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1 **Future Climate Change Enhances Rainfall Seasonality**
2 **in a Regional Model of Western Maritime Continent**

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1 **Abstract**

2 In this study, future changes in rainfall due to global climate change are investigated over
3 the western Maritime Continent based on dynamically downscaled climate projections using
4 the MIT Regional Climate Model (MRCM) with 12 km horizontal resolution. A total of nine
5 30-year regional climate projections driven by multi-GCMs projections (CCSM4, MPI-ESM-
6 MR and ACCESS1.0) under multi-scenarios of greenhouse gases emissions (Historical:
7 1976-2005, RCP4.5 and RCP8.5: 2071-2100) from phase 5 of the Coupled Model Inter-
8 comparison Project (CMIP5) are analyzed. Focusing on dynamically downscaled rainfall
9 fields, the associated systematic biases originating from GCM and MRCM are removed
10 based on observations using Parametric Quantile Mapping method in order to enhance the
11 reliability of future projections. The MRCM simulations with bias correction capture the
12 spatial patterns of seasonal rainfall as well as the frequency distribution of daily rainfall.
13 Based on projected rainfall changes under both RCP4.5 and RCP8.5 scenarios, the ensemble
14 of MRCM simulations project a significant decrease in rainfall over the western Maritime
15 Continent during the inter-monsoon periods while the change in rainfall is not relevant during
16 wet season. The main mechanism behind the simulated decrease in rainfall is rooted in
17 asymmetries of the projected changes in seasonal dynamics of the meridional circulation
18 along different latitudes. The sinking motion, which is marginally positioned in the reference
19 simulation, is enhanced and expanded under global climate change, particularly in RCP8.5
20 scenario during boreal fall season. The projected enhancement of rainfall seasonality over the
21 western Maritime Continent suggests increased risk of water stress for natural ecosystems as
22 well as man-made water resources reservoirs.

23

24

1 **1. Introduction**

2 Rainfall over the Maritime Continent reflects a set of complex non-linear processes,
3 which are acting on different spatial and temporal scales. On the large-scale and low-
4 frequency modes, the Maritime Continent is significantly influenced by the inter-annual
5 variability associated with Indian Ocean Dipole (IOD) and El-Nino Southern Oscillation
6 (ENSO) (Ashok et al. 2001; Wang et al. 2003; Chang et al. 2004; Juneng and Tangang 2005;
7 Tangang et al. 2012; Salimun et al. 2014, 2015), the Hadley and Walker circulations (Neale
8 and Slingo 2003), and the Asian-Australian monsoon system through teleconnections (Chang
9 et al. 2005; Moron et al. 2009; Robertson et al. 2011; Juneng and Tangang 2010; Tangang et
10 al. 2012). On the other end, the convective activities at the local and regional scales generated
11 by the orography and sea-breeze convergence also play a critical role in shaping the mean
12 climate over the Maritime Continent through the modulation of the diurnal variation of
13 rainfall (Neale and Slingo 2003; Qian 2008; Im and Eltahir 2017).

14 The limited accuracy of climate models, their inability to resolve multi-scale phenomena
15 and their interactions, and the insufficient level of our current understanding of the associated
16 physical processes result in a high level of uncertainty regarding future changes in rainfall
17 over the Maritime Continent. The Working Group I for the Fifth Assessment Report (AR5) of
18 the Intergovernmental Panel on Climate Change (IPCC) (Christensen et al. 2013) assessed
19 future changes in rainfall on the basis of global climate models (GCMs) projections under
20 Representative Concentration Pathways (RCPs) emission scenarios, participating in Coupled
21 Model Intercomparison Project Phase 5 (CMIP5, Taylor et al. 2012). For the western
22 Maritime Continent (defined here as 10° S to 8° N, and 95° E to 120° E), the projected
23 changes in rainfall exhibit a mixed signal with both increasing and decreasing patterns. More
24 importantly, most of regions around the western Maritime Continent suffer from the lack of

1 inter-model agreement: there are little robust patterns of future rainfall projections in either
2 change sign (e.g. increase or decrease) or magnitude (e.g. strong or weak) under global
3 climate change.

4 GCMs reveal significant deficiency in simulating key climate features over the Maritime
5 Continent. More precise representation of land-sea distribution and complex topography can
6 improve climate simulations over the Maritime Continent (e.g. Arakawa and Kitoh 2005;
7 Schiemann et al. 2014). Large-scale circulations and variability (e.g. ENSO) play an
8 important role in shaping the main pattern and variability in the climate of the Maritime
9 Continent. However, GCMs seem to perform poorly in simulating the climate of this region.
10 Previous studies have showed that GCMs are not accurate enough in simulating the detailed
11 characteristics of rainfall over the Maritime Continent (Zhou and Wang 2006; Qian 2008;
12 Ploshay and Lau 2010; Love et al. 2011) mainly due to their coarse resolution. The typical
13 horizontal resolution of more than 100 km is not suitable to resolve the distinct geography of
14 the region, which features several land masses with steep topography (e.g. Malay Peninsula,
15 Sumatra, Borneo and Java islands), surrounded by warm and shallow ocean water. In
16 particular, GCMs reveal their deficiencies in the simulation of convective processes varying
17 diurnally and regionally, which in turn induce substantial errors in the propagation of the
18 diurnal phase and amplitude of the rainfall that are critical for determining the mean climate
19 over the Maritime continent.

20 Regional climate models (RCMs) are useful tools for improving the simulation of rainfall
21 climatology in terms of daily or sub-daily characteristics at the local and regional scales. A
22 significant body of research has demonstrated the positive impact of higher resolution on
23 rainfall simulations such as diurnal variation and extremes based on the climate modeling
24 studies (Liang et al. 2004; Ploshay and Lau 2010; Love et al. 2011; Peatman et al. 2015; Im

1 and Eltahir 2017). In particular, Im and Eltahir (2017) stress that a realistic coastline and a
2 sharp gradient of elevation, as captured by a high resolution grid system, would enhance the
3 local circulation associated with land-sea breeze and topographic complexity, and hence bring
4 more physical realism to representation of rainfall formation within models.

5 In this study, we project future changes in rainfall under global climate change over the
6 western Maritime Continent using the latest version of the Massachusetts Institute of
7 Technology (MIT) regional climate model (MRCM) that has been tested by previous studies
8 in its ability to simulate rainfall characteristics including time-mean fields as well as diurnal
9 variation over this region (Im and Eltahir 2017). Significant efforts to produce high resolution
10 climate projections have been recently made based on the dynamical downscaling using
11 RCMs within the well-coordinated framework (e.g. Coordinated Regional Climate
12 Downscaling Experiment, CORDEX; Giorgi et al. 2012). However, this research effort
13 mostly targeted North America, Africa, Europe and East Asia (Giorgi et al. 2012; Vautard et
14 al. 2013; Lucas-Picher et al. 2013; Mariotti et al. 2014; Park et al. 2016), but not the Maritime
15 Continent. There are a few studies that attempted to generate the dynamically-downscaled
16 future climate information over some regions included in the Maritime Continent based on
17 the IPCC Fourth Assessment Report (AR4) framework (e.g. global projections participating
18 in the CMIP3 project and the Special Report on Emissions Scenarios [SRES] emission
19 scenarios). For instance, Loh et al. (2016) projected the weakening of the monsoon trough
20 during the boreal winter and spring seasons, which results in drier and warmer climate over
21 northern Borneo and Malaysia Peninsula under both high and low level emission scenarios
22 (e.g. SRES A2 and B2). On contrary, Chotamonsak et al. (2011) showed that northern Borneo
23 and Singapore will experience substantial increase of rainfall in winter under the middle level
24 of emission scenario (e.g. SRES A1B). This contrast in past research results suggests great

1 uncertainty still exists, inviting further systematic investigations. In addition, it is necessary
2 to update our experimental protocols to reflect the latest progress (e.g. CMIP5 global
3 projection and RCP emission scenarios).

4 Here, we perform the dynamical downscaling of CMIP5 projections forced by RCP4.5
5 and RCP8.5 emission scenarios using MRCM. For ensemble regional projections, we
6 generate three MRCM projections driven by three different GCMs that are carefully selected
7 through a rigorous evaluation of their reference simulations (see section 2.3). Also, the mean
8 biases of MRCM simulations are statistically corrected at the daily time-scale using the
9 Parametric Quantile Mapping method (see section 2.4). To the best of our knowledge, there is
10 minimal literature on ensemble regional projections targeted at the western Maritime
11 Continent, taking multi-GCMs and multi-scenarios into consideration within the IPCC AR5
12 framework. Therefore, the updated assessment presented in this study can provide an
13 opportunity not only to fill the gap of climate change research over this region but also to
14 build on previous findings and progress achieved by other research groups.

15

16 **2. Model description and Experimental Design**

17 **2.1 The MIT Regional Climate Model**

18 MRCM (Im et al. 2014) used for the dynamical downscaling in this study is based on
19 ICTP-Regional Climate Model Version 3 (RegCM3, Pal et al. 2007) but with several
20 improvements, including coupling to the Integrated Biosphere Simulator (IBIS) land surface
21 scheme (Winter et al. 2009), new surface albedo assignment (Marcella and Eltahir, 2012),
22 modified boundary layer height and boundary layer cloud scheme (Gianotti 2012), irrigation
23 scheme (Marcella and Eltahir 2014), new convective cloud scheme (Gianotti and Eltahir
24 2014a) and new convective rainfall autoconversion scheme (Gianotti and Eltahir 2014b). As a

1 result of such efforts that incorporate new physical schemes or modify original schemes,
2 MRCM showed comparable or better performance in simulating key climate features across
3 various regions (e.g., North America, West Africa, Southwest Asia, Maritime Continent)
4 compared to other regional climate models (Winter et al. 2009; Im et al. 2014; Marcella and
5 Eltahir, 2012; Gianotti and Eltahir 2014a; Gianotti and Eltahir 2014b; Im and Eltahir 2017).
6 Furthermore, Im and Eltahir (2017) demonstrate that enhanced horizontal resolution can
7 contribute to a better capability of MRCM by comparing the results from different resolutions
8 (27 km vs. 12 km) that are performed under the same model configuration except for the
9 horizontal resolution. On the basis of the improved performance of MRCM with 12 km
10 horizontal resolution over the western Maritime Continent, we adopt the same version of
11 MRCM used in Im and Eltahir (2017).

12

13 **2.2 Experimental design**

14 The MRCM domain covers the western Maritime Continent with 240 x 172 grids,
15 centered at 0.8°S, 107°E. The horizontal resolution is 12 km which is fine enough to represent
16 geographical complexity (Fig. 1). For detailed characterization of rainfall across
17 geographically diverse regions, the land area within our domain is divided into **nine sub-**
18 **region.**

19 **In particular, Peninsula Malaysia is divided into two sub-region (west and east) while Borneo**
20 **Island is divided into three sub-region (northwest, northeast, and south), based on previous**
21 **studies that have emphasized distinct local rainfall patterns over the Maritime Continent**
22 **(Aldrian and Susanto 2003; Tangang et al. 2008; Chen et al. 2013a; Loh et al. 2016; Juneng et**
23 **al. 2016; Cruz et al. 2017). The longitude and latitude ranges for each sub-region are as**
24 **follows; A: 114.3°E-119.3°E, 1.2°N-7.5°N (Borneo-Northeast), B: 108.5°E-114.3°E, 1.2°N-**

1 7.5°N (Borneo-Northwest), C: 108.5°E-119.3°E, 4.5°S-1.2°N (Borneo-South), D: 102°E-
2 104.5°E, 1°N-5.7°N (Peninsula Malaysia-East), E: 100°E-102°E, 1°N-5.7°N (Peninsula
3 Malaysia-West), F: 103.6°E -104.1°E, 1.18°N -1.48°N (Singapore), G: 95°E-104.5°E, 0°-6°N
4 (Sumatra-North), H: 95°E-106.3°E, 6°S-0° (Sumatra-South), and I: 105°E-115.9°E, 9°S-5.7°S
5 (Java).

6 For the initial and boundary conditions that are prescribed for MRCM, the output
7 representing atmospheric conditions every 6-hour simulated by three selected GCMs are
8 downloaded from the CMIP5 data archives. CMIP5 global projections are generated by fully
9 coupled Atmosphere-Ocean GCMs. The reference simulation corresponds to a “historical”
10 run in CMIP5 label, not “historicalNat” and “historicalGHG” which represent the historical
11 simulation but with natural forcing only and historical simulation but with greenhouse gas
12 (GHG) forcing only, respectively (Taylor et al. 2012). Therefore, the CMIP5 global
13 projections include not only the responses to anthropogenic forcings but also natural forcings.

14 While the reference simulation (1975-2005) is forced by historical GHGs concentration, two
15 future projections (2070-2100) are forced by the Representative Concentration Pathway
16 (RCP)4.5 and RCP8.5, corresponding to a medium-mitigation and business-as-usual emission
17 scenarios (Moss et al. 2010). Therefore, a total of nine GCM projections are dynamically
18 downscaled using the MRCM. The first year of MRCM simulations in both the reference and
19 future periods has been discarded in the analysis as a spin-up period. The methodology for
20 the selection of three GCMs is described in detail in Section 2.3.

22 **2.3 GCMs selection**

23 The suitable GCMs that are used to drive MRCM are selected among the CMIP5
24 participant models through the following steps.

1 1) We first select 19 models out of 28 CMIP5 GCMs which are able to capture the
2 significant climate features over the region of Southeast Asia including the Maritime
3 Continent based on the analysis of McSweeney et al. (2015a). Their study systematically
4 evaluates GCMs that participated in CMIP5, and provides overall performance metrics over
5 the continental-scale regions such as Southeast Asia, Europe and Africa.

6 2) We exclude the GCMs with relatively coarser horizontal resolution, such as atmospheric
7 and oceanic component models coarser than 2° and 1.2° resolution, respectively. Through this
8 criteria, we select six GCMs from the **first 19 selected** GCMs.

9 3) The reference simulations from the selected six GCMs are evaluated over the western
10 Maritime Continent focusing on the relevant features of specific interest in this study. More
11 specifically, the performances of how reasonably the models simulate rainfall, temperature,
12 wet-bulb temperature, and humidity are assessed in terms of spatial pattern, normalized root
13 mean square error (NRMSE) and annual cycle over land and ocean, by comparing them with
14 Climatic Research Unit (CRU: Harris et al. 2014) and ERA Interim Reanalysis (ERA-Interim:
15 Dee et al. 2011) data.

16 As a result of the screening process described above, three GCMs are finally selected:
17 Community Climate System Model Version 4 (CCSM4), Australian Community Climate and
18 Earth System Simulator Version 1.0 (ACCESS1.0) and Max-Planck-Institution Earth System
19 Model running on Medium Resolution grid (MPI-ESM-MR). More information about these
20 GCMs is presented in Table 1.

21

22 **2.4 Statistical bias correction**

23 The results simulated by any regional climate model may contain a systematic bias
24 arising from lateral boundary conditions (i.e., global climate model) as well as imperfect

1 RCM physics (Liang et al. 2008; Ehret et al. 2012). To enhance the reliability of future
2 climate projections, a statistical bias correction method is applied involving the assumption
3 that the bias in the reference simulation remains the same in the future projections. In case
4 of the rainfall, a Parametric Quantile Mapping (PQM) is commonly used and it can
5 effectively remove the systematic bias based on the assumption that both observed and
6 simulated rainfall intensity distributions are well approximated by the gamma distribution
7 (Piani et al. 2010). Here, we apply the PQM for bias correction of simulated daily rainfall. In
8 doing this, the cumulative frequency distributions for the modeled and observed daily rainfall
9 are calculated for each month from January to December, and simulated distribution is then
10 fitted to observed one by matching the cumulative quantiles. As for the observational data, we
11 use the Tropical Rainfall Measuring Mission (TRMM) 3B42 Version 7 (Huffman and Bolvin,
12 2012) products. Since TRMM data is not available during the same period of reference
13 simulations, 18-year (1998-2015) climatological features are compared with both GCM and
14 MRCM simulations based on 30-year (1976-2005) climatology. To facilitate the direct
15 comparison with MRCM results, TRMM data with $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution is
16 aggregated into the MRCM grid (12 km).

17

18 **2.5 Estimation of rainfall seasonality**

19 To quantitatively estimate the changes in seasonal variation of rainfall, we use a simple
20 index (\mathbf{S}) that describes the rainfall seasonality as follows. \mathbf{S} is the rainfall difference between
21 the months with maximum and minimum monthly rainfall normalized by average monthly
22 rainfall. \mathbf{S} is helpful in assessing the seasonality in rainfall amounts between dry and wet
23 seasons, presented in dimensionless form.

$$24 \quad \mathbf{S} = (R_{\max} - R_{\min}) / R_{\text{mean}}$$

1 Where, R_{mean} is average monthly rainfall, and R_{max} and R_{min} are the maximum and
2 minimum monthly rainfall during the year, respectively.

3. Results

3.1 Verification of MRCM simulation with bias correction

6 The evaluation of the MRCM performance is an essential prerequisite to ensure the
7 reliability of future projections. Prior to downscaling of “non-perfect” GCM boundary
8 conditions, Im and Eltahir (2017) performed the dynamical downscaling of the ERA Interim
9 reanalysis data using MRCM, so-called “perfect boundary condition” experiment, and
10 demonstrated a reasonable performance of MRCM in simulating the spatial and temporal
11 structure of rainfall for present-day conditions, based on the analysis of 30-year (1982-2011)
12 climatological statistics. We then perform climate change experiments using the same version
13 of MRCM, but driven with three different GCMs. Prior to the analysis of future changes, we
14 examine 1) whether dynamically downscaled MRCM results provide the added value over
15 driving GCM, and 2) whether PQM applied for the bias correction step improves the results
16 by effectively removing the systematic bias.

17 Figure 2 presents the spatial distributions of climatological rainfall averaged over wet
18 (November-December-January: NDJ) and dry (May-June-July: MJJ) seasons as well as inter-
19 monsoon (February-March-April: FMA, August-September-October: ASO) seasons. These
20 months are chosen based on the annual cycle of rainfall around the center of the region, near
21 Singapore. For example, NDJ typically receives the largest seasonal and daily totals of
22 rainfall in Singapore and neighboring islands of Indonesia and Borneo (McSweeney et al.
23 2015b). Model results are displayed as the ensemble mean based on the arithmetic average of
24 three different members. MRCM ensemble mean with and without bias correction are

1 denoted as MRCM_BC and MRCM hereafter. First of all, the added value of MRCM over
2 GCM can be found in the pattern of seasonal variation. Since GCM overestimates rainfall
3 during dry season (MJJ) but underestimates it during the wet season (NDJ), its seasonal
4 variation is much smaller than that of TRMM. On the other hand, MRCM captures the
5 seasonal variation with similar relative magnitudes to TRMM in spite of underestimation of
6 the rainfall for both seasons. This behavior is quantitatively described by the area-averaged
7 rainfall over land as indicated by Fig. 2. In addition to the improved seasonal variation, the
8 spatial details captured by higher resolution can contribute to the enhancement of the added
9 value of downscaled MRCM results. In Malay Peninsula, the area emerging with stronger
10 rainfall in ASO and reaching the peak in NDJ is only captured in MRCM, not GCM ENS.
11 However, MRCM produces excessive rainfall along the high mountainous region, which does
12 not appear in TRMM observed pattern. This problematic feature of MRCM can be interpreted
13 as the typical error simulated by other high resolution RCMs (Solman et al. 2008; Gianotti
14 2012). Alternatively, this discrepancy between MRCM and TRMM can partly be due to
15 observational under-sampling where short-lived intensive rainfall could have been missed by
16 the 3-hourly sampling period of 3B42 TRMM observation (Teo et al. 2011). Once PQM is
17 applied to MRCM, the deficiency of MRCM raw data can be statistically corrected,
18 suggesting the effectiveness and usefulness of PQM in correcting the systematic bias in
19 rainfall simulations. By comparison with MRCM, MRCM_BC is in better agreement with
20 TRMM in terms of the spatial distribution and area-averaged rainfall over land, which is to be
21 expected.

22 Figure 3 shows the annual cycle of area-averaged rainfall over whole land domain. Both
23 GCM and MRCM fail to capture a bimodal distribution with two asymmetric peaks
24 characterized by the observed pattern in TRMM. Furthermore, GCM shows much smaller

1 seasonality than that of TRMM because GCM overestimates rainfall from May to September
2 but underestimates it from October to April. The improvement of MRCM is found in the
3 seasonality, bringing it closer to TRMM. MRCM_BC tends to enhance the maximum rainfall
4 amount, but to be less effective in correcting qualitative aspects (e.g. bimodal structure). In
5 contrast this limited accuracy in terms of the gross pattern averaged over whole land area,
6 MRCM_BC demonstrates encouraging performance in simulating the annual cycle and peak
7 timing of rainfall averaged over nine sub-region (see the explanation in Fig. 5).

8 In order to examine the daily statistics of rainfall at local scale, we compare the frequency
9 distribution of daily rainfall at Changi (located in Singapore) and Malacca (located in
10 Peninsula Malaysia) stations (Fig. 4). For this analysis, in-situ observations at the Changi
11 (1.35°N, 103.99°E) and Malacca (2.26°N, 102.25°E) stations are obtained from the Integrated
12 Surface Database (Smith et al. 2011). To avoid large number of missing values included in
13 Malacca station data, the analysis period is limited to the recent 15-year (2001-2015) in terms
14 of the station and TRMM data. To facilitate the comparison, MRCM data is exacted for the
15 last 15-year of reference simulation (1991-2005) at the grid points closest to the stations. For
16 both stations, the shape of distribution is noticeably different between wet (e.g. NDJ) and dry
17 (e.g. MJJ) seasons. The frequency of daily rainfall in wet season decreases more slowly as the
18 intensity increases with a long tail. In general, MRCM is capable of reproducing the
19 frequency distribution characteristics, corresponding to the wet and dry seasons. However, its
20 accuracy is limited when looking into quantitative aspect. MRCM tends to underestimate
21 rainfall in the range of the low to mid-intensities, but produces unrealistically extreme rainfall
22 such as 200 mm/day that is absent in TRMM observation. The PQM application brings
23 positive effects, reducing the errors that appeared in MRCM distribution. MRCM_BC shows
24 a substantial improvement not only in mean value but also 95% and 99% level. However,

1 MRCM_BC still retain significant errors in very extreme cases such as over 100 mm/day for
2 dry season and over 200 mm/day for wet season at Changi station. By comparing the
3 characteristics of distribution at both stations, daily rainfall at Changi station shows the larger
4 seasonality than that at Malacca with higher mean and extremes values (e.g. 95% and 99%).
5 MRCM_BC exhibits a skill in simulating these qualitative aspects, in spite of some
6 quantitative discrepancies.

7 In summary, MRCM_BC shows reasonable performance in capturing seasonally varying
8 patterns with respect to their spatial distributions, and also in capturing daily statistics. In the
9 next section, we focus on the future projections of rainfall under the RCP4.5 and RCP8.5
10 scenarios.

11

12 **3.2 Future changes in rainfall and related circulation patterns**

13 In this section, we investigate the future rainfall projections derived from the ensemble
14 mean of MRCM simulations forced by three GCM projections. The same bias-correction
15 factors derived from the reference simulation are applied to the RCP future projections, under
16 the assumption of “stationarity” implying that systematic bias does not change with time.
17 Future changes are calculated by the difference between reference simulation (1976–2005,
18 referred to REF) and two future projections (2071–2100) under the RCP4.5 and RCP8.5
19 emission scenarios (referred to RCP4.5 and RCP8.5).

20 Figure 5 presents the annual cycle of area-averaged rainfall across all nine sub-region
21 depicted in Fig. 1. To investigate the MRCM_BC performance of how it reasonably captures
22 the region-specific characteristics, the degree of accuracy in simulating peak timing and
23 seasonality across different regions is evaluated against TRMM climatology. In general, REF
24 is able to capture the distinct features of the annual cycle of rainfall varying from region to

1 region due to unique geographical properties (Aldrian and Susanto 2003). For example,
2 Peninsular Malaysia is characterized by substantial difference in rainfall pattern between
3 western and eastern parts (Tangang et al. 2008, 2017; Chen et al. 2013a,b; Loh et al. 2016;
4 Jamaluddin et al. 2017). Loh et al. (2016) demonstrated that it is difficult for climate models
5 to accurately reproduce the peak timing in the annual cycle of rainfall over east coast of
6 Peninsular Malaysia. REF, simulated using high-resolution and well-optimized MRCM,
7 apparently differentiates region-specific patterns between western and eastern parts of
8 Peninsular Malaysia, in particular capturing the exact timing of maximum rainfall (e.g.
9 December) over east coast. More importantly, comparing rainfall averaged over east coast of
10 Peninsular Malaysia and northern Borneo (both northeast and northwest) further supports the
11 reasonable performance of MRCM_BC. REF is in a good agreement with TRMM,
12 reproducing the different timing characterizing the maximum rainfall over these regions,
13 being delayed by one month in northern Borneo compared to east coast of Peninsular
14 Malaysia. These results are in line with the results presented in Chen et al. (2013a) that
15 emphasized the different mechanisms of rainfall formation based on the comprehensive
16 analysis of various observational dataset. While relatively earlier peak of rainfall in east coast
17 of Peninsular Malaysia is mainly due to the cold surges vortex and heavy rainfall propagating
18 from the Philippine area and Borneo, the major course of the rainfall maximum in northern
19 Borneo is rain-producing disturbance from South China Sea (Tangang et al. 2008, 2017;
20 Chen et al. 2013a,b). A detailed investigation of rainfall formation mechanisms across
21 different regions is beyond the scope of this study, but the fact that REF is able to capture
22 these regional-dependent features implicitly supports the sound physical basis of MRCM and
23 the added value of dynamical downscaling using the high-resolution RCM. REF also shows a
24 skill in capturing the different characteristics of annual cycle of rainfall between northwest

1 and northeast Borneo, similar to TRMM. Rainfall pattern averaged over northwest Borneo
2 shows the strong seasonal variation with the peak value reaching up to 15 mm/day, whereas
3 there is weak seasonality in northeast Borneo. For other regions, the maximum rainfall peak
4 appears to be later in Southern Sumatra and Java located at the south of equator, compared to
5 Singapore near equator.

6 Moving to future rainfall changes, the differences (% , color bars in lower panel) between
7 REF and RCP4.5 or RCP8.5 are also presented in Fig. 5 to quantitatively describe the change
8 in rainfall under climate change conditions with respect to REF. A two-tailed Student's t test
9 is performed for the statistical significance of future changes against REF (2071–2100
10 relative to 1976–2005). Black dots above color bars in Fig. 5 indicate that rainfall changes are
11 statistically significant at the 95% level. In addition to the typical statistical significance test,
12 the consistency among the different ensemble members is also assessed. The asterisk above
13 bar indicates that the rainfall changes from the three MRCM members all have the same sign
14 of increase or decrease, and hence future change seems to be robust behavior in response to
15 rising concentrations of CO₂ independent of the selected GCM boundary forcing.

16 For future rainfall changes, the most consistent pattern appearing in many regions, except
17 for northern Borneo (Fig. 5a-b) regions, is the predominant decreases in rainfall during inter-
18 monsoon seasons, such as August-September-October (ASO, from boreal summer monsoon
19 to boreal winter monsoon) and February-March-April (FMA, from boreal winter monsoon to
20 boreal summer monsoon). This decreasing signal seems to be stronger in RCP8.5 than in
21 RCP4.5 and is not a random feature appearing in a certain simulation driven by a specific
22 GCM, but rather a robust pattern seen in all members driven by the three different GCMs. In
23 addition, a majority of decreasing signal also satisfy the statistical significance at the 95%
24 confidence level. This implies that the forced signal (e.g. rainfall decrease) in response to the

1 RCP scenarios seems to overwhelm the internal variability (i.e., inter-annual and inter-
2 decadal variability). On the other hand, the increasing rainfall feature appears intermittently,
3 but its magnitude is not high and robustness in terms of statistical significance and model
4 agreement is also very limited. More importantly, the change in rainfall along the annual
5 cycle tends to be sensitive to latitudinal location of landmasses. While western part of
6 Peninsula Malaysia and northern Sumatra exhibit a significant decrease in rainfall from
7 February to April (e.g. boreal spring), southern Borneo, eastern part of Peninsula Malaysia,
8 southern Sumatra and Java undergo much stronger decrease in rainfall from August and
9 October (e.g. boreal fall). Interestingly, Singapore near the equator shows the decreasing
10 rainfall signal in both boreal spring and fall seasons. Slight increase or no changes in rainfall
11 during the wet season but significant decreases in rainfall during the inter-monsoon seasons
12 result in the intensification of rainfall seasonality. Table 2 clearly shows this pattern of change
13 in a quantitative manner. For the REF, eastern part of Peninsula Malaysia and Java show high
14 seasonality due to a large difference between rainfall minima and maxima, implying a
15 challenge in water reservoirs management. Furthermore, accelerated GHG concentration
16 described by RCP8.5 emission scenario leads to more pronounced challenges of water stress
17 in natural ecosystems, and water management in man-made systems. Except for Northern
18 Sumatra, all other regions are projected to confront intensified seasonality of rainfall and the
19 resultant water stress in warmer climates.

20 To gain insight into the mechanism behind rainfall changes, we need to understand the
21 asymmetric behavior within the annual cycle and along latitudinal locations. For further
22 details of the characteristics of rainfall changes, we present the latitude-time cross section of
23 zonally averaged (from 95°E to 119°E) total rainfall as well as convective and large-scale
24 (non-convective) rainfall (Fig. 6). For the purpose of assessing the consistency among the

1 MRCM_BC results driven by the three different GCMs, a perfect agreement between the
2 three members in terms of the direction of the projected change are illustrated in stippling for
3 each grid point.

4 Based on this analysis, the relative role of convective and large-scale rainfall in determining
5 the changes in total rainfall can be identified. The most striking feature in both RCP4.5 and
6 RCP8.5 is a remarkable decrease in total rainfall at the south of equator from August to
7 October, which is attributed to the decreases in both convective and large-scale rainfall. In the
8 case of RCP4.5, the increases in large-scale rainfall appear along the whole latitudinal band,
9 but with no consistency among different three projections.

10 In the following, we focus on the detailed regional patterns and different behaviors of
11 rainfall changes for wet season (NDJ) and inter-monsoon seasons (ASO and FMA). Figure 7
12 presents the spatial distribution of rainfall changes for wet season. The ensembles of
13 projections from the GCMs and MRCM_BC are presented with the same format in order to
14 compare the large-scale patterns between MRCM_BC projections and driving GCMs.
15 Stippling marked for each grid point indicates the model agreement. It supports the
16 robustness of the conclusion that enhanced GHGs forcing can trigger a common response,
17 with the same direction of change, in the three different GCMs. Consistent with the latitude-
18 time cross section seen in Fig. 6, RCP4.5 projection shows that most regions are prone to
19 increase in rainfall. Although there are some regions where three ensembles members all
20 produce a consistent change signal of rainfall increase, other regions suffer from a lack of
21 models agreement with relatively weak magnitudes of changes. For RCP8.5 projection,
22 MRCM_BC shows quite mixed signals for the rainfall change.

23 Figures 8 and 9 present the spatial distribution of rainfall changes during inter-monsoon
24 transitional seasons (ASO and FMA) and the dominance of rainfall decrease is clearly

1 contrasted with rainfall changes for wet monsoon season. By comparing GCM projections
2 between ASO and FMA, the increasing or decreasing sign of rainfall changes are flipped
3 roughly along the equator, with very different magnitudes of the change. MRCM_BC shows
4 a tendency to follow the GCM patterns, but exhibits more extended area with decrease in
5 rainfall. MRCM seems to amplify the physical processes that lead to the favorable condition
6 for rainfall inhibition under global warming (see the explanation in Figs. 10 and 11).
7 Although there is clear signal of rainfall decrease, the magnitude of change is significantly
8 less in FMA than in ASO, supporting asymmetric pattern of rainfall changes within the
9 annual cycle as seen in Figs. 5 and 6.

10 This reversed and asymmetric pattern can be partly explained by the dynamic components
11 describing atmospheric vertical motion. Figures 10 and 11 present the omega (p velocity) for
12 the REF and its future changes under RCP4.5 and RCP8.5 scenarios. For the REF of ASO,
13 rising branches broadly occupied the whole northern part of the domain and sinking motion at
14 the edge of southern boundary maintaining a meridional overturning circulation. As the
15 seasons progress to FMA, the ascendance region and subsidence region are switched, leading
16 to reversed circulation. An important point is that the strength of circulation in ASO is not
17 held during FMA. Asymmetry of the seasonal march between boreal fall and boreal spring is
18 attributed to the distribution of lower boundary between land and ocean and the differences
19 between land and ocean in their thermal memories (Chang et al. 2005). The strength of
20 circulation for REF is likely to determine the degree of future changes in response to rising
21 concentration of GHGs. For RCP8.5 projection during ASO, the emergence of strong positive
22 anomaly of omega is consistent with a large decrease of rainfall, particularly south of equator.
23 By comparison, the change in omega is less relevant during FMA, again matching the rainfall
24 change pattern. Back to the comparison of rainfall changes between MRCM_BC projections

1 and driving GCM projections, the decreases in rainfall are more significant in MRCM_BC
2 than GCM. That is because the extent and magnitude of positive anomaly of omega is much
3 less in the GCM (not shown) than in MRCM seen in Figure 10(c). A more realistic coastline
4 and a sharp gradient of topography derived from higher resolution of MRCM are able to
5 enhance the circulation and regional changes in response to the assumed forcing (e.g. rising
6 concentration of GHGs) (Im and Eltahir 2017).

7 The different behavior in accordance with the low-level circulation between ASO and
8 FMA seasons can be seen more clearly in Fig. 12 which presents the moisture flux and
9 convergence at 850 hPa derived from REF and its change under RCP8.5 scenario. For REF,
10 climatological moisture flux is apparently reversed between ASO and FMA, which in turn
11 leads to the strong moisture convergence north and south of equator respectively. Under
12 RCP8.5, anomalous flux is stronger in ASO than in FMA, which is in line with the magnitude
13 of changes in rainfall and vertical motion. Most land area is dominated by low-level
14 horizontal divergence, consistent with the vertical sinking motion.

15

16 **4. Summary and conclusions**

17 In the study, the impact of climate change over the western Maritime Continent is
18 investigated based on the regional climate projections dynamically downscaled using MRCM
19 with 12 km horizontal resolution. The surface and lateral boundary conditions used to force
20 MRCM are taken from three CMIP5 participant models, namely, CCSM4, MPI-ESM-MR,
21 and ACCESS 1.0, which are selected through a screening process based on the model
22 performance in simulating present-day climate, and its horizontal resolution. Dynamical
23 downscaling using MRCM is conducted for a total of nine 31-year regional climate
24 projections under multi-GCMs (CCSM4, MPI-ESM-MR, and ACCESS 1.0) and multi-

1 scenarios of emission (REF: 1975-2005, RCP4.5, and RCP8.5: 2070-2100, first 1 year is used
2 for spin-up). In order to enhance the reliability of future projections, the PQM method, which
3 is widely used for statistical bias correction, is applied to MRCM raw data in order to
4 minimize the systematic errors due to the imperfections of both MRCM physics and driving
5 GCM forcings.

6 Based on validation analysis of ensemble mean of REF, the MRCM_BC provides added
7 value over GCM and improved performance over MRCM both quantitatively and
8 qualitatively. Seasonally averaged pattern and daily frequency distribution derived from the
9 MRCM_BC reasonably agree with the TRMM observed rainfall patterns. Note that bias
10 correction is not likely to significantly affect the future change pattern, in contrast with the
11 significant difference in the performance of the REF. It is because the systematic bias of
12 model can be mostly eliminated by subtracting the climatological mean of the REF from that
13 of the RCP future projections, under the assumption of “stationarity” that bias pattern does
14 not change with time. Based on the projections used in this study, the future change patterns
15 with and without bias correction are not much different in terms of climatological mean (not
16 shown).

17 Under RCP4.5 and RCP8.5 scenarios, MRCM_BC projections show a significant
18 decrease in rainfall with a high degree of robustness evident in the agreement among the
19 three projections driven by different GCMs. More importantly, the pattern of projected
20 change in the different seasons is characterized by asymmetric behavior varying between
21 different latitudinal locations, north or south of equator. The decrease in rainfall is
22 predominantly during the inter-monsoon seasons (e.g., ASO and FMA), however, the
23 intensity and extent of change are different between ASO and FMA. A more significant
24 decrease in rainfall is expected south of equator during ASO than north of equator during

1 FMA. Interestingly, Singapore located near equator is likely to experience a decrease in
2 rainfall in both ASO and FMA. The projected regional climate change features a more intense
3 seasonality of rainfall, with potentially important implications for seasonal water stress of
4 natural ecosystems, and new challenges for management of man-made reservoirs.

5 The main factor behind the projected rainfall changes can be at least partly explained by
6 the changes in vertical atmospheric motion and associated meridional overturning circulation.
7 Based on analysis of atmospheric vertical motion fields, the ascending motion of REF is
8 weakened and or displaced by anomalous descending motion. The different strength of
9 circulation between ASO and FMA for REF leads to different magnitudes of response under
10 future condition. RCP8.5 simulations project strong positive anomaly of omega, which is
11 consistent with a large decrease of rainfall, particularly south of equator over the western
12 Maritime Continent during ASO. Our conclusions are consistent with various studies on
13 climate change (e.g., Vecchi and Soden 2007; Bony et al. 2013; Lau and Kim 2015) which
14 suggested that rainfall is projected to decrease in tropical western Pacific due to ITCZ
15 movement and weakening of Hadley circulation.

16 In this study, we attempt to provide a region-specific fine-scale climate projections that
17 are produced to study climate change impacts over the western Maritime Continent.
18 Projections of climate change under different scenarios are often dynamically downscaled
19 using a high-resolution RCMs but mostly focusing on North America, Europe, and East Asia.
20 In this regard, this research performed applying a state-of-the-art experimental framework (12
21 km resolution of RCM, multi-GCM driving forcings from CMIP5, multi-RCP scenarios) fills a
22 gap in climate change research over this region, while effectively building on previous
23 research by this group and other published studies.

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14 **Table and Figure Captions**

15 Table 1. Descriptions of global climate models selected as lateral boundary forcings for
16 MRCM simulation in the study.

17 Table 2. Rainfall seasonality derived from historical, RCP4.5 and RCP8.5 over nine sub-
18 region. Brackets indicate seasonality change (%).

19

20 Fig. 1. MRCM simulation domain and topography (unit: m). Boxes indicate the nine sub-
21 region used for regional analysis in this study. Two red dots indicate the in-situ
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26 TRMM, (b, f, j, n) ensemble mean of GCMs (denoted by GCM ENS), (c, g, k, o)
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3 Fig. 3. Annual cycle of total rainfall (unit: mm/day) averaged over the land area of domain
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6 Fig. 4. Histogram of daily rainfall at Changi and Malacca stations derived from in-situ
7 observations (green), TRMM 3B42 (black), MRCMs (blue) and MRCM_BC (red)
8 during dry (MJJ: a,c) and wet (NDJ: b,d) seasons.

9 Fig. 5. Annual cycle of total rainfall (unit: mm/day) averaged over nine sub-region derived
10 from TRMM (black), REF (blue), RCP4.5 (green) and RCP8.5 (red) and monthly
11 rainfall change (unit: %) under RCP4.5 and RCP8.5. Asterisk indicates that 3
12 MRCMs agree in the sign of change signal. Black dot indicates that rainfall change is
13 statistically significant at the 95% confidence level based on a two-tailed Student's t-
14 test.

15 Fig. 6. Latitude-time cross section of monthly mean changes in total, convective, and large-
16 scale rainfall averaged from 95°E to 119°E under (a, c, e) RCP4.5 and (b, d, f) RCP8.5.
17 Stippled area indicates that 3 MRCMs agree in the sign of same signal (unit: %).

18 Fig. 7. NDJ mean percentage changes in ensemble mean rainfall for RCP4.5 and RCP8.5
19 from (a, c) GCMs (denoted by GCM ENS) and (b, d) MRCMs (denoted by
20 MRCM_BC). Stippled area indicates that 3 GCMs (or MRCMs) agree in the sign of
21 same signal (unit: %).

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24 MRCM_BC). Stippled area indicates that 3 GCMs (or MRCMs) agree in the sign of

1 same signal (unit: %).

2 Fig. 9. FMA mean percentage changes in ensemble mean rainfall for RCP4.5 and RCP8.5
3 from (a, c) GCMs (denoted by GCM ENS) and (b, d) MRCMs (denoted by
4 MRCM_BC). Stippled area indicates that 3 GCMs (or MRCMs) agree in the sign of
5 same signal (unit: %).

6 Fig. 10. Latitude-height cross sections of p velocity (ω , 10^{-3} Pa s^{-1}) and vector (v ; $w \cdot 10^{-3}$)
7 zonally-averaged from 95°E to 119°E during ASO season derived from (a) REF and
8 its change under (b) RCP4.5 and (c) RCP8.5.

9 Fig. 11. Latitude-height cross sections of p velocity (ω , 10^{-3} Pa s^{-1}) and vector (v ; $w \cdot 10^{-3}$)
10 zonally-averaged from 95°E to 119°E during FMA season derived from (a) REF and
11 its change under (b) RCP4.5 and (c) RCP8.5.

12 Fig. 12. Moisture flux (vector, $\text{g kg}^{-1}\text{m s}^{-1}$) with convergence and divergence (shading, 10^{-6} s^{-1})
13 at 850hPa for reference period (REF) and its change under RCP 8.5 during (a, c) ASO
14 and (b, d) FMA seasons.

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14 Table 1 Descriptions of global climate models selected as lateral boundary forcings for
15 MRCM simulation in the study.

Model name	ATM resolution (lat x lon)	OCN resolution (lat x lon)	Main reference
CCSM4	0.9° x 1.25°	1.11° x 0.27° ~0.54°	Gent et al. 2011
MPI-ESM-MR	T63 (~1.875°)	0.4° x 0.4°	Giorgetta et al. 2013
ACCESS 1.0	1.25° x 1.875°	1/3° ~ 1°	Bi et al. 2013

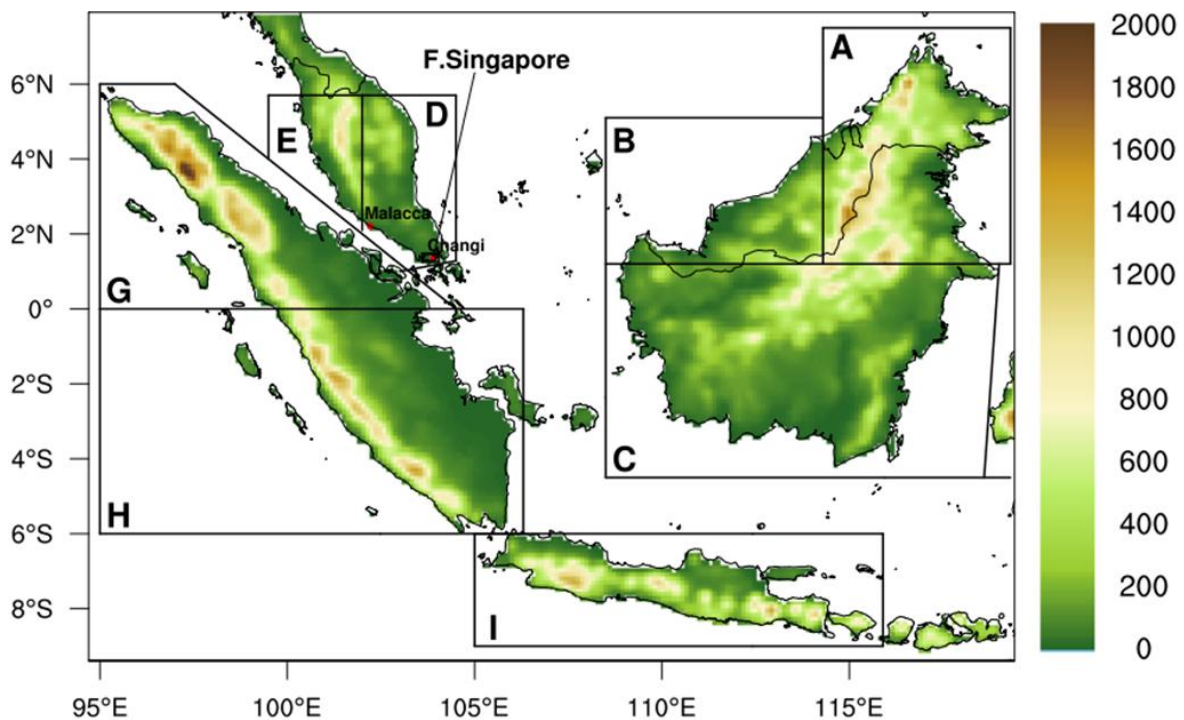
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19 Table 2 Rainfall seasonality derived from historical, RCP4.5 and RCP8.5 over nine sub-
20 region. Brackets indicate seasonality change (%).

Sub-region	TRMM	REF	RCP4.5	RCP8.5
A: Borneo (Northeast)	0.4	0.4	0.6 (50%)	0.6 (50%)

B: Borneo (Northwest)	0.9	0.9	0.9 (0%)	1.0 (11%)
C: Borneo (South)	0.7	0.6	0.7 (17%)	0.8 (33%)
D: Peninsula Malaysia (East)	1.4	1.1	1.5 (36%)	1.4 (27%)
E: Peninsula Malaysia (West)	0.8	0.8	1.0 (25%)	1.0 (25%)
F: Singapore	0.8	0.9	1.2 (33%)	1.2 (33%)
G: Sumatra (North)	0.7	0.6	0.6 (0%)	0.6 (0%)
H: Sumatra (South)	0.7	0.7	0.8 (14%)	1.1 (57%)
I: Java	1.5	1.5	1.5 (0%)	2.0 (33%)

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Fig. 1 MRCM simulation domain and topography (unit: m). Boxes indicate the nine sub-region used for regional analysis in this study. Two red dots indicate the in-situ observational stations at Changi (1.35°N, 103.99°E) and Malacca (2.26°N, 102.25°E)

1 located in Singapore and Peninsula Malaysia, respectively.

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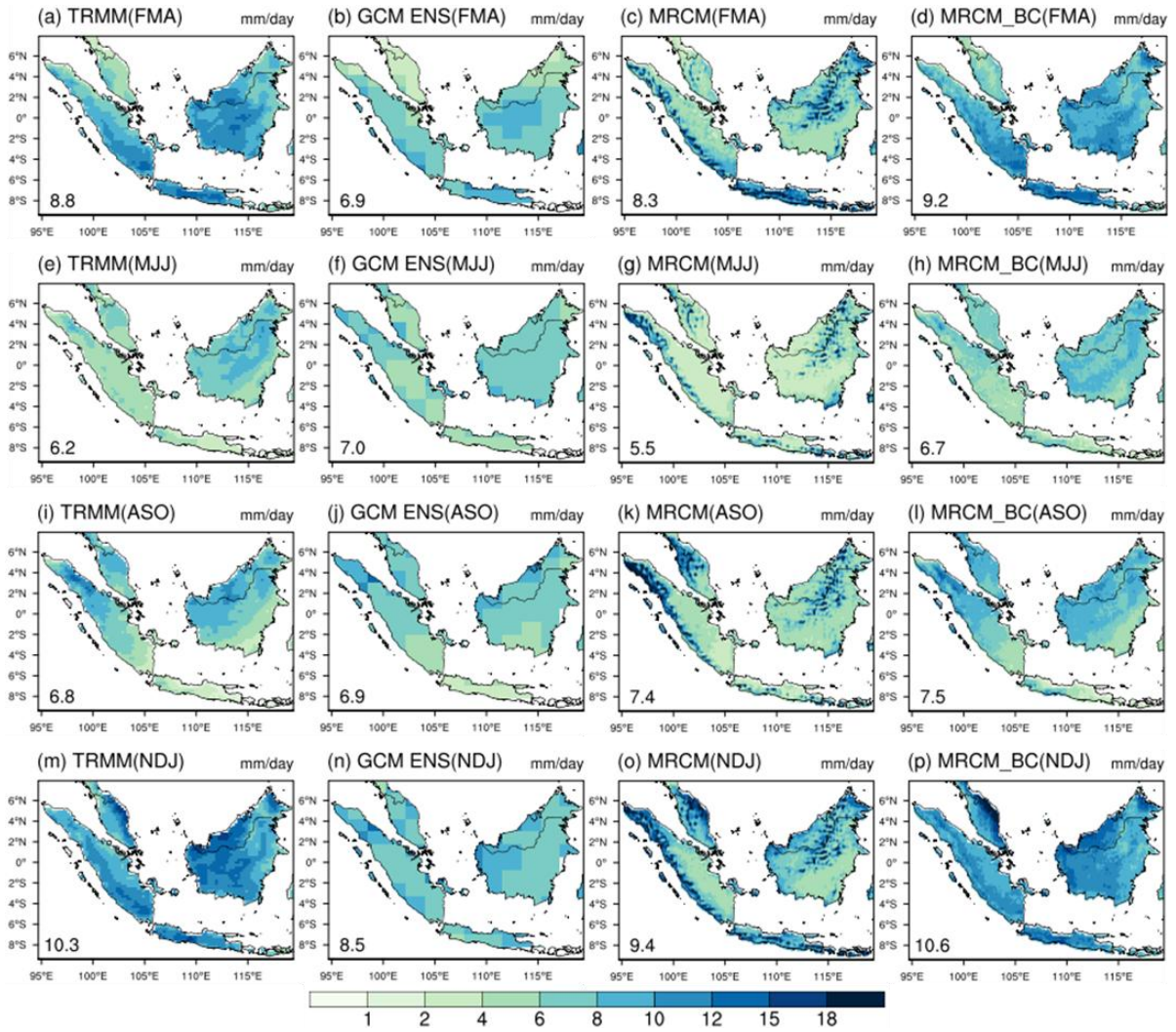
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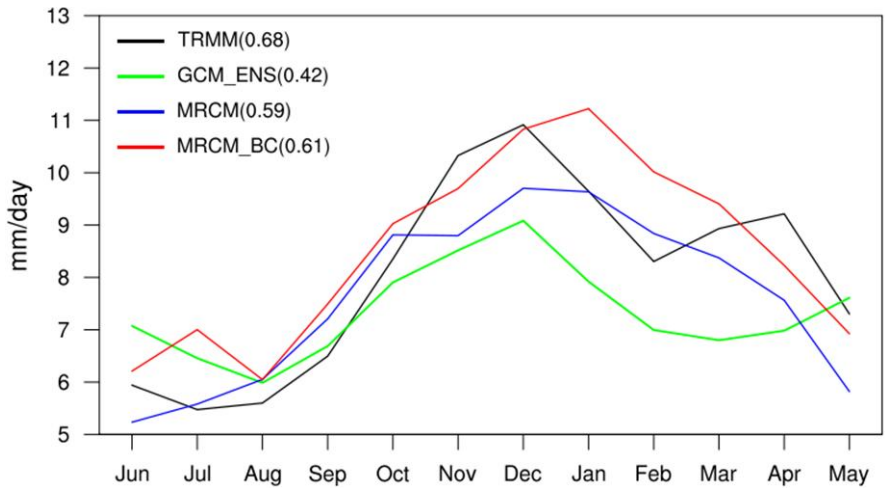
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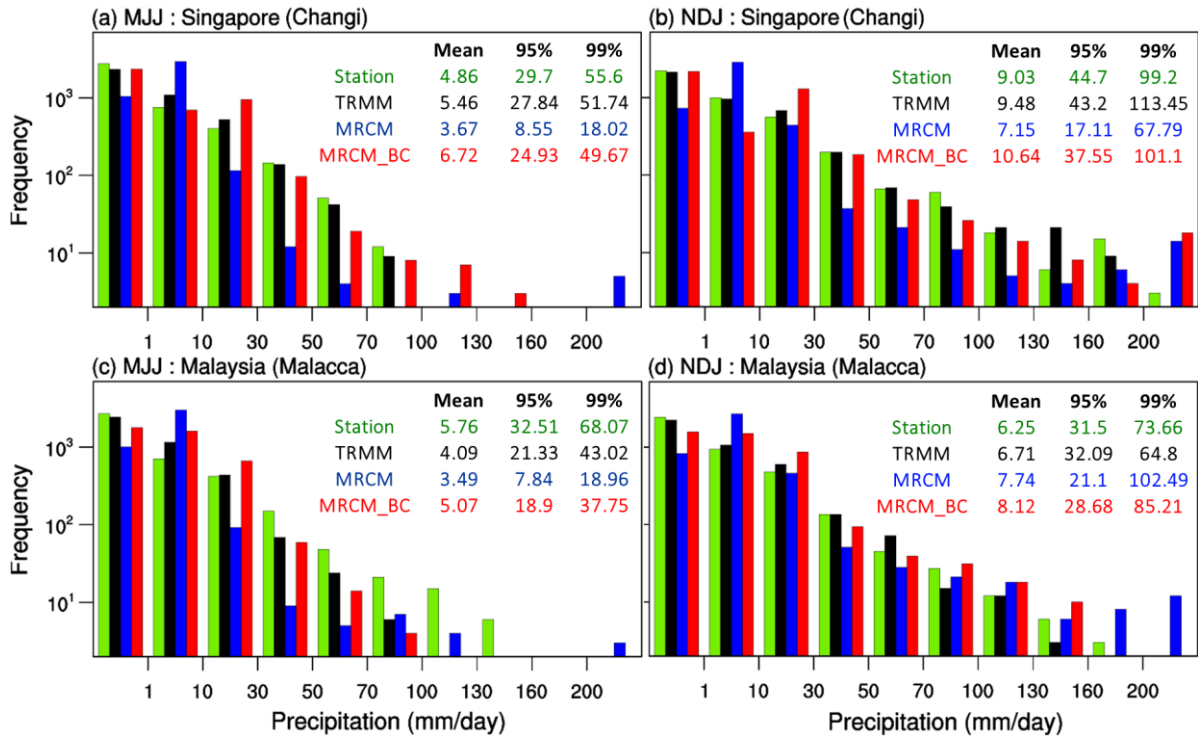
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Fig. 2 Spatial distribution of seasonal rainfall for inter-monsoon seasons (FMA: a-d, ASO: i-l), and dry (MJJ: e-h), and wet (NDJ: m-p) seasons derived from the (a, e, i, m) TRMM, (b, f, j, n) ensemble mean of GCMs (denoted by GCM ENS), (c, g, k, o) ensemble mean of MRCMs (denoted by MRCM), and (d, h, l, p) ensemble mean of bias-corrected MRCMs (denoted by MRCM_BC). Area-averaged value over land is included in the bottom left corner of each plot (unit: mm/day).



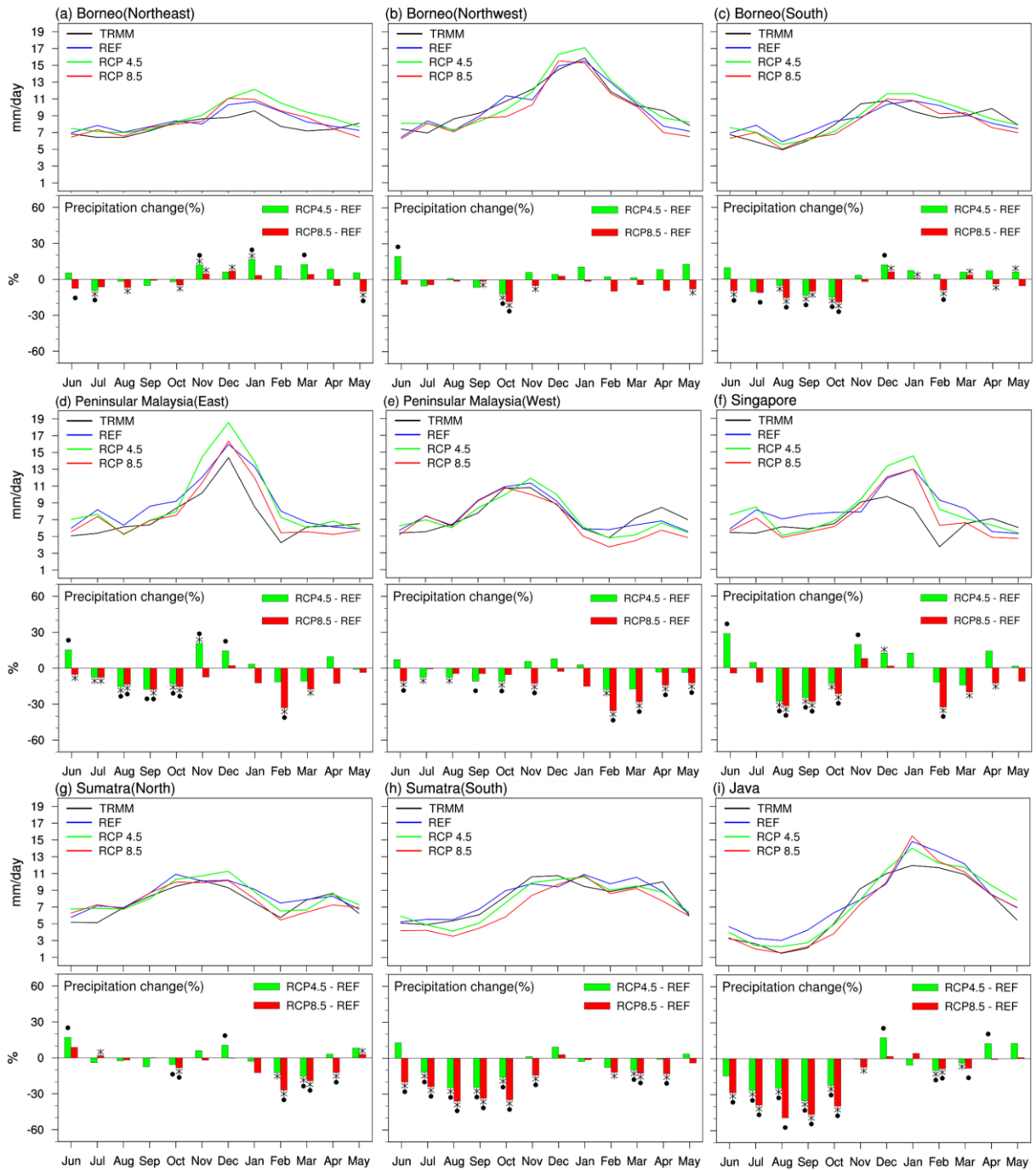
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 2 Fig. 3 Annual cycle of total rainfall (unit: mm/day) averaged over the land area of domain
 3 derived from TRMM (black), GCM_ENS (green), MRCM (blue) and MRCM_BC
 4 (red). Number in bracket indicates seasonality of rainfall.

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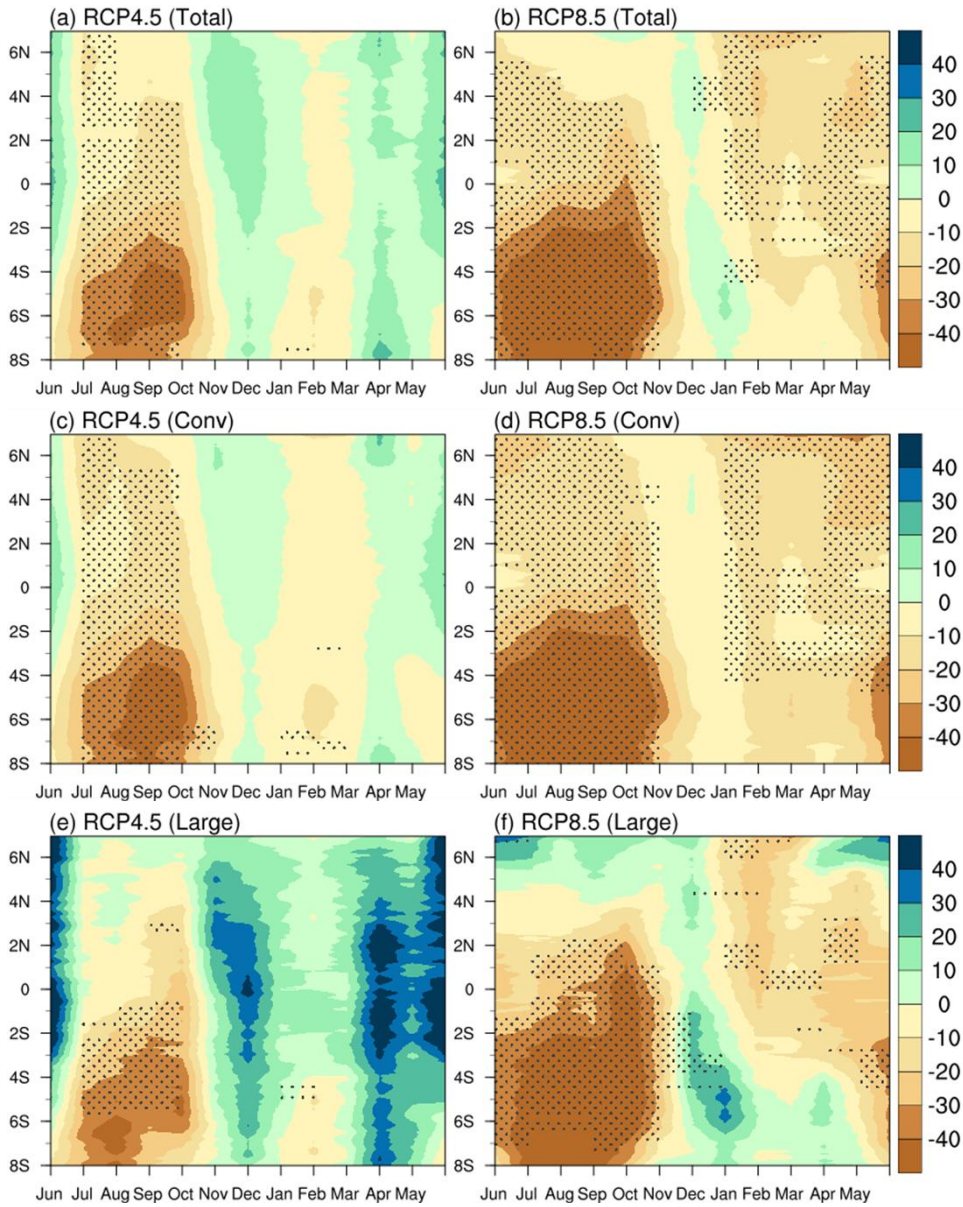
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Fig. 5 Annual cycle of total rainfall (unit: mm/day) averaged over nine sub-region derived from TRMM (black), REF (blue), RCP4.5 (green) and RCP8.5 (red) and monthly rainfall change (unit: %) under RCP4.5 and RCP8.5. Asterisk indicates that 3 MRCMs agree in the sign of change signal. Black dot indicates that rainfall change is statistically significant at the 95% confidence level based on a two-tailed Student's t-test.

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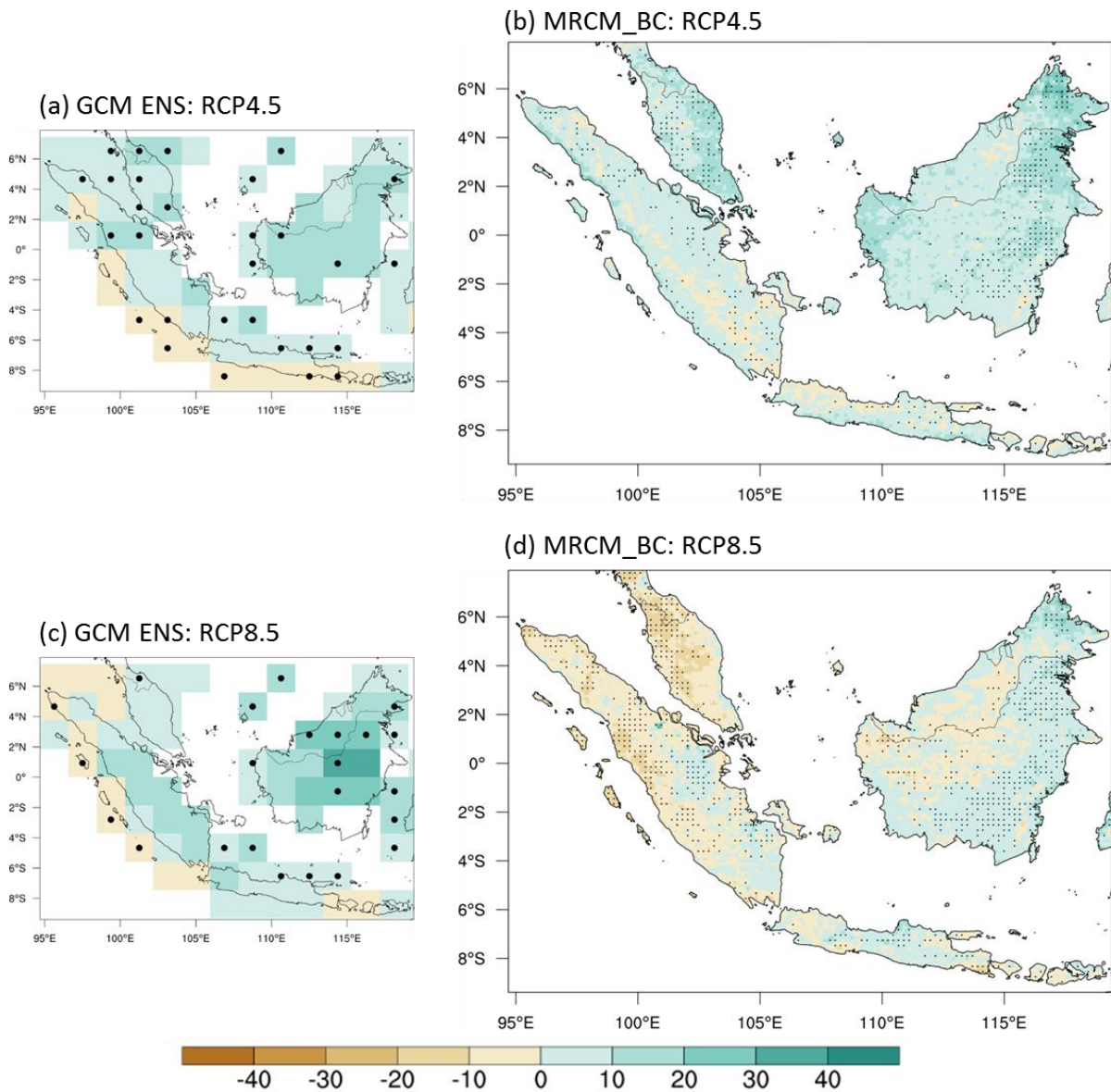
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Fig. 6 Latitude-time cross section of monthly mean changes in total, convective, and large-scale rainfall averaged from 95°E to 119°E under (a, c, e) RCP4.5 and (b, d, f) RCP8.5. Stippled area indicates that 3 MRCMs agree in the sign of same signal (unit: %).

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3 Fig. 7 NDJ mean percentage changes in ensemble mean rainfall for RCP4.5 and RCP8.5 from
4 (a, c) GCMs (denoted by GCM ENS) and (b, d) MRCMs (denoted by MRCM_BC).
5 Stippled area indicates that 3 GCMs (or MRCMs) agree in the sign of same signal
6 (unit: %).

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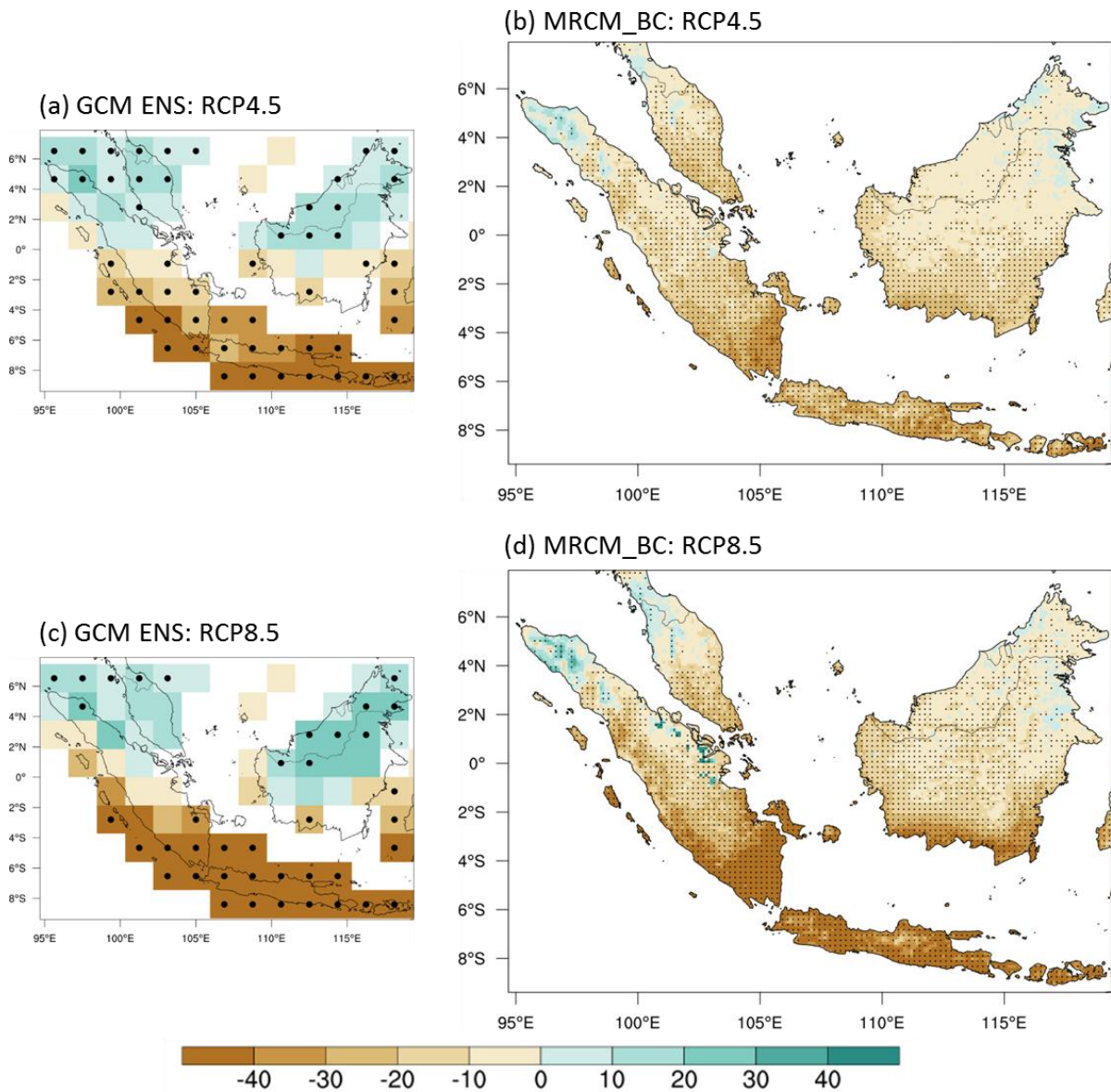
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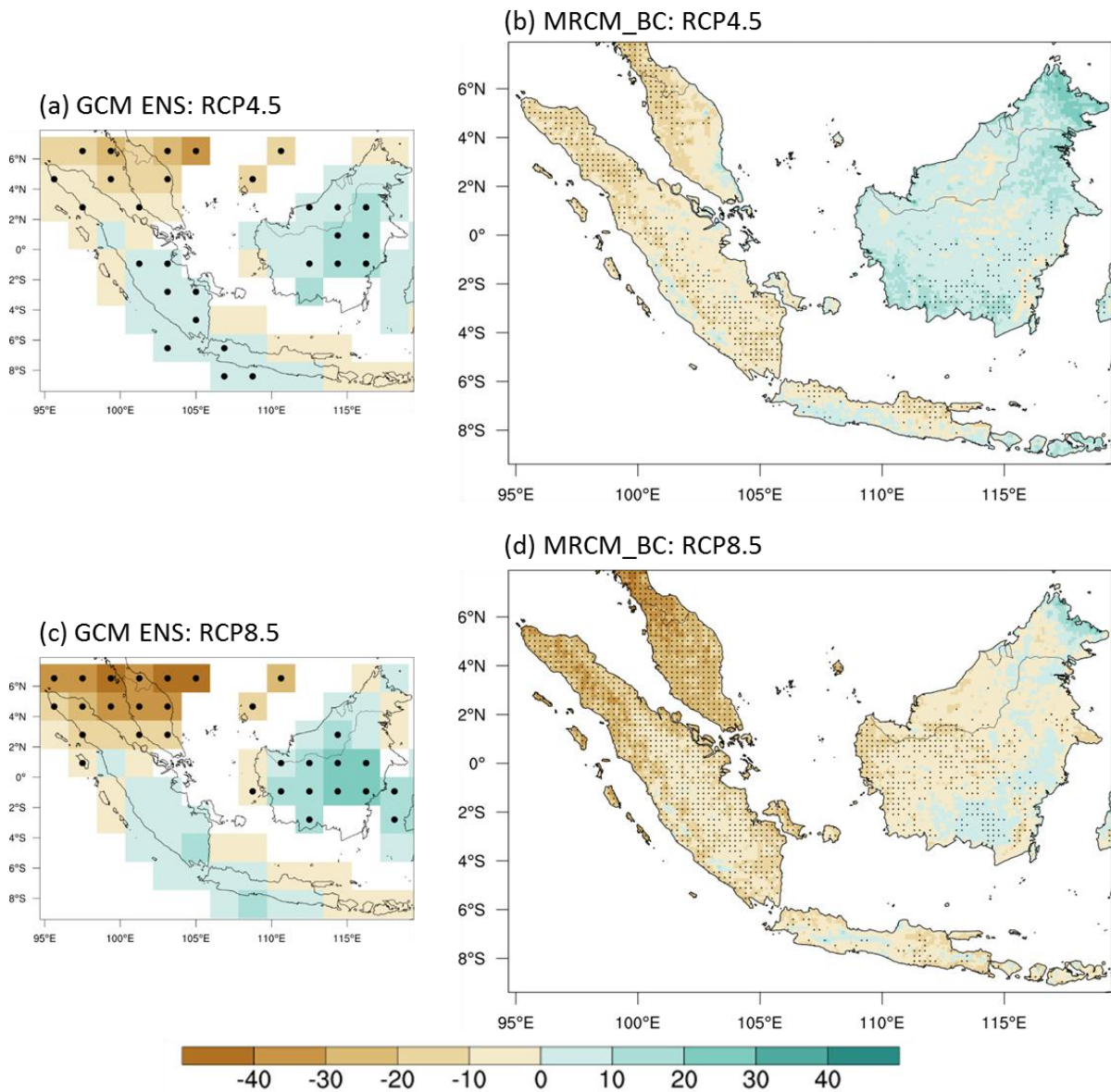
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Fig. 8 ASO mean percentage changes in ensemble mean rainfall for RCP4.5 and RCP8.5 from (a, c) GCMs (denoted by GCM ENS) and (b, d) MRCMs (denoted by MRCM_BC). Stippled area indicates that 3 GCMs (or MRCMs) agree in the sign of same signal (unit: %).

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Fig. 9 FMA mean percentage changes in ensemble mean rainfall for RCP4.5 and RCP8.5 from (a, c) GCMs (denoted by GCM ENS) and (b, d) MRCMs (denoted by MRCM_BC). Stippled area indicates that 3 GCMs (or MRCMs) agree in the sign of same signal (unit: %).

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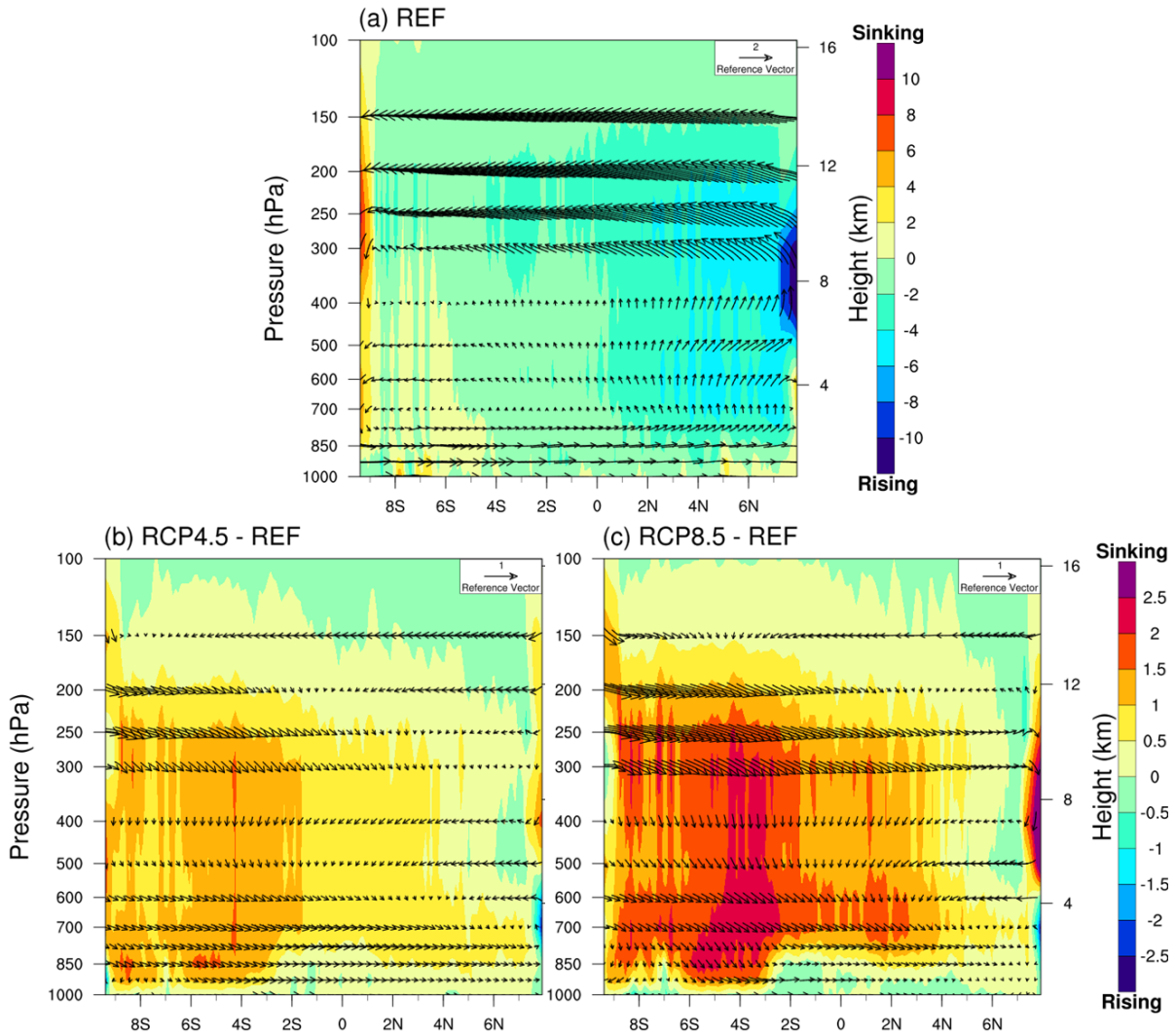
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Fig. 10 Latitude-height cross sections of p velocity (ω , $10^{-3} \text{ Pa s}^{-1}$) and vector (v ; $w \cdot 10^{-3}$) zonally-averaged from 95°E to 119°E during ASO season derived from (a) REF and its change under (b) RCP4.5 and (c) RCP8.5.

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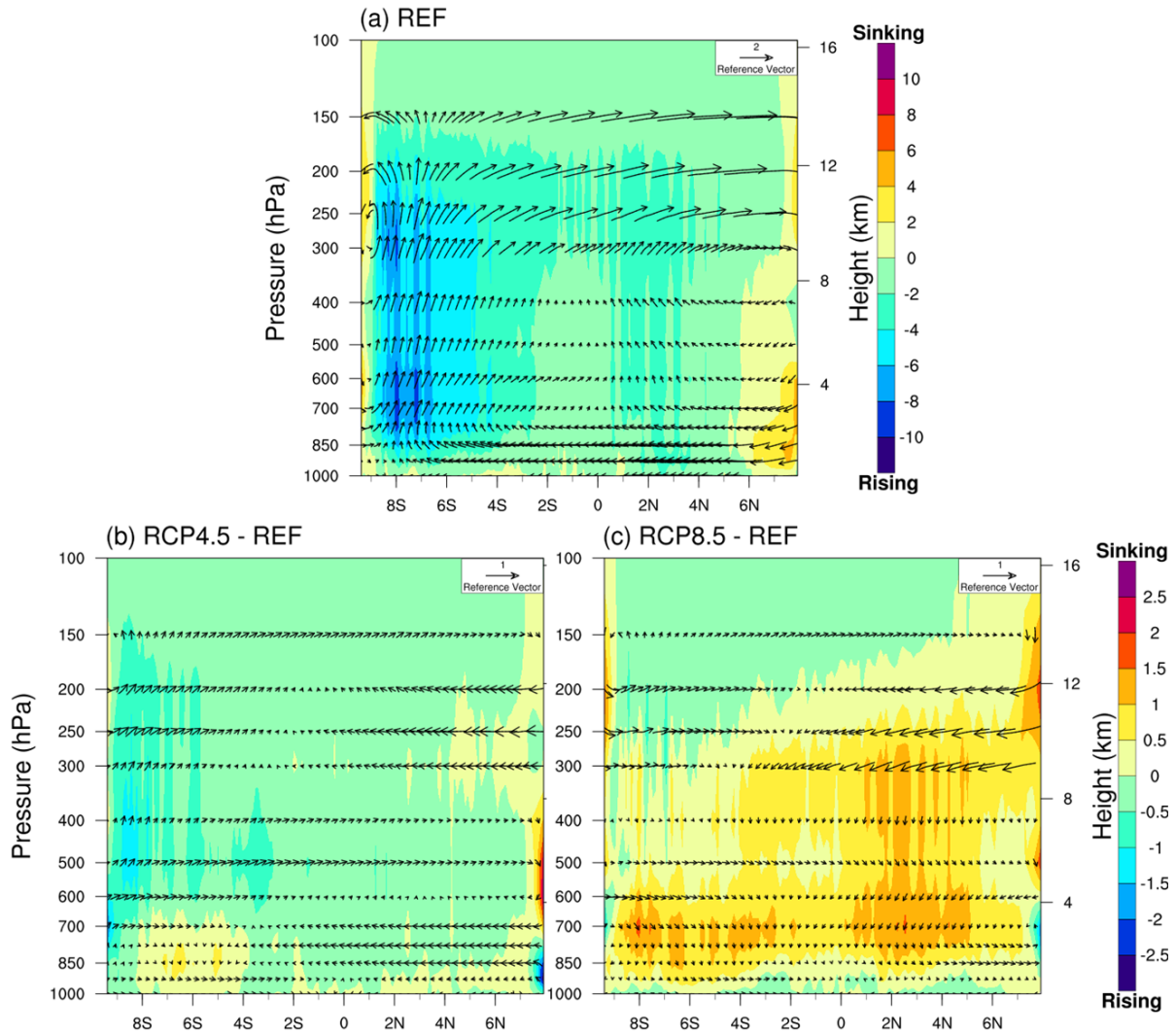
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3 Fig. 11 Latitude-height cross sections of p velocity (ω , $10^{-3} \text{ Pa s}^{-1}$) and vector (v ; $w \cdot 10^{-3}$)
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5 its change under (b) RCP4.5 and (c) RCP8.5.

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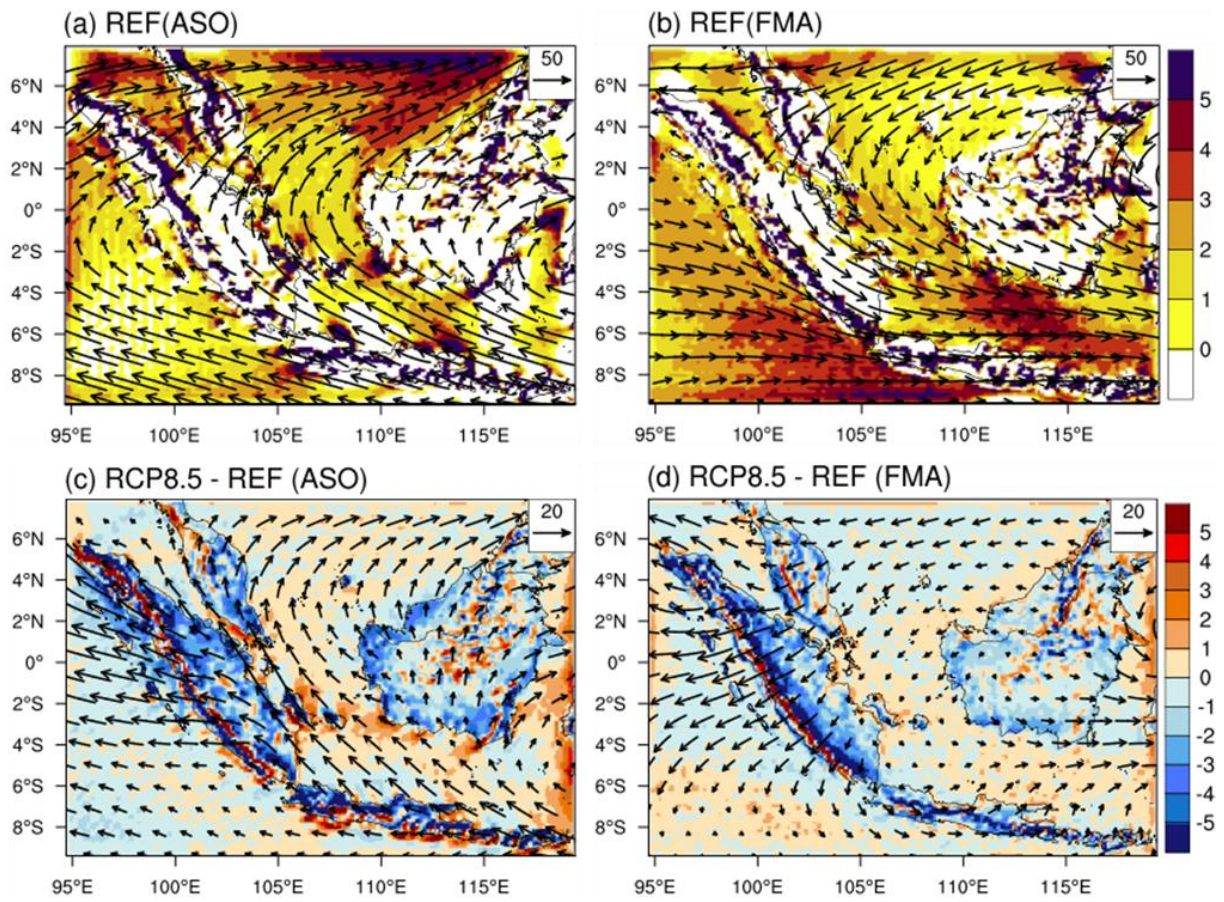
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3 Fig. 12. Moisture flux (vector, $\text{g kg}^{-1}\text{m s}^{-1}$) with convergence and divergence (shading, 10^{-6} s^{-1})

4 at 850hPa for reference period (REF) and its change under RCP 8.5 during (a, c) ASO

5 and (b, d) FMA seasons.

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