Environmental Research Letters

LETTER

Impacts of half a degree additional warming on the Asian summer monsoon rainfall characteristics

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Keywords: HAPPI, Paris Agreement, Asian summer monsoon, extreme precipitation, Clausius-Clapeyron relation

Supplementary material for this article is available online

Abstract

This study investigates the impacts of global warming of 1.5 °C and 2.0 °C above pre-industrial conditions (Paris Agreement target temperatures) on the South Asian and East Asian monsoon rainfall using five atmospheric global climate models participating in the 'Half a degree Additional warming, Prognosis and Projected Impacts' (HAPPI) project. Mean and extreme precipitation is projected to increase under warming over the two monsoon regions, more strongly in the 2.0 °C warmer world. Moisture budget analysis shows that increases in evaporation and atmospheric moisture lead to the additional increases in mean precipitation with good inter-model agreement. Analysis of daily precipitation characteristics reveals that more-extreme precipitation will have larger increase in intensity and frequency responding to the half a degree additional warming, which is more clearly seen over the South Asian monsoon region, indicating non-linear scaling of precipitation extremes with temperature. Strong inter-model relationship between temperature and precipitation intensity further demonstrates that the increased moisture with warming (Clausius-Clapeyron relation) plays a critical role in the stronger intensification of more-extreme rainfall with warming. Results from CMIP5 coupled global climate models under a transient warming scenario confirm that half a degree additional warming would bring more frequent and stronger heavy precipitation events, exerting devastating impacts on the human and natural system over the Asian monsoon region.

1. Introduction

The goal of the Paris Agreement is to hold global warming below 2 °C and to pursue efforts to limit it to 1.5 °C above preindustrial level. Scientific assessments of the risk and impact of global warming on the local-scale climate and extremes are highly demanded after the Paris Agreement. Despite the increased interest in the 1.5 °C and 2.0 °C mitigation targets, associated assessments of regional-scale climate change and impacts have been made limitedly based on the Representative Concentration Pathway (RCP) scenarios from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble (Fischer and Knutti 2015, Knutti et al 2016, Schleussner et al 2016). The CMIP5 experiments were, however, basically designed to project future climate conditions as transient responses to the specified radiative forcing, being potentially inappropriate to assess climate responses to the equilibrium global warming condition of the 1.5 °C and 2.0 °C targets. Further, the small ensemble size of CMIP5 (<50) is a major limitation to quantify impacts of target temperatures on weather and climate extremes which occur rarely by definition (Mitchell et al 2016, Sanderson et al 2017). In this respect, recently, new large-ensemble (>100 members) climate model
experiments were conducted under the ‘Half a degree Additional warming, Prognosis and Projected Impacts’ (HAPPI) project, which enable one to evaluate additional half a degree warming impacts on climate and extreme weather events (Mitchell et al. 2017).

With frequent occurrences of climate extreme events such as heat waves, droughts, and heavy precipitation, the Asian summer monsoon domain is one of the most vulnerable regions to global warming (IPCC 2013). Previous studies based on global and regional climate models consistently predicted that mean precipitation will increase over the South Asian and East Asian monsoon regions under RCP scenarios (IPCC 2013, Kitoh et al. 2013, Endo and Kitoh 2014, Freychet et al. 2015, Li et al. 2015, Lee et al. 2017). Intensity and frequency of extreme precipitation are also expected to increase over the regions in the future (IPCC 2013, Kitoh et al. 2013, Freychet et al. 2015, Lee et al. 2017, Chen and Sun 2017).

To assess impacts of the Paris Agreement warming targets on the Asian monsoon domain, the present study conducts an analysis of the responses of Asian summer monsoon rainfall to the equilibrium global warming of 1.5 °C and 2.0 °C using the multiple atmospheric global climate model (AGCM) simulations from the HAPPI experiment. A particular focus is let on changes in extreme rain events over the two Asian monsoon sub-regions (South Asia and East Asia) under different target temperatures, which will give an insight into potential benefits of the reduced global warming through greenhouse gas mitigation. To consider possible limitation of HAPPI AGCM experiments having no air-sea interactions, we also analyze the outputs from CMIP5 coupled GCMs and compare results with the HAPPI-based ones, which will also help to assess the robustness of our findings.

This paper is structured as follows. In section 2, HAPPI and CMIP5 datasets are described, and analysis methods are explained including the moisture budget and the daily precipitation intensity and frequency. Results are provided in section 3 for the mean and extreme precipitation changes, changes in precipitation characteristics, and temperature and extreme precipitation relationship. Summary and discussions are given in section 4.

2. Data and methods

2.1. Data

We use data from large-ensemble (>100 members) simulations of the five AGCMs participating in the HAPPI project (table 1). Each member of AGCM provides 10 year simulation data for the current climate (2006–2015, HIST), and corresponding 1.5 °C and 2.0 °C warmer conditions (Plus15 and Plus20, respectively). The five AGCMs have different resolutions and physics but were integrated under the identical boundary conditions. The observed sea surface temperature and sea-ice conditions were prescribed in the HIST experiment. The SST boundary condition for Plus15 and Plus20 experiments were prepared by adding a SST warming pattern estimated from CMIP5 multi-models (based on RCP2.6 and RCP4.5 scenario runs from 23 models, Mitchell et al. 2017) to the observed, and equilibrium forcings of aerosols and greenhouse gases were implemented following CMIP5 RCP experiments. For the sea ice, due to low reproducibility of CMIP5, linearized function of meridional temperature was used to estimate sea-ice conditions in warmer worlds over the pole regions. Details of the HAPPI experimental design are referred to Mitchell et al. (2017). Before analysis, we interpolated all model data into the identical observed grid (1° × 1°, based on GPCP v1.2 data) and then the identical GPCC land mask was applied. Since different AGCMs have different ensemble sizes ranging from 100–500 (table 1), we calculate ensemble averages of each AGCM and then obtain multi-model ensemble means (hereinafter referred to as MME).

In order to check potential impacts of the air-sea coupling on our results, which is known to be important for the Asian monsoon domain (e.g. Webster 2006, Dong et al. 2017), we repeat our analyses using 32 coupled global climate model (CGCM) data from the CMIP5 RCP8.5 scenario experiment (table S1 available at stacks.iop.org/ERL/13/044033/mmedia), following previous studies (Fischer and Knutti 2015, Knutti et al. 2016, Schleussner et al. 2016). Note that for some models, we extend the data to before 2006 using ‘historical’ experiment. Using single member (r1i1p1) of each CGCM, 30 year periods having 1.5°C and 2.0°C warming relative to the preindustrial level (1861–1880 mean) are selected (table S1). And then changes of the Asian summer monsoon rainfall under two transient warming conditions are analyzed in the same way as done for the HAPPI AGCM data.

Considering that each ensemble member of the HAPPI experiments consists of 10 year data, we define three variables of mean and precipitation extremes as follows. First, we use summer (June–July–August) mean of daily precipitation (Rm) calculated for each member. Secondy, for each member, we extract JJA maximum of daily precipitation from each year, and then calculate its 10 year average (Rx). To get more extreme events, we obtain 10 year maximum of summer daily precipitation over the whole 10 years (Rx10).

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Table 1. List of five AGCMs used in this study. All ensemble members provide 10 year simulation data for the HIST, Plus15, and Plus20 experiments.

| Model name   | Horizontal Resolution (# lon. × # lat.) | No. of ensemble members |
|--------------|----------------------------------------|-------------------------|
| CanAM4       | 128 × 64                               | 100                     |
| CAM4-2degree | 144 × 96                               | 500                     |
| E CHAM6.3-LR | 192 × 96                               | 100                     |
| MIROC5       | 256 × 128                               | 100                     |
| NorESM1-HAPPI| 288 × 192                               | 125                     |
Rx and Rx_{10} approximately correspond to 2 year and 10 year return values, respectively, under the independence assumption between ensemble members. They are also largely comparable to 99th and 99.9th percentiles of daily precipitation. In case of 30 year data from CMIP5 CGCM runs, we divide each 30 year data into three 10 year chunks and calculate Rx, Rx, and Rx_{10} from each 10 year chunk for consistency with the HAPPI data processing. This is also to increase the sample size of CMIP5 data. However, it should be noted that the three 10 year chunks do have different global mean warming levels (±0.4 K based on MME) due to the transient nature of the CMIP5 experiments, which makes it difficult to compare the HAPPI and CMIP5 experiments in a completely consistent fashion.

2.2. Moisture budget analysis
A moisture budget contribution analysis was introduced by Seager et al. (2010) to examine thermodynamic and dynamic mechanisms of hydrological trends during the long-term period and this approach has been widely applied to different warming scenarios (Seager and Naik 2012, Gao et al. 2012, Endo and Kitoh 2014, Li et al. 2015, Lee et al. 2017). Long-term mean water budget can be expressed as follows with identical unit (mm day\(^{-1}\)):

\[ \delta P = \delta E + \delta TH + \delta DY + \delta NL + \delta TE \]  \tag{1}

\[ \delta TH = -\frac{1}{\rho w g} \int \nabla \cdot (\delta \overline{u} \delta \overline{q}) \, dp \]  \tag{2}

\[ \delta DY = -\frac{1}{\rho w g} \int \nabla \cdot ((\delta \overline{u}) \delta \overline{q}_{\text{HIST}}) \, dp \]  \tag{3}

\[ \delta NL = -\frac{1}{\rho w g} \int \nabla \cdot (\delta \overline{u} \delta \overline{q}) \, dp \]  \tag{4}

\[ \delta (\cdot) = (\cdot)_{\text{Plus}} - (\cdot)_{\text{HIST}} \]  \tag{5}

where P is precipitation, E is evaporation from the surface, u is the horizontal wind vector, q is the specific humidity, p is the pressure, \( \rho_w \) is the water density, g is the gravitational acceleration, and \( \overline{p}_g \) is the surface pressure. Overbars indicate climatological monthly means (seasonal results are obtained by averaging monthly means). Subscripts HIST and Plus indicate historical period (HIST: 2006–2015) and future period (Plus15 and Plus20), respectively. Transient eddy term (\( \delta TE \)) is not considered here due to its negligible magnitude compared to the \( \delta TH \) and \( \delta DY \) terms (Gao et al. 2012, Li et al. 2015). Therefore, we only analyze changes (\( \bullet \)) in precipitation (P = Rm), evaporation (E), thermodynamic (TH), dynamic (DY) and nonlinear (NL) terms, which are calculated using monthly mean values. Vertical integrations for TH, DY, and NL terms are conducted using twelve standard pressure levels (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150 and 100 hPa; specified in the HAPPI experiment) within the troposphere.

2.3. Precipitation frequency and intensity
Spatiotemporal complex characteristics can be fairly considered by using percentiles of precipitation amounts (Freychet et al. 2015). We analyze precipitation characteristics based on percentiles estimated from aggregated daily data from all ensemble members for each HAPPI AGCM (note that we use single ensemble member from each CGCM for CMIP5 analysis). For example, in case of CAM4-2°, we estimate 10th–90th percentiles of precipitation on every grid from about 460 000 data (500 ensemble members × 92 days during JJA × 10 years). By aggregating all ensemble members, we can assess changes in extreme precipitation events above 99th percentile with enough number of samples (at least 1000 samples are needed to estimate 99.9th percentile intensity). To better identify changes in precipitation extremes, we specifically use bins of 10% width from 1st to 90th percentiles (1st percentile represents minimum precipitation intensity), bins of 1% width from 90th to 99th percentile, and bins of 0.1% width from 99.0th to 99.9th percentiles, in a similar way to Freychet et al. (2015). For the CMIP5 multi-CGCM analysis, we confine our analysis up to 99th percentiles because of smaller sample size (90–92 summer days × three 10 year chunks for each model). Next, changes in frequency are also examined following Freychet et al. (2015) by counting days at each grid where precipitation amount is greater than or equal to the precipitation percentile and less than the next level intensity, using the percentiles estimated from the historical period (2006–2015). For example, to get future changes in 80th percentile frequency, we count days where daily precipitation is equal or larger than the historical 80th percentile and also less than the historical 90th percentile. In the frequency analysis, changes in dry days are additionally examined, where dry days are defined as days with precipitation less than 1st percentile.

3. Results
3.1. Summer mean and extreme precipitation
Spatial patterns of the mean and extreme rainfall for HIST, Plus15, and Plus20 simulations, and their differences are displayed in figure 1. Compared to the observations, HAPPI HIST runs well reproduce mean (Rm) and extreme precipitation (Rx and Rx_{10}) in Asian monsoon regions but with some underestimation of extreme precipitation intensity (see below). HAPPI future runs predict overall increases in mean and extreme precipitation over the Asian monsoon region. At least four out of five AGCMs have the same sign of changes (areas hatched in figure 1), indicating good inter-model agreement. Based on MME, stronger increases are projected for extreme
Figure 1. Spatial distribution of summer mean (Rm) and extreme (Rx: annual maximum; Rx$_{10}$: decadal maximum) precipitation from HAPPI historical experiment (HIST, 2006–2015) and future changes (Plus15-HIST, Plus20-HIST) and their differences (Plus20–Plus15) (mm day$^{-1}$). Hatching represents grids where more than 80% of AGCMs agree on the sign of change or difference. Bars (multi-model mean) and marks (five individual AGCMs: magenta, orange, blue, aqua and purple for CanAM4, CAM4-2$^\circ$, ECHAM6.3-LR, MIROC5 and NorESM1-HAPPI, respectively) show land-averaged values over South Asian monsoon (SAS: 5$^\circ$N–25$^\circ$N, 65$^\circ$E–110$^\circ$E) and East Asian monsoon (EAS: 25$^\circ$N–45$^\circ$N, 110$^\circ$E–145$^\circ$E) domains as indicated by grey boxes in the spatial patterns. Multiplication ($\times$) mark represents observations (GPCP). Note that in the bar graphs, different unit is applied for historical simulations (mm day$^{-1}$) and future changes and their differences (%).

precipitation (5–20 mm day$^{-1}$) than mean precipitation (<5 mm day$^{-1}$), for which all five AGCMs predict its intensification over the Asian monsoon regions. Rx$_{10}$ generally exhibits stronger increases than Rx, suggesting stronger intensification of more-extreme precipitation as reported by previous studies (Freychet et al 2015, Lee et al 2017, Chen and Sun 2017). Differences between Plus20 and Plus15 suggest that a large part of the Asian monsoon region will experience additional intensification of precipitation, particularly extremes, due to the half a degree additional warming.

To explore regional characteristics, we define two sub-regions of South Asia monsoon (SAS) and East Asia monsoon (EAS) and examine area-mean changes in precipitations for Rm, Rx, and Rx$_{10}$ (figure 1, bar graphs). HAPPI AGCMs reproduce the observed precipitation (x mark) reasonably for both mean and extreme precipitation although models tend to underestimate Rx and Rx$_{10}$ over SAS and overestimate Rx$_{10}$ over EAS. Plus15 results show stronger increase in Rm over EAS (MME value: 7.7%) than SAS (2.5%). Similar increases in extreme precipitation are found between SAS and SAS with stronger changes in Rx$_{10}$ (SAS: 7.6%, EAS: 8.3%) than Rx (SAS: 5.8%, EAS: 6.7%). Note that these percentage changes are not much different between Rx and Rx$_{10}$ but Rx$_{10}$ has much stronger changes than Rx when considering absolute units (mm day$^{-1}$) as can be seen from the spatial patterns of HIST (figure 1). Plus20 results predict more increase in extreme precipitation with about 10% (based on MME) for Rx and about 12% for Rx$_{10}$ over both SAS and EAS regions. Differences between Plus20 and Plus15 results, which indicate potential benefits of the global warming mitigation, show relatively small (less than 2%) increases in Rm but larger increases of about 3%–5% (based on MME) in Rx and Rx$_{10}$ for both monsoon regions. The Rx$_{10}$ results in particular show good inter-AGCM agreement and suggest the robust intensification of more-extreme precipitation due to the additional warming, corroborating previous findings (Freychet et al 2015, Lee et al 2017, Chen and Sun 2017).

CMIP5 results based on transient warming conditions from 32 CGCMs (figure S1) are very similar to those from HAPPI AGCMs, confirming larger changes in more-extreme rainfalls over the Asian summer monsoon region. As expected, inter-model differences are larger in CMIP5 results than in the HAPPI ensemble because of the larger inter-CGCM difference in internally-driven SSTs unlike the identically prescribed
SSTs (see section 2 above). Nevertheless, it is notable that results from five CGCMs corresponding to the HAPPI AGCMs (table S1) spread widely in the historical climatology, future changes, and Plus20-Plus15 differences (figure S1, × marks), reasonably covering the CMIP5 ranges.

In order to understand mechanisms of precipitation changes under Plus15 and Plus20 experiments, results from the moisture budget analysis for Rm are illustrated in figure 2. All HAPPI AGCMs project increase in evaporation (E) and thermodynamic term (TH) under warming, while larger inter-model differences exist in dynamic term (DY). SAS and EAS area-mean results (figure 2, bar graphs) confirm that the increases in Rm over the Asian monsoon region are driven majorly by the increases in E and TH while the DY contribution is relatively uncertain with larger inter-model differences, which is in accord with previous studies (Endo and Kitoh 2014, Li et al. 2015, Lee et al. 2017). A quick check from an inter-model correlation analysis indicates that the DY increases (decreases) are largely associated with the strengthening (weakening) of the monsoon circulations (not shown). This issue on uncertainty sources warrants comprehensive analysis. NL term is much smaller than other terms, as in other studies (e.g. Seager et al. 2010, Lee et al. 2017). Differences between Plus20 and Plus15 indicate that E and TH terms explain the enhanced mean rainfall for both SAS and EAS regions, implying that thermodynamic mechanisms are critical to the additional increase of summer mean precipitation. Results of moisture budget analysis from the CMIP5 CGCMs (figure S2) generally support those from the HAPPI AGCMs, also confirming previous studies (Endo and Kitoh 2014).

3.2. Daily precipitation changes
Changes in daily precipitation characteristics are assessed for the SAS and EAS regions. First, precipitation intensity corresponding to 1st to 99.9th percentiles is estimated from HIST, Plus15, and Plus20 experiments, and then the future changes relative to HIST and the difference between Plus20 and Plus15 are obtained (figure 3). Results of HIST simulations show that HAPPI AGCMs (bars) capture the observed distribution (x marks) of precipitation intensity for both monsoon regions although some overestimations of precipitation intensity are seen at low percentiles (<50th percentile). Under warmer conditions of Plus15 and Plus20 experiments, all HAPPI AGCMs predict increase in precipitation intensity by about 3%–10% compared to the corresponding HIST values (based on MME) at high percentiles (>90th). Importantly, as the percentile gets higher (i.e. more-extreme precipitation), the stronger increase in precipitation intensity is projected for both Plus15 and Plus20 scenarios, which is more clearly observed in the SAS region. It is notable that by definition, absolute changes and associated impacts will be even larger at these high percentiles due to the stronger magnitude of climatology, which is consistent with our comparisons among Rm, Rx, and Rx_{10} given above (figure 1). For SAS, changes in medium precipitation intensity between 10th to 80th percentiles are uncertain with
mixtures of increases and decreases among models, which might be related to a stronger influence of dynamic contribution in SAS than in EAS (figure 2; Endo and Kitoh 2014, Freychet et al 2015, Vittal et al 2016, Roxy et al 2017). Light precipitation lower than 10th percentile is expected to decrease in SAS. Accordingly, distribution of difference in precipitation intensity between Plus20 and Plus15 indicates that the additional half a degree warming will strengthen extreme precipitation above 90th percentile by about 1%–4% whereas a decrease in light precipitation below 10th percentile is expected by about 3% with larger uncertainty over SAS. The EAS region exhibits different patterns of change. Precipitation intensity is projected to increase at all percentiles, indicating a shift of precipitation distribution. This is consistent with Freychet et al (2015), who found a similar overall intensification of precipitation over EAS using CMIP5 models. We also find same results from 32 CMIP5 CGCMs (figure S3). Accordingly, Plus20-Plus15 results for EAS show precipitation increases at all percentiles, and particularly, about 2%–3% increases are observed for extreme precipitation (>90th percentile) and for light precipitation (<50th percentile).

In short, for both Asian monsoon regions, HAPPI AGCM simulations consistently project further intensification of extreme precipitation due to additional half degree warming, which becomes stronger for more-extreme precipitation. This implies that possible benefits of global warming mitigation will be identified more strongly for extreme precipitation events which usually deliver larger impacts. CMIP5 results for the intensity changes under 1.5 and 2.0 degree warming scenarios (under transient world assumption) resemble those from the HAPPI ensemble for both SAS and EAS regions (figure S3), suggesting the minor role of air-sea coupling in the assessment of precipitation intensity distribution. As expected, the CMIP5 ensemble exhibits larger inter-model differences in future projections and differences between Plus20-Plus15 than the HAPPI results.

Changes in frequency of daily precipitation are similarly examined for the percentiles from 1st to 99.9th percentiles that are estimated from the HIST experiments (figure S4). All HAPPI AGCMs agree on more frequent extreme rain events above 90th percentile, supporting the intensity changes (figure 3). Non-linear increases in frequency are notable particularly above 99th percentile, reaching more than 60%

Figure 3. Distribution of daily precipitation intensity (bar: multi-model mean, error bar: min-max ranges of five AGCMs) for the quantiles from 1%–99.9% obtained from HIST climatology (mm/day), future changes (relative to the corresponding HIST value) in Plus15 (green) and Plus20 experiments (red), and their difference (Plus20–Plus15) over the South Asian monsoon (SAS, upper) and East Asian monsoon (EAS, lower) regions. Precipitation is divided into 10 bins (from 1–90), the last 10% is also divided into 10 bins of 1% each (from 90–99), and the last 1% is also divided into 10 bins of 0.1% each (from 99.0–99.9). Multiplication mark (x) represents the observed (GPCP) values. Note that the percentiles and corresponding rainfall intensities are calculated from each experiment separately (HIST, Plus15, and Plus20).
increase at 99.9th percentile under the 2°C warmer world. This behavior seems to be related to stronger moisture constraint on more-extreme precipitation (Allen and Ingram 2002). On the other hand, three or four out of five HAPPI AGCMs predict more frequent dry days for the two monsoon regions, which are consistent with previous projections based on CMIP5 models (Kitoh et al. 2013, Freychet et al. 2015, Lee et al. 2017). Differences between Plus20 and Plus15 indicate a sharp increase at extreme precipitations above 99th percentile. We also analyze CMIP5 CGCMs models for frequency changes under 1.5°C and 2.0°C warming scenarios and obtain overall similar results (figure S5).

3.3. Mechanisms for extreme precipitation intensification

Previous studies suggested that extreme precipitation changes follow the Clausius-Clapeyron (C-C) relation at global scales (e.g. Allen and Ingram 2002, Min et al. 2011, Kharin et al. 2013) and also at regional scales (e.g. Pall et al. 2007, O’Gorman and Schneider 2009, Lee et al. 2017). In order to explore physical mechanisms behind the stronger responses (or benefits) in more-extreme precipitation, inter-model relationship is examined between area-mean temperature changes and precipitation intensity changes using HAPPI AGCMs. The five AGCMs under the Plus15 and Plus20 scenarios provide ten samples (ensemble mean of each model). To consider the small number of models of HAPPI experiments as well as the possible limitation of AGCM experiments based on a single SST boundary condition and with no air-sea interactions, we also examine the temperature-extreme precipitation relationship using 32 CGCMs from the CMIP5 ensemble, which provide 64 samples representing both 1.5°C and 2.0°C warmer conditions in the transient world assumption (table S1). HAPPI results show that AGCM responses in temperature and precipitation over the two Asian monsoon regions are quite different across models, although identical SST conditions are prescribed (figure 4). This suggests considerable influences of the differences in model physics such as convective parameterization and land surface schemes (cf. Song and Zhou 2014, Lee et al 2016, 2017).

Statistically significant relationships are observed between regional-mean temperature changes and extreme precipitation exceeding 99th percentiles in the both SAS and EAS regions from HAPPI AGCMs (figure 4). EAS region exhibits a significant temperature-precipitation relation at 90th percentile as well. The
resultant linear regression slopes of extreme precipitation (99th and 99th percentiles) onto temperature are generally well in accord with the C-C relation (7%/°C) for both monsoon regions, representing the important role of moisture increase under warming in the intensification of extreme precipitation. When checking the temperature-extreme precipitation relationship using the individual HAPPI models, the regression slopes deviate a lot from the C-C scaling (3%–20%/°C for 99th and 99.9th percentiles), but most of the models generally support the C-C relation. CMIP5 results show statistically significant links between extreme precipitation and temperature at both 90th and 99th percentiles, supporting the HAPPI-based results. Noticeable difference includes the weaker regression slope (5.3%/°C) in CMIP5 over EAS region, which may represent stronger influence of air-sea interactions in CGCMs on this region, compared to SAS region (e.g. Dong et al 2017). Nevertheless, regression slopes are greater at 99th percentile than at 90th percentile in both regions and from both AGCM and CGCM ensembles. Likewise, regression slopes at 99.9th percentiles (10.13 and 6.86%/°C for SAS and EAS, respectively) are also slightly greater than at 99th percentiles (9.36 and 6.73%/°C) in HAPPI GCMs. This clearly indicates the stronger contribution of moisture increase (C-C relation) on the strengthening of more-extreme precipitation over the Asian monsoon region, which has not been demonstrated before. This regression analysis based on Plus20 and Plus15 data also implies that global warming mitigation from 2°C to 1.5°C target temperatures would provide potential benefits as weaker increases in heavy precipitation intensities, for example, by 3%–5% at the 99.9th percentile values (figure 3). On the other hand, regression lines for the 99th and 99.9th percentiles in figure 4 pass very close to the origin but not exactly through it, which indicates that the temperature-extreme precipitation relation could be in fact nonlinear due to other effects including dynamic contribution on extreme precipitation (Freychet et al 2015, Lee et al 2017, Pfahl et al 2017).

4. Summary and discussion

In this study, we examine impacts of 1.5°C and 2.0°C equilibrium warming (compared to the preindustrial condition) on summer rainfall over the Asian monsoon regions using five AGCM datasets from the HAPPI project. In order to consider potential limitation of the AGCM experiments based on the identical SST boundary conditions with no air-sea coupling, multi-CGCMs from the CMIP5 ensemble (32 models form the RCP8.5 scenario experiment) are also analyzed although they represent transient responses to the two target temperatures of the Paris Agreement. Results show that summer precipitation will increase in both means and extremes over the South Asian monsoon (SAS) and East Asian monsoon (EAS) regions. Larger increase is expected in more-extreme precipitation which will exert stronger influences on the human society and economy over the Asian monsoon regions (figure 1). Differences between 1.5°C and 2°C warmer conditions suggest that half a degree additional warming will lead to the intensification of extreme precipitation. Results from a moisture budget analysis for summer mean precipitation indicate that mean precipitation increase is determined by increase in evaporation and the thermodynamic term (atmospheric moisture) with large inter-GCM differences in the dynamic term responses associated with changes in atmospheric circulations (figure 2). This is well consistent with previous studies based on CMIP5 models (Endo and Kitoh 2014), partly supporting the validity of HAPPI AGCMs in terms of mechanisms for the precipitation projections under warming. In this respect, recently, Pfahl et al (2017) showed that the dynamic contribution plays a critical role in determining regional patterns of extreme precipitation responses to global warming, amplifying increases over the Asian monsoon region.

Changes in daily precipitation characteristics are further examined considering intensity and frequency (figure 3, figure S4). All HAPPI simulations predict increase in the intensity and frequency of extreme precipitation in both warmer worlds. Warming reduction by a half degree is expected to induce less frequent and weakened extreme precipitation events over both SAS and EAS regions. Further, inter-model relationship between temperature and precipitation intensity is examined using the HAPPI AGCM responses to two equilibrium target temperatures (figure 4). A positive relationship between temperature and precipitation is found in both monsoon regions for extreme precipitation exceeding 90th percentiles. This scaling becomes stronger as more-extreme precipitation is considered, being in line with the C-C relationship (moisture increase). This indicates that potential benefits of reduced warming through mitigation will be better identified in more-extreme precipitation that exerts huge socioeconomic impacts on the entire Asian monsoon region.

Results from CMIP5 multi-CGCM data generally support those from the HAPPI AGCM ensemble although they are based on a transient world assumption: (1) general increase in mean and extreme precipitation over the SAS and EAS regions (figure S1), (2) larger increase in the intensity and frequency of extreme precipitation exceeding 90th percentile (figure S3, figure S5), and (3) statistically significant relationship between temperature and extreme precipitation intensity (figure 4), and (4) stronger response of additional warming (or larger benefit of mitigated warming) identified in more-extreme precipitation.
exceeding 99th percentile. Good agreement in results between the two AGCM and GCCM ensembles provides the robustness of our findings, also supporting that the HAPPI framework reasonably projects possible changes in the Asian summer monsoon rainfall under global warming.

It should be noted that many caveats remain in this study due to (1) potentially large uncertainties in SST patterns estimated for the warmer worlds and (2) the absence of air-sea interactions, both of which are known to importantly affect the Asian summer monsoon climate and extremes (e.g. Webster 2006, Dong et al 2017). In this regard, the tier 2 experiments of the HAPPI project will utilize SST patterns from the individual CGCM model (Mitchell et al 2017), aiming at quantifying influences of different SST patterns and assessing associated uncertainties in extreme responses. In particular, influences of SST patterns and air-sea coupling can be different within Asian monsoon regions such as SAS and EAS, and distinct physical mechanisms relevant for each region warrant further investigation (e.g. He and Zhou 2015). Also, some observational studies indicated that the local variations in monsoon precipitation are dominated by the dynamic responses rather than the thermodynamics (e.g. Vittal et al 2016, Roxy et al 2017). This inconsistency between observed and modeled trends in monsoon precipitation might be due to a few factors including single vs. multiple realizations, weaker vs. stronger forcings, and model biases associated with clouds and convections. Relative contribution of these factors to the observation-model disagreement needs to be explored.

Acknowledgments

We thank two anonymous reviewers for their thoughtful and constructive comments. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (no. 2017R1A2B2008951). 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 (listed in table S1 of this paper) for producing and making available their model output. HS was supported by the Integrated Research Program for Advancing Climate Models (TOUGOU program) from the Ministry of Education, Culture, Sports, Science and Technology, Japan and ERTDF 2–1702 of Environmental Restoration and Conservation Agency, Japan. NorESM contributions have received support from the Research Council of Norway (261821) and UNINETT Sigma2 (ns9082k). LL was supported by funding from the Bundesministerium für Bildung und Forschung (BMBF). This research used science gateway resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the US Department of Energy under Contract No. DE-AC2-5CH11231.

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Acknowledgments

We thank two anonymous reviewers for their thoughtful and constructive comments. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (no. 2017R1A2B2008951). 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 (listed in table S1 of this paper) for producing and making available their model output. HS was supported by the Integrated Research Program for Advancing Climate Models (TOUGOU program) from the Ministry of Education, Culture, Sports, Science and Technology, Japan and ERTDF 2–1702 of Environmental Restoration and Conservation Agency, Japan. NorESM contributions have received support from the Research Council of Norway (261821) and UNINETT Sigma2 (ns9082k). LL was supported by funding from the Bundesministerium für Bildung und Forschung (BMBF). This research used science gateway resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the US Department of Energy under Contract No. DE-AC2-5CH11231.

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