**Investigating Future Changes in Southern China Precipitation
Characteristics Based on Dynamically Downscaled CMIP5 Climate
Projections**

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23 The Regional Climate Model version 4 (RegCM4) has been used to dynamically
24 downscale outputs from four different general circulation models (GCM) participating
25 in the Coupled Model Intercomparison Project Phase 5 (CMIP5) to the horizontal
26 resolution of 25 km $\times$ 25km, in order to study 2050-to-2099 changes in the Southern
27 China hydrological cycle according to Representative Concentration Pathway (RCP)
28 8.5, relative to the period of 1979 to 2003. The mean summertime precipitation is
29 projected to increase by 0.5 – 1.5 mm/day over coastal Southern China, and with
30 significantly enhanced interannual variability. In boreal spring, similar increase in both
31 the seasonal mean and its year-to-year variation north of 25°N is also found. A novel
32 moisture budget analysis shows that changes in mean background humidity (anomalous
33 wind convergence) dominates the increase in the interannual precipitation variability in
34 spring (summer). Extreme daily precipitation (based on the 95th percentile) is projected
35 to become more intense, roughly following the Clausius–Clapeyron relation for the
36 aforementioned seasons.

37 On the other hand, autumn mean rainfall rate will be reduced over a broad area in
38 Southern China (although this might be subjected to models' ability in capturing
39 tropical cyclone activities). The annual number of maximum consecutive dry days
40 (CDD) is found to increase by about 3 to 5 days over locations south of 32°N. Analyses

41 of GCM raw outputs indicate that strengthened northerlies over coastal East Asia ,
42 which is likely associated with the so-called tropical expansion, are responsible for the
43 drier autumn.

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45 **Keywords:** regional climate model; dynamical downscaling; climate change;
46 precipitation characteristics; Southern China

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52 **Code availability:** CDO 1.6.9 and NCL 6.3.0 are used to process the outputs from
53 CMIP5 GCMs and RegCM4.6. Custom codes will be made available on reasonable
54 request.

1. Introduction

With diverse terrain, including valleys, mountains and coastline, it is known that precipitation has a complex spatial-temporal pattern in Southern China (Dai, 2001; Hirose and Nakamura, 2005; Zhou and Yu, 2005; Chen et al., 2009; Xu et al., 2009; Yang et al., 2010; Niu, 2013)- a region in which the annual hydrological cycle is shaped by the Asian Monsoon (Ding, 1992, 1994; Chan and Zhou, 2005; Ding and Chan, 2005; Zhou, 2011). Starting from mid-May, there is increase in both precipitation and temperature associated with warm and moist air streams from the South China Sea (SCS) and nearby oceans; the wet season, reaching a peak in June to August (Wang and LinHo, 2002) ends with the Siberian High development in late September, due to the rapid cooling of the East Asian continent. The latter leads to a high-pressure anomaly which pushes air towards the ocean and produces low-level northeasterlies over a broad continental region. The dry northerly effectively reduces the humidity and precipitation, starting from October, followed by winter monsoon in late November, characterized by cold and dry circulations, throughout December to February. The winter monsoon starts retreating in late-February. Maritime airstream from the south and southeast induces wet and warm weather in spring during the March-to-May season (MAM). In addition to annual variations, there is also prominent sub-daily land-sea breeze due to land-sea temperature contrast (Zhou and Yu, 2005; Chen et al., 2016). Locally, the average

74 annual precipitation can reach 1500 mm or even exceed 2000 mm in some coastal
75 locations such as Hong Kong (Zhang and Cong, 2014). Such a large amount of rainfall
76 has important consequences on water resource management, agriculture, and hazard
77 mitigation in this region. For example, seasonal to interannual rainfall variations
78 determine the productivity and types of agriculture (Tao et al., 2004). Rainfall with
79 shorter timescales can be very intense and causes hazards such as flooding and
80 landslides in the wet seasons (Lyu et al., 2018).

81 From the Intergovernmental Panel on Climate Change Fifth Assessment Report
82 (IPCC AR5), changes in precipitation due to warming climate behave in a complex
83 manner in Asia, owing to topographic effects, large scale circulation, etc. From
84 observations, the mean state rainfall is becoming more intense over Southern China
85 starting from the 1950s using land-station data (Zhang and Cong, 2014). For the
86 projected future climate, it was found that most regions have a general reduction in
87 background wind circulation; however, enhanced moisture capacity of the troposphere
88 results in stronger precipitation, based on the projection of the Coupled Model
89 Intercomparison Project Phase 5 (CMIP5) models (IPCC AR5 WGI Sections 14.2.1,
90 Christensen et al., 2013; Hsu et al., 2013). Meanwhile, East Asian summer monsoon
91 (EASM) rainfall is projected to increase in the future. A strengthened EASM with a
92 moister atmosphere increases the regional precipitation significantly in summer (IPCC

AR5 WGI Sections 14.2.2, Christensen et al., 2013; Wang et al., 2014).

The interannual precipitation variability over Southern China is expected to increase, especially during summer, based on CMIP3 and CMIP5 model projections (IPCC AR5 WGI Sections 14.2.1 and 14.2.2, Christensen et al., 2013). There is high confidence that El Niño–Southern Oscillation (ENSO) will remain the dominant mode of interannual global climate variability in the future (Collins et al., 2010; Guilyardi et al., 2012). A reduction in the number but an intensification in the magnitude of tropical cyclones (TCs) and related precipitation over the western North Pacific were projected by most models (Murakami, 2012; Ying et al., 2012; Cha et al., 2020). For coastal Southern China, projected intensification in landfalling TCs (Lok and Chen, 2018) and their related rainstorms (Lui et al., 2019b) increase precipitation variability. On the other hand, reduction in TC landfalls (Lok and Chen, 2018) and shift in tracks (Murakami, 2012; Wang and Wu, 2015; Nakamura et al., 2017; Cha et al., 2020) can suppress this variability. The net effect of climate change in TC-related precipitation interannual variability over Southern China is still uncertain.

Generally, the impacts of a warmer climate on extreme rainfall will be stronger compared to that on mean state rainfalls (Easterling et al., 2000; Trenbeth, 2011). The increase in extreme precipitation rates roughly follows the Clausius–Clapeyron relation (CC relation) according to observational studies (e.g. Schroer and Kirchengast, 2018)

and high-resolution general circulation model (GCM) experiments (Lui et al., 2019b). The CC relation indicates that saturated water vapor pressure increases with temperature thermodynamically. Under typical situations of the atmosphere, there will be about a 7% increment in moisture holding capacity, thus the resulting extreme precipitation rates, per one degree Celsius of low-level tropospheric temperature rise (Pall et al., 2007). Apart from pure thermodynamic reasoning, changes in extreme precipitation can also be attributed to other factors, such as those in regional total precipitation amount (Zhai et al., 2005), TC rainfall (Ying et al., 2012; Lui et al., 2019b; Cha et al., 2020), monsoon characteristics (Christensen et al., 2013; Zhang et al., 2015) and large-scale circulation (Wang and Zhou, 2005). These factors can affect extreme precipitation rates and make them deviate from the CC relation. Many regional climate model (RCM) studies also indicate a significant intensification in extreme precipitation in Southeast Asia and Southern China (e.g. Gao et al. 2002; Fischer et al. 2013; Ngo-Duc et al. 2017).

Although there were many studies on projecting the hydrological characteristics over different domains, most of them using GCMs give a strong consensus only over a broad region and for large-scale phenomena. On the other hand, finer-scale simulations using RCMs can improve the interaction between climate variables and topography as well as representations of processes in the subgrid-scale regime in GCMs (Dickinson

131 et al., 1989; Giorgi, 1990; Beniston et al., 2007). Climate projections based on RCM
132 make use of the dynamical downscaling technique, in which the model is forced by
133 initial conditions and lateral boundary conditions (ICBC) taken from GCM outputs (e.g.
134 Wood et al., 2004; Giorgi and Gutowski, 2015). RCM simulated climate phenomena,
135 especially for the weather extremes and cumulus convection which have small scales
136 in both time and space, thus tend to be more reliable with finer features. Also, note that
137 a lot of running time is spent on the grids over regions that are not of interest in GCM
138 simulations; RCM can save computation time by limiting the simulation within the
139 domain of interest. This advantage also makes RCM simulations with multi-model or
140 multi-physics ensembles more effective.

141 In this research, RCM dynamical downscaling was carried out for projecting the
142 hydrological characteristics over Southern China. GCMs having good performance in
143 simulating climate variables over the western North Pacific-Southeast Asia region were
144 first selected for downscaling (details of GCM selection can be found in **Appendix**).
145 The performance of RCM was also evaluated by comparing runs using reanalysis as
146 well as GCM boundary conditions with observations. The simulation products of
147 selected GCMs for the 2050 – 2099 era based on RCP8.5 were also downscaled.
148 Comparison between the downscaled products of historical and future simulations was
149 then conducted for precipitation characteristics at various time scales over Southern

China. Details of RCM and GCMs used for the dynamical downscaling and the observation/reanalysis data used are outlined in Section 2. Section 3 gives the dynamical downscaling results as well as the impacts of climate change on Southern China rainfall. Discussion and conclusion are provided in Section 4.

2. Model experiments and data used

The Regional Climate Model system Version 4.6 (RegCM4.6) was adopted for dynamical downscaling in this study. It is a hydrostatic model with a staggered Arakawa B-grid system, developed by the International Centre for Theoretical Physics (ICTP, Giorgi et al., 2012). RegCM4 and its previous versions have been extensively used for numerous climate studies for different regions in the world, such as the Coordinated Regional Downscaling Experiment (CORDEX) (<https://cordex.org/>) (Giorgi et al., 2009; Gu et al., 2012; Oh et al., 2014; Lui et al., 2019a). Here the model was integrated at the horizontal resolution of $25\text{ km} \times 25\text{ km}$, with 18 sigma levels, over the region of $1^{\circ}\text{S} - 40^{\circ}\text{N}$, $105 - 135^{\circ}\text{E}$ (see **Fig. 1**).. Detailed configuration of RegCM4 is given in **Tab. 1**. In particular, the Emmanuel scheme (Emmanuel, 1991; Emanuel and Živković-Rothman, 1999) is chosen as the cumulus convective scheme over the whole domain, based on the results of Li et al. (2016) and Lui et al. (2019a), which indicate that the scheme can produce the most reasonable precipitation at a variety of timescales over Southern China.

169 The performance of RegCM4 in capturing the present-day climate was first
 170 evaluated, by downscaling ERA-interim data from 1979 to 2003 (Dee et al., 2011). For
 171 comparing precipitation characteristics, TRMM (Tropical Rainfall Measuring Mission;
 172 Huffman et al., 2007)) (1998 – 2018), and station-based APHRODITE (Asian
 173 Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation;
 174 Yatagai et al., 2012) (1979 – 2003) were used. (Note that TRMM might tend to
 175 overestimate daily precipitation over Southern China; see Zhao and Yatagai, 2014).
 176 After the evaluation, four GCMs, namely ACCESS1-3, CNRM-CM5, GFDL-CM3, and
 177 MPI-ESM-MR, from CMIP5 (Taylor et al., 2012), were dynamically downscaled by
 178 RegCM4. They were found to give the best overall performance in the domain of
 179 interest. (Details of GCM selection are provided in **Appendix**.) Here RegCM4 was
 180 integrated during the 1979 to 2003 era (the “historical period”), and also from 2050 to
 181 2099 (the “future period”) for RCP8.5 based on outputs from these GCMs. Hereinafter,
 182 downscaled products of RegCM4 using outputs from ERA-interim, ACCESS1-3,
 183 CNRM-CM5, GFDL-CM3, and MPI-ESM-MR are referred to as RegCM4_EA,
 184 RegCM4_AC, RegCM4_CN, RegCM4_GF, and RegCM4_MP, respectively. Finally,
 185 multi-model ensemble (MME) mean values were obtained by averaging simulations
 186 forced by different GCMs within the same period, so as to reduce uncertainties in
 187 climate projections (Tebaldi and Knutti, 2007). The difference between two MME

averages for the historical (MME_HIST) and future (MME_RCP8.5) simulations were then examined, in order to infer climate change signals over Southern China.

3. Results

3.1 Performance of RegCM4

Outputs of RegCM4_EA are first compared with ERA-interim for wind and with TRMM and APHRODITE for precipitation. **Fig. 2** shows the mean 850hPa wind from ERA-interim, precipitation from TRMM (1998 – 2018) and APHRODITE (1979 – 2003), and those from RegCM4_EA (1979-2003), for JJA and DJF. Overall, a slight warm (cold) bias over land (the oceanic area north of 10°N) is seen throughout the whole year, with a magnitude about 1°C or more. Most low-level wind branches, such as the southwesterly onshore wind over Southern China in JJA and the strong northwesterly to northeasterly wind in DJF, are reasonably reproduced. It is worth noting that the model also tends to give a northerly or northeasterly bias in the low levels over the eastern and southern parts of the domain, especially for DJF. At the same time, a slight southerly bias in the low levels is found near Indochina.

For seasonal mean precipitation, model rainfall is compared with APHRODITE over continental areas. RegCM4 tends to reproduce a wetter climate over Southern China during MAM (not shown) and DJF, with a mean rainfall bias of about 20%. For SON (not shown) and JJA, there is wet bias near the mountainous area in 28 – 35°N,

207 100 – 115°E. During JJA, the rain belt near coastal Southern China is displaced
208 northward by about 2 – 3° in the model; this feature has a magnitude that is comparable
209 to the one more along the coast in APHRODITE. However, note that there is dry bias
210 in SCS in all seasons. Overall, it is seen that compared to precipitation over land,
211 RegCM4 performance is less satisfactory in capturing rainfall over the ocean. The
212 performance of RegCM4 in reproducing the annual number of maximum consecutive
213 dry days (CDD) and summertime diurnal rainfall was also examined. In general,
214 RegCM4 can give reasonable magnitudes and patterns of these precipitation features
215 over Southern China (figures not shown).

216 To ensure the dynamical downscaling can retain general features simulated by the
217 GCMs, downscaled products are also compared with those from the parent GCMs. In
218 general, RegCM4 can reproduce well the 850hPa temperature and zonal wind (see **Fig.**
219 **S2**). However, it is noticed that the low-level meridional wind pattern from the regional
220 model does not match well with those from the parent GCMs in JJA. For ACCESS1-3,
221 downscaling results for the meridional wind seem to deviate from its parent GCM in
222 SON as well. For precipitation, in JJA most models can retain the continental rain
223 features from the parent GCMs, except for RegCM4_GF; it can be seen that the wet
224 zone over coastal Southern China in the GCM disappears after downscaling (see **Fig.**
225 **S3**). Owing to inconsistencies between the RCM and parent GCM mean circulation,

downscaled GFDL-CM3 results for JJA will be discarded.

For SON, the 850hPa easterly wind from 10°N – 30°N is captured after downscaling (see **Fig. S4**). The magnitudes of the meridional component of winds are small over the whole domain, resulting in large sensitivity to small biases as shown in the Taylor diagrams (Taylor 2001). For precipitation over land, features from CNRM-CM5, GFDL-CM3, and MPI-ESM-MR are well reproduced after downscaling. For ACCESS1-3, RegCM4_AC produces even stronger wet biases, making the downscaled SON rainfall deviates even more from APHRODITE. Thus, for SON, RegCM4_AC is discarded due to its overly wet conditions, and also its poor performance in reproducing the low-level meridional wind. During MAM and DJF, RegCM4 can reproduce most of the features of the continental precipitation and 850hPa wind (not shown), consistent with **Fig. S2**. The spatial patterns of the downscaled products also resemble those based on APHRODITE.

It is particularly noteworthy that, over the oceanic region, RegCM4 with this configuration oftentimes cannot reproduce the rainfall from raw GCMs. In JJA, SCS becomes much drier after downscaling for all models. Similarly, in SON RegCM4 performs inadequately in simulating precipitation over the ocean, irrespectively of the parent GCM. The inter-model consensus in the oceanic precipitation pattern is also rather poor. For DJF and MAM, over the ocean, RegCM4 precipitation is still drier than

the raw GCM outputs, although its performance is better than that in JJA or SON. The above suggests it might not be suitable to consider precipitation over SCS in RegCM4 for all seasons.

To summarize, after reviewing the performance of RegCM4 and dynamical downscaling of the four selected models, it was decided to exclude RegCM4_GF (RegCM4_AC) from the MME mean in analyses of the JJA (SON) precipitation characteristics and focus on the analysis of continental rainfall only.

3.2 Seasonal Mean Climate Projection

We first analyse changes in the mean climate in Southern China, based on the difference between the multi-model ensemble mean of downscaled future (MME_RCP8.5) and historical simulations (MME_HIST). **Fig. 3** shows the results of the seasonal mean precipitation, 850hPa wind, and temperature (see **Figs. S5** and **S6** for values from the historical and future-projected runs). There is temperature increase over the whole region, with generally stronger warming over land and in higher latitudes, especially for SON and DJF. The whole domain is warmed by about 2 to 3°C in the low levels in MAM and JJA. More than 4°C warming is found over locations north of 25°N in SON and DJF. Changes in the DJF low-level wind however are negligible. Slightly stronger southwesterly is seen on the continent over 25 – 30°N in MAM. For JJA, low-level westerlies are enhanced over 5 – 15°N. There is a

strengthened low-level cyclonic flow near the eastern boundary centered at 25°N, 135° E in SON. Enhanced easterlies north of 30°N are found over the continent and produce anomalous northerlies over Southern China. Liu et al. (2011) also reported a similar feature in their RCM simulations. This induces a stronger northerly wind component over Southern China, the consequence of which on the regional precipitation will be further examined.

For precipitation, during MAM, it is increased by about 1 – 2 mm/day (20%) over the inland area of 25 – 35°N, 105 – 120°E, collocated with the enhanced low-level southwesterly. Rainfall changes over the coastal area, however, are not significant. For JJA, precipitation increases generally for about 0.5 – 1.5 mm/day (10 – 15%) over the whole Southern China. Precipitation in SON, however, shows an opposite trend compared to MAM and JJA. In particular, there is a prominent dry signal south of 35°N; rainfall reduces by 15 – 20% for most of the land area. It is noticeable that an anomalous anticyclone over the eastern half of the simulated domain brings stronger northerly over continental China. The relationship between the enhanced northerly and the reduced rainfall will be further discussed. For DJF, there is no significant difference in the mean precipitation intensity and pattern for MME_HIST and MME_RCP8.5. The change in DJF mean precipitation rate is less than 0.3 mm/day (about 5 – 8%) for most regions.

3.3 Interannual variability of seasonal precipitation

We now examine how interannual precipitation variations over Southern China might change in the future climate. Precipitation variability is represented by computing the variance of the seasonal mean rainfall. **Fig. 4** shows the difference in precipitation variance between MME_RCP8.5 and MME_HIST (values from MME_HIST and MME_RCP8.5 are given in **Fig. S7**). Significant increase in variance is found only during MAM and JJA over Southern China, with much stronger change in the latter (about 30%) than that in the former season (about 15%). Most locations with increased interannual variability collocate with the projected wetter regions (see **Fig. 3**). Changes in SON and DJF are rather small with noisy patterns.

Here we introduce a novel method for attributing changes in precipitation variability, based on a modified form of the moisture budget equation. Starting from the moisture budget equation $P = E - \frac{1}{g} \nabla \cdot \int_0^{p_s} q \mathbf{V} dp$, where P and E are the time mean precipitation and evaporation respectively, E , and with the vertically integrated moisture flux denoted by $\vec{Q} = \frac{1}{g} \int_0^{p_s} q \mathbf{V} dp$, (standard notations for other variables), considering the anomalies and by multiplying the equation with the sign of anomalous precipitation, one arrives at:

$$|\overline{P'}| = \overline{\hat{P}' E'} - \overline{\hat{P}' \left(\frac{1}{g} \nabla \cdot \int_0^{p_s} q \mathbf{V} dp \right)'} = \overline{\hat{P}' E'} - \overline{\hat{P}' \nabla \cdot \vec{Q}}, \quad (1)$$

where prime indicates the deviations from the climatological mean, with $\hat{P}'$ is the sign of P' , and overbar denotes the long-term mean. $|\overline{P'}|$ is the time mean of the absolute

302 values of P' , which is close to the standard deviation of precipitation, $\overline{\hat{P}'E'}$ and
 303 $-\overline{\hat{P}'\nabla \cdot \vec{Q}}$ are contributions from evaporation and moisture flux convergence to the
 304 interannual precipitation variability, respectively. Equation (1) can shed light on
 305 precipitation variance and its relationship with circulation changes. The difference
 306 between MME_HIST and MME_RCP8.5 for $\overline{|P'|}$, $\overline{\hat{P}'E'}$, and $-\overline{\hat{P}'\nabla \cdot \vec{Q}}$ are shown in
 307 **Fig. 5**. In both MAM and JJA, the differences in $\overline{\hat{P}'E'}$ between MME_HIST and
 308 MME_RCP8.5 are negligible. On the other hand, changes in $-\overline{\hat{P}'\nabla \cdot \vec{Q}}$ resemble those
 309 in $\overline{|P'|}$ in both seasons, with comparable magnitudes and patterns. Therefore,
 310 precipitation variance is closely associated with variation in moisture flux convergence.

311 The $-\overline{\hat{P}'\nabla \cdot \vec{Q}}$ term in (1) can be further decomposed as:

$$312 \quad -\overline{\hat{P}'\nabla \cdot \vec{Q}} = -\overline{\hat{P}' \left(\frac{1}{g} \nabla \cdot \int_0^{p_s} q \mathbf{V} dp \right)'} \approx -\overline{\hat{P}' \frac{1}{g} \nabla \cdot \int_0^{p_s} (\bar{q} \mathbf{V}' + q' \bar{\mathbf{V}}) dp}, \quad (2)$$

313 where $\bar{q} \mathbf{V}'$ and $q' \bar{\mathbf{V}}$ are two terms related to the deviation in velocity and specific
 314 humidity respectively. One can interpret $\bar{q} \mathbf{V}'$ as the dynamical effect (i.e. related to
 315 anomalous wind circulation) while $q' \bar{\mathbf{V}}$ as the thermodynamic effect (due to
 316 anomalous specific humidity) contributing to the interannual variability of seasonal
 317 precipitation. Changes in the dynamical term outweigh the thermodynamic term in both
 318 seasons (see **Fig. 6**). The result indicates that changes in dynamical variables are
 319 responsible for interannual variability in moisture flux convergence, as well as the
 320 precipitation variability. Note that, for MAM, there is a region with a negative change

321 in the dynamical term over 22 – 26°N, 110 – 114°E, with magnitudes comparable to
 322 positive change in the thermodynamic term. The cancelation between these two terms
 323 yields a relatively small change in moisture flux convergence variability there (see **Fig.**
 324 **5c**).

325 Furthermore, changes in the dynamical term $-\overline{\hat{P}' \frac{1}{g} \nabla \cdot \int_0^{p_s} \bar{q} \mathbf{V}' dp}$ from historical
 326 simulations to future simulations can be further decomposed since:

$$\begin{aligned}
 327 \quad & \delta \left(-\overline{\hat{P}' \left(\frac{1}{g} \nabla \cdot \int_0^{p_s} (\bar{q} \mathbf{V}') dp \right)} \right) \\
 328 \quad & \approx -\frac{1}{g} \delta \left(\int_0^{\bar{p}_{sH}} \left(\overline{\hat{P}' \mathbf{V}' \cdot \nabla \bar{q}} + \overline{\bar{q} \hat{P}' \nabla \cdot \mathbf{V}'} \right) dp \right) \\
 329 \quad & \approx -\frac{1}{g} \int_0^{\bar{p}_{sH}} \left[\overline{\hat{P}'_H \nabla \cdot (\delta(\bar{q}) \mathbf{V}'_H)} + \delta(\overline{\hat{P}' \mathbf{V}'}) \cdot \nabla(\bar{q}_H) + \bar{q}_H \delta(\overline{\hat{P}' \nabla \cdot \mathbf{V}'}) \right] dp, \quad (3)
 \end{aligned}$$

330 where $\delta(\cdot) = (\cdot)_F - (\cdot)_H$ indicates the change in quantities under a warmer climate,

331 with subscripts H and F denote the quantities from historical and future simulations.

332 The three terms in the integral, $\overline{\hat{P}'_H \nabla \cdot (\delta(\bar{q}) \mathbf{V}'_H)}$, $\delta(\overline{\hat{P}' \mathbf{V}'}) \cdot \nabla(\bar{q}_H)$ and $\bar{q}_H \delta(\overline{\hat{P}' \nabla \cdot \mathbf{V}'})$,

333 represent contributions from changes in background humidity ($\delta \bar{q}$), anomalous

334 moisture advection ($\delta(\mathbf{V}' \cdot \nabla \bar{q})$), and anomalous wind convergence ($\delta(\nabla \cdot \mathbf{V}')$)

335 respectively. For MAM, the values of $\delta \bar{q}$, $\delta(\mathbf{V}' \cdot \nabla \bar{q})$, and $\delta(\nabla \cdot \mathbf{V}')$ terms averaged

336 over the continental area within 20 – 32°N, 110 – 125°E (region covering Southern

337 China) are 2.14×10^{-1} , -6.00×10^{-3} , and 3.56×10^{-2} , in mm/day, respectively. Among

338 them, $\delta \bar{q}$ term is one order higher than the other two terms, indicating that changes in

339 the background specific humidity are the major contributor to the dynamical effect in

340 MAM. For JJA, values of the three terms averaged over the same area are 1.83×10^{-1}
341 mm/day ($\delta \bar{q}$), 7.09×10^{-2} mm/day ($\delta(\mathbf{V}' \cdot \nabla \bar{q})$), and 2.19×10^{-1} mm/day ($\delta(\mathbf{V}' \cdot \nabla \bar{q})$).
342 The $\delta(\nabla \cdot \mathbf{V}')$ term is the largest, suggesting that the changing anomalous circulation
343 can lead to stronger wind (hence moisture flux) convergence. Although the area-
344 averaged $\delta \bar{q}$ term is still large, the $\delta(\nabla \cdot \mathbf{V}')$ term is more spatially correlated with
345 the region with a positive change in the dynamical term over Southern China (see **Figs.**
346 **6c** and **S8f**). Overall, enhanced anomalous wind convergence contributes most to the
347 dynamical effect in relation to increased JJA precipitation variability.

348 3.4 Daily precipitation extremes

349 The impacts of a warmer climate to extreme daily rainfall is also investigated
350 based on the RegCM4 outputs. Precipitation extreme is indicated using the 95th
351 percentile of daily rainfall for “rain days” (days with precipitation more than 1.0
352 mm/day) (referred to as 95PC). To maintain a reasonable presentation of the statistics,
353 95PC is investigated separately for each model. The increase in extreme precipitation
354 rates roughly follows the Clausius–Clapeyron relation (CC relation), which states that
355 there will be ~7% increase of saturated water vapor pressure (hence extreme rainfall
356 intensity on daily or longer time scales) per °C warming in low-level tropospheric
357 temperature, under the typical conditions of the Earth. The intensification rate of
358 extreme precipitation seems to follow the CC relation according to observational

studies (e.g. Schroeder and Kirchengast 2018) and high-resolution GCM experiments (Lui et al. 2019b).

The fractional changes in 95PC per degree change in 850hPa seasonal mean temperature $\left(\frac{\Delta 95pc}{\Delta T}\right)$ from each downscaled model are shown in **Figs. S8** and **S9**. Here, we focus on changes in MAM and JJA, when the most robust increase in daily extreme precipitation with stronger intermodel consensus of the sign change of 95PC are found. The probability density functions (PDFs) accounting for the probability of continental grids having certain $\frac{\Delta 95pc}{\Delta T}$ values within the area 22 – 32°N, 110 – 120°E are also given in **Fig. 7**. For MAM, RegCM4_AC does not reproduce a significant change in 95PC over Southern China. Most values from RegCM4_GF and RegCM4_CN are centered around 5%/K, which is close to but slightly smaller than that from the CC relation. RegCM4_MP matches the theoretical CC values and has its peak value at about 7%/K. The MME mean of downscaled models has also a peak at 5%/K but with a rather wide distribution. These results suggest that extreme daily precipitation change is broadly consistent with the CC relation over Southern China in MAM. In JJA, RegCM4_AC and RegCM4_CN give values of $\frac{\Delta 95pc}{\Delta T}$ along the rain-belt of about 6 to 9 %/K, while RegCM4_MP gives smaller values of about 2 to 6%/K. RegCM4_GF is the only model showing reduced 95PC and is discarded from our analysis. The PDFs of all other models have a similar shape and peak at about 5%/K. The change of daily precipitation

extremes in JJA is also comparable to the CC relation with less regional dependence than that in MAM.

3.5 Changes in length of the dry season

Finally, in addition to the mean precipitation, the mean annual number of maximum consecutive dry days (CDD) in MME_HIST and MME_RCP8.5 are also examined. CDD was calculated by counting the maximum consecutive days with daily precipitation less than 1.0 mm/day in one year, then taking the average over the whole period. For the purpose of computing CDD, the annual period starts from 1st June to 31st May of the next year to ensure the counting period adequately covers the dry seasons of SON and DJF. MME_HIST gives a comparable length and spatial pattern of CDD with RegCM4_EA and APHRODITE (not shown), indicating the capability of the downscaled models in capturing the length of the dry period. CDD from MME_HIST and MME_RCP8.5 and their difference are shown in **Fig. 8**. CDD averaged over Southern China is about 25 to 40 days. It was found that CDD over regions south of 32°N is significantly lengthened by about 3 to 5 days, including Southern China. Robust signals of longer CDD are also captured in the raw GCM projections (not shown), which gives credence to the lengthening of the dry season in the downscaling results.

To unveil the reasons for the drying of the SON season and increase of CDD,

projected circulation changes in the region are re-examined. For the mean 850hPa wind, a strengthened northerly component covering the whole Southern China is identified in SON (see **Fig. 3c**), associated with suppressed precipitation. Here the month-to-month anomalous circulation in the South China/Western North Pacific region in the South China/Western North Pacific region from the GCMs data is further inspected. Eddy sea-level pressure (SLP*, defined as sea-level pressure deviation from the area mean over 0 – 50°N, 90 – 150°E) and 850hPa wind from the MME average of GCMs results are plotted in **Fig. 9**. Anomalous northerly is likely to related to negative SLP* to the east, at about 10 – 35°N: the projected land-sea longitudinal pressure gradient becomes more negative across coastal eastern China, resulting in stronger low-level northerly wind over Southern China and intrusion of dry air from the north. Consequently, the moisture flux convergence is reduced, causing a reduction in SON precipitation and a lengthened dry season.

The abovementioned anomalous circulation in turn is related to the northward shift of western north Pacific subtropical high (WPSH). The maximum longitudinally averaged SLP* over 20 – 40°, 150°E – 150°W, indicating the position of low-level WPSH, is found at more northern locations in GCM projections during SON (see **Fig. S11b**). This period is also the only season with significantly strengthened northerly found over Southern China (see **Fig. S11a**). It seems that WPSH tends to stay at a more

416 northern location in SON under a warmer climate before retreating equatorward,
 417 leading to anomalously low SLP* at about 20 – 25°N in the oceanic region (see **Fig.9**).
 418 For the northward shift of WPSH in SON, this could be related to the so-called tropical
 419 expansion, which has affected various general circulation elements such as the mid-
 420 latitude jet stream, Hadley circulation, and height of tropopause, based on observational
 421 or reanalysis data (Seidel et al., 2008; Lucas et al., 2014; Grise et al., 2018; Maher et
 422 al., 2020). The expansion was projected to continue in the near future based on GCM
 423 simulations under various climate forcing (Lucas et al., 2014). Barnes and Polvani
 424 (2013) conducted a study using CMIP5 model outputs and projected similar changes
 425 over the western North Pacific under RCP8.5 as well, especially in SON. Tropical
 426 expansion over the North Pacific by about 1 to 2° during SON is also found in our GCM
 427 outputs based on the longitudinally averaged near-surface zonal wind, which is an
 428 indicator for the tropical width (Davis and Birner, 2017) (see **Figs. S11c – S11e**). A
 429 similar result is found using the maximum 850hPa zonal wind as the definition of the
 430 edge of Hadley cells (Polvani et al., 2011; Davis and Rosenlof, 2012). In short,
 431 significant tropical expansion during SON is suggested to be the cause of the poleward
 432 displacement of WPSH. The northward displaced subtropical high and the low-pressure
 433 trough in the monsoon area results in the negative SLP* anomaly over the western
 434 North Pacific. It induces anomalous northerlies and brings drier climate over Southern

435 China during SON.

436 **4 Discussions and conclusion**

437 The RegCM4.6 have been used to dynamically downscale four GCMs (namely
438 ACCESS1-3, CNRM-CM5, GFDL-CM3, and MPI-ESM-MR) for the period of 1997 –
439 2003, and also for the 2050–2099 era based on RCP8.5 projection. It was found that in
440 the 2050–2099 period over the Southern China land area, surface temperature will
441 become warmer by 2 to 3 °C during MAM and JJA, and 4°C or more north of 25°N in
442 SON and DJF. Mean precipitation will increase by ~1 to 2 mm/day in the MAM and
443 JJA seasons; in SON rainfall is projected to be reduced by ~1 mm/day, while changes
444 in DJF are negligible. Interannual variations seasonal precipitation variability were also
445 investigated using a novel moisture budget analysis method. Precipitation variance in
446 MAM (JJA) over the continental Southern China was projected to increase by 15%
447 (30%) in the 2050–2099 period, according to RCP8.5. Projected changes in SON and
448 DJF were found to be rather small. From the moisture budget analysis, enhanced
449 precipitation variance in MAM can be mainly attributed to increased background
450 humidity; in JJA, stronger interannual variations in the wind circulation (hence stronger
451 moisture flux convergence) under a warmer climate was responsible for increase in the
452 precipitation variability. Besides the seasonal mean and its variations, projected
453 changes in extreme rainfall over Southern China were also examined. For MAM and

JJA, the 95th percentile of daily rainfall was found to increase by 5% per one degree of low-level tropospheric warming, which is broadly consistent with (but slightly less than) the CC relation. Signals in extreme daily rainfall changes are less regionally dependent in JJA than that in MAM.

The length of the dry season, as indicated by CDD, showed a robust increase by about 3 to 5 days in the region south of 32°N. Further investigation on the GCM outputs found that the strengthened dry northerly over East Asia due to the stronger negative pressure gradient was responsible for the drier SON. The anomalous low pressure over the western North Pacific was suggested to be the result of a northward displaced WPSH. Based on the latitudinal profile of the zonally averaged low-level wind from the GCM outputs, there was evidence showing a poleward expansion of tropics in SON over the North Pacific region. Tropical expansion was suggested to be the cause of the northward displaced WPSH and induced the strengthened northerly, which brought a drier SON climate to Southern China. Note that SON is within the TC season for Southern China. There is uncertainty in whether TC activity bias in the regional model would affect the SON rainfall projections. Further investigation is needed to ascertain how TC related rainfall over Southern China might change under a warmer climate.

We have also examined how global warming might affect the JJA diurnal rainfall (DR) cycle. Both MME_HIST and MME_RCP8.5 have a similar magnitude and pattern

473 compared to RegCM4_EA. There is no significant difference between MME_HIST and
474 MME_RCP8.5. Further investigation based on empirical orthogonal function analyses
475 and diurnal range (defined as the average maximum difference of hourly precipitation
476 rate within a day) gives the same result. Overall, the JJA DR cycle over Southern China
477 is not projected to change significantly under a warmer climate. In fact under global
478 warming, the change in land-sea temperature contrast in JJA is small (see **Fig. 3f**).
479 Given the importance of land-sea temperature contrast in determining the properties of
480 DR, this could be the reason why the change in DR is not significant.

481 More than half of the tested GCMs cannot reproduce good climate features over
482 the South China-Western North Pacific region in our CMIP5 GCM selection. The
483 performance of GCMs in simulating ENSO and monsoon variability is also generally
484 poor. Datasets of CMIP6, with an updated set of atmosphere-ocean coupled models,
485 have been available since 2019 (<https://esgf-node.llnl.gov/projects/cmip6/>, Eyring et al.,
486 2016). More realistic simulations of the global climate are expected after the
487 improvement in model physics, such as aerosol, clouds, and land-sea interaction. Future
488 works on regional climate projections in this area will be carried out by using CMIP6
489 outputs.

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749

750 **Figures**

751

752 Figure 1. Surface elevation over the Southeast and East Asian region (units: m). Domain

753 for regional climate model simulations is bounded by the red box.

754

755 Figure 2. (a, b, c) JJA and (d, e, f) DJF mean precipitation (shading; units: mm/day)
 756 based on (a, d) TRMM 3B42, (b, e) APHRODITE data and (c, f) RegCM4_EA
 757 simulations. Also shown are the corresponding seasonal mean 850hPa wind (arrows;
 758 see scale arrow in upper right, in units of ms⁻¹) based on (a, d) ERA-interim and (c, f)
 759 RegCM4_EA.

760

761 Figure 3. (a, b, c, d) Changes in mean precipitation (shading; units: mm/day) and
 762 850hPa wind (arrows; see scale arrow in upper right in units of ms^{-1}), and (e, f, g, h)
 763 850hPa temperature, for the seasons of (a, e) MAM, (b, f) JJA, (c, g) SON, and (d, h)
 764 DJF, based on the difference between MME mean RCP8.5 projections and historical
 765 runs. Only wind anomalies passing the 90% significance level are shown, while
 766 precipitation changes with the same statistical significance are indicated by dots.
 767 Signals of mean temperature changes over almost the whole domain pass the 90%
 768 confidence level. RegCM4_GF (RegCM4_AC) is excluded from the MME for JJA
 769 (SON). See text for details.

770

771 Figure 4. Same as Figs. 3a to 3d but for precipitation variance (units: $(\text{mm/day})^2$) and
 772 without 850hPa wind.

773

774 Figure 5. Changes in the (a, d) $\overline{|P'|}$, (b, e) $\overline{\hat{P}'E'}$, and (c, f) $\overline{-\hat{P}'\nabla \cdot \vec{Q}}$ terms from the
 775 modified moisture budget for interannual variability, for the seasons of (a, b, c) MAM
 776 and (d, e, f) JJA, based on the difference between MME mean RCP8.5 projections and
 777 historical runs (units: mm/day). RegCM4_GF is excluded from the MME for JJA. See
 778 text for details.

779

780 Figure 6. Differences in the (a, c) dynamical term ($\bar{q}V'$) and (b, d) thermodynamic term
 781 ($q'\bar{V}$) by decomposing the $-\overline{\hat{P}'\nabla \cdot \vec{Q}}$ term in modified moisture budget for interannual
 782 variability, for (a, b) MAM and (c, d) JJA, based on the difference between MME mean
 783 RCP8.5 projections and historical runs (units: mm/day).

784

785 Figure 7. PDF of changes in 95PC for 1°C rise in 850hPa temperature for (a) MAM and
 786 (b) JJA, by comparing RCP8.5 projections and historical simulations in the region of
 787 22 – 32°N, 110 – 120°E. See text for details.

788

789 Figure 8 – Annual mean maximum consecutive dry days (CDD) computed based on
 790 MME mean values of (a) historical runs, and (b) RCP8.5 projections. (c) Difference
 791 between (a) and (b), with changes passing the 90% significant level denoted by dots.
 792 (Units: days.)

793

794 Figure 9 – Monthly plots of eddy sea-level pressure (i.e. deviation from the area mean
 795 over 0 – 50°N, 90 – 150°E) (shading; units: hPa) and 850hPa wind (arrows; see scale
 796 arrow in upper right in units of ms^{-1}) for (a, b) September, (c, d) October, and (e, f)
 797 November, for (a, c, e) historical simulations, and (b, d, f) RCP8.5 projections minus
 798 historical runs, based on the MME mean of raw data from four selected GCMs.

799 **Tables**

800

Horizontal Grids	150 zonal × 180 meridional, $\Delta x = 25.0$ km, centered at (20°N, 120°E)
Vertical Levels	18 sigma levels
Cumulus Convective Scheme	Emanuel scheme, for both land and sea
Boundary-Layer Scheme	Holtzlag PBL (Holtzlag et al. 1990)
Ocean Flux Scheme	Zeng et al. 1998
Land Surface Processes	CLM4.5
Simulation Period	Historical: Jan 1979 to Dec 2003 (25 years) Future (RCP8.5): Jan 2050 to Dec 2099 (50 years)
Buffer Zone	12 grids

801

802 Table 1 – RegCM4 configuration used in this study.

803 **Appendix**

804 GCM selection

805 22 GCMs from the Coupled Model Intercomparison Project, Phase 5 (CMIP5)
806 (Taylor et al., 2012) were first ranked according to their performance in simulating
807 important climate variables or circulation elements over Southern China, in order to
808 select suitable models for providing ICBC for dynamical downscaling. **Tab. S1** gives
809 the analyzed CMIP5 models and reanalysis/observational data used. CMIP5 model
810 integrations from 1979 to 2005 were compared with ERA-interim Reanalysis and
811 HadISST for the same period. TRMM data for the period 1998 – 2013 was used for
812 evaluating model precipitation. Here we focus on eight circulation variables/elements
813 for evaluating the performance of CMIP5 models (see **Tab. S2**). To evaluate the model
814 outputs, spatial correlation, standard deviation, and root mean square error were
815 computed for most variables, with results summarized using Taylor diagrams (Taylor,
816 2001). For wind and temperature, most models give magnitudes comparable to those
817 from the reference data. For precipitation and some of the regression maps, because
818 some models cannot generate reasonable amplitudes/patterns, visual inspection was
819 used.

820 **Fig. S1** gives Taylor diagrams for monsoon wind climatology, 850hPa seasonal
821 mean temperature, sea-surface temperature (SST) pattern related to ENSO, and

circulation patterns related to EASM and East Asian winter monsoon (EAWM) variability. For monsoon winds (**Fig. S1a**), although their performance can vary to some extent, most models can generate a reasonable magnitude and spatial distribution. For 850hPa temperature (**Fig. S1b**), reasonable summer temperature can be captured and all models perform rather well for winter.

Summertime precipitation was examined by visual inspection based on TRMM 3B42, because most models cannot give a reasonable magnitude, especially in the coastal area in Southern China. We chose to focus on the major rain-band location and the local maximum over southeastern China as two important features. ACCESS1-3 and HadGEM2-ES give similar pattern and magnitude to TRMM, while bcc-csm1-1 and FGOALS-g2 are found to give unreasonable pattern and an unusual dry zone over Southern China.

ENSO variability was evaluated by both Taylor diagrams (SST; **Fig. S1c**) and visual inspection (focusing on low-level wind anomalies over Southern China/SCS) for DJF and MAM. Most models can reproduce a reasonable (fair) pattern of warm SST over the eastern Pacific during the positive Niño3.4 period in DJF (MAM) but with some variations in their magnitudes. However, they cannot reproduce the magnitude or pattern of the Philippine Sea anticyclone, except bcc-csm1-1-m, CNRM-CM5, and GFDL-CM3.

Monsoon variability was also examined through Taylor diagrams (**Fig. S1d and S1e**) and visual inspection. We focus on the 850hPa zonal (meridional) wind and precipitation (850hPa temperature) regressed onto the monsoon indices for summer (winter) monsoon variability (Wang and Fan, 1999; Wang and Chen, 2014). Taylor diagrams show that some models such as MIROC-ESM and MIROC-ESM-CHEM (bcc-csm1-1 and HadGEM2-ES) cannot capture the summer (winter) monsoon related circulation changes. Further evaluation through visual inspection found that more than half of the models examined can perform reasonably in simulating the monsoon variability.

By consolidating their skills in capturing these circulation elements, four models, namely ACCESS1-3, CNRM-CM5, GFDL-CM3, and MPI-ESM-MR, were found to have the best overall performance and were chosen for dynamical downscaling. Note that ACCESS1-0 was not selected in spite of its good performance; we opt to select only one model per institute for downscaling, in order to have an even sampling of model types. More details of GCM selection can be found in Liu (2020).

Supplementary Figures

Figure S1 – Taylor diagrams for examining the GCMs’ performance in (a) monsoon climatology, (b) 850hPa seasonal mean temperature, (c) SST related to ENSO variability, (d) EASM variability, and (e) EAWM variability. Please refer to text and Tabs. S1 and S2 for details.

864

865

866 Figure S2 – Taylor diagrams examining the performance of dynamical downscaling for

867 the (a, b) MAM, (c, d) JJA, (e, f) SON, and (g, h) DJF mean 850hPa (green) temperature,

868 meridional (blue) and zonal (red) wind for (a, c, e, g) historical (1979 – 2003) and (b,
869 d, f, h) RCP8.5 (2050 – 2099) simulation. So RegCM4 downscaled products, for
870 ACCESS1-3, CNRM-CM3, GFDL-CM3, and MPI-ESM-MR are labelled by 1,2,3, and
871 4, respectively. REF refers to the corresponding raw GCMs products.

872

873

874 Figure S3 – JJA historical mean (1979 – 2003) precipitation (shading, units: mm/day)
 875 and wind (arrows, units: ms⁻¹) from (a) RegCM4 downscaled results and (b) raw GCM
 876 outputs for (i) ACCESS1-3, (ii) CNRM-CM5, (iii) GFDL-CM3, and (iv) MPI-ESM-
 877 MR.

878

879

880 Figure S4 – Same as Fig. S2 but for SON.

881

882

883 Figure S5 – Precipitation (shading, units: mm/day) and 850hPa wind (arrows, units:ms⁻¹) for (a, c, e, g) MME_HIST and (b, d, f, h) MME_RCP8.5 in (a, b) MAM, (c, d) JJA,
 884 1) for (a, c, e, g) MME_HIST and (b, d, f, h) MME_RCP8.5 in (a, b) MAM, (c, d) JJA,
 885 (e, f) SON, and (g, h) DJF. RegCM4_GF(RegCM4_AC) is excluded in the JJA(SON)
 886 MME mean.

887

888 Figure S6 – Same as Fig. S4 but for 850hPa temperature (shading, units: K).

889

890

891 Figure S7 – (a, c, e, g) MME_HIST and (b, d, f, h) MME_RCP8.5 interannual seasonal
 892 precipitation variance (upper, units: $(\text{mm/day})^2$) for (a, b) MAM, (c, d) JJA, (e, f) SON,
 893 and (g, h) DJF. RegCM4_GF(RegCM4_AC) is excluded in the JJA(SON) analysis.

894

895

896 Figure S8 – Decomposed dynamical term explaining the contribution from change in
 897 (a, d) mean specific humidity ($\delta\bar{q}$), (b, e) moisture advection ($\delta(\mathbf{V}' \cdot \nabla \bar{q})$), and (c, f)
 898 anomalous wind convergence ($\delta(\nabla \cdot \mathbf{V}')$) for (a, b, c) MAM and (d, e, f) JJA, with all
 899 units converted into mm/day. RegCM4_GF is excluded in the JJA analysis. Please refer
 900 to text for details.

901

902 Figure S9 – Changes in 95PC per degree rise in 850hPa temperature (units: %/K) in (a,
 903 b, c, d) MAM and (e, f, g, h) JJA for (a, e) RegCM4_AC, (b, f) RegCM4_CN, (c, g)
 904 RegCM4_GF, and (d, h) RegCM4_MP. Results from RegCM4_GF for JJA are also
 905 shown for a reference without any further interpretation.

906

907 Figure S10 – Same as Fig. 8 but for (a, b, c, d) SON and (e, f, g, h) DJF. Results from

908 RegCM4_AC for SON are also shown for a reference without any further interpretation.

909

910

911 Figure S11 – Monthly mean of (a) area-averaged 850hPa meridional wind (units: ms^{-1})
 912 over Southern China (20 – 35°N, 115 – 125°E) and (b) latitude with maximum zonally
 913 averaged SLP* over the western and central North Pacific (20 – 40°N, 150°E – 150°W)
 914 from the MME mean of GCMs for (solid blue line) historical runs and (dash red line)
 915 RCP8.5. (c – d) are monthly mean longitudinally averaged 1000hPa zonal wind over
 916 150°E – 150°W from the MME mean of GCMs for (solid blue line) historical runs and
 917 (dash red line) RCP8.5 for (a) September, (b) October, and (c) November.

Model Number	Acronym of Model	Modeling Center/Institute
1	ACCESS1-0	Commonwealth Scientific and Industrial
2	ACCESS1-3	Research Organization and the Bureau of Meteorology, Australia
3	bcc-csm1-1	Beijing Climate Center (BCC), Yunnan
4	bcc-csm1-1-m	University, and China Meteorological Administration
5	CanESM2	Canadian Centre for Climate Modelling and Analysis
6	CMCC-CM	Euro-Mediterranean Center on Climate Change, Italy
7	CNRM-CM5	National Centre for Meteorological Research, France
8	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization and Queensland Climate Change Centre of Excellence, Australia
9	FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
10	GFDL-CM3	NOAA Geophysical Fluid Dynamics
11	GFDL-ESM2G	Laboratory, USA

12	GFDL-ESM2M	
13	HadGEM2-ES	Met Office Hadley Center, UK
14	IPSL-CM5A-LR	Institut Pierre Simon Laplace, France
15	IPSL-CM5A-MR	
16	IPSL-CM5B-LR	
17	MIROC5	Japan Agency for Marine-Earth Science and
18	MIROC-ESM	Technology, Atmosphere and Ocean
19	MIROC-ESM- CHEM	Research Institute (The University of Tokyo), and the National Institute for Environmental Studies
20	MPI-ESM-MR	Max Planck Institute for Meteorology, Germany
21	MRI-CGCM3	Meteorological Research Institute, Japan
22	NorESM1-M	Norwegian Climate Center, Norway

Observational/Reanalysis Data

ERA-interim (1979 – 2005)	European Centre for Medium-Range Weather Forecasts (ECMWF)
TRMM 3B42 (1998– 2013)	NASA and the Japan Aerospace

Exploration Agency	
HadISST (1979 – 2005)	Met Office Hadley Center, UK
Global Precipitation Climatology Project (GPCP) (1979 – 2005)	World Climate Research Programme (WCRP)

918

919 Table S1 – CMIP5 models with their corresponding model number and also the
920 reference datasets. Most reference variables are from the reanalysis data from ERA-
921 interim (1979 – 2005), except for precipitation which is taken from TRMM (1998 –
922 2013) and GPCP (1979 – 2005), and the sea surface temperature from HadISST (1979
923 – 2005). Selected models for dynamical downscaling are highlight by blue color.

Circulation variables/elements	Method
1. Summer Monsoon	Taylor diagram of 850hPa JJA u-wind over (5-25°N, 90-130°E)
2. Winter Monsoon	Taylor diagram of 850hPa DJF v-wind over (25-50°N, 110-140°E)
3. Summer Temperature	Taylor diagram of 850hPa JJA temperature over the domain of interest
4. Winter Temperature	Taylor diagram of 850hPa DJF temperature over the domain of interest
5. Summer Precipitation	Visual inspection (5-25°N, 90-140°E)*
6. ENSO Variability	Taylor diagram & visual inspection of regressed DJF & MAM 850hPa wind & SST on Niño3.4 index*
7. Summer Monsoon Variability	Taylor diagram & visual inspection of regressed 850hPa wind & precipitation on EASM index**
8. Winter Monsoon Variability	Taylor diagram & visual inspection of regressed 850hPa wind & precipitation on EAWM index*

#: GPCP dataset is used such that the reference data and model simulations cover the same period.

*: Please refer to the text and Liu (2020) for the algorithm to examine the performance of these variables.

Table S2 – The summary of eight circulation variables/elements examined in CMIP5 models and the corresponding testing methods.