A Study on Future Projections of Precipitation Characteristics around Japan in Early Summer Combining GPM DPR Observation and CMIP5 Large-Scale Environments

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(Manuscript received 1 October 2018, in final form 10 April 2019)

ABSTRACT

This study estimates future changes in the early summer precipitation characteristics around Japan using changes in the large-scale environment, by combining Global Precipitation Measurement precipitation radar observations and phase 5 of the Coupled Models Intercomparison Project climate model large-scale projections. Analyzing satellite-based data, we first relate precipitation in three types of rain events (small, organized, and midlatitude), which are identified via their characteristics, to the large-scale environment. Two environmental fields are chosen to determine the large-scale conditions of the precipitation: the sea surface temperature and the midlevel large-scale vertical velocity. The former is related to the lower-tropospheric thermal instability, while the latter affects precipitation via moistening/drying of the midtroposphere. Consequently, favorable conditions differ between the three types in terms of these two environmental fields. Using these precipitation–environment relationships, we then reconstruct the precipitation distributions for each type with reference to the two environmental indices in climate models for the present and future climates. Future changes in the reconstructed precipitation are found to vary widely between the three types in association with the large-scale environment. In more than 90% of models, the region affected by organized-type precipitation will expand northward, leading to a substantial increase in this type of precipitation near Japan along the Sea of Japan, and in northern and eastern Japan on the Pacific side, where its present amount is relatively small. This result suggests an elevated risk of heavy rainfall in those regions because the maximum precipitation intensity is more intense in organized-type precipitation than in the other two types.

1. Introduction

Over East Asia in early summer (May–July), a large amount of precipitation is associated with a quasi-stationary front called the baiu front in Japan (also called the mei-yu front in China and the changma front in South Korea), which is characterized by a strong gradient of the near-surface equivalent potential temperature θ_e (Ninomiya

1984). The onset and withdrawal of the rainy season of East Asia is related to the northward seasonal march of this front. Intense precipitation often occurs associated with the baiu front, especially just before the withdrawal of the rainy season (e.g., Akiyama 1978, 1979, 1984; Kato et al. 2003; Ninomiya 1978, 2000; Ninomiya et al. 1981; Chen and Yu 1988). Takayabu and Hikosaka (2009) statistically showed that, in the late baiu season, the contribution to the surface rainfall from precipitation with echo tops higher than ~ 9 km becomes significant associated with increasing θ_e at the lowest level.

Owing to the Tropical Rainfall Measuring Mission (TRMM) satellite and the successive Global Precipitation Measurement (GPM) satellite, a variety of

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precipitation characteristics in early summer, including heavy precipitation, have been revealed throughout East Asia (Takayabu and Hikosaka 2009; Xu et al. 2009; Xu 2013; Yokoyama et al. 2014, 2017; Park et al. 2016). Based on three-dimensional observations of precipitation by the TRMM satellite-borne Precipitation Radar (PR), Yokoyama et al. (2014) showed that precipitation characteristics drastically change in the meridional direction across the baiu front, which is detected as a boundary between the tropics and midlatitudes based on the large-scale environment. In their study, mesoscale organized precipitation systems are shown to be abundant to the south of the baiu front, where vigorous precipitation is more frequently observed compared to the northern region. Their results suggest that precipitation characteristics at a given location may significantly change in association with slight changes in the large-scale environment, such as a shift in the baiu front by a few degrees in the meridional direction. Because the way it rains greatly influences the livelihood of people living in East Asia, the question of where and how precipitation characteristics will change in the future is of considerable importance.

Future changes in the East Asian summer monsoon precipitation have been investigated by climate models. Increased precipitation over summertime East Asia in a warmer climate has been projected by many studies (e.g., Kripalani et al. 2007; Lee and Wang 2014; Li et al. 2011; Kusunoki and Arakawa 2012; Seo and Ok 2013). Seo et al. (2013) showed that, statistically, summertime precipitation will significantly increase in the baiu region and to the north and northeast of the Korean Peninsula toward the end of the twenty-first century under the representative concentration pathway (RCP) 6.0 scenario of phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012); this is attributed to increases in both the evaporation and the moist flux convergence. As for the precipitation intensity, Chen and Sun (2013) suggested an increased frequency of intense precipitation in the baiu rainband south of Japan at the end of the twenty-first century under the RCP4.5 scenario of CMIP5. Increased summertime precipitation intensity over East Asia is also projected by high-resolution atmospheric general circulation model (AGCM) simulations (Kusunoki et al. 2006; Kusunoki and Mizuta 2008; Kusunoki and Arakawa 2012). Using large ensemble simulations with a 60-km mesh AGCM, Endo et al. (2017) reported that precipitation extremes, such as the annual maximum one-day precipitation total, will robustly increase throughout East Asia under 4-K warmer climates.

Even though some aspects of precipitation can be investigated with climate models, as mentioned above, such models still have difficulties simulating detailed precipitation characteristics in general. The reproducibility

of the East Asian summertime precipitation has improved with CMIP5 models compared to CMIP3 models (Seo et al. 2013; Kusunoki and Arakawa 2015); however, its features still remain inadequate, for example, the amount of precipitation is underestimated (Chen and Sun 2013; Kitoh et al. 2013; Lee and Wang 2014) as well as its intensity (Kusunoki and Arakawa 2015). More importantly, climate models cannot appropriately represent mesoscale precipitation systems, which are often accompanied by heavy and extreme precipitation. In mesoscale organized precipitation systems, for example, both an area of vigorous convective precipitation and a wide area of stratiform precipitation are maintained with the help of mesoscale dynamics (e.g., Houze et al. 1989), which cannot be resolved at the coarse resolution of climate models. Therefore, heavy and extreme precipitation outputs simulated by climate models differ from observations.

Based on precipitation outputs of a 5-km-mesh non-hydrostatic regional climate model nested in an outer 20-km-mesh global atmospheric climate model, Osakada and Nakakita (2018) recently showed a statistically significant increase in the baiu heavy rainfall in northern Japan and areas next to the Sea of Japan. They also pointed out that the increase in heavy rainfall in these regions is caused by an increase in the westward-protruding Pacific high and the northward-invading vapor flux along the periphery of that high. Even with high resolution, however, the precipitation is output based on the model assumptions.

Meanwhile, climate models are capable of projecting large-scale environment variables, such as sea surface temperature (SST) and atmospheric circulations, in a more reasonable manner than the precipitation characteristics. Based on the projected changes in large-scale environmental variables and the observed relationship between the precipitation characteristics and the large-scale environment, the motivation of this study is to identify likely changes in the precipitation characteristics in the future climate.

As for the large-scale environment, enhanced convective instability owing to the low-level inflow of air with a high θ_e to the baiu front has been recognized as a primary factor generating intense convective precipitation in the baiu region (e.g., Akiyama 1979; Kato et al. 2003). In addition, it has been suggested that the subtropical jet is another important factor in the formation of the baiu front (Kodama 1993). Upper-tropospheric circulations significantly affect the synoptic variability of precipitation over summertime East Asia and the northwestern Pacific (Horinouchi 2014; Hirota et al. 2016; Horinouchi and Hayashi 2017; Horinouchi et al. 2019).

Via an analysis of TRMM and GPM precipitation radar data, Yokoyama et al. (2017) identified three types of rainfall events (REs) in the baiu season: midlatitude, organized, and small. They also found that environments favorable for these three types of REs differ from one another in terms of lower-tropospheric convective instability and the subtropical jet. Small-type precipitation depends on lower-tropospheric convective instability, while organized-type precipitation can exist even in a region with relatively low instability if the subtropical jet is strong. Lower-tropospheric convective instability plays a role in generating shallow convection, and highly unstable fields promote the development of deep convection without the aid of mesoscale organization. The subtropical jet produces environments favorable for organization of cumulus convection via the moistening of the midtroposphere owing to the ascent associated with secondary circulations of the jet. Meanwhile, midlatitude-type precipitation is often associated with extratropical cyclones. It also appears associated with strong subtropical jets but tends to appear in less unstable regions than other types.

Under the assumption that these current precipitation–environment relationships obtained from observations can be applied to future climates, we can estimate future changes in each type of precipitation using the projected changes in the large-scale environment. In this study, we aim to create and examine the feasibility of a prototype method to identify future changes in precipitation characteristics around Japan in early summer by combining satellite observations and climate models. Based on the work of Yokoyama et al. (2017), we first quantify the relationships between the satellite-observed precipitation characteristics and the large-scale environment and develop lookup tables with reference to the indices of the large-scale environment for midlatitude-type, organized-type, and small-type precipitation. Using these lookup tables, we then reconstruct the precipitation from the large-scale environments simulated by climate models and project the future changes in the precipitation. Here, we would like to emphasize that we do not use the climate model precipitation outputs in this study; instead, we estimate changes in the precipitation characteristics using precipitation data reconstructed from the modeled large-scale environmental fields.

The remainder of this paper is organized as follows. Section 2 provides a brief summary of the data and methodology used in this study. Section 3 describes the characteristics of the three types of REs. Section 4 introduces the lookup tables used to reconstruct the precipitation with the large-scale environmental fields. Section 5 describes the large-scale environmental fields and their future changes simulated by the CMIP5 climate

models. Future changes in the reconstructed precipitation are shown in section 6. A summary and discussion are given in section 7.

2. Data and methodology

We developed lookup tables to reconstruct the precipitation with reference to indices of large-scale environmental fields, using the RE database generated from the Ku-band radar orbital data (2AKu, version 5) of the GPM satellite-borne dual-frequency precipitation radar (DPR). Each RE is defined as contiguous pixels with near-surface precipitation rates greater than or equal to 0.5 mm h^{-1} , and the RE characteristics, such as size, stratiform precipitation ratio, and the maximum near-surface precipitation intensity, are stored in this database. To analyze the large-scale environment, the Japanese 55-yr Reanalysis (JRA-55) data (Kobayashi et al. 2015) and the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature (OISST), version 2, high-resolution dataset (Reynolds et al. 2007) were used. The JRA-55 data were averaged daily on a grid of 2.5° latitude $\times$ 2.5° longitude. The OISST daily data were spatially averaged in the same way. To construct the lookup tables, data over 120° – 180° E and 20° – 50° N during May–July for 4 years (2014–17) were utilized.

Following the work of Yokoyama et al. (2017), we classified the observed REs into the three types: midlatitude, organized, and small. Figure 1 shows examples of the three types of REs observed during May–July over 120° – 180° E and 20° – 50° N. The flowchart for the classification is shown in Fig. 2. The three types were distinguished using the size and stratiform precipitation ratio of each RE. All REs, except one-pixel REs, which often result from noise, were first divided by a size threshold of $10^{3.5} \text{ km}^2$. Larger REs were further divided by a threshold of 80% for the stratiform precipitation ratio. Large REs with stratiform precipitation ratios $< 80\%$ are classified into organized-type REs, representing mesoscale convective systems, which consist of both an area of convective precipitation and a large area of stratiform precipitation. Conversely, large REs with stratiform precipitation ratios $\geq 80\%$ are categorized as midlatitude-type REs, which have a wide area of stratiform precipitation, often associated with extratropical cyclones.

The second step was to relate each type of RE to the large-scale environmental conditions. The favorable conditions differ between the three types of REs around Japan in early summer in terms of lower-tropospheric convective instability and the subtropical jet (Yokoyama et al. 2017). Considering both this knowledge and its applicability to large-scale projections generated by CMIP5

FIG. 1. Examples of the three-dimensional structures of (a) small-type, (b) organized-type, and (c) midlatitude-type REs. These structures were observed (a) at 25.7°N and 136.7°E on 31 Jul 2016, (b) at 34.1°N and 122.4°E on 4 Jul 2016, and (c) at 43.5°N and 144.5°E on 16 May 2014. The noted position and observational time of the REs are for the pixel with the maximum surface precipitation intensity for the RE.

climate models, we chose the vertical pressure velocity at 500 hPa (ω_{500}) and the SST as indices of the large-scale environment. While ω_{500} represents the large-scale atmospheric circulation and has an effect of moistening/drying the midtroposphere (e.g., Takayabu et al. 2010), the SST is closely related to lower-tropospheric thermal instability (appendix A).

Instantaneous precipitation data observed over each $2.5^\circ \times 2.5^\circ$ grid of the analysis domain ($120^\circ\text{--}180^\circ\text{E}$, $20^\circ\text{--}50^\circ\text{N}$) by the GPM DPR are related to the daily large-scale environment. The unconditional mean precipitation rate R_{ij} for the i th bin of the 40 SST bins from 0 to 40 K and the j th bin of the 40 ω_{500} bins from -0.8 to 0.8 Pa s^{-1} is expressed in the following manner:

$$R_{ij} = \frac{\sum_l \sum_m \sum_n \delta(\text{SST}_{l,m,n} - \text{SST}_i) \delta(\omega_{500,l,m,n} - \omega_{500_j}) w_n r_{l,m,n}}{\sum_l \sum_m \sum_n \delta(\text{SST}_{l,m,n} - \text{SST}_i) \delta(\omega_{500,l,m,n} - \omega_{500_j}) w_n}. \quad (1)$$

Here, $r_{l,m,n}$ is the total precipitation for each type of RE on a grid over the l th orbit at the m th longitude and the n th latitude. $\text{SST}_{l,m,n}$ ($\omega_{500,l,m,n}$) represents SST (ω_{500}) for that grid, and δ is the delta function. Because the GPM satellite observes more frequently at higher latitudes, we adjusted the sampling bias using a weighting factor w_n , which is the latitudinal distribution of the

inverse of the total number of grids observed by the GPM DPR over $120^\circ\text{--}180^\circ$ during May–July for 2014–17. If the number of total observational pixels of the 2AKu orbit data over the grid was less than 1250, we did not count the GPM DPR data over a given grid. This threshold value is half the number of pixels that are supposed to be included in each grid if we approximate a $2.5^\circ \times 2.5^\circ$ grid by $250 \text{ km} \times 250 \text{ km}$ and 1 pixel of 2AKu by $5 \text{ km} \times 5 \text{ km}$. Note that this threshold is only used to determine the grids for the analyses and that it is not used for other procedures in developing the lookup

FIG. 2. A flowchart for the classification of REs into three types.

TABLE 1. List of CMIP5 models analyzed in this study.

Institution	Model
Commonwealth Scientific and Industrial Research Organization, and Bureau of Meteorology	ACCESS1.0
	ACCESS1.3
National Center for Atmospheric Research	CCSM4
Centro Euro-Mediterraneo per i Cambiamenti Climatici	CMCC-CESM
	CMCC-CM
	CMCC-CMS
Centre National de Recherches Meteorologiques, Meteo-France, and Centre Europeen de Recherches et de Formation Avancee en Calcul Scientifique	CNRM-CM5
Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence	CSIRO Mk3.6.0
Canadian Centre for Climate Modeling and Analysis	CanESM2
LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences; and CESS, Tsinghua University	FGOALS-g2
Geophysical Fluid Dynamics Laboratory	GFDL CM3
	GFDL-ESM2G
	GFDL-ESM2M
Institut Pierre Simon Laplace	IPSL-CM5A-LR
	IPSL-CM5A-MR
	IPSL-CM5B-LR
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC-ESM-CHEM
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC5
Max Planck Institute for Meteorology	MPI-ESM-LR
	MPI-ESM-MR
Meteorological Research Institute	MRI-CGCM3
	MRI-ESM1
Norwegian Climate Centre	NorESM1-M
Beijing Climate Center, China Meteorological Administration	BCC_CSM1.1
	BCC_CSM1.1(m)

tables. The position of an RE is represented by the latitude and longitude of its maximum near-surface precipitation intensity. Hereafter, we refer to diagrams of the unconditional mean precipitation rates with reference to $\omega 500$ and SST, which are produced by the above-mentioned process, as lookup tables.

Using the lookup tables, we reconstructed the daily distributions of the precipitation for the three types of REs referring to the daily large-scale environments of the CMIP5 climate models. In other words, the reconstructed precipitation from each type of RE at a given grid and day for each model is expressed as the value of the lookup table for SST and $\omega 500$ for that grid. A total of 25 models had adequate data of $\omega 500$ and SST during May–July both in the present (1980–2005) climate of the historical experiment and in the future (2075–2100) climate of the RCP8.5 experiment. Table 1 summarizes the climate models analyzed in this study and their institutions. Note that we used 24-yr data excluding 2095 and 2100 for CMCC-CESM because there were no SST data for these 2 years. All the CMIP5 model outputs were regridded to a common $2.5^\circ \times 2.5^\circ$ grid. The ensemble member, r6i1p1, was used for CCSM4, while the ensemble member, r1i1p1, was used for the other models. We first reconstructed

precipitation with reference to the large-scale environment of each CMIP5 model and then made a multimodel ensemble (MME) mean of the reconstructed precipitation over the 25 models.

3. Comparison of the precipitation characteristics of the three types of REs

In this study, future changes in the precipitation characteristics are attributed to the changes in the precipitation from the three types of REs. In this section, we examine what differences are found between the different RE types in terms of the precipitation characteristics. Over 120°E – 180° and 20° – 50°N during May–July 2014–17, 1824 organized-type REs, 1135 midlatitude-type REs, and 125 528 small-type REs are observed. Here, we focus on the maximum near-surface precipitation intensity, the maximum height of the precipitation tops, and the maximum 40-dBZ echo-top height, which indicates the existence of convectively intense updraft. As well as the size and the stratiform precipitation ratio, which are used to identify the three types of REs, these parameters determine how it rains. In this study, all these parameters are collectively called “precipitation characteristics.”

FIG. 3. Normalized frequency (%) of the maximum near-surface precipitation intensities for each type of RE. Small, midlatitude, and organized types are depicted by the black line with closed circles, the blue line with rectangles, and the red line with open circles, respectively. The frequency normalized (a) by the total number of REs for each type (small: 125 528, organized: 1824, and midlatitude: 1135) and (b) by the number of REs with a 40-dBZ echo for each type (small: 9589, organized: 1673, and midlatitude: 694). The abscissa indicates the precipitation rates on a dBR scale $= 10 \times \log_{10}[\text{precipitation intensities (mm h}^{-1})]$. The plot is for precipitation with an intensity $< 300 \text{ mm h}^{-1}$, which is the threshold value of the 2AKu product.

Figure 3a shows the normalized frequency of the maximum near-surface precipitation intensity for the three types of REs. The abscissa indicates precipitation rates in dBR, where $\text{dBR} = 10 \times \log_{10}[\text{precipitation rates (mm h}^{-1})]$. The three types have distinct peaks. The mode value of the organized type is near 18 dBR ($\sim 63 \text{ mm h}^{-1}$) and is the strongest of the three types. Organized-type REs tend to result in much more intense precipitation than other two types. For example, REs with a maximum precipitation intensity $\geq 100 \text{ mm h}^{-1}$ account for 27% of the organized type, while the corresponding fractions of the midlatitude and small types are 6.9% and 0.16%, respectively.

The mode value of the small type appears at a smaller precipitation intensity ($\sim 0 \text{ dBR}$) than those of the two types (Fig. 3a). This is because shallow REs, which are generally weak, are dominant in the small type, as will be shown later in Fig. 4a. However, less-organized tall REs, which often result in localized heavy showers, are also included in the small type. To focus on relatively intense REs, the normalized frequency of the maximum near-surface

precipitation intensities for REs with echoes greater than or equal to 40 dBZ is shown in Fig. 3b. Note that small-type REs with 40-dBZ echoes account for only 8% of the small type in number. The frequency distribution for small-type REs with 40-dBZ echoes shifts toward greater precipitation intensities compared to that for all small-type REs, although still much weaker than that of the organized type. Conversely, the organized type has similar frequency distributions in Figs. 3a and 3b for all organized-type REs and those with 40-dBZ echoes, respectively.

Figure 4a shows the normalized frequency of the maximum heights of the precipitation tops, which are defined as the largest heights with precipitation intensities greater than or equal to 0.3 mm h^{-1} . The organized type has a peak maximum precipitation top height at approximately 9–11 km, which is larger than peak heights of the other types. For the small type, it is confirmed that REs with shallow tops at approximately 3–4 km occur most frequently.

To examine the characteristics of intense REs, the normalized frequency of the maximum 40-dBZ echo-top

FIG. 4. Normalized frequency (%) of (a) the maximum precipitation top height (km) and (b) the maximum 40-dBZ echo-top height (km) for each type of RE. The small, midlatitude, and organized types are depicted by the black line with closed circles, the blue line with rectangles, and the red line with open circles, respectively. Frequency normalized (a) by the total number of REs for each type (small: 125 528, organized: 1824, and midlatitude: 1135) and (b) by the number of REs with a 40-dBZ echo for each type (small: 9589, organized: 1673, and midlatitude: 694).

heights is shown in Fig. 4b. Organized-type REs have larger maximum 40-dBZ echo-top heights than other types, indicating that they include strong convective cores. For the small type, the maximum 40-dBZ echo-top heights range widely and include relatively large heights (>5 km).

The midlatitude type is intermediate between the organized and small types in terms of the maximum precipitation intensity and the maximum precipitation top heights (Figs. 3a, 4a). The peaks of the maximum precipitation intensities for the midlatitude type are near 10 mm h^{-1} , and the maximum precipitation top heights are close to 9 km. Note that the frequency of the maximum 40-dBZ echo-top heights rapidly decreases for heights exceeding 5 km (Fig. 4b), indicating that the convective updrafts of midlatitude-type REs are relatively weak compared to those of other types.

These results show that the precipitation characteristics of the three types significantly differ from each other, indicating that the precipitation characteristics can drastically change at a given location if the proportion of precipitation from the three types changes. Organized-type REs occur relatively infrequently compared to small-type

REs; however, when they occur, they can result in severe precipitation.

4. Lookup tables to reconstruct the precipitation from the large-scale environment

a. Lookup tables

Based on the results of Yokoyama et al. (2017) and the further considerations stated in section 2, we associate precipitation from organized, midlatitude, and small types of REs with the large-scale environment in terms of SST and ω_{500} . Figure 5 shows horizontal distributions of the precipitation from the three types of REs observed by the GPM DPR. The value shown is the unconditional mean volumetric precipitation (i.e., the unconditional mean of the total precipitation rates from all pixels) for each type of RE over each $2.5^\circ \times 2.5^\circ$ grid, and the unit is $\text{mm h}^{-1} \times \text{pixel}$. Note that color scales in the three panels differ from each other. The large-scale SST and ω_{500} fields are overlaid with their contours. Differences in the precipitation distributions between the three types of REs are obvious. Small-type precipitation (Fig. 5a) basically increases southward over the ocean, roughly corresponding to the

FIG. 5. Precipitation of (a) small-type, (b) organized-type, and (c) midlatitude-type REs observed by the GPM DPR during the period of May–July for 2014–2017 (colors; $\text{mm h}^{-1} \times \text{pixel}$). The unconditional mean of the total precipitation of each type over every $2.5^\circ \times 2.5^\circ$ grid is shown. The mean SST of the OISSTv2 data (the blue dashed contours with an interval of 4°C starting at 8°C) and ω_{500} of the JRA-55 data (the black solid contours for -0.06 , -0.04 , and -0.02 Pa s^{-1}) are also shown.

SST distribution. Conversely, organized-type precipitation (Fig. 5b) is dominant southwest of Japan, where the large-scale ascent is relatively strong. Midlatitude-type precipitation (Fig. 5c) is distributed widely and evenly in relatively lower-SST regions.

Figure 6 shows the unconditional mean volumetric precipitation from each type binned into SST and ω_{500} . Note that precipitation over land, which is shown in Fig. 5, is not used in Fig. 6 because the SST is undefined in these regions. Excluding the dotted parts of the diagrams where extrapolation of the data is performed for very high SSTs (see the detailed explanation later in this section), statistical

RE–environment relationships differ greatly between the three types in a manner consistent with the findings of Yokoyama et al. (2017). All three types of REs tend to result in more precipitation in locations where large-scale ascent exists. Small-type precipitation is found even in regions of large-scale subsidence (i.e., parts of the diagrams where $\omega_{500} > 0$) where precipitation from organized-type and midlatitude-type REs is suppressed. Small-type precipitation has a clear tendency to dominate in higher-SST regions. Conversely, organized-type precipitation is more strongly influenced by ω_{500} than other types of precipitation. Organized-type precipitation has a tendency to increase with increasing large-scale ascent (negative values of ω_{500}). Midlatitude-type precipitation is dominant in lower-SST regions compared to other types.

These results indicate that the favorable conditions for each precipitation type can be reasonably captured with the two environmental indices of SST and ω_{500} . Therefore, differences in the precipitation characteristics can be expressed using these large-scale environmental parameters. In later sections, Fig. 6 is used as a lookup table to reconstruct the precipitation distributions of each type of RE with reference to the large-scale environment. Referring to SST and ω_{500} at a given grid and day, the reconstructed precipitation of each RE type for that grid is looked up in Fig. 6. To examine whether the precipitation in each bin of Fig. 6 is statistically significant, a bootstrap resampling procedure with 1000 repetitions was conducted. Precipitation that is not statistically significantly different from 0 at the 10% significance level is categorized as 0 (gray-colored bins in Fig. 6). Undefined values are set for bins with a total number of GPM DPR overpasses less than 5 (white-colored bins in Fig. 6).

For very high SSTs, which are not currently observed but are projected in future climates, table values are extrapolated. Because of the nearly linear relationships between SST and lower-tropospheric thermal instability (Figs. A1a and A1b in appendix A), we linearly extrapolate for such high SSTs. When table values are not undefined for at least three of the highest five SST bins at each ω_{500} bin, extrapolation is performed. After interpolating undefined bins of the highest five SST bins, smoothing is conducted for the five bins through three-time running mean with adjacent three SST bins. Then, values for higher SSTs are linearly extrapolated with the highest two SST bins. Attention is required because of the uncertainties when reconstructing precipitation in such high-SST regions.

b. Self-consistency check

To validate our method of reconstructing the precipitation by means of lookup tables with indices of SST and ω_{500} , a self-consistency check was conducted. Here,

FIG. 6. The unconditional mean precipitation ($\text{mm h}^{-1} \times \text{pixel}$) for each ω_{500} (Pa s^{-1}) and SST ($^{\circ}\text{C}$) for each type of RE. A bootstrap resampling procedure with 1000 repetitions was conducted to examine whether the precipitation in each bin is statistically significantly different from 0 at the 10% significance level. Gray indicates a value of zero, and white indicates an undefined value. Black dots denote where extrapolation is performed for high SSTs that are not currently observed but are to be projected in future climates. In the text, this figure is called the “lookup table.”

we reconstruct the distributions of the precipitation from the three types of REs with OISSTv2 daily data and JRA-55 daily ω_{500} , which were used to make the lookup tables (the left panels of Fig. 7).

The distributions of the reconstructed precipitation are similar to those of observed precipitation for all

three types of REs over the ocean (Fig. 5). The reconstructions successfully capture the key features of the distributions of the three types, such as the dependence of the small-type precipitation on SST, the existence of small-type precipitation in regions with large-scale subsidence, the dependence of organized-type precipitation

FIG. 7. Horizontal distributions of the precipitation for (a) small-type, (c) organized-type, and (e) midlatitude-type REs, which are reconstructed using the SST of the OISSTv2 data and ω_{500} of the JRA-55 data during the period of May–July for 2014–17 (colors; $\text{mm h}^{-1} \times \text{pixel}$). Mean SST of the OISSTv2 data (the blue dashed contours with an interval of 4°C starting at 8°C) and ω_{500} of the JRA-55 data (the black solid contours for -0.06 , -0.04 , and -0.02 Pa s^{-1}) are also shown. The longitudinal mean of the precipitation over 120°E–180° is also shown for the (b) small, (d) organized, and (f) midlatitude types. The red solid line and the black dashed line denote the reconstructed precipitation and the precipitation observed by the GPM DPR, respectively. The green line in (f) is for the case where the precipitation is reconstructed using the “raw” lookup table, which is not statistically tested for precipitation in all the ω_{500} –SST bins with a number of observations ≥ 1 .

on $\omega 500$, and the northeastward expansion of midlatitude-type precipitation.

The right panels in Fig. 7 show the latitudinal distributions of the zonally averaged precipitation over the ocean for the three types of REs. For the small and organized types, the reconstructed precipitation reproduces peaks at nearly the same latitudes as the observed peaks, even though there are some quantitative differences between the reconstructed and observed precipitation (Figs. 7b,d).

For the midlatitude type, on the other hand, Fig. 7f shows that the reconstructed precipitation does not reproduce the observed sharp peak near 45°N. In addition, Fig. 7f shows a large underestimation for the reconstructed midlatitude-type precipitation. This is because the lookup table for midlatitude-type precipitation (Fig. 6c) includes many bins where the unconditional mean volumetric precipitation is not statistically significant and these table values are taken to be $0 \text{ mm h}^{-1} \times \text{pixel}$. Using a lookup table with many zero values results in a reconstructed precipitation that is largely underestimated. In fact, the reconstructed precipitation becomes closer to the observation, if the “raw” lookup table, which is not statistically tested for precipitation in all $\omega 500$ –SST bins with at least one observation, is applied (the green line in Fig. 7f). With the raw lookup table, however, the peak of the reconstructed precipitation near 45°N is still wider than that of the observed precipitation. This is likely due to the lookup table method, where the reconstruction is conducted using mean values of the table and the reconstructed precipitation is therefore smoothed to some degree.

Even though there is room for improvement for the lookup table, especially for precipitation from midlatitude-type REs, the reconstructed precipitation from each RE type generally captures its basic relationship with the large-scale environment in a manner consistent with the observations. Therefore, it is meaningful to examine future changes in the reconstructed precipitation for the three types of REs using our method. In section 6, we will project the precipitation distributions for the three types of REs using both the lookup tables and the large-scale CMIP5 model environments.

5. Large-scale environments and their future changes

Before examining future changes in the CMIP5 reconstructed precipitation, the large-scale environments simulated by the 25 CMIP5 climate models and their future changes are shown in this section. MME mean environment fields for the present climate (the contours in the left panels of Fig. 8) were compared

using climatologies based on OISSTv2 and JRA-55 (the color shades in the left panels of Fig. 8). In addition to SST and $\omega 500$, which are used to reconstruct the precipitation, the zonal velocity at 250 hPa is also shown to examine changes in the subtropical jet. The simulated SST increases southward, which is similar to the OISSTv2 climatology except that the high-SST regions retreat comparatively southwestward in the CMIP5 simulations. Large-scale ascent is found south of the subtropical jet, which appears with its center near 37°–40°N. Even though there are some biases such as a slightly northward displacement of the ascent regions, the CMIP5 climate models capture the overall characteristics of the atmospheric circulations in the mid–upper troposphere in a manner consistent with the JRA-55 climatology.

As for future changes (the color shades in the right panels of Fig. 8), SST is projected to increase by 2°–6°C over all regions. A large (4°–6°C) increase in the SST is projected over the Sea of Japan, the Yellow Sea, and the oceans around Japan to the north of 40°N. The subtropical jet in the future will intensify on the southern peripheries of the present subtropical jet, resulting in southward shifts of the subtropical jet and ascent regions.

Overall, the mean distributions of the large-scale environment will not drastically change in the future climate, although absolute values will change. Additional analyses on the indices of the large-scale environment also suggest that the large-scale environment will only slightly shift on average in the future climate (appendix A). Thus, our estimation method based on the assumption that the current precipitation–environment relationships can be maintained in the future climate is reasonable.

6. Reconstructed precipitation with CMIP5 large-scale environments and its future changes

Finally, we investigate future changes in the precipitation reconstructed using the 25 CMIP5 climate model large-scale environments by applying the method developed in this study. Figure 9a shows the climatology of the organized-type precipitation reconstructed with JRA-55/OISSTv2. Figures 9b and 9c show the MME mean precipitation reconstructed using the 25 CMIP5 models for the present and future climates, respectively. For the MME mean precipitation, we first reconstructed precipitation using the large-scale environments of each CMIP5 model (Fig. 10) and then averaged the precipitation over the 25 models. Future changes (future minus present) in the MME mean precipitation and ratios of the future changes to the present climate

FIG. 8. Horizontal distributions of the large-scale environment. (a),(b) SST ($^{\circ}\text{C}$), (c),(d) zonal winds at 250 hPa (m s^{-1}), and (e),(f) ω_{500} . Units for color scales in (e) and (f) are Pa s^{-1} and $10^{-3} \text{ Pa s}^{-1}$, respectively. In (a), (c), and (e), the shading indicates OISSTv2 or JRA-55 data (May–July 1988–2017) and the contours indicate the CMIP5 MME present climate. In (b), (d), and (f), the shading indicates the CMIP5 MME future changes (future minus present) and the contours indicate the CMIP5 MME present climate.

$[(\text{future} - \text{present}) (\text{present})^{-1}]$ are shown in Figs. 9d and 9e, respectively. (Figures 11 and 13 are similar to Fig. 9 but for small-type and midlatitude-type precipitation, respectively.)

In general, characteristics of the precipitation distributions for each type are well reconstructed using the CMIP5 large-scale environments. Meanwhile, there are some differences between the climatology of the precipitation reconstructed using the JRA-55/OISSTv2 (Figs. 9a, 11a, 13a) and the MME mean precipitation for the present climate (Figs. 9b, 11b, 13b). For example, organized-type precipitation is less obvious east of 160°E in the MME mean than in the JRA-55/OISSTv2 climatology. As for the small type, the MME precipitation decreases significantly eastward, leading to a pronounced zonal contrast in the precipitation, which is less obvious in the JRA-55/OISSTv2 climatology. Part of these discrepancies may be related to the low biases of the SST at low latitudes, as well as the

northward displacement of the ascent regions, as already shown in Fig. 8. These discrepancies may affect future projections of this study. However, as will be shown later, our primary results on future changes in the precipitation of each RE type are confirmed in the 25 models, which vary in the distributions of the reconstructed precipitation in the present climate, and seem relatively robust.

In the future climate, organized-type precipitation, which is often associated with heavy precipitation (Fig. 3), is projected to increase around Japan (Figs. 9b–e). The influence of organized-type precipitation will be extended northeastward. In the present climate, organized-type precipitation is found in regions of large-scale ascent and SSTs higher than $\sim 20^{\circ}\text{C}$. In the future climate, a larger area will meet these conditions because of the northward expansion of regions with SSTs greater than 20°C , resulting in the northeastward expansion of the organized-type precipitation region. North of 35°N around

FIG. 9. Horizontal distributions of the precipitation of organized-type REs, which are reconstructed using SST and ω_{500} . (a) The color indicates the precipitation reconstructed using the SST of OISSTv2 data and ω_{500} of the JRA-55 data ($\text{mm h}^{-1} \times \text{pixel}$; May–July 1988–2017). (b) The color indicates the precipitation reconstructed using the CMIP5 SST and ω_{500} in the present climate ($\text{mm h}^{-1} \times \text{pixel}$). The MME ensemble mean of the precipitation is shown. (c) As in (b), but for the future climate. In (a)–(c), the mean SST ($^{\circ}\text{C}$; the blue dashed contours with an interval of 4°C starting at 20°C) and ω_{500} (Pa s^{-1} ; the purple solid contours for -0.06 , -0.04 , and -0.02 Pa s^{-1}) are also shown. (d) The color indicates the future changes in the MME mean of the reconstructed precipitation ($\text{mm h}^{-1} \times \text{pixel}$). The black dots denote where more than 90% of the CMIP5 climate models agree on the signs of the future changes. The contours indicate the reconstructed precipitation in the CMIP5 present climate. (e) Ratios of the future changes to the present climate [$(\text{future} - \text{present}) / (\text{present})^{-1}$].

Japan, a pronounced increase in organized-type precipitation is projected. Over the Japanese archipelago, it is suggested that the area along the Sea of Japan and the northern and eastern areas on the Pacific side (east of 140°E and north of 35°N) may experience such changes. In these regions, the amount of organized-type precipitation is currently small compared to the southwestern side of Japan; however, it will significantly increase in the future. A large increase in the organized-type precipitation by 30%–150% compared to the present climate is estimated over these regions (Fig. 9e).

The features shown in the MME mean organized-type precipitation are also confirmed in each model (Fig. 10). Overall, their patterns are similar despite some disagreements. Including the northward enhancement of the organized-type precipitation, more than 90% of

climate models agree with respect to the signs of future changes in most regions north of 32.5°N (the dotted regions in Fig. 9d).

Contrastingly, projections vary widely between models south of 32.5°N , resulting in a low degree of agreement in such regions. Uncertainties in the future changes may be high in the southern domain where high SSTs that are not currently observed often appear in the future simulations. For such high SSTs, the precipitation is reconstructed using the extrapolated part of the lookup tables.

Figures 11b–e show that small-type precipitation in the future climate generally increases in response to the overall increase in the SST. In Fig. 11d, a pronounced increase in small-type precipitation is found southwest of the Japanese archipelago. The Pacific side of southwestern Japan will therefore be greatly affected by this precipitation type. An increase in small-type

FIG. 10. Future changes in the precipitation of organized-type REs for each CMIP5 climate model (colors; $\text{mm h}^{-1} \times \text{pixel}$). The contours indicate the precipitation of organized-type REs in the current climate.

FIG. 11. As in Fig. 9, but for small-type precipitation.

precipitation by more than 50% compared to the present climate is estimated in many areas of Japan south of 37.5°N (Fig. 11e). Increases in small-type precipitation are projected in nearly all regions of the domain for more than 90% of models (the dotted regions of Fig. 11d, and Fig. 12).

On the other hand, midlatitude-type precipitation will likely significantly decrease south of 35°N around Japan with a high degree of agreement (Figs. 13b–e). This type of precipitation tends to decrease with increasing SST, because the lookup table shows that there is less precipitation from midlatitude-type REs for higher SSTs (Fig. 6c). Note that there is no robust change in the midlatitude-type precipitation in the northern half of the domain (Figs. 13d, 14). Low biases in the reconstructed midlatitude-type precipitation at higher latitudes, which were mentioned in section 4b, may contribute to the uncertainty.

7. Summary and discussion

This study presented and examined the feasibility of a prototype method to identify future changes in the precipitation characteristics around Japan in the early

summer season by combining both GPM DPR observations and CMIP5 model large-scale projections. Lookup tables with the two indices of SST and ω_{500} for precipitation from small, organized, and midlatitude types of REs, which are identified around Japan in early summer, were developed based on the GPM DPR data. The early summer precipitation was then reconstructed using large-scale CMIP5 projections, and the future changes were estimated.

The large-scale environment will not drastically change in the future climate, suggesting that the assumption that the current precipitation–environment relationships can be applied to future climates is reasonable. Meanwhile, our method also has a limitation; because we use absolute SST values as an index of the large-scale environment in this study, changes in SST thresholds for occurrence of convection and intense precipitation, which will increase in future climates (e.g., Knutson and Manabe 1995; Stowasser et al. 2009), cannot directly be expressed and cannot be discussed in a strict manner. Further studies considering relative SST effects are needed for more accurate estimation.

In our method, however, relative effects of the large-scale environment on the precipitation are considered

FIG. 12. As in Fig. 10, but for small-type precipitation.

FIG. 13. As in Fig. 9, but for midlatitude-type precipitation.

by $\omega 500$ (appendix A). Figure 15a (Fig. 15b) shows a histogram of daily grids in terms of CMIP5 SST and CMIP5 reconstructed total precipitation (CMIP5 model precipitation outputs). For the reconstructed precipitation, the peaks are found near 26°C of SST and near 7°C of SST in the present climate, and they will shift toward higher SSTs in the future climate (Fig. 15a). It is also shown that the precipitation rises near 20°C both in the present and future climates. These features for the histogram of the reconstructed precipitation are similar to those for the histogram of the model precipitation outputs (Fig. 15b). The overall displacement of the histogram toward higher SSTs is shown not only for the reconstructed total precipitation but also for the reconstructed precipitation of each RE type (appendix B). Thus, precipitation tends to occur in areas where SSTs are higher than in the surrounding regions in our future projections, although we use absolute SST values as an index of large-scale environments.

The key findings of this study are as follows. First, the three types of REs, which have different precipitation characteristics, can be distinguished from each other via the large-scale environmental indices. Second, future changes in the precipitation vary widely between the

three types in association with the large-scale environment. Consequently, each type of precipitation will change significantly in each region of Japan and the adjacent oceans over 20°–50°N and 120°E–180° in the future because of the changes in the large-scale environment.

Significant changes in each type of precipitation are suggested with more than 90% of models agreeing on the sign of the changes as summarized below.

- 1) Organized-type precipitation will increase over nearly all regions north of 32.5°N. The region affected by organized-type precipitation will expand northward, resulting in a substantial increase in this type of precipitation in the area of the Japanese archipelago along the Sea of Japan and northern and eastern Japan on the Pacific side, where its present amount is relatively small.
- 2) Small-type precipitation will increase over the entire analysis region. A pronounced increase in this type of precipitation is found southwest of Japan.
- 3) Midlatitude-type precipitation will decrease over the ocean around Japan. A pronounced decrease in precipitation is found around Japan south of 37.5°N and over the East China Sea.

FIG. 14. As in Fig. 10, but for midlatitude-type precipitation.

FIG. 15. (a) A histogram of daily grids in terms of CMIP5 SST ($^{\circ}\text{C}$) and CMIP5 reconstructed total precipitation ($\text{mm h}^{-1} \times \text{pixel}$). (b) A histogram of daily grids in terms of CMIP5 SST ($^{\circ}\text{C}$) and CMIP5 model precipitation outputs (mm day^{-1}). The black (red) line is for the present (future) climate. For all panels, MME over 120°E – 180° and 20° – 50°N for May–July are shown. Contours are for 1, 10, 50, 100, 200, and 300.

In total, precipitation will generally increase around Japan with its center at 30° – 40°N , except regions southwest of Japan, where precipitation will decrease (Fig. 16). The decrease in the precipitation southwest of Japan is less certain, because future projections of organized-type precipitation vary widely among models. This pattern well corresponds to Figs. 3b and 4a of Seo et al. (2013): a statistically significant increase in the precipitation near 30° – 40°N and 135° – 160°E , and a nonsignificant decrease southwest of Japan.

Because future changes in the precipitation differ between the three types of REs, the future distributions of the precipitation contributions from each type will differ from the present. Figure 17 shows the

FIG. 16. A horizontal distribution of the reconstructed total precipitation of all three RE types. The color indicates the future changes in the MME mean of the reconstructed precipitation ($\text{mm h}^{-1} \times \text{pixel}$). The contours indicate the reconstructed precipitation in the CMIP5 present climate.

precipitation contributions from each type of RE for the total precipitation from all three types. In general, the contribution of the midlatitude-type precipitation will decrease. Meanwhile, the contribution of the organized-type precipitation will increase in the future around Japan except in some areas in southwestern Japan, where the contribution of small-type precipitation becomes larger than in the present climate. These results suggest that the shift in the climate associated with global warming may lead to substantial changes in the way it rains in each region, because precipitation characteristics such as precipitation intensity, the existence of convectively intense updrafts, and the extent of stratiform precipitation differ widely between the three RE types.

Small-type precipitation, which results from both shallow cumulus convection and unorganized deep cumulus convection, correlates well with lower-tropospheric convective instability (Yokoyama et al. 2017). This study shows that, corresponding to an overall increase in the SST, small-type precipitation will increase over the entire analysis region but, generally, more to the south. In other words, the initiation of convection and the development into unorganized deep convection will be promoted by the destabilization in the lower troposphere associated with increasing SST.

Meanwhile, organized-type precipitation is affected not only by the lower-tropospheric convective instability but also by the subtropical jet, which produces favorable environments for the organization of cumulus convection south of the jet via the moistening of the midtroposphere owing to the large-scale ascent associated with secondary circulations (Yokoyama et al. 2017). This study emphasizes that, for projections of

FIG. 17. Precipitation contributions (%) of each type of RE to the total precipitation of all three RE types. Precipitation contributions of (a),(b) organized-type, (c),(d) small-type, and (e),(f) midlatitude-type REs are shown for the (left) present and (right) future climates.

organized-type precipitation, it is crucial to consider both the effects of both the upper-midtropospheric circulations and the lower-tropospheric thermal instabilities. In the future climate, the large-scale ascent will shift only slightly southward associated with the southward shift of the subtropical jet, while the region of high SSTs will noticeably expand northward. Consequently, the region that is favorable for the organization of cumulus convection will expand northward compared to the present. In the area of the Japanese archipelago along the Sea of Japan and in the northern

and eastern areas of Japan on the Pacific side, the effect of weakened ascent will be counteracted by a substantial increase in the SST, resulting in increased organized-type precipitation.

As for midlatitude-type precipitation, the lookup table shows that it drastically changes at $\sim 27^{\circ}\text{C}$, with little or no precipitation at higher SSTs (Fig. 6c). Over the ocean south of Japan, on average, the SST is less than 27°C in the present climate but is expected to rise by $\sim 4^{\circ}\text{C}$ in the future (Fig. 8b). Therefore, it appears that the decrease in the midlatitude-type precipitation south

of Japan will likely be caused by an increased appearance of high SSTs exceeding 27°C. Note that the lookup table reflects the fact that midlatitude-type precipitation is found in relatively low-SST regions in the present climate; however, there is room for discussion as to whether we can apply the present relationship between midlatitude-type precipitation and the absolute values of the SST to the future climate. We also need to consider that baroclinic instability, which is the primary dynamic trigger for midlatitude-type precipitation, primarily depends on the temperature gradient rather than the temperature itself. Further investigations of the large-scale indices with respect to midlatitude-type precipitation are necessary.

The following points regarding the estimation results of this study should also be noted. First, there is large intermodel variability in the precipitation changes over some regions, even though the above-mentioned changes are relatively robust. For example, future changes in organized-type precipitation vary widely between climate models south of 32.5°N, resulting in small amplitudes for the future changes in the MME mean. Projections of organized-type precipitation in that region are therefore highly uncertain. Second, the reconstructed future precipitation was extrapolated for very high SSTs that are not currently observed. We need to be cautious regarding projections in such high-SST regions. Third, future changes in the precipitation characteristics over land, such as the Japanese archipelago, are not strictly estimated in this study because SST data are used to reconstruct the precipitation. However, based on some previous studies (e.g., Fig. 1a of Takayabu 2006), the precipitation characteristics over Japan tend to be similar to those over the adjacent oceans. Therefore, precipitation characteristics over Japan may be approximately interpolated from those over the adjacent oceans, even though land effects should also be considered.

Despite these limitations, it is of great social significance to obtain information concerning future changes in the detailed precipitation characteristics. In terms of disaster prevention, we need to pay particular attention to increases in heavy precipitation. The maximum intensities of REs are significantly more intense for organized-type REs than for the other two types. Our study suggests that in the future climate, organized-type precipitation will significantly increase in the area of the Japanese archipelago along the Sea of Japan and in northern and eastern Japan on the Pacific side, where its present amount is relatively small. These results also support for recent model-based results for future changes in baiu heavy precipitation (Osakada and Nakakita 2018). Appropriate actions should be taken in

those regions because an increase in organized-type precipitation translates to an elevated risk of heavy precipitation events. On the Pacific side of southwestern Japan, a substantial increase in small-type precipitation is projected. Precaution should be taken against increases in heavy showers resulting from unorganized deep cumulus convection, which is included in small-type REs.

Acknowledgments. This study is supported by the University of Tokyo through a project “Research hub for the big data analysis of global water cycle and precipitation in changing climate,” JSPS KAKENHI Grants 15H02132 and 19K21050, the Environment Research and Technology Development Fund (2-1503, 2-1904) of Environmental Restoration and Conservation Agency, and the Eighth RA of the Japan Aerospace Exploration Agency (JAXA) Precipitation Measuring Mission science. The authors would like to express their gratitude to Drs. H. Annamalai and W. Xu and an anonymous reviewer for their very helpful comments. The authors also thank JAXA and the National Aeronautics and Space Administration (NASA) for providing the TRMM and GPM data. The JRA-55 data used in this study were provided by the Japan Meteorological Agency (JMA). NOAA High Resolution SST data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, from their website at <https://www.esrl.noaa.gov/psd>. We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups for producing and making available their model output. For CMIP the U.S. Department of Energy’s Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

APPENDIX A

Analyses on the Large-Scale Environmental Indices

First, we examine whether a same local SST means a same local thermal instability after the background SST has increased. Figure A1a shows a histogram of daily grids in terms of CMIP5 daily SST and lower-tropospheric convective instability, which is defined as the vertical gradient of θ_e between 1000 and 700 hPa. In the present climate, lower-tropospheric convective instability is nearly linearly related to SST. The relationship between SST and lower-tropospheric convective instability in the future climate is similar to that in the

FIG. A1. (a) A histogram of daily grids in terms of SST and lower-tropospheric convective instability (LCI; $K hPa^{-1}$), which is defined as vertical gradient of equivalent potential temperature between 1000 and 700 hPa. The black (red) line is for the present (future) climate. Positive values of the ordinate are for unstable conditions. (b) As in (a), but for a histogram in terms of SST and lower-tropospheric instability ($K hPa^{-1}$), which is defined as vertical gradient of virtual temperature between 1000 and 700 hPa. Positive values of lower-tropospheric instability are for unstable conditions. (c) Profiles of specific humidity ($g kg^{-1}$) sorted with ω_{500} . The colors (contours) are for the present (future) climate. (d) As in (c), but for anomalous specific humidity from the mean. For all four panels, CMIP5 MME data over $120^{\circ}E-180^{\circ}$ and $20^{\circ}-50^{\circ}N$ for May–July are used.

present climate, although the slope is slightly steeper in the future. The similar results are also found in the relationship between SST and lower-tropospheric instability, which is defined as vertical gradient of virtual temperature between 1000 and 700 hPa (Fig. A1b).

Next, profiles of specific humidity sorted with ω_{500} are examined. Specific humidity will generally increase in the future climate (Fig. A1c). For profiles of anomalous specific humidity from the mean, dry (moist) anomalies are found in regions of large-scale subsidence (ascent) in the present climate (Fig. A1d). The relationship between ω_{500} and specific humidity in the future climate is similar to those in the present climate, although a contrast in specific humidity between ascent and subsidence regions is slightly larger in the future climate. Thus, relative effects of ω_{500} on the tropospheric moisture content will not largely change in the future climate, suggesting that the relationship between

precipitation and ω_{500} in the present climate may be maintained in the future climate in a relative sense. It is an open question how overall increases in specific humidity affect precipitation.

APPENDIX B

Relationships between SST and the Reconstructed Precipitation of Each Type of RE

Figure B1 shows histograms of daily grids in terms of CMIP5 daily SST and the reconstructed precipitation. For both the total precipitation (Fig. B1a; the same as Fig. 15a) and the precipitation of each RE type (Figs. B1b–d), the present precipitation–SST relationships are generally displaced toward higher SSTs in the future climate.

FIG. B1. MME histograms of daily grids in terms of CMIP5 SST ($^{\circ}\text{C}$) and CMIP5 reconstructed precipitation ($\text{mm h}^{-1} \times \text{pixel}$). (a) Total precipitation from all three RE types, (b) organized-type precipitation, (c) small-type precipitation, and (d) midlatitude-type precipitation. The black (red) line is for the present (future) climate. The data over 120°E – 180° and 20° – 50°N for May–July are used. Contours are for 1, 10, 50, 100, 200, and 300.

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