Remote Sens. **2013**, *5*, 4107-4123; doi:10.3390/rs5084107

OPEN ACCESS

Remote Sensing

ISSN 2072-4292

www.mdpi.com/journal/remotesensing

Article

Evaluating Satellite Products for Precipitation Estimation in Mountain Regions: A Case Study for Nepal

Nir Y. Krakauer [1,*], Soni M. Pradhanang [2], Tarendra Lakhankar [1] and Ajay K. Jha [3]

[1] Department of Civil Engineering and NOAA-CREST, The City College of New York, NY 10031, USA; E-Mail: tlakhankar@ccny.cuny.edu

[2] Institute for Sustainable Cities, City University of New York, NY 12401, USA; E-Mail: soni.pradhanang@hunter.cuny.edu

[3] Department of Horticulture and Landscape Architecture, Colorado State University, Fort Collins, CO 80523, USA; E-Mail: ajay.jha@colostate.edu

* Author to whom correspondence should be addressed; E-Mail: nkrakauer@ccny.cuny.edu; Tel.: +1-212-650-8003.

Received: 26 June 2013; in revised form: 12 August 2013 / Accepted: 13 August 2013 / Published: 16 August 2013

Abstract: Precipitation in mountain regions is often highly variable and poorly observed, limiting abilities to manage water resource challenges. Here, we evaluate remote sensing and ground station-based gridded precipitation products over Nepal against weather station precipitation observations on a monthly timescale. We find that the Tropical Rainfall Measuring Mission (TRMM) 3B-43 precipitation product exhibits little mean bias and reasonable skill in giving precipitation over Nepal. Compared to station observations, the TRMM precipitation product showed an overall Nash-Sutcliffe efficiency of 0.49, which is similar to the skill of the gridded station-based product Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE). The other satellite precipitation products considered (Global Satellite Mapping of Precipitation (GSMaP), the Climate Prediction Center Morphing technique (CMORPH), Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS)) were less skillful, as judged by Nash-Sutcliffe efficiency, and, on average, substantially underestimated precipitation compared to station observations, despite their, in some cases, higher nominal spatial resolution compared to TRMM. None of the products fully captured the dependence of mean precipitation on elevation seen in the station observations. Overall, the TRMM product is promising for use in water resources applications.

Keywords: quantitative precipitation estimation; Nash-Sutcliffe efficiency; Nepal; Himalayas; monsoon Asia

1. Introduction

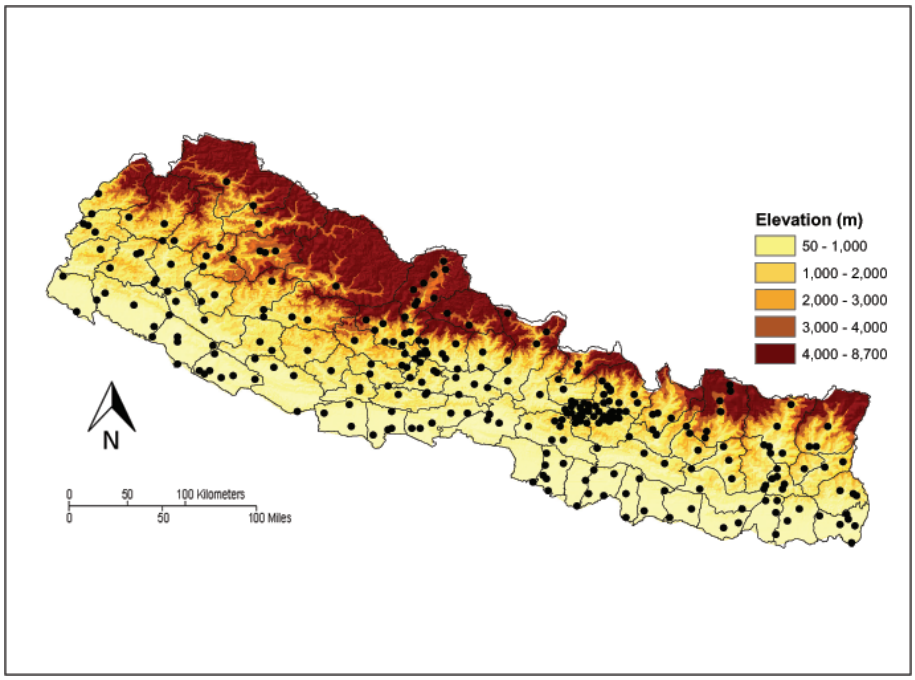
Mountain regions are critical to regional water resources, with often heavy precipitation supplying river flow to extensive downstream reaches, and are also vulnerable to hydrological hazards, such as flooding [1,2]. Since precipitation in mountain regions may vary strongly in space, accurate spatially distributed data are critical to assessing mountain water resources; however, in many regions, few weather station measurements are available in near real time. Although remote sensing precipitation products based on satellite observations offer potentially high spatial and temporal resolution and low latency, discrepancies between available products put their accuracy for mountain regions in question [3], necessitating a full evaluation of their skill before they can be recommended for operational use.

Here, we evaluate the accuracy of satellite precipitation products for Nepal, located between latitudes 26°–31°N and longitudes 80°–89°E in the north of the Indian subcontinent on the southern flank of the Himalayas (Figure 1) [4]. Nepal's low and middle foothills receive large amounts of rain from about July to September as part of the South Asian monsoon (summer rainy season), but populations there may experience water shortages during the rest of the year [5,6]. While the Himalayan peaks and the Tibetan plateau to the north are in a relatively dry "rain shadow" [7], winter snow at high elevations nevertheless contributes to spring and summer streamflow [8]. Precipitation amount and timing impact key regional hazards, such as flooding and landslides [9–11]. Few rain gauge measurements from Nepal are publicly available, especially in near real time, and the national network is inadequate to capture precipitation variability in mountain regions [12,13].

Several studies have previously applied satellite precipitation products for the Indian subcontinent or for the Himalayas region, which includes Nepal. For example, Bhatt and Nakamura [14] and Bookhagen and Burbank [15] used the Tropical Rainfall Measuring Mission (TRMM) satellite-borne precipitation radar to study the seasonality and diurnal variation of precipitation around the Himalayas, but without validating the satellite precipitation estimates against other observations. Brown [16] compared available daily station data from India and Sri Lanka to two satellite precipitation products, using, as a criterion for accuracy, the discrepancy between the gauge and satellite yearly accumulations. Islam and Uyeda [17] compared precipitation seasonal cycles and number of rain days in two versions of the TRMM precipitation product to station measurements over Bangladesh, showing that a low bias in TRMM monsoon rainfall was mitigated in a more recent version. Yatagai and Kawamoto [18] found that the TRMM Precipitation Radar (PR) product underestimated summer precipitation by 28–38% over the Himalayas. Focusing specifically on Nepal, Shrestha *et al.* [19] found that streamflow in the Bagmati river (in a region of Nepal with relatively dense station coverage) was simulated poorly when forced by basin-wide precipitation from a Climate Prediction Center (CPC) satellite-derived product compared to using interpolated rain gauge measurements, since the CPC product failed to capture some of the heaviest precipitation events. Similarly, Islam *et al.* [20] found that Version 6

of the TRMM product generally underestimated daily precipitation over Nepal compared to available station data. They then used linear regression to calibrate the TRMM product, although without considering geographic variation in the calibration factor. Duncan and Biggs [21], on the other hand, found that TRMM generally overestimated precipitation over Nepal compared to the gridded station measurement product Asian Precipitation-Highly Resolved Observational Data Integration towards Evaluation of Water Resources (APHRODITE), concluding that TRMM, therefore, is of limited use for water resource management or hazard planning in Nepal. Andermann *et al.* [22] found that APHRODITE did better at matching station-measured precipitation amounts at several watersheds and swath profiles in Nepal and adjacent countries than any of the remote sensing products evaluated, including TRMM. Yamamoto *et al.* [23] compared the mean seasonal and diurnal cycles of precipitation measured by a single high-altitude automated weather station in Nepal with those of several remote sensing-based precipitation products, finding that TRMM best represented the mean seasonal cycle, while the Global Satellite Mapping of Precipitation (GSMaP) products performed particularly poorly; interannual variability was not considered.

Figure 1. Topography and district boundaries of Nepal. Circles show the locations of stations with precipitation data (from the Department of Hydrology and Meteorology (DHM), People and Resource Dynamics Project (PARDYP) or Stations at High Altitude for Research on the Environment (SHARE)) used in this study.



In this work, our goal is to systematically quantify the performance of satellite precipitation products over Nepal compared to station observations. To do this, we evaluate both absolute amounts of precipitation and patterns of spatial and temporal variability. We focus on the monthly timescale, which is relevant for water resources applications, such as agriculture and hydropower. We compare mean spatial patterns and interannual variability of precipitation, as well as mean precipitation by altitude and season between the satellite products and, where possible, with observations. We use several versions

of Nash-Sutcliffe efficiency to quantify the degree of agreement between station observations and each satellite precipitation product along some dimensions of interest, such as mean spatial distribution, the seasonal cycle, and interannual variability.

2. Methods

2.1. Gridded Precipitation Products

We sought to include in our evaluation satellite precipitation products that are available in near real time and, also, had at least several years of archived fields available. The archived products are what we actually evaluate in this paper using time series of station observations, while the availability of a near real time version would enable these products to be operationally used for water resources applications in Nepal. Given the sharp topographic contrasts in precipitation known to exist in Nepal, we sought satellite products with as high a spatial resolution as possible, but at least 0.25°.

TRMM Product 3B-43 is released by the Goddard Space Flight Center of the National Aeronautics and Space Administration (NASA). TRMM is a satellite launched in late 1997 that includes several instruments for monitoring precipitation using microwave, infrared and visible wavelengths [24]. Product 3B-43 aggregates to calendar months the three-hour precipitation product, 3B-42, which incorporates microwave and infrared observations from multiple satellites, including TRMM. 3B-43 uses rain gauge data in order to remove any detected biases from the estimated precipitation field [25] and has a spatial resolution of 0.25°. A version of the three-hour product is processed in near real time. An advantage of TRMM 3B-43 compared to other satellite products is extensive validation and bias adjustment based on ground measurements. We used the latest research version (7A) of TRMM 3B-43, which was available from 1998 through September, 2012.

The GSMaP project is carried out by the Japan Aerospace Exploration Agency (JAXA). Near-real-time and reanalyzed hourly precipitation products are available at 0.1° spatial resolutions. These are based on both microwave and infrared satellite radiometry, combined using a Kalman filter [26,27]. We used the daily-aggregated version of the reanalysis product (Version 5.222), available for March 2000 to November 2010.

The CPC Morphing technique (CMORPH) aims to produce global precipitation analyses at very high spatial and temporal resolution by propagating precipitation estimated from satellite microwave observations using cloud movements obtained from geostationary satellite infrared sensors [28]. This product is available in near real time at 0.073° and 0.25° spatial resolutions at ftp://ftp.cpc.ncep.noaa.gov/precip/global_CMORPH/ . We used CMORPH fields archived at the 0.25° resolution, available for 2003 to 2010.

The University of California at Irvine's Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks-Cloud Classification System (PERSIANN-CCS) [29] uses geosynchronous satellite infrared cloud imagery, trained against satellite microwave data and ground-based gauges and radar, to achieve high spatial and temporal resolutions for precipitation estimation. The archived PERSIANN product was available for the Indian subcontinent at 0.04°, three-hour resolution for 2006–2010 (http://chrs.web.uci.edu/PERSIANN-CCS/data.html), which we

aggregated in time to monthly ones. The spatial resolution is thus the highest of any of the products evaluated here. A near-global near real time PERSIANN product with the same 0.04° spatial resolution is available at http://chrs.web.uci.edu/persiann/.

The APHRODITE project has produced a daily precipitation dataset over Asia based solely on rain gauge measurements [30]. The measurements used include station data obtained from national meteorological agencies, including Nepal's Department of Hydrology and Meteorology (DHM). Station data were interpolated using an algorithm that takes topography into account and uses climatology to estimate missing values. We used the APHRODITE V1101 monsoon Asia product at the best available resolution of 0.25°, available for 1951–2007. We aggregated the daily values to monthly ones. While APHRODITE is not currently available in near real time, we considered it important to include it in our evaluation, because it offers long-term spatial fields of precipitation distribution that are based on station data and because considering its skill in reproducing station observations may give an indication of how well satellite products can be expected to perform for precipitation estimation for water resources applications compared with interpolation from available station data.

2.2. Station Precipitation Data

Almost complete daily precipitation series for 11 major stations, covering 1988–2007, were obtained from DHM, comprising a total of 2,666 observations (complete station-months). As well, incomplete precipitation series for 2008–2012 were obtained from the DHM website for 265 stations (Figure 1), totaling 4,615 observations. Additional observations (701 station-months) were obtained for 1993–2000 from 12 stations in the Jhikhu Khola watershed, gauged as part of the People and Resource Dynamics Project (PARDYP) [31]. Observations from four high-elevation sites over the period 2002–2008 (72 station-months) were obtained from the Stations at High Altitude for Research on the Environment (SHARE) project [32].

Since the station observations from DHM (through 2007) were among those used to construct the APHRODITE product [30], comparison with the DHM observations should show better performance for APHRODITE, compared to satellite products that did not use many of these observations for calibration. By contrast, the PARDYP and SHARE measurements were not used to construct APHRODITE; so, these represent more independent data [22]. However, preliminary sensitivity analysis did not show systematic differences between DHM and the other station observation networks in terms of their fit to APHRODITE *versus* the satellite-based gridded products; so, we consider here all the station precipitation data together without distinction.

2.3. Metrics for Precipitation Product Quality

We compared the average nationwide precipitation by year and maps of the distribution of mean precipitation between the satellite precipitation products and the gridded station-based APHRODITE. Because the station observations are sparse and, in most cases, are not complete over multi-year periods, we do not attempt here to reconstruct the average nationwide precipitation by year or to make national maps based on the station observations. Instead, we average the station precipitation as a function of elevation (aggregating into 100-m elevation bands, then using a cubic spline to smooth) and compare this

with the mean precipitation from each product as a function of elevation within Nepal. We also compare the mean seasonal cycle of precipitation between the precipitation products and the station observations. Another measure of product quality is the mean bias in each precipitation product compared to station observations, defined by the difference between the mean station-observed precipitation and that given by the product averaged over the same grid cells and months.

Our primary metric for the degree to which each gridded precipitation product reproduces station observations is the Nash-Sutcliffe efficiency, NSE, which is based on the magnitude of the residual variance relative to the variance of the measured data [33]. Here, high NSE indicates a small mean square difference between station observations and the precipitation product:

$$\mathrm{NSE} = 1 - \frac{\langle (P_1 - P_2)^2 \rangle}{\langle (P_1 - \langle P_1 \rangle)^2 \rangle} \tag{1}$$

where P_1 refers to station observations and P_2 to a precipitation product, and $\langle \cdot \rangle$ denotes an average across observation stations and months. $\mathrm{NSE} = 1$ would mean that the product agrees exactly with the station observations, while $\mathrm{NSE} = 0$ indicates that the mean square error of the product is as large as just using the mean observed value as the predictor. Unlike the correlation coefficient, r, between a precipitation product and station observations, NSE penalizes systematic bias in the product's precipitation estimates, as well as irregular discrepancies.

Note that the station observations measure precipitation over the very small surface area of the rain gauge, whereas the precipitation products being compared with the observations nominally represent precipitation averaged over a much larger grid cell that includes the rain gauge location. Thus, we do not expect perfect correspondence ($\mathrm{NSE} = 1$) between the station observations and any of the precipitation products. Nevertheless, we expect that the degree to which the different products approach the station-measured precipitation, as measured by NSE, offers a reasonable overall metric of their relative quality.

In order to evaluate how well the precipitation products represent different aspects of precipitation means and variability, we consider the following forms of the NSE metric:

- NSE_{all} calculated using all the monthly measurements;
- NSE_{mean} using the mean annual values for each station (this quantifies how well the product represents spatial variability in mean precipitation, irrespective of its timing within each station record);
- $\mathrm{NSE}_{seasonal}$ using stations' mean seasonal cycles (for each station, these were expressed as 12 elements that give the fraction of the yearly mean precipitation seen in each month; this quantifies how well each product represents seasonal precipitation patterns);
- $\mathrm{NSE}_{variability}$ using monthly values with the station climatology subtracted (this quantifies how well each product represents interannual variability in precipitation).

Because each precipitation product considered is available for a different time period, the NSE values for each precipitation product are calculated using station observations overlapping with that product, which is a somewhat different set of observations for each product. To check whether this materially affects our evaluations of product quality based on NSE, we also computed *pairwise* NSE_{all} values: for example, the value of NSE_{all} for precipitation product A calculated for only those observations when

product B is also available is based on exactly the same observation set as that computed for product B using only those observations when A is also available, and hence, these two pairwise NSE_{all} values can be directly compared to evaluate the relative quality of products A and B.

3. Results

3.1. Mean and Interannual Variability

Mean precipitation observed at the stations was 1,578 mm/year. The TRMM product's mean at the observation locations and months was 2% lower than the observations, while APHRODITE was 9% lower (Table 1). The other products averaged some 30–50% less precipitation than the station observations showed, implying that they are substantially miscalibrated over Nepal (Table 1).

Table 1. Evaluation of precipitation products against station observations. TRMM, Tropical Rainfall Measuring Mission; GSMaP, Global Satellite Mapping of Precipitation; CMORPH, Climate Prediction Center Morphing; PERSIANN, Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks; APHRODITE, Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources.

	Bias in Mean	$\mathbf{NSE}_{all}$	$\mathbf{NSE}_{mean}$	$\mathbf{NSE}_{seasonal}$	$\mathbf{NSE}_{variability}$
TRMM	−2%	0.488	0.753	0.817	0.095
GSMaP	−42%	0.312	0.452	0.758	0.042
CMORPH	−29%	0.365	0.542	0.729	0.065
PERSIANN	−54%	0.231	0.028	0.571	−0.016
APHRODITE	−9%	0.385	0.683	0.954	−0.047

Figure 2 shows that interannual variability in the TRMM precipitation product is largely coherent with APHRODITE during their period of overlap. The absolute amounts of precipitation over the whole country differ, with APHRODITE being 20% lower than TRMM, and are lower than the average at the observation stations, because the stations are concentrated in the wet low-to-middle elevations (see below). The interannual coefficient of variation for Nepal-mean precipitation is 11% for both products (Table 2). APHRODITE Nepal-wide precipitation showed a marginally significant linear increasing trend ($r = +0.28, p = 0.034$ for the correlation coefficient of precipitation with time and the probability of a correlation coefficient of this magnitude under the null hypothesis of no time trend, respectively), similar to the finding of Duncan *et al.* [34], who found mostly increasing trends in precipitation for APHRODITE over Nepal, particularly for the pre-monsoon season (March–May). By contrast, TRMM showed a marginally significant decreasing trend over its shorter period of observation ($r = -0.55, p = 0.035$). Over their shorter available periods, PERSIANN and GSMaP show substantially less precipitation and less interannual variability than TRMM or APHRODITE, while CMORPH showed also generally lower precipitation, but high interannual variability, thanks to a large precipitation amount estimated during its first year, 2003 (Figure 2; Table 2).

Figure 2. Mean annual precipitation over Nepal from TRMM (1998–2011), GSMaP (2001–2009), CMORPH (2003–2010), PERSIANN (2006–2010) and APHRODITE (1951–2007). Least-squares linear trend fits for the TRMM and APHRODITE products, which have the longest available time series, are also shown (thin dashed lines).

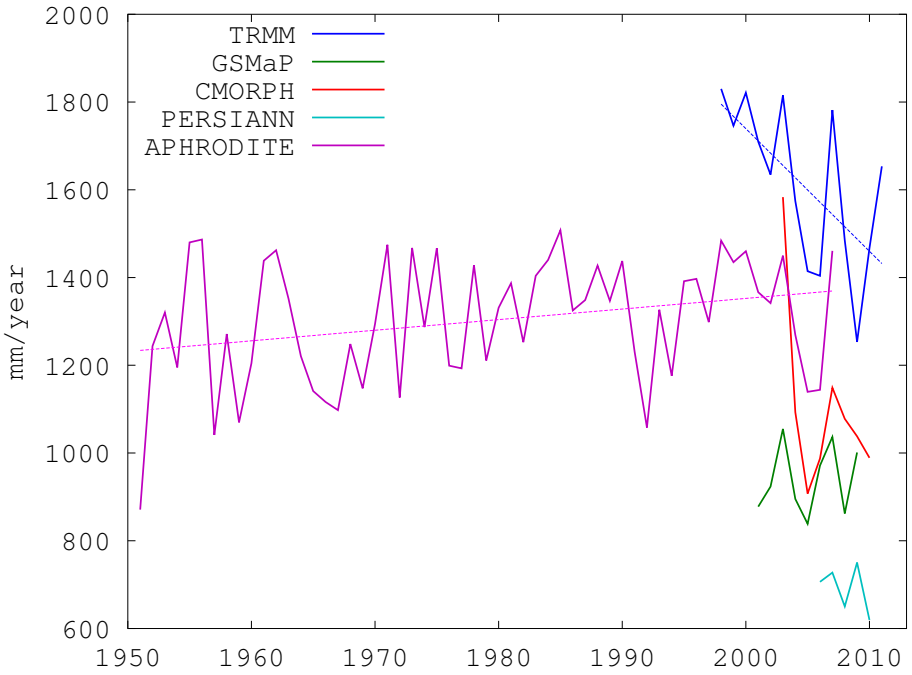


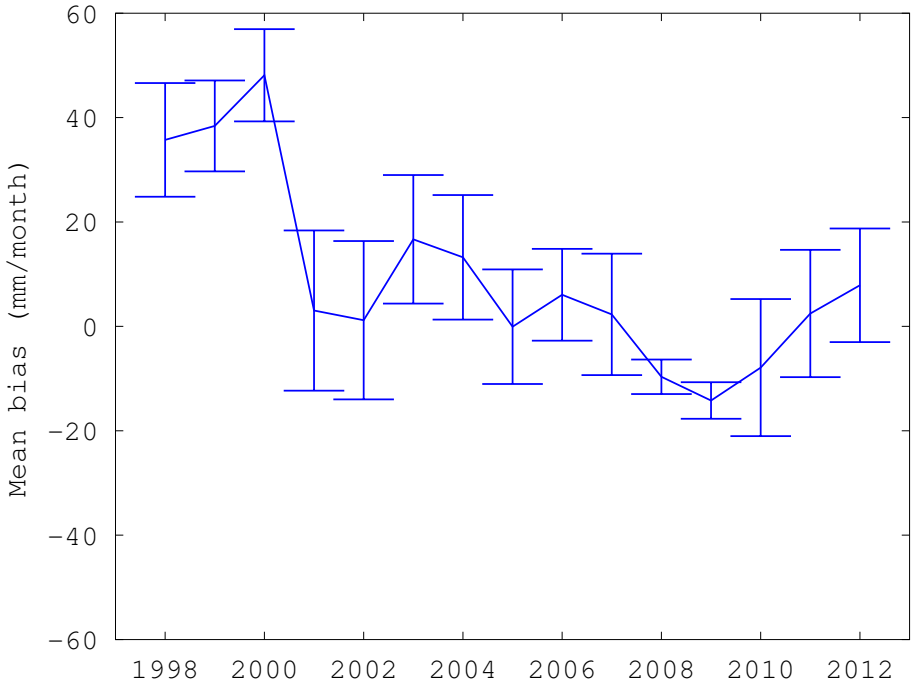
Table 2. Mean precipitation over Nepal (mm/year) and its coefficient of variation (CV, interannual standard deviation divided by the mean) for different precipitation products.

	Mean	**CV**
TRMM	1,614	0.114
GSMaP	940	0.084
CMORPH	1,103	0.188
PERSIANN	691	0.079
APHRODITE	1,302	0.110

We also looked more closely at how the TRMM product, which was available and archived for a longer period (1998–2012) than any of the other satellite precipitation products evaluated, compares with station observations over time. Inspection of the differences between the product and station observations showed that the average bias in monthly precipitation (TRMM minus station) was -2.7 mm, not significantly different from zero (the standard error (SE) of the mean was 2.0 mm). Averaged over each calendar year, however, TRMM shows a substantial positive bias over the first years of the product (1998–2000, mean $\pm$ SE is $+40.8 \pm 5.5$ mm/month) and a smaller generally negative bias over the other years (2001–2012, -8.6 ± 2.1 mm/month with no significant linear trend over the period) (Figure 3). Thus, it is possible that the decreasing trend in precipitation seen by TRMM may be due to product inhomogeneity, rather than to a real decrease in precipitation over Nepal in recent years. Still,

the on average small bias in TRMM, especially for the more recent years, is better than any of the other satellite precipitation products considered (Table 1).

Figure 3. Mean bias in the TRMM precipitation product, compared to Nepal station observations, by year. Error bars show the standard error of the bias over each year.



3.2. Spatial and Orographic Variability

The nature of differences between the gridded precipitation fields is shown in Figure 4. While the large-scale features are quite similar between TRMM and APHRODITE, the APHRODITE mean precipitation field is less smooth than TRMM's, with much more variation between adjacent pixels. One possible explanation for the difference would be that APHRODITE is better at resolving orographic variation in precipitation near its grid scale. This may be due to the 1° resolution of some of the precipitation fields used to construct the TRMM product [25], which does not adequately resolve topographic variability in this region. However, as we shall see below, APHRODITE does not appear to be better than TRMM in capturing observed inter-station variability, at least as judged by NSE. The PERSIANN product, though it nominally has the highest spatial resolution of the products evaluated here, misses broad regions of enhanced precipitation seen in both the TRMM and APHRODITE products and, also, shows some indications of striping, presumably due to processing artifacts. The GSMaP and CMORPH products similarly underestimate precipitation in many low and middle elevation areas compared to TRMM and APHRODITE.

Figure 5 shows the altitude distribution in Nepal, compared to the distribution of available station measurements. Stations are fairly well distributed in altitudes up to about 2,400 m; however, only 5% of the precipitation data are from stations above 2,400 m, compared with 37% of Nepal's area.

Figure 4. Mean precipitation (mm/year) over Nepal from (**a**) TRMM; (**b**) GSMaP; (**c**) CMORPH; (**d**) PERSIANN and (**e**) APHRODITE products. The color scale is the same for all panels. North is up; longitude (°E) and latitude (°N) are shown for reference.

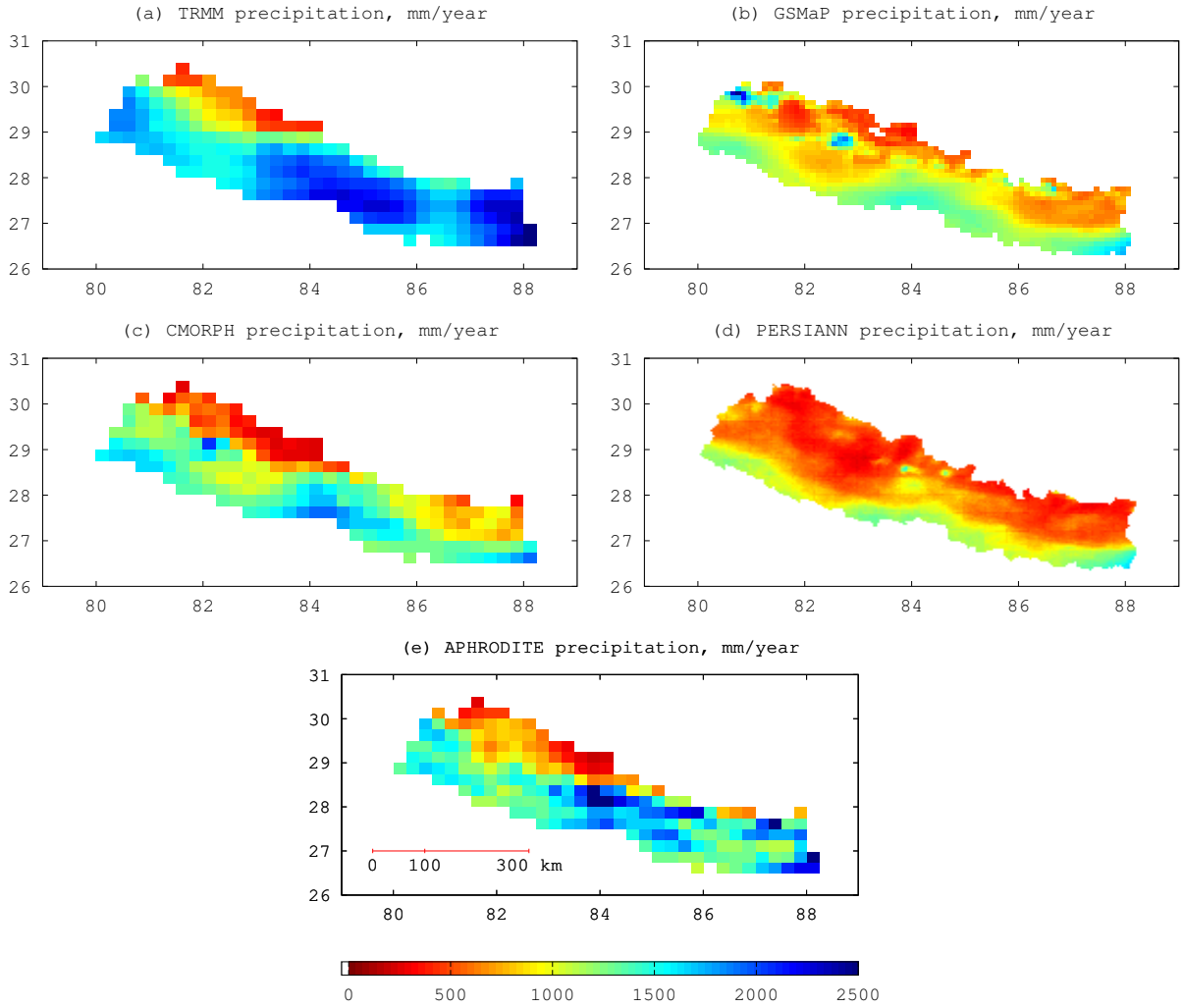


Figure 6 shows the mean precipitation in Nepal by altitude as estimated from the station measurements compared with the gridded products. The station measurements hint at a secondary peak in precipitation at the lowest elevations (< 500 m) and show a pronounced primary peak between about 1,500–2,000 m, with sharply drier conditions above 3,000 m. The APHRODITE and TRMM products both show substantially less dependence of precipitation on altitude, with TRMM showing consistently more precipitation than APHRODITE at any given altitude. APHRODITE is closer in precipitation amount to station observations below about 1,300 m, while TRMM is closer for 1,300–2,500 m. Both products show too much precipitation above 3,000 m compared to the mean inferred from the few available station data. GSMaP, CMORPH and PERSIANN all exhibit a peak in precipitation at the lowest altitude band and, especially over the middle elevations around 1,500–2,500 m, have precipitation that is much too low compared to station observations.

Figure 5. Distribution of Nepal's area and of station precipitation measurements by altitude.

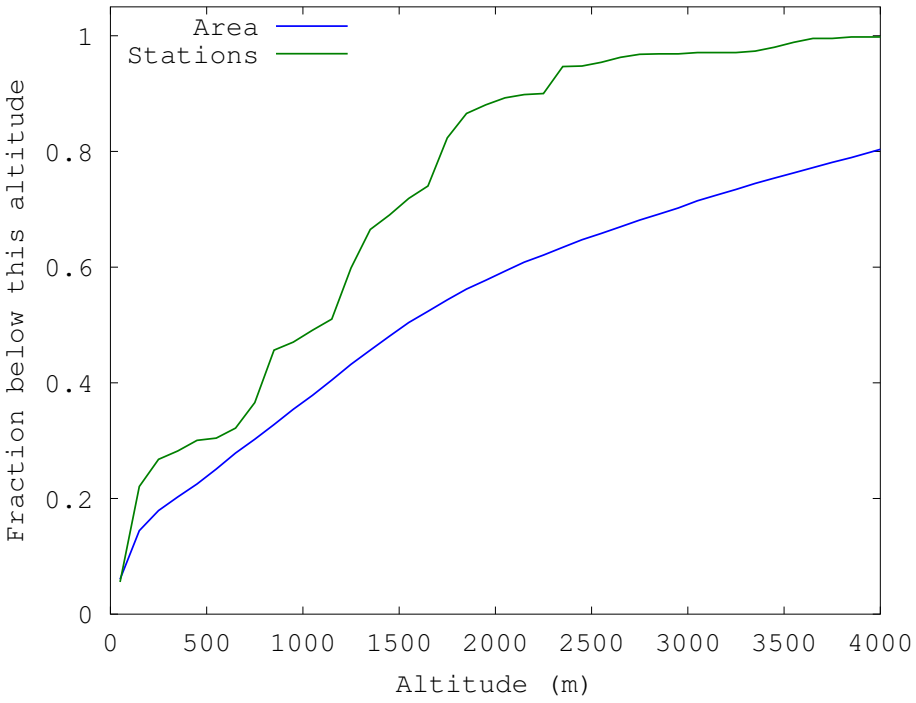


Figure 6. Mean precipitation in Nepal by altitude, estimated from station measurements and from the gridded products.

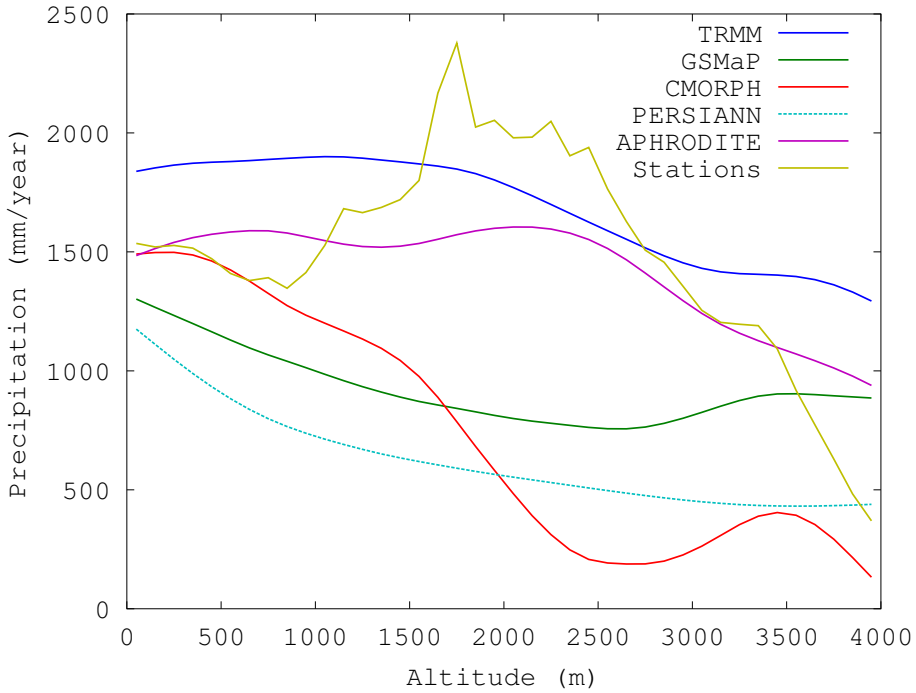
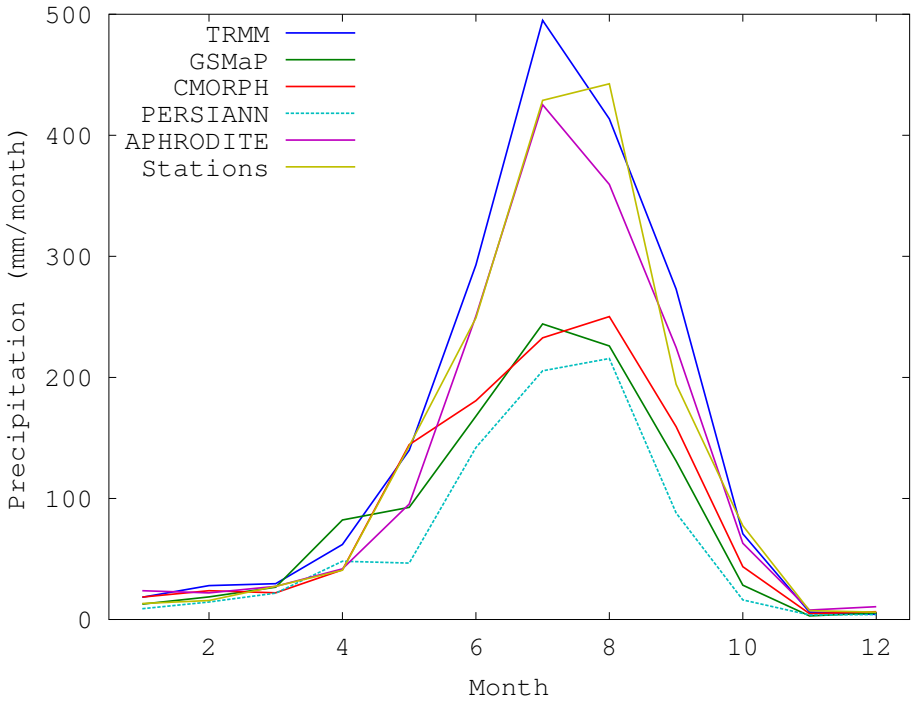


Figure 7 shows the mean seasonal cycle of precipitation over the lower altitudes where the stations are concentrated (below 2,400 m). All the products show a seasonality broadly consistent with the station observations. Interestingly, the observations, CMORPH and PERSIANN show peak precipitation in August, while TRMM, GSMaP and APHRODITE show it in July. Further investigation is required

to understand the origin of this difference; since the different products span different time periods, interannual variability in the monsoon could be a factor.

Figure 7. Climatology of mean precipitation in Nepal (averaged over elevations below 2,400 m), estimated from station measurements and from the gridded products.



3.3. Measures of Correspondence with Station Observations

The PERSIANN product had the lowest NSE_{all}, indicating that it had large mean square differences from station observations, despite it nominally featuring the highest spatial resolution of any of the products evaluated. TRMM had the best NSE_{all}, at 0.49, APHRODITE had an intermediate NSE_{all} of 0.38 and GSMaP and CMORPH had NSE_{all} lower than TRMM and APHRODITE, but higher than PERSIANN (Table 1).

Looking at NSE variants intended to measure the ability of products to reproduce various aspects of the observed field, TRMM was somewhat better than APHRODITE in representing the spatial distribution of mean precipitation over the available stations (NSE_{mean} in Table 1); this is despite the smoother appearance of the mean precipitation field from TRMM compared to APHRODITE (Figure 4). The seasonality of precipitation was relatively well captured by all the products, with APHRODITE giving the best performance ($\mathrm{NSE}_{seasonal}$ in Table 1). The interannual variability of precipitation was TRMM's weakest aspect, but its $\mathrm{NSE}_{variability}$ was still better than either APHRODITE or any of the other satellite precipitation products (Table 1).

Considering NSE_{all} for pairwise station observation sets to enable more rigorous comparison of any two precipitation products (Table 3), we see that there is some variation in NSE_{all} for a given product depending on which subset of station observations is used. However, the TRMM product has the highest NSE_{all} across subsets (first row with numbers in Table 3), while APHRODITE ranks second

(last row of Table 3), and the other products underperform both TRMM and APHRODITE in terms of correspondence with station observations.

Table 3. NSE_{all} computed for subsets of station observations where pairs of precipitation products are both available. For example, NSE_{all} for station observations evaluated for the TRMM product when the APHRODITE product was also available was 0.425, while NSE_{all} for the APHRODITE product evaluated with the same station observations was 0.374.

	TRMM	**GSMaP**	**CMORPH**	**PERSIANN**	**APHRODITE**
TRMM	0.488	0.492	0.503	0.504	0.425
GSMaP	0.312	0.312	0.330	0.343	0.119
CMORPH	0.365	0.363	0.365	0.381	0.150
PERSIANN	0.231	0.230	0.231	0.231	0.056
APHRODITE	0.374	0.347	0.371	0.376	0.385

4. Discussion

We presented an evaluation of several precipitation products over Nepal. We found that, compared to available station measurements, the TRMM satellite monthly precipitation product was, on average, almost unbiased and had some skill (positive NSE). The skill of the TRMM product in reproducing station precipitation, as measured by NSE_{all}, is competitive with that of the gridded station product APHRODITE, where TRMM has the advantage of being available for recent years (with a version even available in near real time). While local rain gauge networks combined with ground-based radar should offer the best accuracy for assessing precipitation amounts, we conclude that well-calibrated satellite products, such as TRMM, can be very useful, where, as is usually the case in Nepal, adequate ground data are not collected or available.

It may be possible to use systematic features of the station-TRMM mismatch identified here, as in the altitude dependence of precipitation, to improve the TRMM product for particular spatial scales and applications. There may also be other geographic differences in the skill of precipitation products (e.g., eastern *versus* western Nepal) that could be important for water resources applications. Furthermore, the ability of TRMM to capture interannual variability may be improved by better corrections for satellite orbit and sensor drift [35,36]; the time dependence that we discovered in the TRMM bias over Nepal (Figure 3) may perhaps be mitigated by such improvements in the TRMM precipitation estimation algorithm, which will hopefully be reflected in future versions of the TRMM precipitation product.

It is interesting that APHRODITE had larger mean bias in precipitation amount than TRMM (and generally lower NSE), even though the products were compared to some of the same station data used to generate APHRODITE in the first place. The bias of APHRODITE is apparently not specific to the particular set of stations we used, because a similar bias toward low precipitation amounts was found in the evaluation of APHRODITE with a different compilation of station data for Nepal and nearby areas [22]. It therefore seems likely that this regional bias is an artifact of the processing methods used in APHRODITE, and it should be possible to remove it in a future version of APHRODITE. On the other hand, we found little mean bias for TRMM (particularly after 2000), which is different from previous

studies [20,22]. Perhaps, this difference reflects the improved correction of bias at large spatial scales in the most recent version of TRMM, which we used.

The other three satellite products evaluated—GSMaP, CMORPH and PERSIANN—greatly underestimated the mean precipitation, and their elevation dependence of precipitation matched station observations poorly, despite the substantially better nominal spatial resolution of GSMaP and PERSIANN compared to TRMM. This suggests that there is still much work to be done in appropriately leveraging the high spatial resolution and temporal coverage of geostationary satellites to improve precipitation estimates at fine scales and short latency, particularly for mountainous areas, such as Nepal, where limited ground-based data is available for calibration and validation in near real time. Cokriging or related approaches could be tested for optimally merging station observations with remote sensing products having different resolutions to form an accurate high-resolution precipitation map [13,37].

Another future direction is to evaluate the near real time versions of the satellite precipitation products at daily and subdaily resolutions, which would be particularly useful for applications such as flood and landslide prediction and warning [38]. In general, it is expected that correlations between satellite and gauge precipitation measurements, and even correlations between gauges, worsen at these fine temporal resolutions [39,40], making this a more challenging task.

5. Conclusions

We found that the TRMM 3B-43 precipitation product exhibits reasonable skill in giving precipitation over Nepal. The TRMM product shows promise for use in water resource applications. The other satellite products evaluated showed substantially worse performance in reproducing station precipitation amounts, despite, in some cases, nominally higher spatial resolution, suggesting that there is still much scope for improvement in the algorithms used.

Acknowledgments

We are grateful to the Nepal Department of Hydrology and Meteorology and the PRADYP and SHARE projects for collecting station precipitation data and for the TRMM, GSMaP, CMORPH, PERSIANN and APHRODITE projects for creating and making available their precipitation products. This work is part of the project “Adaptation for climate change by livestock smallholders in Gandaki river basin”, supported by the USAID Feed the Future Innovation Lab for Collaborative Research for Adapting Livestock Systems to Climate Change at Colorado State University under subaward 9650-32. All statements made are the views of the authors and not the opinions of the funders or the US government.

Conflicts of Interest

The authors declare no conflict of interest.

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