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Evaluation of the Hydro-Estimator satellite rainfall algorithm and its utility in hydrological prediction in a mountainous region

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Abstract The performance of the NOAA/NESDIS operational rainfall estimation algorithm, the Hydro-Estimator (HE), is investigated with and without its orographic correction method, to assess its depiction of the timing, intensity and duration of convective rainfall, in general, and of the topography–rainfall relationship, in particular. With a few exceptions, validation of satellite rainfall estimates in complex terrain has been lacking to date, due to the paucity of pre-existing dense observation networks in mountainous areas. An event rainfall observation network in northwestern Mexico, established as part of the North American Monsoon Experiment (NAME), provides gauge-based precipitation measurements with sufficient temporal and spatial sampling characteristics to examine the climatological structure of diurnal convective activity over northwest Mexico. While the HE with orographic correction captures the spatial distribution and timing of diurnal convective events to some extent, elevation-dependent biases exist, which are characterized by underestimation of the occurrence of light precipitation at high elevations and overestimation of the occurrence of precipitation at low elevations. The potential of the HE to provide high spatial- and temporal-resolution data is tested in a hydrological application over the NAM region. The findings suggest that continued improvement of the HE orographic correction scheme is warranted, in order to advance quantitative precipitation estimation in complex terrain regions, and for use in hydrological applications.

Key words rainfall algorithm; topography; satellite; observation; Hydro-Estimator (HE)

INTRODUCTION

In support of the National Weather Service's (NWS) flash flood warning and heavy precipitation forecast efforts, the National Oceanic and Atmospheric Administration/National Environmental Satellite Data and Information Service (NOAA/NESDIS) has been providing satellite-based rainfall algorithms operationally since 1978. Operational satellite rainfall estimates originated with the Interactive Flash Flood Analyzer (IFFA; Scofield & Oliver, 1977)—a technique based on measurements from the GOES longwave IR window (10.7 μm). To improve the timeliness of the IFFA and to extend the areal coverage of their satellite rainfall products, NESDIS developed an automatic precipitation estimation algorithm called the Hydro-Estimator (HE; Scofield & Kuligowski, 2003), which uses an approach that discriminates rainfall areas from non-rainfall areas without radar data. Generally, comprehensive validation of satellite-estimated precipitation characteristics, such as diurnal variations, intensity, and diurnal evaluation and its relation to the complex local topography, have been lacking due to the unavailability of pre-existing dense observation networks in mountainous regions. The NAME (North American Monsoon Experiment) Event Rain gauge Network (NERN), was established in the Sierra Madre Occidental Mountains in northwest Mexico to sample temporal and spatial patterns of rainfall across regional topographic gradients. The ability of NERN to capture the diurnally- and regionally-varying characteristics of North American Monsoon (NAM) precipitation was demonstrated by Gochis *et al*. (2003, 2004, 2007). The purpose of the present work is to evaluate the performance of the existing operational HE algorithm, and a recent orographic correction scheme, in depicting surface precipitation characteristics in the orographically complex NAME region. We also examine the utility of the HE in estimating runoff using a currently operational land surface parameterization. The 4-km rainfall estimates of the HE were validated using 48 and 79 tipping-bucket NERN raingauges in the warm-season period of 1 July–30 September, in 2002 and 2003, respectively.

DESCRIPTION OF NERN DATA, ALGORITHM AND HYDROLOGICAL MODEL

The study area located in the semi-arid climate region of northwestern Mexico and the network configuration consisting of six west–east transects through the Sierra Madre Occidental mountains are shown in Fig. 1. The elevation breakdown partitioned the terrain elevation into six categories (0–500, 500–1000, 1000–1500, 1500–2000, 2000–2500 and 2500–3000 m a.s.l.) in order to show how rainfall characteristics vary as a function of elevation. The overall range in elevation sampled by the network is between 5 and 2979 m, with a mean value of 1226 m. This configuration provides a well-matched distribution of raingauges with respect to elevation, and avoids a low-elevation bias with respect to the regional topography that is common in complex terrain environments.

The HE, which is the operational algorithm at NESDIS, computes real-time estimates of instantaneous rain rate from infrared window (10.7 µm) brightness temperatures, accounting for both the temperature at the pixel of interest and its value relative to its surroundings to discriminate raining from non-raining clouds. The brightness temperature–rain rate relationship, which is a variant of the original regression-based curves, is also adjusted for the effects of such relevant processes as subcloud evaporation and orographic uplift based on numerical weather model data. The HE also includes the convective equilibrium correction (Scofield, 2001), the orography and parallax corrections (Vicente *et al*., 2002), and correction for satellite zenith angle (adapted from Joyce *et al*., 2001).

The community Noah land surface model (LSM; Ek *et al*., 2003) forced by North American Regional Reanalysis (NARR; Mesinger *et al*., 2006) meteorological forcing (e.g. temperature, humidity, incoming radiation, wind speed and pressure) and HE-estimated precipitation is used to understand the impact of the different HE rainfall products on model simulated hydrological fluxes from catchments in western Mexico. The model is driven in a gridded 1-D (vertical) mode (4-km grid matching the HE grid) without horizontal routing and all simulated flux values are averaged over five medium-sized (e.g. 1000–5000 km^2) catchments located in western Mexico (Fig. 1). Meteorological forcing fields from the NARR are bi-linearly interpolated to the 4-km HE grid.

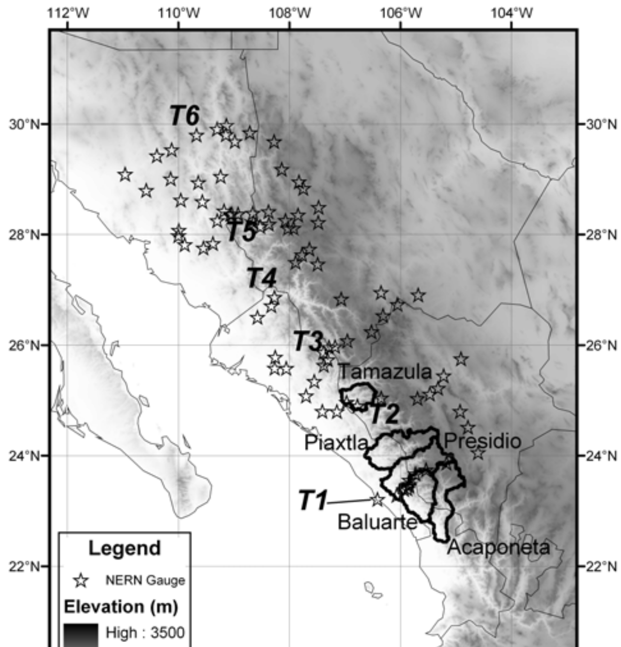

Fig. 1 Map of the study area showing where the raingauges are installed along six west–east transects (T1–T6). Five basins used for hydrological model simulations are also shown.

RESULTS

Satellite rainfall data derived from the HE with and without orographic correction were used in the comparison. Hereafter, the operational HE with orographic correction and the operational HE without orographic correction are referred to as HE-O and HE-N, respectively.

Comparison of daily precipitation

Figure 2 shows mean event separations (e.g. inter-storm period), storm durations and conditional rain rates (fraction of hours with measurable precipitation) for each elevation band for summer 2002 (Fig. 2(a)) and summer 2003 (Fig. 2(b)). The estimates generally depict less frequent rainfall events (i.e. a longer separation period) and shorter rainfall event duration than gauge observations at all elevation bands in both years. The gauge-observed rain events are more frequent (every two days or less) and longer in duration at high terrain elevations than those at low elevations. In contrast, the profile from satellite estimates generally shows a very weak elevational dependence in rain event separation and duration periods. It is notable that summer 2002 was wetter in this particular region than summer 2003, especially at higher terrain elevations (>1000 m), and the observed mean duration in 2002 (4.0 d) is greater than that in 2003 (3.3 d). Correspondingly, the HE also depicts a wetter summer in 2002, as the network mean duration (2.3 d for both HE-O and HE-N) in 2002 is greater than that (2.0 d for both HE-O and HE-N) in 2003. Figure 2 also shows that conditional rain intensity decreases as gauge elevation increases for both the gauges and the HE estimates. This behaviour implies a strong high bias in low-elevation conditional rain rates in both HE products during 2002. However, the magnitude of this bias and its elevational trend vary significantly between 2002 and 2003. The smaller network mean error in 2003 implies that the HE algorithm performs better for moderately shorter-duration and less frequent rain events (see Table 1 for mean errors in both years). In general, the HE-O across the bands is closer to observed conditional rain than HE-N in both years. For example, in summer 2003, network mean conditional rain is 7.9, 7.8 and 8.4 mm/d for observation, HE-O and HE-N, respectively.

The wet-day analysis for the HE algorithms was expanded to examine the elevational dependence of precipitation occurrence for light, moderate and heavy rain events. Figure 3(a)–(d) shows probability of rain, light rain, moderate rain and heavy rain, respectively, as a function of elevation for observation, HE-O and HE-N in 2003. Figure 3(a)–(b) shows a clear tendency for the

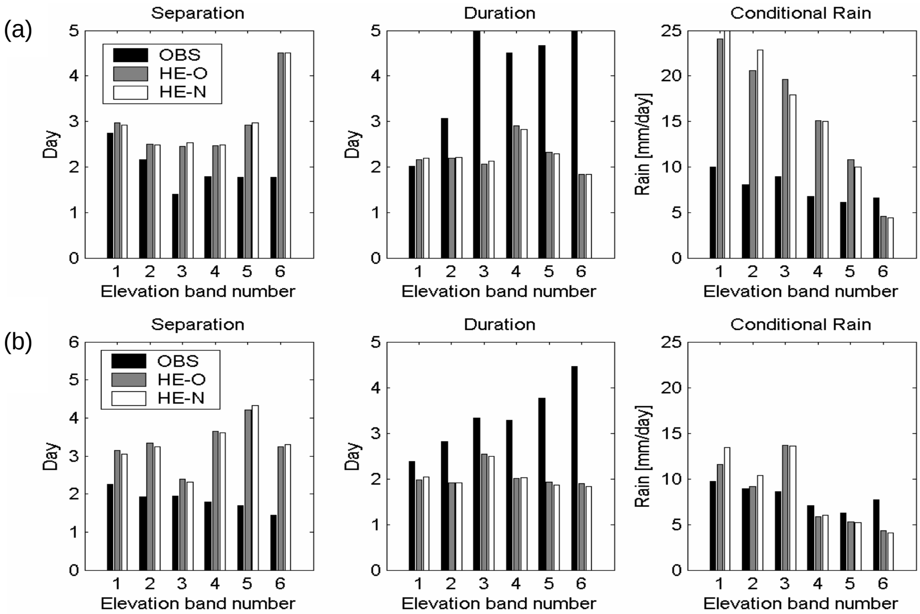

Fig. 2 Mean separation, duration and conditional rain rate of rain events at each elevation band for: (a) summer 2002; and (b) summer 2003.

Table 1 Mean root mean square error (RMSE) and bias of daily rain rates at each elevation band (B1–B6) and for the whole network, for the HE-O and HE-N, in 2002 and 2003.

Elevation bands	Network mean		B1		B2		B3		B4		B5		B6	
	HE-O	HE-N	HE-O	HE-N	HE-O	HE-N	HE-O	HE-N	HE-O	HE-N	HE-O	HE-N	HE-O	HE-N
2002:														
RMSE (mm/d)	27.80	28.96	34.27	36.54	30.27	33.90	29.81	27.39	22.26	21.97	21.68	18.90	9.43	9.30
Bias (mm/d)	2.58	2.63	8.55	9.17	8.94	10.18	8.79	7.58	6.04	6.01	3.84	3.17	–1.02	–1.13
2003:														
RMSE (mm/d)	15.07	15.71	16.54	18.16	17.71	19.07	19.54	19.10	13.88	13.96	10.97	10.42	12.49	12.21
Bias (mm/d)		1.08	2.10	3.25	1.28	2.04	4.27	4.52	–0.15	0.00	–0.35	–0.46	–2.03	–2.24

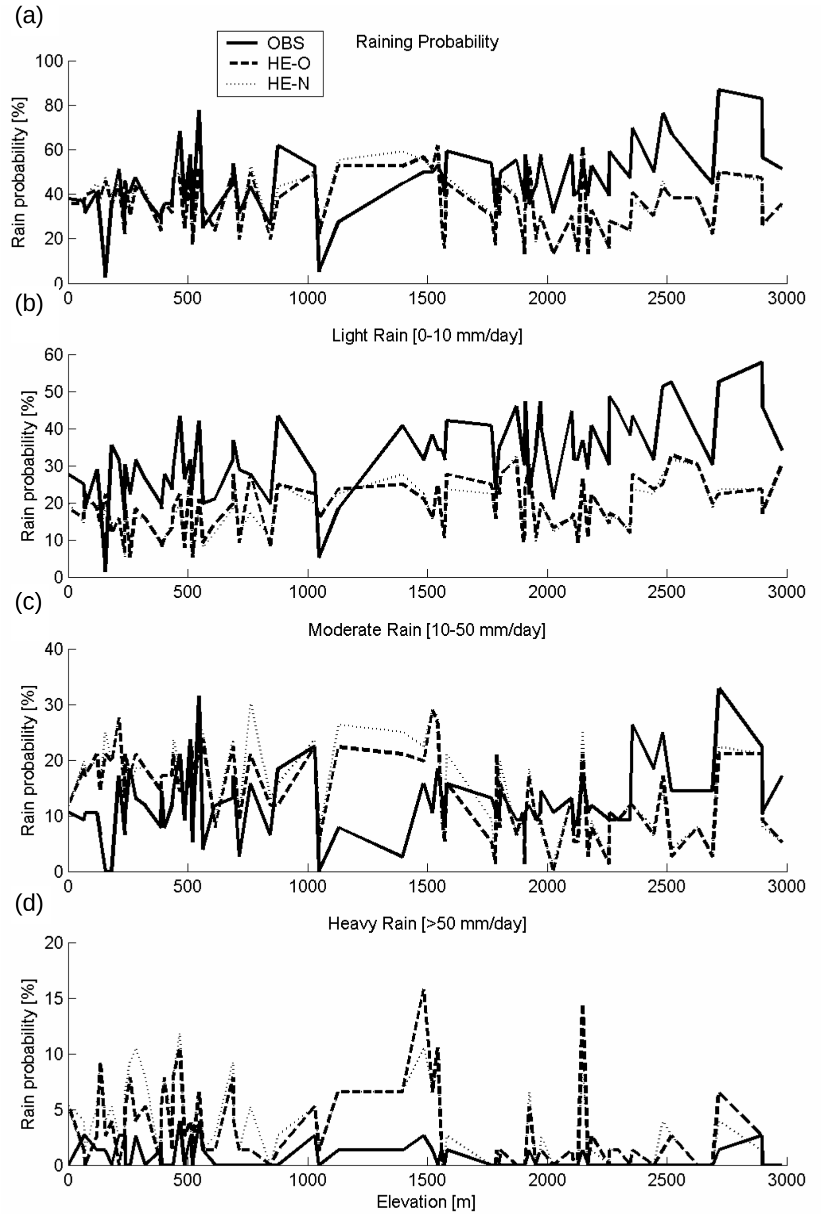

Fig. 3 Comparison of probability of: (a) rainy days, (b) light rain, (c) moderate rain and (d) heavy rain over summer 2003 as a function of elevation for observation, HE-O and HE-N.

HE to underestimate the occurrence of precipitation at lower thresholds, which is most noticeable at higher elevations. However, this systematic bias largely disappears for moderate rain events in Fig. 3(c), but the HE overestimates the occurrence of heavy precipitation events along the elevation profile in Fig. 3(d). While there is no difference in general between the HE with and without orographic correction for light rain threshold events, at some elevation points, the orographic correction (HE-O) brought the rainfall closer to the observed values for moderate and heavy precipitation events.

Diurnal cycles

Figure 4(a)–(c) shows the gauge-observed, HE-O and HE-N mean diurnal cycle of hourly precipitation frequency (fraction of hours with measurable precipitation), respectively for each of the six elevation bands separately and for the network as a whole in summer 2002; while Fig. 4(d)–(f) shows the corresponding information for summer 2003. The network mean precipitation frequency from satellite estimates generally follows the behaviour of network mean of the observed rain frequency throughout the diurnal cycle. The amplitude of the diurnal cycle from the HE during daytime matches well with observations, though the HE underestimates precipitation frequency during early morning. The satellite estimates at each elevation band in Fig. 4(b), (c), (e)

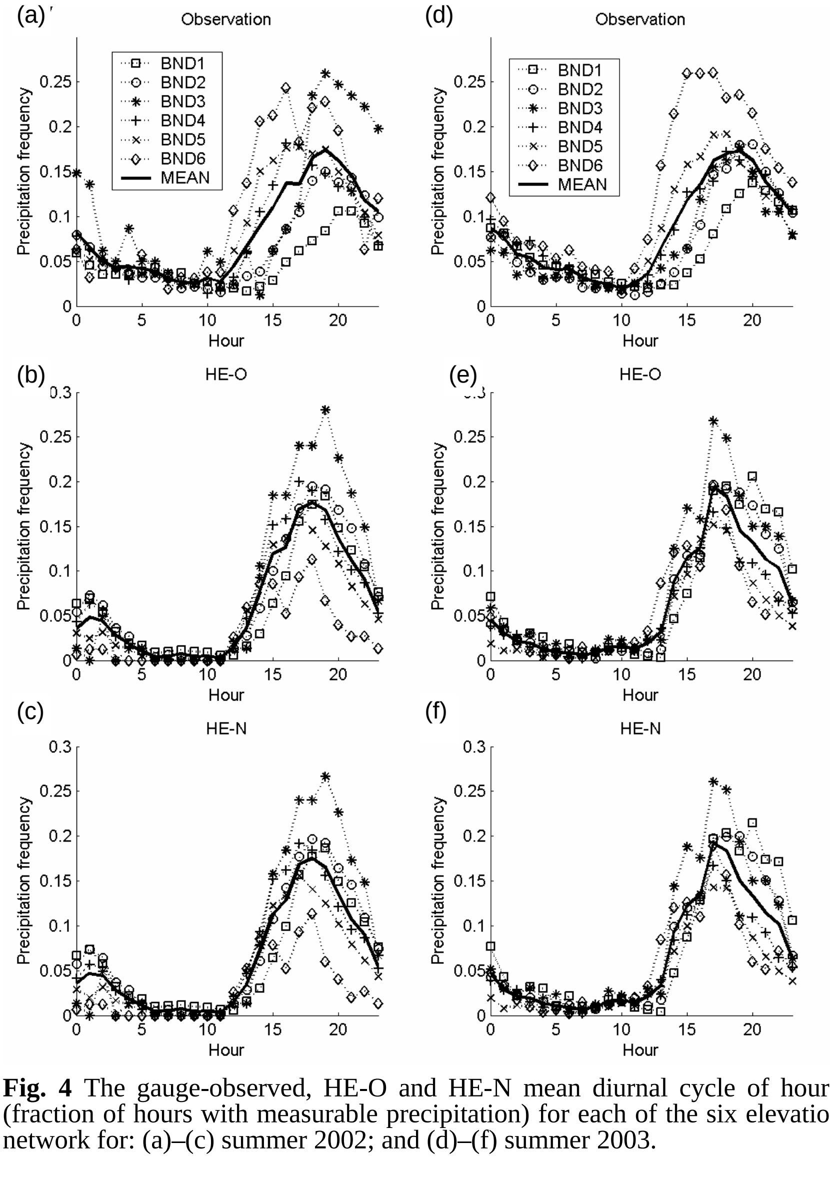

Fig. 4 The gauge-observed, HE-O and HE-N mean diurnal cycle of hourly precipitation frequency (fraction of hours with measurable precipitation) for each of the six elevation bands and for the whole network for: (a)–(c) summer 2002; and (d)–(f) summer 2003.

and (f) do not appear to capture some of the characteristic features of terrain-induced daily precipitation frequency. For example, unlike the observed rainfall frequencies, whose peak values shift toward later time periods with decreasing elevation, the satellite-estimated frequencies do not exhibit significant differences in peak frequency with elevation. However, the estimates in 2003 do tend to show slightly better performance in this regard.

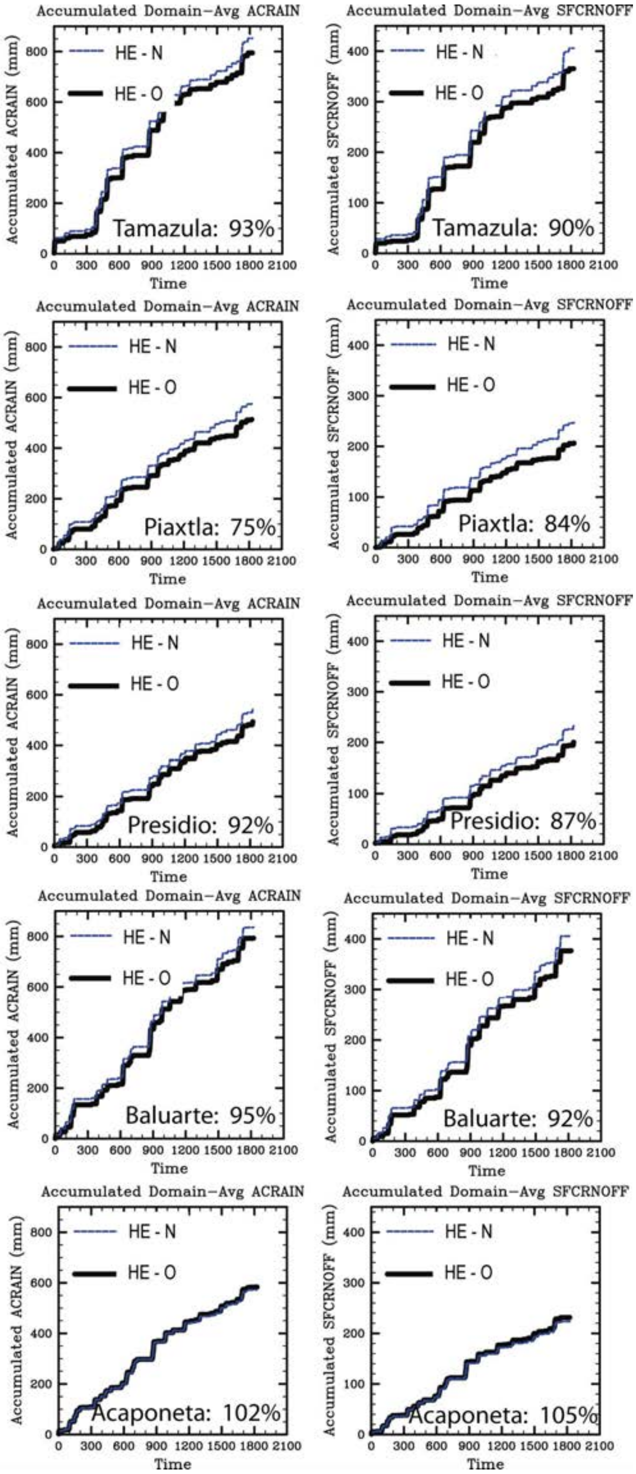

Fig. 5 Basin-averaged accumulated rainfall (left panel) and Noah-estimated surface runoff (right panel) in summer 2002. Percentage change in accumulated values when the HE orographic adjustment is used is shown in each graph.

Use of the HE data in a hydrological model

The impact of the HE data with and without orographic correction on simulating basin-averaged surface accumulated rainfall and surface runoff was investigated for the 2002 warm season. Figure 5 shows the differences in basin-averaged accumulated precipitation and surface runoff from the five basins for the HE-O and HE-N rainfall products. Also shown inset in each figure panel is the percent difference of the HE-O rainfall or simulated runoff compared with the HE-N values. In five out of the six basins, the HE-O produces less total rainfall and less total runoff compared with the HE-N. The one basin which received greater rainfall and runoff using the HE-O algorithm is the Acaponeta basin, which is located the farthest south in the study area. As shown by the percentage differences, the response in runoff is not always in direct proportion to that of rainfall, though the values are generally similar. Essentially, the small to modest differences in estimated rainfall from the two algorithms do have an equivalent impact on modelled runoff in these basins. There is a tendency for greater intensity values, particularly for heavy rainfall events, to occur in the HE-N compared to the HE-O. Thus, we conclude that the differences in heavy rainfall intensity values between the HE-N and the HE-O are largely the reason for the differences in modelled runoff.

SUMMARY AND CONCLUSIONS

Rainfall from the NESDIS HE operational rainfall algorithm, with and without orographic correction, was evaluated against data observed by a new event-based raingauge network installed in the complex terrain region of northwestern Mexico for the summer monsoon periods of 2002 and 2003. Comparisons show that spatial and temporal rainfall characteristics over the NAM region are generally captured by the HE estimates in both years. However, some systematic bias structures exist that need to be addressed. The primary conclusions of the present research are summarized as follows:

(1) The HE algorithm shows a tendency to overestimate precipitation at lower elevations. The positive bias appears to be more noticeable with heavy rainfall events: overestimation principally occurs during larger, more organized convective storms.

(2) The HE rainfall estimates underestimate the occurrence of light precipitation, particularly toward high elevations. The elevation-dependent bias structures in the HE result in a positive network average bias at both hourly and daily time scales. Such bias in summer 2002 is substantially higher than that in 2003.

(3) The diurnal cycles of satellite-estimated precipitation frequency at each elevation band do not exhibit as clear a relationship to elevation as do gauge observations. However, there is modest agreement in depicting that precipitation originates in the early afternoon at the highest elevation bands and slightly later at lower elevations. Such behaviour is better shown with 2003 data, particularly in capturing the timing of rain frequency along with elevation bands.

(4) Two years' evaluation shows that summer 2002 has longer mean event durations toward high elevation bands than summer 2003, in both the observations and HE estimates. This implies that the HE has a weaker performance during longer wet periods due to tendency of the algorithm to overestimate.(5)The addition of orographic correction to the HE algorithm somewhat affects the rainfall. Error statistics show that, across the network, the correction method improved the rainfall by 4% in both years, but mostly over the lower elevations.

(6) The HE-N tends to produce more surface runoff than the HE-O. This is consistent with the HE analyses, in that the HE-N shows generally greater rainfall amount than the HE-O.

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