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Validation of GSMAp products for a heavy rainfall event over complex terrain in Mongolia captured by the GPM core observatory

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Abstract

This paper focuses on the uncertainty of summer precipitation estimations produced by Global Satellite Mapping of Precipitation (GSMaP) over Mongolia, a region that has complex terrain and sparse weather observation networks. We first compared average summer precipitation over Mongolian territory as reported by several precipitation products. Although the interannual variability of the product was comparable, the amount of recorded precipitation differed among the various products. The rain-gauge-based analysis reported the lowest amount of precipitation, while the satellite-based GSMaP_MVK reported the highest amount. Our results represent a first estimate of the characteristic differences among the various precipitation-monitoring products, including GPM-based products, as they relate to climatic and hydro-meteorological assessments in Mongolia. We then made a detailed comparison using a case study in which a heavy rainfall event was captured by the Global Precipitation Measurement (GPM) mission's core observatory near Ulaanbaatar in July 2016. In this case, gauged and ungauged GSMaP estimates of the precipitation over the mountain area differed substantially between algorithm versions 6 and 7. An intercomparison of atmospheric numerical modeling, the GPM core observatory, and rain gauge observation showed that the rain gauge calibration of GSMaP effectively moderates the large error of the ungauged GSMaP data. The source of the significant ungauged GSMaP error is likely to be the rain rate estimates in version 7 of the algorithm. However, GSMaP gauge-calibrated estimates of the precipitation over mountainous areas may be affected by a potential underestimation of gauge analysis due to the missing localized precipitation occurring in the large gaps of the routine observation network. We expect that these findings will be helpful for developers seeking to further improve the GSMaP algorithm.
Keywords: GSMaP, precipitation dataset, orographic classification, gauge calibration, Ulaanbaatar
1. Introduction

Mongolia, situated in northeastern Eurasia, is characterized by a meridional gradient climatic zone determined by precipitation as well as temperature. Annual precipitation varies from less than 100 mm in the desert and arid/semiarid regions in the southern part of Mongolia to more than 350 mm in the boreal forest region in the north. Summer precipitation in June, July, and August account for 50–60% of the annual precipitation. Following the United Nations Framework Convention on Climate Change, the Third National Communication of Mongolia (Ministry of Environment and Tourism 2018) reported that summer precipitation occasionally induces natural disasters produced by short-range events of heavy rain and flash floods. Such disasters account for 22.4% of the total in the territory of Mongolia. Over the past decade, the occurrence of extreme events related to atmospheric phenomena has doubled. To properly assess hydrology and socioecology, accurate measurement and monitoring of precipitation over a sufficient period and geographic area are crucial. The sparseness of the meteorological observation network in Mongolia, however, limits the country’s ability to satisfy the growing societal demand for reliable meteorological information. The government currently operates 70 manned meteorological stations and 60 automatic stations (Battur 2010). The complexity of mountains that occupy most of Mongolia (Fig. 1a) and divide the meridional climatic regimes makes it difficult to create a dense observation network. Such a sparse meteorological network could very well miss precipitation occurring in remote areas far removed from the gauged stations in the short term and potentially hide the total amount of terrestrial water across the national territory.

Satellite measurement is one of the most powerful tools for monitoring global precipitation, especially in areas such as Mongolia which lack sufficient surface observational networks. In February 2014, the Global Precipitation Measurement
(GPM) mission (Hou et al. 2014), a successor to the Tropical Rainfall Measuring Mission (TRMM), was launched as the mission’s core satellite observatory. The GPM core observatory carries both a dual-frequency precipitation radar (DPR) and a multi-channel GPM microwave imager (GMI) developed by the Japan Aerospace Exploration Agency (JAXA) and the National Aeronautics and Space Administration (NASA), respectively. The DPR operates in two radar bands (13.6 GHz for the KuPR and 35.5 GHz for the KaPR) designed to directly capture the vertical structure of the precipitation. It is well known that satellite-based precipitation estimates have a substantial degree of uncertainty, especially at higher latitudes (Tian and Peters-Lidard 2010). Even though the swath width of the GPM core observatory is rather narrow, it has greatly expanded coverage to include mid/high latitudes (65° N/S) as compared to the more limited coverage of TRMM (35° N/S), with its non-synchronous orbit (Skofronick-Jackson et al. 2017). It is thus anticipated that measurements by the GPM core observatory will help to reveal the Earth’s water distribution and energy cycle in mid/high latitude land areas.

In addition to the GPM, the development of precipitation products based on multi-satellite combinations has been ongoing. For example, JAXA’s GSMaP (Global Satellite Mapping of Precipitation; Kubota et al. 2007), provides gridded precipitation rates in high temporal (1-hour intervals) and spatial (0.1 degrees in longitude and latitude within 60° N/S) resolutions using a combination of microwave and infrared radiometers on multiple satellites and the Moving Vector algorithm with Kalman filter (Ushio et al. 2009; hereafter called GSMaP_MVK). GSMaP_MVK can also be calibrated by rain gauge observation (Mega et al. 2018) using NOAA/CPC gauge-based analyses of global daily precipitation with a 0.5 degree grid (Xie et al. 2007; Chen et al. 2008). This GSMaP product is called the GSMaP_Gauge.

Many studies based on statistical indices on various spatiotemporal scales have
evaluated the systematic error and bias of GSMaP in the central and east Asian areas surrounding Mongolian territory by comparing the performance of GSMaP to gridded analysis originating from rain gauge observatories (e.g., Tan et al. 2017; Ning et al. 2017; Deng et al. 2018; Guo et al. 2017). Generally speaking, the rain-gauge-calibrated GSMaP_Gauge performs better than the GSMaP_MVK in these regions. Calibration by the gridded analysis of rain gauge observations effectively reduces errors and biases related to factors such as season, rain type, rain intensity, land surface condition, and topography. The benefit of rain gauge calibration, however, depends on the density of the gauge network or the source of the dataset; in some cases, such calibration can cause overcorrection or invalid results, especially in mountainous regions (e.g., Derin et al. 2016, 2019; Deng et al. 2018; Rozante et al. 2018; Takido et al. 2016; Yuan et al. 2019). Moreover, multi-satellite combination products such as GSMaP depend on the sensors on each satellite (microwave imager, sounder, and infrared radiometer). Chen et al. (2019) found that the precipitation estimates of GSMaP using GMI measurement, which works as a reference for partner satellites in the GPM constellation, tend to have relatively large biases for spring and summer rainfall over the Chinese mainland. The authors pointed out that the unsatisfactory detection capability of GSMaP’s GMI algorithm, which resulted in a relatively large hit and miss biases, needs to be further improved.

Although anterior statistical analysis has shown the general error features of GSMaP in the region by using a large number of grids and time series, it remains unclear when and under what circumstances the uncertainty associated with these satellite-based precipitation estimates tends to be most serious. To bridge the gap, an accumulation of case-based analyses of specific satellite precipitation errors in conjunction with national-scale climatological analyses would be of great help in identifying the error structure and improving the algorithm used for satellite
precipitation estimation. Notably, a general or severe error in specific grids due to
the algorithm might not always result in a significant mistake in climatic or national
scale precipitation estimates. Averaging over a longer period and in a broader area
may cancel out the error components in the individual grids. Thus, the combination
of a case study focused on a small region and climatic analysis averaged over a
national-scale area should give users more helpful information regarding the
performance of GSMaP.

The present paper reports a case study involving a heavy rainfall event captured
by the GPM core observatory in the vicinity of Ulaanbaatar (UB), Mongolia, in July
2016. Here, GSMaP_MVK and GSMaP_Gauge showed a significant difference in
their precipitation measurements. To assess measurement reliability, we compared
the precipitation structure described by GSMaP, atmospheric numerical modeling,
and the GPM core observatory’s active and passive measurement (KuPR and GMI)
with area rain gauge observations. Of course, this single case study does not
establish the general features of satellite retrieval and gauge calibration errors.
However, we believe that our results represent a useful step toward improving
satellite estimation of daily-scale rainfall in the GPM era. Moreover, to the best of our
knowledge, there have been few validation studies of GSMaP focused on high-
latitude Eurasia (Guo et al. 2017). The performance of GSMaP and gauge calibration
is still unclear in Mongolia, with its complex mountainous terrain and sparse
meteorological network. In this study, we first compared the national-scale summer
precipitation estimates of gauged and ungauged GSMaP with other precipitation
products (rain-gauge-based analysis, atmospheric reanalysis, and a combined
satellite and rain gauge product). More specifically, we made a simple comparison
of the interannual variability and average amount of precipitation over Mongolia for
the various products. This enabled us to make an educated first guess of the
characteristic differences among the products in their climatic and hydrological assessments. However, it should be noted that a detailed statistical analysis to validate GSMaP for the Mongolian territory is beyond the scope of this study.

2. Data

2.1 Precipitation products of GSMaP

In conducting our analysis, we used the standard products of version 6 and 7 of the GSMaP algorithms (Kubota et al. 2020). The GSMaP microwave radiometer algorithm detects the precipitation rate based on the measured brightness temperature and a look-up table. Over the land region, the retrieval algorithm relies only on the scattering signature from ice crystals over the spectrum of higher frequencies (e.g., 89 GHz), as the high and variable emissivity over land inhibits the use of an emission signature over the spectrum of lower frequencies (Aonashi et al. 2009). The look-up table is produced by a radiative transfer model using both atmospheric gridded analysis and a precipitation database built by TRMM precipitation radar (version 6) and GPM_KuPR (version 7). Moreover, the GSMaP algorithm since version 6 installs an orographic/nonorographic rainfall classification scheme. This scheme is expected to reduce underestimation owing to shallow precipitation systems over the mountainous regions and improve precipitation estimates over the TRMM observation area (Shige et al. 2013, Taniguchi et al. 2013, Yamamoto and Shige 2015). The threshold for orographic rainfall detection is based on the magnitude of both moisture flux convergence and the forced vertical motion \( w \) derived from the horizontal wind speed in the atmospheric gridded analysis. When the threshold is satisfied, the look-up table switches to an orographic table. Therefore, the estimated precipitation rate will differ from the native microwave radiometer estimate. Version 6 of the algorithm, however, overestimates orographic...
rainfall because both wind speed references at the surface and the threshold of $w$
are fixed (Yamamoto et al. 2017). Accordingly, version 7 of the algorithm modifies
the definition of horizontal wind speed and uses the upstream and low-level
atmosphere, adopting a fractional threshold of $w$ that is dependent on the magnitude
of the wind speed (Yamamoto et al. 2017). Subsequently, the gauge calibration
adjusts the hourly precipitation rate following optimal theory to fit the daily value of
the CPC gauge-based analyses (Mega et al. 2018). As a result, the precipitation
estimates by GSMaP with or without the gauging process will differ, even though the
same satellite measurement is referenced. In this paper, we call the products of
version 7 GSMaP_MVK and GSMaP_Gauge, while those of version 6 are referred
to as GSMaP_MVK$_{v6}$ and GSMaP_Gauge$_{v6}$. Daily precipitation was calculated from
the hourly product. For the intercomparisons of summer precipitation (June, July,
and August), we used the monthly product from 2014 to 2017, since GSMaP
includes measurements by the GPM observatories after March 2014. We also
referred the re-analysis version of GSMaP prior to 2014 compiled using version
6 of the algorithm without GPM observatories, calling the products GSMaP_RNL and
GSMaP_Gauge_RNL.

2.2 GPM observation

In the case study, we focused on the precipitation event around UB in Mongolia
on 09 July 2016. The GPM core observatory (orbit number 013432) passed near UB
at approximately 23:57 UTC and captured heavy precipitation. We used the
GPM_KuPR, GPM_KaPR, and DPR products compiled with a level-2 algorithm
version 05A (Iguchi et al. 2018, Seto et al. 2021). The GPM_KuPR product consists
of 150 vertical layers with 125 m intervals; the spatial resolution is 5 km, covering a
245 km-wide swath scanned by 49 beams. The matched scan of GPM_KaPR covers
a 125 km-wide swath scanned by 25 beams inside the swath of GPM_KuPR. The normal DPR scan data were used in this study. On the other hand, the horizontal swath width of GMI is approximately 904 km, which is significantly broader than that of GPM_KuPR. The retrieval from GMI is derived by the Goddard Profiling algorithm (Kummerow et al. 2001), hereafter called GMI/GPROF.

2.3 Other precipitation datasets, rain gauge observation, and numerical model configuration

For the rain-gauge-based dataset, we used Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Extreme Events (APHRODITE-1, v1101) data from 1979 to 2007 and APHRODITE-2 (v1901) data from 1998 to 2015 (Yatagai et al. 2012, Yatagai et al. 2020). For the combination of satellite and rain gauge observations, data from the Global Precipitation Climatology Project (GPCP) version 2.3 for 1979 to 2017 (Adler et al. 2003) and version 3.1 for 1984 to 2017 (GPCPV31, Huffman et al. 2020) were used. The horizontal grid spacing of both are 2.5 and 0.5 degree longitude and latitude grids, respectively. GPCPV31 also serves the precipitation estimate without gauge calibration (hereafter GPCPV31_SatOnly). Thus, it can compare to that of GSMaP_MVK. Moreover, the information about the relative weight of the rain gauge on each grid point is also introduced to quantify the gauge analysis’s percent weighting merged to the satellite-only estimate.

The estimation of precipitation by atmospheric reanalysis used ERA5 data produced by the European Centre for Medium-Range Weather Forecasts from 1979 to 2017, with 0.25 degree grids (Hersbach et al. 2020). We also used ERA5 to detect the synoptic atmospheric condition for the case study. All products are converted to monthly precipitation; the various time series of summer precipitation averaged over
the Mongolian territory were compared.

As a reference for the satellite measurements and GSMaP estimates, we used the rain gauge observation records from the Bagabayan station, installed by the Information and Research Institute of Meteorology, Hydrology and Environment in Mongolia. The Bagabayan rain gauge was set on a mountainside located approximately 35 km north of the Chinggis Khaan International Airport (Fig. 1b). It observed precipitation in 10-minute intervals over the entire summer season of 2016. Because Bagabayan was outside the routine observation network, we treated the Bagabayan observation data as independent from the satellite measurements and the data calibrated by rain gauge observation.

As a second reference, we applied the regional atmospheric modeling approach used by the Weather Research and Forecasting model version 4.0 (WRF; Skamarock et al. 2019). The regional atmospheric model gave us the capacity to examine precipitation that occurs in gaps of the surface observation networks such as in mountainous regions. Thus, WRF could help establish a reliable distribution of accumulated precipitation. The model domain, which consists of 230 × 196 grids with 5 km resolution, covers the northern part of Mongolia centered around UB (Fig. 1a). The vertical resolution has 51 layers, up to 50 hPa. Model integration began at 12:00 UTC on 09 July 2016, which preceded by approximately 12 hours the time at which the GPM core satellite passed above UB. The initial and lateral boundary conditions used ERA5, which operates every hour on 37 pressure levels. As for the microphysics scheme in the model, the Thompson scheme that includes ice, snow, and graupel processes (Thompson et al. 2008) was used to calculate the cloud microphysics; the Rapid Radiative Transfer Model for GCMs (Iacono et al. 2008) was used for short and longwave radiation; the Unified Noah Land Surface model (Tewari et al. 2004) served as the land surface model; Mellor–Yamada Nakanishi
and Niino (MYNN) level 2.5 (Nakanishi and Niino 2009) was used for both the atmospheric boundary scheme and the surface layer scheme. The sub-grid cumulus scheme was not adopted. Since WRF outputs the precipitation level every 10 minutes, we were able to evaluate total precipitation in 10-minute intervals.

3. Results

3.1 Summer precipitation represented by GSMaP and various datasets

a. Horizontal pattern over East Eurasia and Mongolia

We first examined the fundamental characteristics of the summer precipitation represented by GSMaP, focusing on the eastern part of Eurasia (Fig. 1a). The distribution of the rain gauge networks is dense at low latitudes area and sparse at high latitudes (Fig. 1a). The gauge grid points (APHRODITE and NOAA/CPC) in Mongolian territory are relatively poor coverage compared to the East-Asia and India. In the enlarged map around UB (Fig. 1b), gauge-stations are mainly located at relatively-low elevations such as at valley and basin in the complex terrain.

Figures 2a and 2b indicate the accumulation of summer precipitation represented by GSMaP_Gauge and GSMaP_MVK, averaged from 2014 to 2017. The distribution of summer precipitation indicated by GSMaP_Gauge tends to be quite smooth, in contrast to the GSMaP_MVK distribution, which shows a jagged pattern owing to some considerable precipitation in small regions. The GSMaP_Gauge minus GSMaP_MVK precipitation difference tends to be negative at higher latitudes and positive at lower latitudes (Fig. 2c), indicating that calibration by rain gauge observation decreases the precipitation estimated by satellite-only means at higher latitudes. The region showing the largest decrease corresponds to the northern side of the mountainous region in northern Mongolia (Figs. 1a and 2c). Figures 2d and 2e indicate the standard deviation of daily precipitation in GSMaP_Gauge and
GSMaP_MVK, which was calculated using days with more than 1 mm of daily precipitation. The variability of daily precipitation for GSMaP_MVK is higher than that for GSMaP_Gauge, which reflects the more complicated distribution of precipitation characterized by extreme values in narrow regions. In the northern part of Mongolia, GSMaP_Gauge damps the high variability estimated by GSMaP_MVK.

The differences found between GSMaP_Gauge and GSMaP_MVK were also identified between GPCPV31 and GPCPV31_SatOnly, averaged the same period of GSMaP (Figs. 2f, 2g, and 2h). The horizontal pattern of the anomaly which is characterized by positive at low latitudes and negative at high latitudes is consistent with that of GSMaP, although the magnitude was small (Figs. 2c and 2h). The northern part of Mongolian territory was also characterized by negative anomalies, which implies that the satellite-only precipitation estimates likely to be large (Figs. 2b and 2g) but the gauge calibration moderates them (Figs. 2a and 2f). This region could be regarded as one region that the quality of the rain gauge dataset should be careful because the weight of gauge analysis is higher than the surrounding region, which is more than 60% weighting to the satellite-only estimates (Fig. 2i).

Overall, the calibration by rain gauge observation reduces the mean and variability of precipitation determined by satellite measurement at higher latitudes. If a product based on sparse rain gauge observations tends towards underestimation, using such observations to calibrate satellite measurements may lead to a misrepresentation of actual precipitation and a loss of spatial variability in some areas.

b. Interannual variability and amount of precipitation

Next, we compared the interannual variability and the average amount of summer precipitation over Mongolia indicated by the various precipitation products (Fig. 3).
The variability of each product tended to show similar fluctuations. The correlation coefficients of ERA5, GPCPV31, and GPCP against APHRODITE between 1984 and 2015 were 0.88, 0.89, and 0.98, respectively (the APHRODITE time series was coupled with v1 and v2 from 1998 onward to construct the long-term series). The correlation coefficient for GSMaP_Gauge_RNL between 2000 and 2013 was 0.95, while the satellite-only product for GSMaP_RNL had a slightly lower coefficient of 0.72. GSMaP_Gauge also showed the same interannual fluctuations as ERA5 and GPCP, although the observation period here is very short. Algorithm versions 6 and 7 of GSMaP produced almost identical results to those of GSMaP_MVKs and GSMaP_Gauges. Thus, the difference in algorithms had little bearing on outcomes—producing neither a large improvement nor a significant deterioration of the quality of national-scale precipitation estimates over Mongolia.

Based on these comparisons, the implication is that the differences among products pose no serious problem for a climatic assessment of Mongolia focused on variability on the national scale. However, for estimating water resources, care should be taken in the selection of the precipitation dataset, since the amount varies greatly depending on the source of the products. APHRODITE, based on rain gauge observations, estimates lower precipitation than the others, while GSMaP_MVKs and GSMaP_RNL, based only on satellite measurements, show a considerably higher amount of precipitation. ERA5, GPCP, and GSMaP_Gauges estimate similar amounts, especially over the recent decade, even though their data sources are different; ERA5 is the forecast of an atmospheric model, while the others are a combination of satellite and rain gauge observations. The estimated amounts fall between those of APHRODITE and satellite-based GSMaP products. Interestingly, the modern GPCPV31 is nearly comparable to APHRODITE. The amount of precipitation over Mongolia in GPCPV31 well fits the gauge analysis than that of the
previous GPCP although the correlation coefficient slightly falls.

At first glance, it appears that rain gauge observation corrects the overestimation of satellite measurement but that the other products still overshoot APHRODITE, except for GPCPV31. Although APHRODITE and other rain-gauge-based datasets are believed to approximate the truth, insufficient surface observation networks like those in the high latitudes of Eurasia with complex terrain could cause substantial uncertainty due to the broad gaps between observation points.

3.2 Heavy precipitation event around Ulaanbataar

a. Synoptic scale atmospheric condition

To further examine differences among the GSMaP products and satellite radar measurements, we focused on a single heavy precipitation event in the vicinity of UB. On 09 July 2016, the GPM observatory captured heavy precipitation in the UB area. Figure 4a displays a composite map showing the surface precipitation rate estimated by GPM_KuPR and GMI/GPROF (The variables used here are precipRateESurface in GPM_KuPR and surfacePrecipitation in GMI/GPROF, respectively). The GPM observatory passed over UB between 23:57 to 23:59 UTC, which corresponded to 07:57 and 07:59 Local Time of UB. A synoptic-scale atmospheric condition characterized by a geopotential height of 850 hPa indicated a cyclonic system located in the northeastern part of Mongolia (Fig. 4b). The precipitation occurred on a large horizontal gradient of potential temperature identified by northwestern cold air and eastern warm air (Figs. 4a and 4b). The vertically integrated moisture flux and precipitable water showed that there were two streams of moisture transport (Fig. 4c): One was an abundant south-westerly moisture flux passing over a desert region in southern Mongolia. The other was a north-westerly moisture flux that came from the boreal forest region. In this case,
these features indicated that a large-scale atmospheric frontal system related to the
synoptic disturbance was the dominant driver of the precipitation. The GPM core
observatory passed just along the convergent zone of moisture fluxes.

b. Precipitation structure captured by GPM DPR

Figures 5a and 5b show the precipitation pattern captured by GPM_KuPR,
magnified around UB and Bagabayan, respectively. GPM_KuPR estimated a
precipitation rate exceeding 50 mm hr$^{-1}$ at the surface of the mountains northeast of
UB, not far from the Bagabayan rain gauge station (topography is shown in Fig. 6a).
Figures 5c and 5d show the vertical structures of the precipitation system depicting
the precipRate in the GPM_KuPR product. Two lines have been drawn through
Bagbayan’s location. Line A–B corresponds to the direction in which the precipitation
system was traveling; line C–D runs parallel to the frontal system. In Figures 5b and
5c, a precipitation rate exceeding 50 mm hr$^{-1}$ occurred in a narrow region on the
windward side of the mountains. The vertical structure along with the frontal system
(Fig. 5d) shows a precipitation rate of approximately 1 mm hr$^{-1}$ at a height of nearly
8 km aloft of the lower-level heavy rainfall area northeast of Bagabayan. The
GPM_KuPR algorithm involves a rain type classification module that classifies three
main types of rain (stratiform, convective, and other), as referenced by vertical profile
and horizontal distribution of the radar reflectivity factor, which are called V method
and H method (Awaka et al. 2016). While a few pixels were classified as convective
rain in this case, large parts of the precipitation were classified as stratiform rain
(Figs. 5c and 5d).

To clarify the difference in the precipitation along the mountain slope, we show
the average vertical profiles of the measured and attenuation-corrected radar
reflectivity factors ($Z_m$ and $Z_e$, called zFacotorMeasured and zFactorCorrected in the
product, respectively) by both GPM_KuPR and KaPR (Fig. 6). Additionally, Figure 6 displays the mean diameter of the precipitation parcel ($D_m$, which is stored in paramDSD in the product) as estimated by the DPR algorithm drop size distribution module (Iguchi et al. 2018, Seto et al. 2021). The vertical gradients of $Z_m$ and $Z_e$ from beneath the bright band to the surface provide additional information regarding rain type. Kobayashi et al. (2018) showed that the downward increase of $Z_e$, which results from raindrop growth related to warm-type clouds, is frequently found under the stratiform rain pixel over the North Pacific Ocean and East Asia. Porcacchia et al. (2019) also sought to detect the signatures of the reflectivity factor in DPR dominated in a collision–coalescence process focused on the contiguous United States. Following Porcacchia et al. (2019), $Z_m$ of KuPR in the liquid layer tends to increase toward the surface when the collision–coalescence process dominates. The profiles in Figure 6 were chosen at three locations: 1) the windward side, 2) the hillside, and 3) near the mountain peak indicated in Figures 5c and 6a. They have an average width of 55 km (11 beams) along the track of the GPM satellite, such as between $\alpha$ and $\beta$ in Figures 5d and 6a. The average procedure is only conducted if all 11 beams store no-missing data in each vertical level. The mean topographic height at each location were roughly 1380, 1700, and 1930 m (The variable used here is the elevation in GPM_KuPR). The surface precipitation rate estimated by GPM_KuPR and KaPR indicated that the hillside of the mountain experienced relatively intense precipitation compared to the others, reaching approximately 54.1 and 12.7 mm hr$^{-1}$, respectively (Fig. 6b).

The average vertical profiles of KuPR showed that the melting layer, which was characterized by the peak of $Z_m$ and $Z_e$, was located beneath the level of 0$^\circ$ C height (Figs. 6b and 6c). Such $Z_m$ and $Z_e$ shapes are similar to a typical stratiform rain
situation. The melting layer’s height gradually increased from the windward side to the mountain peak, which implies a cloud base lies along the mountain slope. This feature suggests to us that the low-level atmosphere was forced to rise by the orography and formed a cloud. Beneath the melting layer, $Z_m$ of KaPR decreased with decreasing height, meaning that KaPR suffered from large attenuation by rain particles at lower-levels, especially on the hillsides and near the peaks of the mountain range ($Z_{m2}$ and $Z_{m3}$). Whereas the vertical gradients of $Z_m$ in KuPR were nearly zero beneath the melting layer (Fig. 6b), those of $Z_e$ in KuPR slightly increased towards the surface, especially on the hillsides ($Z_{e2}$ in Fig. 6c).

The vertical distribution of $D_m$ also differed noticeably among locations (Fig. 6d); the large diameter for the entire level was estimated at the hillside ($D_{m2}$). Thus, the raindrop size might contribute to intensifying the precipitation rate. $D_{m2}$ and $D_{m3}$ also slightly increased towards the surface, which is reflected in the profiles of $Z_e$, especially in the liquid layer below the $0^\circ$ C height. Such features lead us to expect that the growth of raindrops by the collision–coalescence process might have occurred in this case. The downward increase in $Z_m$ in KuPR, which, according to Porcacchia et al. (2019), is one feature of a dominant collision–coalescence process, was not found in our case (Fig. 6a).

c. Intercomparison of several precipitation estimates

This section examines the reliability of precipitation estimates by several products comparing to observations. The time series of surface precipitation recorded by the Bagabayan station is shown in Figure 7.

In terms of sub-hourly precipitation, the rain gauge observed surface rainfall of approximately 9.6 mm hr$^{-1}$ between 23:50 and 00:00 UTC on 10 July 2016 when the
near synchronism time of the GPM core satellite. The GMI/GPROF and GPM_KuPR grid points nearest to Bagabayan estimated surface precipitation rates of 7.8 and 19.8 mm hr$^{-1}$, respectively. While the GMI/GPROF value was close to the in-situ observation, the GPM_KuPR estimate was markedly larger. In contrast to GPM_KuPR, the horizontal pattern of the precipitation rate produced by GMI/GPROF mostly showed weak precipitation of less than 10 mm hr$^{-1}$ (Fig. 8a). This pattern followed that of the polarization-corrected brightness temperature at 89 GHz observed by GMI (GMI_PCT89, Fig. 8g), as precipitation retrieval uses the high-frequency band of GMI over the land region. The definition of PCT89 here follows Cecil and Chronis (2018). PCT89 shows a relatively lower temperature in the area northeast of Bagabayan. Thus, GMI measured high ice scattering at a higher level, especially around Bagabayan, and GMI/GPROF used it to estimate the surface precipitation rate. Conversely, precipitation retrieval by space-borne radar systems such as GPM_KuPR is regarded as superior to that achieved by microwave radiometers such as GMI, particularly over land. The surface precipitation rate of GPM_KuPR is extrapolated from the upper-level precipitation rate above the clutter-free bottom (dotted lines in Figs. 5c and 5d). The heavy precipitation system detected by GPM_KuPR is somewhat reasonable for the area near Bagabayan, as the rain gauge recorded intense rainfall of about 20 mm hr$^{-1}$ before the passing of the GPM core observatory (Fig. 7a). Additionally, WRF succeeded in evaluating a similar tendency and intensity of observed precipitation (Fig. 7b), slightly delayed relative to the actual state (the peak of precipitation delayed about 30 minutes). The horizontal distribution by WRF also suggested intense precipitation around UB similar to that of GPM_KuPR (Fig. 8b). Thus, we expected that GMI/GPROF would potentially underestimate the snapshot precipitation rate, especially around the hillside of the mountain. A lower-atmospheric process, such as collision—
coalescence, may cause a difference in precipitation intensity estimates between GMI/GPROF and GPM_KuPR.

In terms of hourly precipitation, the gauge observation recorded 12.2 mm between 23:00 and 00:00 UTC (Fig. 7a). If we evaluate hourly precipitation by a snapshot precipitation intensity, the GMI/GPROF (7.8 mm hr$^{-1}$) explains about 64% of the observed amount of hourly precipitation while the observation (9.4 mm hr$^{-1}$) explains 77% of oneself. In Figure 7b, the WRF hourly precipitation (WRF_1hr) well replicated that of observation as estimate at 13.0 mm; the window of 1-hour precipitation was between 23:30 and 00:30 UTC to fit the actual precipitation tendency. The WRF’s snapshot precipitation rate displayed at 00:20 UTC, which was regarded as the corresponding time to the GMI/GPROF, was 5.5 mm hr$^{-1}$, which explains 42% of hourly precipitation in oneself. Therefore, the snapshot precipitation intensity of GMI/GPROF also slightly underestimates if it is regarded as the amount of hourly precipitation in this case. However, the horizontal pattern of GMI/GPROF can be qualitatively representative of that hourly state of WRF, at least around Bagabayan (Figs. 8a and 8e).

In contrast to GMI/GPROF, GSMaP_MVK estimated a more extreme value (58.2 mm hr$^{-1}$) than the other GSMaP products, even though a GMI was installed (Fig. 7a). The horizontal pattern of GSMaP_MVK indicated that the extreme amounts of precipitation—over 50 mm hr$^{-1}$—mostly appeared on the surface of the mountain slope around UB (Fig. 8c). On the other hand, GSMaP_MVKv6 estimates were closer to the GMI/GPROF values (Fig. 8d). It means that the difference in the algorithms caused this extreme estimate of precipitation. It is possible that version 7 of the algorithm succeeded in detecting orographic rainfall in this case but considerably overestimated its amount. After the extreme precipitation period, GSMaP_MVK again indicated greater precipitation than did GSMaP_MVKv6 between 01:00 and
02:00 UTC when the microwave measurement was performed (Fig. 7a).

Comparisons to observations show that GSMAp_MVK_v6 and GSMAp_Gauge produced a relatively reliable precipitation rate around Bagabayan, at least in this case. Especially for GSMAp_Gauge, data from the routine observation site situated somewhat close to Bagabayan effectively moderated the extreme precipitation rate of GSMAp_MVK. Conversely, GSMAp_Gauge_v6 indicated the lowest precipitation rate due to the over-calibration of GSMAp_MVK_v6, whose estimates were near the observed values. Based on this narrow comparison, GSMAp_Gauge could be regarded as a better product than the other GSMAp products. However, the calibration by rain gauge observation significantly damped the horizontal pattern of precipitation (Figs. 8f and 8g). Over the mountains, the GSMAp_MVK estimates are mostly similar to the horizontal pattern of GMI_PCT89, whereas GSMAp_Gauges presents a much smoother picture, especially GSMAp_Gauge_v6, which show a modest pattern. These results imply a loss of structure detail with rain gauge calibration.

d. Difference between gauged and ungauged GSMAp in 24-hour accumulation

Finally, we examined the accumulated precipitation. Figure 9a shows the 24-hour accumulated precipitation from 18 UTC 09 July as evaluated by WRF, which is regarded as replicating the precipitation system. The largest accumulated precipitation was found in the northern part of the mountains rather than around UB. Thus, the heavy rainfall system around UB captured by GPM_KuPR (Fig. 5) was merely episodic. Figures 9b and 9e show the accumulated precipitation estimated by GSMAp_MVK and GSMAp_MVK_v6. The precipitation patterns were nearly the same, except around UB, where GSMAp_MVK produced overestimates. Both products also indicated a relatively large amount of rainfall in the northern part of the
mountains, similar to WRF in spatial distribution. Although estimates of the occurrence of extreme rainfall around UB appear unreliable, the large rainfall estimate in the northern part of the mountains could be considered consistent as it is similar to the WRF output. On the other hand, the calibration by rain gauge observatories encompassing the mountains reduced the precipitation not only around UB but also in broad regions over the mountain (Figs. 9c and 9f). This may reflect that the sparse gauge observation network is unable to detect local precipitation in their gaps, especially over the mountain. As a result, the horizontal patterns of accumulated precipitation to be much smoother than those of GSMaP_MVKs. In fact, the reduction of precipitation exceeded 15 mm in the northern part of the mountains (Figs. 9d and 9g), which corresponds to roughly half the GSMaP_MVK estimate. These results suggest that GSMaP_Gauge may be affected overcorrection in the gaps between rain gauge observatories, particularly over mountain regions, where the sparse observatories potentially miss localized precipitation.

4. Discussion

An intercomparison of GPM_KuPR, GMI/GPROF, and GSMaP products for the case described in this study suggests that the precipitation estimates of GSMaP products are affected by uncertainties caused by both differences in the algorithms and the use of rain gauge calibration, especially over remote mountainous regions. The former uncertainty may be linked to estimated rain rates over a delineated orographic area even where the latest algorithm succeeds in detecting orographic rainfall. The latter is likely the result of gaps in ground-based observatories. These uncertainties can occur frequently and contribute to estimates of the total precipitation in a specific region, as they are strongly related to geographic location.
To demonstrate other cases, we compared hourly precipitation observed at Bagabayan and the estimates of the various GSMaP products over the entire 2016 summer season. Figure 10 shows scatter diagrams of the results of the observations and GSMaP products. The selected cases satisfied two requirements: They involved 1) GSMaP installed microwave radiometer measurement, and 2) observation or GSMaP products recorded over 0.1 mm hr$^{-1}$. The total precipitation for all cases observed at the Bagabayan station was 168 mm, as compared to the GSMaP_MVK and GSMaP_MVK$_{v6}$ estimates of 349.7 mm and 229.5 mm, respectively. The overestimation by GSMaP_MVK was largely due to two extreme cases where roughly 40 and 60 mm hr$^{-1}$ were reported (Fig. 10a); the latter was the case described in this study. In both cases, GSMaP used GMI measurement but it is unclear such overestimation solely depended on GMI or not because the sampling number is very small (only one summer season and one grid point). At least this comparison, the precipitation rate evaluated by version 7 of the algorithm tended to be considerably overestimated than those of version 6 of the algorithm. Although differences in the algorithm results might be negligible for national scale precipitation (Fig. 3), such extreme precipitation rates could well lead to a significant error in estimates of the total rainfall in a small area. Rain gauge calibration moderated these errors, at least for Bagabayan, but produced a slight over-calibration (Fig. 10b).

To assess these errors for other locations, we investigated each grid of GSMaP around UB, focusing on the 2014 and 2017 summer seasons. Figure 11a shows the frequency with which GSMaP_MVK with microwave measurements recorded over 1 mm hr$^{-1}$ in the hourly products. A relatively large number of precipitation events were estimated at the mountain northeast of Bagabayan. The root-mean-squared error (RMSE) for GSMaP_MVK and GSMaP_MVK$_{v6}$ in this northeastern mountain area, which was calculated using all events for each grid was large (Fig. 11b), indicating
a significant difference between the products in this area. On the other hand, while a large number of precipitation events was also recorded at the mountain located at approximately 51° N and 102° E (Fig. 11a), the RMSE was smaller than at the northeastern mountain (Fig. 11b). Thus, the mountain northeast of Bagabayan was regarded as one of the sensitive areas, likely due to the differences in the algorithm.

The ratio of the mean precipitation rate of GSMaP_MVK to the mean rate of GSMaP_MVK_v6 showed that the upgrade of the algorithm from version 6 to version 7 generally increased the estimated precipitation rate at high latitudes and in mountain areas (Fig. 11c). Based on the results reported in this paper, the increased precipitation rate estimated by version 7 of the algorithm did not always mean an improvement in the estimate, especially at higher latitudes, where precipitation is less than at lower latitudes. Rain gauge calibration decreased the mean precipitation rate of GSMaP_MVK by more than half everywhere (Fig. 11d). More specifically, while the decrease in the rate near the grids of the observatory tended to be suppressed by roughly 50%, the gaps between observatories in the southern desert region were affected by the slightly strong attenuation. The gauge calibration algorithm in GSMaP considers the reliability of CPC data by counting the number of rain gauges within the 7 × 7 grid area around each grid and subsequently applies a weight to the CPC rainfall rate (Mega et al. 2018). This approach, however, would likely evaluate nearly all of the grids in Figure 11 as reliable. Thus, a rainfall rate stored in non-gauge grids can be introduced to the calibration even if the CPC data involves underestimates. The strong attenuation in the southern desert region, where precipitation is less, is perhaps reliable, but over the mountain and boreal forest regions at high latitudes, it could result in over-calibration. In such a high-latitude region, GPCPV31 adopts the relatively high weight of the gauge analysis to merge satellite-only precipitation estimates (Fig. 2i). Thus, the GPCPV31 may also
be affected by the calibration error due to the gauge analysis which potentially misses the precipitation in the gap of observatories.

5. Conclusion

The present study provided two analyses. The first compared the performance of gauged and ungauged GSMaP (GSMaP_Gauge and GSMaP_MVK) with several other precipitation products estimating summer precipitation in eastern Eurasia and the Mongolian territory to judge their climatic assessment capability. The second analysis focused on a case study of extreme precipitation events observed in July 2016 in the vicinity of UB in Mongolia. It was found that the precipitation estimates of the GSMaP products were affected by the uncertainties associated with the different algorithm versions and by the use of rain gauge calibration.

For national scale precipitation, while the impact of algorithm differences is generally negligible, the use of rain gauge calibration can effectively correct the tendency of satellite-only GSMaP products to overestimate precipitation. Based on the results from several datasets, GSMaP_Gauge estimates were found to be comparable to other precipitation estimates. However, gauge-corrected satellite precipitation and atmospheric reanalysis, excepted for GPCPV31, tended to record higher amounts of precipitation than the rain-gauge-based APHRODITE, although the variability of the measurements was nearly the same.

Several implications emerge from the case study. We found that GSMaP_Gauge may overcorrect over a mountain region encompassed by the surface observation network. It also appeared that the gridded analysis of rain gauge observation potentially underestimates the actual precipitation over mountainous areas, especially in the gaps of the observation network. Thus, as Mongolia has a complex
terrain and a sparse observation network, reported amounts of precipitation should be treated with some degree of skepticism, even in cases where the analysis is based on rain gauge observations. The uncertainty of rain-gauge-based analysis resulting from sparse observational networks is likely to limit the accuracy of satellite-based precipitation estimates.

When the focus shifts to smaller regions, the uncertainty due to the different algorithm versions increases in importance. Version 7 of the algorithm in GSMaP_MVK leads to better estimates for cases over TRMM observation areas owing to the improvement of the orographic/nonorographic scheme relative to version 6 (Shige et al. 2013, Taniguchi et al. 2013, Yamamoto and Shige 2015, Yamamoto et al. 2017), and succeed in replicating the signature of intense rainfall along the mountain slope captured by GPM’s precipitation radar. The evaluated precipitation amount over the delineated orographic area was, however, considerably amplified. Such extreme values can produce significant errors in the estimate of the total amount of precipitation in a specific region where rainfall is relatively low, such as at higher latitudes. GSMaP_Gauge is able to correct such unreliable extreme rainfall estimates; however, the tradeoff is a loss of the horizontal distribution of precipitation due to the large gaps between observatories, especially over a mountain. In brief, GSMaP users should carefully select the GSMaP products and their algorithm versions to fit their particular scientific scope.

The algorithm versions of GPM DPR also should be carefully selected. This study used the product compiled by the algorithm version 05A but that of algorithm version 06A has been released during our analyses. Iguchi et al. (2018) noted that the DPR and Ku rain estimates in version 06 agree better with ground validation data over the United States and the rain classification algorithm improved. Comparing between 05A and 06A for the case under this study, we found that the surface precipitation
rate over Bagabayan estimated by KuPR of 06A consists to those of the rain gauge
and GMI/GPROF than 05A (9.0 mm hr⁻¹ in 06A and 19.8 mm hr⁻¹ in 05A). The
horizontal and vertical structures characterized by the extreme precipitation rate in
Figure 5 are to be modest in 06A (Fig. S1), which looks more reliable than 05A.
The results of the present study are based on simple comparisons and a single
case study, which means that they do not establish in statistical terms the general
features of the error component of GSMaP for the Mongolian territory. An intensive
observation campaign aimed at filling the gaps in the observation network would
serve to improve the GSMaP algorithm, gauge calibration, and the performance of
gauge-based analysis in Mongolia. We hope that the results reported here will be
helpful for the developers of the GSMaP algorithm.
Regarding precipitation monitoring, the availability of the standard product of
GSMaP (including GSMaP_Gauge) remains limited by the three-day latency in the
product release. Today, satellite-based precipitation products are expected to
provide real-time monitoring for disaster prevention and/or hydrological assessment.
To address the societal demand for more immediate information, JAXA has newly
provided a near-real-time version of GSMaP and a bias-adjusted variation
(GSMaP_NRT and GSMaP_Gauge_NRT, respectively), with the latency period
shortened to four hours. The error calibration of GSMaP_Gauge_NRT uses
parameters based on a GSMaP_Gauge historical database covering the previous
30 days. A very recent preliminary study reported that, while GSMaP_Gauge_NRT
effectively reduces the bias of GSMaP_NRT, its ability to accurately detect
precipitation over the Chinese mainland did not improve significantly (Lu and Yong
2020). It is quite possible that the historical parameter for bias correction is affected
by the quality of the original rain gauge analysis. To better respond to societal
demands, future validation studies should focus on the accuracy or performance of
such near-real-time versions as well as the standard products.
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Fig. 8 Horizontal patterns of the surface precipitation rate (mm hr$^{-1}$) estimated by a) GMI/GPROF, b) WRF, c) GSMaP_MVK, d) GSMaP_Gauge, e) WRF_1hr, f)
GSMaP_MVK
GSMaP_Gauge
Same as a) but for PCT89 estimated by GMI (K). The range of the drawings is the same as in Figure 5a. GMI/GPROF is a snapshot at the same time as in Figure 4a. WRF indicates the precipitation rate calculated between 00:20 and 00:30 UTC, and WRF_1hr shows the hourly precipitation estimated between 23:30 and 00:30 UTC. GSMaP products show the 1-hour precipitation rate between 23 and 00 UTC. The solid and dotted lines show the topography identified by 1500 m and the swath coverage of GPM_KuPR, respectively. The black circle and black star indicate the locations of Bagabayan and Chinggis Khaan International Airport, respectively.

Fig. 9 24-hour accumulated precipitation (mm) estimated by a) WRF and b) GSMaP_MVK, c) GSMaP_Gauge, and d) the anomaly of GSMaP_Gauge vs GSMaP_MVK; e), f) and g) are same as b), c) and d) but for version 6 of the algorithm. The range of drawings is the same as in Figure 1b. The contour line indicates the topography identified by 1500 m. The dotted lines in a), b), c), e) and f) show the swath coverage of GPM_KuPR. The gray-shaded boxes in c), d), f) and g) are grid cells that have more than one rain gauge station in the NOAA/CPC gauge analysis. The black star indicates the location of Chinggis Khaan International Airport.

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Fig. 8 Horizontal patterns of the surface precipitation rate (mm hr⁻¹) estimated by

a) GMI/GPROF, b) WRF, c) GSMaP_MVK, d) GSMaP_Gauge, e) WRF_1hr, f) GSMaP_MVK_v6, and g) GSMaP_Gauge_v6; h) Same as a) but for PCT89

estimated by GMI (K). The range of the drawings is the same as in Figure 5a.

GMI/GPROF is a snapshot at the same time as in Figure 4a. WRF indicates the precipitation rate calculated between 00:20 and 00:30 UTC, and WRF_1hr shows the hourly precipitation estimated between 23:30 and 00:30 UTC. GSMaP
products show the 1-hour precipitation rate between 23 and 00 UTC. The solid and dotted lines show the topography identified by 1500 m and the swath coverage of GPM_KuPR, respectively. The black circle and black star indicate the locations of Bagabayan and Chinggis Khaan International Airport, respectively.
Fig. 9 24-hour accumulated precipitation (mm) estimated by a) WRF and b) GSMaP_MVK, c) GSMaP_Gauge, and d) the anomaly of GSMaP_Gauge vs GSMaP_MVK; e), f) and g) are same as b), c) and d) but for version 6 of the algorithm. The range of drawings is the same as in Figure 1b. The contour line indicates the topography identified by 1500 m. The dotted lines in a), b), c), e) and f) show the swath coverage of GPM_KuPR. The gray-shaded boxes in c), d), f) and g) are grid cells that have more than one rain gauge station in the NOAA/CPC gauge analysis. The black star indicates the location of Chinggis Khaan International Airport.
Fig. 10 a) Scatter diagram of the hourly precipitation observed at Bagabayan and estimated by GSMaP_MVKs between June and August 2016. The red star and blue circle indicate versions 6 and 7, respectively. The filled circle indicates that the installed microwave radiometer in GSMaP is GMI. The amount of accumulated precipitation (mm) by Obs, MVK, and MVKv6 are shown inside the diagram. The scatter diagram enlarged by the axis range of 9 mm hr\(^{-1}\) is embedded at the top right in the diagram; b) Same as a) but for GSMaP_Gauges.
Fig. 11 a) Map of the frequency with which the hourly product of GSMaP_MVK estimated a precipitation rate of more than 1 mm hr$^{-1}$ during the summer seasons between 2014 and 2017. The gray-shaded boxes are grid cells that have more than one rain gauge station in the NOAA/CPC gauge analysis. The contour line indicates the topography identified by 1500 m; b) Same as a) but for RMSE for hourly precipitation rate between GSMaP_MVK and GSMaP_MVK_v6; c) Same as a) but for the ratio of the average precipitation rate of GSMaP_MVK to the average rate of GSMaP_MVK_v6; d) Same as c) but for GSMaP_Gauge and GSMaP_MVK.