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Performance ranking of multiple CORDEX-SEA sensitivity experiments: towards an optimum choice of physical schemes for RegCM over Southeast Asia

Thanh Ngo-Duc¹ · Tung Nguyen-Duy^{1,2} · Quentin Desmet³ · Long Trinh-Tuan⁴ · Louis Ramu⁵ · Faye Cruz⁶ · Julie Mae Dado⁶ · Jing Xiang Chung⁷ · Tan Phan-Van⁸ · Ha Pham-Thanh⁸ · Kien Truong-Ba⁹ · Fredolin T. Tangang^{10,11} · Liew Juneng¹¹ · Jerasorn Santisirisomboon¹² · Ratchanan Srisawadwong¹² · Donaldi Permana¹³ · Utoyo Ajie Linarka¹⁴ · Dodo Gunawan¹⁵

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Abstract

This study conducted and evaluated 44 experiments using the non-hydrostatic version of the regional climate model RegCM4 (RegCM4-NH) and an additional three experiments with RegCM version 5 (RegCM5) over Southeast Asia for the period 2010–2015. The initiative was part of the coordinated regional climate downscaling experiment—Southeast Asia (CORDEX-SEA) project, in preparation for downscaling the latest coupled model intercomparison project Phase 6 (CMIP6) global climate models (GCMs). The RegCM4-NH experiments, forced by the ERA5 reanalysis, were configured using combinations of four cumulus, three planetary boundary layer (PBL), and three explicit moisture schemes. The spatiotemporal variability of simulated 2 m-temperature and rainfall for 2010–2015 was evaluated against observational datasets. The best experiments demonstrated reasonable reproduction of observed annual cycles and spatial distribution, while many exhibited unrealistic biases. A score ranking system was implemented to objectively compare the performance of experiments, enabling the identification of top-ranked experiments for Southeast Asia. The ensemble mean of the 44 RegCM4-NH experiments exhibited commendable performance, ranking 11th overall. Furthermore, the three additional RegCM5 experiments did not yield improved results compared to RegCM4-NH under the same physical configuration, suggesting that opting for RegCM4-NH would be a prudent choice for the CORDEX-SEA community in the forthcoming CMIP6 downscaling cycle for Southeast Asia.

Keywords Ensemble ranking · CORDEX-SEA · RegCM · Southeast Asia · Regional climate change

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1 Introduction

The Southeast Asia region, with a population of approximately 690 million people, i.e. about 8.6 percent of the world's population, is frequently exposed to extreme climate events (Hijioka et al. 2014). To be able to make appropriate climate change adaptation plans to climate change for the future, having detailed and reliable information about regional climate estimates is necessary.

To date, global climate models (GCMs) still have relatively coarse resolution, thus not providing enough detail for assessments of climate change and its impacts at the regional scale (Giorgi 2019). Consequently, numerous efforts have been made to obtain finer-scale information from these models. While some studies in Southeast Asia have employed statistical downscaling (SD) techniques (Tran-Anh et al. 2022, 2023), the broader use of dynamical downscaling has been favored due to limitations in long-term observed data that is used for constructing SD transfer functions, and the inability of SD to preserve the physical relationships between variables. The dynamical downscaling method employs regional climate models (RCMs) that perform high-resolution integrations within a specific domain, using initial and boundary conditions (ICBC) from GCMs (Giorgi 1999, 2019). Despite its high computational and storage demands, dynamical downscaling offers the advantage of interpreting the dynamical evolution, physical properties, and feedback processes within the climate system, which is invaluable for studies investigating the mechanisms and characteristics of climate change.

Some dynamical downscaling efforts have been individually conducted for a number of countries in the region, including Indonesia (McGregor et al. 2016), Malaysia (Chung et al. 2023; Kang et al. 2019; Ngai et al. 2020), the Philippines (Cruz et al. 2016; Villafuerte et al. 2020), Singapore (Doan et al. 2021, 2022; Simón-Moral et al., 2021), Thailand (Manomaiphiboon et al. 2013; Octaviani & Manomaiphiboon 2011), and Vietnam (Doan et al. 2019; Doan & Kusaka 2018; Katzfey et al. 2016; Phan et al. 2009; Van Khiem et al. 2014). Rahmat et al. (2014) provided downscaled climate projections at 0.22° resolution over Southeast Asia, based on 17 RCM experiments under the A1B emission scenario from the Special Report on Emissions Scenarios (SRES) (IPCC-SRES 2000).

In the first phase of the coordinated regional climate downscaling experiment—Southeast Asia (CORDEX-SEA) project (Tangang et al. 2020), dynamical downscaling experiments at 25 km resolution were conducted for the domain of (89.5°E–146.5°E, 14.8°S–27°N). The downscaling runs used 7 RCMs, including among others the regional climate model version 4.3 (RegCM 4.3)

(Giorgi et al. 2012), driven by the outputs of 11 GCMs participating in the coupled model intercomparison project phase 5 (CMIP5). In order to help configuring RegCM 4.3 for those future scenario runs, 18 different physical parameter combinations had been tested and evaluated beforehand (Cruz et al. 2017; Juneng et al. 2016; Ngo-Duc et al. 2017). This sensitivity analysis facilitated the selection of the MIT-Emmanuel convection scheme (Emanuel & Živković-Rothman 1999) combined with the BATS1e land surface scheme (Dickinson et al. 1993).

So far, investigations into dynamical downscaling results in Southeast Asia have primarily used downscaled outputs from either CMIP3 (Manomaiphiboon et al. 2013; McGregor et al. 2016; Ngo-Duc et al. 2014; Rahmat et al. 2014) or CMIP5 (Herrmann et al. 2020; Ngai et al. 2022; Supari et al. 2020; Tangang et al. 2020). It is crucial to note that the latest results presented in the intergovernmental panel on climate change (IPCC) sixth assessment report (AR6) (IPCC 2021) were based on data from CMIP6 GCMs integrated with the Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2016). Nevertheless, the spatial resolution of CMIP6 GCMs remains coarse, typically ranging from 100 to 200 km horizontally. Consequently, there is a need for downscaling CMIP6 outputs. It is pertinent to highlight that, as of now, there have been no studies focusing on the dynamical downscaling of CMIP6 products specifically tailored for the Southeast Asia region.

Within the framework of CORDEX-SEA and in preparation for downscaling the outputs of CMIP6 GCMs, this study aims to assess the performance of the non-hydrostatic version of the regional climate model RegCM4 (RegCM4-NH; Coppola et al. 2021), which is the latest stable version at the time of conducting the experiments, with various physical parameterization schemes over the CORDEX-SEA domain. Notably, the study domain now expands farther north than in the first phase, encompassing Myanmar—a country that was not fully covered in the model domain previously. This sensitivity assessment is essential to identify the most suitable physical parameterization configurations, thereby enabling the selection of optimal RegCM settings for downscaling CMIP6 GCMs in future periods over Southeast Asia.

2 Study domain, data, and method

2.1 Study domain

The study domain spans Southeast Asia (89.18°E–146.61°E, 14.72°S–29.36°N), covering 11 countries, namely Myanmar, Laos, Cambodia, Vietnam, Thailand, the Philippines, Malaysia, Singapore, Indonesia, Brunei, and East Timor.

In the assessment, climate variable values are computed specifically over land areas, chosen for the availability of

reference observational-based data sources for temperature and rainfall. Additionally, temporal evaluations are localized to three distinct sub-regions, as illustrated in Fig. 1: analysis domain 1 (AD1; Indochina), AD2 (Maritime Continent); and AD3, covering areas of the Philippines. This categorization aligns with the classification proposed by Desmet and Ngo-Duc (2022) considering the distinct seasonal behaviors of the sub-regions.

2.2 Numerical experiments

The RegCM4-NH model (Coppola et al. 2021) was employed to perform sensitivity experiments in this study. The model was configured with 281×230 longitude-latitude points, covering the CORDEX-SEA domain at 25 km resolution (Fig. 1). It included 18 vertical σ -levels, with the top level set at 5 mb, and employed the normal Mercator projection. As we focus exclusively on land within the aforementioned three sub-regions, the final analysis does not include data from the buffer zone.

Initial and time-dependent boundary conditions (ICBC) for RegCM4-NH were obtained from the fifth generation ECMWF reanalysis data (ERA5) (Hersbach et al. 2020) with a horizontal grid spacing of $0.25^\circ \times 0.25^\circ$ and a 6-h time interval. The model was continuously integrated from 00Z on January 1, 2010 to 18Z on December 31, 2015. The year 2010 is designated as the spin-up time, and only the period 2011–2015 was used for evaluation. It is worth noting that to conduct multiple experiments with affordable computing resources, we opted for a rather short period, 2010–2015, with the first year used for spinning up. The analysis period, 2011–2015, during which January

2011–March 2012 corresponds to a cold ENSO phase, and October 2014–December 2015 corresponds to a warm ENSO phase (Nguyen-Le et al. 2014; Nguyen-Thanh et al. 2023), while the remaining months are neutral. Therefore, as the later warm phase offsets the earlier cold phase, the 2011–2015 average can be considered a proxy for the region's climatology.

It is also important to note that we chose ERA5 as the ICBC for optimizing the schemes used in RegCM4-NH rather than optimizing them with each CMIP6 GCM. This is because the GCM used could exhibit significant biases when compared to observations. Optimizing the schemes with such biased ICBC complicates the analysis and makes it difficult to assess the accuracy and reliability of the RCM's outputs: it becomes challenging to attribute the sources of the model's errors to either the quality of the RCM itself or the quality of the ICBC. Instead, we need to select schemes that ensure the RCM performs optimally with perfect ICBC. Since ERA5 is a state-of-the-art reanalysis dataset that incorporates a large and diverse range of observations into its assimilation system (Hersbach et al. 2020), it can be considered a proxy for perfect ICBC. Therefore, we chose ERA5 as the ICBC in this study.

48 configurations were implemented using RegCM4-NH, incorporating diverse physical parameterizations. A detailed technical summary of these configurations is provided in Table 1. Four cumulus schemes were employed, namely MIT (Emanuel & Živković-Rothman 1999), Tiedtke (Tiedtke 1989), Kain-Fritsch (KF) (Kain 2004), and Grell (Grell 1993). The four planetary boundary layer (PBL) schemes include: Holtslag (Holtslag et al. 1990), University of Washington (UW) (Bretherton et al. 2004), global

Fig. 1 Study domain of CORDEX-SEA and its topography (shaded, in m). Boundaries of the three sub-regions used for temporal evaluations, namely AD1 (Indochina), AD2 (Maritime Continent), and AD3 covering areas of the Philippines, are highlighted in red, orange, and blue, respectively

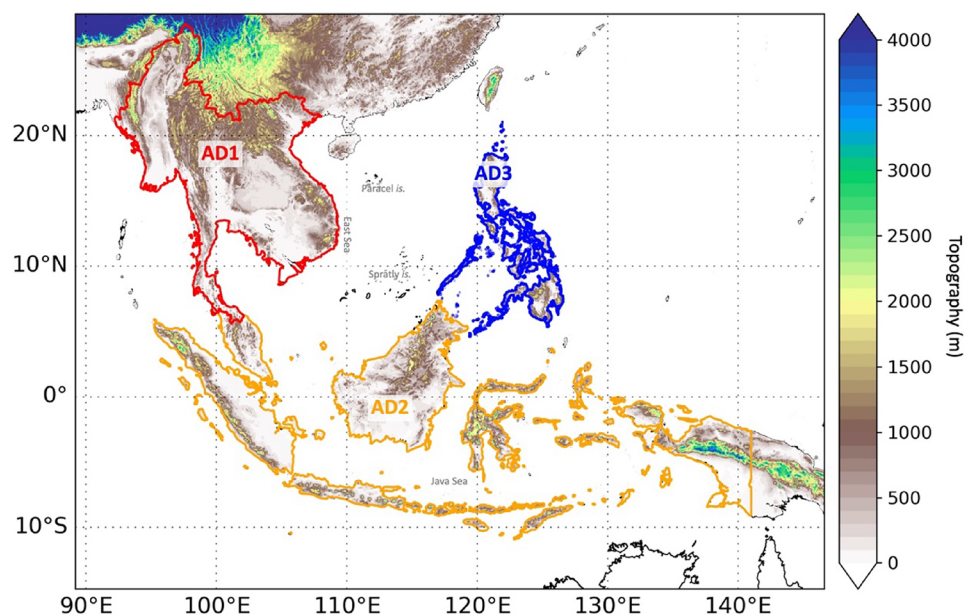


Table 1 List of 48 sensitivity experiments conducted with RegCM4-NH, numbered from 1 to 48, and three additional experiments conducted with RegCM5, called R5-exp16, R5-exp28, and R5-CORE

Exp	Cumulus	PBL	Moisture	Group	Exp	Cumulus	PBL	Moisture	Group
1	MIT	Holtslag	SUBEX	UKM	27	KF	Holtslag	NT	RU
2	MIT	Holtslag	WSM5	UKM	28	KF	UW	SUBEX	USTH
3	MIT	Holtslag	NT	UKM	29	KF	UW	WSM5	USTH
4	MIT	UW	SUBEX	UKM	30	KF	UW	NT	USTH
5	MIT	UW	WSM5	UKM	31	KF	GFS2011	SUBEX	USTH
6	MIT	UW	NT	UMT	32	KF	GFS2011	WSM5	USTH
7	MIT	GFS2011	SUBEX	MO	33	KF	GFS2011	NT	USTH
8	MIT	GFS2011	WSM5	MO	34	KF	MYJ	SUBEX	USTH
9	MIT	GFS2011	NT	MO	35	KF	MYJ	WSM5	USTH
10	MIT	MYJ	SUBEX	MO	36	KF	MYJ	NT	USTH
11	MIT	MYJ	WSM5	BMKG	37	Grell	Holtslag	SUBEX	USTH
12	MIT	MYJ	NT	BMKG	38	Grell	Holtslag	WSM5	UMT
13	Tiedtke	Holtslag	SUBEX	IMHEN	39	Grell	Holtslag	NT	UMT
14	Tiedtke	Holtslag	WSM5	IMHEN	40	Grell	UW	SUBEX	UMT
15	Tiedtke	Holtslag	NT	IMHEN	41	Grell	UW	WSM5	UMT
16	Tiedtke	UW	SUBEX	IMHEN	42	Grell	UW	NT	UMT
17	Tiedtke	UW	WSM5	IMHEN	43	Grell	GFS2011	SUBEX	UMT
18	Tiedtke	UW	NT	HUS	44	Grell	GFS2011	WSM5	UMT
19	Tiedtke	GFS2011	SUBEX	HUS	45	Grell	GFS2011	NT	UMT
20	Tiedtke	GFS2011	WSM5	HUS	46	Grell	MYJ	SUBEX	UMT
21	Tiedtke	GFS2011	NT	HUS	47	Grell	MYJ	WSM5	UMT
22	Tiedtke	MYJ	SUBEX	RU	48	Grell	MYJ	NT	UMT
23	Tiedtke	MYJ	WSM5	RU	R5-exp16	Tiedtke	UW	SUBEX	USTH
24	Tiedtke	MYJ	NT	RU	R5-exp28	KF	UW	SUBEX	USTH
25	KF	Holtslag	SUBEX	RU	R5-CORE	Tiedtke	Holtslag	NT	MO
26	KF	Holtslag	WSM5	RU					

Experiments 12, 24, 36, and 48 were not performed due to model instability issues. The table also indicates the eight research groups in the region that conducted the experiments, including: (1) Universiti Kebangsaan Malaysia (UKM), Malaysia, (2) Universiti Malaysia Terengganu (UMT), Malaysia, (3) Manila Observatory (MO), Philippines, (4) Agency for Meteorology Climatology and Geophysics (BMKG), Indonesia, (5) Institute of Meteorology, Hydrology and Climate Change (IMHEN), Vietnam, (6) Hanoi University of Science (HUS), Vietnam, (7) Ramkhamhaeng University (RU), Thailand, and (8) University of Science and Technology of Hanoi (USTH), Vietnam

forecast system 2011 (GFS2011) (Han & Pan 2011), and Mellor–Yamada–Janjić (MYJ) (Janjić, 2002). Resolved-scale precipitation schemes consist of the sub-grid explicit moisture (SUBEX) scheme (Pal et al. 2000), the single-moment five-class microphysics scheme of the WRF model (WSM5) (Hong et al. 2004), and Nogherotto/Tompkins (NT) scheme (Nogherotto et al. 2016). The remaining options used the default settings of RegCM4-NH, including the community climate model version 3 (CCM3) radiative transfer scheme (Kiehl 1996), the community land surface model version 4.5 (CLM4.5) (Oleson et al. 2013), the Zeng ocean flux scheme with the roughness option 1 (Zeng et al. 1998), and the original SUBEX option for the cloud fraction algorithm. It should be noted that a sensitivity test for ocean flux schemes was not conducted, as previous studies had demonstrated minimal effects on temperature and precipitation over Southeast Asia (Cruz et al. 2017; Juneng et al. 2016;

Ngo-Duc et al. 2017). Moreover, RegCM4-NH provides two options for land surface parameterization: CLM4.5 and the biosphere–atmosphere transfer scheme (BATS1e) (Dickinson et al. 1993). Chung et al. (2018) evaluated the performance of these schemes within RegCM4 for simulating precipitation over Southeast Asia. Their results indicated the advantages of CLM4.5 and suggested its utilization for further CORDEX-SEA simulations. Consequently, our study adopted the recommended CLM4.5 scheme.

Each research group within the CORDEX-SEA member countries was assigned a subset of experiments to conduct on their computing systems (refer to Table 1). Out of the 48 designed experiments, those numbered 12, 24, 36, and 48 (Table 1), which combined the MYJ and NT schemes (hereinafter referred to as MYJ + NT), were not performed due to model instability issues. Generally, instability issues occur if there is a violation of the Courant–Friedrichs–Lewy

(CFL) condition (Courant et al. 1928), i.e., if the selected time step is not small enough or if the computed wind speed at a specific location is excessively high. In our set of experiments, the MYJ+NT runs often crashed, despite setting the time step very small. For instance, while the time step in other combinations was typically set to 60 s, even reducing the time step to 1 s for the MYJ+NT combination could not resolve the issue. Consequently, the evaluation is presented for the 44 experiments with stable results.

It should be noted that RegCM4-NH was the latest version during the implementation of the aforementioned 44 experiments. Subsequently, the RegCM version 5 (RegCM5), featuring a new non-hydrostatic dynamical core from the weather prediction model MOLOCH, has become available (Giorgi et al. 2023). To assess whether the new model version could impact the results, three additional experiments were conducted with RegCM5: two experiments configured with the two top-ranked physical configurations for RegCM4-NH (experiments numbered 16 and 28, see Sect. 3.2), and one experiment configured with the optimal physics options chosen by the CORDEX Coordinated Output for Regional Evaluations (CORE) community (Coppola et al. 2024), but without the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA2) aerosol climate dataset—to maintain consistency with our initial RegCM4-NH experiments. The three additional experiments are respectively named R5-exp16, R5-exp28, and R5-CORE (Table 1). The results of these three new experiments are included in the performance ranking and compared to the 44 experiments conducted with RegCM4-NH as detailed above.

The performance evaluation and ranking of the experiments were also compared with the ERA5 reanalysis products at 0.25° resolution. This assessment aims to identify whether the regional simulations could yield added values compared to the ERA5 data source used as ICBC. Additionally, the ensemble mean (ENS_MEAN) of the 44 experiments with RegCM4-NH is included in the ranking.

2.3 Datasets

To assess the sensitivity of the experiments, we compared the simulation results of 2 m-temperature and rainfall with reference datasets, referred to as OBS. Specifically, we utilized the Asian precipitation—highly-resolved observational data integration towards evaluation of water resources (APHRODITE) dataset at a resolution of 0.25°×0.25°. For rainfall, we employed the V1101EX_R1 version (Yatagai et al. 2012), while for temperature, we used the AphroTemp_V1808 version (Yasutomi and Hamada 2011). These OBS datasets, hereinafter referred to as OBS_APHRO were derived from quality-controlled station data. It is worth noting that we conducted the evaluation solely over land, as

station networks are typically located there, providing reliable reference datasets.

To verify the robustness of the results, we conducted additional analyses using the climate research unit (CRU) data version TS v4.05 (Harris et al. 2014) as an alternative reference dataset. In the evaluation process against CRU, the resolution of model outputs was downgraded to match that of the CRU, i.e. 0.5°.

2.4 Ranking methodology

Desmet and Ngo-Duc (2022), henceforth referred to as DN22, introduced a methodology to evaluate the performance of CMIP6 models across Southeast Asia. This approach involved assessing the models' ability to reproduce regional climate features, such as near-surface temperature and rainfall. Subsequently, each model was assigned a ranking number, facilitating recommendations for selecting suitable CMIP6 GCMs for downscaling activities within the CORDEX-SEA domain.

Here, we apply the DN22 method to rank the sensitivity experiments, their ensemble means, and the initial ERA5 outputs. We focus solely on near-surface temperature and rainfall due to the availability of the reference datasets, and these are the two most commonly used variables for assessing model performance over land (Cruz et al. 2017; Juneng et al. 2016; Nguyen-Duy et al. 2023). The DN22 ranking method is summarized below.

A score ranging from 0 to 1 is computed for each experiment and variable, taking into account the experiment's capability to reproduce both temporal and spatial patterns observed in the variable. The evaluation of the temporal aspect is conducted using the climatological 12-month seasonal cycle, averaged across each sub-region. Metrics such as the correlation coefficient (CC), mean bias (MB), and normalized standard deviation (NSTD, defined as the ratio between the standard deviation of the modeled signals and that of the observed ones) are employed to assess the accuracy of these temporal cycles. Specifically, CC is used to compare phases, MB is for differences in mean values, and NSTD is for assessing differences in amplitude variability between the modeled and observed signals. In terms of spatial patterns, the evaluations focus on two seasonal means: boreal winter (December–January–February; DJF) and boreal summer (June–July–August; JJA) using the spatial versions of CC and NSTD. In Southeast Asia, DJF and JJA represent the two main seasonal patterns of the year and notably highlight the winter and summer monsoon, respectively (Chang et al. 2005). The seasonal patterns are sufficiently distinguishable for the two seasons over all the three analysis domains, ADI–3 (refer to Figs. 4 and 5 in the next section). Therefore, the capability to represent these distinct seasons is an important criterion for assessing the

performance of the experiments, explaining why we specifically selected these two seasons in the present study.

Subsequently, each computed value for CC, NSTD, or MB undergoes a transformation to $X = CC - 1, -|NSTD - 1|, -|MB|$, respectively. Thus, X falls within the interval $[-\infty, 0]$, and better performance corresponds to a higher X value.

Next, a score $S(X)$ is calculated, varying between $[0, 1]$, for each variable, aspect (temporal/spatial), sub-region/season, and statistic X using the formula:

$$S(X) = \beta^{\sigma(X+\delta)} \quad (1)$$

Here, three parameters, namely the tolerance δ , the scale factor σ , and the base β , are computed separately for each criterion based on the ensemble E of the 49 X values for the related metric (assessing 44 RegCM4-NH experiments, three additional RegCM5 experiments, the ensemble mean, and the ERA5 result), as follows:

$$\delta = |\max_E(X)| \quad (2)$$

$$\sigma = |\text{ave}_E(X + \delta)|^{-1} \quad (3)$$

$$\beta = \text{argmax}_{\beta \in [1, +\infty]} \text{std}_E(S(X)) \quad (4)$$

Finally, an overall score for each experiment is derived by successively averaging the scores obtained in the evaluation process: one score for each statistic (CC, NSTD, and MB), one score for each sub-region/season, one score for the temporal/spatial aspect, one score for temperature/rainfall, and ultimately, the overall score.

It is important to highlight that using an exponential base in the scoring system leads to a distribution that favors better performances: higher-quality simulations are assessed with tougher exigences and receive significantly higher scores, whereas lower-performing simulations result in less distinguishable scores. The methodology of the ranking algorithm, as thoroughly documented in (Desmet and Ngo-Duc 2022), has been employed to rank the best CMIP6 GCMs over the Southeast Asia region (Desmet and Ngo-Duc 2022) and Vietnam (Nguyen-Duy et al. 2023).

3 Results

3.1 Model performance

Figure 2 displays the annual temperature cycles across the three sub-regions of the CORDEX-SEA domain for the 44 RegCM4-NH experiments, their ensemble mean (ENS_MEAN), three additional RegCM5 experiments, ERA5 reanalysis output, and the reference dataset (OBS_APHRO). The RegCM4-NH experiments can effectively

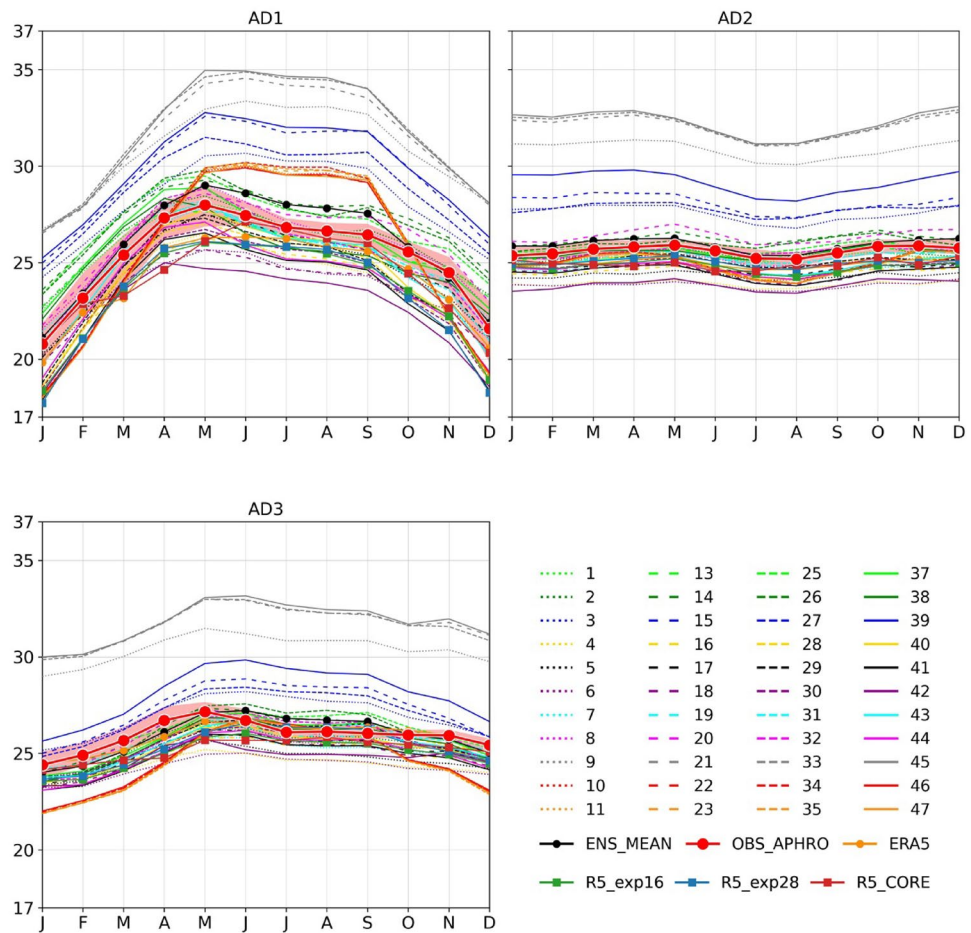
capture the annual temperature variations within sub-regions, with a relatively large range in AD1 (around 8 °C), a smaller range in AD3 (around 3 °C), and a relatively flat cycle in AD2. However, substantial biases in absolute temperature values exist between the models and OBS under certain configurations. Particularly noteworthy is the influence of the combined PBL and moisture schemes on temperature simulation. For ease of reference, experiments sharing the same PBL and moisture scheme combination are depicted with the same color in Fig. 2, while different line styles represent the four distinct cumulus schemes. It can be seen that experiments labeled 9, 21, 33, and 45 (GFS2011 and NT combination for PBL and moisture, respectively) consistently overestimate temperature by approximately 5–8 °C across all sub-regions. Experiments 3, 15, 27, and 39 (Holtslag and NT) exhibit an overestimation of about 2–5 °C. Conversely, Experiments 6, 18, 30, and 42 (UW and NT) consistently underestimate temperature. Experiments using the MYJ PBL scheme, including Experiments 10, 22, 34, and 46 (MYJ and SUBEX), 11, 23, 35, and 47 (MYJ and WSM5), yield similar results regardless of the cumulus and moisture schemes chosen. They typically underestimate temperatures across AD2 and AD3 throughout the year. This underestimation extends to AD1 during winter but shifts to an overestimation during the summer months.

One can note that the NT moisture scheme leads to either overly high (when combined with GFS2011 or Holtslag) or excessively low (when combined with UW) temperatures, or unstable condition (when combined with MYJ). The MYJ PBL scheme also produces a typical temperature underestimation. Consequently, the adoption of NT or MYJ for future downscaling activities using RegCM over Southeast Asia should be approached with caution.

In the remaining experiments, the absolute temperature differences are not excessively significant when compared to OBS, even though biases are unavoidable. Certain experiments produce results remarkably close to OBS, for instance, Experiments 19 and 31 over AD1, and 25 and 38 over AD2. ENS_MEAN demonstrates better performance compared to the majority of individual experiments, especially in AD2 and AD3. This suggests that averaging the experiments can alleviate the influence of outliers, thereby improving overall results. ERA5 and the three RegCM5 simulations can effectively capture the annual temperature cycles. However, they systematically underestimate temperatures, particularly over AD1 and AD2.

Figure 3 illustrates the annual rainfall cycles across the three sub-regions for the experiments and OBS. In AD1 and AD3, OBS values exhibit the characteristics of the summer monsoon, with a peak in rainfall occurring during JJA. Conversely, OBS depicts a winter monsoon peak over AD2. While most experiments successfully capture the rainfall

Fig. 2 Annual cycle of temperature over the three sub-regions of the CORDEX-SEA domain. The plots include data from the 44 RegCM4-NH experiments, their ensemble means (ENS_MEAN), ERA5, three additional RegCM5 runs, and the reference OBS_APHRO dataset. Pink shading indicates the inter-annual range of OBS_APHRO during 2011–2015. Unit in °C



peaks in the sub-regions, not all can reproduce the OBS amplitude accurately.

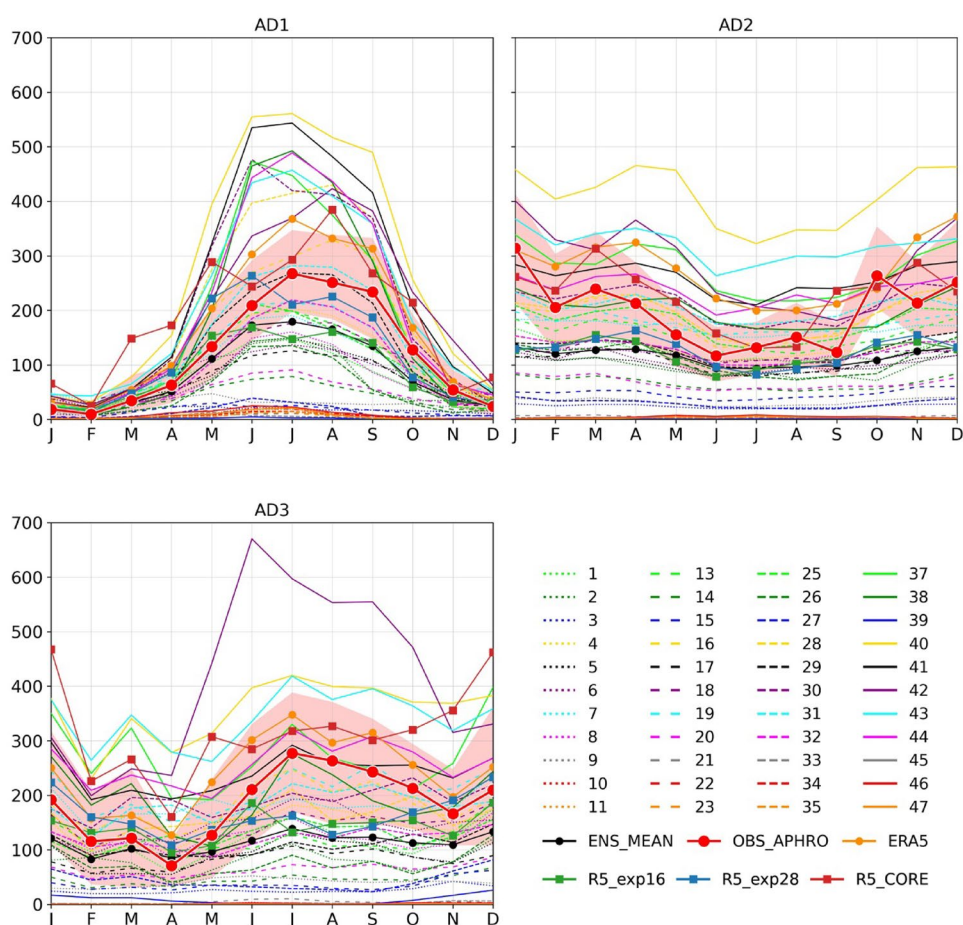
Several experiments employing the Grell cumulus scheme tend to overestimate rainfall, as seen in Experiments 40, 41, 42 (Grell and UW), 43 (Grell, GFS2011 and SUBEX), and 44 (Grell, GFS2011 and WMS5). In contrast, certain experiments exhibit unreasonably low rainfall values, particularly those utilizing the NT moisture scheme, such as Experiments 3, 15, 27, 39 (Holtlag and NT), 9, 21, 33, 45 (GFS2011 and NT), as well as experiments using the MYJ PBL scheme, including Experiments 10, 22, 34, 46 (MYJ and SUBEX), 11, 23, 35, 47 (MYJ and WSM5). It is noteworthy that experiments using the NT or MYJ schemes also yield unsatisfactory results for temperature, as shown in Fig. 2.

It can be seen that although ENS_MEAN performs better than many experiments, it largely underestimates the OBS values due to a high number of experiments that underestimate rainfall across the three sub-regions. ERA5 and the three RegCM5 simulations can effectively capture the annual rainfall cycles. However, while ERA5 and R5_CORE generally overestimate rainfall values across the three sub-regions, R5_exp16 and R5_exp28 consistently underestimate rainfall

over AD2 throughout the year and over the other two sub-regions during the rainy months. On another note, comparing the performance of R5_exp28 with the corresponding RegCM4-NH experiment, i.e. experiment 28, without considering statistical quantities is challenging (Fig. 3). However, it becomes evident from Fig. 3 that experiment 16 with RegCM4-NH aligns more closely with OBS than R5_exp16, observed in both better seasonal variations and smaller biases across the three sub-regions. This outcome suggests that the new RegCM version 5, featuring the new dynamical core MOLOCH noted for its improved computational efficiency (Giorgi et al. 2023), does not necessarily enhance the model’s performance over Southeast Asia.

Figure 4 displays the spatial distribution of JJA and DJF temperatures, represented by OBS, the most accurate experiment for spatial temperature distribution (experiment 29, depicted in Fig. 6a), and ENS_MEAN, along with the standard deviation of the 44 RegCM4-NH experiments. In JJA, observed temperatures are relatively high, generally exceeding 25 °C across the entire domain, with some areas, notably in AD1, experiencing temperatures above 28 °C. Experiment 29 demonstrates overall good performance with an NSTD of 1.07 and a CC of 0.88. Remarkably, experiment

Fig. 3 As in Fig. 2, but for rainfall. Units in mm/month



29 effectively captures lower temperatures resulting from elevated topography in mountainous regions such as western Vietnam, the southwest part of Sumatra and Java, and the mountains in Borneo. ENS_MEAN well represents the observed patterns over AD2 and AD3. However, it tends to overestimate JJA temperatures in AD1, leading to an overall increase in NSTD to 1.19, despite maintaining a comparable CC with experiment 29 (0.87). The standard deviation, considered as an indicator of the similarity among the 44 experiments, indicates notably high values in AD1, exceeding 3 °C, thus suggesting a significant level of uncertainty in the simulation results for this sub-region.

In DJF, observed temperatures increase from below 20°C in the northern part of AD1 to around 25 °C and above in the southern part of Southeast Asia. The DJF spatial temperature pattern is well represented by experiment 29 and ENS_MEAN, with NSTDs of 1.13 and 1.09, respectively, and with the same CC value of 0.94. Similar to JJA, the experiments can accurately capture the relatively lower temperature values resulting from elevated topography in the study domain. The standard deviation, similar to JJA, shows high values in AD1. Additionally, the spread in DJF is slightly higher than that in JJA over AD2, indicating a relatively higher level

of uncertainty in simulating temperatures over this analysis domain in DJF compared to JJA.

Figure 5 is similar to Fig. 4 but focuses on rainfall. Rainfall amounts are higher in JJA compared to DJF in AD1 and AD3. Conversely, in AD2, DJF rainfall is higher than JJA rainfall. The best experiment for spatial rainfall distribution (Experiment 28, as depicted in Fig. 6b) demonstrates overall reliable seasonal large-scale patterns. However, in JJA, Experiment 28 fails to reproduce local-scale patterns in certain areas, such as the notable intensification of rainfall over AD1. This discrepancy results in a high NSTD of 2.15 and a relatively low CC of 0.65. An additional analysis of low-level atmospheric circulation, specifically focusing on 850 hPa wind, shows that the summer monsoon is significantly overestimated over AD1 in experiment 28 (Supplemental Figure A4). This overestimation leads to more moisture being brought from the Indian Ocean to the Indochina Peninsula during JJA, primarily explaining the wet bias of the experiment over AD1. Experiment 28 performs better in capturing OBS in DJF, with an NSTD of 0.92 and a CC of 0.71. The ensemble mean ENS-MEAN smooths out the spatial variability in both JJA and DJF, yielding lower NSTD values of 0.88 and 0.57, respectively. The lower performance

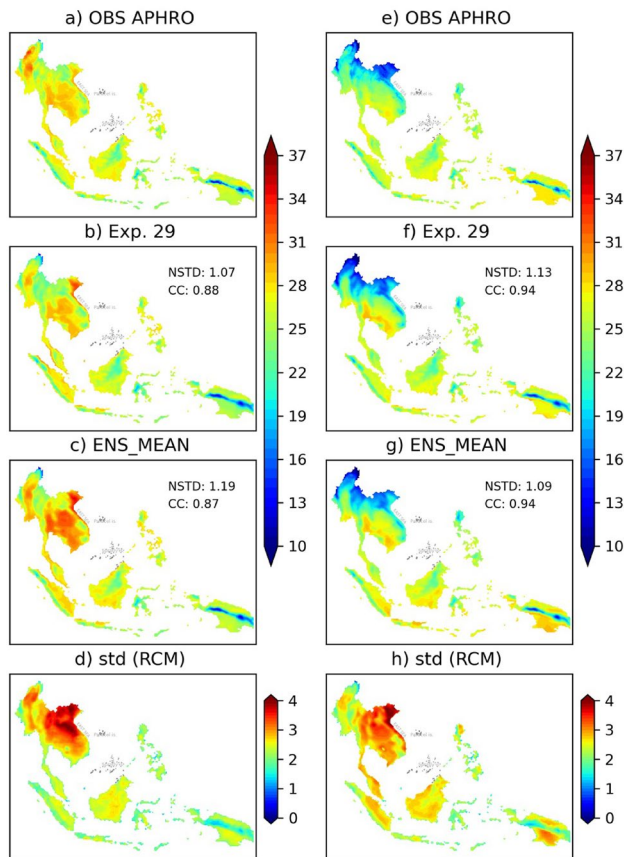


Fig. 4 Spatial distribution of JJA (left) and DJF (right) temperatures for **a, e** OBS, **b, f** the experiment best representing spatial temperature distribution, i.e. Experiment 29, **c, g** the ensemble mean, and **d, h** the standard deviation of the 44 sensitivity experiments using RegCM4-NH. Text inside **b** and **f** (**c** and **g**) indicates the NSTD and CC values between the best experiment (the ensemble mean) and OBS. Units in °C

of ENS-MEAN compared to Experiment 28 is further supported by its lower CC values (0.53 and 0.64 in JJA and DJF, respectively). In JJA, the ensemble standard deviation is relatively high in AD1 and in the western part of AD3 where the summer monsoon dominates. In DJF, the deviation is relatively high in AD2 and the southern part of AD3, where the winter monsoon prevails. This indicates a relatively high uncertainty in the simulation results for these sub-regions during the respective JJA and DJF periods of the year.

3.2 Experiment ranking

Figure 6 depicts the final ranking of the experiments, obtained after the scoring method we explained in Sect. 2.4. Four configurations distinctly stand out: experiments 31, 16, 29, and 28, all achieving similar scores of approximately 0.6. The subsequent six experiments in the top-ten exhibit noticeably lower scores, decreasing from around 0.55 to 0.5.

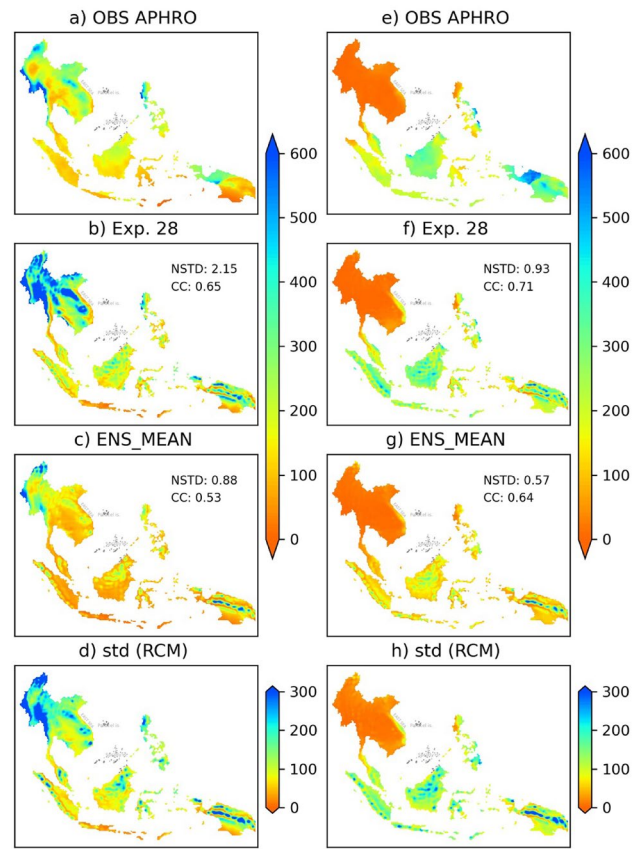


Fig. 5 Same as Fig. 4 but for rainfall. The experiment best representing spatial rainfall distribution is experiment 28. Units in mm/month

Generally, the top-ten experiments rank among the bests for both variables, with a few exceptions. For instance, experiment 32 secures the 9th position overall due to its rainfall ranking at 5th place, compensating for a lower temperature score (ranking 18th). On the other hand, despite a poor ranking for rainfall (20th), experiment 17 eventually secures the 10th position, thanks to its top-three performance in temperature.

It is noteworthy that seven out of the top eight ranked experiments among the 44 RegCM4-NH experiments use either the cumulus scheme KF (five experiments: 28–32) or Tiedtke (three experiments: 16, 17, 19), either the PBL scheme UW (five experiments: 16, 17, 28–30) or GFS2011 (three experiments: 19, 31, 32), either the moisture scheme SUBEX (four experiments: 16, 19, 28, 31) or WSM5 (three experiments: 17, 29, 32). Only one experiment using the moisture scheme NT (30) ranks relatively high, at the 7th place. However, it exhibits quite poor results for the time series of temperature and precipitation, compared to other experiments, and therefore mostly gets this high rank from a good performance at reproducing spatial variability. This is also true for R5-exp16, showing a much worse performance at simulating precipitation cycles than

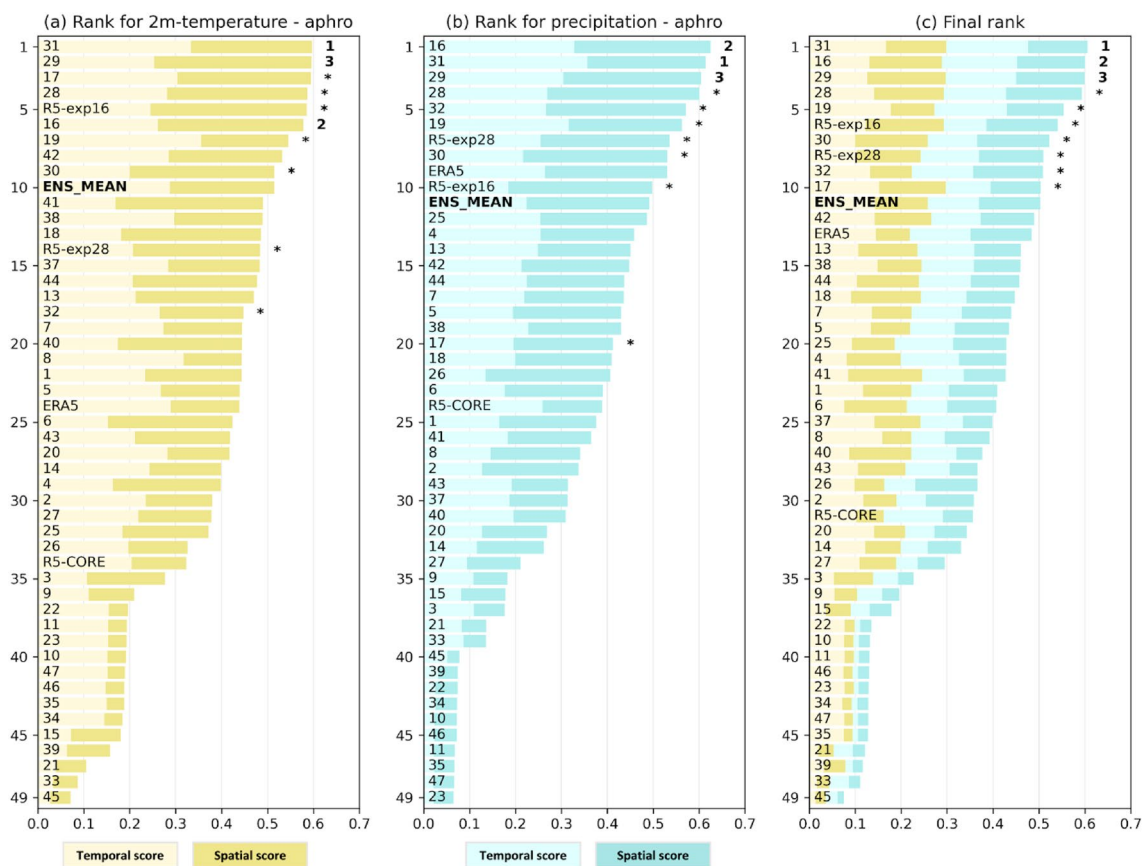


Fig. 6 Scores and rankings of 44 RegCM4-NH experiments, their ensemble mean (ENS_MEAN), three RegCM5 experiments, and ERA5 for **a** temperature, **b** rainfall, and **c** both variables. The contribution of temporal and spatial scores is represented by light and dark

yellow (cyan) for temperature (rainfall), respectively. Bold numbers label the top three experiments, and asterisks mark the subsequent seven experiments in the final ranking

its RegCM4-NH counterpart. Besides, we can observe that the remaining top experiments seem to be supported by a balanced contribution of both temporal and spatial aspects, as well as of both variables.

Among the 16 experiments ranked worst from 34 to 49th, there are eight experiments using the NT moisture scheme (3, 9, 15, 21, 27, 33, 39, 45) and eight experiments using the MYJ PBL scheme (10, 11, 22, 23, 34, 35, 46, 47). Experiments with MYJ (NT) generally give the worst simulation results for rainfall (temperature) followed by experiments with NT (MYJ). Experiments with the Holtslag PBL scheme generally yield low rankings, mostly ranging from 20th to lower positions, with the exception of experiments 13 and 38, which rank 14th and 15th, respectively.

ENS_MEAN exhibits commendable performance, ranking 10th for temperature, 11th for rainfall, and 11th overall. Meanwhile, ERA5 ranked 13th, with its low temperature ranking (24th) offset by its relatively good rainfall representation (9th). Thus, it can be seen that if a suitable configuration is chosen, the regional experiment can provide added

values in simulating rainfall and temperature compared to the reanalysis product used as input ICBC.

Note that the two additional RegCM5 experiments, R5_exp16 and R5_exp28, also secure positions in the top ten (6th and 8th, respectively), although they rank lower compared to their corresponding RegCM4-NH experiments, which use the same physical options—16 and 28 (ranked 2nd and 4th, respectively). Meanwhile, R5-CORE only ranks 31st, with variable rankings of 34th and 24th, respectively for temperature and rainfall. The underperformance of R5-CORE across Southeast Asia can be attributed to the low and moderate capabilities of the NT moisture and the Holtslag PBL schemes, respectively, chosen in its configuration, as demonstrated in the RegCM4-NH experiments.

3.3 Discussions

Considering the chosen resolution and model parameters (i.e. the default, in a number of physics aspects and within the tested schemes), we demonstrated that the MYJ, NT, and Holtslag schemes yield unsatisfactory results in simulating

both temperature and rainfall over Southeast Asia. Conversely, the KF and Tiedtke cumulus schemes, the UW PBL scheme, and the SUBEX moisture scheme appear to dominate the configurations of the top-ranked experiments. It is noteworthy that conducting a comprehensive study to assess the advantage of one scheme over another is beyond the scope of our present research. Nonetheless, prior research efforts have undertaken such comparisons in various domains.

Specifically, the CORDEX-SEA community (Cruz et al. 2017; Juneng et al. 2016; Ngo-Duc et al. 2017) evaluated the sensitivity of RegCM4.3 with the Grell, MIT, and Kuo cumulus schemes, highlighting the advantage of the MIT over Southeast Asia. In our present study, we reveal that the new cumulus schemes integrated into RegCM4-NH, namely Tiedtke and KF, exhibit more favorable results in the region. Given the tropical nature of Southeast Asia, it is important to note that the region experiences a high average percentage of convective rainfall. Consequently, accurately representing this quantity poses a significant challenge for cumulus schemes. For instance, Gianotti and Eltahir (2013), using the Tropical Rainfall Measuring Mission (TRMM) dataset, estimated this percentage to be about 63% over land and 57% over the ocean in the Maritime Continent region. Ngo-Duc et al. (2017), using the ERA-Interim reanalysis product, estimated the convective percentage to be about 80% of the total rainfall. They also demonstrated that certain RegCM configurations tend to overestimate the contribution of convective rainfall in the low-latitude region, reaching around 95% over the Maritime Continent. Previous studies have discussed that this overestimation of convective rainfall is due to the fact that convection is more frequently triggered with certain schemes because of fewer triggering requirements; hence, more precipitation is produced (Im et al. 2008; Zanis et al. 2009).

Among the 48 RegCM4-NH experiments conducted in the present study, the KF cumulus scheme, followed by the Grell and Tiedtke schemes, appears to produce more convective rainfall, while the MIT scheme tends to produce the least across all three sub-regions (Supplemental Figure A1). However, convective rainfall depends not only on the choice of cumulus schemes but also on the combinations between the cumulus scheme and other physical parameterizations. For instance, Experiment 30, combining the KF cumulus, UW PBL, and NT moisture schemes, produces very high convective rainfall during the boreal summer, while Experiment 34, combining the KF cumulus, MYJ PBL, and SUBEX moisture schemes, is very dry in terms of convective rainfall.

Regarding the choice of moisture schemes, Kalmár et al. (2021), using 23 vertical levels with 10 km horizontal resolution, showed that the NT scheme outperforms the default SUBEX scheme in RegCM4.5 over the Carpathian region.

However, our results in the present study indicate that the NT scheme performs notably worse in simulating conditions specific to Southeast Asia. Specifically, almost all experiments employing the NT scheme, except for experiment 42 (Grell, UW, and NT), demonstrate very low levels of large-scale rainfall (Supplemental Figure A2). These suggest that the model's performance with the NT scheme can vary significantly depending on the study region or the model resolution.

Güttler et al. (2014) compared two PBL schemes, Holtslag and UW, implemented in RegCM4.2 and demonstrated the advantage of UW in regions in Europe where significant warm biases are present. In our present study, we further indicate that the MYJ scheme exhibits unsatisfactory results in simulating both temperature and rainfall over Southeast Asia. It is important to note that different PBL options yield varying atmospheric boundary layer (ABL) thicknesses depending on the season and region: Holtslag produces ABL thickness values ranging between 1000 and 2000 m, UW exhibits a relatively low ABL thickness of less than 500 m, GFS2011 generates a wide range of ABL thickness from about 700 m to nearly 2500 m, while MYJ consistently produces stable ABL thickness results regardless of the choice of cumulus or moisture schemes (Supplemental Figure A3). As mentioned earlier, conducting a comprehensive study to assess the advantage of one scheme over another is beyond the scope of our present study. However, it would be of interest for a future study to investigate whether the lack of variability in ABL thickness obtained with the MYJ PBL scheme could potentially hinder its ability to accurately represent temperature and rainfall, thereby contributing to its relatively low performance in the final ranking.

In Southeast Asia, rainfall is closely associated with monsoon activities (Herrmann et al. 2020, 2022; Tangang et al. 2020). To examine whether the performance of the RegCM4-NH experiments in representing monsoon circulation correlates with simulated rainfall, we conducted additional analysis of low-level atmospheric circulation, specifically focusing on 850 hPa wind, during JJA and DJF for RegCM4-NH experiments with the best (Exp28), worst (Exp45), and median (Exp38) performance in terms of spatial rainfall score (Supplemental Figures A4 and A5). We observed that for JJA, while Exp28 somewhat overestimates the wind speed compared to ERA5, it accurately represents the wind direction. However, Exp45, the worst-performing experiment, fails to capture the correct summer circulation, particularly over the western part of Indochina and the ocean in western Philippines. The wind direction in the median experiment, Exp38, exhibits a northward bias in western Indochina and low accuracy over AD3 and the surrounding region. Regarding DJF, the best and median experiments fairly represent the low-level atmospheric circulation. Conversely, the worst experiment, Exp45, struggles to reproduce

850 hPa wind speed and direction at various locations, such as the northeastern part of AD1, southern AD3, and over the ocean south of AD2. In brief, we observed that the model's capability in representing atmospheric circulation can significantly impacts its performance in reproducing rainfall distribution.

The latest RegCM5 version did not show improvement over RegCM4-NH, based on the three model configurations we tested. Such results suggest that upgrading to RegCM5 is not a straightforward process, and thorough testing appears to be a prerequisite before embarking on this path. Hence, opting for downscaled projections using RegCM4-NH is a prudent choice for the CORDEX-SEA community, in the framework of the forthcoming CMIP6 downscaling cycle over Southeast Asia.

As uncertainties may exist in the observational datasets within Southeast Asia (Juneng et al. 2016), the ranking results could be sensitive to the choice of reference datasets. To assess the robustness of the results in this regard, we performed additional rankings using CRU as an alternative reference dataset. The findings reveal that the ranking outcomes remain consistent across different reference data sources (Supplemental Figure A6). When evaluating the experiments with CRU, nine (eight) out of the top-ten experiments in reproducing temperature (rainfall) also feature in the top-ten of the ranking versus APHRODITE, although the specific order may vary. Notably, three experiments consistently appear in the the top-five experiments across all rankings: experiment 16 (Tiedtke, UW, SUBEX), experiment 28 (KF, UW, SUBEX), and experiment 31 (KF, GFS2011, SUBEX). This suggests that the CORDEX-SEA community may need to prioritize these configurations for long-term projection experiments when downscaling CMIP6 GCMs.

4 Conclusions

In this study, we conducted and assessed the performances of multiple experiments using RegCM with different physical parameterization configurations over the CORDEX-SEA domain (Table 1). In general, the best experiments with RegCM4-NH demonstrated reasonable reproduction of the spatiotemporal variability of 2 m-temperature and rainfall, while many exhibited unrealistic biases. Implementing the score-based ranking system proposed by DN22, we could assign a performance rank to each experiment (Fig. 6). Three RegCM4-NH experiments consistently appear in the top-five across all rankings, including experiments 16, 28, and 31. The ensemble average of the 44 RegCM4-NH experiments performs better than the majority of individual experiments and ranks 11th overall. Additionally, the experiments with appropriate configurations can provide added value compared to the ERA5 ICBC product. We also demonstrated that

the experiments conducted with the latest RegCM version 5 did not necessarily produce improved results compared to RegCM4-NH under the same physical configuration.

In the past decade, the CORDEX-SEA community has conducted downscaling experiments for CMIP5 GCMs over Southeast Asia (Tangang et al. 2020). We are now entering the next downscaling cycle for the latest CMIP6 GCMs. It is worth noting that selecting an appropriate model configuration in terms of physical parameterization schemes holds crucial significance in producing well-performing simulations for the study area. The findings in this study suggest that the adoption of Grell cumulus, MYJ PBL, or NT moisture schemes over the region should be approached with caution. Furthermore, opting for RegCM4-NH with the top-ranked physical options (e.g. options selected in Experiments 16, 28, or 31) would be a prudent choice for the CORDEX-SEA community in the forthcoming CMIP6 downscaling cycle for Southeast Asia.

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Author contributions All authors contributed to the design and implementation of the sensitivity experiments. T. Ngo-Duc conceptualized the research and wrote the first draft of the manuscript. Data collection and analysis were performed by T. Nguyen-Duy, Q. Desmet and L. Ramu. All authors read, commented, and approved the final manuscript.

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Data availability The outputs from the sensitivity experiments conducted for this study and used for the analysis can be made available upon request.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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