

Intercomparison of the Relationship between Precipitation and Elevation among Gridded Precipitation Datasets over the Asian Summer Monsoon Region

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Abstract

The authors conducted an intercomparison of the elevation dependency of precipitation over the Asian summer monsoon region among 16 gridded precipitation datasets that consisted of rain-gauge-based (GAUs), satellite-based (SATs), and gauge-satellite combination datasets (MRGs). The elevation dependencies of the mean terrestrial precipitation in the gridded precipitation datasets were qualitatively consistent. The SATs were generally less than the GAUs at low and middle altitudes, but comparable at high altitudes. The scatter of the differences among the GAUs was smaller than that of the SATs. The elevation dependency of the mean intensity of the heavy terrestrial precipitation, defined as the 95th percentile of daily precipitation, was similar to that of the mean precipitation. The scatter of the differences in the elevation dependency among the SATs was greater than that among the GAUs. These results imply that differences in spatial interpolation methods have little impact on the differences among GAUs but that differences in the rainfall retrieval algorithm have a large impact on the quantitative differences among SATs.

Key words: elevation dependency, gridded precipitation, rain-gauge, satellite

1. Introduction

Precipitation is one of the most fundamental and important physical variables for describing weather and climate. Gridded precipitation datasets have been used in studies on variations with time scales ranging from less than a day to decades. In addition to averages, recent growing concern has focused on extreme events closely related to natural disasters (*e.g.*, floods and droughts). Precipitation is also important to numerical weather and/or climate models, which are powerful tools for long-term climate research as well as short-term weather forecasts. Therefore a gridded precipitation dataset with finer temporal resolution as well as higher spatial resolution is required.

This study performs an intercomparison among gridded precipitation datasets to examine differences among rain-gauge-based datasets, and among satellite-based datasets. It also examines the differences between rain-gauge-based datasets and satellite-based datasets. The target area is the Asian summer monsoon region (Fig. 1). Through intercomparison, it analyzes the features of and differences between rain-gauge-based and satellite-based datasets.

The authors focus on the elevation dependency of

precipitation. Water is essential to all life on the Earth. Most sources of the water that is essential to human activities are rivers, ground water and lakes. Their origin is precipitation over mountainous regions. Intercomparison of gridded precipitation datasets would be useful in clarifying the characteristics of precipitation at high altitudes in the present-day climate and in validating the reproducibility of precipitation at high altitudes in climate models.

The authors chose the Asian summer monsoon region, including the Tibetan Plateau, because the Tibetan Plateau and surrounding mountainous regions are the headwater regions of large rivers (*e.g.*, Yellow, Yangtze, Red, Mekong, Brahmaputra, Ganges, Indus, Tarim, Amudar'ya, and Syrdar'ya Rivers), with more than one third of the Earth's population living in the catchment of these rivers (World Bank, 2010). The water usage demands of the people who live in arid or semi-arid regions depend largely on rivers whose headwater regions are far from where they live.

Many studies have compared gridded precipitation datasets around the globe (*e.g.*, Adler *et al.*, 2001) or in certain regions (*e.g.*, Rajeevan *et al.*, 2006 for India; Zao & Fu, 2006 for China; Roongroj & Chiu, 2008 for Thailand; Schiemann *et al.*, 2008 for Central Asia;

Kubota *et al.*, 2009 for Japan). Most previous studies on the elevation dependency of precipitation have used rain gauge observations and focused on a relatively small spatial scale (*e.g.*, Sasaki & Kurihara, 2008 for Japan; Gouvas *et al.*, 2009 for Greece; Kuraji *et al.*, 2009 for northern Thailand; Suprit & Shankar, 2008 for the Indian west coast). No study has focused on the elevation dependency of precipitation in gridded precipitation datasets.

The rest of this paper is organized as follows. Section 2 briefly describes the gridded precipitation datasets used in this study. Section 3 describes the analyzed region and topography. Sections 4, 5, and 6 present the results. Sections 7 and 8 provide a discussion and concluding remarks.

2. Data

Gridded precipitation datasets are roughly classified into three categories: rain-gauge-based (GAUs), satellite-based (SATs), and gauge-satellite combination datasets (MRGs). Rain-gauge observations and an objective analysis technique are utilized to construct GAUs. Production of SATs utilizes information acquired by sensors installed in satellites and a physical-model-based retrieval algorithm that has been actively developed for the last few decades. Rain gauge observations and information from satellites are synthesized to construct MRGs. In this study, the authors used 16 gridded precipitation datasets (Table 1) obtained via the Internet. Six are GAUs, eight are SATs, and two are MRGs. Two of the GAUs are

daily, and the others are monthly. One of the SATs is monthly, and the others are daily or sub-daily. For the sub-daily datasets, the authors use their daily accumulation in this study. No GAU used in this study distinguished rainfall from snowfall. The period analyzed in this study was 1979 through 2004 for the GAUs, except for that of CRU_TS2.1, which was 1979 through 2002, due to the limitation of that rain gauge dataset. For the SATs, the authors used their time series for as long as they were available due to their shorter time in existence compared with the GAUs and MRGs. Inconsistency in the periods of time series among the SATs may have had some impact on the intercomparison among the SATs. For the MRGs, the analyzed period was the same as that of the GAUs.

3. Region and Topography

Figure 1 shows the spatial distribution of the region analyzed in this study (65° E to 130° E, 5° N to 35° N). The topography dataset used in this study was GTOPO30, developed by the US Geological Survey (USGS). The horizontal resolution is 1/120°. The topography in the target region is characterized by highlands mainly occupied by the Tibetan Plateau and by some mountain ranges.

Our focus was on the elevation dependency of precipitation. Figure 2 illustrates the elevation dependencies of the land area in six different horizontal resolutions, one of which is the grid spacing of the topographic data

Table 1 Summary of the gridded precipitation datasets used in this study.

Dataset	Resolution	Region	Period (*1)	Interval (*2)	Source	Reference
APHRO_MA0902	0.5°	60° E–150° E 0° N–55° N	1979–2004	Daily	Rain gauge	Yatagai <i>et al.</i> , 2009
CPC_UNIGLB	0.5°	Globe	1979–2004	Daily	Rain gauge	Chen <i>et al.</i> , 2008
CRU_TS2.1	0.5°	Globe	1979–2002	Monthly	Rain gauge	Mitchell and Jones, 2005
GPCCv4_full	0.5°	Globe	1979–2004	Monthly	Rain gauge	Schneider <i>et al.</i> , 2008
PREC/L	0.5°	Globe	1979–2004	Monthly	Rain-gauge	Chen <i>et al.</i> , 2002
UDEL	0.5°	Globe	1979–2004	Monthly	Rain gauge	Matsuura and Willmott, 2009
TRMM_PR3A25V6	0.5°	0° E–360° E 36° S–36° N	1998–2008	Monthly	Satellite	Iguchi <i>et al.</i> 2000
GSMaP/MWR	0.25°	0° E–360° E 60° S–60° N	1998–2006	Hourly	Satellite	Aonashi <i>et al.</i> , 2009
NRL-blended	0.25°	0° E–360° E 60° S–60° N	2004–2008	3-hourly	Satellite	Turk and Miller, 2005
PERSIANN	0.25°	0° E–360° E 60° S–60° N	2001–2008	3-hourly	Satellite	Sorooshian <i>et al.</i> , 2000
GPCP1dd v1.1	1.0°	Globe	1997–2008	Daily	Satellite (*3)	Huffman and Bolvin, 2009a
TRMM_3B42V6	0.25°	0° E–360° E 50° S–50° N	1998–2008	3-hourly	Satellite (*3)	Huffman <i>et al.</i> , 2007
GSMaP/MVK	0.1°	0° E–360° E 60° S–60° N	2003–2006	Hourly	Satellite	Ushio <i>et al.</i> , 2009
CMORPH	0.25°	0° E–360° E 60° S–60° N	2003–2008	3-hourly	Satellite	Joyce <i>et al.</i> , 2004
GPCPv2.1	2.5°	Globe	1979–2004	Monthly	Gauge+ Satellite	Huffman and Bolvin, 2009b
CMAP	2.5°	Globe	1979–2004	Monthly	Gauge+ Satellite	Xie and Arkin, 1997

(*1) The period analyzed in this study is presented.

(*2) This column indicates the temporal resolution in each datasets.

(*3) These datasets are calibrated by rain gauges so that their monthly mean is consistent with the monthly mean of rain gauges.

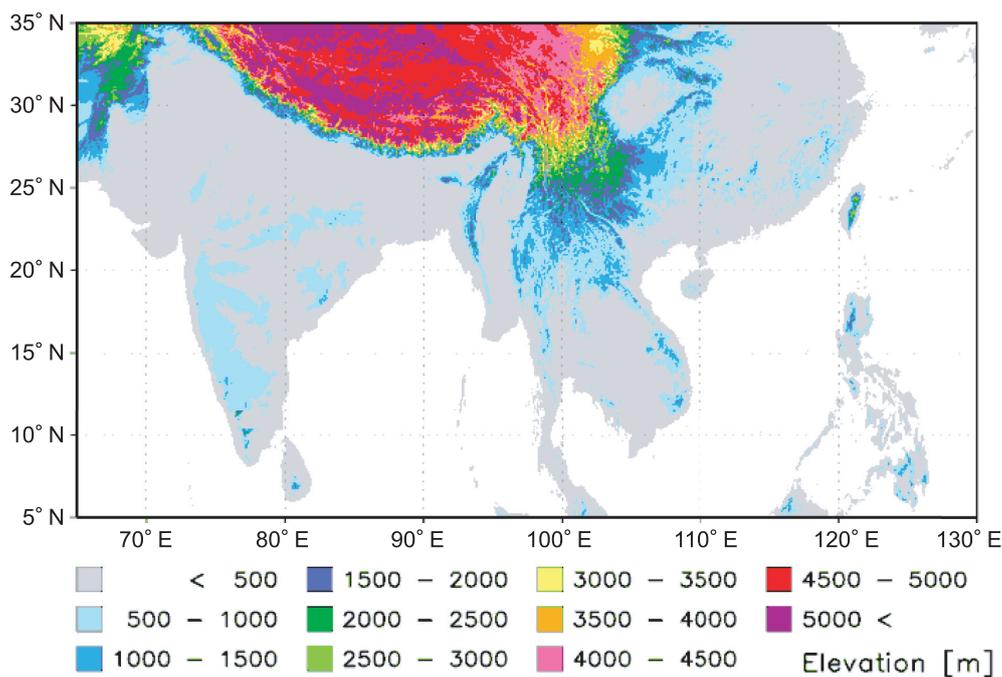


Fig. 1 Spatial distribution of the elevation of the surface [m] over the analyzed region, 65°E to 130°E, 5°N to 35°N.

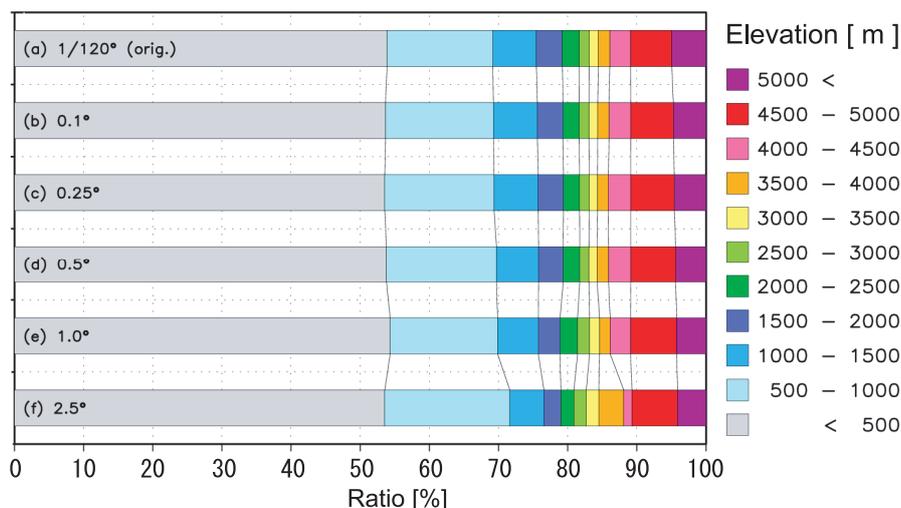


Fig. 2 Elevation dependency of the land area in the target region presented as the ratio of the area in each bin to the total land area [%]. The width of each bin is 500 m, except for both the lowermost and the uppermost bins. The lowermost bin includes altitudes of 500 m or less and the uppermost bin includes altitudes above 5,000 m. The colors and bars are the same as those in Fig. 1. (a) The elevation dependency of the land area in 1/120°×1/120° grids; (b), (c), (d), (e) and (f) the same as (a) except that the grids are (b) 0.1°×0.1°, (c) 0.25°×0.25°, (d) 0.5°×0.5°, (e) 1.0°×1.0°, and (f) 2.5°×2.5°.

used, GTOPO30; the others are the horizontal resolution of gridded datasets used in this study. This figure indicates that 20% of the land in the target region is located at altitudes above 2,000 m, with 10% at altitudes above 4,500 m, due to being on the Tibetan Plateau. It also indicates that there are small differences among topographic data with different horizontal resolutions.

4. Spatial Characteristics of Mean Terrestrial Precipitation

Before analyzing the elevation dependency of precipitation, this section describes the spatial characteristics of the mean precipitation in boreal summer (June–July–August, JJA). Figure 3 presents the spatial distribution of the JJA mean precipitation of 16 gridded

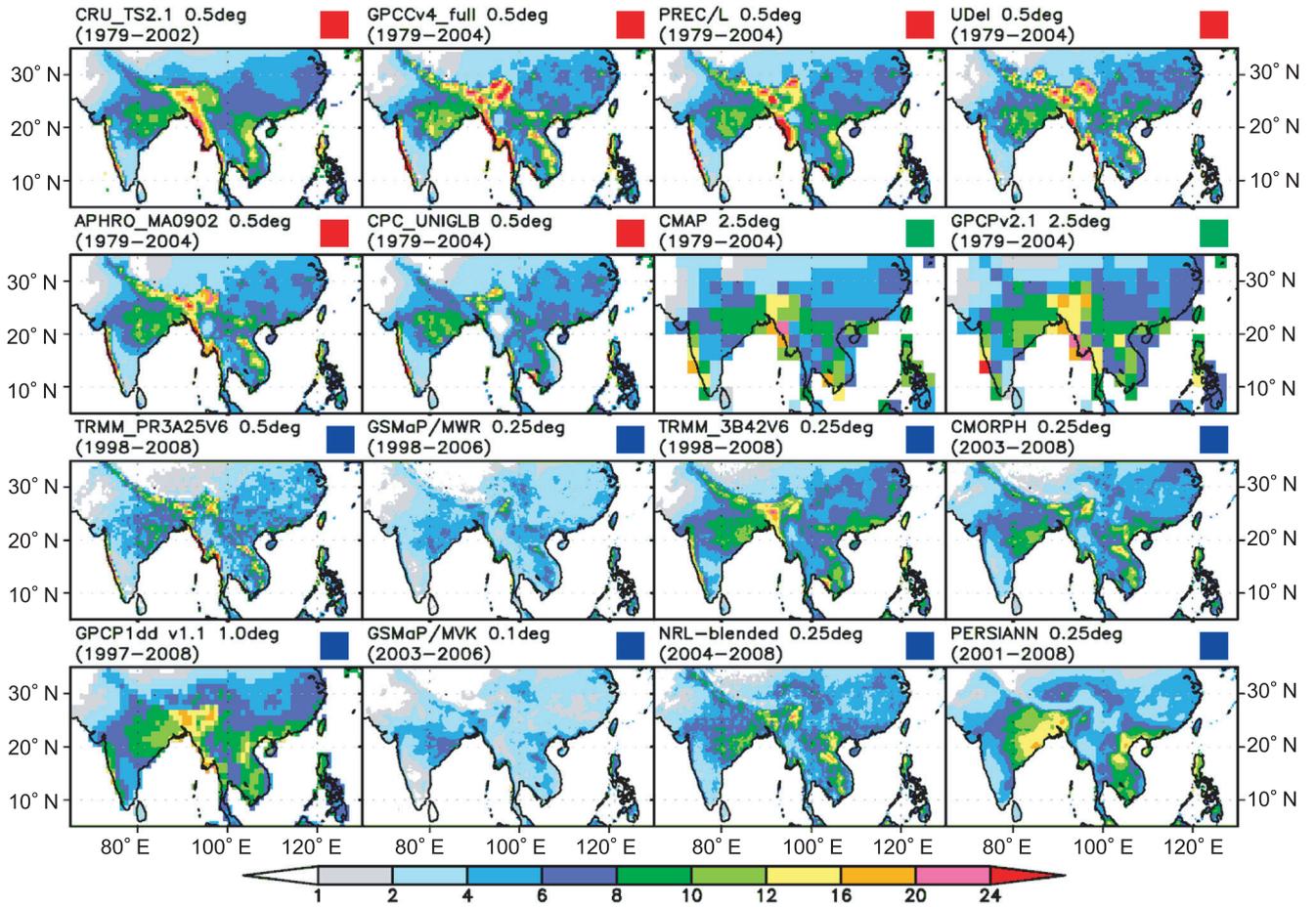


Fig. 3 Spatial distribution of the June-July-August (JJA) mean terrestrial precipitation of 16 gridded precipitation datasets [mm d^{-1}] over the target region. ■, ■, and ■ indicate rain-gauge-based, satellite-based and combined datasets, respectively.

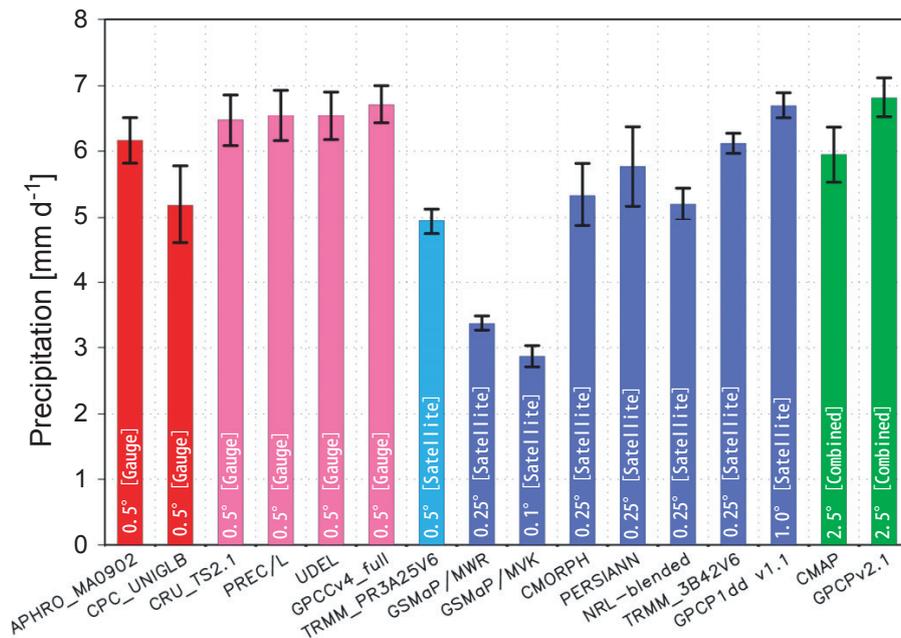


Fig. 4 Area-weighted average of JJA mean terrestrial precipitation [mm d^{-1}] over the target region. The error bars denote the standard deviation for interannual variability. Bars with red, pink, light blue, blue, and green are daily rain-gauge-based datasets, monthly satellite-based datasets, daily or sub-daily ones, and gauge-satellite combinations.

precipitation datasets. Strong precipitation is found over the windward slope of mountain ranges such as the western side of the Western Ghats. The amplitude of such orographic precipitation in the SATs was smaller than in the GAUs, even though the spatial resolution of most of the SATs was finer than that of the GAUs. The spatial distribution of precipitation in the combined datasets (MRGs) was generally consistent with that of both the GAUs and the SATs. However, they have poor reproducibility of precipitation distribution associated with topography because their horizontal resolution is too coarse to resolve topography with small spatial scales or asymmetrical shapes, *i.e.*, mountain ranges. From the viewpoint of large-scale features, all gridded precipitation datasets used are generally consistent, taking into consideration the fact that their horizontal resolutions differ.

Figure 4 shows the area-weighted averaged JJA mean precipitation over the target region in Fig. 1. The error bars indicate the standard deviation for interannual variability of JJA mean precipitation. The area-averaged mean values of JJA precipitation in the SATs were smaller than those in the GAUs, but with greater scatter among the SATs than among the GAUs. For interannual variability, six (TRMM_PR3A25V6, TRMM_3B42V6, GSMaP/MWR, GSMaP/MVK, GPCP1dd v1.1, and NRL-blended) had standard deviations smaller than those of both the GAUs and the MRGs. The others, CMORPH and PERSIANN, had standard deviations greater than those of the GAUs. It is noteworthy that the standard deviation for interannual variability of some of the SATs may be overestimated because the length of the time series was much shorter than those of the GAUs and MRGs. There was little dependency of mean precipitation on the horizontal resolution of the datasets indicating

that the difference resulted from other factors. One such factor may be differences in retrieval algorithms used to construct the SATs.

5. Elevation Dependency of Mean Terrestrial Precipitation

This section focuses on the elevation dependency of mean precipitation. Since precipitation over mountainous regions is essential to human societies in arid and semi-arid regions, a gridded precipitation dataset should have precise spatial distribution not only horizontally but also vertically. In order to describe differences in the elevation dependencies of mean precipitation among gridded precipitation datasets, the authors used two diagnostics: (1) the elevation dependency of mean precipitation and (2) the elevation dependency of accumulated precipitation. The former provides information on the elevation dependency of mean precipitation intensity, and the latter indicates how precipitation amounts are distributed with altitude.

Figure 5 indicates the elevation dependency of JJA mean precipitation. Generally speaking, the mean precipitation has its maximum at low altitudes and decreases with altitude. The GAUs had their maxima at altitudes below 1,000 m, and secondary peaks at altitudes of 3,500 m to 4,000 m. Values in monthly-based datasets (CRU_TS2.1, PREC/L, GPCCv4_full, and UDEL) tended to exceed those in daily-based datasets (APHRO_MA0902 and CPC_UNIGLB) at all altitudes. The mean precipitation of CPC_UNIGLB is clearly less than that of the other GAUs at low altitudes. The scatter among the GAUs was at most about 2 mm d⁻¹ at all altitudes. The SATs also had their maxima at altitudes below 1,000 m, and secondary maxima at altitudes of 3,500 m to 4,500 m,

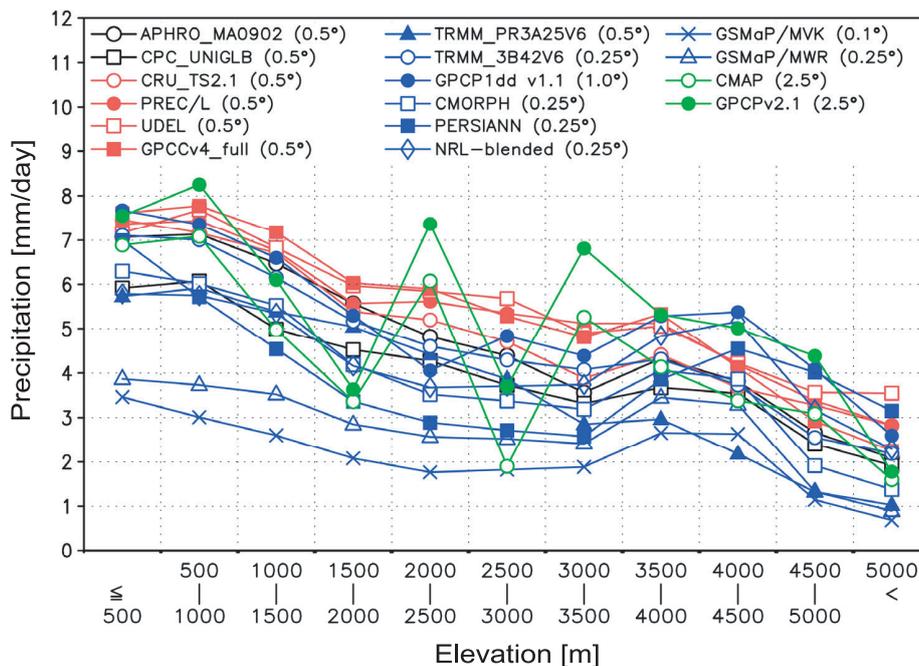


Fig. 5 Elevation dependency of JJA mean terrestrial precipitation [mm d⁻¹]. The spatial resolution is shown in parentheses in a legend for each dataset.

slightly higher and more prominent than those of the GAUs. The elevation dependency of TRMM_PR3A25V6 was similar to those of the others; however, its secondary peak was relatively weak. Its mean precipitation was less than that of the GAUs at all altitudes. Its elevation dependency seemed to be similar to those of the GAUs rather than the other SATs. GSMaP/MWR and GSMaP/MVK indicated less precipitation than the others at all altitudes, especially at low altitudes, and their maxima at altitudes below 500 m were as great as their secondary peaks at altitudes of 3,500 m to 4,000 m. The mean precipitations of GPCP1dd v1.1 and TRMM_3B42V6 were comparable to or slightly less than those of the GAUs at all altitudes. The mean precipitations of PERSIANN, CMORPH, and NRL-blended were less than those of the GAUs at low and middle altitudes but comparable at high altitudes. Although the SATs had elevation dependencies of mean precipitation qualitatively comparable to those of the GAUs, the scatter of the differences among them was twice as great as that among the GAUs. The elevation dependencies of the MRGs were quite bumpy at middle altitudes, because their grid size of 2.5° was too coarse to resolve the topography at a regional scale in the target region. GPCPv2.1 exceeded CMAP at all altitudes. The difference between GPCPv2.1 and CMAP was greater at high altitudes than at low altitudes. Except for middle altitudes, their mean precipitations were comparable to

those of the GAUs. Comparison of the GAUs and the SATs indicated that the mean precipitation of the GAUs exceeded that of the SATs at altitudes below 3,000 m, and that the GAUs were comparable to the SATs at altitudes above 3,000 m, with a greater scatter among the SATs than among the GAUs.

Since the land area varies with altitude, it is worthwhile to examine how accumulated precipitation is distributed with altitude. Figure 6 shows the elevation dependency of accumulated precipitation in JJA, as the ratio of accumulated precipitation in each altitude band to the area-averaged accumulated precipitation. The 16 gridded precipitation datasets generally indicated similar elevation dependencies. Eighty percent of accumulated precipitation occurred at altitudes below 1,000 m, and 10% at altitudes above 2,500 m, most of which occurs on the Tibetan Plateau. The GAUs had quite similar elevation dependencies, although the ratio of UDEL at high altitudes was relatively larger than those of the others. The elevation dependencies of the SATs were similar to those of the GAUs. However, the differences in elevation dependency among the SATs exceeded those among the GAUs, with the difference in horizontal resolution between them taken into consideration. For the MRGs, the elevation dependency was similar to that of the GAUs, with their coarse horizontal resolutions taken into consideration.

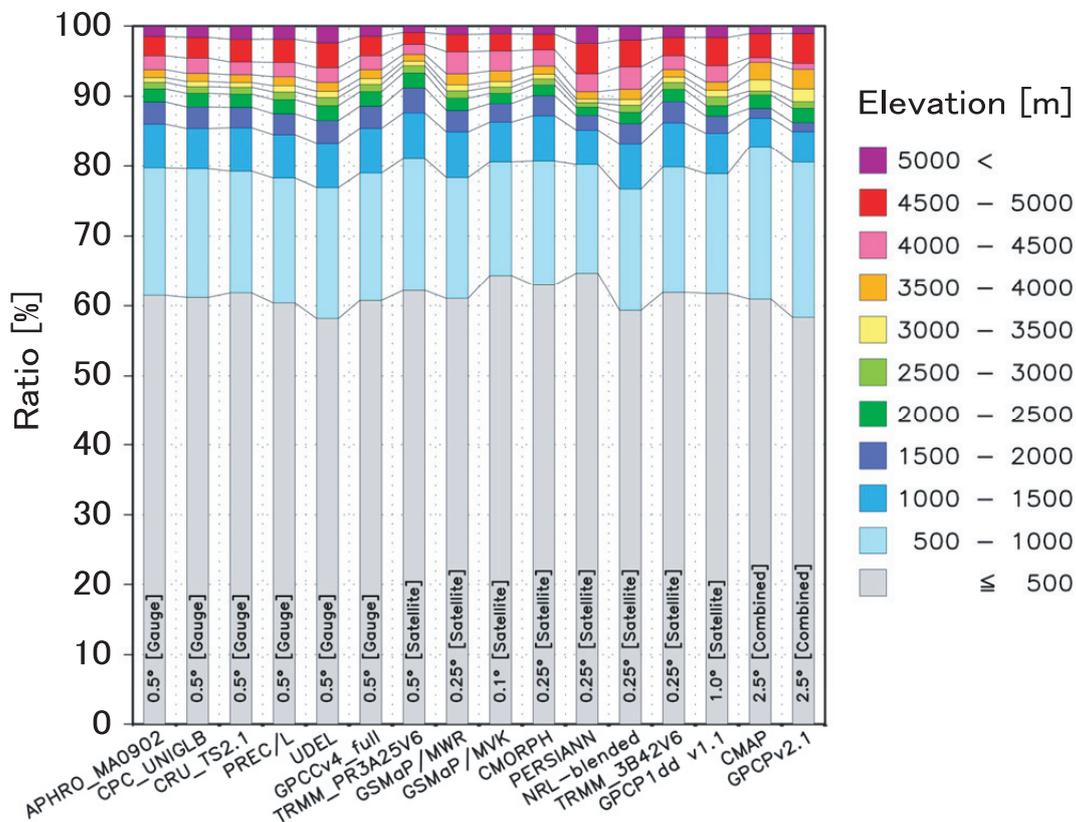


Fig. 6 Elevation dependency of JJA accumulated terrestrial precipitation indicated as the ratio of accumulated precipitation in each bin to total precipitation [%]. Colors and bins are the same as in Fig. 1.

6. Elevation Dependency of Heavy Terrestrial Precipitation

Concern about extreme weather such as heavy precipitation and droughts has been growing year by year (IPCC, 2007). Therefore, gridded precipitation datasets are expected to have the ability to handle extreme events. In this study, our concern with regard to extreme events was the elevation dependency of heavy precipitation because the precise representation of heavy precipitation is important to the understanding of the elevation dependency of any strength of precipitation, as well as mean precipitation. In this study, the authors refer to the 95th percentile or more of daily precipitation as heavy precipitation. They used two GAUs (APHRO_MA0902 and CPC_UNIGLB), and seven SATs (TRMM_3B42V6, GPCP1dd v1.1, CMORPH, PERSIANN, NRL-blended, GSMaP/MWR, and GSMaP/MVK). These are the gridded datasets whose daily precipitation is available for examining the elevation dependency of heavy precipitation.

Figure 7 indicates the elevation dependencies and the area averages of heavy precipitation in JJA. For the GAUs, the mean intensity of heavy precipitation generally decreases with altitude, similar to the mean precipitation, and has its maximum at altitudes below 500 m and a secondary maximum at altitudes of 3,500 m to 4,000 m. The differences among them are at most 2 to 3 mm d^{-1} at all altitudes; therefore, the area averages are almost the same. The elevation dependencies of the SATs are similar to those of the GAUs: their maxima are at altitudes below 500 m, and their secondary peaks are at altitudes of

3,500 m to 4,500 m, and they are more prominent than in the GAUs. The differences among them, however, range from 10 mm d^{-1} to 25 mm d^{-1} , several times those of the GAUs. The range of the area averages is about 20 mm d^{-1} , which is comparable to the mean intensity of the area averages in the gridded precipitation datasets used. TRMM_3B42V6 has heavy precipitation that is much stronger than those of the GAUs, while its mean precipitation is comparable to those of the GAUs at all altitudes. GPCP1dd v1.1 has the same tendency as TRMM_3B42V6, but with less heavy precipitation at low altitudes and more at middle and high altitudes than TRMM_3B42V6. In CMORPH, PERSIANN, NRL-blended, and GSMaP/MWR, the heavy precipitation is comparable to or exceeds those of the GAUs, while the mean precipitation is generally less than those of the GAUs. GSMaP/MVK has much less heavy precipitation than the GAUs at all altitudes, except for at altitudes of 3,500 m to 4,000 m, where it has its secondary maximum. Comparison of the GAUs with the SATs indicates that the mean intensity of heavy precipitation in the GAUs is slightly less than that in the SATs, whereas the scatter of the differences among the GAUs is much smaller than that among the SATs.

7. Discussion

The elevation dependency of mean precipitation shows that the secondary maximum is more prominent in the SATs than in the GAUs (Fig. 5). There are a small number of rain gauge observations at high altitudes because of the difficulty of maintaining rain gauge

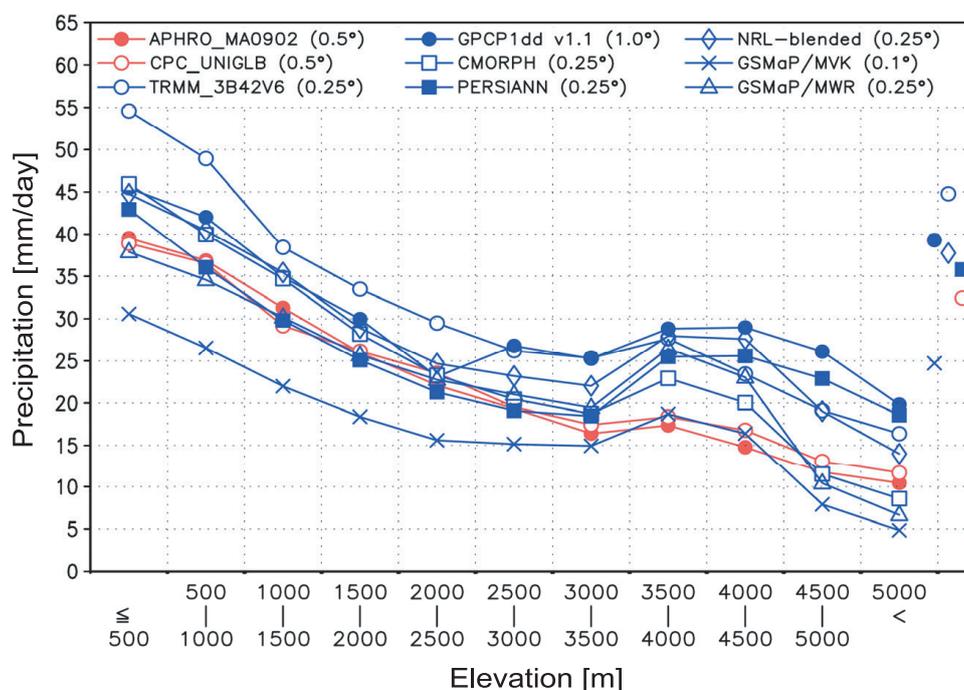


Fig. 7 Elevation dependency of the mean intensity of heavy terrestrial precipitation [mm d^{-1}] in JJA. Nine datasets whose daily precipitation is available are used. Heavy precipitation is defined as daily precipitation of the 95th percentile or more. Symbols on the right end are the area-averaged mean intensity of heavy terrestrial precipitation. The value in parentheses is the horizontal resolution of datasets.

observation networks at high altitudes. Thus, the precipitation detected in satellite observations may not be observed in rain gauge observations. This may be associated with the secondary maximum being more prominent in the SATs than in the GAUs.

The mean intensity of heavy precipitation in the SATs is generally more than that in the GAUs (Fig. 7). However, the mean precipitation in the SATs is comparable to or less than that in the GAUs (Fig. 5). There is a difference in the temporal characteristics of precipitation observations between rain gauges and satellites. Precipitation derived from satellite observation is a temporal average of a rainfall rate which sensors installed in satellites observed. On the other hand, precipitation acquired from rain gauge observations is an accumulated precipitation during a period (*e.g.*, a day). In addition, the number of wet days (defined as a day of precipitation of more than 0.1 mm d^{-1}) in the SATs is smaller than that in the GAUs (fig. not shown). These results may explain the difference between the GAUs and the SATs in mean precipitation and heavy precipitation. The difference in number of wet days between the GAUs and SATs may be associated with the following. (1) There are the differences among GAUs in the number of rain gauge observations, their spatial distribution and their temporal resolution. (2) Among the SATs, there may be differences in rain/no-rain determination in rainfall retrieval algorithms, (3) Some sensors cannot reasonably detect certain kinds of rainfall such as rainfall from low clouds. (4) The frequency of observation by low-orbit satellites is not uniform either temporally or spatially.

The regional averaged mean precipitation shows a smaller standard deviation for interannual variability in the SATs than in the GAUs (Fig. 4). The difference between the GAUs and SATs may be partly affected by differences in analysis period between the GAUs and SATs. A comparison during the period of 1998 through 2004, in which the majority of datasets in this study were available, was performed (fig. not shown). The standard deviation for interannual variability was comparable among the SATs. Among the GAUs, CPC_UNIGLB, UDEL, and GPCCv4_full had standard deviations comparable to the SATs. On the other hand, APHRO_MA0902 and PREC/L had standard deviations larger than the SATs. The differences in standard deviation among the GAUs may have resulted from differences in rain gauge observations (number of observations and their spatial distribution) because the spatial interpolation method used to construct GAUs in this study was independent of time. In summary, the differences in standard deviation for interannual variability among the datasets shown in Fig. 4 may result from (1) differences in analysis period among all precipitation datasets and (2) differences in rain gauge observations (number of gauge observations and/or their spatial distribution) used in the GAUs. The differences in standard deviation for interannual variability among the GAUs may be associated with differences in the temporal variation of rain gauge observations used in the GAUs. In APHRO_MA0902,

numbers of rain gauge observations in the year of 1998 and 1999 were considerably greater than those in the other years during the analysis period in this study (Yatagai *et al.*, 2009). Kamiguchi *et al.* (2010) showed that the temporal variation in rain gauge observations affected the long-term trend of annual maximum daily precipitation as well as that of annual mean precipitation. Therefore, differences in standard deviation of regional averaged mean precipitation for interannual variability imply that caution is needed regarding the impact of the temporal variation of rain gauge observations on long term climate analysis.

8. Concluding Remarks

No rain-gauge-based gridded precipitation datasets used in this study distinguished rainfall from snowfall. Since the impact on rain gauge observations of the undercatch by evaporation loss and drift of drops and snow particles by the wind is greater for snowfall than for rainfall, adjustment of the undercatch for snowfall would require snow precipitation data to be included in gridded precipitation datasets. The undercatch in rain gauge observations has been examined with many types of rain gauges (Goodison *et al.*, 1998). Yang *et al.* (2005) applied bias correction for the undercatch to rain gauge observations over the Northern Hemisphere high latitudes. Adam and Lettenmaier (2003) applied the correction for such bias to UDEL and estimated the impact of the bias correction method on the climatology of a gridded precipitation dataset. However, there are no historical rain-gauge-based datasets that use such a method to adjust the undercatch. The development of long-term rain-gauge-based datasets with adjustment of the undercatch is expected.

This study showed that satellite-based datasets have some problems. Improvements are expected in the mitigation of quantitative differences among them. However, their advantage of wide-area, real-time observation is useful for monitoring heavy rainfall events that often result in natural disasters such as floods and landslides. The flash-flood monitoring system that was recently developed and is being operated by national weather services in some nations and regions is based on the fact that satellite observation enables the spatial distribution of precipitation events to be grasped over a wide area in near real-time by combining multiple sensors and/or multiple satellite observations (*e.g.*, Scofield & Kuligowski, 2003). The Global Precipitation Measurement (GPM) project is planned as one of the next generation of satellite-based precipitation observation programs. This project will improve precipitation estimates by satellites and increase the accuracy of satellite-based gridded precipitation datasets.

Finally, the authors suggest in this study that gridded precipitation datasets should be used with consideration of both their own values and their error values. Gridded precipitation datasets have uncertainties that originate from observations and spatial interpolation. The authors

propose the use of the ensemble mean of gridded precipitation datasets and the standard deviation of their anomaly from the ensemble mean as observed precipitation and its error estimation. Considering uncertainty as well as precipitation itself would enable us to validate the performance of precipitation in climate models more quantitatively.

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