average of rainfall at all locations for monthly and annual aggregates, respectively.

Table 3. Statistical analysis based on monthly and annual data aggregation**.**

	STATION	MONTHLY					ANNUAL				
		R	rBIAS	MBE (mm)	MAE (mm)	RMSE (mm)	R	rBIAS	MBE (mm)	MAE (mm)	RMSE (mm)
Southern UIB	***Burzil***	0.55	-0.28	-56.80	58.73	112.81	0.43	-1.05	-391.5	391.5	407.7
	Deosai	0.22	0.17	21.65	43.62	78.95	-0.37	0.24	146.6	201.4	234.6
	Rama	0.54	-0.36	-78.26	79.54	165.86	0.78	-2.05	-538.5	538.5	574.8
	Rattu	0.20	-0.20	-39.31	61.32	119.10	0.30	-0.58	-264.9	274.1	353.8
Eastern UIB	***Shigar***	0.02	-0.21	-19.42	36.56	78.26	-0.11	-0.62	-133.2	179.7	249.8
	Hushey	0.09	-0.24	-29.19	39.72	101.95	-0.15	-0.79	-193.2	230.3	339.6
North-Western UIB	***Khot***	0.51	-0.21	-26.52	39.47	74.14	0.29	-0.65	-182.0	242.7	250.9
	Naltar	0.60	-0.31	-58.62	60.17	120.63	0.12	-1.32	-395.1	395.1	416.3
	Shendoor	0.42	0.08	6.53	22.08	37.34	0.54	0.13	40.4	66.4	99.1
	Ushkor	0.52	-0.03	-1.82	19.19	39.41	0.62	-0.05	-14.7	79.1	110.5
	Yasin	0.21	1.36	118.35	126.68	241.25	0.10	0.72	806.0	806.0	827.5
	Zani	0.49	-0.34	-75.05	77.98	154.91	0.52	-1.69	-508.3	508.3	532.6
Northern UIB	***Khunjrab***	0.39	0.05	2.26	13.13	23.40	-0.28	0.09	18.3	52.0	70.0
	Ziarat	0.38	-0.07	-5.39	15.23	32.62	0.55	-0.15	-30.6	73.4	104.7
Average (all stations in UIB)		0.61	-0.23	-9.09	14.15	20.98	0.57	-0.24	-117.3	117.3	134.1
Maximum		0.60	1.36	118.35	126.68	241.25	0.78	0.72	806.03	806.03	827.54
Minimum		0.02	-0.36	-78.26	13.13	23.40	-0.37	-2.05	-538.50	51.96	69.96

Our comparison of the observed and TRMM monthly and annual aggregated rainfall also showed a highly variable MAE across the UIB, ranging from 13.13 mm/month to 126.68 mm/month, in case of monthly aggregates and from -538.5 mm/year to 806.0 mm/year for annual aggregates (**Table-4**). The values for MAE were high throughout most of compared locations in UIB, with an average MAE of 14.15 mm/month and 117.3 mm/year, for the all locations average monthly and annual rainfall across UIB, respectively. The spatial pattern of the errors observed in case of monthly and annual aggregates as well as the predominant under-estimation at most location was similar to that observed for the daily aggregates The North-Western parts of the UIB showed the highest and the most variable MAE, while the TRMM data showed huge under-estimation across most of the UIB (average MBE of a (-)tive 9.09 mm/month and -117.3 mm/year). The Eastern part UIB, showed a distinct under-estimation by TRMM rainfall, across all the studied locations. In case of the Southern UIB, the under-estimation was even higher but observed at three out of the four location, while at one location (Deosai), an over estimation of 21.65 mm/month was observed. The stations located in the North-western UIB had a mixed trend, where TRMM data showed a moderate to high, under-estimation at four of the studied locations while the opposite in the remaining two, for both monthly and annual aggregates. The MBE for the total of two location evaluated in the northern UIB, showed

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a mixed results with one station (Khunjrab) showing slight over-estimation (0.05 mm/month and 18.3 mm/year), while the other (Ziarat) showing a negative MBE (-0.07 mm/month and -30.6 mm/year).

3.1.3. Skill Statistics for TRMM precipitation estimates (Seasonal aggregates)

The seasonal statistical indices (Table 4) have comparable trends in terms of magnitude, however, show a different pattern than the monthly- or annually computed ones. For example the in summer season the TRMM showed positive BIAS for a few location where the monthly and annual aggregates show a negative one (i.e. Rattu, Ushkor). Results for the winter season predominantly show negative BIAS- values, similar to monthly and annual aggregation. The overall range of MBE for the stations evaluated varies from—268.8 mm to 593.6 mm for the summer season and from -339.9 mm to 212.5 mm for winter season. The MBE for average rainfall across all location in UIB, was -5.18 and -96.51 mm for summer and winter respectively. These MBE value are comparatively lower in case of summer season, are suggestive of a situation where the under or over-estimation occurring in the different months of the seasons, cancel each other out to give an overall low MBE.

Table 4. Statistical analysis based on summer and winter season data aggregation

Regions	*STATIONS*	SUMMER SEASON					WINTER SEASON				
		R	rBIAS	MBE (mm)	MAE (mm)	RMSE (mm)	R	rBIAS	MBE (mm)	MAE (mm)	RMSE (mm)
Southern UIB	***Burzil***	0.35	-0.48	-190.8	190.8	201.5	0.05	-0.50	-200.7	200.7	226.0
	Deosai	-0.42	0.27	68.1	101.0	123.5	-0.14	0.31	78.6	116.9	139.6
	Ramma	0.68	-0.54	-198.7	198.7	213.9	0.60	-0.92	-339.9	339.9	371.4
	Rattu	0.49	0.09	25.8	101.0	127.9	-0.01	-1.00	-290.8	290.8	357.1
Eastern	***Shigar***	-0.09	-0.22	-36.9	106.0	156.6	-0.10	-0.57	-96.3	105.4	127.9
	Hushey	0.22	-0.35	-83.2	103.7	156.3	-0.55	-0.46	-109.9	132.2	189.3
North-Western UIB	***Khot***	-0.11	-0.03	-4.1	38.1	48.3	0.33	0.16	22.2	29.2	34.8
	Naltar	0.48	-0.50	-203.8	203.8	220.6	0.17	-0.47	-191.6	191.6	205.9
	Shendoor	0.57	0.42	56.1	56.7	79.6	-0.02	-0.12	-15.9	61.1	65.6
	Ushkor	0.49	0.17	31.0	71.9	84.1	0.65	-0.25	-45.9	55.3	85.7
	Yasin	-0.35	2.94	593.6	593.6	615.2	0.22	1.05	212.5	212.5	244.1
	Zani	0.52	-0.66	-268.8	268.8	301.3	0.57	-0.59	-239.8	239.8	256.1
Northern UIB	***Khunjrab***	0.09	-0.21	-41.3	91.8	109.2	0.56	-0.72	-141.1	157.5	166.9
	Ziarat	0.56	-0.02	-2.5	36.2	47.4	0.54	-0.20	-28.4	44.8	65.3
Average (all stations in UIB)		0.60	0.00	-5.18	30.1	38.7	0.36	-0.4	-96.51	96.5	109.1
Maximum		0.68	2.94	593.6	593.6	615.2	0.65	1.05	212.5	339.9	371.4
Minimum		-0.42	-0.66	-268.8	36.2	47.4	-0.55	-1.00	-339.9	29.2	34.8

The R ranges showed better values for the summer season (0.6) in comparison to winter season, for the basin average seasonal aggregates, while it ranged from -0.42 to 0.68 and -0.55 to 0.65 for the summer and winter seasons respectively.

3.2. Categorical statistics

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The results for the six categorical indices, as described in Section 2.3 are listed in Table 5 and they show how the TRMM-data match the ground-based gauge data at daily resolution. Thus the values for the first index, accuracy (*Ac)* are well above 0.50 for all stations, with an average of 0.58.

The frequency bias index *FBI* has neither very high positive nor negative values, but varies on both sitdes with 9 stations showing overestimation, and the remaining 5 an underestimation. The average *FBI* for all stations is 1.05, i.e. indicates a slight overestimation of the TRMM rainfall.

The other categorical indices (see Eq. 8- 11) do not show very good results either. Thus, for most of the stations the values of the probability of detection (*POD*) is below 0.5, with only 4 stations having values above it. The False Alarm Ratio (*FAR*) for all stations, but one, are too high, with an average of 0.56. In the same way, both the CSI- and the TSS values are also not very promising as only 3 stations have values above 0.30 for the former and only one station has a value of about 0.20 for the latter.

Thus, overall, these results of the categorical statistics indicate that TRMM rainfall estimates do not have a very good match with the ground-based gauge data and, therefore, should only be used after some corrections and adjustments have been made.

Table 5. Categorical statistics for daily TRMM estimate and gauge rain data.

Regions	*STATIONS*	Ac	FBI	POD	FAR	CSI	TSS
Southern UIB	***Burzil***	0.5	0.7	0.42	0.45	0.3	0.1
	Deosai	0.5	1.0	0.61	0.39	0.4	0.1
	Ramma	0.5	1.2	0.50	0.61	0.2	0.0
	Rattu	0.5	1.4	0.56	0.62	0.2	0.0
Eastern UIB	***Shigar***	0.60	1.30	0.41	0.68	0.22	0.08
	Hushey	0.57	0.83	0.40	0.52	0.28	0.10
North-Western UIB	***Khot***	0.6	1.3	0.57	0.58	0.3	0.2
	Naltar	0.6	0.8	0.40	0.53	0.2	0.1
	Shendoor	0.5	1.1	0.40	0.65	0.2	0.0
	Ushkor	0.6	1.0	0.42	0.60	0.2	0.1
	Yasin	0.6	1.0	0.44	0.58	0.2	0.2
	Zani	0.5	0.8	0.35	0.59	0.2	0.0
Northern UIB	***Khunjrab***	0.55	1.04	0.43	0.58	0.27	0.06
	Ziarat	0.60	0.73	0.35	0.52	0.25	0.10
Average (all stations in UIB)		0.58	1.05	0.45	0.56	0.28	0.11
Maximum		0.6	1.4	0.61	0.68	0.4	0.2
Minimum		0.5	0.7	0.35	0.39	0.2	0.0

Regions	*STATIONS*	Ac	FBI	POD	FAR	CSI	TSS

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Southern UIB	***Burzil***	0.5	0.7	0.42	0.45	0.3	0.1
	Deosai	0.5	1.0	0.61	0.39	0.4	0.1
	Ramma	0.5	1.2	0.50	0.61	0.2	0.0
	Rattu	0.5	1.4	0.56	0.62	0.2	0.0
Eastern UIB	***Shigar***	0.60	1.30	0.41	0.68	0.22	0.08
	Hushey	0.57	0.83	0.40	0.52	0.28	0.10
North-Western UIB	***Khot***	0.6	1.3	0.57	0.58	0.3	0.2
	Naltar	0.6	0.8	0.40	0.53	0.2	0.1
	Shendoor	0.5	1.1	0.40	0.65	0.2	0.0
	Ushkor	0.6	1.0	0.42	0.60	0.2	0.1
	Yasin	0.6	1.0	0.44	0.58	0.2	0.2
	Zani	0.5	0.8	0.35	0.59	0.2	0.0
Northern UIB	***Khunjrab***	0.55	1.04	0.43	0.58	0.27	0.06
	Ziarat	0.60	0.73	0.35	0.52	0.25	0.10
Average (all stations in UIB)		0.58	1.05	0.45	0.56	0.28	0.11
Maximum		0.6	1.4	0.61	0.68	0.4	0.2
Minimum		0.5	0.7	0.35	0.39	0.2	0.0

3.3. Visual comparison

For visual comparison, monthly-, annually- and seasonally aggregated time series of the TRMM-rainfall estimates and of the various gauge stations are plotted.

Figs. 2 and 3 show these time series plots for the two stations Yasin and Khunjrab, respectively. One may notice that for the station Yasin (Fig. 2) shows huge biases and errors at all three time scales considers, whereas for the other station Khunjrab, a better match, especially, at the annual and seasonal resolution is obtained. The corresponding plots for the others stations reveal patterns somewhere in between the two stations shown here.

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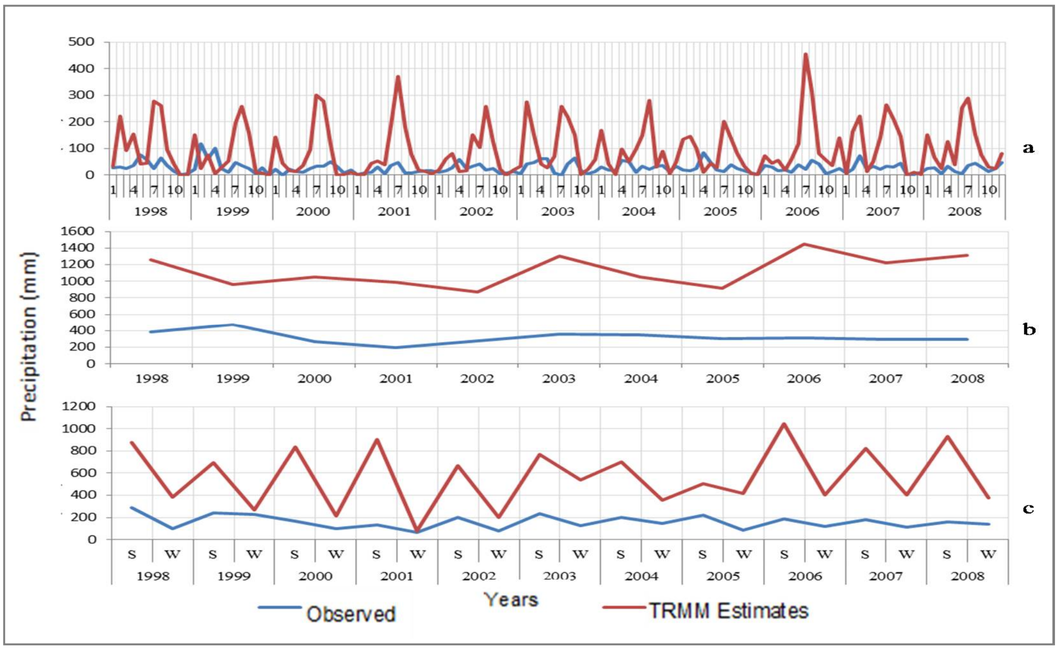

Figure 2: Time series of TRMM estimates and gauge data for rainfall totals at Yasin station; a. monthly, b. annual, and c. seasonal (S=Summer, W=Winter)

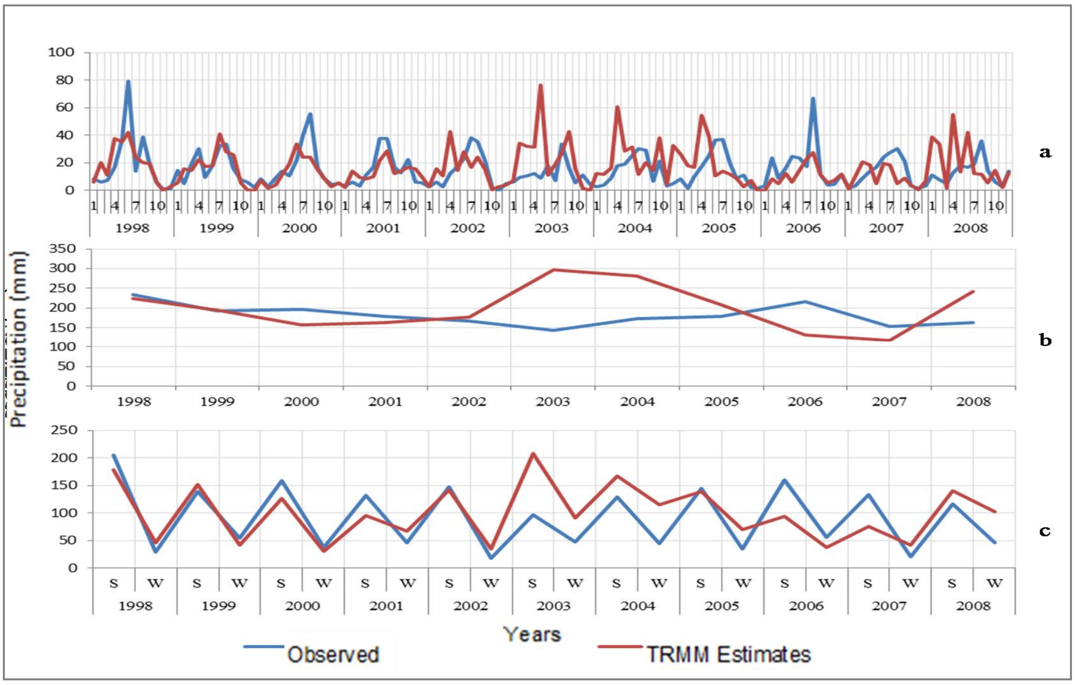

Figure 3: Time series of TRMM- estimates and observed gauge data for mean rainfall totals at Khunjrab station; a. monthly, b. annual, and c. seasonal (S=Summer, W=Winter)

The monthly TRMM- and gauge rainfalls averaged over all stations and the full length of period considered (1998-2008), is plotted in Fig. 4. The figure also have demarcation of the seasons. From the figure an underestimation of the TRMM- rainfall in the winter months and a mix of under and overestimation in the summer months can clearly be seen.

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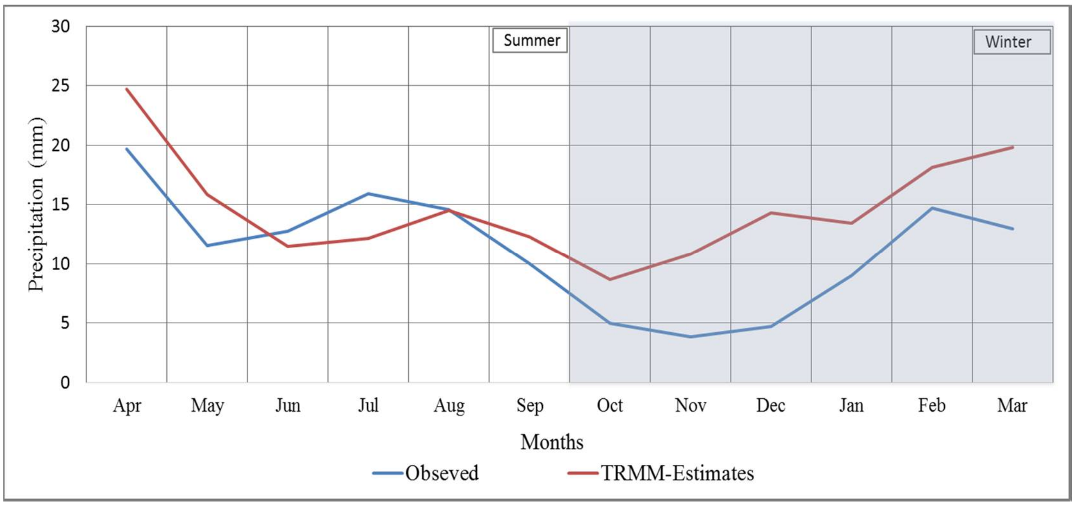

Figure 4. Comparison of TRMM-estimates and gauge data for mean monthly rainfall for all stations with seasonal demarcation.

Finally, the monthly-, annually- and seasonally aggregated time series of the TRMM- rainfall estimates of the average rainfall across all the studied gauge stations are plotted in **Fig-5.** Though there is almost a persistent underestimation by the TRMM estimates, the peaks and troughs, in most instances followed similar patterns.

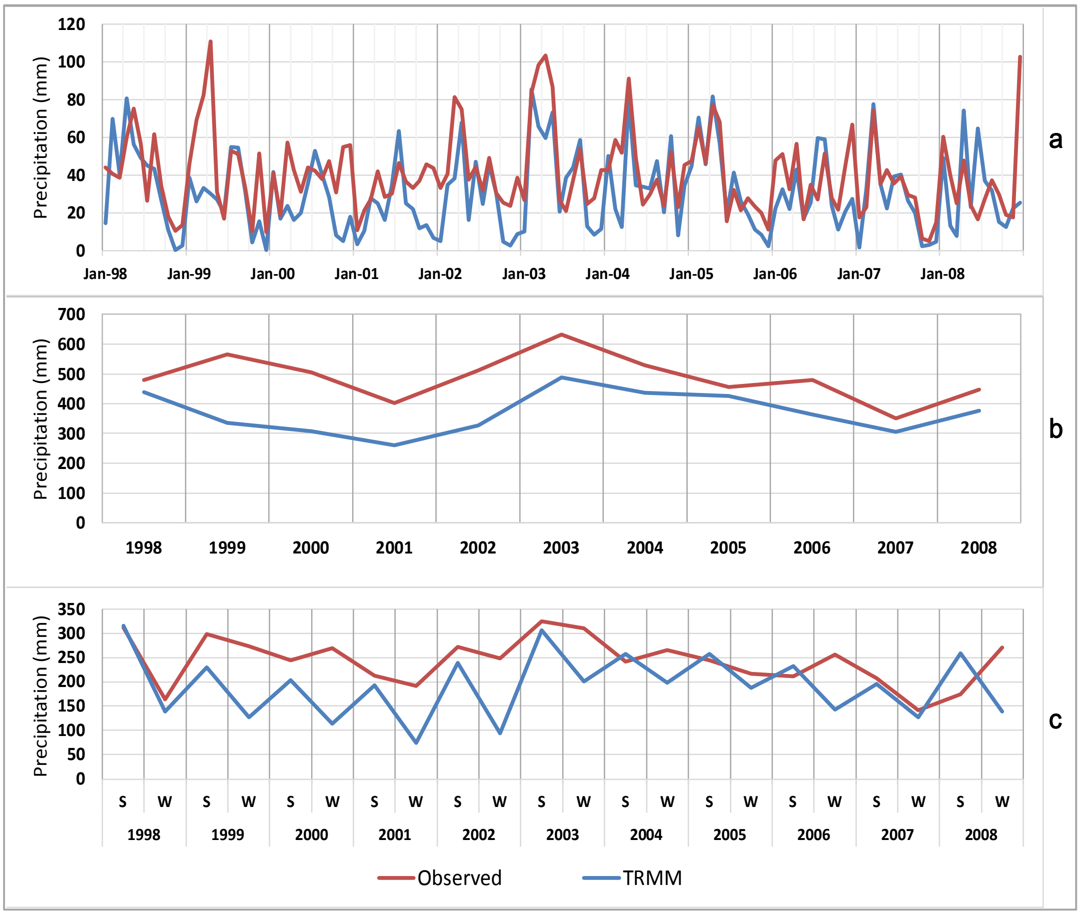

Figure 5: Time series of TRMM- estimates and observed gauge data for mean rainfall totals over the study area, for all the gauge stations ; a. monthly, b. annual, and c. seasonal (S=Summer, W=Winter)

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4. Discussions and Conclusions

In this study a TMPA product - TRMM 3B42 V7 data for the Upper Indus basin, Pakistan, for the period 1998-2008 has been assessed and evaluated on a point-to-point basis, using rain gauge data from 14 stations. These assessments have been performed at monthly, seasonal and annual aggregation scales. The results indicate that the TMPA product has considerable errors in estimating the rainfall amounts at the various gauge stations throughout the study area and throughout the total time period studied. There is a predominant trend of under- estimation across the study area as at most of the gauge stations, the TRMM product tends to under-estimate the gauge-measured rainfall,. The seasonal TRMM- rainfall values, though, show a specific pattern, with the summer rainfall slightly overestimated, but those for the winter predominantly underestimated at almost all locations and all aggregation time scales.

These overall results are in conformity of the previous studies, which, in most cases, suggest that neither the sparsely observed station data and gridded data products based on them, nor the sensors based data, fully represent the precipitation regime of the region [41], with strong non-representation or underestimation [16] of regional precipitation amounts, especially for higher altitudes by [41, 20, 22]. In fact the *in situ* meteorological observations in UIB are sparse and mostly taken at valley based stations. This data provide low spatial coverage and is scant for higher altitudes. Furthermore, the complex orography of the UIB region also affects the amounts, spatial patterns and seasonality of precipitation. Additionally, most of the authors have indicated that the observation network across the UIB, also show underestimation of precipitation amounts by [20, 22, 41–43], with an average underestimation of around 166%, which may reach even in excess of 300% over some parts of the basin [43]. This means that the TRMM product may even be underestimating the true areal precipitation by a much greater margin, as the true areal precipitation is estimated to be much higher [43] than the gauge observation records.

The comparison of any gridded or sensor based dataset against the observed precipitation, may not be taken, therefore, as a conclusive evidence for declaring the evaluated data as unappropriated in terms of usability but rather show the degree to which these data sets match for magnitudes or occurrences with the observed precipitation, which by no means is perfect., and a better match may also indicate the evaluated data also may have tendencies to underestimate the real areal precipitation over the UIB. Furthermore, the resolution of the TRMM product (0.25° X 0.25°), may also pose limitations, especially for distributed hydrological modelling and investigations, as at this resolution, the orographic influences on the precipitation regime cannot be mapped, while the hydrological models may also require precipitation data at a much finer scale.

The main conclusion which can be drawn from our study may be summed up as: 1) The TRMM 3B42 V7 product has an overall poor agreement with the observed rainfall gauge data in the study area, and this holds for all temporal scales considered; and 2) our results, eventually means that the TMPA-TRMM 3B42 V7 product may only be regarded as suitable for further rainfall analyses and subsequent hydrological applications in the study region, if some improvements, down-scaling and local calibrations of its output data are carried out first.

Author Contributions:

Asim Jahangir Khan conceived and designed the experiments, conducted the analysis and is responsible for writing; Manfred Koch helped developing the idea, supervised the analyses and the writing process and he is responsible for parts of the text; Karen Milena Chinchilla is responsible for parts of the statistical analysis and helped developing ideas.

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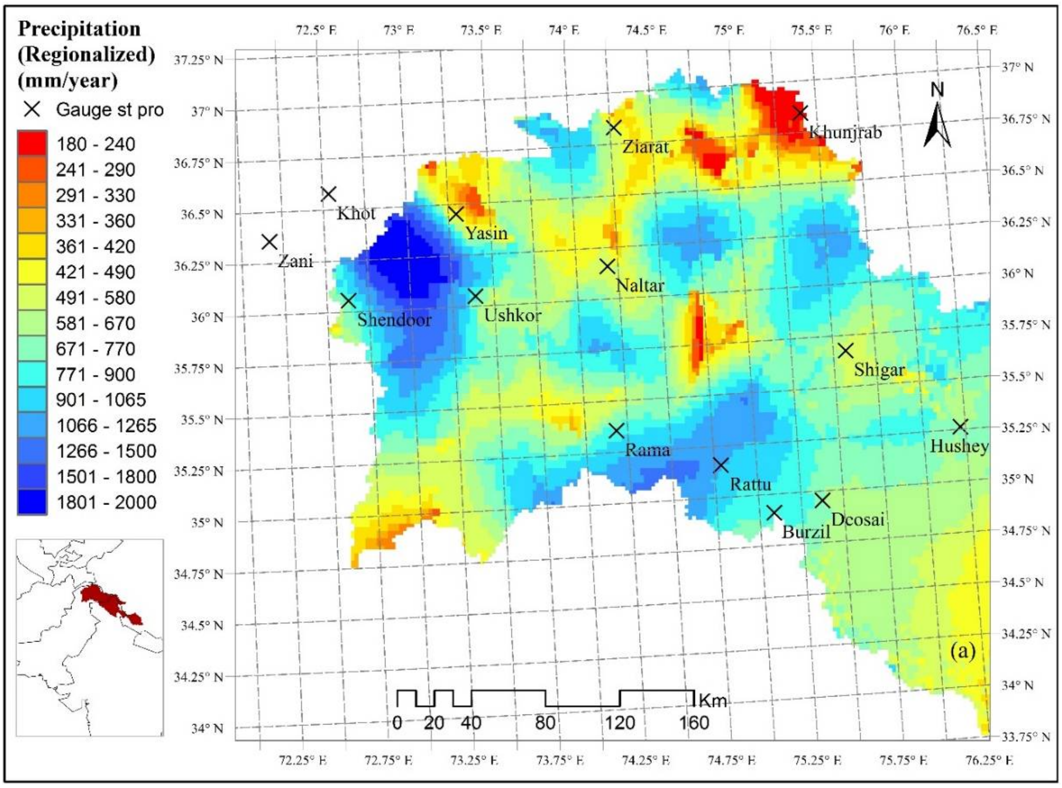
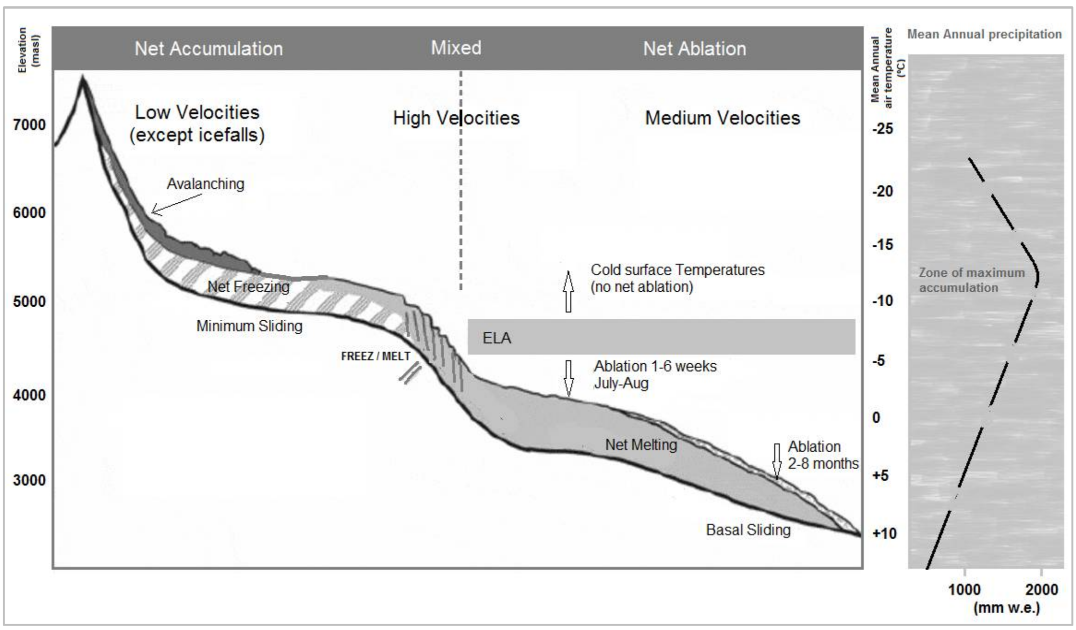
Appendices-Supplementary Materials

App.I : Spatial Precipitation regimes in UIB (adopted from Khan and Koch unpublished)



App.II Vertical meteorological and cryspheric regimes in UIB (modified from Hewitt 2007)



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