

Future Changes of Extreme Precipitation and Related Atmospheric Conditions in East Asia under Global Warming Projected in Large Ensemble Climate Prediction Data

SICHENG HE^{a,b} AND TETSUYA TAKEMI^a

^a *Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan*

^b *Graduate School of Science, Kyoto University, Kyoto, Japan*

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ABSTRACT: Extreme precipitation is expected to pose a more severe threat to human society in the future. This work assessed the historical performance and future changes in extreme precipitation and related atmospheric conditions in a large ensemble climate prediction dataset, the database for Policy Decision-making for Future climate change (d4PDF), over East Asia. Compared with the Tropical Rainfall Measuring Mission (TRMM) and fifth major global reanalysis produced by ECMWF (ERA5) datasets, the historical climate in d4PDF represents favorably the precipitation characteristics and the atmospheric conditions, although some differences are notable in the moisture, vertical motion, and cloud water fields. The future climate projection indicates that both the frequency and intensity of heavy precipitation events over East Asia increase compared with those in the present climate. However, when comparing the atmospheric conditions in the historical and future climates for the same precipitation intensity range, the future climate indicates smaller relative humidity, weaker ascent, less cloud water content, and smaller temperature lapse rate, which negatively affect generating extreme precipitation events. The comparison of the precipitation intensity at the same amount of precipitable water between the historical and future climates indicates that extreme precipitation is weaker in the future because of the more stabilized troposphere in the future. The general increase in extreme precipitation under future climate is primarily due to the enhanced increase in precipitable water in the higher temperature ranges, which counteracts the negative conditions of the stabilized troposphere.

SIGNIFICANCE STATEMENT: Extreme precipitation can have disastrous effects on human lives, economy, and ecosystems and is anticipated to significantly increase in both intensity and frequency under future climate. The purpose of this study is to investigate the mechanism for the future change of extreme precipitation. We examined the relationship between future changes in extreme precipitation and changes in the related atmospheric conditions. It is important for reducing uncertainties in future projections of extreme precipitation. Our results highlight that the future atmospheric condition is unfavorable for generating future extreme precipitation events in terms of stability and humidity changes. The increase in the column moisture content is the primary factor for the increase of extreme precipitation, which counteracts the negative conditions.

KEYWORDS: Extreme events; Precipitation; Climate change; Climate models; Model evaluation/performance

1. Introduction

Precipitation is one of the key players in the atmospheric processes and is critically important for the existence of nature, living creatures, and human society. At times, intense precipitation can cause significant impacts on our society. As a high-impact weather event, extreme precipitation causes severe losses for human society, world economies, and the ecosystem and affects the livelihoods of billions of people (Meehl et al. 2000; Lesk et al. 2016). East Asia is particularly sensitive and vulnerable to extreme precipitation events associated with the East Asian summer monsoon and typhoons (Easterling et al. 2000; Zhang et al. 2017; Li and Wang 2018). Therefore,

realistic simulations and predictions of the intensity and total amount of extreme precipitation are important, although scientifically challenging, for preventing and mitigating disasters and enabling effective policy decisions.

In addition to the intensity of extreme precipitation, the duration of heavy rainfall is also an important aspect for predicting extreme precipitation. Hazardous conditions associated with extreme precipitation events, such as widespread summer flooding and landslides in East Asia, are usually the result of large amounts of accumulated precipitation from prolonged and sustained rainfall that lasts for several days (Kendon et al. 2018; Hatsuzuka et al. 2021). For example, an extreme heavy rainfall event occurred in Zhengzhou, Henan Province, China, during mid-July in 2021, when the maximum daily rainfall reached 552.5 mm, causing more than \$17 million in economic losses and affecting approximately 1.48 million people (Zhou et al. 2022; Sun et al. 2022). In addition, consecutive days of continuous precipitation will cause water to infiltrate into the soil layers, which may eventually lead to soil saturation and trigger landslides (Takemi 2019; Du et al. 2022). Another example is

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Corresponding author: Sicheng He, he_s@storm.dpri.kyoto-u.ac.jp

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the landslide that occurred in Atami, Shizuoka Prefecture, Japan, in July 2021, when Atami received more than 500 mm of rainfall in a 3-day period; the resultant landslide caused more than 20 deaths, and more than 100 houses and buildings were washed away or damaged (Zhang et al. 2022). Given that the highest precipitation accumulation occurs in regions of both high intensity and prolonged duration, comprehending the characteristics of extreme precipitation events in terms of both intensity and duration is critical for the detection and prediction of severe precipitation events (Beguería et al. 2009).

Climate change has been linked to a growing occurrence of extreme precipitation in global monsoon areas as well as in East Asia, as evidenced by several studies (e.g., Kharin et al. 2013; Ma et al. 2015; Zhang and Zhou 2019). According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), additional global warming is expected to increase the frequency and intensity of heavy precipitation events in East Asia. The mechanism of this increase can be separated into thermodynamic and dynamic contributions: The thermodynamic change is driven by the changes associated with atmospheric moisture content, whereas the dynamic change is mainly due to the change in atmospheric vertical motion (Emori and Brown 2005; Sudharsan et al. 2020). The Clausius–Clapeyron (CC) relationship dictates that the moisture-holding capacity of the atmosphere increases by around 7% with every 1°C rise in temperature (Trenberth 1999; Allen and Ingram 2002; Nayak et al. 2018). That is, warmer air can hold more moisture, resulting in spatially uniform thermodynamic increase in the frequency and intensity of precipitation events. However, the projections of future extreme precipitation display a regional dependence, likely because the dynamics driving these phenomena exhibit regional variability (Norris et al. 2020). In some regions, a positive dynamical contribution is expected to strengthen, favoring more precipitation; however, in other regions, a negative dynamical contribution can offset or even negate the positive thermodynamic increases (Emori and Brown 2005; Lu et al. 2014; Chen and Zhou 2015; Pfahl et al. 2017; Tandon et al. 2018; Norris et al. 2019; Chen et al. 2020). For example, Emori and Brown (2005) demonstrated that the upward motion frequency decreased over many parts of the subtropics, whereas it increased over the equatorial Pacific. Pfahl et al. (2017) analyzed 22 CMIP5 models and found that a negative dynamical contribution was sufficiently strong over subtropical oceans to result in a robust regional decrease in extreme precipitation. Li and O’Gorman (2020) further found that the changes in vertical velocity contribute to the intensity of extreme precipitation changes, which is due to changes in moist static stability. Although a negative dynamical contribution has been demonstrated in various studies, the reasons for these changes remain poorly understood.

Moreover, these studies have often examined vertical velocity changes, usually at the 500-hPa level, during extreme precipitation events as the dynamical contribution (Emori and Brown 2005; Sugiyama et al. 2009). Such changes have been referred to as “extreme ascent” (Lu et al. 2014; Tandon et al. 2018) and have been regarded as a great source of uncertainty in projections of extreme precipitation intensity (Pfahl et al. 2017).

However, the changes in other atmospheric conditions for the occurrence of extreme precipitation, such as relative humidity, cloud water content, and convective instability, have rarely been examined. Understanding the changes in atmospheric conditions as well as the dynamical contributions is important to reduce uncertainties in future projections of extreme precipitation.

In this study, we examine the characteristics of extreme precipitation and the associated atmospheric conditions in both the historical and future climates. To this end, we use output from a large-ensemble climate simulation dataset: the database for Policy Decision-making for Future climate change (d4PDF) (Mizuta et al. 2017). The historical credibility of the simulation is first examined, and the future changes in both extreme precipitation and atmospheric conditions are investigated.

The details of the d4PDF and methods are described in section 2, the historical performance and future changes simulated using the d4PDF data are described in sections 3 and 4, respectively, a discussion follows in section 5, and a summary is provided in section 6.

2. Datasets and methodologies

a. Reference datasets and climate model outputs

As the reference for precipitation, the observational dataset from the National Aeronautics and Space Administration Tropical Rainfall Measuring Mission (TRMM 3B42) satellite was used here. The dataset provides records from December 1997 to January 2020 with a spatial resolution of $0.25^\circ \times 0.25^\circ$ (Huffman et al. 2007). The reanalysis dataset retrieved from the fifth major global reanalysis produced by ECMWF (ERA5; Hersbach et al. 2018), which provides gridded data of the atmospheric environments, was here regarded as the atmospheric reference. The ERA5 dataset has a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and 37 pressure levels for the time period from 1979 to the present.

The d4PDF, which is a large-ensemble climate simulation dataset designed for climate change risk assessments (Mizuta et al. 2017; Ishii and Mori 2020), was used in the present study. The global atmospheric climate model used to generate the d4PDF dataset was the MRI Atmospheric General Circulation Model, version 3.2 (MRI-AGCM3.2; Mizuta et al. 2012), with a horizontal resolution of 60 km and 12 vertical layers. Climate simulations for the past historical period and a future period with a +4 K warming scenario were conducted in the d4PDF experiments. In the historical simulation, observed sea surface temperature (SST), sea ice concentration (SIC) of the Centennial Observation-Based Estimates of SST, version 2 (COBE-SST2; Hirahara et al. 2014), and constructed sea ice thickness (SIT; Bourke and Garrett 1987) were used as the lower boundary conditions. The historical simulation of d4PDF contains 100-member ensemble simulations conducted with small perturbations in SSTs (δ SSTs), covering the time period from 1951 to 2010. In the 60-yr future climate simulation, the +4 K warming condition was used in this study. The future SST fields as forcing for the climate predictions were generated by adding detrended observations to the monthly SST trends of six CMIP5 model

experiments with the RCP8.5 warming scenario: CCSM4 (Gent et al. 2011), GFDL-CM3 (Delworth et al. 2006; Donner et al. 2011), HadGen2-AO (Collins et al. 2011; Martin et al. 2011), MIROC5 (Watanabe et al. 2010), MPI-ESM-MR (Giorgetta et al. 2013), and MRI-CGCM3 (Yukimoto et al. 2011, 2012). For each CMIP5 model with different warming patterns, the Δ SST field is rescaled in +4 K of global mean warming. For each SST trend case, 15 sets of experiments with perturbations to oceanic boundary conditions were conducted. In total, there were 90 ensemble members in the future climate simulation.

b. Analysis methods

To evaluate the performance of the historical climate simulations, the common time period of the TRMM and d4PDF datasets from 1998 to 2010 was used. For assessing future changes, projected future climate simulations were compared with the historical simulation for the whole 60 years in d4PDF. This study focused on the summer season of June–August (JJA) over an East Asia domain (20°–50°N, 100°–160°E). All the variables were daily temporal frequency. Among the atmospheric variables in ERA5, those at the same 12 layers as d4PDF were selected. To avoid the effect of the resolution difference on the results, all of the datasets were interpolated into $1^\circ \times 1^\circ$ grids by the nearest-neighbor interpolation method (Accadia et al. 2003; He et al. 2019).

There may be an argument as to the potential influences of the interpolation method on the representation of precipitation. For example, Sivapalan and Blöschl (1998) discussed how the area reduction factor of rainfall intensity changed with the spatial extent and rainfall event return period. Thus, how the spatial interpolation and/or filtering affect the quantitative representation of precipitation should be carefully examined before conducting statistical analyses. Thus, this study examined and compared the differences in the precipitation representation (in terms of frequency distribution against daily precipitation intensity) before and after interpolating each dataset. We found that for TRMM, the interpolation indeed affected the frequency distribution of extreme precipitation than for d4PDF, with more fluctuations in the distribution of extreme intensity ranges but confirmed that the present interpolation did not impact the relative relationship between the two datasets. In addition, we compared the conservative scheme with other interpolation methods in terms of the precipitation frequency distribution and found that there were no significant differences in the results. Thus, we consider that the present interpolation method will not affect the following analyses. Note also that there are no considerable differences in precipitation characteristics of land and ocean grids. Therefore, we conducted our analysis using all the grids over the domain without separating land and ocean grids. All the calculations were done at each grid and then averaged within the analysis domain.

Both relative and absolute thresholds of extreme precipitation were examined in this study. A relative threshold is defined as the precipitation intensity rain rate (RR) exceeding a specific percentile (e.g., 90th, 95th, or 99th percentile), whereas an absolute threshold is defined as the RR exceeding

50 and 100 mm day^{−1} on the basis of the definition of heavy rainfall by the China Meteorological Administration and in other studies (e.g., Matsumoto and Takahashi 1999; He et al. 2019).

To validate the performance of extreme precipitation, several widely used extreme precipitation indices were calculated in this study (http://etccdi.pacificclimate.org/list_27_indices.shtml). A wet day w is defined as having a daily precipitation intensity $RR \geq 1$ mm. The six selected indices and definitions are as follows:

- 1) PRCPTOT (annual total precipitation on w): $PRCPTOT_j = \sum_{w=1}^W RR_{wj}$, where RR_{wj} is the daily precipitation amount on w in period j .
- 2) R50mm (annual heavy rainfall days): Count the number of days where $RR \geq 50$ mm.
- 3) R99p (annual total precipitation amount when $RR > 99$ th percentile): $R99p = \sum_{w=1}^W RR_{wj}$, where $RR_{wj} > RR_{wn99}$, where RR_{wn99} is the 99th percentile of precipitation on w in the reference period (1961–90).
- 4) Rx1day (maximum 1-day precipitation): $Rx1day_j = \max(RR_{wj})$.
- 5) SDII (simple precipitation intensity index): $SDII_j = \sum_{w=1}^W RR_{wj}/W$.
- 6) CWD (consecutive wet days): Count the largest number of consecutive days where $RR_{wj} \geq 1$ mm.

Note that the reference climatology period used for computing R99p is 1961–90 in the definition; however, because the common time period of TRMM and d4PDF is only available from 1998 to 2010, the reference period for computing R99p was set to be the same period.

To describe the distribution of precipitation frequency as a function of extreme precipitation duration, we computed the frequency of each duration bin. We defined an extreme precipitation threshold and obtained the time series of RR for individual grid cells of each dataset. The maximum number of consecutive days with RR consecutively exceeding the threshold is counted as i -day duration cases. The frequency is normalized by the total number of extreme precipitation cases. The normalized frequency of each duration case was then calculated as

$$\text{frequency of duration}_i = \frac{\text{Num}_i}{\text{TotNum}} \times 100\%, \quad (1)$$

where Num_i is the number of i -day duration cases and TotNum is the total number of RR exceeding the threshold.

To measure the moistness of the atmosphere, the total column of precipitable water (PW) was calculated as

$$PW = \frac{1}{\rho g} \int_{p_1}^{p_2} x \, dp, \quad (2)$$

where ρ is the density of liquid water, g is the acceleration due to gravity, p_1 and p_2 indicate the pressure levels at the ground surface and the top of the layer, respectively, and $x(p)$ is the mixing ratio at pressure level p .

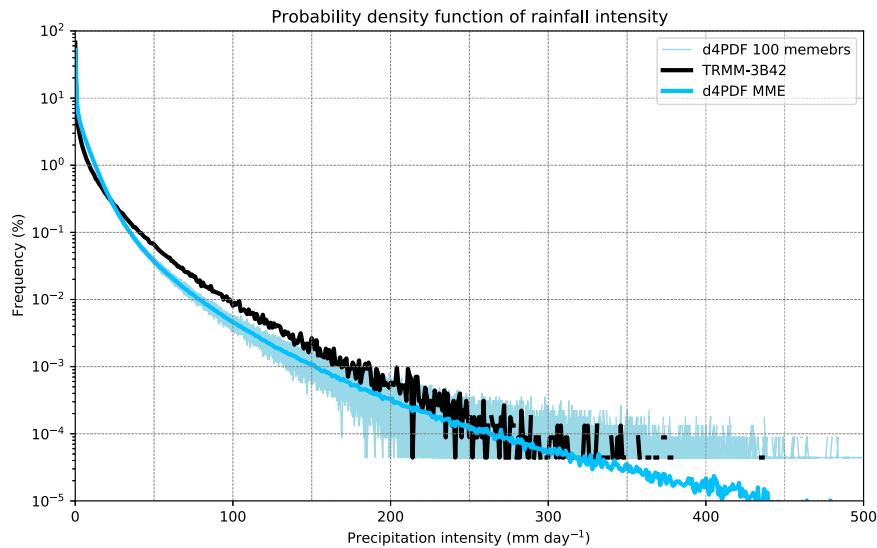


FIG. 1. The frequency distribution of daily rainfall in the TRMM-3B42 (black line) and d4PDF (blue lines) data. The light-blue and dark-blue lines indicate the rainfall distributions for d4PDF 100 ensemble members and for MME, respectively. The intensity bin is set as 1 mm day^{-1} .

To measure the stability of the atmosphere, an indicator for describing the severe thunderstorm potential, the K index (KI), was calculated as follows:

$$\text{KI} = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700}), \quad (3)$$

where T and T_d are the air temperature and the dew temperature, respectively, at a specific pressure level (i.e., 850, 700, or 500 hPa). The KI comprises three parts based on the vertical temperature lapse rate ($T_{850} - T_{500}$), the moisture content in the lower troposphere (T_{d850}), and the vertical extent of a moist layer ($T_{700} - T_{d700}$). KI is generally used as a measure of thunderstorm potential in climate studies in order to diagnose stability conditions (e.g., Takemi 2012; Takemi et al. 2012; Unuma and Takemi 2016). A higher KI indicates a greater potential for thunderstorm development.

3. Representations of extreme precipitation and atmospheric conditions in the historical simulation of d4PDF

a. Extreme precipitation performance

Initially, we examined the overall representations of precipitation in d4PDF in terms of the frequency distribution of daily precipitation in the analysis domain of East Asia. Figure 1 compares the daily precipitation frequency in the historical simulation using the d4PDF against TRMM. Both indicate that the frequency decreases with increasing precipitation intensity. As a reference dataset, TRMM indicates that the daily precipitation intensity is maximized at $\sim 400 \text{ mm day}^{-1}$ and the frequency of the 100 (200) mm day^{-1} event is $\sim 0.01\%$ ($\sim 0.001\%$). Compared with the TRMM data, d4PDF generally exhibits a similar frequency–intensity distribution. Although d4PDF underestimates the frequency of $30\text{--}250 \text{ mm day}^{-1}$ rainfall

against TRMM, d4PDF better captures the frequency distribution in this rainfall range compared with ERA5 (results not shown). Note that TRMM and d4PDF have different initial horizontal resolutions (0.25° and 60 km), and the underestimate of precipitation intensity of d4PDF may be partly due to the coarse resolution.

We next examined the representation of extreme precipitation in terms of its temporal duration. The frequency distribution of extreme precipitation duration is shown in Fig. 2. In general, the longer extreme precipitation persists, the less frequently it occurs. Both the maximum duration and frequency generally decrease as the extreme precipitation threshold increases. For the relative thresholds of extreme precipitation (Fig. 2a), the precipitation events with intensities of $\text{RR} > 90\text{th}$ and $\text{RR} > 95\text{th}$ last as long as 5 days and those with an intensity of $\text{RR} > 99\text{th}$ last up to 3 days in TRMM. The d4PDF shows similar frequency–duration distributions while it overestimates the frequency and maximum duration days. Specifically, d4PDF indicates that both the $\text{RR} > 90\text{th}$ and $\text{RR} > 95\text{th}$ extreme precipitation events last longer than 10 days. The $\text{RR} > 99\text{th}$ extreme precipitation event is shown to last as long as 8 days in d4PDF, which is 5 days longer than in TRMM. The overestimation of the relative extreme precipitation frequency and duration in d4PDF might be partly due to the different actual intensities in the different datasets (not shown): d4PDF indicates weaker precipitation intensity than TRMM in all the relative threshold cases, especially for $\text{RR} > 95\text{th}$ and $\text{RR} > 99\text{th}$.

For the absolute threshold of extreme precipitation (Fig. 2b), d4PDF displays similar frequency–duration distributions as TRMM. Extreme precipitation lasts as long as 6 days for $\text{RR} > 50 \text{ mm day}^{-1}$ and 3 days for $\text{RR} > 100 \text{ mm day}^{-1}$ in TRMM. The frequency of 6-day events is $\sim 0.001\%$. d4PDF generally simulates 3–4 days longer than TRMM, with a slight overestimation of frequency in $\text{RR} > 50 \text{ mm day}^{-1}$.

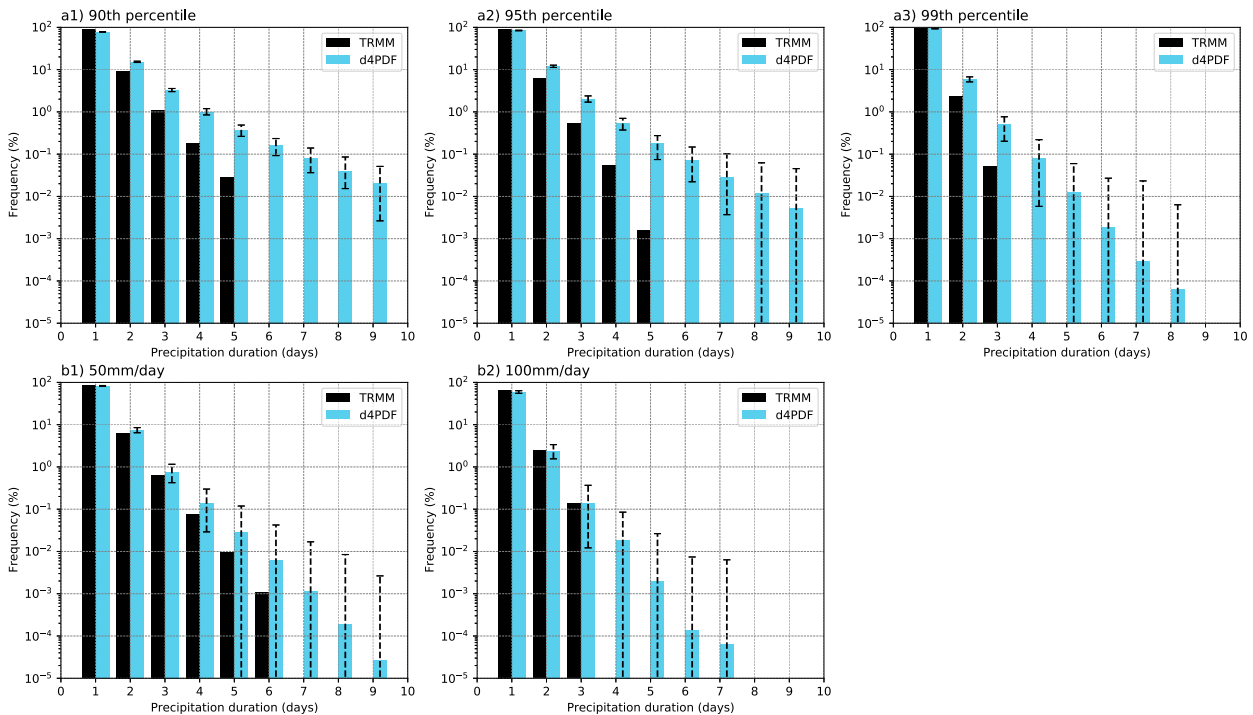


FIG. 2. Annual extreme precipitation frequency–duration distribution in the TRMM (black bar) and d4PDF (blue bar) in (upper) relative thresholds and (lower) absolute thresholds of extreme precipitation. Dashed lines represent the error bar of individual ensemble members in d4PDF.

The spatial distribution of several extreme precipitation indices in the three datasets is shown in Fig. 3. The TRMM data indicate a larger amount of PRCPTOT over the southern China coastal region and the Japan–Korean Peninsula region (Fig. 3a). Compared with TRMM, d4PDF well captures the spatial pattern of the rainfall amount, although there are regions with higher values (over the Sichuan Basin) and lower values (over the South China coast and Japan–Korean Peninsula region). In terms of the number of extreme precipitation days (R50mm), d4PDF obviously underestimates the value of R50mm represented in TRMM (Fig. 3b), while higher values appear only over the Japan–Korean Peninsula region. Higher values of Rx1day are observed over the coastal and sea areas of East Asia in TRMM than in d4PDF (Fig. 3c). Higher values of R99p and SDII in the TRMM data appear over the oceanic regions off the coasts of South and East China and the Japanese islands (Figs. 3d,e). d4PDF captures the spatial pattern of R99p (but with generally smaller values), as indicated in TRMM (Fig. 3d), and largely underestimates the values of SDII (Fig. 3e). For the CWD, d4PDF indicates overly enhanced values in the southern region compared with TRMM (Fig. 3f). The large bias, as observed in the R99p, SDII, and CWD results, might be due to the common bias in climate models that produce too much light rainfall (e.g., drizzle) (Dai 2006; Zhang et al. 2016). Consistent performance was confirmed in previous studies of both the d4PDF dataset (e.g., Duan et al. 2019) and other global climate models (e.g., Sillmann et al. 2013; Jiang et al. 2015).

b. Atmospheric condition simulations

The representations of the atmospheric conditions in d4PDF were evaluated with the ERA5 reanalysis fields. The atmospheric conditions in the troposphere were examined with respect to the precipitation intensity and duration. Although extreme precipitation exhibits some variabilities in their spatial distribution, the analysis of atmospheric conditions focuses more on the vertical structure of the troposphere.

The vertical profiles of the tropospheric variables composited with precipitation intensity are examined in Fig. 4. The composite of tropospheric variables in ERA5, separated by precipitation intensity indexed by TRMM, is taken as the reference (denoted as TRMM/ERA5). The composited tropospheric conditions in d4PDF with the d4PDF precipitation (denoted as d4PDF) are compared with the reference. The reference conditions indicate that, with the increase in precipitation intensity, the troposphere becomes moister not only in the lower layer but also in the middle and upper troposphere. With an increase in precipitation intensity, stronger upward motion and more cloud water content appear in the middle layer. The reference feature displays a very wet column with two enhanced peaks in the lower (700–500 hPa) and upper (300–200 hPa) troposphere in the extreme precipitation range exceeding 100 mm day^{-1} . By contrast, d4PDF indicates insufficient humidity in the upper troposphere but excessive humidity in the lower troposphere. The upward motion in d4PDF is stronger than that in TRMM/ERA5 in stronger precipitation cases. Consistent with the overestimated upward motion in d4PDF, the cloud water content in

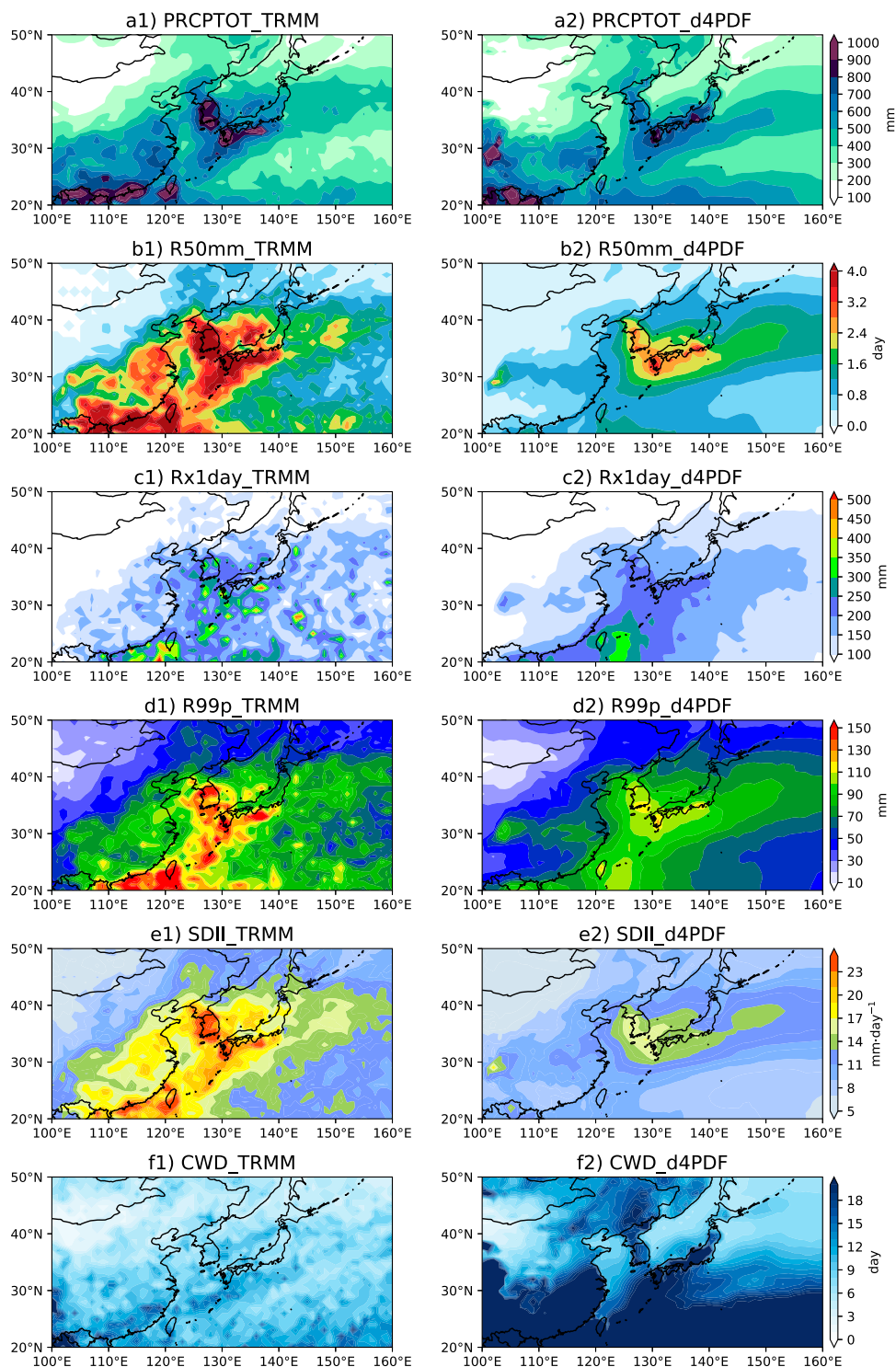


FIG. 3. Spatial distribution of annual extreme precipitation indices in (left) TRMM and (right) d4PDF. (from top to bottom) The indices of PRCPTOT, R50mm, Rx1day, R99p, SDII, and CWD. The d4PDF results are the 100-member ensemble mean.

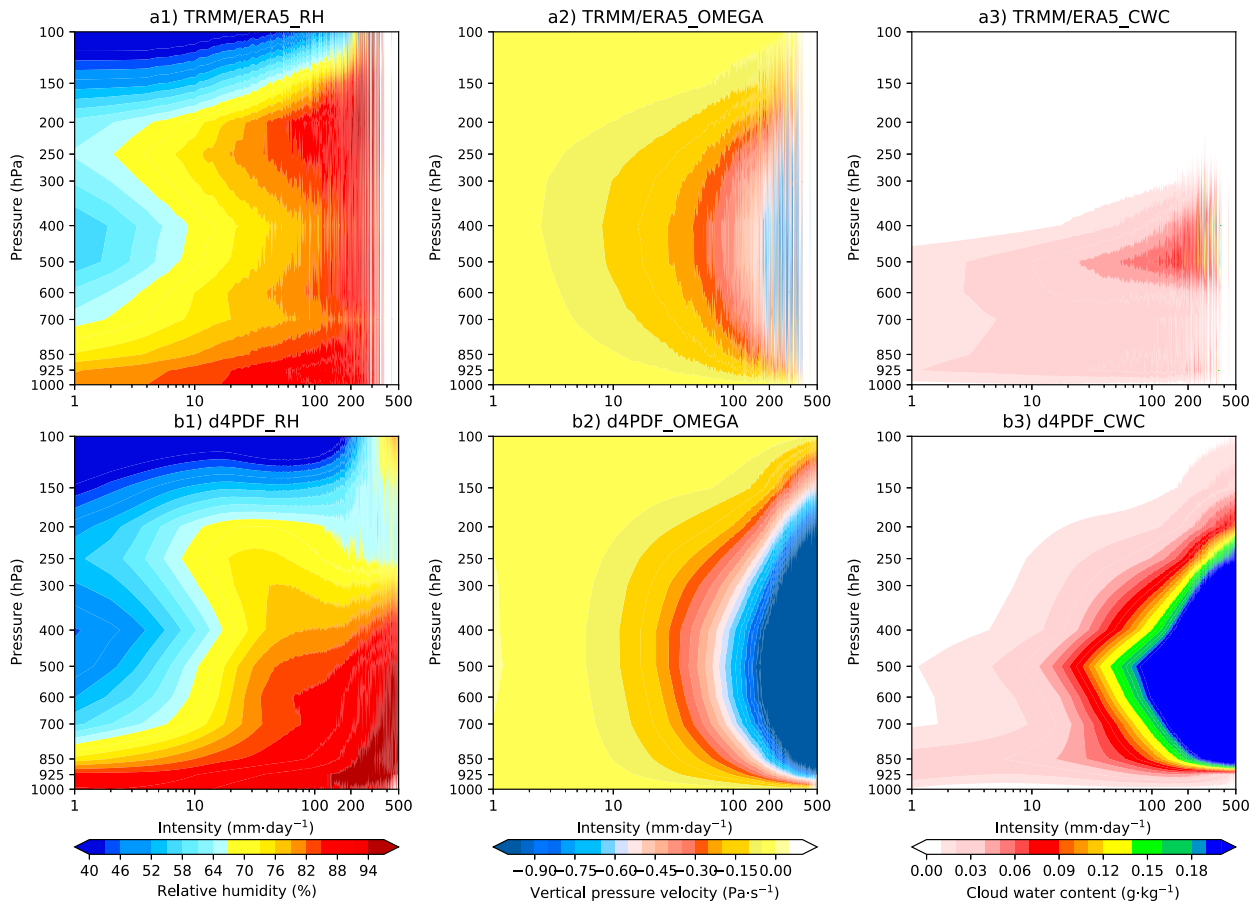


FIG. 4. Composite vertical profiles of (left) relative humidity, (middle) vertical pressure velocity, and (right) cloud water content with respect to precipitation intensity in the ERA analysis with (top) the TRMM precipitation data and (bottom) the d4PDF present-climate data. The composition is averaged over the domain. The d4PDF results are the 100-member ensemble mean.

d4PDF is largely overestimated against the reference field. Despite this large bias, the height at which the peak of the cloud water content appears is ~ 500 hPa, which is consistent with the TRMM data.

The composites of atmospheric variables with respect to the temporal duration of extreme precipitation are shown in Fig. 5. Here, we used the absolute threshold of a precipitation intensity that exceeds 50 mm day^{-1} as the extreme precipitation. The TRMM/ERA5 reference indicates that long-lasting extreme precipitation tends to have higher relative humidity almost throughout the troposphere, stronger upward motion at the middle level (especially for 2–4 days), and higher cloud water content in the middle level. This feature is overall reproduced in d4PDF. Specifically, TRMM/ERA5 indicates relative humidity peaks at the low level near the surface and the middle level of ~ 500 hPa for longest events lasting 5–6 days, whereas d4PDF generally represents the low-level peak well for all durations and reproduces the second peak at a middle level of approximately 600–500 hPa. However, d4PDF indicates a less relative humidity in the middle to upper layer compared to TRMM/ERA5. For the upward motion and cloud water content, d4PDF indicates stronger upward

motion and more cloud water than represented in TRMM/ERA5. For the long-duration precipitation events (7–9 days) in d4PDF, they indicate a larger relative humidity, upward motion, and cloud water content throughout the whole troposphere.

The relationship between the total column water vapor content, i.e., the PW, and precipitation intensity and duration was further examined. The composite of PW derived from ERA5, indexed by precipitation intensity (duration) derived from TRMM, is taken as the reference (denoted as TRMM/ERA5). Higher PW leads to stronger rainfall intensity (Fig. 6a) and a longer duration of extreme precipitation (Fig. 6b). TRMM/ERA5 indicates that the extreme precipitation (i.e., intensity $> 100 \text{ mm day}^{-1}$) requires $\text{PW} > 70 \text{ kg m}^{-2}$. d4PDF indicates a similar PW–intensity relationship as TRMM/ERA5, except for the cases with $\text{PW} < 5 \text{ kg m}^{-2}$. Notably, d4PDF slightly underestimates the intensity for $50 < \text{PW} < 75 \text{ kg m}^{-2}$ and overestimates that for $\text{PW} > 75 \text{ kg m}^{-2}$. In addition, d4PDF generates extremely high PW (as high as $\sim 95 \text{ kg m}^{-2}$), greatly extending the maxima in TRMM/ERA5. Extreme precipitation events do not last for longer than 1 day until the PW exceeds 60 kg m^{-2} in TRMM/ERA5 and 75 kg m^{-2} in d4PDF.

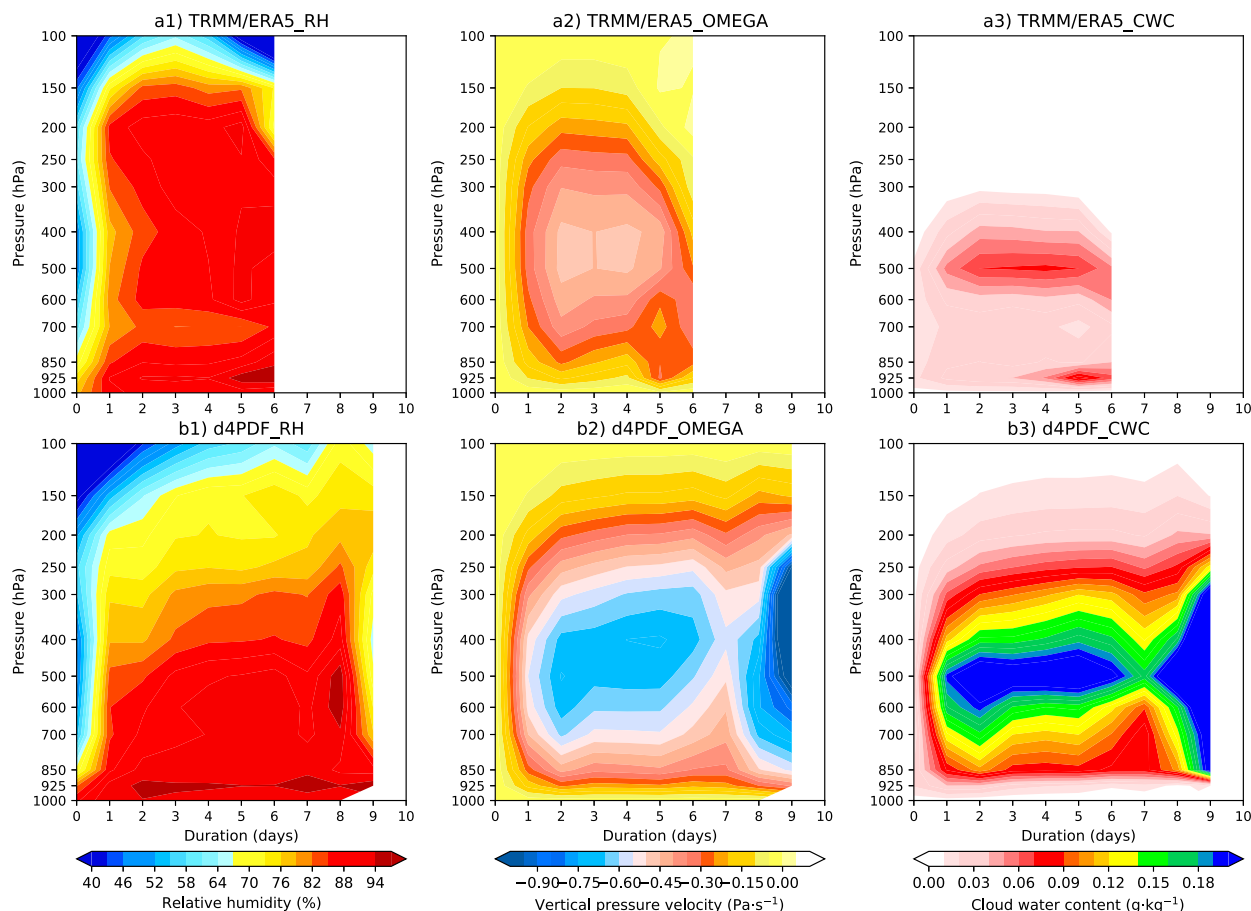


FIG. 5. As in Fig. 4, but the x axis is the extreme rainfall ($RR > 50 \text{ mm day}^{-1}$) duration.

The PW–duration distribution varies substantially among 100 ensemble members, especially for the higher PW range.

4. Future changes in extreme precipitation and atmospheric conditions

In this section, future changes in extreme precipitation and the associated atmospheric conditions in the d4PDF simulation are examined. Here, we specifically focus on the characteristics of extreme precipitation using various indices. We then examine the atmospheric conditions for the precipitation generation and compare the atmospheric conditions in extreme precipitation occurrences with those in the other precipitation cases.

a. Extreme precipitation changes

First, the frequency distributions of daily precipitation in both the historical and future simulations are shown in Fig. 7. Compared with the historical simulation, the future simulation indicates that both the intensity and frequency of extreme precipitation will increase (Fig. 7a). Furthermore, the duration and frequency of long-duration extreme precipitation events are also projected to increase in the future (Fig. 7b). The future increase can be identified not only for the multimodel ensemble

(MME) mean but also for the six warming pattern means. The magnitude of the frequency increases with increasing precipitation intensity and duration increases.

Second, the spatial distributions of six extreme precipitation indices in the future simulation are shown in Fig. 8. The location of maxima of each index is consistent with those in the present-climate simulation, locating over the South China coast region, the Sichuan Basin, and the Japan–Korean Peninsula region. The future anomaly indicates that extreme precipitation indices will generally increase in the future climate, with some exceptions. The total precipitation amount (PRCPTOT) indicates a slight decrease over the Japan–Korean Peninsula region, Taiwan Island, and Sichuan Basin in the future [Fig. 8b(1)]. R50mm and SDII exhibit a significant decrease over the Japan–Korean Peninsula region [Figs. 8b(2),b(5)].

b. Atmospheric condition changes

Future changes in the atmospheric conditions with respect to precipitation intensity were examined in terms of the vertical structure of temperature, humidity, convective motion, and cloud formation.

The vertical profiles of the tropospheric variables composited with future precipitation intensity are presented in Fig. 9. We

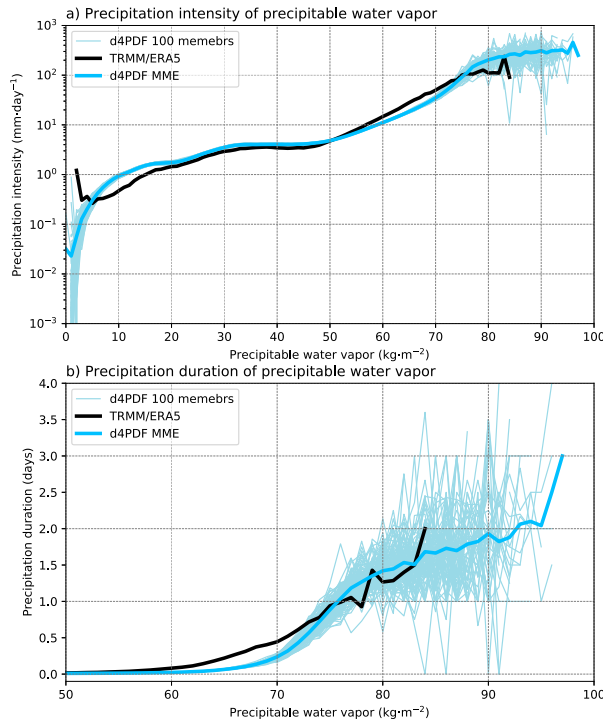


FIG. 6. The distribution of (a) precipitation intensity and (b) duration as a function of PW in TRMM/ERA5 (black line) and d4PDF (blue line). The light-blue and dark-blue lines indicate the cases for the d4PDF 100 ensemble members and for MME, respectively.

here focus on the extreme precipitation range ($>100 \text{ mm day}^{-1}$). Features of the atmospheric conditions in the future climate appear to be similar to those in the historical simulation. However, in terms of the changes between the historical and future climates, most of the troposphere in the future indicates smaller relative humidity except in the middle to upper levels (400–250 hPa) when the precipitation intensity exceeds 100 mm day^{-1} [Fig. 9b(1)], although the specific humidity is generally increased especially in the low to middle levels (1000–400 hPa) in the warmer future climate [Fig. 9b(5)]. Upward motion is mostly suppressed in the future, especially in the lower to middle troposphere (1000–500 hPa), whereas upward motion is enhanced in the upper troposphere when the precipitation intensity exceeds 300 mm day^{-1} . The cloud water content decreases in the lower troposphere (i.e., below 500 hPa) but increases in the upper troposphere (i.e., above 500 hPa). Air temperature increases throughout the troposphere, with a greater increase in the upper troposphere (above 300 hPa), which indicates a smaller vertical temperature lapse rate in the future, especially when the precipitation intensity exceeds 300 mm day^{-1} . Also, the specific humidity of the atmosphere indeed generally increases, which indicates a favorable condition for the increase of the extreme precipitation intensity.

We further examined the characteristics of the future changes in precipitation intensity in terms of the total column moisture content, i.e., the PW (Fig. 10). Both the future and

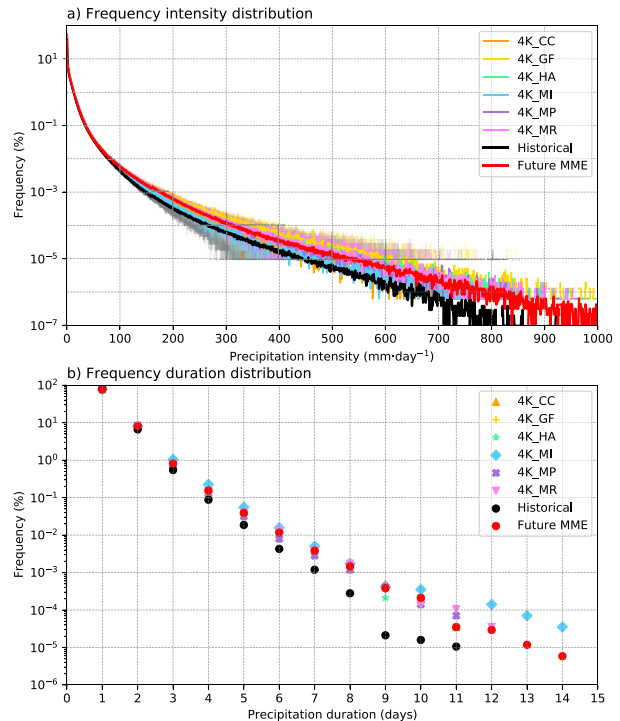


FIG. 7. The frequency distribution of (a) precipitation intensity and (b) precipitation duration in the d4PDF historical and future +4 K simulation. Black lines (markers) indicate the historical simulation (1951–2010), red lines (markers) indicate the future MME simulation (2051–2111), and thin lines indicate the ensemble members of each simulation. Six colored lines (markers) denote the ensemble means of six SST warming patterns. The abbreviation is for each GCM in the legend, e.g., “4K_MR.”

historical simulations show a similar feature that a higher PW leads to greater rainfall intensity. The maximum PW value will reach nearly 120 kg m^{-2} in the future, compared to 100 kg m^{-2} in the present climate. Notably, the same amount of PW in both climates leads to weaker precipitation intensity in the future than in the present climate, especially when the PW exceeds 50 kg m^{-2} . It suggests that extreme precipitation in the future climate will occur only with an extreme amount of PW, which never appears in the present climate. This point is further investigated in section 5.

5. Discussion: Possible role of stability changes

In this section, a possible reason for the future changes in extreme precipitation is discussed. Previous studies have confirmed a robust relationship between PW and extreme precipitation in both observation and model results (e.g., Roman et al. 2015; Hagos et al. 2021). However, recent works have reported that more moisture indeed increases the frequency of intense rains in southern Europe but increases their magnitudes much less (Yano and Manzato 2022) and that subtropical regions exhibit a weaker relationship (Kim et al. 2022). This study has indicated that extreme precipitation in the future climate would occur only with an extreme amount of PW

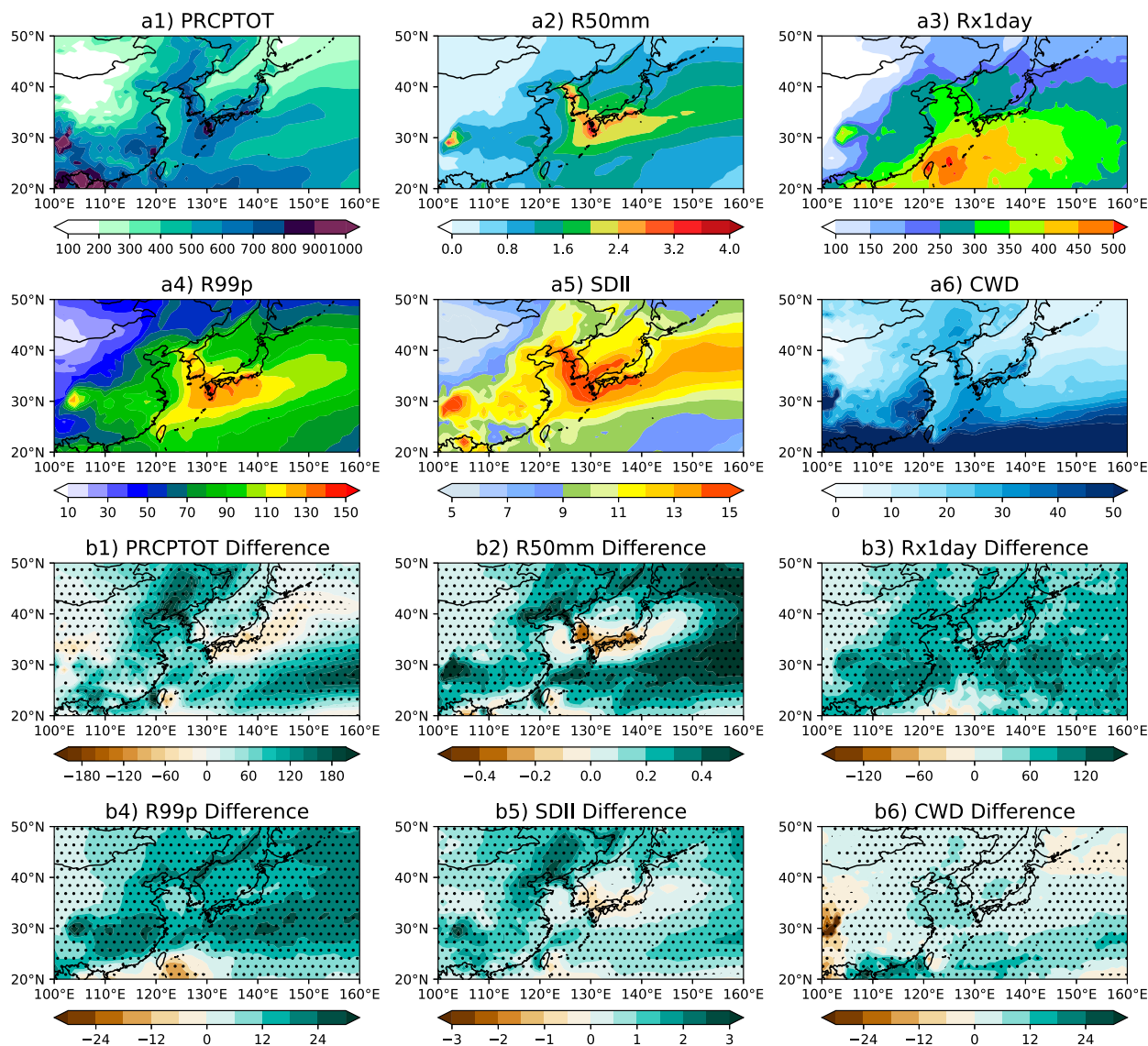


FIG. 8. Spatial distribution of the annual extreme precipitation indices in d4PDF. (a) The upper six panels indicate absolute values in the future simulation and (b) the lower six panels show the difference between future and historical simulations. The results are shown with the 100-member ensemble means in the d4PDF present-climate simulation and the 90-member ensemble means in the future simulation. Dots indicate significance test passed the 95% confidence level.

and that the same amount of PW leads to weaker precipitation intensity in the future than in the present climate in a certain range of PW (as shown in Fig. 10). Here, we focused on the atmospheric stability to explain why the same amount of PW between the historical and future climates leads to weaker precipitation intensity in the future climate than in the present climate.

Figure 11 compares the spatial distributions of mean PW and temperature lapse rate averaged in the historical and future climates and also exhibits the spatial distribution of those changes from the historical to the future climates. The PW values are generally increased in the future, and the region of higher PW values seems to shift northward. Despite the shift

of locations toward higher latitudes for future climates with the same PW values compared to the present climate, however, the decreasing temperature lapse rate (TLR) is observed generally throughout the East Asia domain. This condition indicates that the stability in terms of the temperature lapse rate becomes more stabilized in the future climate throughout the East Asia domain. Therefore, even if the PW values, assessed as temporal averaged over the historical and future time periods, are the same, the atmospheric stability is generally more stabilized in the future.

To diagnose the atmospheric stability, an indicator for describing the severe thunderstorm potential, the KI, was employed here. The relationship between the KI and PW and

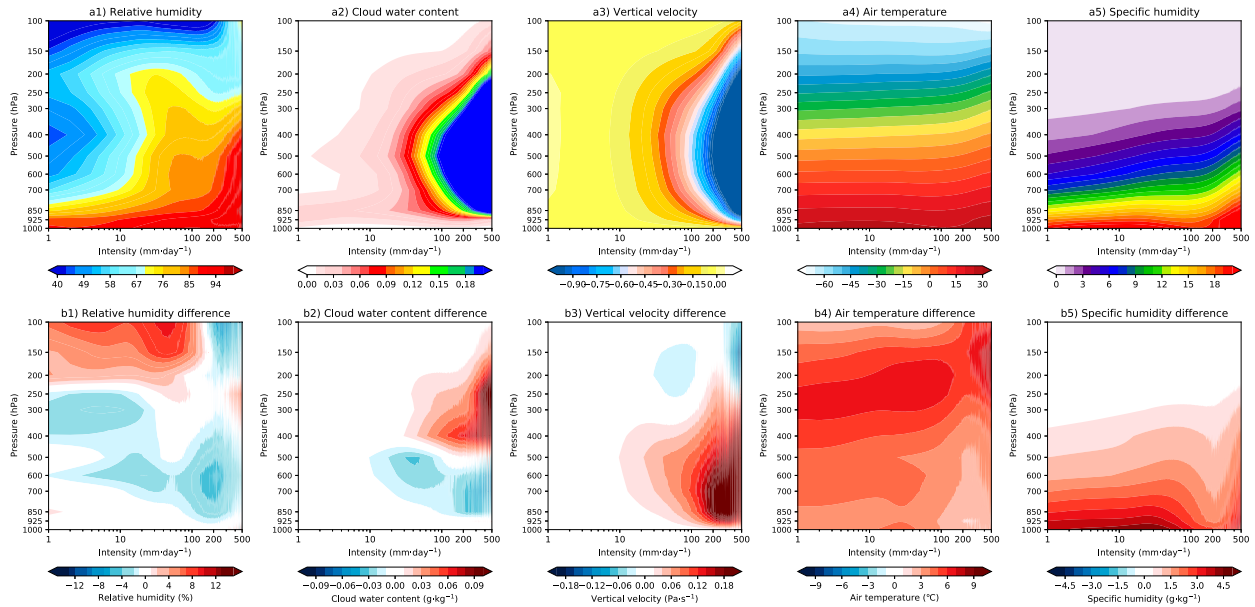


FIG. 9. Composite vertical profiles of (left) relative humidity, (middle left) cloud water content, (middle) vertical pressure velocity, (middle right) air temperature, and (right) specific humidity with respect to precipitation intensity in (top) the d4PDF future simulation data and (bottom) the difference between the future- and present-climate simulations. The results are the 100-member ensemble mean of the d4PDF present-climate simulation and the 90-member ensemble mean of the future simulation.

between precipitation intensity and KI was calculated (Fig. 12). A higher KI indicates a more unstable condition and a greater probability of the occurrence of a thunderstorm. Figure 12a shows that the KI is smaller in the future climate for $40 \leq PW \leq 90 \text{ kg m}^{-2}$; this feature is reversed for $90 \leq PW \leq 95 \text{ kg m}^{-2}$.

However, for the same KI value, the precipitation intensity is weaker in the future climate (Fig. 12b). KI includes both moisture content and vertical temperature lapse rate information, and in the previous analysis, we found that in the future climate, the temperature lapse rate will decrease while the moisture (PW) will increase. Therefore, weaker precipitation in the future at the same KI value indicates that the negative

impact of the decrease in temperature lapse rate on precipitation is greater than the positive impact of the increase in moisture. In other words, under future climate conditions, higher KI values are needed to produce precipitation of the same intensity as the present climate, which means that more moisture content is needed to overcome the negative impact of the decreased temperature lapse rate.

As shown in the previous results, both the intensity and frequency of extreme precipitation will increase in the future; however, the atmospheric conditions are generally more stabilized over the analysis area, which appears to be unfavorable for generating extreme precipitation. The weaker precipitation intensity in the future climate in this PW range is demonstrated in Fig. 10. We therefore examined the relationship between the PW and precipitation intensity in terms of the frequency distribution of precipitation intensity against the PW; the results are shown in Fig. 13. In the present climate, extreme precipitation with an intensity that exceeds 100 mm day^{-1} only occurs when the PW is >70 (and as high as ~ 100) kg m^{-2} ; by contrast, in the future climate, such extreme precipitation is projected to occur in the case of $90 \leq PW \leq 120 \text{ kg m}^{-2}$. That is, in the future, more moisture will be required for precipitation development (i.e., greater PW) for extreme precipitation to occur (e.g., for a precipitation intensity $> 100 \text{ mm day}^{-1}$). This finding further suggests that extreme precipitation in the future climate will develop only when an extreme amount of PW is available to overcome the unfavorable conditions in terms of a more stable temperature lapse rate. This result is qualitatively consistent with the findings of a previous study that reported that, as a thermodynamic contribution, an increase in water vapor reduces the magnitude of the vertical motion required to generate the same

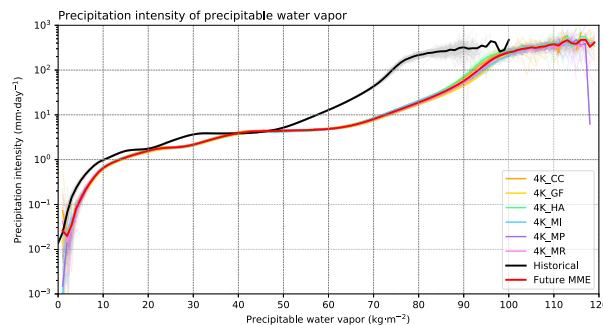


FIG. 10. The distribution of precipitation intensity as a function of PW in d4PDF. The black line indicates the historical simulation results (1951–2010), and the red line indicates the future MME simulation results (2051–2111). The six colored lines are the ensemble means of six warming SST patterns. Thin lines represent the individual ensemble members of the corresponding simulation.

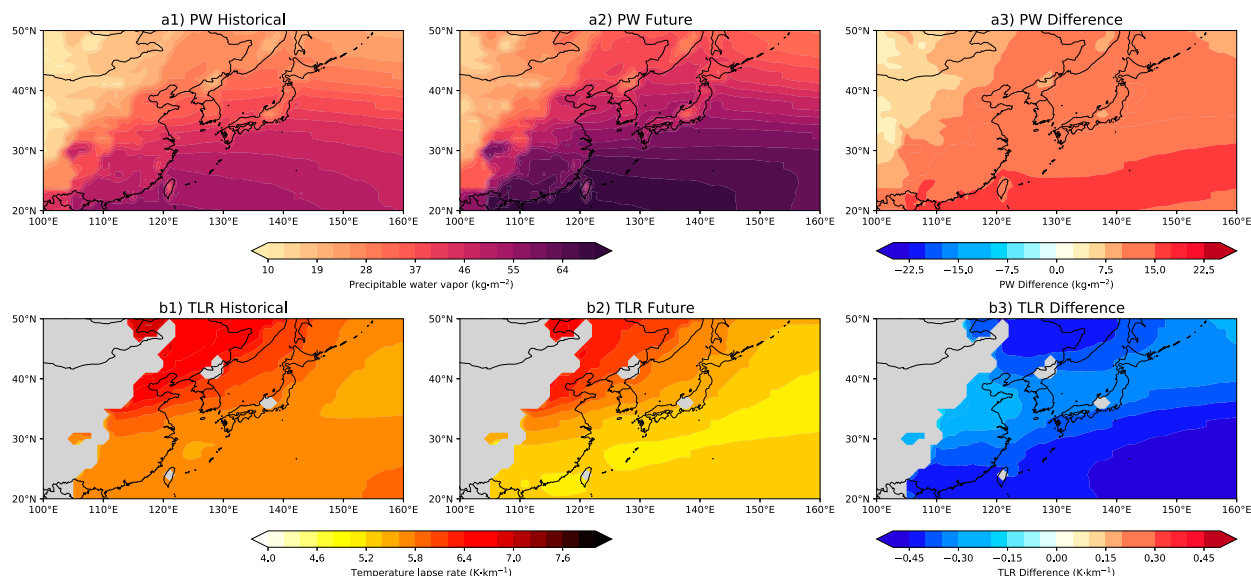


FIG. 11. Spatial distribution of (top) PW and (bottom) TLR between 1000 and 300 hPa in (left) present climate, (middle) future climate, and (right) the difference between the future- and present-climate simulations.

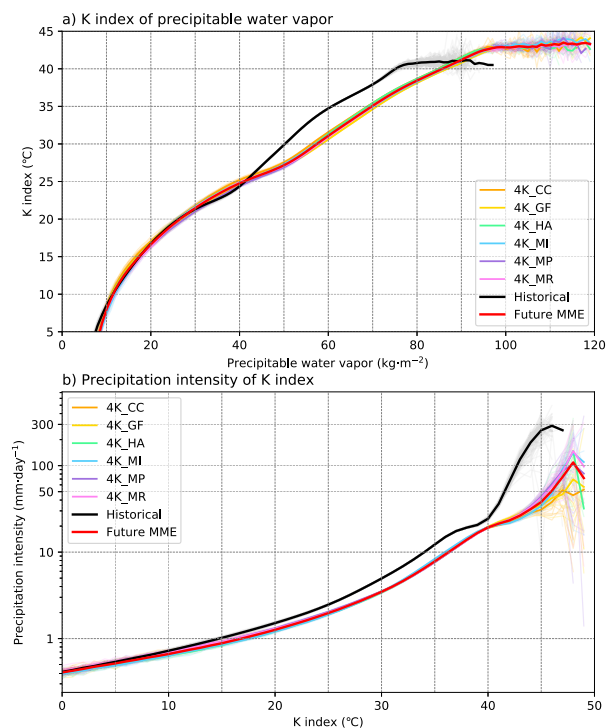


FIG. 12. The distribution of (a) the KI as a function of PW and (b) precipitation intensity as a function of KI in d4PDF. The black line indicates historical simulation results (1951–2010), and the red line indicates future MME simulation results (2051–2111). The six colored lines for the ensemble mean represent the six warming SST patterns. Thin lines represent individual ensemble members of the corresponding simulation.

intensity of precipitation, resulting in an increase in precipitation frequency (Chou et al. 2012). Previous relevant studies that examined the changes in precipitation by separating two main mechanisms reached consistent results. For example, Chou et al. (2012) confirmed that most changes in extreme precipitation frequency are induced by the positive effect of the thermodynamic component, whereas the dynamic component has a relatively weak negative effect on the precipitation frequency because of the more stable atmosphere. However, for the heaviest precipitation events, Chou et al. (2012) reported enhanced dynamic components. In addition, Norris et al. (2020) also demonstrated that an amplification/damping of the ascent pattern weakened precipitation for moderate extremes and intensified the most extreme precipitation, consistent with the reversed KI for $90 \leq \text{PW} \leq 95 \text{ kg m}^{-2}$ in Fig. 12. However, the dynamic contribution is reported to be relatively inconsistent among climate models and regions (Chou et al. 2009); the definition of extremes also varies (Pendergrass 2018; Norris et al. 2020). Thus, further analysis is needed to clarify these details and draw robust conclusions. Note that the regional mean of extreme precipitation (Rx1day) and PW changes are close to the Clausius–Clapeyron scale, while when examining the spatial distribution (Fig. 8 for Rx1day, Fig. 11 for PW, as well as their percentage changes which are not shown), the future changes in extreme precipitation exhibit significant regional variability, which in some parts, the increase of Rx1day is smaller than the increase of PW.

6. Conclusions

Extreme precipitation events have potentially disastrous effects on human health, the global economy, social infrastructure, and the ecosystem and are projected to substantially

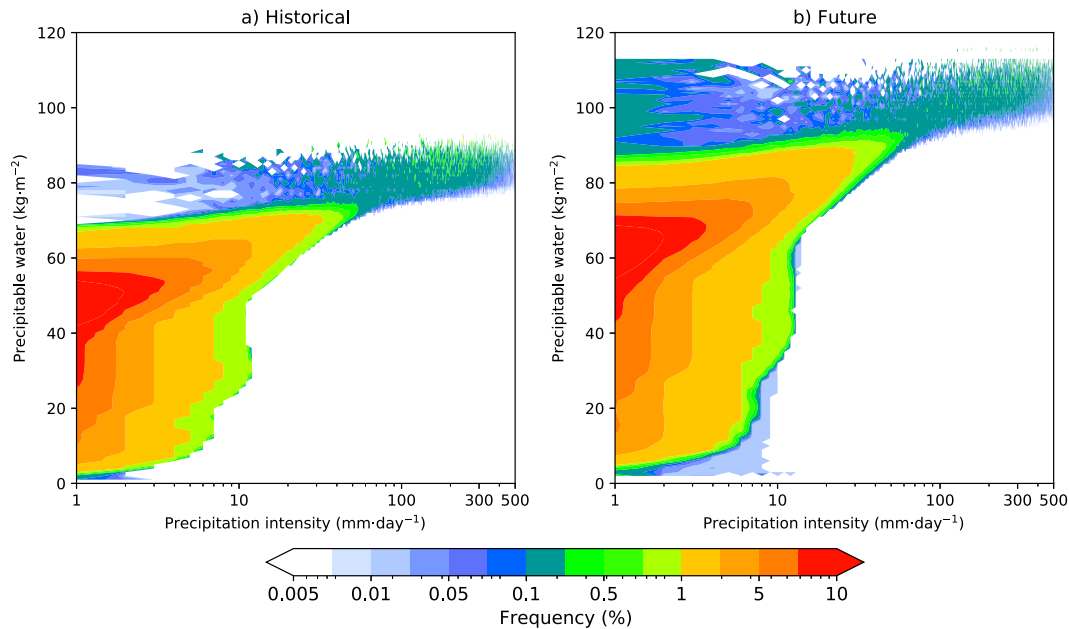


FIG. 13. The colored frequency distribution of precipitation intensity based on each PW (1 mm bin) in the d4PDF (a) historical climate and (b) future climate. Both results are the ensemble mean of 100 and 90 ensemble members of the corresponding simulation.

increase in both intensity and frequency in the future under a warming climate. However, the mechanisms responsible for the future changes in extreme precipitation events remain unclear. This work assessed both historical and future changes in extreme precipitation and the related atmospheric conditions over East Asia in the d4PDF dataset.

First, the historical performance of extreme precipitation and atmospheric conditions in the d4PDF dataset was assessed through a comparison with the TRMM satellite observation dataset. d4PDF generally represents precipitation frequency–intensity distribution realistically, reproducing intensity $> 300 \text{ mm day}^{-1}$ whereas underestimating the frequency of 30–250 mm day^{-1} rainfall against the TRMM rainfall product. In terms of the temporal duration of extreme precipitation, the frequency distribution depends on the definition of extremes. d4PDF overestimates the frequency and maximum duration of extreme precipitation in comparison with TRMM for the relative threshold of extreme precipitation (e.g., RR $> 90\text{th}$, 95th , and 99th). However, d4PDF corresponds well with TRMM for absolute thresholds of extremes (e.g., RR > 50 , 100 mm day^{-1}) while it slightly overestimates the frequency and duration for RR $> 50 \text{ mm day}^{-1}$. When evaluated in terms of extreme precipitation indices as compared with TRMM observations, d4PDF well captures the spatial pattern of PRCPTOT but slightly underestimates the R50mm, Rx1day, R99p, and SDII and overestimates the CWD.

The performance of the d4PDF simulation was further evaluated in terms of the vertical profiles of the atmospheric variables composited with precipitation intensity. Compared with the TRMM/ERA5 reference, d4PDF indicates insufficient relative humidity in the upper troposphere but excessive in the lower troposphere, along with stronger upward motion,

and overestimates cloud water content for both the high-intensity and the long-duration cases of extreme precipitation. By examining the relationship between precipitation and the total column water vapor content, i.e., PW, d4PDF displays a similar distribution as the TRMM/ERA5 reference, except reproducing more PW, which demonstrates extended ranges of the maxima in d4PDF.

After confirming the performance of the d4PDF simulation in representing the historical climate, we examined the future changes in extreme precipitation and the associated atmospheric conditions in d4PDF. The intensity and duration of extreme precipitation and their frequency increase in the future climate simulations. The spatial distributions of the six extreme precipitation indices indicate general increases in the future climate, except for PRCPTOT, which indicates a significant decrease over the Sichuan Basin and the Taiwan region, and for R99p, which shows a decrease over the Taiwan region.

The atmospheric conditions in the higher-intensity ranges of extreme precipitation indicated lower relative humidity, weaker upward motion, less cloud water content, and less temperature lapse rate in the future, which suggests that the conditions have negative effects in generating intense extreme precipitation events. In addition, the maximum value of atmospheric moisture content (i.e., the PW) will increase to nearly 120 kg m^{-2} in the future climate from only 100 kg m^{-2} in the present climate. With the same amount of PW available in the present and future climates, precipitation intensity will be weaker in the future climate, especially when the PW exceeds 50 kg m^{-2} .

A possible role of stability changes was explored. It was found that the atmospheric conditions will tend to become

more stable in the future, which is unfavorable for generating stronger precipitation. Extreme precipitation in the future climate will develop only when an extreme amount of PW is available to overcome unfavorable conditions in terms of a more stable temperature lapse rate. Therefore, we concluded that a primary factor for the increase in the intensity and frequency of extreme precipitation in the future is the increase in the column moisture content.

This work provides a fundamental evaluation of historical extreme precipitation in d4PDF datasets over East Asia and demonstrates how the future atmospheric conditions will change in regard to extreme precipitation changes. Although this study indicates that future atmospheric condition changes are unfavorable for generating future extreme precipitation events from a viewpoint of stabilized vertical temperature profile in the future, the factors affecting the changes in atmospheric conditions still require further investigation, for example, the circulation pattern and the moisture transport, which we are investigating as an ongoing work. In addition, the present results may be relevant to phenomena primarily in East Asia whose summer climate is strongly controlled by East Asian summer monsoon, and therefore, it is necessary to examine other climate regions as well as use various climate model outputs in order to gain more robust conclusions that would apply more commonly to extreme precipitation throughout the globe.

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Data availability statement. The TRMM 3B42 dataset is openly available at https://disc.gsfc.nasa.gov/datasets/TRMM_3B42_7/summary. The ERA5 reanalysis dataset was downloaded from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview>. The d4PDF dataset was derived from the following public domain resources: https://search.diasjp.net/en/dataset/d4PDF_GCM.

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