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Measuring precipitation in Eastern Himalaya: Ground validation of eleven satellite, model and gauge interpolated gridded products

--Manuscript Draft--

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Abstract:	Precipitation plays a key role in shaping land surface processes in Himalaya and it is also the most challenging meteorological variable to model in climate change studies due to inadequate ground data. Gridded Precipitation Products (GPPs) are useful alternatives to ground data but require validation, especially in topographically complex and wet Eastern Himalaya. This study presents a fine-scaled ground-validation of an eleven GPPs, including five satellite (GPM-IMERGV06, TRMM-3B42V7, TRMM-3B42V7RT, CHIRPS-2.0 and PERSIANN-CCS), four reanalysis models (ERA5, ERA5-Land, AgERA5, and WRF) and two gauge-interpolated (IMD-0.25° and APHRODITE-2V18) in Eastern Himalaya. Hourly precipitation data from 27 rain gauges (gauges) from Sikkim, representing the Eastern Himalayan climatology, is used to statistically validate the GPPs and assess their ability to capture diurnal and seasonal patterns, and extreme events. Overall, GPM-IMERG, WRF, and IMD-0.25° outperformed the other satellite, model, and interpolated GPPs, respectively, in comparison to gauges. Near real-time TRMM-3B42RTV7 performed better than TRMM-3B42V7 for high-intensity precipitation and large storms, but not in overall performance. CHIRPS-2.0 and PERSIANN-CCS showed the least detectability and highest errors; however, PERSIANN-CCS was better at reproducing known spatial patterns in ground precipitation. The GPPs underestimated (overestimated) precipitation frequencies and volumes below (above) 3000 masl, and high (low) intensities. The highest detectability and lowest errors were observed at mid-elevation (1000-2000 masl), and in monsoon (JJASO) and summer (MAM), whereas winter (NDJF) precipitation was overestimated in high false hits. Strong diurnal cycles in precipitation were observed in gauges with peaks around late-night-early morning (2300-0300 h) in monsoon and afternoon-evening (1600-1900 h) in summer. Satellite GPPs captured the diurnal cycle in gauges, albeit with lower, whereas model GPPs failed. Owing to their superior performance and fine spatiotemporal resolutions, GPM-IMERG and WRF are recommended for hydrological studies in Eastern Himalaya. The three ERA5-based products (ERA5, ERA5-Land, AGERA5), along with TRMM-3B42RTV7 and IMD-0.25°, showed the lowest bias in tracking large storms (longer than 5 days) and are advocated for understanding extreme events and geohazard applications. IMD-0.25°is recommended for precipitation trend and variability analysis, albeit with suitable bias-correction to address the positive biases at high elevations and in trans-Himalayan regions. The study improves our understanding of remotely-sensed and spatially-gridded precipitation in the world's highest mountain range, where ground observations are likely to be inadequate for years to come.

Suggested Reviewers:	Wouter Buytaert, Ph.D. Reader, Duke University, USA w.buytaert@imperial.ac.uk Dr. Buytaert has considerable experience of working on hydro-meteorology in tropical mountains of Andes and Himalaya using remotely-sensed and ground data.
	Latif Kalin, Ph.D. Professor, Auburn University latif@auburn.edu Prof. Kalin has extensive research experience of working on spatially distributed precipitation and hydroclimate modelling.
	Andrea Momblanch, Ph.D. Academic Fellow, Cranfield University, UK Andrea.Momblanch-Benavent@cranfield.ac.uk Dr. Momblanch has worked on bias correction of satellite and motel-based gridded precipitation products in Western Himalaya, and climate change modelling of water resources in the larger Himalayan region.
	Tommaso Moramarco, Ph.D. Director of Research, Italian National Research Council t.moramarco@irpi.cnr.it Dr. Moramarco has extensive experience of hydro-meteorological research using remotely-sensed data and its application for geohazards and hydrological studies.
	David Hannah, Ph.D. Professor, University of Birmingham, UK d.m.hannah@bham.ac.uk Dr. Hannah is an expert on hydroclimatology and ecohydrology in mountainous regions and has worked on development of new methods for monitoring, analyzing and modelling environmental processes.
Response to Reviewers:	

*Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

Highlights

- GPM-IMERG and WRF are recommended for hydroclimatic applications in Eastern Himalaya
- ERA5, TRMM-3B42RTV7 and IMD-0.25° captured extreme precipitation events satisfactorily
- IMD-0.25° is advised for precipitation trend analysis after suitable bias-correction
- GPPs underestimated (overestimated) precipitation below (above) 3000 masl elevation
- Satellite GPPs captured the seasonal and diurnal cycles with subdued amplitudes.

*Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☒The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

None.

Author contributions:

Manish Kumar: Conceptualization, Methodology, Formal analysis, Visualization, Writing – Original draft preparations**. Øivind Hodnebrog:** Resources, Data Curation, Writing – Review & Editing. **Anne Sophie Daloz:** Resources, Data Curation, Writing – Review & Editing. **Sumit Sen:** Methodology, Writing – Review & Editing. **Shrinivas Badiger:** Methodology, Writing – Review & Editing. **Jagdish Krishnaswamy:** Conceptualization, Methodology, Writing – Review & Editing, Supervision, Project Administration, Funding acquisition.