

ORIGINAL ARTICLE

Analyzing uncertainty in probable maximum precipitation estimation with large ensemble climate simulation data

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Abstract

This study aimed to evaluate probable maximum precipitation (PMP) estimated using surface dew points (SDP) or actual precipitable water obtained from upper-air data (UAD) in the moisture-maximization method with the help of sufficient extreme precipitation events using large-scale climate ensemble simulation data (d4PDF). The deviations between the PMP variables estimated by the SDP and UAD approaches were analyzed for southern and northern areas of Japan to consider the regional characteristics of the deviations. We found that the deviations were high in northern areas where the SDPs are relatively low during precipitation events. The PMPs estimated using each approach were also compared to the extreme-scale reference precipitation proposed in this study. The SDP approach overestimated the PMPs by over 20% compared to the reference precipitation in the northern region. However, the UAD approach showed very low average errors in all southern and northern areas. This tendency of the SDP approach was significantly related to the regional climatic characteristics of the SDP, which indicated that the SDP approach may estimate an uncertain PMP value depending on each regional climatic characteristic compared to the UAD approach. Regional climatic characteristics should be considered when using the SDP approach to estimate the PMP.

KEYWORDS

d4PDF, moisture-maximization method, PMP

1 | INTRODUCTION

Probable maximum precipitation (PMP) is defined as the theoretically greatest depth of precipitation for a given duration that is physically possible over a given storm area at a particular geographical location and time (World Meteorological Organization [WMO], 2009). The PMP also can be defined as a physical upper bound of the precipitation amount, but this concept of PMP has

been criticized as there is no unique method for determining the upper bound of rainfall, assuming that it really exists (Koutsoyiannis, 1999). The PMP is commonly used for estimating the probable maximum flood (PMF), which is the key design parameter for large-scale hydraulic structures such as dams.

To estimate PMP, the WMO suggests employing a moisture-maximization method based on a physical concept (WMO, 1986, 2009). This method is widely used

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worldwide to estimate the amount of PMP, and government agencies in many countries have adopted it for practical purposes (Rouhani & Leconte, 2016). The moisture-maximization method selects large-scale precipitation events and maximizes the observed atmospheric moisture conditions to the historical maximum moisture conditions.

In the moisture-maximization method, the atmospheric moisture condition is represented by the total precipitable water (PW) integrated from the surface to the upper air (300 hPa). The actual PW can be observed by radiosonde measurements, which indicate the PW obtained from upper-air data (UAD). However, the number of radiosonde stations in an area is limited, and the observations contain missing and outlier data. To overcome this limitation, the moisture-maximization method uses the surface dew point (SDP) temperature to estimate the total PW. The SDP can indirectly estimate PW via a pseudo-adiabatic assumption wherein water vapor in the atmosphere is removed as precipitation as soon as it condenses. This is a key process for estimating PMP in the moisture-maximization method.

The PMP should not be underestimated to ensure the safety of people living near large-scale hydraulic structures; furthermore, it should not be overestimated to minimize the possibility of overdesign and wastage of economic resources (Rousseau et al., 2014). However, many studies have reported that the PMP estimation approach based on the PWs estimated by the SDP (SDP-based approach) overestimates the PMP more than the PMP estimation approach based on the PWs obtained from the UAD-based approach, and it is less accurate than the UAD-based approach (Chen & Bradley, 2006; Kim et al., 2019, 2020; Micovic et al., 2015; Rouhani & Leconte, 2020). Rouhani and Leconte (2020) analyzed the deviation between the SDP and UAD approaches using SDP and UAD data obtained from climate models. They concluded that the UAD approach is more physically based than the SDP approach.

Recently, Kim et al. (2020) noticed that the SDP approach is highly likely to overestimate the PMP in regions with relatively low SDPs. They showed clear deviations between the SDP- and UAD-based estimations using the vertical profiles of atmospheric variables (dew point, mixing ratio, and PW) observed from the radiosonde. They concluded that the SDP approach makes it difficult to estimate the PW and PMP reasonably in areas with lower SDPs (e.g., lower than 18°C). Despite the benefits of using SDP for PMP estimation, the SDP approach can lead to uncertainty in PMP estimation using the moisture-maximization method.

SDP-based PMP estimations may require an “evaluation” to provide a reasonable design precipitation value

for large-scale hydraulic structures. However, it is difficult to accurately evaluate the reasonability of the estimated PMP. First, there is an insufficient number of extreme rain events to analyze the reasonability of the SDP-based approach in PMP estimation. The U.S. Weather Bureau (1963, 1960, 1954) recommends applying the SDP approach under conditions of extreme rain events and high moisture cases, which should be sufficient to analyze the reasonability of PW and PMP estimated using the SDP approach, because the approach shows a different tendency compared to the UAD approach in PW and PMP estimations based on the number of extreme events (Micovic et al., 2015). Papalexiou and Koutsoyiannis (2006) reported that SDP-based PMP estimation is sensitive to available data because missing one or two events can change PMPs by at least 20% in the moisture-maximization method. With sufficient precipitation events, the PWs estimated using SDP should be compared with a sufficient number of actual PWs obtained in the UAD. However, historically observed PW in the UAD remains scarce, and the time series is too short for comparison in many regions.

Furthermore, conclusive criteria to assess the PMPs estimated using the SDP and UAD approaches are lacking. Moreover, it is difficult to present a reference precipitation that can be used to evaluate the PMP, which corresponds to the range of 10^{-3} to 10^{-10} in terms of the frequency of probable precipitation, which is a very long return period (Rousseau et al., 2014; Schaefer, 1994; Schaefer & Barker, 2005). Although the precipitation value with a relatively long return period can be presented using historical observed data and frequency analysis, it is unsuitable and highly uncertain because of the very short observation period compared with the long return period of the PMP (Ben Alaya et al., 2018; Klemeš, 1986, 1987, 2000). Therefore, to accurately evaluate the reasonability of PMPs estimated using the moisture-maximization method, the evaluation should be conducted under sufficient extreme precipitation events, actual PWs in the UAD, and SDPs. In addition, an appropriate extreme-scale reference value is required to evaluate the estimated PMP.

To utilize such SDP and UAD data, PMP studies based on SDP and UAD approaches have been conducted using historical observation data and outputs obtained from climate models (Beauchamp et al., 2013; Boucefiane & Meddi, 2022; Chen et al., 2017; Kunkel et al., 2013; Rouhani & Leconte, 2016; Visser et al., 2022). Climate simulation data have been used to overcome the spatiotemporal limitations of SDPs and UADs and to evaluate the uncertainty of PMP estimation using the moisture-maximization method from many SDP and UAD data (Ben Alaya et al., 2018, 2019; Rouhani &

Leconte, 2020; Rousseau et al., 2014). In these previous studies, although abundant SDP and UAD data could be obtained from climate simulation data, the number of extreme precipitation events was still limited because the data period was not sufficiently long. This means that, as with using historical observation data, there are insufficient extreme precipitation events even in climate simulation data to analyze the reasonability of the PMP estimation. Further, it remains difficult to estimate the extreme-scale reference precipitation representing the long return period precipitation using climate simulation data because of the limited number of extreme events.

The Meteorological Research Institute (MRI) of Japan recently produced a large ensemble climate simulation with a high-resolution atmospheric model—the “Database for Policy Decision-Making for Future Climate Change” (d4PDF) (Ishii & Mori, 2020; Mizuta et al., 2017). They produced thousands of climate simulations, and the d4PDF database helps resolve the shortage of extreme rain cases. It provides precipitation, SDP, and actual PW data for over 60 years for each ensemble number (50 ensembles). If the PMP is estimated in each ensemble, 50 PMPs can be estimated in the 50 ensembles. Thus, the d4PDF makes it possible to evaluate the deviation between the SDP- and UAD-based approaches under many available data and sufficient extreme rain events.

Furthermore, the d4PDF database is considered to be sufficiently long to estimate low-frequency weather phenomena representing the long-term return period (Tanaka et al., 2021). The d4PDF provides a large-scale sample size consisting of 3000 annual precipitation series (60 years $\times$ 50 ensembles). Using a large-scale sample, the d4PDF enables reliable estimation of extreme-scale precipitation values with a long-term return period of more than 1000 years through frequency analysis. This large-scale sample size can minimize the uncertainty caused by the small-scale sample size of the precipitation observation data when representing the long-term return period of precipitation in the frequency analysis. Hence, it may be possible to propose a reasonable reference precipitation value with a low frequency and a long return period to evaluate the PMP.

This study aimed to analyze SDP- and UAD-based PMP estimations with extreme-scale reference precipitation values concerning regional climatic characteristics. The d4PDF data based on a large ensemble climate simulation database were utilized. Thus, this study satisfied the following three conditions using the d4PDF data:

1. Analysis was conducted under sufficient extreme precipitation events using data based on large ensemble years (60 years and 50 ensembles).

2. Abundant SDP and UAD data were extracted using climate simulation-based data.
3. An extreme-scale reference precipitation value was estimated using a large-scale sample size consisting of 3000 annual precipitation series.

In this study, PMP variables, such as the event PW, moisture maximizing ratio (MMR), and PMP, estimated using the SDP-based approach were compared to those estimated using the UAD-based approach. Deviation patterns between the values estimated using the two approaches were checked in the context of regional climatic characteristics in the target areas. Extreme-scale reference precipitation values were proposed using the d4PDF database for each area. Based on the reference values, the PMPs estimated using the SDP and UAD approaches were evaluated.

2 | DATA AND METHODS

2.1 | Target area

Eight areas in Japan were selected, as shown in Figure 1. Japan is surrounded by the sea and experiences high moisture conditions through moisture inflow and frequent heavy rain events. Japan is useful for analyzing the deviation of regional climatic characteristics because of its widely established geographical characteristics from the northern to southern latitudes. Southern and northern areas of Japan, with clearly different climatic characteristics, were selected for this study.

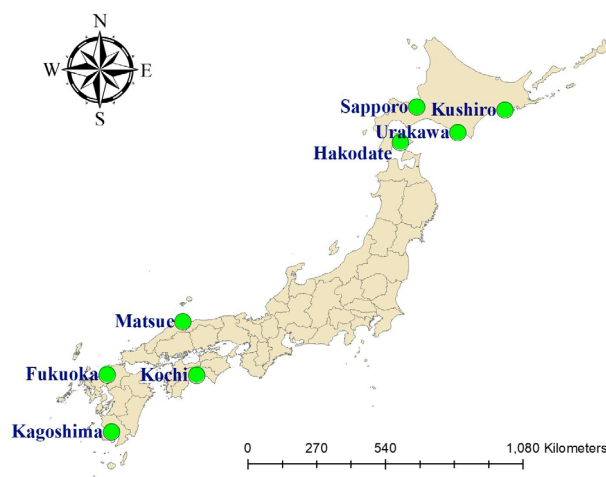


FIGURE 1 Target areas in Japan. Kagoshima, Fukuoka, Kochi, and Matsue are located in the southern part of Japan; Hakodate, Sapporo, Urakawa, and Kushiro are located in the northern part of Japan.

TABLE 1 The average amount of precipitation and 12 h persisting surface dew point for the 3000 annual maximum daily precipitation.

Area	Latitude (°N)	Longitude (°E)	Precipitation (mm)	Surface dew point (°C)	Location
Kagoshima	31.56	130.55	152.69	23.47	Southern part of Japan
Fukuoka	33.58	130.38	129.19	21.90	
Kochi	33.57	133.55	182.78	23.46	
Matsue	35.46	133.07	94.47	20.19	
Hakodate	41.82	140.75	70.50	17.53	Northern part of Japan
Sapporo	43.06	141.33	78.72	15.93	
Urakawa	42.16	142.78	64.74	16.93	
Kushiro	42.95	144.44	70.47	15.15	

Table 1 lists the average amount of precipitation and SDPs for the 3000 annual maximum daily precipitation events. Kagoshima, Fukuoka, Kochi, and Matsue are all located in southern Japan. Hakodate, Sapporo, Urakawa, and Kushiro are all located in northern Japan. Table 1 implies that the southern areas have relatively higher SDPs of more than 20°C when high-magnitude precipitation events occur compared to the northern areas of Japan. In addition, the magnitude of the precipitation events in the southern areas is larger than that in the northern areas. The targeted areas are all adjacent to the sea, where moisture inflow is active and the altitude is relatively low. Thus, it was possible to conduct this study by minimizing the impact of mountainous terrains.

2.2 | d4PDF based on large-scale climate ensemble simulations

The d4PDF consists of outputs from global warming simulations using a global atmospheric model with a horizontal grid spacing of 60 km (AGCM), which was downscaled to 20 km using the nonhydrostatic regional climate model (Sasaki et al., 2008) over Japan. The AGCM used in this study was MRI-AGCM 3.2. This model was developed based on a version of the numerical weather prediction model used operationally by the Japan Meteorological Agency (JMA). Many parameterization schemes for various physical processes have been developed and introduced into models using both JMA and MRI. This model consisted of 64 vertical levels. The top level is 0.01 hPa equivalent to an altitude of about 80 km. This model adopted the cumulus convection scheme called the “YS scheme” (Yoshimura et al., 2015), which was developed from the method of Tiedtke (1989). Further details on the model and its performance can be found from Mizuta et al. (2012). The horizontal grid size of the downscaled d4PDF is 211×175 , which covers

Japan, the Korean Peninsula, and the eastern part of the Asian continent.

Three sets of experiments were performed using the AGCM: a historical climate simulation, a +4-K future climate simulation, and a nonwarming simulation. The sea surface temperature (SST), sea ice concentration (SIC), and sea ice thickness (SIT) were designated as the lower boundary conditions, and the global mean concentrations of greenhouse gases and three-dimensional distributions of ozone and aerosols were designated as the external forces. The duration of each experiment was 60 years. Each set of experiments had large ensemble members, for which the initial and lower boundary conditions were perturbed.

In the historical climate simulation, the observed monthly mean SST and SIC of COBE-SST2 (Centennial Observation-based Estimates of SST, version 2; Hirahara et al., 2014) and the climatological monthly SIT from Bourke and Garrett (1987) were used as the lower boundary conditions. In addition to using different initial conditions, small perturbations of SST (δ SST) based on SST analysis error were added to COBE-SST2 for the ensemble experiments. The details of these perturbations are described by Mizuta et al. (2017). The global mean concentrations of greenhouse gases (CO_2 , CH_4 , N_2O , and chlorofluorocarbons) were set to the observational values for each year. Three-dimensional distributions of ozone from the MRI Chemistry–Climate Model (MRI-CCM; Deushi & Shibata, 2011) and aerosols from the MRI-Coupled Atmosphere–Ocean General Circulation Model, version 3 (MRI-CGCM3; Yukimoto et al., 2012), were used.

The d4PDF database has been applied for the risk assessment of climate-related phenomena with a very low frequency, such as floods and droughts (Döll et al., 2018; Faye et al., 2018; Ishii & Mori, 2020; Kay et al., 2015; Lavender et al., 2018; Mori et al., 2019; Yang et al., 2018). Furthermore, its applicability and reliability

have been reported in many studies (Hanittinan et al., 2020; Ishii & Mori, 2020; Tanaka et al., 2018, 2020, 2021).

MRI-AGCM3.2, which was used for the large ensemble simulation of the d4PDF, has been reported to be more efficient in simulating the seasonal evolution of East Asian precipitation (Chen et al., 2019). MRI-AGCM3.2 demonstrates superior performance in terms of heavy precipitation around the seasonal march of the East Asian summer monsoon (Mizuta et al., 2012). Endo et al. (2017) validated the annual maximum precipitation data of the d4PDF using Tropical Rainfall Measuring Mission (TRMM)-3B42 version 6 (Huffman et al., 2007). They concluded that the observed annual maximum precipitation features were well-reproduced by the d4PDF, especially in East Asia.

This study used the downscaled d4PDF based on a historical climate simulation with a 20 km resolution. For the historical climate simulation, 50 ensembles were generated, for which the historically observed initial conditions and lower boundary conditions were perturbed. Using the d4PDF, a PMP was estimated for each ensemble, and a comparison between PMPs estimated using the SDP- and UAD-based approaches could be conducted for each ensemble. Thus, this comparison could be conducted 50 times for the 50 ensembles. Precipitation, SDP, and PW data obtained from the d4PDF were used in this study.

2.3 | PMP estimation using the moisture-maximization method

In the moisture-maximization method, the observed heavy rain event was maximized for more extreme atmospheric conditions using Equations (1a) and (1b), where P_{observed} denotes the observed precipitation for the event, PW_{max} (mm) denotes the historical maximum PW during the total observation period, PW_{event} (mm) denotes the representative PW for the event, and MMR represents the moisture-maximizing ratio. The maximum PW was estimated with a Gumbel distribution using the PWs obtained for a rainy day and a non-rainy day; the estimated maximum PW corresponded to the 100-year return period. MMR was the ratio of the maximum PW to the event PW and reflected extreme precipitation conditions.

$$\text{PMP} = P_{\text{observed}} \times (PW_{\text{max}} / PW_{\text{event}}) \quad (1a)$$

$$= P_{\text{observed}} \times \text{MMR} \quad (1b)$$

PW is defined as the depth of water in a column of the atmosphere if all the water in that column

precipitated as rain. To characterize the available moisture feeding a storm and overcome the limitation of the observed PW data, a 1000 mbar, 12 h persisting SDP was utilized for estimating PW as an index to represent the mean atmospheric moisture availability. The SDP then estimated PW using a pseudo-adiabatic process under the pseudo-adiabatic assumption in the moisture-maximization method. WMO (1986, 2009) tabulated the relationship between the estimated PW and SDP under the pseudo-adiabatic assumption. Thus, SDP is one of the most important components for estimating PMP.

The pseudo-adiabatic process models the ascent of a saturated air parcel within a convective cell and is utilized to approximate the saturated water vapor in an air column. In the moisture-maximization method, it is assumed that air parcels follow a pseudo-adiabatic process from the surface of the atmosphere, and air parcels are condensed as soon as the air parcel ascends from the surface. This is called the pseudo-adiabatic assumption. Under this assumption, the air parcel begins to ascend from the SDP and follows a pseudo-adiabatic process. The water that condenses during the air parcel ascent is discarded as precipitation. If the SDPs can be easily obtained, it is possible to predict the amount of water from the surface to the upper air under the pseudo-adiabatic assumption.

2.4 | Two-sample Kolmogorov–Smirnov test

A two-sample Kolmogorov–Smirnov (KS) test at a significance level of 5% was conducted to compare the observed data and d4PDF data samples under the null hypothesis that they were drawn from the same unknown prior probability distribution. The statistical value ($D_{n,m}$), which ranged from 0 to 1, was defined as the maximum difference between the two cumulative density functions (CDFs). The null hypothesis was not rejected if the p -value was >0.05 . The main advantage of the KS test was its sensitivity to the shape of the prior distribution, because it could detect differences along the scale (Darling, 1957).

2.5 | Study design

In this study, the precipitation, SDP, and UAD (actual PW) data were collected from 1951 to 2010 for each area and each ensemble of the d4PDF. This study focused on eight areas located in the southern and northern parts of Japan with clearly different climatic characteristics to evaluate the SDP- and UAD-based approaches according

to each climatic characteristic. This study was divided into the following four steps.

First, to examine the reliability of the d4PDF data, the precipitation, SDP, and PW of the UAD extracted from the d4PDF were compared with the observed data. The observed precipitation and SDP data were extracted from the automated meteorological data acquisition system of the JMA in all areas, and the observed PW of the UAD was extracted from the radiosonde station in Kagoshima, Fukuoka, and Sapporo.

Second, the deviation of the PMP variables (event PW, MMR, and PMP) estimated using SDP for those estimated using UAD approaches was estimated, and this deviation was represented as an error value. For 50 ensembles of d4PDF, 50 errors were estimated between the two approaches for each PMP variable. This error estimation was based on the top precipitation event of each ensemble to compare the results of the two approaches for the same event.

Third, a reference value was proposed to evaluate the possibility of PMP overestimation and underestimation by the SDP and UAD approaches. The reference value was estimated using 3000 annual precipitation data points extracted from the d4PDF and frequency analysis for each area. The estimated reference value had a long-term return period of 3000 years. Although the frequency analysis using the small-scale sample size of the observed precipitation data estimated the uncertain precipitation when representing the long-term return period of 3000 years, the frequency analysis based on the d4PDF data estimated a relatively reasonable extreme-scale precipitation with a return period of 3000 years using a large-scale sample size.

This value, based on the statistical concept, may be an arbitrary value for evaluating PMP. However, it has an unprecedented extreme-scale precipitation value like the PMP. In addition, the value was estimated by sufficiently reflecting the regional characteristics of the precipitation magnitude, based on the same criteria in all areas. As this study had not aimed to estimate the accurate PMP for the target area but instead had aimed to analyze the uncertainty of the two approaches concerning the regional climatic characteristics, the use of this value as a reference for identifying the tendency of the overestimation and underestimation of PMPs estimated by the two approaches with the regional climatic characteristics was attempted.

Finally, the 50 PMPs estimated using each approach for the 50 ensembles were compared to the reference values in each area. The differences between the 50 PMPs estimated from each approach and the reference values are represented as an average error. Using the estimated average error, this study evaluated the two approaches

according to regional climatic characteristics in eight areas of Japan. The results allowed a clearer analysis of the reasonability of the PMP estimation based on the moisture-maximization method by evaluating it with a reference value estimated using a large ensemble simulation output called d4PDF.

3 | RESULTS

3.1 | Reliability of the d4PDF data

This study examined the reliability of the d4PDF data by comparing them with the observed data for precipitation, SDP, and PW of the UAD. The moisture-maximization method estimated the PMP based on specific extreme-scale precipitation events. Under the condition of high-magnitude precipitation, the precipitation, SDP, and PW data extracted from the d4PDF should be compared to the observed data. This comparison was conducted based on the 3000 annual maximum daily precipitation events of the d4PDF and the observed annual maximum daily precipitation events from 1973 to 2010.

Figure 2 shows the empirical CDF graphs of the two precipitation datasets for the eight regions. The black line represents the 3000 annual maximum daily precipitation series extracted from the d4PDF. Red circles represent the observed annual maximum daily precipitation from 1973 to 2010. Based on the empirical CDF graphs shown in Figure 2, a two-sample KS test was performed to analyze whether the annual maximum precipitation events extracted from the d4PDF showed a probabilistic function similar to that of the observed precipitation.

Table 2 shows the $D_{n,m}$, and p -values obtained from the KS test. Figure 2 shows a slight bias between the d4PDF and the observed data. The bias resources in the precipitation output based on the GCM are diverse and complicated, even related to the fundamental assumption of the Clausius-Clapeyron relationship (Koutsoyiannis, 2020). However, p -values were higher than 0.05 for all areas. In particular, the p -value for Fukuoka was estimated to be 0.95. This suggested that the probability distribution of annual maximum precipitation events extracted from the d4PDF was similar to the probability distribution of the observed annual maximum precipitation events in all areas targeted in this study.

Both the d4PDF and observed data reflected the annual maximum precipitation characteristics related to the intensity of precipitation in the southern and northern areas. In Figure 2, the graphs of both the d4PDF and the observed data in the southern areas are located on the right side compared to the northern areas, indicating

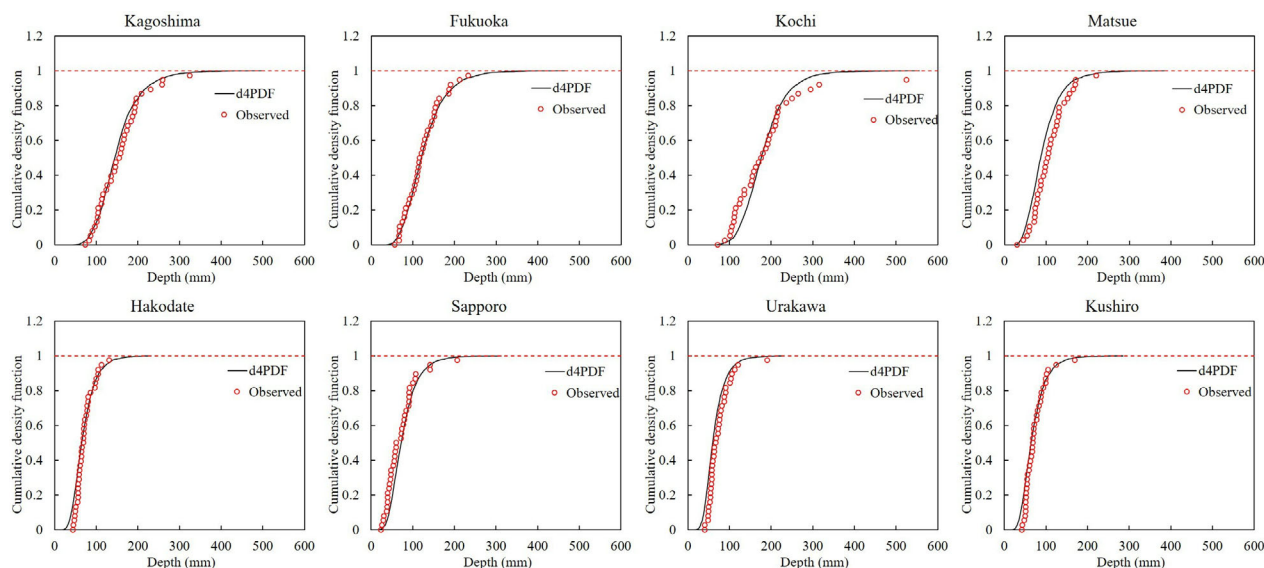


FIGURE 2 The comparison of the precipitation data extracted from the d4PDF with the observed precipitation data. The black line represents a total of 3000 annual maximum precipitations extracted from 50 ensembles. The red circles represent the observed annual maximum precipitations from 1973 to 2010. PW, precipitable water; SDP, surface dew point.

TABLE 2 The result of a two-sample Kolmogorov–Smirnov test of the d4PDF and observed precipitation.

Area	Kagoshima	Fukuoka	Kochi	Matsue	Hakodate	Sapporo	Urakawa	Kushiro
$D_{n,m}$	0.10	0.08	0.18	0.18	0.18	0.22	0.22	0.18
p -Value	0.84	0.95	0.16	0.16	0.16	0.05	0.05	0.15

TABLE 3 Average 12 h surface dew point for the annual maximum daily precipitation obtained from the d4PDF and observation.

Area	SDP (°C)	
	d4PDF	Observation
Kagoshima	23.47	22.58
Fukuoka	21.90	21.38
Kochi	23.46	22.71
Matsue	20.19	20.31
Hakodate	17.53	16.97
Sapporo	15.93	17.09
Urakawa	16.93	16.85
Kushiro	15.15	13.43

Abbreviation: SDP, surface dew point.

that the magnitude of the annual maximum precipitation events is higher in the southern areas than in the northern areas.

Table 3 shows the average 12 h persisting SDPs for the annual maximum daily precipitation of the d4PDF and the observed datasets. The differences between the d4PDF and observed data were low in all areas.

TABLE 4 Average daily precipitable water for the annual maximum daily precipitation obtained from the d4PDF and radiosonde observation.

Area	PW (mm)	
	d4PDF	Observation
Kagoshima	62.33	54.84
Fukuoka	56.72	56.46
Sapporo	40.51	39.51

Abbreviation: PW, precipitable water.

The d4PDF reflected the regional SDP characteristics of the observed data; the southern areas showed relatively high SDPs for both datasets and the northern areas showed relatively low SDPs for both datasets. Table 4 shows the average daily PWs for the annual maximum daily precipitation of the d4PDF and the observed datasets in the areas where radiosonde stations were installed. Fukuoka and Sapporo showed low differences between the d4PDF and the observed datasets. There was a slight bias in Kagoshima. However, the bias was not high, and the d4PDF reflected the regional PW characteristics in that the PW was

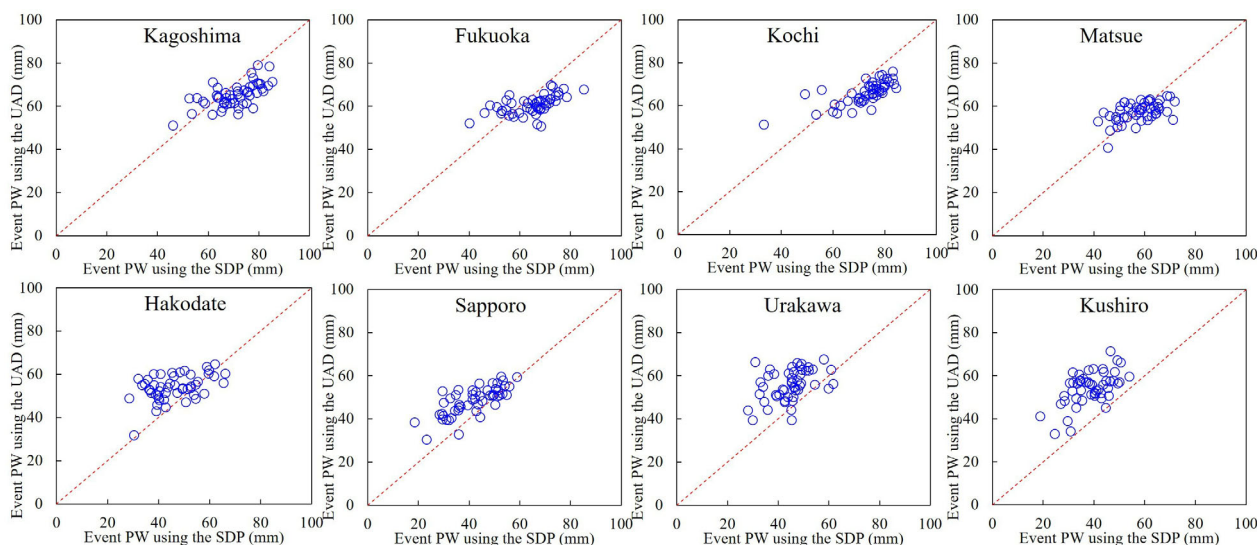


FIGURE 3 The SDP-based event PWs versus the upper-air data (UAD)-based event PWs in Kagoshima, Fukuoka, Kochi, Matsue, Hakodate, Sapporo, Urakawa, and Kushiro. The selected events (blue circle) are based on each top precipitation per ensemble of 50 ensembles of the d4PDF database with a one-day duration. PW, precipitable water; SDP, surface dew point.

relatively high in the southern areas of Japan and relatively low in the northern areas of Japan.

The primary aim of this study was to analyze the deviation between PMPs estimated from the SDP and UAD approaches for PMP estimation in areas with different climatic characteristics, and to evaluate the overestimation and underestimation possibility of PMPs estimated using the two approaches. As the d4PDF data reflected the distribution of the observed annual maximum daily precipitation series and the regional climatic characteristics of the observed SDP and PW in the northern and southern areas of Japan, it was possible to evaluate the uncertainty of the moisture-maximization method related to the two different climatic characteristics according to the purpose of this study. Therefore, here, it was determined that the d4PDF database was sufficient for evaluating the two PMP estimation approaches under each regional climatic condition.

3.2 | Comparison of UAD and SDP approaches

In this study, the PMP variables estimated using the SDP approach were compared to those estimated using the UAD approach. Fifty error values between the two approaches were estimated for the 50 top precipitation events of the 50 ensembles. This study estimated the average value of 50 errors to quantify deviations. The average errors were divided into positive and negative errors. A positive error indicated that the PMP variables using SDP were greater than those using UAD.

Meanwhile, a negative error indicated that the PMP variables using SDP were lower than those using UAD. This was analyzed using the regional climatic characteristics when high-magnitude precipitation events occurred, as shown in Table 1.

3.2.1 | Deviation of event PW

Figure 3 shows the event PWs estimated using the SDP and UAD approaches for 50 precipitation events of 50 ensembles (top daily precipitation). The upper figures show the results for the southern areas of Japan with relatively high SDPs and high magnitudes of precipitation events. The bottom figures show the results for the northern areas of Japan with relatively low SDPs and low magnitudes of precipitation events. The position of each circle in Figure 3 indicates the deviation between the event PW values estimated using SDP and UAD for each area. Table 5 lists the average errors for the PW events in the eight target areas.

As shown in Figure 3 and Table 5, the PW event demonstrated considerably low positive errors within 10% between the SDP and UAD approaches in the southern areas (Kagoshima, Fukuoka, Kochi, and Matsue). The northern areas (Hakodate, Sapporo, Urakawa, and Kushiro) had high negative errors of over 14%. The event PWs using the SDP tended to be overestimated compared with the UAD in the southern areas, but the deviation between the event PWs using the two approaches was relatively low. Meanwhile, the event PWs estimated using the SDP were underestimated more than the event PWs

estimated using the UAD. These results indicated that the SDP approach could estimate PWs similar to the UAD approach in southern Japan; however, the SDP approach may underestimate the event PWs compared to the UAD approach in northern Japan.

3.2.2 | Deviation of MMR

Figure 4 shows the MMRs estimated using UAD and SDP for each top precipitation per ensemble (50 values of 50 ensembles). The position of each circle represents the deviation between the MMRs estimated using SDP and UAD in each area. As shown in Figure 4, the SDP approach overestimated the MMR compared to the UAD approach in the northern area. The SDP approach slightly underestimated MMR in the southern area;

however, the deviation between the two approaches was low. Table 6 lists the average errors of the MMRs for each area. The average errors were low in the southern area, whereas they were relatively high in the northern areas. These results indicated that the SDP approach overestimated the MMR in the northern region compared with the UAD approach. In this analysis, the tendency of overestimated MMRs for the SDP approach was recognized only in northern areas with relatively low SDPs. Hence, the MMRs were overestimated based on the SDP, and the deviation for both approaches may be significantly related to relatively low SDPs for the high-magnitude precipitation event.

As indicated by the box plot in Figure 5, this study analyzed the characteristics of the MMRs for the two approaches in detail. In the southern areas, box plots for

TABLE 5 Average errors of the surface dew point-based event precipitable water (PW) to the upper-air data-based event PWs.

Area	Average error (%)	Location
Kagoshima	8.19	Southern part of Japan
Fukuoka	6.39	
Kochi	9.36	
Matsue	0.48	
Hakodate	−14.42	Northern part of Japan
Sapporo	−14.78	
Urakawa	−19.53	
Kushiro	−28.73	

TABLE 6 Average errors of the surface dew point-based moisture maximizing ratios (MMRs) to the upper-air data-based MMRs.

Area	Average error (%)	Location
Kagoshima	9.19	Southern part of Japan
Fukuoka	8.28	
Kochi	10.89	
Matsue	8.47	
Hakodate	30.99	Northern part of Japan
Sapporo	31.20	
Urakawa	23.77	
Kushiro	21.06	

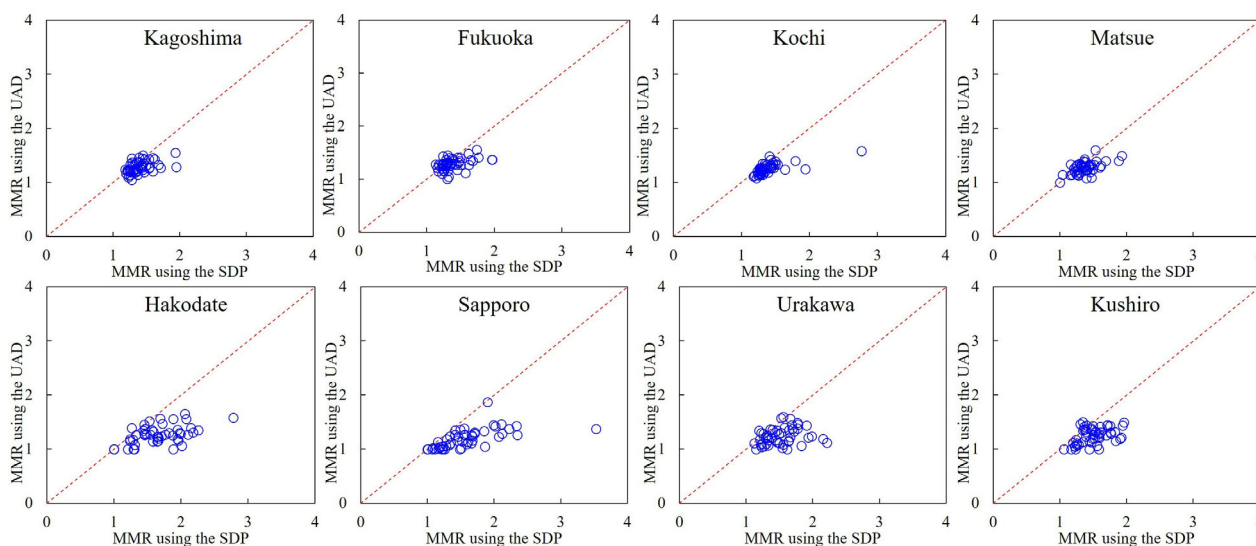


FIGURE 4 The SDP-based moisture-maximizing ratios (MMR) versus the UAD-based MMRs in Kagoshima, Fukuoka, Kochi, Matsue, Hakodate, Sapporo, Urakawa, and Kushiro. The selected events (blue circle) are based on each top precipitation per ensemble of 50 ensembles of the d4PDF database with a one-day duration. SDP, surface dew point; UAD, upper-air data.

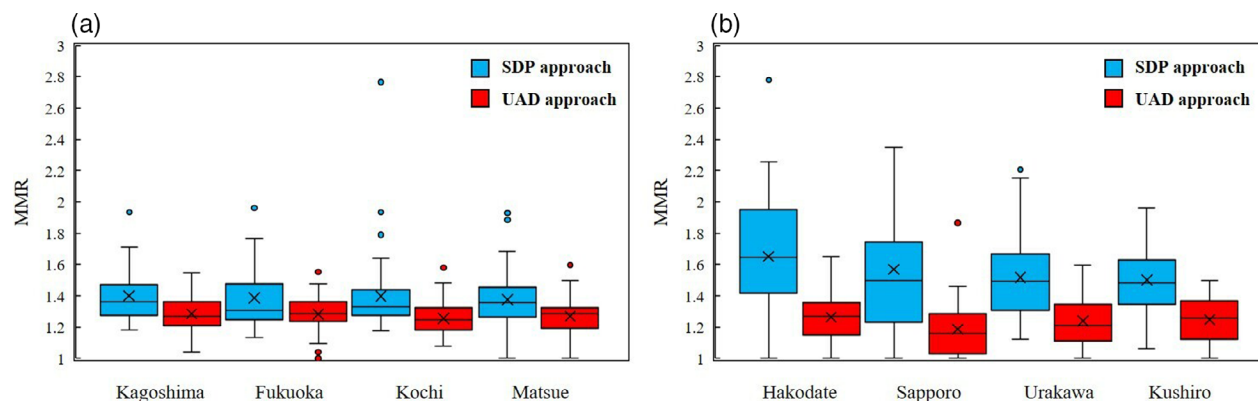


FIGURE 5 Box plots of MMRs estimated using the SDP and UAD in eight areas. (a) areas show relatively high SDPs for high-magnitude precipitation events. (b) areas show relatively low SDPs for high-magnitude precipitation events. MMR, moisture-maximizing ratio; SDP, surface dew point; UAD, upper-air data.

the SDP approach are formed slightly higher than those for the UAD approach, but box plots for both approaches are similarly formed with an MMR of 2.0 or less; the median and mean values of MMRs for the two approaches are similar; between 1.2 and 1.5. These results indicate that the deviation of MMR is low between the SDP and UAD approaches in the southern areas with relatively high SDPs for high-magnitude precipitation events; MMRs estimated using the SDP approach have a tendency similar to those estimated using the UAD approach. However, in the northern areas, box plots of the MMRs for the two approaches are different. The spreads of MMRs using the SDP approach are larger than those using the UAD approach, and the upper whisker shows an MMR of 2.0 or more. This implies that the MMRs estimated using the SDP approach contained some values over 2.0 in the northern areas with relatively low SDPs. Meanwhile, all MMRs of the box plot for the UAD approach were located within 2.0 in the northern areas. The box plots for the UAD approach in the northern areas were similar to the box plots for the two approaches in the southern areas. As a result, the SDP approach overestimated the MMRs more than the UAD approach, and some MMRs represented a value over 2.0 in the northern areas.

Many previous studies have noted that high MMRs over 2.0 may overestimate the PMP. They have also suggested that the upper bound of the MMR should be limited below a specific value to reduce and control the possibility of PMP overestimation (CEHQ & SNC-Lavalin, 2003; Hansen et al., 1988; Jakob et al., 2009; Minty et al., 1996; Rouhani & Leconte, 2016; Rousseau et al., 2014; Schreiner & Riedel, 1978; Walland et al., 2003). Accordingly, the SDP approach has a high possibility of PMP overestimation in northern areas with relatively low SDPs for high-magnitude precipitation events.

3.2.3 | Deviation of PMP

Figure 6 shows the PMPs estimated using UAD and SDP for the top daily precipitation per ensemble (50 values of 50 ensembles). In the southern areas, these points are close to the dashed line. This means that the deviations between the two approaches are very low, and that the SDP approach can estimate the PMP, similar to the UAD approach. However, the deviations in PMP were relatively high between the two approaches in the northern areas, and the SDP approach overestimated the PMPs compared to the UAD-based PMPs.

These results are provided in more detail in Table 7 and are the same as the MMR results, as shown in Table 6. Most average PMP errors were higher than 20% in the northern areas, but the average errors were close to 10% in the southern areas. These overestimated PMPs were due to overestimated MMRs in the northern areas, as mentioned in Section 3.2.2. The deviation between the PMPs using the two approaches showed similar characteristics to the deviation of the PW event. In the southern areas, deviations of both the PW and PMP events were relatively lower than those in the northern areas. However, the deviations were relatively large in the northern areas.

To analyze the relationship between the errors for the event PW and PMP, the errors are shown in Figure 7 as a bar graph. In the southern areas, both the PW and PMP exhibited low average errors. Meanwhile, in the northern areas with relatively low SDPs for the precipitation event, the PW event showed high negative errors and the PMP showed high positive errors. This implied that the SDP approach underestimated the event PW and overestimated the PMP compared to the UAD approach in the northern areas of Japan with relatively low SDPs. In addition, Figure 6 indicates that the error of the event PW may be related to the error of the PMP.

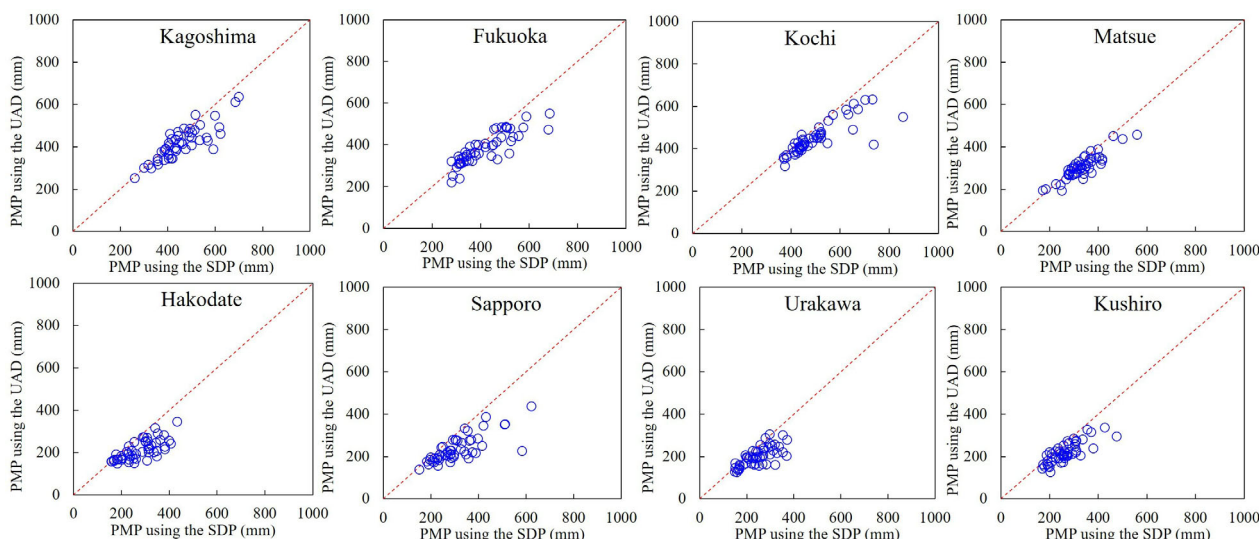


FIGURE 6 The SDP-based PMPs versus the UAD-based PMPs in Kagoshima, Fukuoka, Kochi, Matsue, Hakodate, Sapporo, Urakawa, and Kushiro. The selected events (blue circle) are based on each top precipitation per ensemble of 50 ensembles of the d4PDF database with a one-day duration. PMP, probable maximum precipitation; SDP, surface dew point; UAD, upper-air data.

TABLE 7 Average errors of the surface dew point-based probable maximum precipitation (PMP) to the upper-air data-based PMPs.

Area	Average error (%)	Location
Kagoshima	9.19	Southern part of Japan
Fukuoka	8.28	
Kochi	10.89	
Matsue	8.47	
Hakodate	30.99	Northern part of Japan
Sapporo	31.20	
Urakawa	23.77	
Kushiro	21.06	

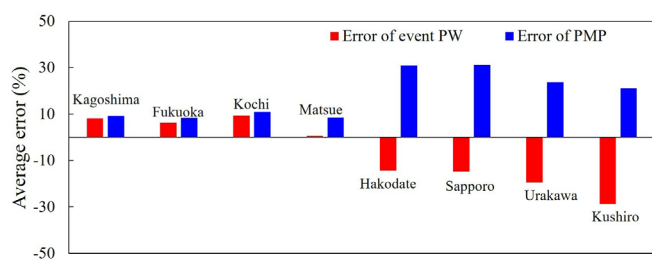


FIGURE 7 Average errors between PMP variables estimated using the SDP and UAD approach in eight areas. Red bars refer to the average error of event PW, and blue bars refer to the average error of PMP. PMP, probable maximum precipitation; SDP, surface dew point; UAD, upper-air data.

This relationship was indicated by Kim et al. (2020), who suggested that high negative errors of the event PW affect the high positive errors of MMR and PMP. Furthermore, they identified the relationship between the high error of event PW and relatively low SDP by comparing the vertical profiles of atmospheric variables (dew point, mixing ratio, and PW) observed at radiosonde stations. The estimated profiles (SDP-based estimated variables in the air column) were underestimated compared to the observed profiles (UAD-based observed variables in the air column) for all vertical atmospheric pressures in areas with relatively low SDPs for precipitation. In particular, they noticed that the SDP approach, which is based on the pseudo-adiabatic assumption, could not accurately predict the atmospheric moisture condition related to PW in the upper air. This led to inaccurate PW estimations, and these inaccurate PWs caused overestimated MMRs in areas with relatively low SDPs.

Consequently, in this study, the SDP approach inaccurately estimated PWs in northern areas with relatively low SDPs, and these event PWs estimated high MMR values of over 2.0. This resulted in a high deviation of more than 20% between the PMPs estimated using the two approaches. A high deviation could be identified in the northern areas, which showed relatively low SDPs below 18°C for the occurrence of high-magnitude precipitation events. Therefore, the deviation between the PMPs estimated using the two approaches showed different patterns, depending on the regional climatic characteristics.

4 | DISCUSSION

4.1 | Estimation of the reference precipitation using the d4PDF

A reference value was proposed to evaluate the PMP values estimated using the SDP and UAD methods. Frequency analysis was conducted based on a large-scale sample of the d4PDF consisting of 3000 annual maximum daily precipitation. In the frequency analysis, the Gumbel distribution was selected to represent the long return period of the reference precipitation as a probability density function. The Gumbel distribution has been widely utilized to estimate the design rainfall with the return period in Japan. The JMA proposed probability rainfall values with a high return period based on the Gumbel distribution. The parameters of the Gumbel distribution were estimated using the L-Moment method. Through frequency analysis, the extreme-magnitude precipitation values with return periods of 1000, 3000, and 5000 years were estimated for each target area.

Table 8 presents the results. The difference between the estimated values with return periods of 1000 and 3000 years was relatively high, at over 10% for all areas. The difference between the estimated values with return periods of 3000 and 5000 years was low, within 5% for all areas. This difference decreased as the return period increased. Thus, even estimating precipitation values with a return period longer than 3000 years will show

similar magnitudes. This study used the precipitation value with a return period of 3000 years as a reference value.

4.2 | Evaluation of the PMPs estimated using the SDP and UAD approaches

In this study, the PMPs of each ensemble estimated using the SDP and UAD approaches were compared with the estimated reference precipitation values (Table 8). Unlike that in Section 3.2, where the top precipitation of each ensemble was analyzed, this study was based on the largest PMP value per ensemble. Figure 8 shows the results of the 50 PMPs of 50 ensembles estimated using the SDP and UAD approaches. The left figure shows Fukuoka and the right figure shows Sapporo. In Figure 8, the red circles refer to PMPs estimated using the UAD approach, blue squares refer to PMPs estimated using the SDP approach, the black dashed line refers to the reference value, the red line refers to the average value of 50 PMPs estimated using the UAD approach, and the blue line refers to the average value of 50 PMPs estimated using the SDP.

Both areas showed a very low deviation between the PMPs estimated using the UAD approach and the reference values in Figure 8. Even in Sapporo, which showed relatively low SDPs, the PMPs using UAD showed a low deviation. Meanwhile, the deviation for the PMPs

TABLE 8 The precipitation values estimated for return periods of 1000, 3000, and 5000 years through frequency analysis based on a large-scale sample of the d4PDF.

Return period (years)	Kagoshima	Fukuoka	Kochi	Matsue	Hakodate	Sapporo	Urakawa	Kushiro
1000	410.29	377.04	447.79	294.80	206.24	242.82	189.23	215.90
3000 (reference)	455.02	420.06	493.80	329.58	231.31	271.32	210.84	241.15
5000	475.81	440.07	515.19	345.75	242.96	284.56	220.89	252.89

Note: (unit: mm).

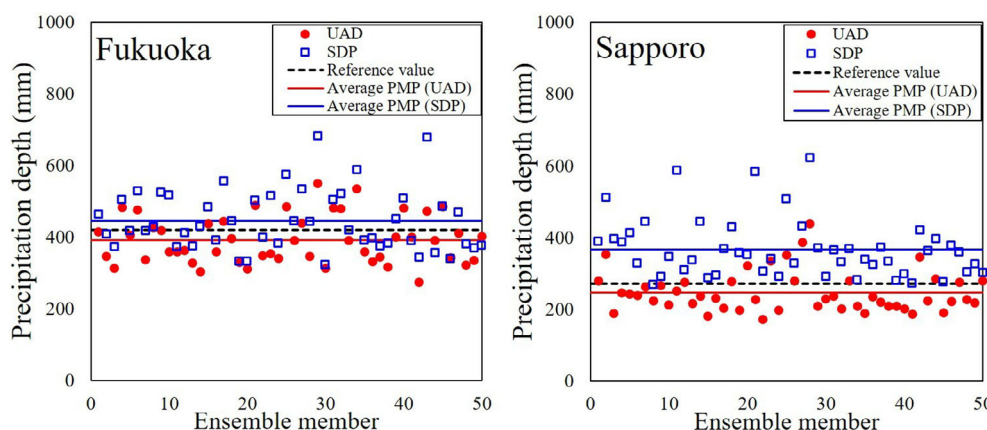


FIGURE 8 Comparison between the PMPs estimated using the SDP and UAD approaches and the largest precipitation obtained from the d4PDF. Left figure shows the Fukuoka area, and right figure shows the Sapporo area. PMP, probable maximum precipitation; SDP, surface dew point; UAD, upper-air data.

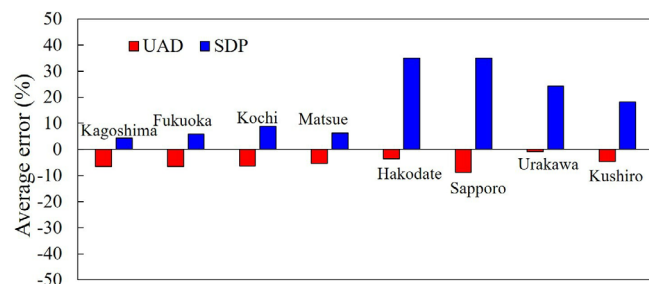


FIGURE 9 Average errors of the PMPs using the SDP and UAD for the largest precipitation in the eight areas. Red bars refer to the average error between the PMPs using the UAD and the largest value; blue bars refer to the average error between the PMPs using the SDP and the largest value. PMP, probable maximum precipitation; SDP, surface dew point; UAD, upper-air data.

estimated using SDP was different from the result of the UAD approach. Fukuoka showed a low deviation of PMPs using SDP to the reference value; however, Sapporo showed a high deviation of PMPs using SDP to the reference value rather than that in the Fukuoka area. This indicated that the SDP approach showed a different tendency for deviation between the estimated PMP and the reference value in the northern and southern areas.

Figure 9 shows the average error of the PMPs estimated using the SDP and UAD approaches for the reference values in the eight areas. The red bars refer to the average error between the PMPs using the UAD and the reference values, and the blue bars refer to the average error between the PMPs using the SDP and the reference values. As shown in Figure 9, the SDP-based PMPs indicated a low average error of within 10% in Kagoshima, Fukuoka, Kochi, and Matsue. The northern areas showed high positive average errors of over 20% for the reference value. This meant that northern areas with relatively low SDPs may have a high possibility of PMP overestimation. Meanwhile, the UAD-based PMPs showed low average errors with the reference value in all southern and northern areas, even if the PMPs were slightly underestimated compared to the reference value in most areas of Japan.

These results indicated that the tendency to underestimate and overestimate the PMP using the UAD approach was not related to regional climatic characteristics. The UAD approach may be used reliably, even without considering regional climatic characteristics, as PMPs estimated in all areas with any climatic characteristics show similar trends. On the other hand, the tendency of PMP overestimation for the SDP approach was significantly related to the regional climatic characteristics, and this may lead to an uncertain PMP value depending on each regional climatic characteristic. The regional

climatic characteristics should be considered when using the SDP approach for PMP estimation.

Although the reference value was arbitrarily proposed, this study found that the SDP approach had a high possibility of PMP overestimation in areas with relatively low SDPs for precipitation events compared to the reference value. Accordingly, by using extreme precipitation reflecting the precipitation characteristics of each area as a reference value, it was possible to understand the tendency of the PMP values estimated using the UAD and SDP approaches according to the regional climatic characteristics.

5 | CONCLUSIONS

For event PW, MMR, and PMP, the deviations between the SDP and UAD approaches were relatively low in the southern areas (Kagoshima, Fukuoka, Kochi, and Matsue) with relatively high SDPs. The deviation of the PMP variables was relatively high between the two approaches in northern areas (Hakodate, Sapporo, Urakawa, and Kushiro) with relatively low SDPs.

The pseudo-adiabatic assumption employed in the SDP approach predicts inaccurately estimates PWs when the SDP is below 18°C (Kim et al., 2020). The northern areas showed relatively low SDPs below 18°C as shown in Table 1. The SDP approach underestimated the PWs compared to the UAD approach in the northern areas. This led to the difference in results between the UAD and SDP approaches in northern areas. Meanwhile, in the southern areas, which showed relatively high SDPs over 18°C as shown in Table 1, the SDP approach estimated the PWs similar to the UAD approach. This led to similar PMP results between the UAD and SDP approaches in southern areas.

Extreme-scale reference precipitation was proposed to evaluate PMPs estimated using the UAD and SDP approaches. The suggested reference value was compared with the PMPs of 50 ensembles of the d4PDF. The SDP approach showed high average errors in the northern areas. The UAD approach showed very low average errors in all the southern and northern areas. This implied that the SDP approach had a high possibility of PMP overestimation in the northern areas with relatively low SDPs for precipitation events. Therefore, the SDP approach may estimate uncertain PMPs based on regional climatic characteristics. To use the SDP approach reasonably, climatic characteristics related to the SDP for precipitation events should be considered for each area.

In this study, the PMP estimation based on the moisture-maximization method was evaluated from

extreme-scale reference precipitation under sufficient extreme events by utilizing the d4PDF. PMP has been widely used for estimating the PMF, a key parameter of dam construction, and for analyzing water-related disasters such as floods and storms. While multiple guidelines exist for evaluating PMP estimates, there is no representative guideline that can be universally trusted and consensus among all researchers. In light of this, this study focused on demonstrating the potential application of the d4PDF as one of the diverse methodologies for evaluating PMP. d4PDF has the capability to estimate a reliable extreme-scale reference rainfall by using a large-scale sample size of the d4PDF in frequency analysis. This reference value may be used for evaluating the estimated PMP.

However, in our study, we did not analyze important precipitation behaviors like spatiotemporal correlation, long-range dependence, and clustering patterns in the d4PDF dataset. These behaviors, known as Hurst phenomenon or long-range dependence, have been observed in regular and extreme precipitation events (Dimitriadis et al., 2021; Iliopoulou & Koutsoyiannis, 2019). Our future research will investigate the spatiotemporal correlation structure of maximum precipitation in the d4PDF, revealing clustering patterns of wet and dry years in time and space. We will also focus on preserving long-range dependence, seasonality, and auto-correlation using alternative stochastic schemes (Dimitriadis & Koutsoyiannis, 2018; Koutsoyiannis & Dimitriadis, 2021), and address the generation of stochastic observables for hydrological models (Beven, 2021). These efforts aim to enhance our understanding and representation of precipitation characteristics in the d4PDF dataset.

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DATA AVAILABILITY STATEMENT

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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