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Sensitivity of Southeast Asia rainfall simulations to cumulus and air–sea flux parameterizations in RegCM4

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ABSTRACT: We investigated the performance of RegCM4 in simulating rainfall over Southeast Asia with different combinations of deep-convection and air–sea flux parameterization schemes. Four different gridded rainfall datasets were used for the model assessment. In general, the simulations produced dry biases over the equatorial region and slightly wet biases over mainland Indo-China, except those experiments with the MIT Emanuel cumulus schemes, in which large positive rainfall biases were simulated. However, simulations with the MIT schemes were generally better at reproducing annual rainfall variations. The simulations were not sensitive to the treatment of air–sea fluxes. While the simulations generally produced the rainfall climatology well, all simulations showed stronger inter-annual variability compared to observations. Nevertheless, the time evolution of the inter-annual variations was well reproduced, particularly over the eastern Maritime Continent. Over mainland Southeast Asia, all simulations produced unrealistic rainfall anomaly responses to surface temperature. The lack of summer air–sea interactions in the model resulted in enhanced oceanic forcing over the regions, leading to positive rainfall anomalies during years with warm ocean temperature anomalies. This shortcoming in turn caused much stronger atmospheric forcing on the land surface processes compared to that of the observation. A robust score-ranking system was designed to rank the simulations according to their performance in reproducing different aspects of rainfall characteristics. The results suggest that the simulation with the MIT Emanuel convective scheme and the BATS1e air–sea flux scheme performs better overall compared to the rest of the simulations.

KEY WORDS: Southeast Asia · Regional climate modelling · RegCM · Rainfall · Simulation validation

1. INTRODUCTION

Regional climate change and its potential impacts on critical sectors such as agriculture and water resources are major issues in Southeast Asia because of the low adaptive capacity of most countries in the region. In the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, Working Group 1 reported that Southeast Asia has already experienced long-term changes in its regional climate

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(Christensen et al. 2013). In addition, IPCC Working Group 2 also highlighted that the Southeast Asia region has already been impacted by regional climate change (Hijioka et al. 2014). Nevertheless, these reports also clearly indicated the existence of considerable knowledge gaps in regional climate change and its impact in the Southeast Asia region due to the limited number of studies carried out thus far. In particular, the lack of studies on impact, adaptation and vulnerability (IAV) of climate change in the region could be attributed to the lack of publicly available regional climate change scenario projections. An impact assessment study usually requires high-resolution climate change information as an input for the impact models. As part of an effort to provide the latest local to regional-scale climate change information for impact assessment, a regional climate downscaling initiative in the Southeast Asia region, viz. the Southeast Asia Regional Climate Downscaling (SEACLID) Project, was established and funded by the Asia Pacific Network for Global Change Research. The initiative was later streamlined under the umbrella of the World Climate Research Programme (WCRP)'s Coordinated Regional climate Downscaling Experiment (CORDEX) (Giorgi et al. 2009) and renamed SEACLID/CORDEX Southeast Asia (www.ukm.edu.my/seaclid-cordex).

The SEACLID/CORDEX Southeast Asia involves a number of countries within and outside the region. It aims to dynamically downscale multiple Coupled Model Intercomparison Project Phase 5 (CMIP5) general circulation models (GCMs) for a common domain of the Southeast Asia region, and create high-resolution regional climate change scenario projections that can be accessed publicly by the IAV community. In this regional climate downscaling project, a regional climate model is required as a tool to dynamically downscale the coarse GCM products. For member countries within the Southeast Asia region, it was also collectively agreed that the latest version of RegCM4, a regional model developed by the Earth System Physics section of the Abdus Salam International Centre for Theoretical Physics (ICTP) (Giorgi et al. 2012), be used. RegCM4 has been applied in various regional climate downscaling projects around the globe (e.g. Almazroui 2012, Coppola et al. 2012, Diro et al. 2012, Gu et al. 2012, Otieno & Anyah 2012, Ozturk et al. 2012, Oh et al. 2013, Sylla et al. 2013, Reboita et al. 2014).

RegCM4 comes with various physics and parameterization schemes (Giorgi et al. 2012), in which their suitability and effectiveness need to be first evaluated in simulating the regional climate and its variability prior to the actual downscaling of the GCMs. In this study, experiments were conducted to evaluate the appropriateness of various options in cumulus and air–sea flux schemes in RegCM4. The choice of appropriate cumulus scheme in RegCM4 is critical in determining the model's ability to reproduce the rainfall characteristics (Giorgi et al. 2012) and ensuring realistic climate states in climate models. RegCM4 comes with several cumulus parameterization options, including the simplified Kuo (Anthes et al. 1987), Grell (Grell 1993), MIT (Emanuel & Zivkovic-Rothman 1999) and Tiedtke (Tiedtke 1989). In this study, we also investigated the effectiveness of 2 air–sea flux schemes, i.e. BATS (Dickinson et al. 1993) and Zeng (Zeng et al. 1998). An ocean flux scheme controls the ocean–atmosphere turbulent exchanges of heat, momentum and moisture (Giorgi et al. 2012). Due to a large portion of ocean coverage in the CORDEX Southeast Asia domain and the convective nature of the rainfall processes in the region, the roles of deep convection and air–sea flux parameterization are deemed important in simulating the regional climate over this region. Hence, evaluating the effectiveness of the deep convective and air–sea flux schemes is crucial.

Previous studies investigating the sensitivity of cumulus and air–sea flux schemes in the Southeast Asia regional climate simulations are limited, particularly for regional simulations using RegCM. In fact, the number of studies on regional climate simulations in the Southeast Asia region using a regional climate model is still minimal (e.g. Aldrian et al. 2004, Phan et al. 2009, 2014, Ngo-Duc et al. 2014). Francisco et al. (2006) evaluated the effects of choices of driving fields and air–sea flux schemes for RegCM3 simulations of summer rainfall in the Philippines. This study concluded that the BATS1e scheme consistently produced more precipitation than the Zeng approach. However, it was also revealed that the response of simulated precipitation using different forcing data is of the same order of magnitude as that using different air–sea flux schemes (Francisco et al. 2006). Octaviani & Manomaiphiboon (2011) carried out a sensitivity experiment examining the appropriateness of the convective and air–sea flux schemes of RegCM3 in simulating the regional climate over Thailand. The study found that the performances of the convective schemes vary with season. In the summer, the MIT Emanuel scheme performs best for temperature. However, in the wet season, the Grell scheme with an Arakawa-Schubert closure assumption produces overall smaller cold biases compared with other schemes. For precipitation, the study found that the performances of the MIT Emanuel and Grell schemes were relatively similar. For air–sea flux, BATS1e simulated the temperature better but yielded more precipitation (Octaviani & Manomaiphiboon 2011). Im et al. (2008) evaluated the effectiveness of 2 convective parameterization schemes, i.e. Grell and MIT Emanuel, in simulating the regional climate of the Korean Peninsula. They concluded that the MIT scheme performed better than the Grell scheme in simulating precipitation and surface temperature. The MIT scheme also better captured the timing and amplitudes of rain bands propagating northward over the Korean Peninsula. According to the previous sensitivity studies related to the comparison of cumulus parameterization, Giorgi et al. (2012) and Reboita et al. (2014) suggested that a mixed configuration with the Grell scheme over land and the MIT scheme over the ocean provides the best results over the tropical region. In addition, Reboita et al. (2014) recommended that the MIT scheme is more suitable for air temperature simulation.

The optimal parameterization setting is likely dependent on domain and grid size (Giorgi et al. 2012). Hence, customization and validation steps must be carried out before conducting specific model runs. Therefore, the purpose of this study was to evaluate the performance of RegCM4 parameterizations in simulating the climate and its variability over Southeast Asia with a focus on rainfall. Several simulations with different cumulus convection and air–sea flux parameterizations were carried out to find the best configuration of RegCM4 over the CORDEX Southeast Asia domain.

2. DATA AND METHODS

2.1. Model and experimental setup

The regional climate model used in this study is the 4th version of the ICTP Regional Climate Model (RegCM4). Initially developed by Giorgi et al. (1993a,b), details of the recent development and improvement of the model can be found in Pal et al. (2007) and Giorgi et al. (2012). The dynamic core of RegCM4 is equivalent to the hydrostatic version of the PSU/NCAR MM5 (Grell et al. 1994).

We examined the performance of RegCM4 in simulating rainfall over the Southeast Asia region using different combinations of deep convection parameterization and air–sea flux treatments. Six different cumulus parameterization schemes were considered, namely (1) the Grell scheme (Grell 1993) with an Arakawa-Schubert (Arakawa & Schubert 1974) closure assumption – Grell(AS); (2) the Grell scheme with a Fritsch-Chappell (Fritsch & Chappell 1980) closure assumption – Grell(FC); (3) the MIT Emanuel scheme (Emanuel & Zivkovic-Rothman 1999); (4) a mixed scheme with the MIT Emanuel scheme over the ocean and the Grell scheme over land; (5) a mixed scheme with the Grell scheme over the ocean and the MIT Emanuel scheme over land; and (6) the Kuo scheme (Anthes et al. 1987). The Tiedtke scheme (Tiedtke 1989) was not included in the list because that scheme has yet to be fully incorporated into the RegCM4 version used in this study.

The Kuo scheme is one of the earliest proposed convective schemes, and is based on a simple assumption that relates deep convection to moisture convergence over the entire atmospheric column (Anthes et al. 1987). It is a static, moisture-controlled scheme, and is activated when the column convergence exceeds a certain threshold value, in which part of the convergence is converted into rainfall as a function of relative humidity while the rest moistens the air column. The resulting latent heat is distributed between the cloud top and bottom with maximum heating at the cloud top. The Grell scheme, on the other hand, is a mass flux scheme, which is activated when a lifted parcel attains moist convection (Grell 1993). It includes the moistening and heating effects of penetrative updrafts and corresponding downdrafts without entrainment or detrainment, and mixing occurs only at the bottom and the top of the cloud. The convective mass flux is determined by the flux required to stabilize an unstable air column. In the Fritch-Chappell closure assumption, the air parcel's buoyant energy is dissipated during a specified convective time period of typically 30 min, whereas in the Arakawa-Schubert closure assumption, the convective available buoyancy energy is released instantaneously (Arakawa & Schubert 1974, Fritsch & Chappell 1980).

The MIT Emanuel scheme includes processes such as cloud microphysics and the entrainment of dry air from the environment. It assumes that cloud mixing is episodic and inhomogeneous (Emanuel & Zivkovic-Rothman 1999). In this scheme, the convective fluxes are determined by a sub-cloud scale model of updraft and downdraft, and convection is initiated when the level of neutral buoyancy is above the cloud base. Between these levels, condensed moisture is converted to clouds and precipitation in which autoconversion and ice-related processes are both considered. The MIT Emanuel scheme is the most sophisticated among all the schemes tested in this current study, and it is known to work best at a high grid resolution. However, previous studies (e.g. Davis et al. 2009, Kang et al. 2014) have reported that the scheme usually produced excessive rainfall over land due to over-activation of the deep convection process once it is initiated.

For the air–sea flux treatment, we considered the Biosphere–Atmosphere Transfer scheme (BATS1e) (Dickinson et al. 1993) and the Zeng scheme (Zeng et al. 1998). For the Zeng scheme, 2 different formulations of the roughness length of the ocean surface (denoted Zeng1 and Zeng2) were tested. The BATS1e scheme uses a constant roughness length of 2×10^{-4} m, whereas the roughness lengths for both Zeng schemes are dependent on friction velocity. Zeng2 also take into account the effect of viscosity in the roughness length calculation. A detailed description of the effectiveness of these 3 air–sea flux schemes in RegCM4 has been reported by Li et al. (2015). Table 1 summarizes the configurations for the 18 simulation experiments considered in our study. Other physics parameterizations used in all simulations include the radiative transfer package of the NCAR Community Climate Model version 3 (CCM3) (Kiehl et al. 1996), the non-local planetary boundary layer scheme of Holtslag et al. (1990) and the Subgrid Explicit Moisture Scheme for the non-convective precipitation processes (Pal et al. 2000) based on the work of Sundqvist et al. (1989).

The simulations were carried out on a 36 × 36 km grid resolution domain centered at 14° N and 112.5° E using a normal Mercator projection. The domain covers the Southeast Asia region from 81.1°–143.9° E in longitude and 15.0° S–39.8° N in latitude. The RegCM4 domain and topography are shown in Fig. 1. Vertically, the model uses 18 sigma levels. The simulations span a period of 20 yr, and they were initialized and laterally forced with the ERA-Interim (Simmons et al. 2007) dataset from 1 January 1989 to 31 December 2008. The simulation of the year 1989 is used for the model spin-up and is excluded in the analysis. Such a long period of simulation allows the evaluation of the models' performances in simulating inter-annual variability.

2.2. Observational data

Four observational datasets were considered in this study, namely, (1) Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE), a land-only dataset created primarily with data obtained from an *in situ* rain gauge observation network (Yatagai et al. 2009); (2) Climatic Research Unit of the University of East Anglia (CRU) dataset, a station-based land-only dataset, which includes both surface air temperature and precipitation (Mitchell & Jones 2005); (3) Global Precipitation Climatology Centre monthly precipitation dataset (GPCC), a gridded gauge-analysis product derived from quality-controlled station data (Schneider et al. 2011); and (4) Tropical Rainfall Measuring Mission (TRMM) 3B42, a satellite-based product, which is available only for precipitation, both on land and in ocean areas (Huffman et al. 2007). While the APHRODITE, CRU and GPCC span the entire simulation period, the TRMM

Table 1. Experimental configurations

Expt	Acronym	Cumulus parameterization schemes	Air–sea flux
01	Grell(AS)/BATS1e	Grell with Arakawa-Schubert closure	BATS1e
02	Grell (AS)/Zeng1	Grell with Arakawa-Schubert closure	Zeng 1
03	Grell(AS)/Zeng2	Grell with Arakawa-Schubert closure	Zeng 2
04	MIT/BATS1e	MIT Emanuel	BATS1e
05	MIT/Zeng1	MIT Emanuel	Zeng 1
06	MIT/Zeng2	MIT Emanuel	Zeng 2
07	MIT+Grell(FC)/BATS1e	MIT Emanuel (land) + Grell (ocean) with Fritsch-Chappell closure	BATS1e
08	MIT+Grell(FC)/Zeng1	MIT Emanuel (land) + Grell (ocean) with Fritsch-Chappell closure	Zeng 1
09	MIT+Grell(FC)/Zeng2	MIT Emanuel (land) + Grell (ocean) with Fritsch-Chappell closure	Zeng 2
10	Grell(FC)/BATS1e	Grell with Fritsch-Chappell closure	BATS1e
11	Grell(FC)/Zeng1	Grell with Fritsch-Chappell closure	Zeng 1
12	Grell(FC)/Zeng2	Grell with Fritsch-Chappell closure	Zeng 2
13	Grell(AS)+MIT/BATS1e	Grell (land) with Arakawa-Schubert closure + MIT Emanuel (ocean)	BATS1e
14	Grell(AS)+MIT/Zeng1	Grell (land) with Arakawa-Schubert closure + MIT Emanuel (ocean)	Zeng 1
15	Grell(AS)+MIT/Zeng2	Grell (land) with Arakawa-Schubert closure + MIT Emanuel (ocean)	Zeng 2
16	Kuo/BATS1e	Kuo	BATS1e
17	Kuo/Zeng1	Kuo	Zeng 1
18	Kuo/Zeng2	Kuo	Zeng 2

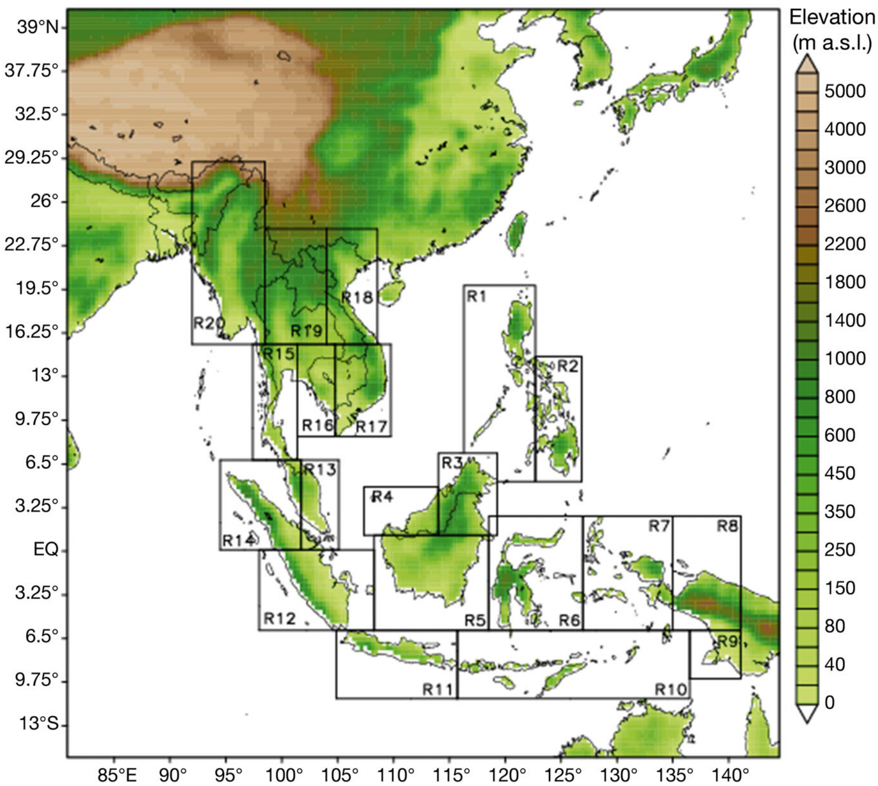

Fig. 1. Simulation domain and topography for the SEACLID/CORDEX-SEA sensitivity test experiments. The boxes indicate the 20 sub-regions used for further regional model performance assessment

precipitation dataset begins only in 1998. Both APHRODITE and TRMM are available on 0.25° × 0.25° resolution grids while CRU and GPCC have a resolution of 0.5° × 0.5°. To facilitate the quantitative analysis, all observed and simulated fields were interpolated bilinearly to identical 0.5° × 0.5° grids.

The quality of gridded observational precipitation datasets depends largely on the quality of the source data used to construct the products (Schneider et al. 2014). For instance, CRU is known to have very poor data coverage at the beginning of the 20th century (Schneider et al. 2014), while TRMM produces high-resolution rainfall estimates over the tropics but contains sampling biases (Yatagai et al. 2005). Several studies of the inter-comparison between the observational datasets show large discrepancies among those datasets (e.g. Xu et al. 2009, Giorgi et al. 2012, Yatagai et al. 2012, Kim et al. 2014). Yatagai et al. (2012) noted that APHRODITE estimates less precipitation than the GPCC product in general. The difference was due to quality controls and the different interpolation methods used (Yatagai et al. 2012, Kim et al. 2014). Meanwhile, TRMM's climatology has a greater similarity to APHRODITE climatology (Yatagai et al. 2012) than that of the GPCC (Yatagai & Kawamoto 2008). Kim et al. (2014) showed that the TRMM dataset has a smaller spatial variability compared with the CRU dataset over the African regions. Also, the CRU dataset tends to have larger precipitation values compared with the TRMM dataset over the African regions (Giorgi et al. 2012, Nikulin et al. 2012). The spatial interpolation method used in the CRU dataset includes a topographic correction routine. The GPCC employed a much more sophisticated data quality control procedure, but the interpolation method did not account for the topography correction. The regridding of APHRODITE is based on the Xie et al. (2007) method that was used to create the East Asian Daily precipitation analysis (EA05), except that there is no topography correction.

Most of the climate change impact studies consider gridded observational datasets as the true values (Sunyer et al. 2013) such that the performance of a climate model is typically assessed by comparing historical climate model simulations to the gridded products. Hence, it is crucial to understand the characteristics and uncertainties of the chosen observational products to avoid misleading conclusions with respect to the performance of the climate model (Gomez-Navarro et al. 2012, Sunyer et al. 2013). Multiple observational datasets can be used to reduce the uncertainties in model evaluations due to the selection of reference data (e.g. Gleckler et al. 2008). Therefore, in this study, 4 observational datasets (i.e. AHPRODITE, CRU, GPCC and TRMM) were used in the comparisons.

2.3. Sub-region selection for regional analysis

The simulation qualities were evaluated by comparing the simulated and observed values for the whole region and a number of sub-regions (Fig. 1). These sub-regions were determined based on the generalization of results from a number of studies related to rainfall in Southeast Asia. Over the equatorial regions, Aldrian & Susanto (2003) divided the Indonesian archipelago into 3 broad rainfall regions, oriented generally west to east, based on the climatology as well as the interannual variabilities. This division delineates the northern half of Sumatra as well as the Sulawesi and Maluku areas in eastern Indonesia from the large part of the country. Over Peninsular Malaysia, the climate is generally separated in the east–west orientation by the Titiwangsa range (Juneng et al. 2007). In addition, previous works also showed that the El Niño-Southern Oscillation modulation of the country's rainfall is most significant over northern Borneo in the states of Sabah and Sarawak (Juneng & Tangang 2005, Salimun et al. 2014). Rainfall in the Philippines is classified into 4 different types by the Philippine Atmospheric, Geophysical and Astronomical Services Administration based on the annual cycles (Francisco et al. 2006). The separation of the rainfall zones is generally northwest–southeast oriented with the northwest regions distinctively dry in April, and generally wet for the rest of the year. In the eastern-southeastern regions, the rainfall is year round with specifically higher amounts during the winter monsoon period. The eastern coast of mainland Southeast Asia is geographically separated from the central regions by the Truong Son mountain range. In Vietnam, the rainfall distribution has a generally north–south orientation. The maximum rainfall in central Vietnam usually occurs in October associated with the winter monsoon and typhoon activities (Nguyen-Thi et al. 2012). In the northern part of the country, the rainfall peaks in the summer months, while the rainfall amount is rather low throughout the year except during the winter in southern Vietnam. A relatively high topography extending from the Shan Plateau southward to the Tenasserim range separates Myanmar from the rest of the countries in mainland Indo-China. The rainfall in Thailand is traditionally divided into 5 different zones based on geography (Chokngamwong & Chiu 2008). However, the general separation is north–south oriented, with the northern regions generally dominated by the summer monsoon rainfall with distinctive monsoon breaks. The southern extension of the country, which connects with the Malay Peninsula, usually receives a high amount of rainfall during the early winter monsoon.

3. RESULTS AND DISCUSSION

3.1. Climatology

The spatial patterns of annual rainfall climatology over Southeast Asia, as depicted by APHRODITE, CRU, GPCC and TRMM, are shown in Fig. 2. The climate is generally wetter over the equatorial region due south, while a drier climate is observed over the Indo-China region, creating a north-to-south, dry-to-wet gradient over land (Fig. 2). Note that there are notable differences in magnitude among these observational datasets, particularly over the equatorial regions. Specifically, APHRODITE shows lower precipitation compared with other datasets in the equatorial regions, especially over the high orographic areas. CRU is wetter over Malaysia, Indonesia and the Philippines. The variations among the gridded observation products are larger over the southern part of Southeast Asia (not shown).

Most experiments simulated less rainfall over the equatorial regions, resulting in a strong dry bias due south, while more rainfall was simulated over the Indo-China region, creating strong wet biases due north (Fig. 3). Most experiments also have difficulties in simulating the rainfall in the mountainous areas and the equatorial regions. The experiments with the Grell(FC) scheme (Experiments [Expts] 10 to 12) produced more precipitation over southwest Indo-China compared with those using the Grell(AS) scheme (Expts 01 to 03). Giorgi & Shields (1999) noted that the Grell(AS) scheme forces dissipation of large-scale buoyant energy within a single model time step, causing it to underestimate the convective precipitation. In addition, other studies also reported that Grell(FC) tends to produce more convective rainfall amounts over land compared with Grell(AS) (e.g. Giorgi et al. 1993a, Davis et al. 2009, Zanis et al. 2009). Previous studies also showed that simulations using the Grell convective scheme generally underestimate precipitation over the tropical domain (Seth & Rojas 2003, Afiesimama et al. 2006, Fernandez et al. 2006, Seth et al. 2007, da Rocha et al. 2009), but these simulations perform reasonably well at mid-latitudes (Giorgi et al. 1994, 2004, Mearns et al. 1995, Pal et al. 2000, Lee et al. 2005). This shortcoming is likely due to the infrequent triggering of the scheme (Gochis et al. 2002, Ratnam & Kumar 2005, Im et al. 2006) over the tropical environment. Although the experiments with the MIT and MIT+Grell(FC) cumulus parameterization schemes generally reproduce the annual climatology spatial pattern well, they produce remarkable wet biases over the equatorial regions (Fig. 3). The MIT scheme is known to overestimate convective rainfall in regions with high water vapour and surface temperature such as the Maritime Continent. Several convective suppression criteria have been introduced to overcome the frequent triggering of convective rainfall in the MIT scheme (Chow et al. 2006). Nev-

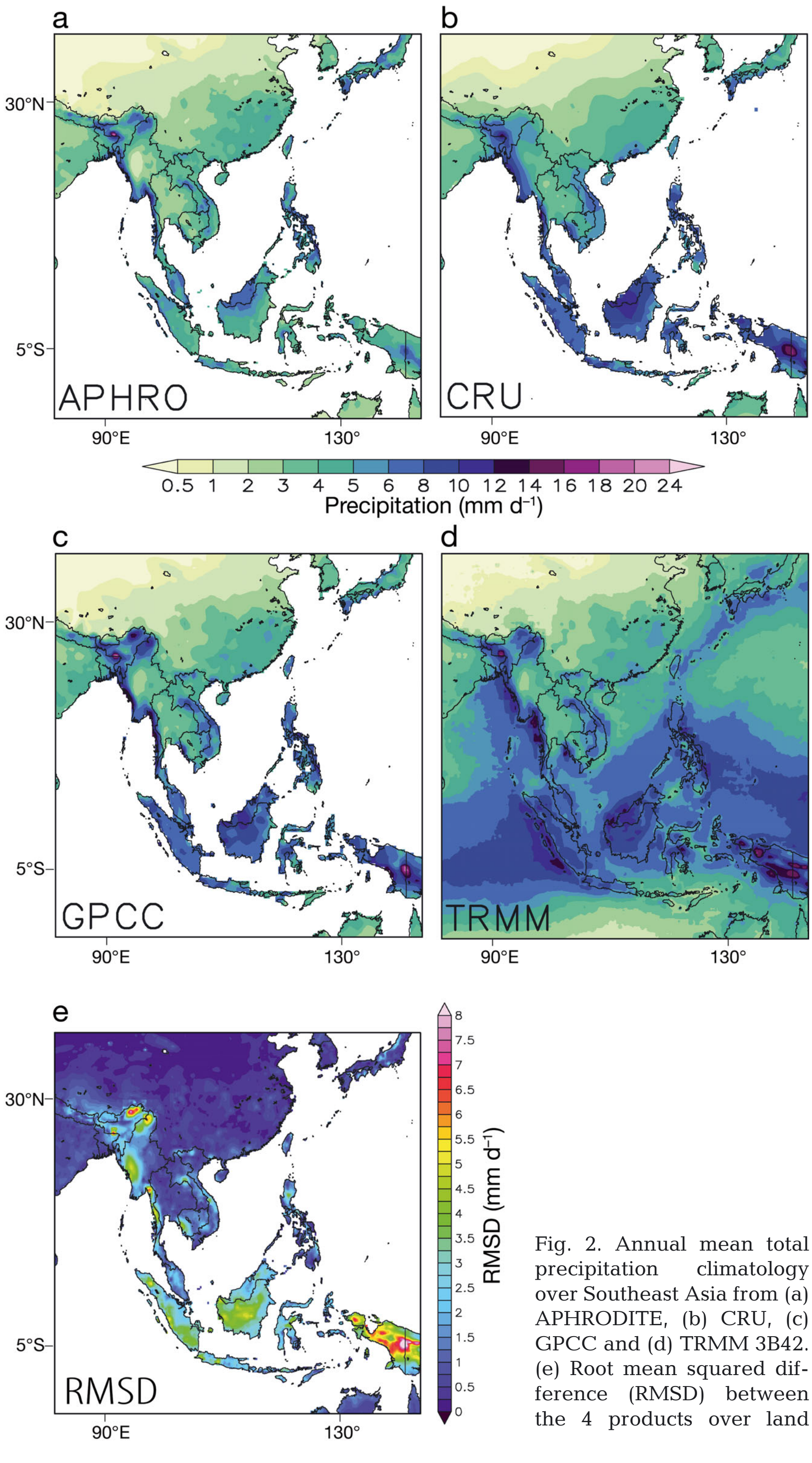

Fig. 2. Annual mean total precipitation climatology over Southeast Asia from (a) APHRODITE, (b) CRU, (c) GPCC and (d) TRMM 3B42. (e) Root mean squared difference (RMSD) between the 4 products over land

ertheless, these criteria were not implemented in any of the experiments using the MIT scheme in this study. Moreover, the experiments using the MIT+Grell(FC) cumulus parameterization scheme produced a very strong land–sea contrast over the equatorial region (not shown), which was not observed in the TRMM annual rainfall climatology (Fig. 2). In general, the experiments with MIT and MIT+Grell(FC) tend to produce more rainfall over land than over the ocean, consistent with other studies (e.g. Im et al. 2008, Davis et al. 2009). However, simulations using the MIT scheme produce a higher wet bias than the mixed MIT+Grell(FC) scheme. This finding is consistent with the study of Reboita et al. (2014) over the tropical regions. In general, the differences between the convection schemes are much larger than those between the 3 air–sea flux schemes.

Fig. 4 compares the domain-averaged stratiform and convective rainfall simulated by the different parameterizations of deep convection. As indicated by the TRMM datasets, the convective rainfall over land is slightly higher than that over the ocean, while the non-convective rainfall over the ocean is slightly higher than that over the land. However, all of the simulations produced much stronger non-convective rainfall over land compared to the ocean. This large discrepancy is likely due to the lack of air–sea interactions in all simulations. The MIT scheme generally produces consistent non-convective rainfall over land that is close to that of the observations, but it overestimates the convective rainfall. The MIT scheme has been reported to produce excessive rainfall because once the scheme is activated, it becomes difficult to slow down the processes involved in the scheme (Davis et al. 2009).

The spatial patterns of annual rainfall over the land area produced by the model from the 18 experiments were further compared in Taylor diagrams (Taylor 2001) (Fig. 5). The results suggest that the skill of the simulations in reproducing the annual rainfall varies remarkably according to the cumulus parameterization schemes used. On the other hand, the variations due to the air–sea flux schemes are

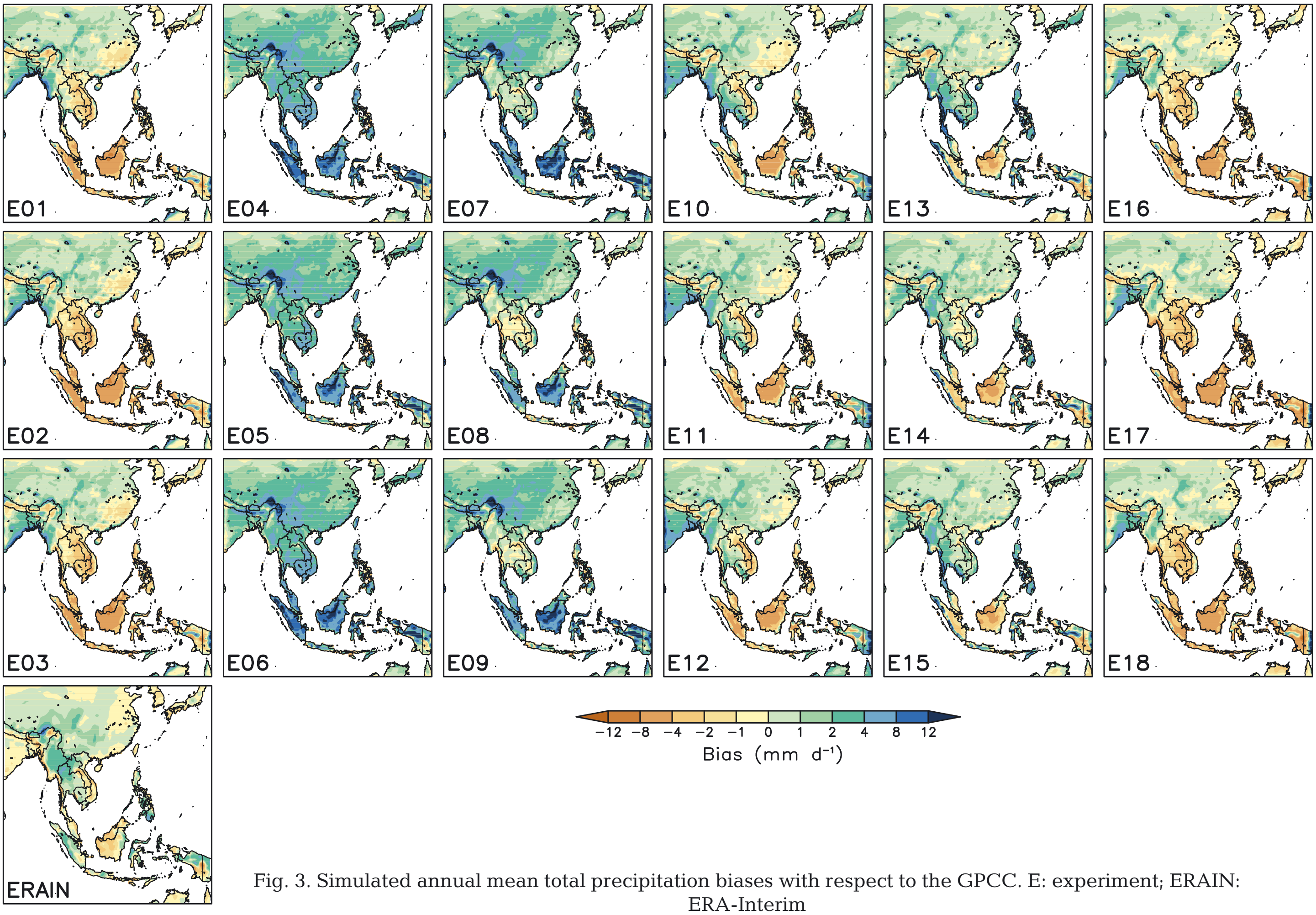

Fig. 3. Simulated annual mean total precipitation biases with respect to the GPCC. E: experiment; ERAIN: ERA-Interim

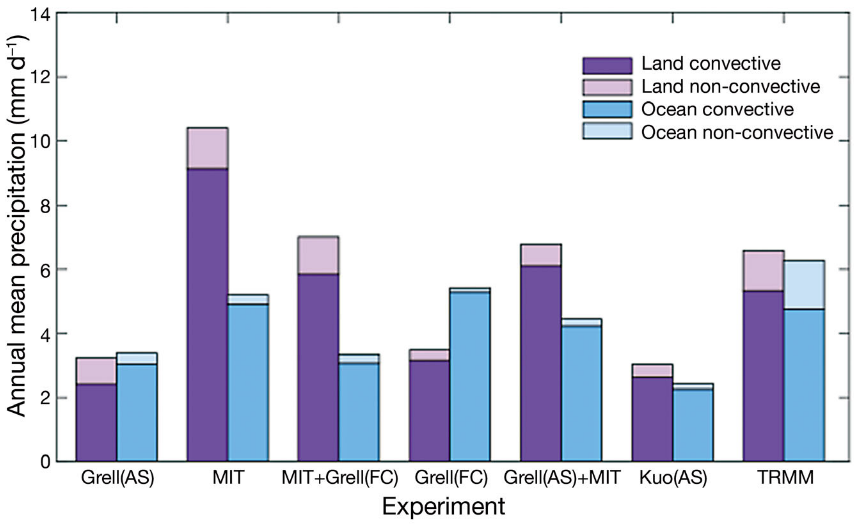

Fig. 4. Domain-averaged convective and non-convective rainfall simulated by the experiments averaged across the different air–sea flux schemes according to different cumulus schemes

minimal. The correlation coefficient between the simulated annual rainfall spatial patterns and those of the 4 observations ranged widely from ~0.2 (weakly correlated) to ~0.65, while the root mean square error (RMSE) ranged from ~2.5 to ~6, and the standard deviation from ~2.5 to ~6.5. Nevertheless, the ERA-Interim seems to have a better annual rainfall pattern consistency over the Southeast Asia region compared to the 4 observational gridded products. The spatial agreement between the ERA-Interim annual rainfall and those of the observations had correlation coefficients ranging from ~0.65 to ~0.85, while the RSME ranged from ~1.5 to ~2, and the standard deviation ranged from ~2 to ~2.5. This better consistency

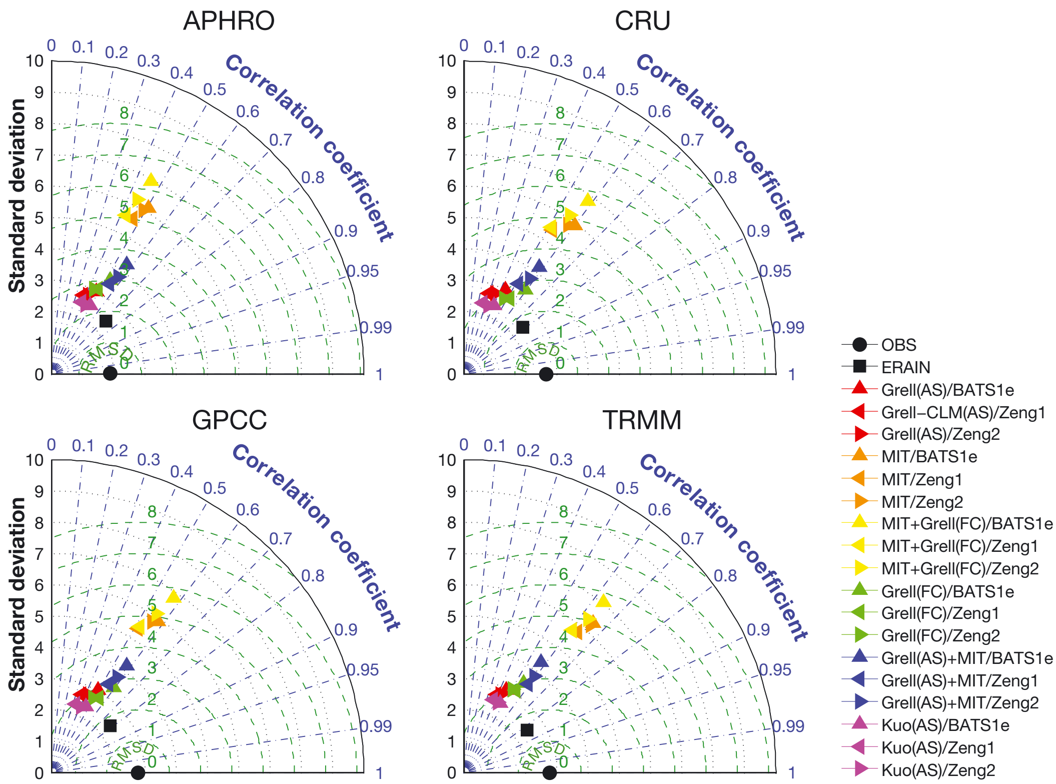

Fig. 5. Taylor diagrams showing the spatial comparison between the observed and simulated Southeast Asia annual mean rainfall over land. Black dots represent the observations (OBS), the black filled square represents the ERA-Interim (ERAIN), and triangles with different colours show the statistics of the simulations. Green dashed lines: centered root-mean-square difference between simulated and observed values

with the observations is expected, since the products of the reanalyses assimilated the observed atmospheric conditions in both space and time.

Three different sets of experiments using different cumulus schemes, namely the MIT, Grell(FC) and Grell(AS)+MIT, generally produced better annual rainfall climatology (Table 1). The Taylor diagram shows that those simulations that used the Grell(AS)+MIT (Expts 13–15) scheme performed better than the other simulations (Fig. 5). The correlation coefficient between the simulated spatial patterns and observations ranged from ~0.5 to ~0.6, while the RMSE ranged from ~3 to ~3.5, and the standard deviation ranged from ~3.5 to ~4.5. The simulations using either the MIT or MIT+Grell(FC) (except MIT+Grell(FC)/BATS1e) were found to have better spatial correlation compared to the observations, with correlation coefficient values ranging between ~0.4 to ~0.65. Nevertheless, their RSME and standard deviation values, ranging from ~4.5 to ~5.5 and ~5.5 to ~6.5, respectively, were relatively large compared to other simulations. This finding is consistent with the large wet biases in the simulations using the MIT schemes.

3.2. Annual cycle

The results in the preceding sections reveal that the configurations with the MIT and the Grell(AS)+MIT simulated rainfall climatology spatial patterns comparatively well. We further examine the performance of the 18 simulations in reproducing the annual cycles over the 20 sub-regions of Southeast Asia (see Fig. 1 for details of the sub-regions). Fig. 6 shows the time series of the observed and the simulated annual curves. The annual cycles of the 4 different observation datasets (CRU, GPCC, APHRODITE, TRMM) are plotted as ranges. The result suggests that the range of the different observation data sets is as large as the simulation uncertainties due to air–sea flux parameterization, but smaller than the uncertainties due to the cumulus parameterization in the simulations. In some regions, for instance in R5 and R14, despite producing larger positive biases, the shapes of the annual curves are better estimated in some simulations while others cannot reproduce the annual cycle correctly even though the simulated errors are relatively small. The correlation coefficients between the simulated and observed annual cycles in these sub-

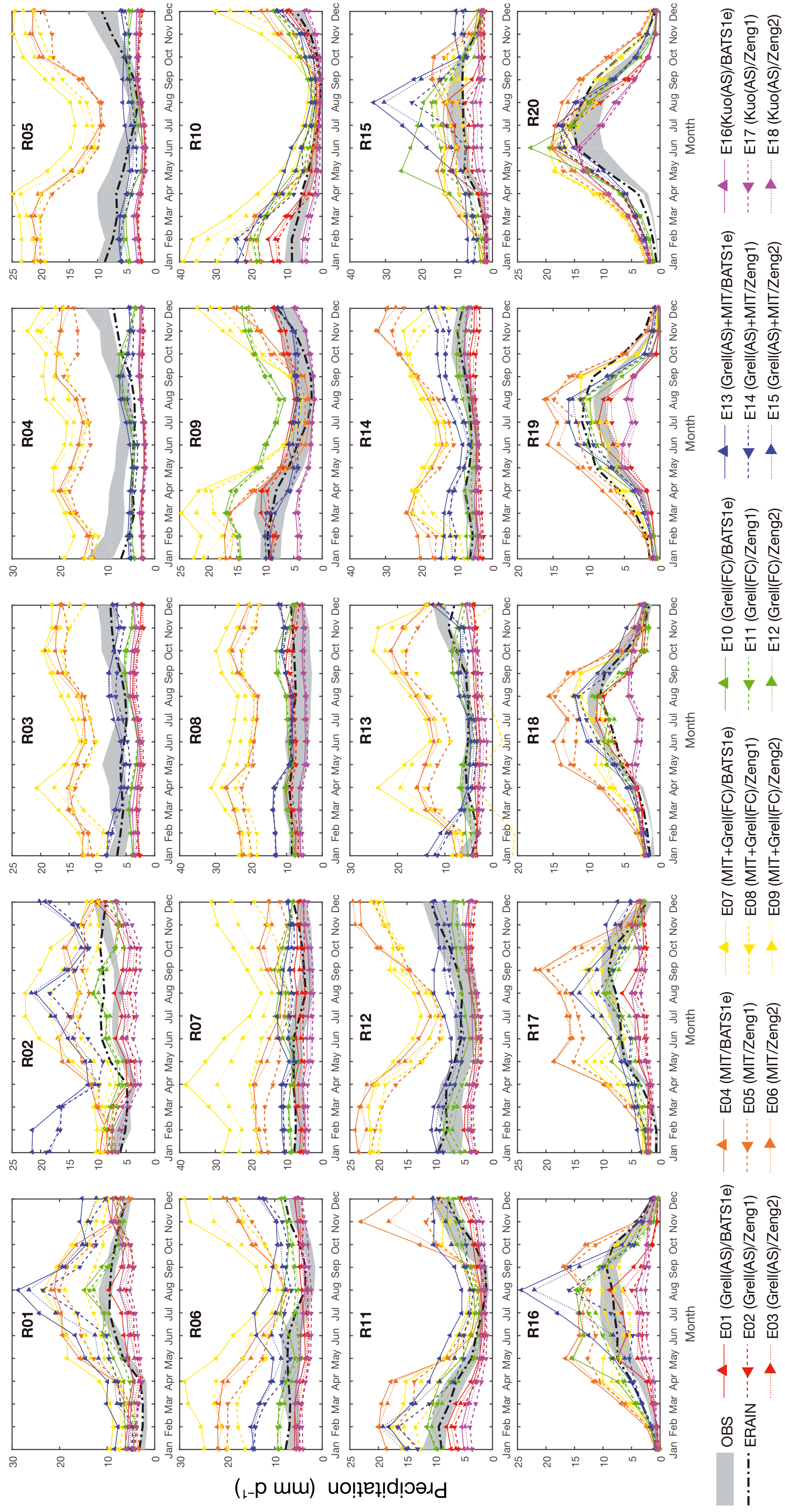

Fig. 6. Area-averaged annual cycle simulated by 18 experiments over 20 defined sub-regions, R (see Fig. 1). OBS: observations, ERAIN: ERA-Interim

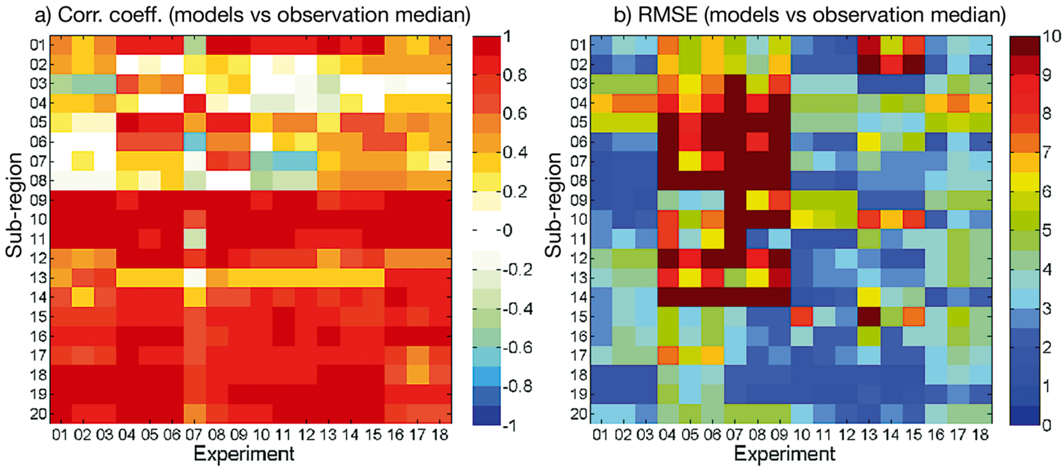

Fig. 7. Median values of (a) correlation coefficients and (b) root mean square error (RMSE) of the simulated total precipitation annual cycle compared to 4 different observational datasets

regions in Southeast Asia are shown in Fig. 7a. Overall, the annual evolution of rainfall in all simulations shows a high consistency with the observations, especially over most of the northern and western parts of Southeast Asia, as indicated by the high correlation coefficients. However, in the Philippines, Borneo and the eastern part of Indonesia (R1–R8), the correlations are lower. In fact, most of the simulations have difficulty reproducing the observed annual cycle over the eastern part of Southeast Asia (Fig. 6). Overall, the simulations with the MIT scheme present the highest correlations over most of the regions. In addition to the correlation, the RMSEs of the simulated and observed annual precipitation cycle are shown in Fig. 7b. The results show that the experiments with the Grell(FC) scheme (Expts 10 to 12) tend to have smaller RMSE values while the second best is the Grell(AS) scheme (Expts 01 to 03). However, the RMSE value is large (>5) over central Southeast Asia and in the Philippines (R01–R14) for the MIT and MIT+Grell(FC) schemes (Expts 04 to 09).

The results from both the spatial rainfall climatology and annual cycles show that the selection of the air–sea flux schemes has a nominal impact on the simulated overland rainfall, although in general, the BATS1e air–sea flux scheme seems to produce a slightly higher amount of rainfall compared to both Zeng schemes. This is consistent with the work of Francisco et al. (2006). Instead, the overland rainfall was more sensitive to the cumulus parameterization scheme chosen. This finding is in agreement with the study by Gianotti et al. (2012). They discovered that using either BATS1e or IBIS surface schemes in RegCM3 produced rather similar results, with small differences in the simulated maritime continent rainfall; the key, instead, is in the choice of cumulus scheme.

3.3. Interannual variability

The strength of interannual variability of precipitation is represented using the coefficient of variation of the mean annual rainfall and the observational values over Southeast Asia (Fig. 8). The interannual variations are generally lower over the equatorial region and slightly larger in the vicinity of the central South China Sea, particularly northern Borneo and the eastern coast of mainland Indo-China. Over the western region of mainland Indo-China, the interannual variations of annual rainfall are rather large, exceeding 20% of the annual mean. Over the northwestern corner of the study domain, the interannual variability exceeds 50% of the annual mean values. The interannual variation signals of the RegCM4 simulations (Fig. 9) are generally stronger compared to those of the observations (depicted in Fig. 8). The amplification of the models' variability is due to their failure to reproduce the complex nonlinear interaction between the monsoonal ocean–atmosphere interaction and the local processes (Webster et al. 1998, Park & Hong 2004, Ramel et al. 2006). Compared to other regional climate simulations over the tropical regions, e.g. in Mexico, Fuentes-Franco et al. (2014) reported that the interannual variability simulated by the RegCM4 model in that region showed comparable strength to the observed interannual variability. An important aspect of interannual variability over this region is the air–sea coupling process that cannot be resolved by atmosphere-only simulations (Zhu & Shukla 2013, Zou & Zhou 2013). Hence, the lack of air–sea coupling in the simulation may contribute to the stronger interannual signal in the simulation. This shortcoming is discussed further in this section.

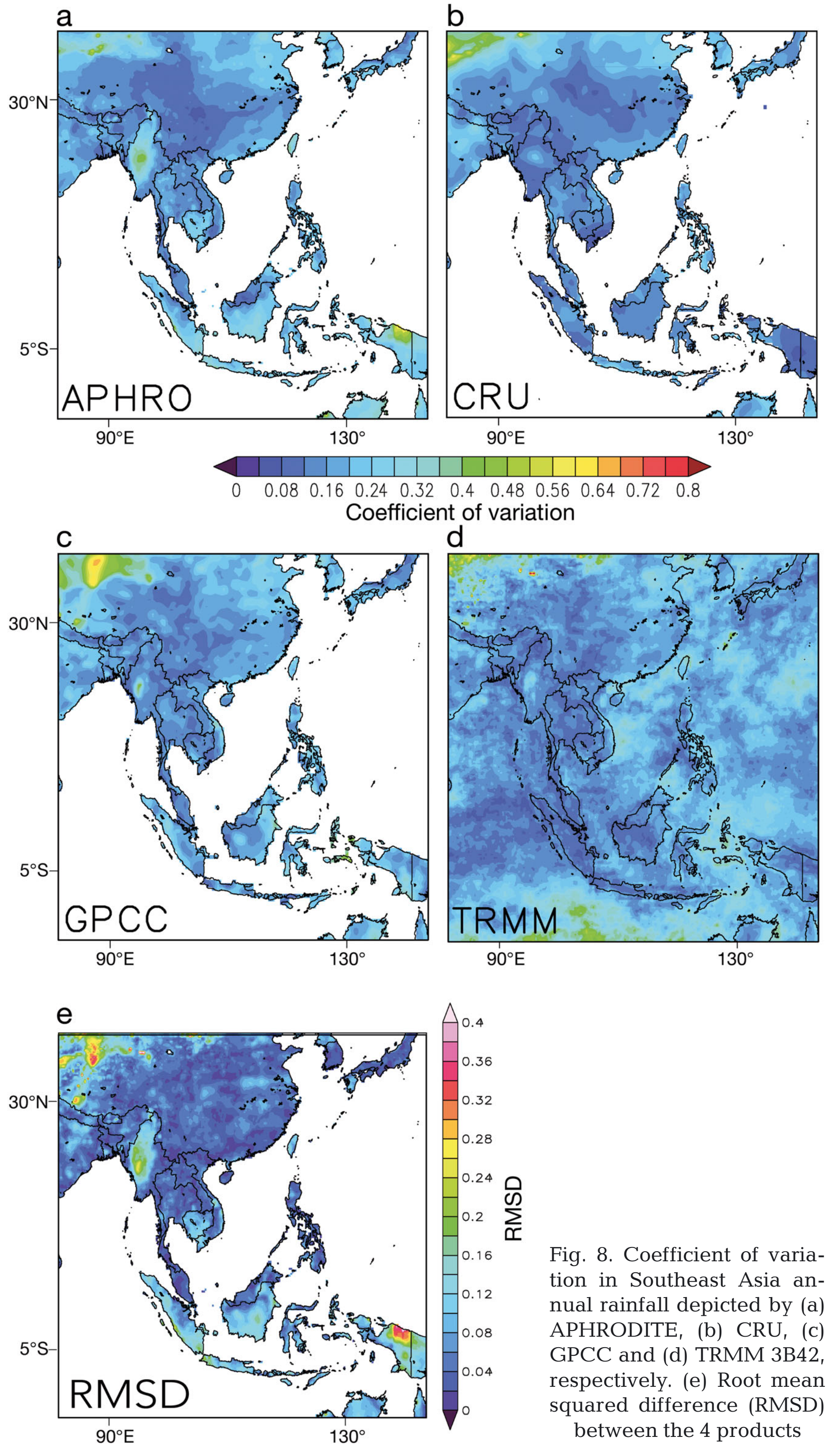

Fig. 8. Coefficient of variation in Southeast Asia annual rainfall depicted by (a) APHRODITE, (b) CRU, (c) GPCC and (d) TRMM 3B42, respectively. (e) Root mean squared difference (RMSD) between the 4 products

The performance of the simulations in reproducing the seasonal changes in the strength of interannual variations is examined for each of the sub-regions and against the 4 gridded observed precipitation products. The results are summarized in Fig. 10, which shows the median values of the RMSE and the correlation coefficient values of the simulations against the observed datasets. The statistics suggest that the simulations generally reproduced the seasonal changes of the interannual variability better over the Maritime Continent compared to the Southeast Asia mainland (R15–R20). This is evident in the much lower correlation coefficient values over the Southeast Asia mainland regions in all of the simulation experiments, and larger RMSE values in most of the experiments, except for the simulations using the Grell(FC) cumulus scheme (Expts 10 to 12) that have much larger RMSE values over the equatorial Maritime Continent regions instead.

Since the simulations were driven by the ERA-Interim, they are expected to reproduce the time evolution of the year-to-year variations. Fig. 11 shows the spatial distribution of the annual mean rainfall correlation values calculated over the 20 yr period between all simulations and the CRU dataset. Correlation maps (not shown) compared with other gridded precipitation products show similar patterns. Despite the generally good agreement with the observations, especially over the equatorial Maritime Continent, a notable weakness of all experiments is the simulated negative correlation values over the mainland Southeast Asia region. The negative correlations are persistent regardless of the experiments, indicating unrealistic rainfall anomaly processes simulated in all experiments. The rainfall anomaly processes involve complex interactions between local processes such as soil moisture (Seth et al. 2007) and large-scale forcings. Further examination reveals that the negative correlation values are prominently simulated during the summer months (figure not shown).

In order to further analyze the potential causes of such negative anomalies, a rainfall index was constructed by taking the averaged values within the re-

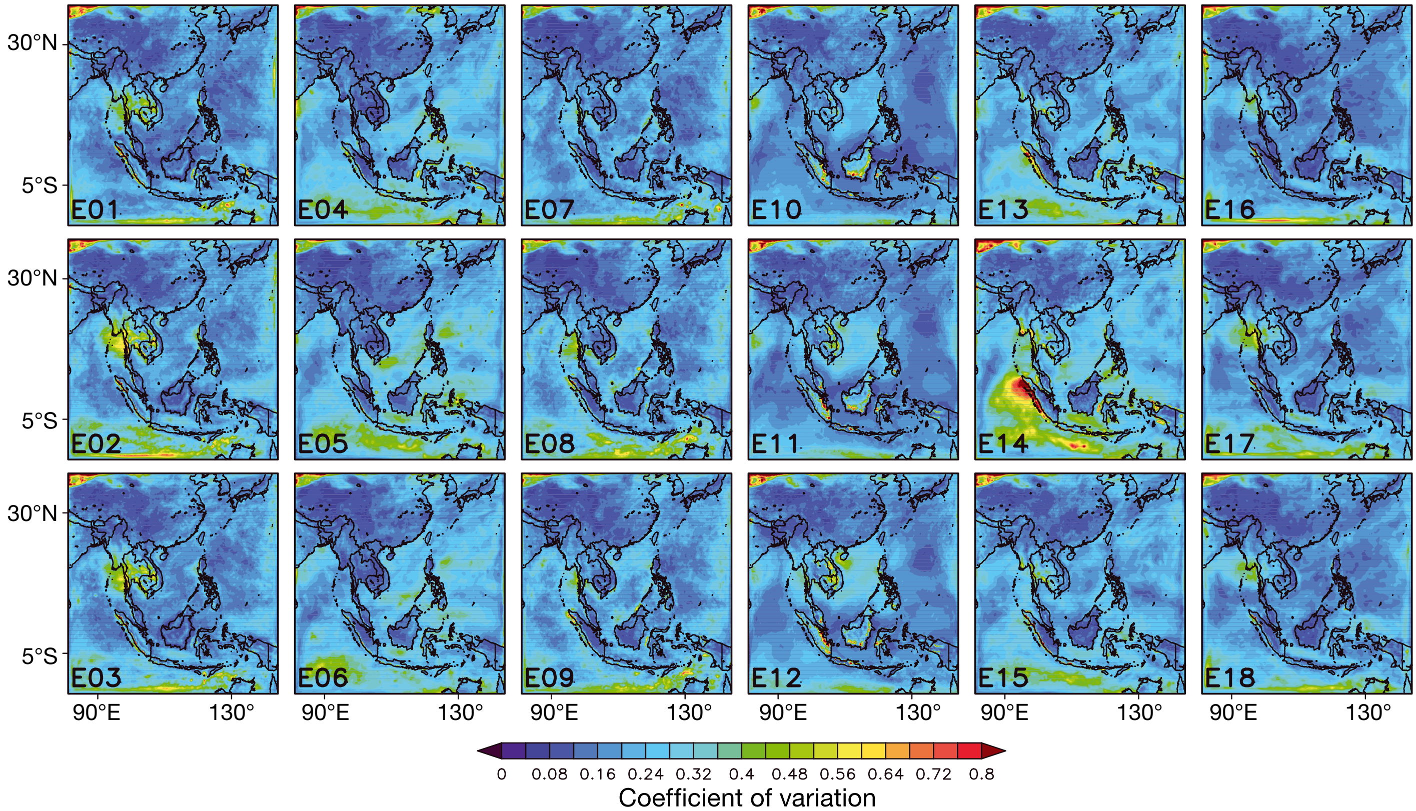

Fig. 9. RegCM4 simulated coefficient of variations of annual rainfall over Southeast Asia. E: experiment

gion 13–20° N, 100–103.5° E as representative of the Southeast Asia mainland rainfall. This was done for the June to August (JJA) rainfall from the MIT/Zeng1 simulation to represent the RegCM4 model. Similar indices were computed for the ERA-Interim and CRU datasets. These Southeast Asia mainland rainfall time series were then correlated to their respective surface variable fields, namely the surface air temperature, 850 hPa circulation and the surface heat fluxes (Fig. 12). However, for the CRU rainfall index, the ERA-Interim surface variable fields were used. Fig. 12 suggests that the RegCM4-simulated summertime Southeast Asia mainland rainfall is positively and strongly associated to the surface temperature over the South China Sea and eastern Indian Ocean. However, both the CRU and ERA-Interim indices only

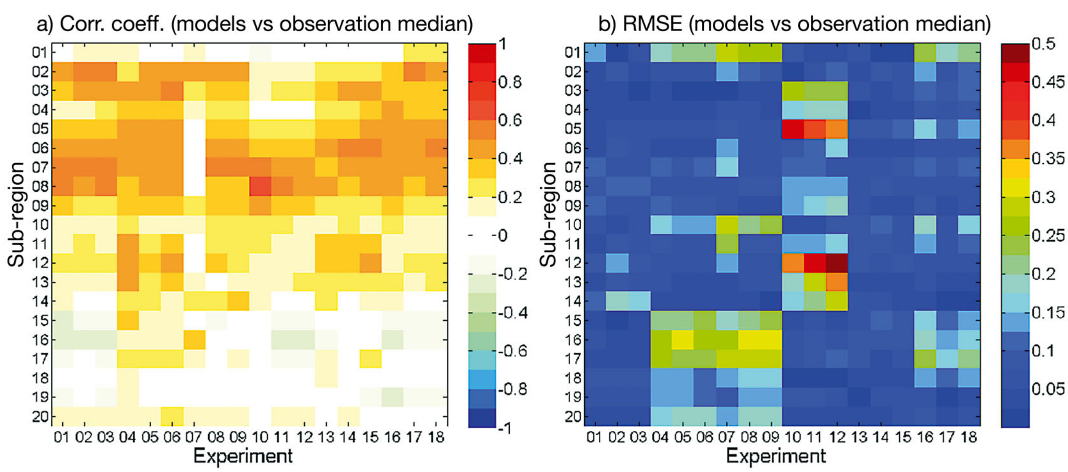

Fig. 10. Median of the root mean square error (RMSE) and correlation coefficient of the simulated interannual cycle compared to 4 different observational datasets

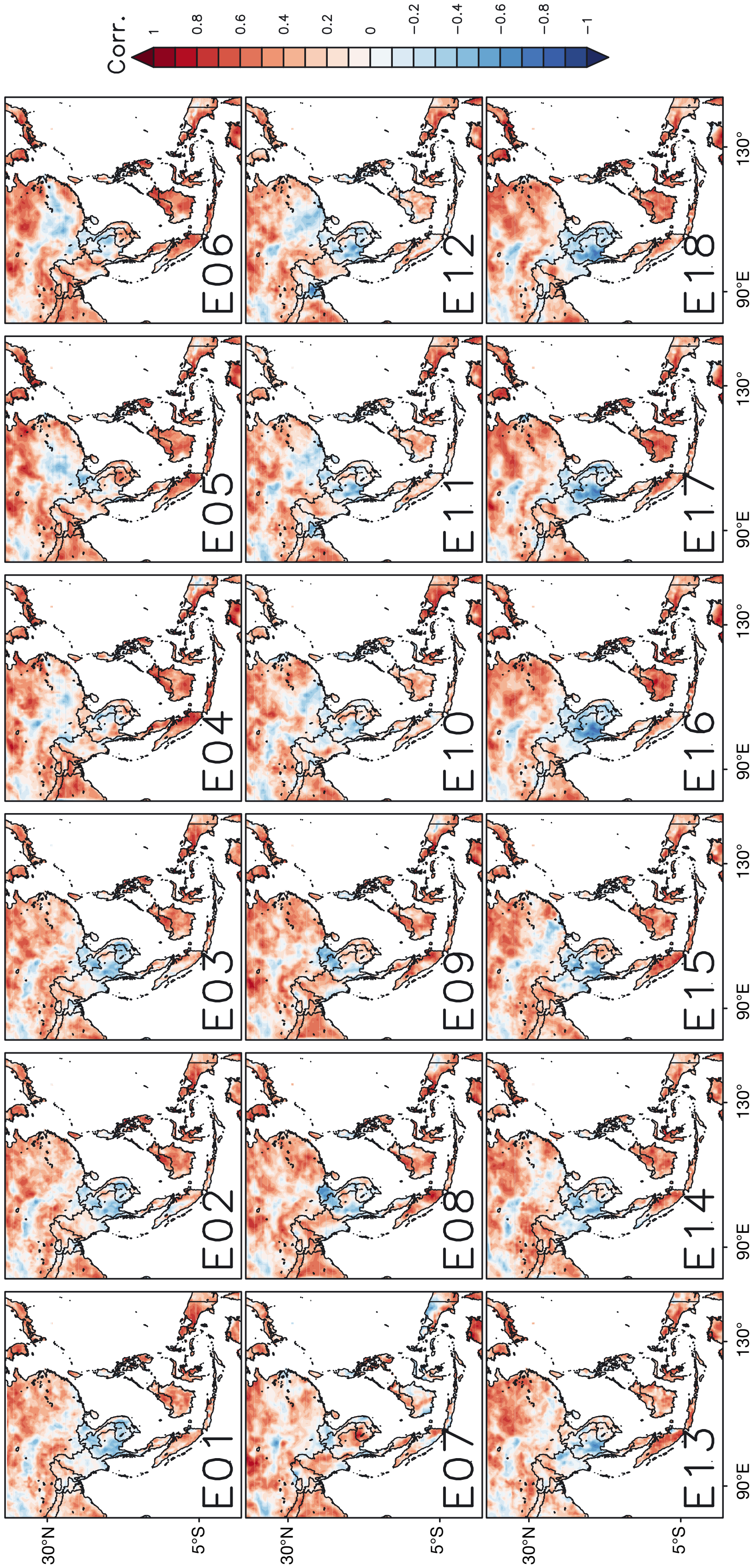

Fig. 11. Annual mean rainfall correlation coefficient (point-to-point) values calculated between the simulations and the CRU datasets

show moderate negative correlations over these regions. Also, the associated monsoon westerly winds over the mainland of Southeast Asia appear much stronger compared to the observations (Fig. 12). This shortcoming is related to the lack of air–sea coupling in the model. The importance of air–sea interaction in regional climate modelling over the western Pacific has been discussed in recent studies (e.g. Cha & Lee 2009, Kim & Hong 2010, Cha et al. 2016). Atmosphere-only numerical simulations during the summertime over the Indo-Pacific sector tend to produce much stronger atmospheric responses due to constant ocean forcings without damping (Zhu & Shukla 2013, Zou & Zhou 2013). This results in a large positive correlation between rainfall and sea surface temperature (Zou & Zhou 2013). However, in reality, the air–sea interaction tends to dampen the forcings where the atmosphere cools the sea surface via precipitation processes. The localized positive association between the mainland Southeast Asia rainfall and both of the surface heat fluxes in the observation (Fig. 12e,f,h,i) suggests that the rainfall anomaly processes in the region during the summer are largely locally forced. Large heat fluxes enhance the moisture supply and increase convective activities. However, due to large oceanic forcing from the adjacent seas, all RegCM4 simulations produce negative correlation coefficients between rainfall and the sensible heat fluxes. This behaviour suggests that the land surface responds to the atmospheric forcings and cools down with heavy precipitation as well as stronger surface winds. This results in negative rainfall anomaly correlations compared to those of the observations.

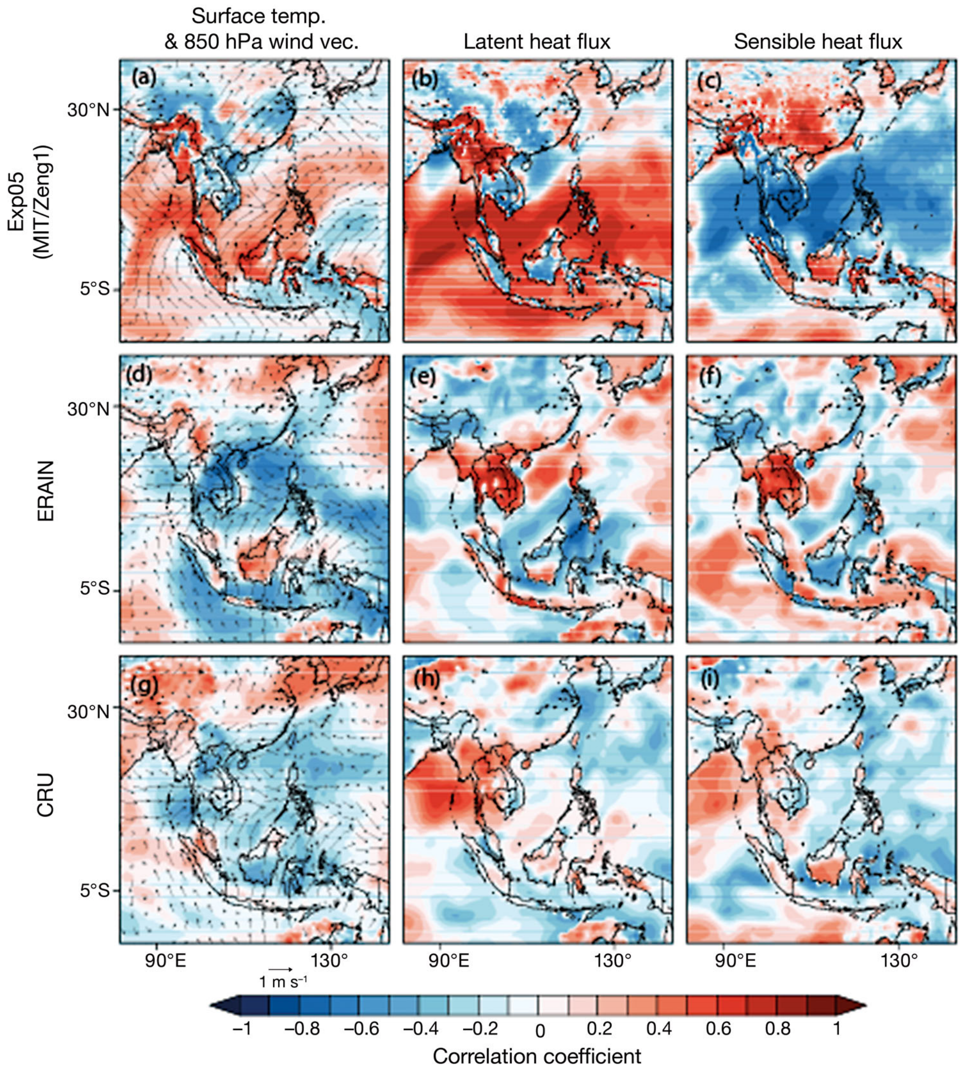

Fig. 12. Correlation between the summertime rainfall time series (see Section 3.3 for description) and (a,d,g) surface air temperature and the 850 hPa circulation, and (b,c,e,f,h,i) the surface heat fluxes in the simulation (first row) as well as the observations (second and third rows). For the CRU rainfall time series, the temperature, circulation and heat flux fields are those from the Era-Interim (ERAIN)

3.4. Selection of the optimal combination of physical parameterizations

The selection of the best combination of physics schemes may depend on which climate variables the simulations are validated against (and also to which observation datasets) and which characteristics and criteria (e.g. climatology, interannual variability, extremes) are examined. Strategically, it is better to consider several 'good' options (Reboita et al. 2014) to allow a sampling of the uncertainties associated with these different physics representations.

In order to have an objective comparison of the relative performance of 18 simulations, a scoring system was designed to rank the collective performance of the simulations, comparing them against each of the observational datasets. The score takes into account multiple criteria and different aspects of rainfall characteristics. To achieve this, the quality of the simulations is ranked in terms of (1) spatial RMSE, (2) spatial correlation coefficient, (3) the amplitude of the annual cycles over the 20 sub-regions, (4) the variation of the annual cycles over the 20 sub-regions, (5) the strength of the interannual variability in terms of coefficient of variation and (6) the actual year-to-year variability in terms of time-series correlation coefficients between the simulated and observed annual rainfall. For each of these 6 criteria assessed, 18 experiments were compared 4 different times using the 4 different observational gridded data products.

This setup results in a total of 24 sets of comparisons among the 18 experiments. An equal score of 1 was given to those experiments that ranked as the first 3 best in each of these 24 sets of comparisons. The distinctive separation of the performance between some simulations is not obvious for certain criteria assessed. However, by selecting the 3 best simulations for each criterion to allow a more robust sampling, the selection of the overall best-performing experiment can be achieved.

Fig. 13 shows the total scores compiled for each of the simulation experiments. The separation of the experiments is largely determined by the use of different cumulus parameterizations rather than the air–sea flux treatments. In general, the simulation with the MIT cumulus scheme and the Grell(FC) scheme appear to perform better compared to the rest of the simulations. In particular, the MIT/BATs1e simulation performed better than the other physics combinations. The MIT scheme had a good performance for many aspects of the rainfall characteristics, although it overestimated the rainfall amplitude.

4. CONCLUDING REMARKS

In this study, we analyzed the best physical configuration for RegCM4 to simulate the annual total rainfall in Southeast Asia. For this purpose, 18 simulation experiments from January 1989 to December 2008 were carried out with different combinations of cumulus parameterization schemes and air–sea flux treatments. The outputs from our 18 experiments were compared with APHRODITE, CRU, GPCC and TRMM to account for the differences among the gridded observational products. The simulation of rainfall in Southeast Asia is more sensitive to the choice of cumulus parameterization schemes than the air–sea flux treatments. Most of the experiments failed to resolve well the north-to-south, dry-to-wet gradient in the annual mean total rainfall climatological pattern of Southeast Asia, except those using the MIT and MIT+Grell(FC). Generally, most cumulus parameterization schemes produced a dry bias in the equatorial region where rainfall is high and a wet bias on the Southeast Asia mainland region where rainfall is low. The MIT scheme produced a wet bias over the entire domain, but the MIT+Grell(FC) resulted in a dry bias over the Indo-China region.

The selection of the best combination of physics schemes to be used in the regional climate projection simulations appears to depend on how simulation assessment is carried out. Arguably, it depends on which climate variables and which aspects of those variables are assessed. Also, it is also dependent on which gridded products are used as reference observations. Hence, to account for uncertainty from various sources, in this study we introduce a robust scoring system by ranking the individual experiments according to their ability to simulate various aspects of rainfall criteria against different observational products. The overall results suggest that the simulation with the combination of the MIT and BATs1e schemes produces better collective performance than the other schemes. However, it is also important to note that the absence of air–sea interactions in the simulations may lead to unrealistic rainfall anomaly processes over mainland Southeast Asia. The result is crucial in the interpretation and analysis of climate change signals when the model is used to produce downscaled climate change projections over the Southeast Asia regions. Also, the identified best combination of the MIT scheme and the BATs1e may be valid only for the domain settings. The obtained result can be sensitive to other different model settings such as location of lateral domain boundaries and the domain size, as well as the model's vertical and horizontal resolutions.

The physical parameterization schemes tested in this study are those from version 4.3 of the RegCM4 modelling system. However, a newer version of the RegCM4 offers several other physical parameterizations including the Tiedtke cumulus parameterization, the University of Washington PBL scheme and the newer CLM land surface model, in addition to the BATS land surface scheme. Several recent studies have reported better performance when the MIT deep convective

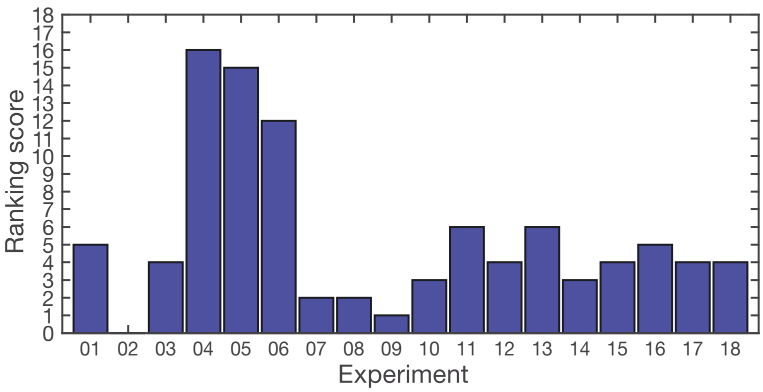

Fig. 13. Ranking scores of the 18 simulation experiments taking into account various aspects of rainfall characteristics

scheme is used in conjunction with the CLM instead of the BATS land surface scheme (Kang et al. 2014). This issue will be further investigated in SEACLID/ CORDEX Southeast Asia to improve our understanding of the roles of convective rainfall and land surface interaction processes in regional climate modelling over the Southeast Asia regions.

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