https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

AIMERG: a new Asian precipitation dataset (0.1°/half-hourly, 2000-2015) by calibrating GPM IMERG at daily scale using APHRODITE

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https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

AIMERG: a new Asian precipitation dataset (0.1°/half-hourly, 2000-2015) by calibrating GPM IMERG at daily scale using APHRODITE

Highlights

- **A new effective daily calibration approach, DSTDCA, for improving GPM IMERG**
- **A new AIMERG precipitation data (0.1°/half-hourly, 2000-2015, Asia) was provided**
- **Bias of AIMERG was significantly improved compared with that of IMERG**
- **APHRODITE is more suitable than GPCC in anchoring IMERG over the Asia**

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

Abstract

Precipitation estimates with finer quality and spatio-temporal resolutions play significant roles in understanding the global and regional cycles of water, carbon and energy. Satellite-based precipitation products are capable of detecting spatial patterns and temporal variations of precipitation at finer resolutions, which is particularly useful over poorly gauged regions. However, satellite-based precipitation product are the indirect estimates of precipitation, inherently containing regional and seasonal systematic biases and random errors. In this study, focusing on the potential drawbacks in generating Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) and its recently updated retrospective IMERG in Tropical Rainfall Measuring Mission (TRMM) era (finished in July, 2019), which were only calibrated at monthly scale using ground observations, Global Precipitation Climatology Centre (GPCC, 1.0°/Monthly), we aimed to propose a new calibration algorithm for IMERG at daily scale, and to provide a new AIMERG precipitation dataset (0.1°/ half-hourly, 2000-2015, Asia) with better quality, calibrated by Asian Precipitation Highly Resolved Observational Data Integration (APHRODITE, 0.25°/Daily) at daily scale for the Asian applications. And the main conclusions included but not limited to: (1) the proposed daily calibration algorithm (Daily Spatio-Temporal Disaggregation Calibration Algorithm, DSTDCA) was effective in considering the advantages from both satellite-based precipitation estimates and the ground observations; (2) AIMERG performed better than IMERG at different spatio-temporal scales, in terms of both systematic biases and random errors, over the China Main land; and (3) APHRODITE demonstrated significant advantages than GPCC in calibrating the

IMERG, especially over the mountainous regions with complex terrain, e.g., the Tibetan Plateau. Additionally, Results of this study suggests that it is a promising and applicable daily calibration algorithm for GPM in generating the future IMERG in either operational scheme or retrospective manner.

The AIMERG data record (0.1°/half-hourly, 2000-2015, Asia) is freely available at http://argi-basic.hihanlin.com:8000/d/d925fecf60/. Additionally, the AIMERG data is also freely accessible at https://doi.org/10.5281/zenodo.3609352 (for the period from 2000 to 2008) (Ma et al., 2020a) and http://doi.org/10.5281/zenodo.3609507 (for the period from 2009 to 2015) (Ma et al., 2020b).

Keywords: Precipitation; IMERG; APHRODITE; Calibration; Daily scale; Asia;

1. Introduction

Precipitation is among the most essential hydroclimatic factors, and also most difficult to estimate due to its great small-scale variabilities (Yatagai et al., 2012; Huffman et al., 2019). High spatio-temporal resolution precipitation dataset with fine quality is essential for various scientific and operational applications, including but not limited to driving the hydrological models, and supporting the predictions of droughts and floods (Beck et al., 2017, 2018). There are mainly two principal approaches for measuring the global precipitation: ground-based gauge observing, and satellite-based remote sensing, which resulting in three mainstreams of global precipitation products, namely gauge analysis

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

precipitation data, satellite-based only precipitation estimates, and satellite-gauge combined precipitation products, based on the consideration that ground-based gauge data are clearly important for anchoring the satellite estimates (Huffman et al., 2007, 2014, 2019).

In recent years, a large number of quasi-global satellite precipitation products with various temporal and spatial resolutions have been developed and released to the public, such as the PMW-based CPC Morphing technique (CMORPH) (hereafter, for Acronyms, see the Appendix) (Joyce et al., 2004), and IR-based PERSIANN (Sorooshian et al., 2000) and PERSIANN-CCS (Hong et al., 2004). As the milestone in the satellite-based precipitation measurement process, the TRMM and its successor GPM developed a flexible framework for generating the most popular near-real-time precipitation products, TMPA (1998-present, 0.25°/3 hourly) and IMERG (2014-present, 0.1°/half-hourly), as well as the retrospective IMERG (2000-present, 0.1°/half-hourly) from GPM era to TRMM era, which aimed at intercalibrating, merging, and interpolating all MW estimates of the GPM constellation, IR estimates, gauge observations, and other data from potential sensors at 0.1° × 0.1° and half-hourly temporal resolutions (Huffman et al., 2014, 2019). The “Final” version of IMERG (Hereafter refer to IMERG), incorporated the monthly gauge analysis, provides the state-of-the-art precipitation estimate with finest spatio-temporal resolutions so far, while it still greatly overestimates the precipitation at daily and hourly scales from regions to regions, especially over the mountainous areas, such as the Tibetan Plateau, China (Tang et al., 2016; Lu et al., 2019; Xu et al., 2019), which is greatly potentially resulted by the calibration procedures in the process of generating the IMERG. Currently, the IMERG product (following the

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

TMPA approach) (Huffman et al., 2007) has been produced by anchoring the satellite-based only precipitation estimates using the monthly analysis Satellite-Gauge product (2.5°/monthly, 1979 to the present, delayed by about 3 months) from the GPCP (Adler et al., 2003, 2018), therefore, the IMERG performed better at monthly and annul scale than those at finer temporal scales (e.g., daily, hourly). And how to calibrate the IMERG at daily scale is one of the next vital focuses by the GPM.

Satellite-based precipitation products have significant advantages in detecting the variations of precipitation at finer spatio-temporal resolutions, especially over the poorly gauged regions. However, as the indirect estimates of precipitation, satellite-based precipitation product are inherently containing regional and seasonal systematic biases and random errors (Ebert et al., 2007; Shen et al., 2014), which could be effectively alleviated by anchoring the satellite-based only precipitation products using gauge-based observations (Huffman et al., 2007; Xie and Xiong, 2011), and great efforts has been focused on generating the Satellite-Gauge combined precipitation products with finer accuracies, most of which calibrations on satellite-based precipitation were conduct at the monthly scale, and very limited explorations at the daily scale (Adler et al., 2003; Huffman et al., 2007, 2014, 2019).

As for anchoring the satellite precipitation estimates, the quality and spatio-temporal resolutions of the gauge analysis precipitation data are the key factors. Though the GPCP has developed a series of gauge-based precipitation analysis datasets with the quality and spatio-temporal resolutions continually improved, accurate estimations of precipitation over the land is still greatly difficult over the land with

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

limited networks of rain gauges. In Asia, great efforts also have been mainly paid on generating gauge-analysis precipitation products at the monthly scale (Chen et al., 2002; Mitchell and Jones 2005; Matsuura and Willmott 2009; Schneider et al. 2008), and limited explorations at the daily scale, e.g., Rajeevan and Bhate (2009) explored daily grid precipitation data over India with data from more than 2,500 rain gauges. Meanwhile, significant differences among those products had been reported by Yatagai et al (2005, 2012). To more accurately monitor and predict the Asian hydro-meteorological environment, the APHRODITE project (starting in 2006) aimed at developing the state-of-the-art gridded precipitation datasets at the resolutions of 0.25°/daily covering the entire Asia based on the largest numbers of ground observations from multi-sources. Since the release of APHRODITE products (1951-2015, 0.25°/daily, Last update October 5, 2018), APHRODITE daily grid precipitation data sets have been widely used, and it distinguished from other gauge analysis data by considering the different interpolation schemes and climatology characteristics, especially over the mountainous regions with complex terrain, e.g., the Tibetan Plateau (Yatagai et al., 2012).

The aim of this study is to explore the calibration approach at daily scale on the retrospective IMERG data using APHRODITE product, in both TRMM and GPM era, from 2000 to 2015. Meanwhile, a new calibration approach, Daily Spatio-Temporal Disaggregation Calibration Algorithm (DSTDCA), was proposed and suggested for the GPM in their future algorithms; and a new AIMERG precipitation dataset (0.1°/ half-hourly, 2000-2015, Asia) (Ma et al., 2020a, b) with better quality was to be provided publicly for the Asian applications.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

2. Data

2.1 IMERG

To generate the IMERG product, GPM focused on intercalibrating, merging, and interpolating "all" satellite MW-based precipitation estimates, together with MW-calibrated IR-based precipitation estimates, precipitation gauge analyses, and potentially other precipitation estimators at fine spatio-temporal scales for the both TRMM and GPM eras over the entire globe. Currently, IMERG is at its Version 06 stage (https://pmm.nasa.gov/sites/default/files/document_files/IMERG_ATBD_V06.pdf), based on which the TRMM era IMERG has been completed at the end of September, 2019, and IMERG is now available back to June 2000 (half-hourly/0.1°) (https://pmm.nasa.gov/data-access/downloads/gpm). IMERG "Final" run combines the GPCC Monitoring product, the V8 Full Data Analysis for the majority of the time (currently 1998-2016), and the V6 Monitoring Product from 2017 to the then-present. The Monitoring Product is poster about two months after the month of observation from ~7,000-8,000 stations world-wide (Schneider et al. 2014, 2018).

2.2 APHRODITE

Since the release APHRODITE product (0.25°/Daily, 1951-2007), it has been widely used as one of state-of-the-art daily grid precipitation datasets over the Asia, for hydro-climatological related studies

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

(Yatagai et al., 2012). APHRODITE has been demonstrated to replicate 'ground truth' observations very well (Duncan and Bigg, 2012) and represents the best tool for analyzing historical precipitation variability and change. Recently, the APHRODITE data had been updated from the former period 1951-2007 to a longer period 1951-2015, in September, 2018, with continuous efforts of quality control (QC) flagging some data (Hamada et al., 2011). The APHRODITE data could be available through the website (http://aphrodite.st.hirosaki-u.ac.jp/download/).

2.3 CMPA

The China Merged Precipitation Analysis (CMPA, 0.1°/hourly, 2008-2015) were generated by using hourly rain gauge data at more than 30, 000 automatic weather stations in China, with the combination of the CMORPH precipitation product, and provided by the Chinese Meteorological Administration (http://data.cma.cn) (Shen et al., 2010). The inverse distance weighting (IDW) interpolation method was adopted to estimate the areal precipitation distribution based on the gauge observations (Yong et al., 2010), but uncertainty still existed in the interpolated precipitation field particularly over West China with relatively sparse gauge networks. For grid boxes with gauges, the observed precipitation values are exactly the gauge observation or the averaged observation when more than one gauge locates in a grid.

2.4 Point-based rain gauge data from meteorological stations

The hourly rain gauge datasets from 57, 835 national ground stations used in this study, in 2015, were collected from the National Meteorological Information Center of CMA (http://data.cma.cn). All the gauge data have undergone strict quality control in three levels, which includes (1) the extreme values' check, (2) internal consistency check, and (3) spatial consistency check (Shen et al., 2010). Most gauges are located over the eastern and southern parts of the Mainland China, and relatively sparse gauge network are located across the northern and western parts, especially over the Tibetan Plateau. The limited number of gauges could be a source of error in evaluation of satellite precipitation products in such areas (Shen et al., 2014).

2.5 Point-based rain gauge data from hydrological stations

The hourly ground precipitation observations from around 500 hydrological stations (the number of station varied from year to year) used in this study were collected from Hydrology Bureau of Zhejiang Province, southeastern China (http://data.cma.cn/). The quality control follows two steps: (1) the datasets are filtered by threshold value after being collected from rain gauges; (2) the outliers are identified through manual processing. With careful data quality control, the rain gauge datasets have satisfying performances on the accuracy and validity.

There were five datasets used in this study (refer to Table 1 for a summary of the datasets). IMERG and APHRODITE were used for generating the AIMERG data, and the others were used for evaluating and comparing the IMERG and AIMERG at different scales.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

Table 1. List of satellite-based, gauge-based, and satellite-gauge combination precipitation products used in this study.

Short name	Full name	Spatial and temporal sampling	Time period	References
IMERG	Integrated Multi-satellitE Retrievals for Global Precipitation Measurement	0.1°/half-hourly	2000-present	Huffman et al. (2019) https://pmm.nasa.gov/data-access/downloads/gpm (last access: 17 January 2020)
APHRODITE	Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources	0.25°/daily	1951-2015	Yatagai et al. (2012) http://aphrodite.st.hirosaki-u.ac.jp/download/ (last access: 17 January 2020)
CMPA	China Merged Precipitation Analysis	0.1°/hourly	2008-present	Shen et al. (2014) http://data.cma.cn (last access: 17 January 2020)
	Point-based rain gauge data	hourly	2010-present	Shen et al. (2010) http://data.cma.cn (last access: 17 January 2020)

3. Methodology

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

3.1 Calibration Procedure of the Daily Spatio-Temporal Disaggregation Calibration Algorithm, DSTDCA

According to previous evaluation investigations on IMERG (Lu et al., 2019; Xu et al., 2019), there were at least two characteristics resulting its significant overestimations: (1) the amplitude of hourly or half-hourly estimated rainfall rates were significantly amplified by IMERG compared with ground observations, which might be caused by the benchmark of GPCC and GPCP SG data for calibrations, and (2) the IMERG algorithm is generally over detecting precipitation events, resulting a large fraction of false alarm but unreal precipitation events. Therefore, this study selected the APHRODITE data as the benchmark for calibrating IMERG at daily scale, based on the proposed approach, DSTDCA, and the main steps of the DSTDCA were shown as follows:

(1) IMERG data (0.1°/half-hourly) were accumulated to those (0.1°/daily), which were used to generate the spatial disaggregation weights. As the spatial resolution of APHRODITE data was 0.25°, the moving window size of 3 by 3 was selected, and the daily spatial disaggregation weights (0.1°) based on IMERG was obtained by calculating the ratios between the daily rainfall accumulations at the central grid and the average daily rainfall accumulations in the corresponding 3 × 3 window. The daily spatial disaggregation weights considered the relative spatial patterns of the precipitation captured by the IMERG;

(2) Based on the daily precipitation accumulations of IMERG, the half-hourly temporal disaggregation weights (0.1°) was derived by calculating the ratios between the each half-hourly

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

precipitation estimates and the corresponding daily precipitation estimates. If the daily accumulation estimate is equal to zero, then each half-hourly temporal disaggregation weights were all set as zero;

(3) As there were a small fraction of grids in APHRODITE with no data at daily scale, the no data grids in APHRODITE data were firstly filled with the data according to its nearest neighbor with effective value;

(4) Spatial calibrations: the daily calibrated IMERG using APHRODITE data were obtained by multiplying the spatial disaggregation weights based on IMERG (0.1°/daily) from step (1) by daily APHRODITE data (0.25°/ daily) from step (3);

(5) Temporal calibrations: the half-hourly calibrated IMERG were obtained by multiplying the half-hourly temporal disaggregation weights (0.1°/half-hourly) from step (2) by the daily calibrated IMERG from step (3);

(6) By considering the situations that APHRODITE data captured the precipitation while the IMERG did not, the half-hourly calibrated IMERG were further processed by equally disaggregating the value from the daily APHRODITE data at the corresponding grid into 48 half-hourly periods, which were regarded as the half-hourly calibrated IMERG values in the corresponding day;

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

(7) By considering the situations that IMERG data captured the precipitation while the APHRODITE did not, the 48 half-hourly calibrated IMERG values in corresponding days and locations were set as zero, to meet the ground truth observations;

After all the above-mentioned procedures, the Final calibrated AIMERG (0.1°/ half-hourly) data were obtained by considering the both the total precipitation controls and the effective precipitation events measured by the "ground truth" observations by APHRODITE data over the Asia.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

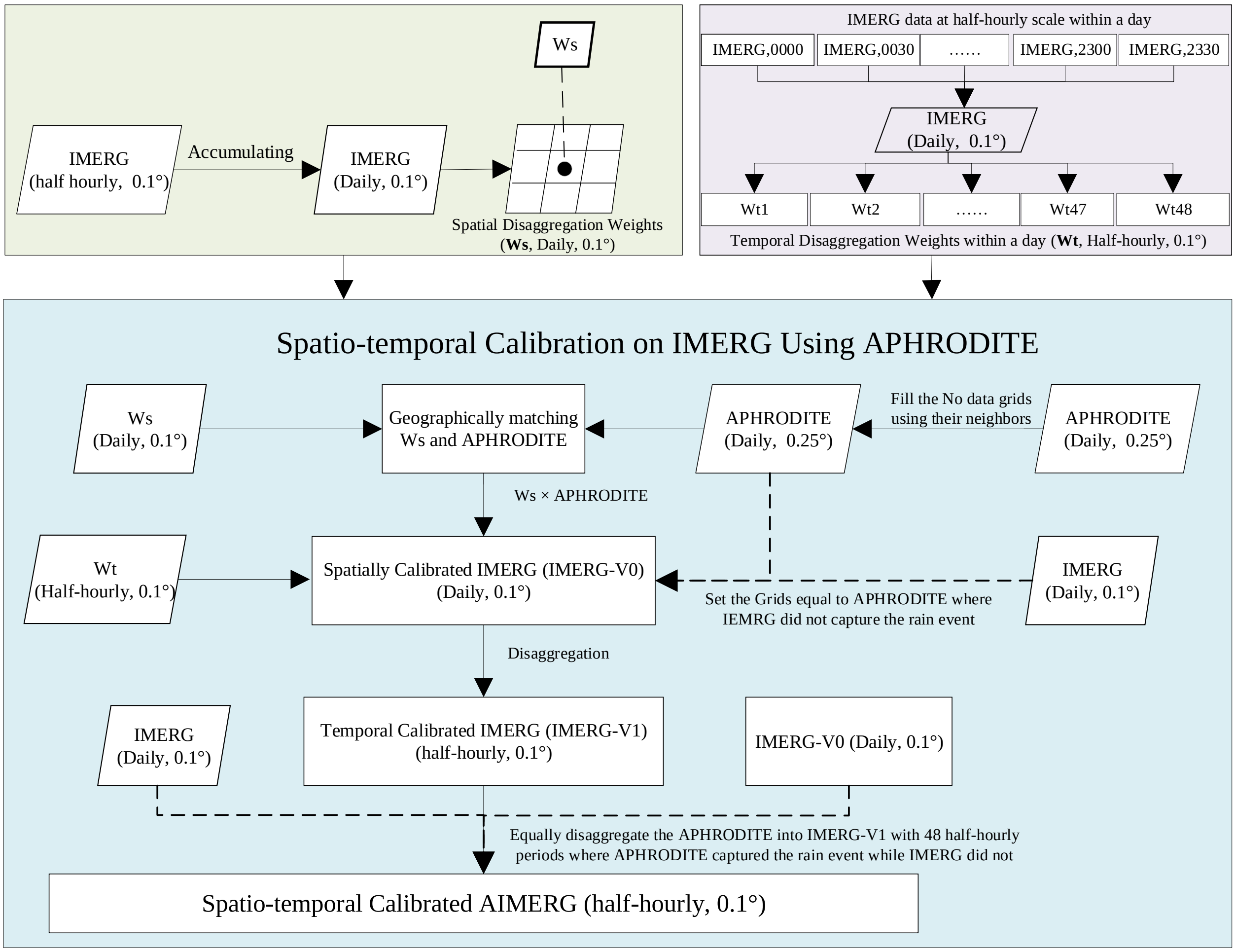


Figure 1. The flowchart of the Daily Spatio-Temporal Disaggregation Calibration Algorithm, DSTDCA, to generate the AIMERG dataset over the Asia, 2000-2015

3.2 Evaluation Metrics

To evaluate the IMERG and its calibrations comprehensively, seven metrics (CC, MAE, BIAS, RMSE, POD, FAR, CSI) were selected (Tang et al., 2016). Generally, CC is used to describe the

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

agreements between satellite estimates and gauge observations; MAE, RMSE, and BIAS are used to indicate the error and bias of satellite estimates compared with gauge observations; and the POD, FAR, and CSI are used to demonstrate the capabilities to correctly capture the precipitation events of satellite precipitation estimates against the ground observations. The detailed information of these evaluation metrics are listed in Table 2.

Table 2 Formulas and perfect values of the evaluation metrics used in this study[a].

Statistic metrics	Equation	Perfect value
Correlation Coefficient (CC)	$CC = \frac{\frac{1}{N}\sum_{n=1}^{N}(S_n - \bar{s})(G_n - \bar{G})}{\sigma_S \sigma_G}$	1
Mean Error (ME)	$ME = \sum_{n=1}^{N}(S_n - G_n)$	0
Relative Bias（BIAS)	$BIAS = \frac{\sum_{n=1}^{N}(S_n - G_n)}{\sum_{i=1}^{n} G_n} \times 100\%$	0
Root Mean Square Error (RMSE)	$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(S_n - G_n)^2}$	0
Probability of Detection (POD)	$POD = \frac{n_{11}}{n_{11} + n_{01}}$	1
False Alarm Ratio (FAR)	$FAR = \frac{n_{10}}{n_{11} + n_{10}}$	0
Critical Success Index (CSI)	$CSI = \frac{n_{11}}{n_{11} + n_{10} + n_{01}}$	1

[a]Notation: n is the sample numbers; S_n is satellite precipitation estimate; G_n is gauge-based precipitation; σ_G is the standard deviations of gauge-based precipitation; σ_S is the standard deviations of satellite-based precipitation estimate. n_{11} is the precipitation event detected by both gauge and satellite simultaneously; n_{10} is the precipitation event detected by the satellite but not detected by the gauge; n_{01} is contrary to n_{10}; n_{00} is the precipitation events detected neither by the gauge nor the satellite.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

4. Results

4.1 AIMERG Product

Generally, both IMERG and APHRODITE shared similar spatial patterns with precipitation volumes decreasing from southeast to northwester in Asia, while compared with APHRODITE data (Fig. 2b), IMERG greatly overestimated the precipitation over Arunachal Pradesh, coastal Indochina and Western Ghats, and the Indonesia (Fig. 2a). Corrected by APHRODITE, the spatial patterns and volumes of AIMERG were much more similar to those of APHRODITE, especially along the Himalayas, coastal Indochina and Western Ghats, and the Indonesia (Fig. 2c). Compared with APHRODITE, AIMERG seems floating up and down in terms of the volumes, for instance, AIMERG is larger and smaller than APHRODITE in eastern Indonesia and northeastern Asia, respectively. Though AIMERG are smaller than IMERG over most regions, there are still some areas where the volumes of AIMERG are larger than those of IMERG, e.g., in western Tibetan Plateau, Middle East, and along the western coast of India (Fig. 2d).

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

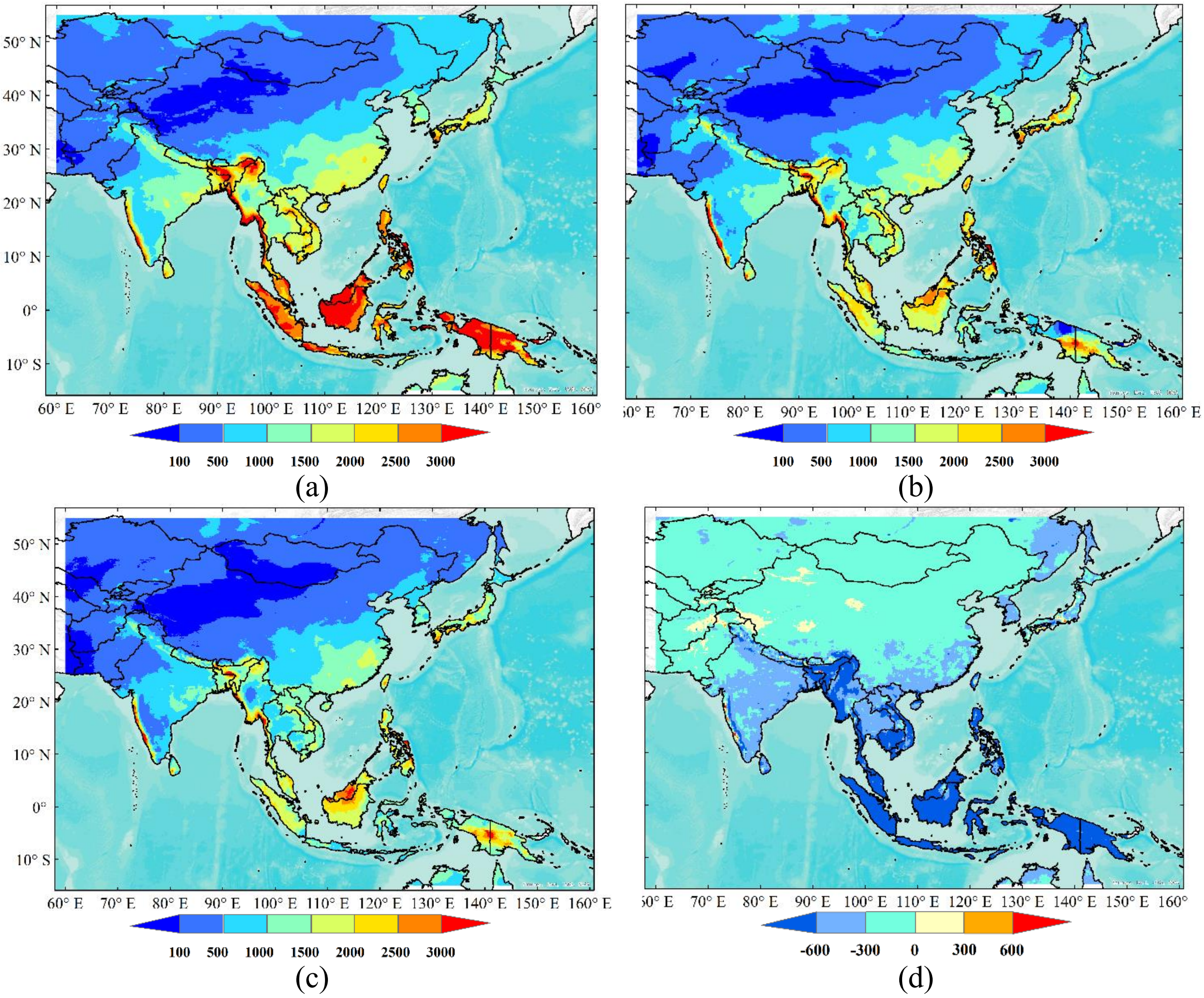
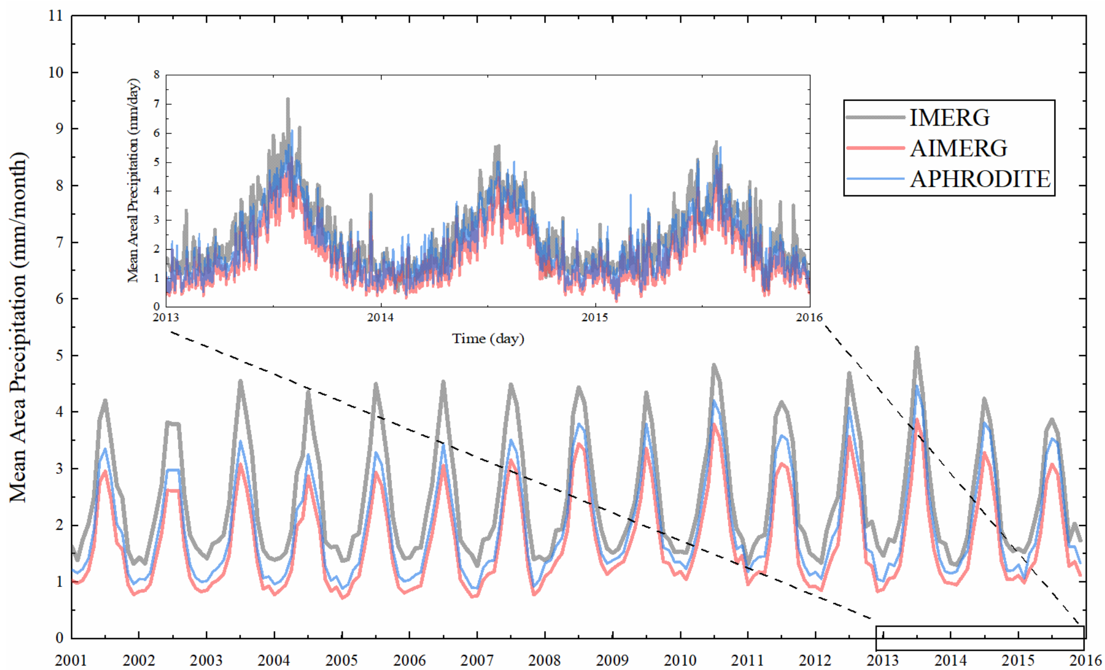


Figure 2. Spatial patterns of Asian mean annual gridded precipitation products of (a) IMERG, 0.1°, (b) APHRODITE, 0.25°, and (c) AIMERG, 0.1°, and (d) AIMERG-IMERG, 0.1°, respectively, during the period of 2001-2015. The background map used in this study was provided by Esri, USGS and NOAA (http://goto.arcgisonline.com/maps/World_Terrain_Base, last access: 17 January 2020).

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

The temporal patterns of the mean areal precipitation over the Monsoon Asia of the three products demonstrated that the systematic bias of IMERG was significantly reduced in both dry and wet seasons, shown in Fig. 3. IMERG is around 1.5 times larger than APHRODITE at monthly scale. Though much more close to the APHRODITE, AIMERG is still a little smaller than the APHRODITE, which means the calibration algorithm proposed by this study tends to underestimate the precipitation compared with calibration benchmark, APHRODITE. At daily scale, IMERG are generally larger than APHRODITE, while at some special days, APHRODITE are larger than IMERG, which might result the AIMERG may be also larger than IMERG.



https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

Figure 3. The temporal variations of mean Asian gridded precipitation products of IMERG, APHRODITE, and AIMERG, respectively, during the period of 2001-2015.

4.2 Assessments on IMERG and AIMERG at national and regional scales

The spatial patterns of CMPA demonstrated much more similar to those of AIMERG, especially in the southeastern China where dense rain gauges are located, while both CMPA and IMERG overestimated the precipitation along the Himalayas where the meteorological gauges were sparse and mainly the satellite-based observations were applied (Fig. 4). Obviously, the IMERG significantly overestimated the precipitation in the southeast coast of China, where typhoons always visit (Fig. 4 b).

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

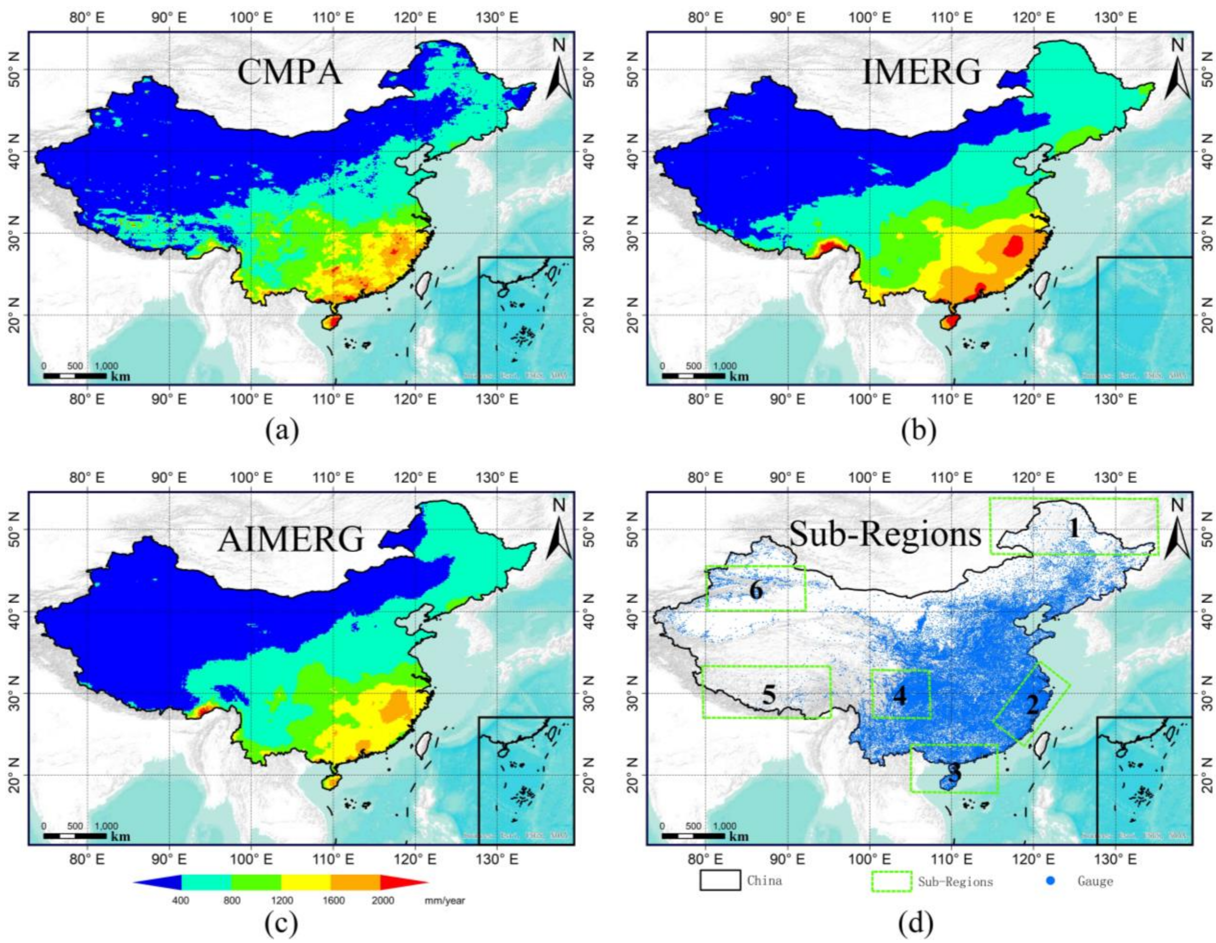


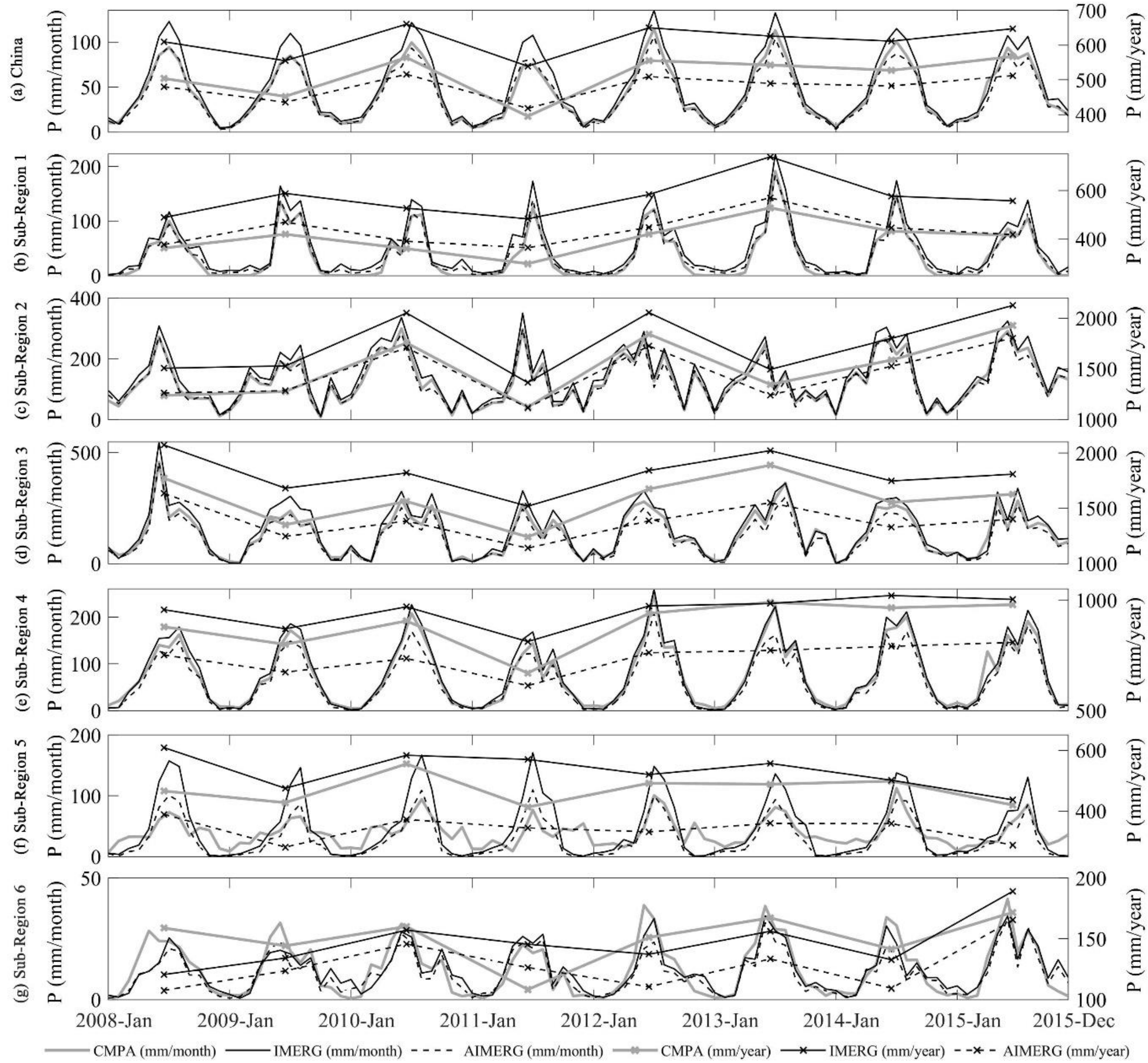
Fig.4 Spatial patterns of (a) CMPA, (b) IMERG, and (c) AIMERG over China Mainland From 2008~2015, and (d) the spatial distributions of the ~ 50, 000 automatic meteorological stations in China Main land. The background map used in this study was provided by Esri, USGS and NOAA (http://goto.arcgisonline.com/maps/World_Terrain_Base, last access: 17 January 2020).

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

The magnitudes of IMERG, AIMERG, and CMPA were compared at national and regional scale over the China Mainland from 2008 to 2015 (Fig. 5). Generally speaking, CMPA and AIMERG were almost same, and were both significantly smaller than IMERG at both annual and monthly scales, additionally, CMPA was still a little bit larger than AIMERG over the China Mainland, which could be possibly resulted from the use of satellite observations in the CMPA and IMERG (Fig. 6a). The overall situations of the three product in sub-region 1 and 2 were similar with those over the China Mainland (Fig. 6 b-c), while both CMPA and IMERG were both significantly larger than AIMERG (Fig. 6 d-f). In sub-region 6, the Tianshan Mountains, CMPA were almost even larger than IMERG, which indicated that large uncertainties should be focused on (Fig. 6 g).

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

286



287 Fig.5 The temporal patterns of mean areal precipitation of the IMERG, CMPA, and AIMERG, over China

288 Mainland and sub-regions from 2008 to 2015, at monthly and annual scales.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

As this study aimed to propose a new algorithm for calibrating the IMERG product at the daily scale, the daily spatial patterns of IMERG, CMPA, and AIMERG were explored, which generally agreed with those of IMERG, CMPA, and AIMERG at monthly scale (Fig. 6). In mountainous region, along the Himalayas, with relatively small precipitation, CPMA were greatly larger and smaller than the other two products (both IMERG and AIMERG) in dry seasons and wet seasons respectively (Fig. 6 f). One phenomenon should be noted that the CPMA seems abnormal along the Himalayas, which might be resulted by the limited ground observations used in CMPA, shown in Fig 4d, while APHRODITE data integrated large numbers of ground observations from the neighbor countries, such as India, Nepal, Bhutan, providing valuable information for retrieving high quality precipitation product around the Tibetan Plateau (Yatagai, 2012). Calibrated by APHRODITE at daily scale, AIMERG were significantly smaller than IMERG and CMPA at both annual and monthly scale, while there were also some situations that AIMERG were larger than IMERG and CMPA at daily scale, for example in sub-region 6, over the Tianshan mountains.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

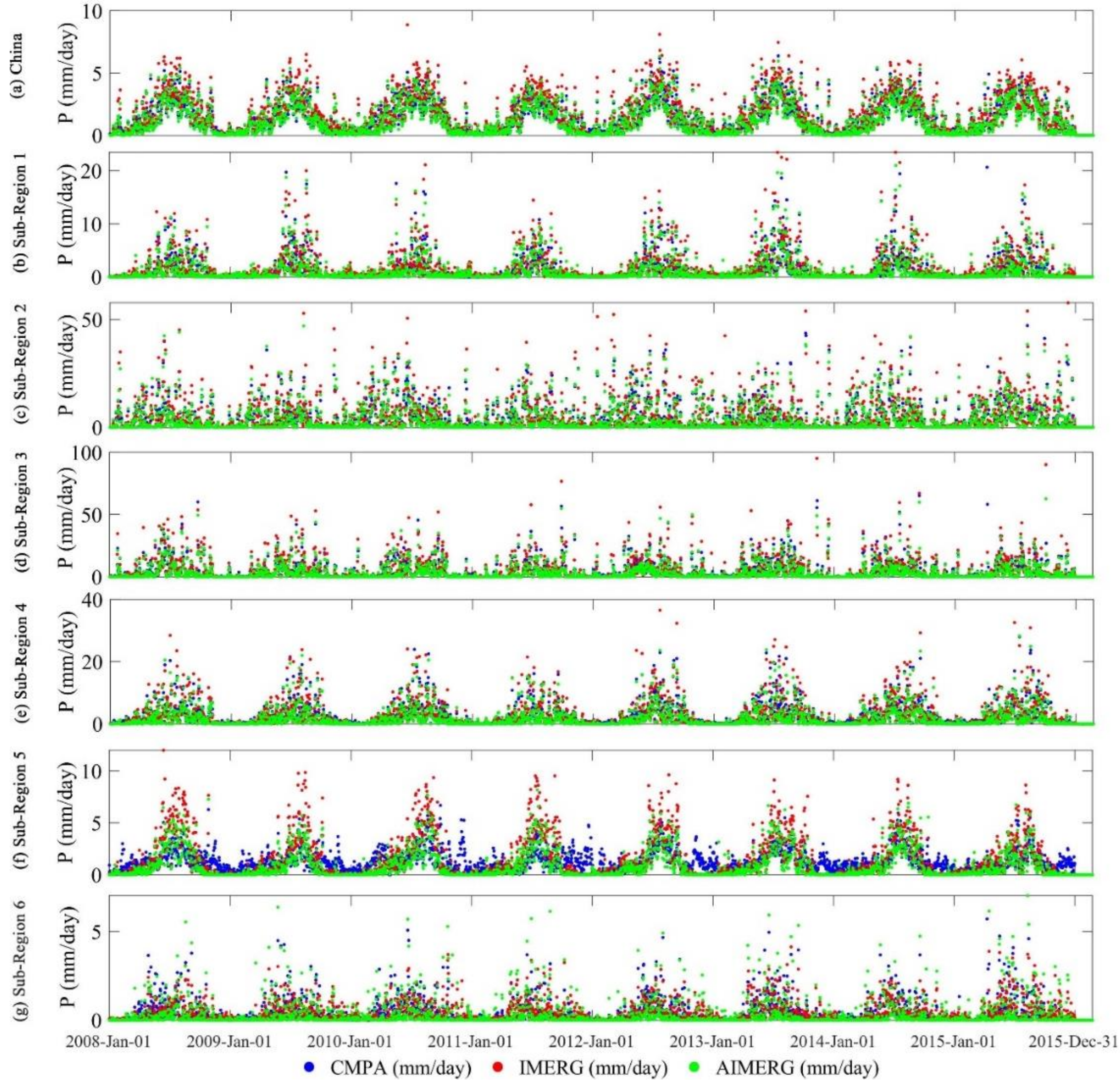


Fig.6 The temporal patterns of mean areal precipitation of the IMERG, CMPA, and AIMERG, over China Mainland and sub-regions from 2008 to 2015, at daily scale.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

Hourly ground observation data from more than 50, 000 meteorological stations were used to assess the quality of the IMERG and its calibrations, AIMERG, over the six sub-regions, in 2015 (Fig. 7). The temporal patterns and volumes of mean areal precipitation by AIMERG and ground observations were almost same, while IMERG were generally larger than AIMERG and ground observations. Meanwhile, the IMERG still has the problems in overestimating and underestimating the precipitation in dry seasons (relatively large precipitation occurring) and wet seasons (relatively small precipitation happening), respectively, for example in sub-region 6, over the Tianshan Mountains. In terms of quantitative indices (Standard deviation, RMSD, and CC), AIMERG generally outperformed the IMERG against the ground observations, especially in sub-region 5, along the Himalayas, which indicated that the ground information from the neighbor countries integrated into the APHRODITE data greatly benefited the calibration results, AIMERG.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

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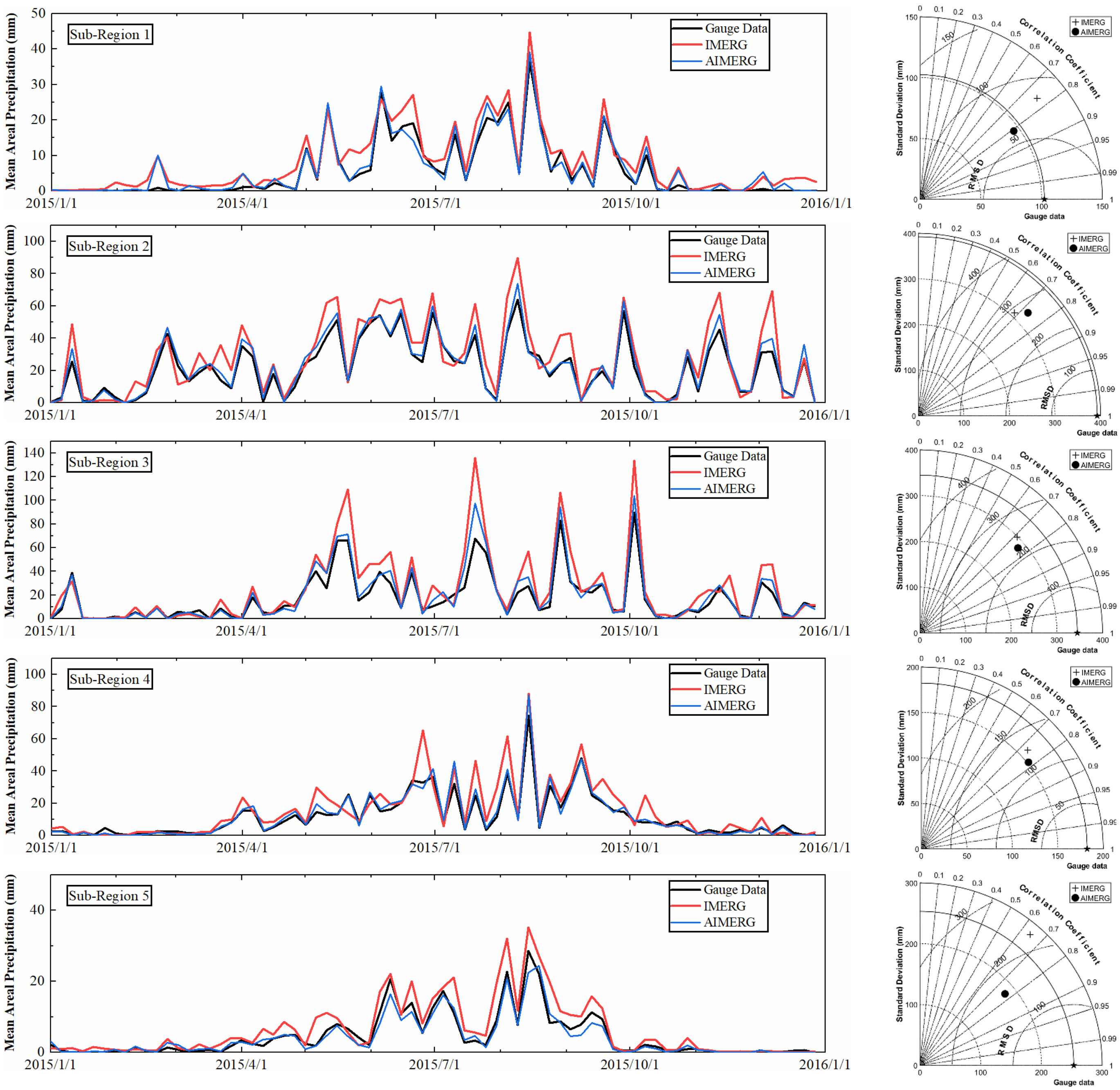

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Preprint. Discussion started: 10 February 2020

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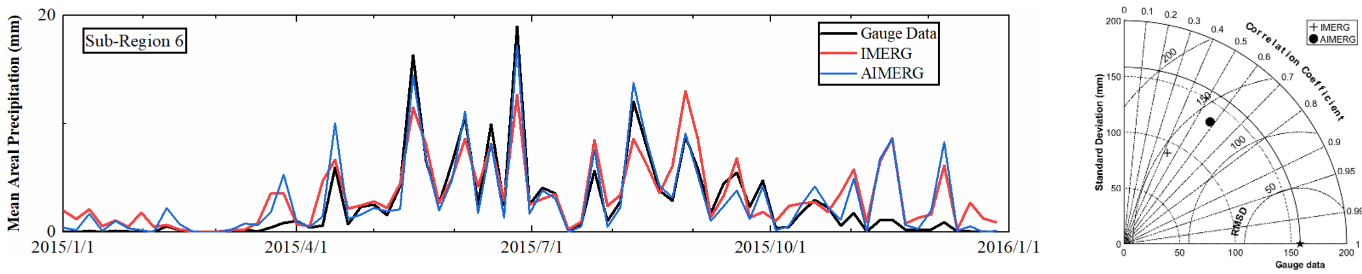

Figure 7. The temporal patterns and the volumes of IMERG, ground observations, and AIMERG, in six sub-regions at daily scale; and the Taylor diagrams of performances on IMERG and AIMERG against ground observations in terms of centered root-mean-square difference, correlation coefficient and standard deviation in the six sub-regions at hourly scale, in 2015.

Figure 8 illustrated the numerical distributions of contingency statistics for IMERG and AIMERG, at hourly scale, in six sub-regions, 2015. Generally, the POD values of AIMERG were larger than those of IMERG (Fig. 8a), and FAR values of AIMERG were overall smaller than those of IMERG in each sub-regions (Fig. 8b), which resulted the better performances of the comprehensive index, CSI, combining both the characteristics of POD and FAR, in each sub-regions (Fig. 8c). Additionally, both the IMERG and AIMERG performed best in sub-region 2, and worst in sub-region 3.

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Preprint. Discussion started: 10 February 2020

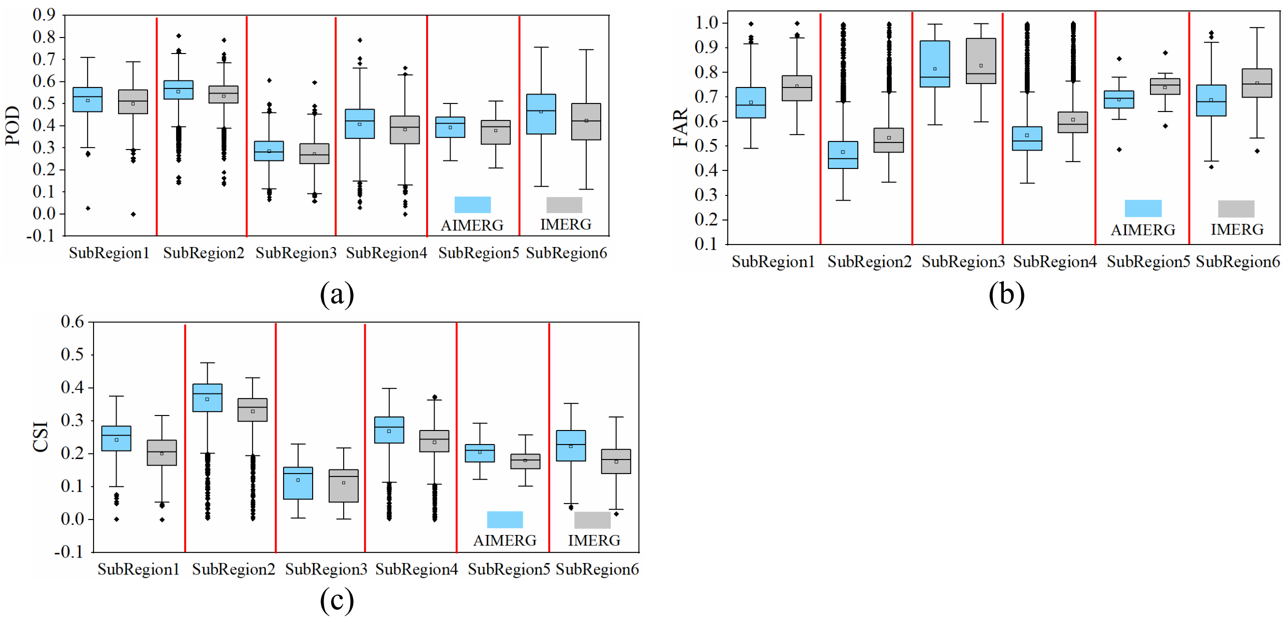


Figure 8. The boxplots demonstrated diagnose of IMERG and AIMERG against the ground observations from the meteorological stations, at hourly scale, in six sub-regions, 2015.

To assess the quality of the IMERG and AIMERG, entirely independent precipitation data from around 500 hydrological stations, at hourly scale, from 2010 to 2015, were applied, which were relatively even distributed in Zhejiang province (Fig. 9a). The POD values of AIMERG (~ 0.9) were general larger than those of IMERG (~ 0.8), while the FAR values of AIMERG (~ 0.3) were significantly smaller than those of IMERG (~ 0.4), which resulted in the overall capabilities of AIMERG to capture the precipitation events were improved more than 10%, compared with IMERG, in terms of the CSI. The relative smaller POD values and larger FAR values of IMERG in the Zhejiang province, southeastern coast of China, might be one of the potential drawbacks in accurately estimating the precipitation both qualitatively and quantitatively.

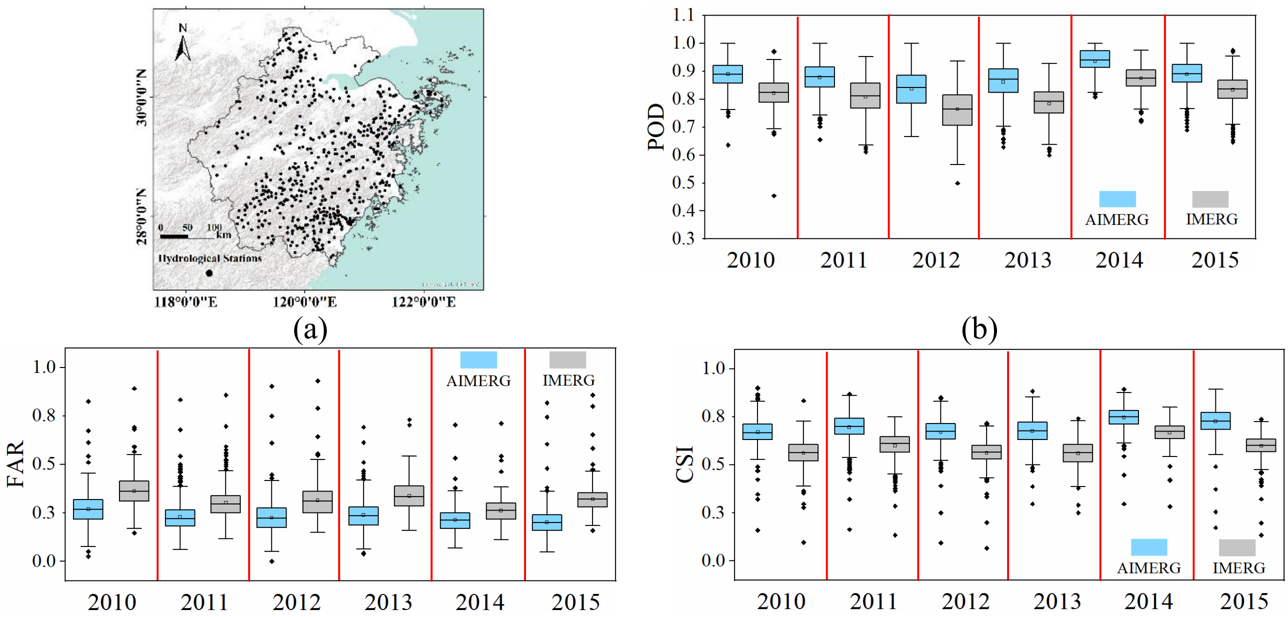


Figure 9. The boxplots demonstrated diagnose of IMERG and AIMERG against the ground observations from hydrological stations, respectively, at hourly scale, in Zhejiang province, 2010-2015. The background map used in this study was provided by Esri, USGS and NOAA (http://goto.arcgisonline.com/maps/World_Terrain_Base, last access: 17 January 2020).

From the temporal patterns of mean areal precipitation of IMERG, AIMERG, and ground observations from hydrological stations, in Zhejiang province, 2010-2015 (Fig. 10), IMERG were general larger than both AIMERG and ground observations. For instance, the IMERG significantly overestimated the precipitation with up to ten times than those of AIMERG and ground observations, such as in the

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

typical periods, 0 a.m., June, 11 – 0 a.m., June, 14, 2015, and 0 a.m., Aug, 29 – 0 a.m., Sep, 1, 2015. Additionally, both the temporal patterns and the magnitudes of AIMERG were almost same with those of ground observations, compared with those of IMERG. Meanwhile, in some pentads with the heavy rain events, both AIMERG and ground observations were larger than IMERG.

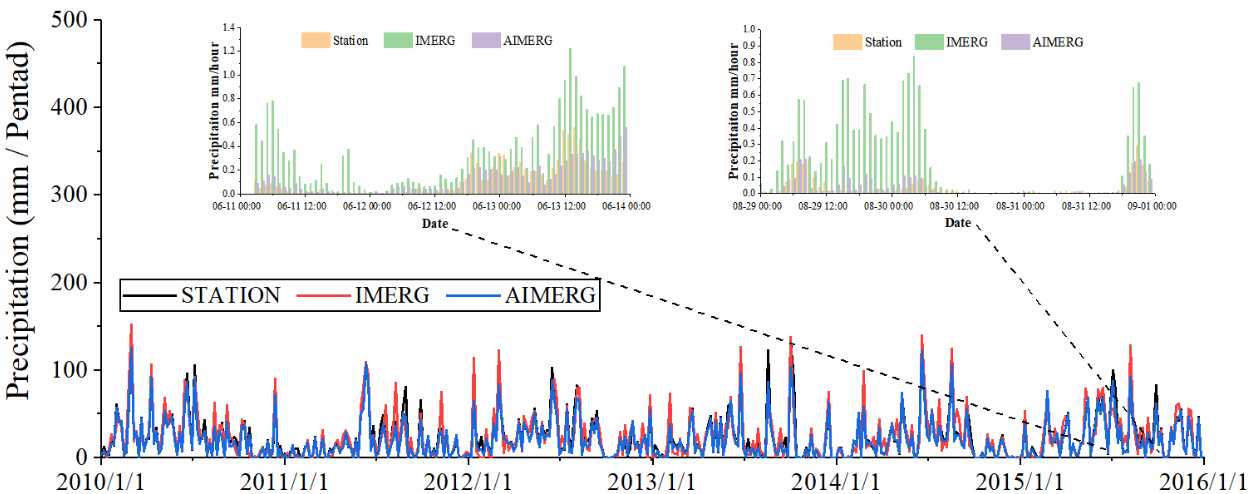


Figure 10. The temporal patterns of mean areal precipitation of IMERG, AIMERG, and the ground observations from the independent hydrological stations, at daily/hourly scale, in Zhejiang province, 2010-2015.

One of the primary aims of the satellite-based precipitation estimates is to provide the high quality precipitation information at hourly scale in the heavy rainfall events. Therefore, one typhoon event, Chan-hom, was selected as an example for assessing the quality of the IMERG and AIMER in Zhejiang

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

Province, where is always threatened by the typhoons, shown in Fig. 11. Though the spatial patterns of IMERG and AIMERG were both similar to those of ground observations, IMERG still underestimated the precipitation, compared with AIMERG (Fig. 11 a-c). From the statistics, not only the systematic bias of IMERG (around -50%) was significantly improved, with bias of AIMERG around -10%, but also the random errors of IMERG (RMSE ~ 2.7 mm/hour, MAE ~ 1.5 mm/hour) were also reduced, compared with AIMERG (RMSE ~ 2.5 mm/hour, MAE ~ 1.4 mm/hour), which meant the calibrations using APHRODITE on IMERG improved the abilities of original IMERG product to more accurately estimate the quantitative precipitation volumes, especially in heavy rainfall events (Fig. 11 c-d).

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

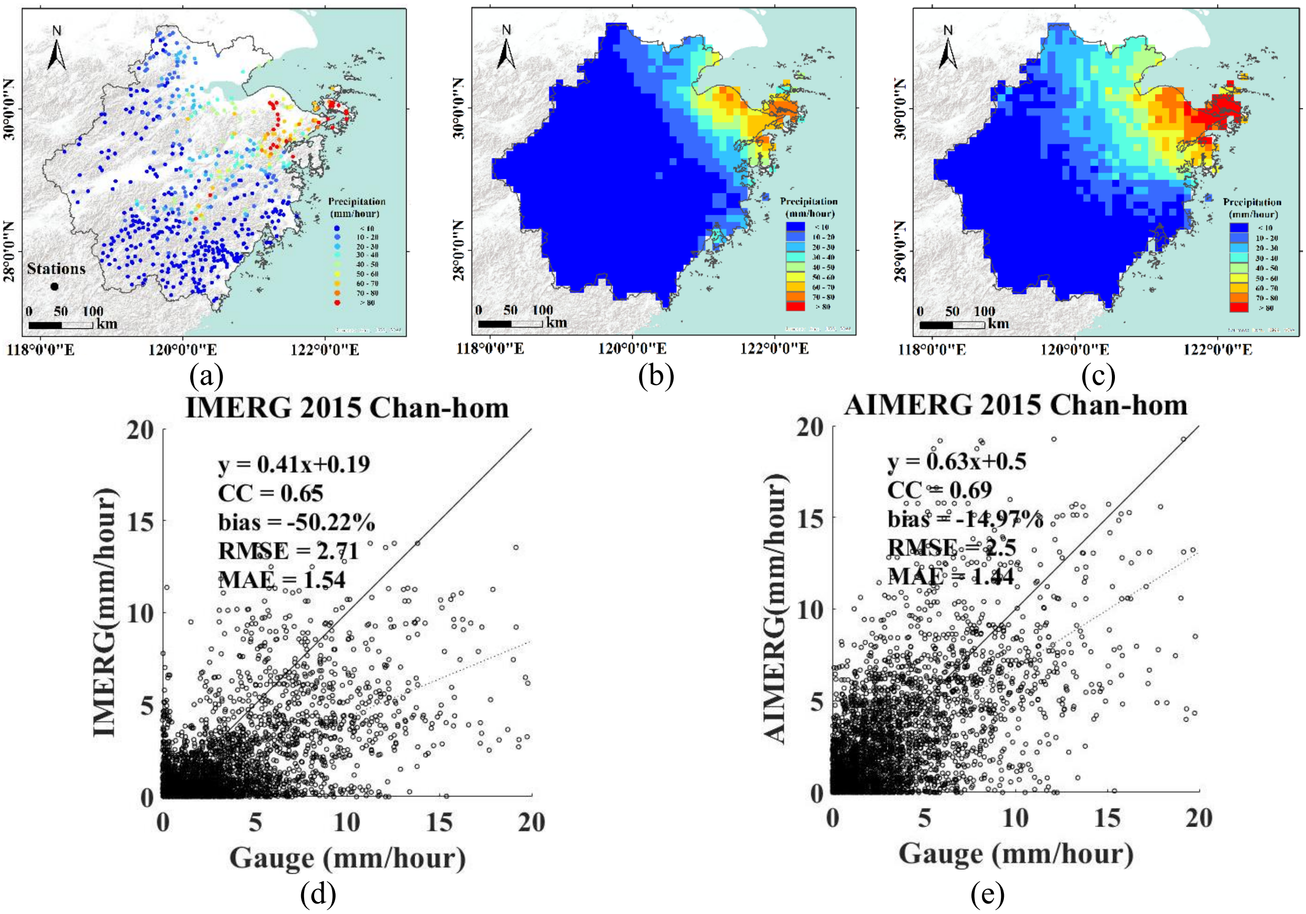


Figure 11. The typhoon, Chan-hom, was selected as an example for assessing the quality of the IMERG and AIMER, occurred in the typical period 0 a.m., – 11 a.m., June, 11, 2015, in Zhejiang Province. The background map used in this study was provided by Esri, USGS and NOAA (http://goto.arcgisonline.com/maps/World_Terrain_Base, last access: 17 January 2020).

5. Discussions

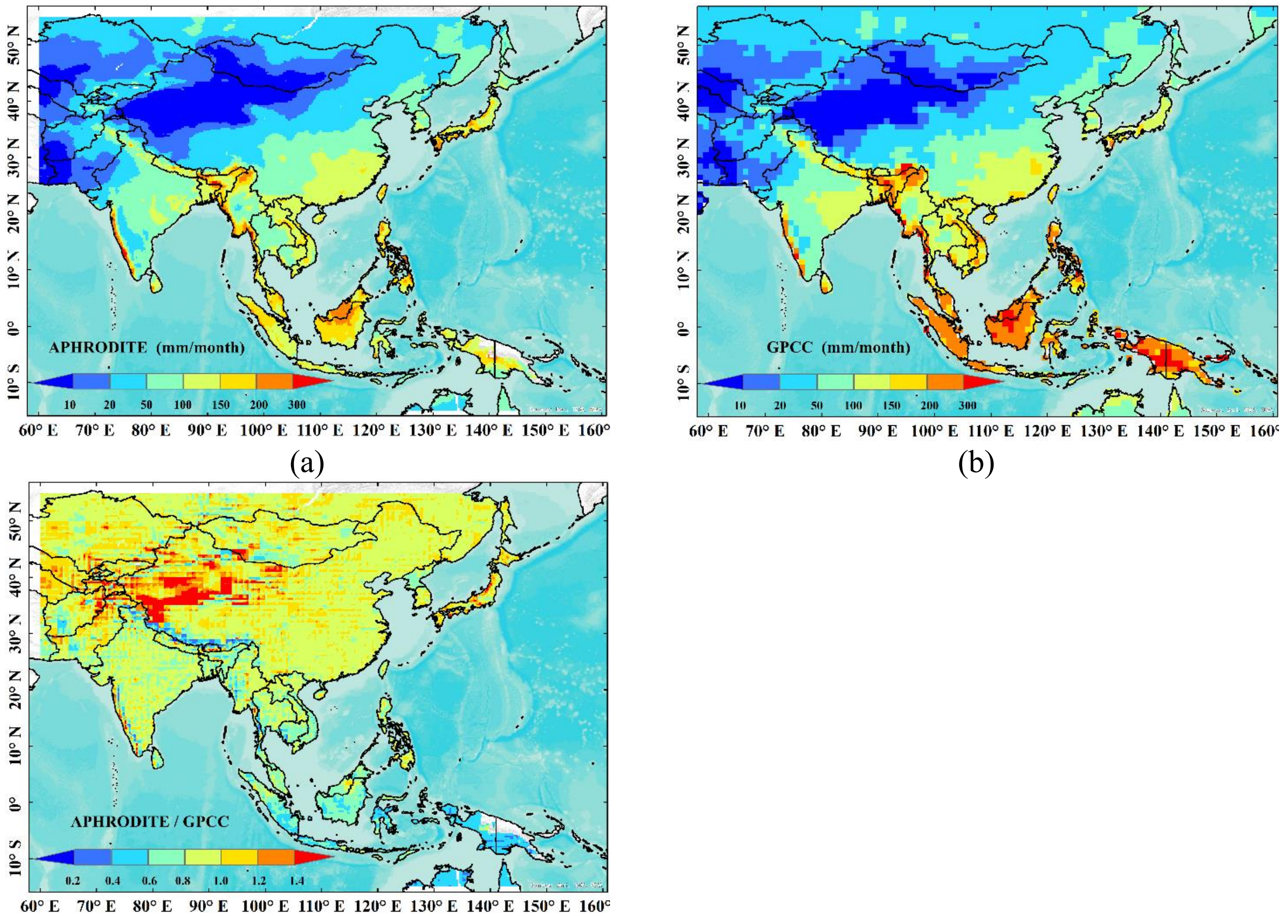
https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

5.1. The potential drawbacks in processing the IMERG product

From the document of "Algorithm Theoretical Basis Document (ATBD) Version 06" for generating the Final IMERG product (Huffman et al., 2019), we found that there were mainly two steps in the process: the first step was to derive the satellite-based only precipitation inversion estimates, and the second step was to calibrate the satellite-based only precipitation estimates using the interpolated precipitation product based on ground observations, e.g., GPCC (monthly, 1.0°×1.0°). As there is no mature calibration algorithm for calibrating the satellite-based only precipitation estimates at daily scale, the current IMERG-Final product are only calibrated using the GPCC at monthly scale. The two aims of this study were to (1) provide a spatio-temporal calibration algorithm (DSTDCA) for anchoring the satellite-based precipitation estimates at daily scale, and (2) a new precipitation product with finer quality, namely AIMERG (half-hourly, 0.1°×0.1°, 2000-2015, Asia) (Ma et al., 2020a, b), for Asian researcher. For anchoring the IMERG final product, we introduced the APHRODITE data (daily, 0.25°×0.25°, 2000-2015, Asia), which were interpolated based on ground observations from the large numbers of rain gauges. Though the general spatial patterns of monthly mean precipitation estimates from both APHRODITE and GPCC, from 1951 to 2015, were similar, the volumes of them demonstrated significant differences, especially along the Himalayas, coastal Indochina and Western Ghats, and the Indonesia (Fig. 12 a-b). To much more clearly demonstrate the relative values of GPCC and APHRODITE, the spatial patterns of the ratio of monthly mean values of APHRODITE to those of GPCC were illustrated in Fig.

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

12 c, from which we found that GPCC significantly overestimated the precipitation in the tropical rain range along the Indonesia, and along the southern Himalayas with complex terrain, while it significantly underestimated the precipitation in the north western Tibetan Plateau and Middle East, compared with the ground “truth” product, APHRODITE. Illustrated by Fig. 12, the GPCC plays vital roles for the final IMERG product, and the introduction of APHRODITE on calibrating the IMERG would be greatly benefiting the quality of the AIMERG.



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Preprint. Discussion started: 10 February 2020

(c)

Figure 12. The spatial patterns of the monthly mean precipitation of (a) APHRODITE and (b) GPCC, and (c) Ratio between monthly mean values of APHRODITE and GPCC, over the Asia in the period from 1951 to 2015. The background map used in this study was provided by Esri, USGS and NOAA (http://goto.arcgisonline.com/maps/World_Terrain_Base, last access: 17 January 2020).

There were mainly two kinds of errors in the satellite-based precipitation product, including systematic bias and random errors (Shen et al., 2014). As seen in the above-mentioned results, the random errors of the AIMERG were alleviated by using the APHRODITE data compared with IMERG (e.g., Fig. 4-11). In terms of the systematic errors, we compared the monthly Asian mean precipitation estimates of both APHRODITE and GPCC, from 1951 to 2015 (Fig. 13). The monthly Asian mean precipitation of APHRODITE varied between ~ 25 mm/month and ~ 100 mm/month, while those of GPCC ranged from ~ 50 mm/month and ~ 150 mm/month, which resulted the ratios of APHRODITE to GPCC fluctuated significantly from ~ 0.2 to ~ 0.9, with average value ~ 0.7, which meant that the GPCC at least overestimated the precipitation more than ~ 30%, compared with the APHRODITE. Therefore, the introduction of APHRODITE data would greatly reduce the systematic errors of the IMERG final product, over the Asia.

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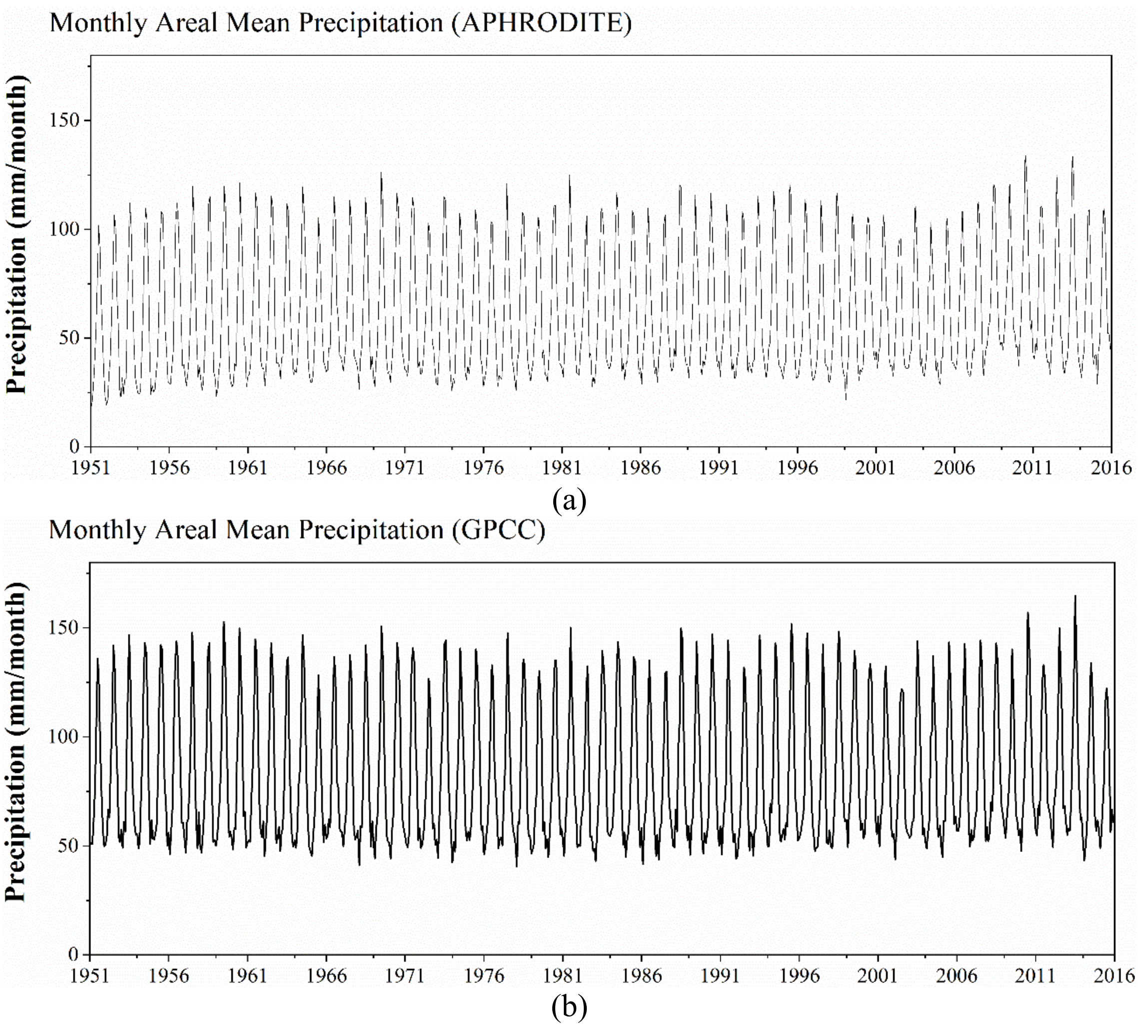
Preprint. Discussion started: 10 February 2020



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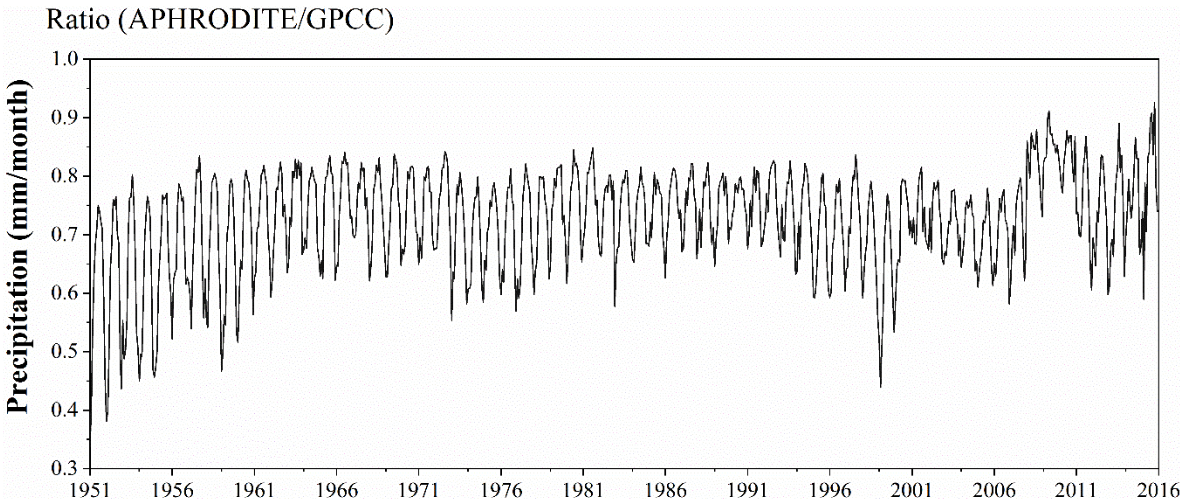
Preprint. Discussion started: 10 February 2020



(c)

Figure 13. The temporal patterns of monthly areal mean precipitation of (a) APHRODITE, (b) GPCC, and (c) APHRODITE/GPCC, 1951-2015.

5.2. The controls on the range of the spatial weights based on IMERG

As demonstrated in the document of the "ATBD", gauge information is introduced into the original multi-satellite-only half-hourly data to generate the final IMERG product. Firstly, the ratio between the monthly accumulation of half-hourly multi-satellite-only field and the monthly satellite-gauge field is calculated, then each half-hourly field of multi-satellite-only precipitation estimates in the corresponding month is multiplied by the ratio field to generate the half-hourly calibrated IMERG. After various experiments, the ratio values between the monthly satellite-gauge and the monthly accumulation of half-hourly multi-satellite-only fields is limited to the range [0.2, 3] (Huffman et al., 2019). The cap of 3 was decided due to the value of 2 (used in TRMM V6) was too restrictive. Additionally, the cap of 3 was

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

finally applied because it performed better in matching the two accumulations than that of other larger values, for instance, the cap of 4 resulted in introducing unrealistic shifts to histogram of half-hourly precipitation rates for the month. Additionally, early in TRMM the lower bound of 0.5 was applied, which suggests a smaller value of the lower bound allows matching between the two accumulations without creating the egregious high snapshot values when the upper bound is expanded too far.

Inspired by the range of the ratio values between the monthly satellite-gauge and the monthly accumulation of half-hourly multi-satellite-only fields in generating IMERG, we considered the range [0, 1.5] of the daily spatial disaggregation weights in this study was reasonable after careful checking the distributions of spatial disaggregation weights. The lower bound of 0 was selected based on the consideration if the IMERG did not capture the daily precipitation event, then the spatial disaggregation weight is still equal to zero, which agreed as most as possible to the original IMERG. While there were at least two reasons for setting the upper bound of the spatial disaggregation weights as 1.5: (1) most numerical values of spatial disaggregation weights were in the range [0, 1.5], and (2) there were obvious anomalies in the final calibrated AIMERG, especially along the coastal regions and edges of the specific precipitation event coverages, where the values of the spatial disaggregation weights were larger than 1.5. Though the range [0, 1.5] of spatial disaggregation weights was applied to obtain the final AIMERG in this study, we also considered that this was still an open-ended question.

5.3. The advantages of APHRODITE data in anchoring the satellite-based precipitation product

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

It has been a great challenge to obtain precipitation estimates over the Tibetan Plateau and its surroundings, as there were very limited ground observations in this region, especially in its western parts (Ma et al., 2017). Incorporating a uniform precipitation gauge analysis is important and critical for controlling the bias that typifies the satellite precipitation estimates, e.g., using GPCC for TMPA and IMERG (Huffman et al., 2019). Those projects (e.g., GPCC, TRMM, GPM) demonstrated that even monthly gauge analyses contributed significant improvements on the satellite-only precipitation estimates, at least for some regions in some seasons. Primarily explorations at CPC suggested substantial improvements in the bias corrections using daily gauge analysis, especially for regions, where there is a dense network of gauges. Foreseeably, GPM would try their best to calibrate the GPM satellite-only precipitation estimates at finer spatio-temporal scales (e.g., 0.25°/daily) worldwide.

Currently, GPCC were used to calibrate the TRMM TMPA and GPM IMERG at monthly scale. The Deutscher Wetterdienst (DWD) Global Precipitation Climatology Centre (GPCC) was established in 1989 to provide high-quality precipitation analyses over land based on conventional precipitation gauges from ~7,000-8,000 stations world-wide (Schneider et al. 2014, 2018). And two GPCC products were applied in the IMERG, the V8 Full Data Analysis for the majority of the time (currently 1998-2016), and the V6 Monitoring Product from 2017 to the then-present. Compared with GPCC, APHRODITE has inherently advantages with significantly larger numbers of ground observations and finer spatio-temporal resolutions, over the Asia. APHRODITE projects aimed at collecting as most gauge information as possible from the Asian countries. There were mainly three kinds of gauge information sources used in

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

APHRODITE analysis, the GTS-based data, data precompiled by other projects or organizations, and APHRODITE's own collection. More detailed information on the APHRODITE' data sources could be found at the website (http://www.chikyu.ac.jp/precip/) and the research of Yatagai (2012). Compared with the GPCC with the limited ground observations in and around the Tibetan Plateau in China, the neighboring countries provided plenty of ground observations in the APHRODITE data, in mountainous regions, and semi-arid and arid regions. Additionally, the spatio-temporal resolutions of APHRODITE (0.25°/daily) were finer than those of GPCC (1.0°/monthly). Therefore, APHRODITE has significant advantages in calibrating the IMERG data at daily scale.

The extent of the AIMERG could cover the Northern Eurasia, Middle East, Monsoon Asia, and Japan. This study mainly evaluated the AIMERG in the China Mainland, which calls for Asia wide evaluations in the future to assess both the algorithm and the corresponding precipitation product.

6. Data Availability

The AIMERG data record (0.1°/half-hourly, 2000-2015, Asia) is freely available at http://argi-basic.hihanlin.com:8000/d/d925fecf60/. Additionally, the AIMERG data is also freely accessible at https://doi.org/10.5281/zenodo.3609352 (for the period from 2000 to 2008) (Ma et al., 2020a) and http://doi.org/10.5281/zenodo.3609507 (for the period from 2009 to 2015) (Ma et al., 2020b).

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https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

Open Access Earth System Science Data Discussions

7. Conclusions

As the milestone in the satellite-based precipitation measurement process, the TRMM and its successor GPM generate the most popular and the state-of-the-art satellite precipitation products for both water cycle related scientific research and applications, TMPA (1998-present, 0.25°/3 hourly) and IMERG (2014-present, 0.1°/half-hourly), as well as the retrospective IMERG (2000-present, 0.1°/half-hourly) from GPM era to TRMM era. In this study, focusing on the potential drawbacks in generating IMERG and its recently updated retrospective IMERG (finished in July, 2019), which were only calibrated at monthly scale using limited ground observations, GPCC (1.0°/monthly), resulting the IMERG with large systematic bias and random errors, we introduced another daily gauge analysis product, APHRODITE (Last update October 5, 2018), to calibrate the IMERG at 0.25°/daily scale. Compared with GPCC, APHRODITE has inherently advantages with significantly larger numbers of ground observations and finer spatio-temporal resolutions (0.25°/daily), over the Asia.

We have proposed a new algorithm (Daily Spatio-Temporal Disaggregation Calibration Algorithm, DSTDCA) for calibrating IMERG at daily scale, and provided a new AIMERG precipitation dataset (0.1°/half-hourly, 2000-2015, Asia) (Ma et al., 2020a, b) with better quality, calibrated by APHRODITE at daily scale for the Asian applications. And the main conclusions included but not limited to: (1) the proposed daily calibration algorithm was effective in considering the advantages from both satellite-

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

based precipitation estimates and the ground observations; (2) AIMERG performed better than IMERG at different spatio-temporal scales, in terms of both systematic biases and random errors, over the China Main land; and (3) APHRODITE demonstrated significant advantages than GPCC in calibrating the IMERG, especially over the mountainous regions with complex terrain, e.g., the Tibetan Plateau. Additionally, Results of this study suggests that it is a promising and applicable daily calibration algorithm for GPM in generating the future IMERG in either operational scheme or retrospective manner.

Author Contributions

Dr. Ziqiang Ma designed and organized the manuscript. Drs. Jintao Xu, Siyu Zhu, and Yuanjian Yang prepared the related materials and run the models for generating AIMERG and the related assessments. Dr. Guoqiang Tang and Prof. Zhou Shi made contributions on the scientific framework of this study and discussed the interpretation of results. Prof. Yang Hong co-advised this study. All authors discussed the results and commented on the manuscript.

Competing interests

The authors declare they have no competing financial interests.

Acknowledgments

This study was financially supported by the National Natural Science Foundation of China (Grant No. 41901343); the Key R&D Program of Ministry of Science and Technology, China (Grant No. 2018YFC1506500); the China Postdoctoral Science Foundation (No. 2018M630037, and 2019T120021); the Open Fund of the State Key Laboratory of Remote Sensing Science, China (Grant No. OFSLRSS201909), the State Key Laboratory of Resources and Environmental Information System, China.

The contribution of the data providers is also greatly appreciated, including the Chinese Meteorological Data Sharing Service System (http://cdc.nmic.cn/home.do), the APHRODITE data provider (http://aphrodite.st.hirosaki-u.ac.jp/download/), and the IMERG data provider (https://pmm.nasa.gov/data-access/downloads/gpm).

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Open Access Earth System Science Data Discussions

Appendix A: Acronyms with definitions used in this study.

AIMERG	Asian precipitation dataset by calibrating GPM IMERG at daily scale using APHRODITE
APHRODITE	Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of Water Resources
ATBD	Algorithm Theoretical Basis Document
BIAS	Relative Bias
CC	Correlation Coefficient
CLIMAT	Monthly Climatological Data
CMA	Chinese Meteorological Administration
CMORPH	CPC Morphing
CPC	Climate Prediction Center
CSI	Critical Success Index
DSTDCA	Daily Spatio-Temporal Disaggregation Calibration Algorithm
DWD	Deutscher Wetterdienst
FAR	False Alarm Ratio
GEWEX	Global Energy and Water Exchange
GPCC	Global Precipitation Climatology Centre
GPM	Global Precipitation Measurement
GTS	Global Telecommunications System

https://doi.org/10.5194/essd-2019-250
Preprint. Discussion started: 10 February 2020

IDW	Inverse Distance Weighting
IMERG	Integrated Multi-satellitE Retrievals for GPM
IR	Infrared
ME	Mean Error
MW	Microwave
NHMs	National hydrological and meteorological services
NMIC	National Meteorological Information Center
PERSIANN	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks
PERSIANN-CCS	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System
PMW	Passive Microwave
POD	Probability of Detection
QC	Quality Control
RMSD	Root-mean-square Deviation
RMSE	Root Mean Square Error
SG	Satellite-Gauge
SYNOP	Synoptic Weather Report
TMPA	TRMM Multi-satellite Precipitation Analysis
TRMM	Tropical Rainfall Measuring Mission