Singapore's Regional Climate Model SINGV-RCM

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6.1 Introduction

With the advancements in supercomputing over the recent decade, GCMs are now capable of global climate simulations of order of few hundred years at a grid resolution of 50-100 km (Eyring et al. 2016; Haarsma et al. 2016), which can be further downscaled using a regional climate model to a 10-20 km grid resolution to capture regional scales in detail (Zhao et al. 2021; Gianotti et al. 2012; Qian 2008).

While a grid resolution of 10-20 km is found to perform reasonably well in the extra tropical regions (Ban et al. 2014), it is difficult to justify if such a coarse grid resolution, where one needs convective parameterisation, will perform equally well in a tropical region like Singapore where the processes (e.g., localized thunderstorms) that characterise the local climate are small- scale (Ngo-Duc et a.l. 2017; Nguyen et al. 2022; Hariadi et al. 2022).

Based on our own experience in weather modelling and the results from existing literature (Marsham et al. 2013; Birch et al. 2014; Prein et al. 2015; Huang et al. 2019; Dipankar et al. 2020; Li et al. 2020a, 2020b; Dipankar et al. 2021; Lee et al. 2021), we believe that a convection-permitting grid resolution, although considerably computationally expensive, is better suited to study the climate change impact on the city state Singapore. Our aim of this study is to document the development of a reliable and high-grid resolution climate modelling system over the Maritime continent for downscaling CMIP6 models for Singapore's Third National Climate Change Projections (V3) studies.

To customize and improve the model for the tropical region, particularly around Singapore, in partnership with the UK Met Office, CCRS-Singapore developed a numerical weather prediction model called SINGV (Huang et al. 2019), which is now run operationally by the Meteorological Service Singapore (MSS) for daily weather predictions. SINGV benefits from daily scrutiny by forecasters and its performance is assessed using a wide range of objective evaluation metrics. This is a very strong basis to establish Singapore variable grid resolution model (SINGV) as the regional climate model (RCM) of choice to complete the third National Climate Change projections (V3).

High spatial resolution (~ 2-8 km) climate information is of much relevance to Singapore due to the size of the city-state. Due to the coarse grid resolutions of the GCMs (~ 50-100 km), it is necessary to downscale the climate information from GCMs, to improve the understanding of climate processes at small-scales that can be resolved by RCMs unlike GCMs. Therefore, simulating sufficiently very high resolution atmospheric variables (at km-scale) around the Singapore – Malay Peninsula region (SG-domain) and a larger domain covering the entire Maritime Continent (MC-domain) at 2km and 8km grid resolutions, respectively using ERA5 fields as a driving model, serves as a benchmark for SINGV-RCM simulations over the region to conduct Singapore's Third National Climate Change Projections (V3).

Earlier Studies done by Kendon et al. (2012, 2014) showed, that the United Kingdom Met Office (UKMO) RCM simulated rainfall characteristics are better than using coarse-grid resolution simulations from other models or using the same model at a high resolution of 1.5 km, produced a much better results, a testimony to model skills when moving from RCM to convection enabling resolutions in UKMO model, which gives confidence to us that the SINGV-RCM shares the same infrastructure of UKMO model and better tuned to the Singapore region and tropics in general.

In this study detailed analyses are done to investigate the SINGV-RCM model performance to reproduce the observed climate at all spatial and timescales. Model is tested with best possible dynamics and physics to fairly reproduce the observed diurnal cycle, observed spatial climatology and observed distribution of heavy rainfall and also tested for the evolution of the peak diurnal timing and intensity of rainfall.

The contents of the manuscript are as follows, the description of data and modelling framework are dealt in section 2, section 3 examines the results and finally the summary and discussions are in section 4 respectively.

6.2 SINGV Model setup

In this section we present the details of the model set up of SINGV. Specifically, we present details on the modelling framework used, dynamics, physics and model versions used, the model nesting suite, observational data used for validation, and the reanalysis datasets used as forcing fields.

6.2.1 Modelling framework

The modelling experiments are conducted to explore SINGV's potential as a Regional Climate Model (RCM) for the MC domain; previously several studies were conducted with the SINGV-NWP system and found to have high skills in predicting the convection realistically over the Singapore region. (Huang et al. 2019; Dipankar et al. 2020; Doan et al. 2021). Results presented in this study are for two versions of SINGV namely, version v5.0 and the earlier version v4.1. SINGV v5.0 is based on the dynamical core of Unified Model (UM) version 11.1, and the Physics basis from the tropical version of the UM known as RA1T (Regional Atmosphere 1 – Tropical) (Bush et al. 2019). SINGV v5.0 is the version of the RCM proposed for the delivery of V3 study (Timbal et al. 2019).

UK Met Office's unified model (UM), a seamless modelling system in which largely the same model is used to simulate the atmosphere at all scales, from the large-scale global circulation to finer-scale grid resolution regional weather. This seamless system provides a consistent modelling approach and has significant advantages for nested modelling approach, in which high-grid resolution models are embedded within the coarser grid resolution models (Golding et al. 2014; Boutle et al. 2016; Bush et al. 2019), by enhancing the horizontal grid resolution a more detailed atmospheric simulations can be obtained (Golding et al. 2014; Boutle et al. 2016; Bush et al. 2019). The current modelling system which is, Singapore regional climate model (SINGV-RCM) to be used for the third National Climate Change projection studies (V3) is based on the UM modelling system.

The nesting suite infrastructure of SINGV-RCM will be able to provide high-grid resolution precipitation simulation along with other atmospheric variables. ERA5 reanalysis output is used for initial condition (IC), lateral boundary conditions (LBC) and surface boundary (SST) to drive the SINGV Model in a nesting suite setup to achieve 8km and 2km grid resolutions. Additional experiments are also conducted at 9km, 4.5km and 1.5km grid resolutions with an earlier version of SINGV-RCM (v4.1) and the results are then validated against the Satellite based observation to quantify the accuracy of the SINGV-RCM model's skill in simulating the precipitation over the vicinity of SINGV-domain (SG-domain) and the entire Maritime Continent (MC-domain). The new version of SINGV (v5.0) and the previous version of SINGV (v4.1) differ majorly only in the surface ancillaries and a few minor changes in terms of physics and dynamics. These minor changes in Physics won't change the simulation results significantly.

The dynamical core for the SINGV model used in this study is from the Met Office Unified model [UM v11.1 & v10.6] for the Singapore versions [SINGV v5.0 & v4.1] configured as a suite of models nested to one another and decreasing in domain size while increasing in model grid resolution. The current configuration of the suite ranges from 8km to 2km as one set with SINGV v5.0 and 9km to 4.5km and finally to 1.5km grid sizes as another set with SINGV v4.1, the lateral boundary conditions (LBCs) are from the ~31 km ERA5 reanalysis model data and are used to drive the next higher grid resolution nested model. Use of the same model for the nested suite means that treatment of the dynamics and the parameterised and resolved physics processes are consistent.

The downscaling is performed using ERA5 initial condition (IC), lateral boundary conditions (LBC) and surface boundary (SST) at different horizontal grid resolutions nested to one another as shown by the schematic diagram (Figure 6.1). The current version of SINGV-RCM (v5.0) tested for V3 domains are shown in solid boxes 8 km (D1) and 2 km (D2) and a slightly earlier version of SINGV-RCM (v4.1), which was tested for different set of domains, are shown in red dashed boxes, 9 km and 4.5 km (D3), 1.5 km (D4) and a common domain for comparison of all results are shown by dotted and dashed box for MC and SG domains.

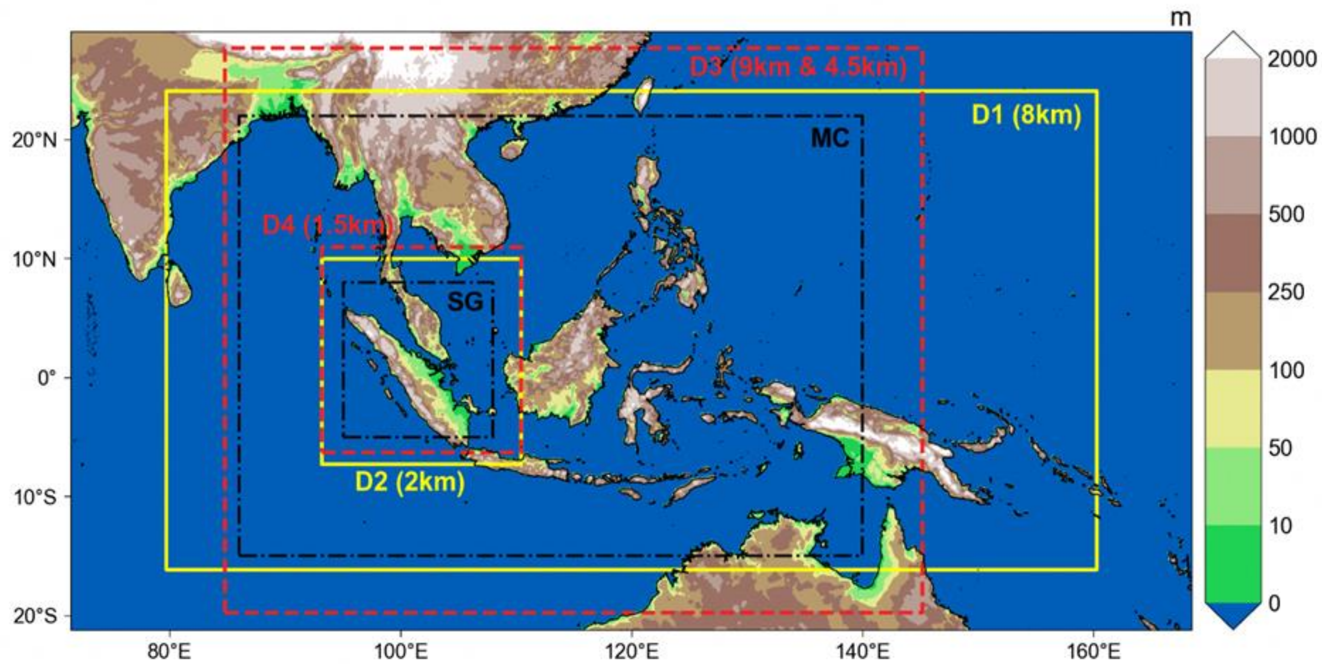

Figure 6.1: Downscaling domains tested for V3 study. D1 (16.16 S – 24.08 N; 79.68 E – 160.248 E) is the 8 km domain, and D2 (7.29 S – 9.972 N; 93.16 E – 110.422 E) is the 2 km domain (in solid line). D3 (16.16 S – 24.08 N; 79.68 E – 160.248 E) is the 9 km and 4.5 km domains and D4 (7.29 S – 9.972 N; 93.16 E – 110.422 E) is the 1.5 km domain (in dashed lines). Box for MC domain (-15-22N; 86-140E) and SG domain (-5-8N; 95-108E) selected for comparison of results for respective domains (in dotted & dashed line).

6.2.2. Dynamics, Physics and model versions used in SINGV-RCM

The SINGV-regional climate model (SINGV-RCM) consists of key components of dynamics and physics, which are explained briefly in this section.

The set of basic equations representing the model dynamics are non-hydrostatic finite difference models with full equations. The prognostic variables are horizontal and vertical wind components, potential temperature, pressure, density, specific humidity, cloud liquid water content etc. The integration domain is the entire Maritime continent (@8km grid resolution) and Singapore domain (@2km grid resolution) forced by the 8km domain output. The horizontal grid consists of a spherical latitude-longitude grid with Arakawa C-grid staggering of variables. The vertical grid consists of 80 levels extending from surface to 38.5km at the top, the levels are height-based hybrid-η vertical coordinate with Charney and Phillips (1953) grid staggering of variables. Semi-lagrangian is used to treat the advection term and semi-implicit method for time integration. The model time steps are roughly 240 seconds (4mins) for 8km and 120 seconds (2mins) for 2km. Additional configurations are Maritime continent (@9km and @4.5km grid resolutions with model time steps 4mins & 3mins) and Singapore domain (@1.5 km grid resolution @1min model time step).

Some details of Physics options used in the model are given below.

1. The cloud scheme is the Prognostic cloud fraction and condensate cloud scheme (PC2 scheme) of Wilson et al. (2008a, b). Precipitation is treated by Wilson and Ballard (1999) single-moment bulk microphysics scheme, coupled with the PC2 cloud scheme.
2. Radiation in the model is treated by Edwards and Slingo (1996) radiation scheme with non-spherical ice spectral files with 6 absorption bands in the SW (shortwave) and 9 bands in the LW (Longwave).
3. The Boundary Layer scheme includes a blending of 1D boundary-layer scheme for vertical mixing by Lock et al. (2000, 2001) and 2D scheme following Smagorinsky (1963). The Gravity wave drag is treated by Orographic scheme including a flow blocking scheme, which represents the effects of sub-grid scale orography and the non-orographic spectral scheme is also included which represents the effect of gravity waves in the

stratosphere and mesosphere. Land surface scheme used in the model is the Joint UK Land Environment Simulator (JULES) (Best et al. 2011) 4-layer soil model using Genuchten (1980) soil hydrology.

Table 6.1 shows the details of the two different configurations with respect to model dynamics, physics and the actual model setup.

Table 6.1: Model parameters and setup for two versions of SINGV-RCM

Model	**SINGV-RCM (v5.0) current version used for V3 study**	**SINGV-RCM (v4.1) previous version tested for V3 study**
Dynamics/ Physics	(UM - Version 11.1) - End-Game Dynamical core with Physics package: RA1T	(UM - Version 10.6) - End-Game Dynamical core with Physics package: RA
Horizontal grid resolution	SINGV-RCM: 8.0km Grids: 1120 x 560 and 2.0 km Grids: 960 x 960.	SINGV-RCM: 9.0km Grids: 642 x 546, 4.5km Grids: 1304x1112 and 1.5km Grids: 1092 x 1026.
Time steps	8km: 240 seconds (4minutes); 2km: 120 seconds (2minutes).	9km: 240 seconds (4minutes); 4.5km: 180 seconds (3minutes); 1.5km: 60 seconds (1minute).
Surface ancillary files	Tested for both CCI and IGBP Land-surface ancillaries. CCI (Climate Change Initiative) from the European Space agency uses latest satellite data for preparing the latest ancillary files.	Only IGBP Land-surface ancillaries. IGBP (international Geosphere-Biosphere Program) program produced the ancillary dataset, which is based on an old global dataset and
Surface B. C.	Sea Surface Temperature (SST) from ERA5 reanalysis interpolated to 8.0km and 2.0km grid resolutions of SINGV-RCM.	Sea Surface Temperature (SST) from ERA5 reanalysis interpolated to 9.0km, 4.5km and 1.5km grid resolutions of SINGV-RCM.
Driving model	Global Driving Model: ERA5 (~31km) and ERA-Interim (~75km)	
SST update Frequency	Updated 8 times daily @ 3-hourly frequency- (00, 03, 06, 09, 12, 15, 18, 21 UTC)	
Initial condition (I.C)	ERA5-IC: Jan1, 2001	
Boundary condition (LBC)	Global model: ERA5 – LBC @3hr interval (~31 km grid resolution)	
Vertical grid resolution	L80: 80 levels (surface to ~38.5 km height)	
Simulation & Analysis period	Simulation for periods: Jan1, 2001 to Jan31, 2001 (31 days) and analysis period: Jan2, 2001 to Jan 30, 2001 (29days).	
Radiation Process	Edwards-Slingo general 2-stream scheme (Edwards and Slingo 1996)	
Surface soil Process	Joint UK Land Environment Simulator (JULES) (Best et al. 2011): 4-layer soil model using Genuchten (1980) soil hydrology	
PBL Process	A 2D and 1D vertical blended scheme. 1D boundary-layer scheme for vertical mixing Lock et al. (2000, 2001) and 2D Smagorinsky scheme (Smagorinsky 1963)	
Microphysics	Mixed-phase precipitation (Wilson and Ballard 1999)	
Gravity Wave Drag	Gravity Wave drag due to orography	

The model setup is similar to the SINGV-NWP setup, except that it is a free run with the regular update of sea surface temperature at 3 hourly intervals. These similar SINGV-NWP configurations were also used in other applications like urban studies (Simon et al.

2020; Doan et al. 2021), and it was demonstrated that the model configuration is evaluated well over this region.

Before running the UM model on climate mode for multiple domains with incremental spatial-grid resolutions, the ancillary files are prepared using the rose suite, central ancillary program (CAP) and Ancillary tool software (ANTS). The hierarchy of ancillary datasets are given by, 1) Land-Sea Mask, 2) Model orography, 3) Soil parameters, 4) Vegetation, surface type and Leaf Area Index, 5) Soil moisture and snow climatology, 6) Aerosol climatology, 7) SST and Sea Ice climatology.

The ancillary data provides the external driving conditions for the model. Ancillary files hold data relating to model orography, soil and vegetation types, climatologies for sea surface temperature and sea ice amongst others. The CAP or ANTS creates the ancillary files by reading post-processed source data and writing them in UM fields-file format.

6.2.3 SINGV model nesting suite's experimental setup

The UM model is set to run on a multiple one-way nesting mode. The set-up of both experiments (SINGV5.0 and SINGV4.1) are broadly similar except for horizontal grid resolutions. The increased grid resolution improves the model results considerably (Stein et al. 2014, 2015; Clark et al. 2016). The time step of each nesting domain must be reduced by a similar magnitude to the reduction in grid-length, to ensure a similar level of stability and accuracy of the model dynamics.

The vertical grid spacing of the nesting suite is kept at 80 levels as used in the operational model. The model turbulence parameterisation is not changed but kept as it is (as used in the operational model), which includes a blending of 1D boundary-layer scheme for vertical mixing (Lock et al. 2000, 2001) and 3D Smagorinsky scheme (Smagorinsky 1963; Boutle et al. 2010). Both versions of SINGV-RCMs (SINGV4.1 and SINGV5.0) uses PC2 schemes. The critical relative humidity, a parameter used in the cloud scheme that represents the relative humidity at which clouds will start to form, varies from 0.96 to 0.81 up to 14 levels from the surface and at 0.8 (constant) above this level (total 80 levels) in this study.

The domain is centred over Singapore (centre grid of latitude and longitude: 0.0N; 112.0E). The simulations were done for a month-long period (Jan1-Jan 31, 2001) and are compared with the observational dataset. The model versions used for these experiments (SINGV4.1 and SINGV5.0) are based on the Unified model (Vn. 10.6 and Vn. 11.1) respectively.

6.2.4 Observational data for validation

The Integrated Multi-satellitE Retrievals for GPM (IMERG) algorithm combines information from the GPM satellite constellation to estimate precipitation over the majority of the Earth's surface (Huffman et al. 2020). In the latest Version 06 release of GPM-IMERG the algorithm fuses the early precipitation estimates collected during the operation of the TRMM satellite (2000 - 2015) with more recent precipitation estimates collected during operation of the GPM satellite (2014 - present). GPM-IMERG data are available from 2001 to present. These data are available on a 0.1° spatial grid between the coordinates 60°S to 60°N and 0° to 360° E-W. The half-hourly data are processed to obtain hourly, daily and monthly value, when necessary, over the study period.

6.2.5 Reanalysis data as forcing fields

ERA5 is a global atmospheric reanalysis from 1979 produced by the European Centre for Medium range Weather Forecasting (ECMWF), UK. Six hourly surface and vertical pressure fields for important meteorological variables at a grid resolution of 0.25° were downloaded from the data website and used as a forcing field for SINGV-RCM model simulations for the 8km-Maritime continent domain. Hersbach et al. (2019, 2020) have documented the ERA5 reanalysis product in detail.

6.3 From SINGV-NWP to SINGV-RCM

Here we discuss the evolution of SINGV-RCM from SINGV-NWP and the modifications/changes made to the model with the previous version of the model. We also discuss the result obtained from the sensitivity experiments done with the improved version compared to the previous version. The SINGV-

NWP model has been adapted to perform as SINGV-RCM for V3 studies. The adopted SINGV-RCM model is used for dynamical downscaling over the Maritime Continent (MC) and Singapore (SG) domains with the nesting suite to achieve an inner nest of higher grid resolution (to the order of a few kms). The details of the experimental setup using initial (IC) and boundary conditions (LBC) from ERA5 (~30km) to the MC domain (9km, 8km, 4.5km) and the SG-domain (2 km, 1.5km) is shown in Table 6.1. Multiple nests are used in the SINGV-RCM to achieve high-grid resolution climate simulation (downscaling of atmospheric variables), in which the 30km ERA5 is progressively nested in increasing grid resolutions over the maritime continent domain at 9km, 8km, 4.5km and finally to 2km and 1.5km over SG domain. As part of sensitivity studies, we conducted several experiments to assess model performance with respect to the model changes. Some of them, which we believe are important, are listed below.

6.3.1 Implementation of prescribed Diurnal cycle of SST

SST fields are interpolated from the ERA5 data (~30km grid resolution) to the SINGV-RCM grid resolutions (9km, 8km, 4.5km, 2km and 1.5km) and updated every 3 hours. The ancillary files like SST and Sea ice are created using the X-ancils application and are then linked in the namelist file of the RA1T science configuration file. The 3 days of 3 hourly input SST from the driving model and the corresponding hourly output from the SINGV-RCM are shown in Figure 6.2. Earlier TRMM based precipitation studies have brought out the importance of observed diurnal variability of precipitation over maritime continent a few to mention (Mori et al., 2004; Ichikawa and Yasunari, 2006) and role of diurnal cycle of SST becomes more important over the maritime continent, as the diurnal changes in SSTs and the interaction of land-Sea breezes with the topographic changes to contribute to the diurnal precipitation changes. Recently, Dipankar et al. (2019) using data from the pilot field campaign of Years of the Maritime Continent (pre-YMC) Yoneyama and Zhang (2020) are used to understand the model biases, their results also support the earlier findings that the convection over coastal land and sea is strongly coupled. They also found that EC-SST fields when corrected for bias up to 2-degree K, found that the simulation improved in the representation of diurnal convective activity and comparable to the Ocean point observation (where MIRAI ship was stationed) about 55km away from the coastal station Bengkulu. This result strongly suggests the high temporal frequency of SST update can help the model to capture the diurnal variability of convection over the Maritime Continent. Therefore using 3-hourly input SSTs can improve the diurnal variability of precipitation over the Maritime continent.

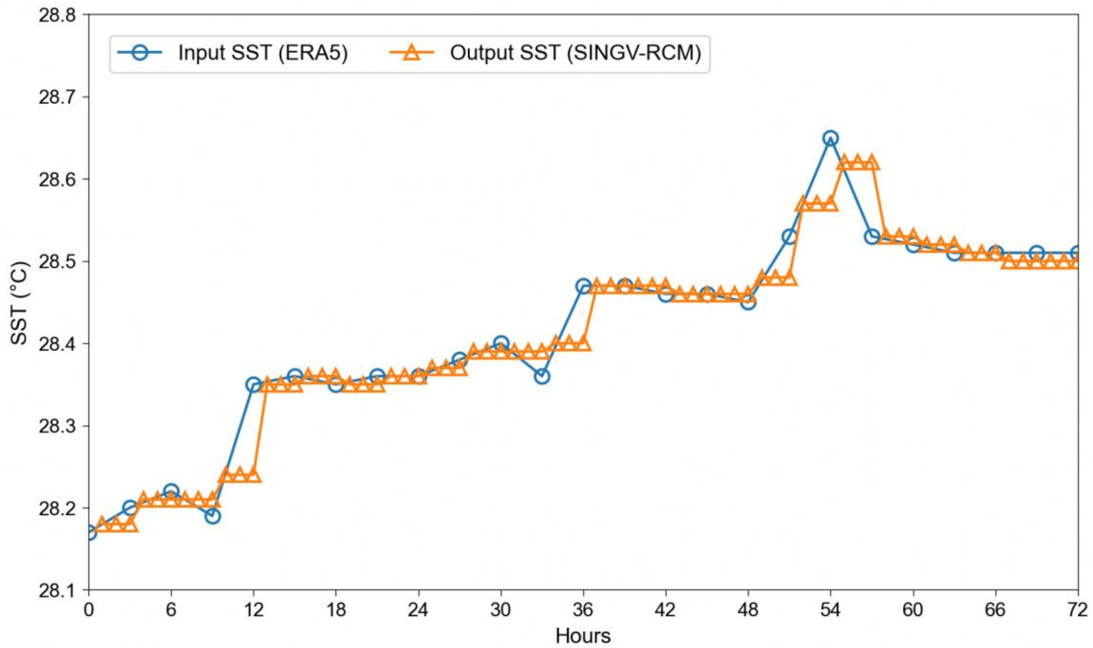

Figure 6.2: Domain averaged input SST profiles from ERA5 driving model (~30km) at 3hr frequency and output SST profiles from SINGV-RCM (~8 km) at 1hr frequency for 3 consecutive days are shown here. Units in degree C.

6.3.2 Changes to the land—surface representation

We modified the IGBP land use data (vegetation) to CCI land use data (vegetation fraction) (Figure 6.3a, b).

We also modified the Land Use and Land cover Change (LULC) non-vegetation fraction ancillary along with vegetation fraction ancillary to the latest European Space Agency (ESA) based Climate change Initiative (CCI) data, it is a global LULC climatology data computed at 300m grid resolution from 1992 to 2020, compared to the previously used data of International Geosphere Biosphere Program created (IGBP) LULC data a coarse-grid resolution of 1km. More realistic Urban Land fraction for Kuala Lumpur and Singapore is evident from the CCI data as shown in Figure 6.4 (a, d) compared to IGBP data Figure 6.4 (b, e) and are compared with satellite images for Kuala Lumpur figure 6.4 (c) and Singapore figure 6.4 (f).

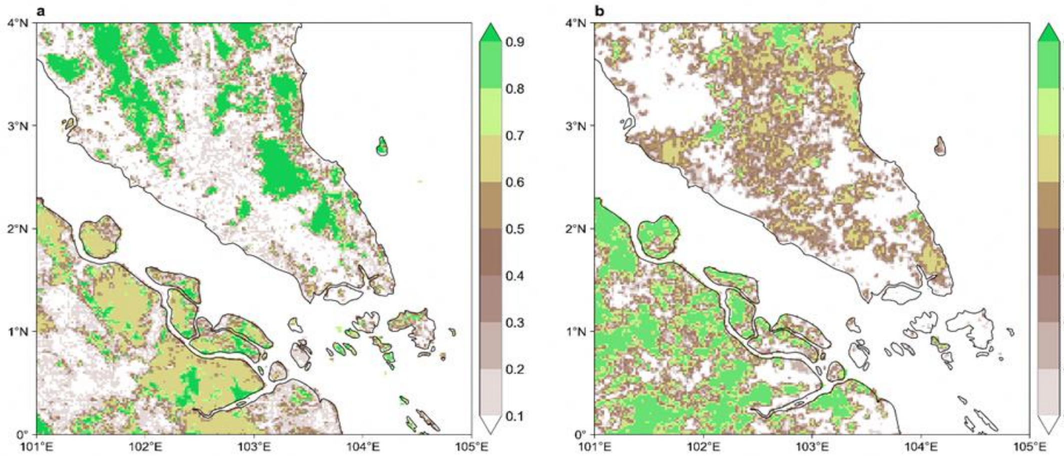

Figure 6.3: Broad Leaf fraction comparison. a) CCI data, b) IGBP data. Units in fractions.

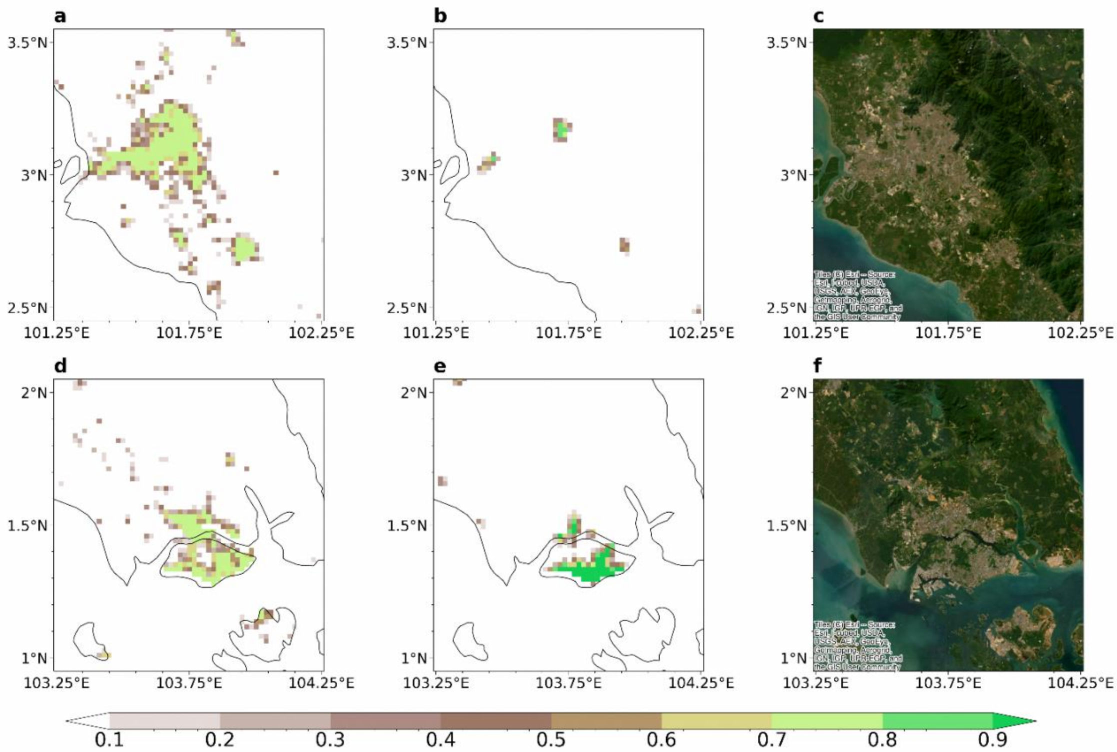

Figure 6.4: Urban Land fraction comparison. a) CCI data for Kuala Lumpur, b) IGBP data for Kuala Lumpur, c) Satellite image for Kuala Lumpur, d) CCI data for Singapore, e) IGBP data for Singapore, f) Satellite image for Singapore. Units in fractions.

CCI data corrects the land use and land cover fraction in IGBP, as it is the latest improved version of land use and land cover fraction data available on a continental scale. We notice less broad leaf fraction in the CCI data over our region compared to IGBP; IGBP shows more vegetation fraction over Indonesia and less over Malaysia, while CCI is vice versa Figure 6.3 (a, b). But in the urban tile, CCI data has captured the urban extent of Kuala Lumpur much better than the IGBP data compared to satellite map as shown in Figure 6.4 (a, b, c) and the urban extent of Singapore and Johor Bahru much better than the IGBP data compared to satellite map as shown in Figure 6.4 (d, e, f). Overall, the CCI data is a more improved data compared to IGBP. Considerable differences are noted in the representation of vegetation fraction as well as in the urban tile in these two datasets, CCI-data has shown improved representation of urban extent.

We studied the impact of vegetation + non vegetation fraction ancillary changes in the model simulations and noted only marginal improvements in the model precipitation simulation (Figure 6.6a) due to the length of the simulation being a short run (one month long); while a long-term simulation for over 30-year period might have a significant change from modifying the IGBP land use data (vegetation + non vegetation fraction) to CCI land use data (vegetation + non vegetation fraction) (Figure 6.3a, b, Figure 6.4a, b and Figure 6.4d, e).

The orography of the 2km model clearly brings out the finer details of the orographic height compared to the 8km smoothed orography over the region as shown in Figure 6.5 (a, b). Precipitation is less intense with smoothed orography; the impact of high-resolution orography is visible in the vicinity of areas with high orography (Figure 6.6b). Rainfall intensity is increased in the run with better resolved orography (Figure 6.6b) which is in accord with the earlier findings (Sethunadh et al. 2019).

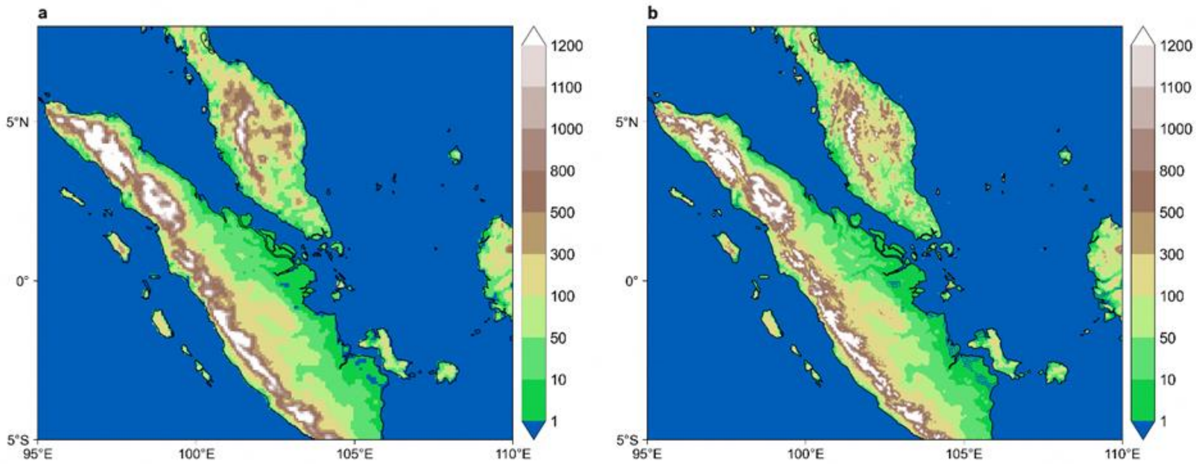

Figure 6.5: Coarse grid resolution (8 km) vs. fine grid resolution (2 km) orography. Units in m.

The orography over the Singapore domain (SG) tested with an 8km smoothed orography and a fine grid resolution of 2km orography and found only marginal improvements in the model precipitation simulation over the Indonesian and Malaysian regions due to the length of the simulation being only one month long (Figure 6.6 b). Previous studies have also noted the importance of the interaction between landmasses, low-level flow, with orography, to capture the diurnal cycle and the development of heavy rainfall events over peninsular Malaysia and Sumatra Island (Nor et al. 2020).

Tan et al. (2020) explored the role of topography on a Madden–Julian Oscillation (MJO) event in the Maritime Continent (MC) using a regional model and found that low-resolution simulations with its inadequate representation of topography combined with the deficiency from cumulus parameterisation have difficulty in simulating MJO across the MC and suggested that the improvement in the simulated MJO in the high horizontal-resolution compared to the low horizontal-resolution model may come, not only from the absence of cumulus parameterisation, but also from the better representation of topography in higher resolution simulation.

6.3.3 Updating Model forcing fields (ERA5 vs ERA-I)

We also looked at the SINGV-RCM precipitation biases (Figure 6.6c), if any systematic difference in precipitation bias arise in the ERA5 newer reanalysis (~30km) driving fields versus the older version of reanalysis ERA-Interim (~75km) driving fields, no systematic differences are evident as we can only observe noisy pattern emerge from the differences between ERA5 and ERAI forced runs (Fig. 6.6c).

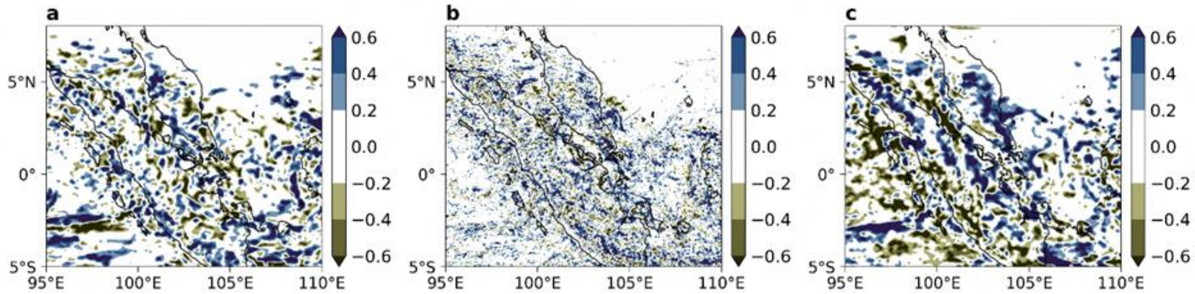

Figure 6.6: (a) Impact on Precipitation difference (CCI – IGBP ancillaries), (b) Impact on Precipitation difference (2 km Orography – smoothed 8 km orography), (c) Impact on Precipitation difference (ERA5 – ERA-Int.) Units in mm/hr.

6.3.4 Changes to the vertical resolution of the forcing field data

Most of the CMIP6 model data are coarsely resolved in the vertical as compared to SINGV-RCM that uses 80 levels up to z = 38.5 km. Vertical interpolation of driving data to higher resolution are known to produce model biases. To get an understanding of expected model bias in the future climate projections due to the loss of vertical resolution in the driving data, we compared the simulations driven using ERA5 data with full (137) vertical levels and the simulation with only 37 levels in the vertical against the ERA5 reanalysis. Focus is given to the vertical velocities considering its role driving convection in the region. From the test results, very small differences on large domain (MC) were noted (Figure 6.7a), but more sizeable in the small domain (SG) is evident (Figure 6.7b) between the runs. We also noted that the ERA5 vertical velocities (omega) are much stronger compared to the downscaled ones, this is largely due to reduced convection in SINGV-RCM (Figure 6.7 a, b). The lower boundary condition in ERA5 (i.e. SSTs) also showed colder SST bias with respect to O-I SST (figure not shown) adjacent to the Singapore and Malaysian archipelago compared to the entire Maritime continent domain. Also, studies done by Yang et al (2021) have shown that ERA5 SST product has a colder bias over the maritime continent when compared to the ensemble median of SST products for the period of 1982–2002.

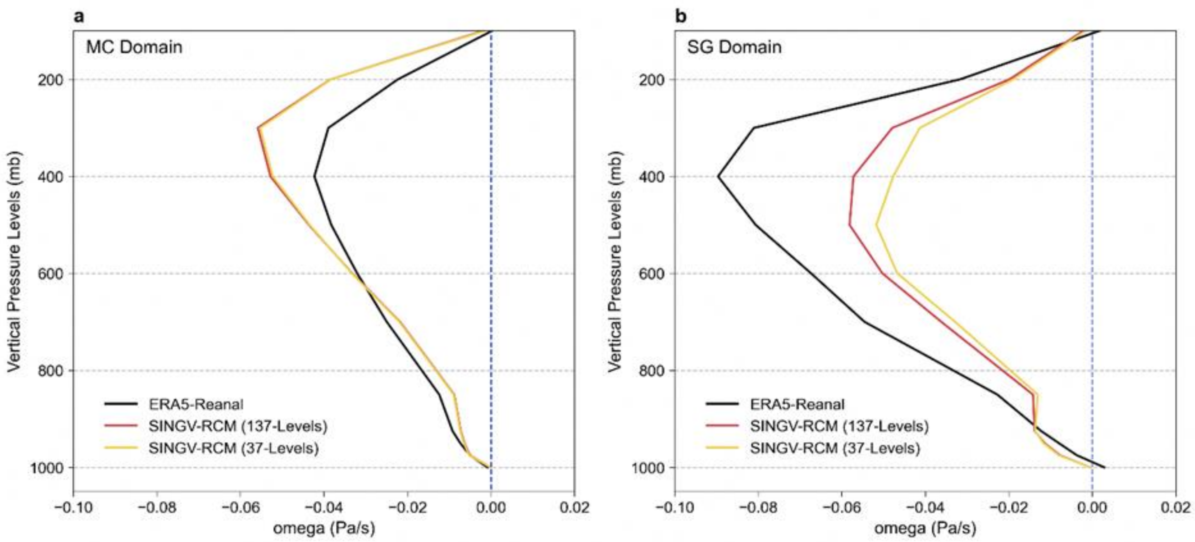

Figure 6.7: Impact of vertical levels in the forcing fields (ERA5-Reanalysis: ~30km, SINGV-RCM: 9 km). SINGV-RCM forced with ERA5-137 levels; vs ERA5-37 levels. a) MC domain b) SG domain. Units in Pa/Sec.

Though the ratio of MC land points to total grids points is 18% compared to the ratio of SG land points to the total grids at 27% (Slightly higher compared to MC domain), one of the reasons for less convection in the SINGV-RCM over the SG domain may be attributed to the colder SSTs seen around the SG domain in the ERA5 driving model, as evidenced by dry precipitation bias prevailing over the SG domain (look at Figure 6.10 a-d and 6.11. a-d, precipitation biases for different grid resolutions) in SINGV-RCM.

6.3.5 Sensitivity to Model grid resolutions

We tested the SINGV-RCM with different model grid resolutions and domain sizes with the MC domain having grid resolutions like only 9km, 8km, 4.5km and the SG-domain having additional grid resolutions like 2 km, 1.5km respectively. Figure 8 shows the area averaged diurnal precipitation cycle over the common and overlapping grid resolutions for MC and SG domains area bound by the dashed and dotted boxes shown in Figure 6.1.

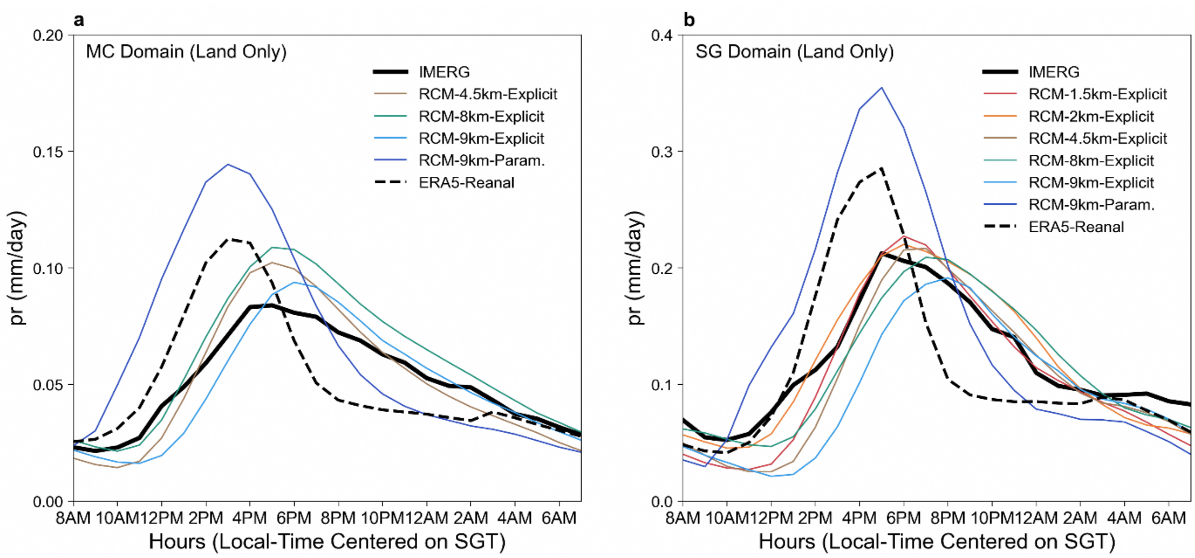

Figure 6.8: Diurnal cycle of Precipitation area averaged over MC and SG domains. The MC-domain (9 km, 8 km, 4.5 km) and the SG-domain (9 km, 8 km, 4.5 km, 2 km, 1.5 km). Units in mm/hr.

We notice from the Figure 6.8a that SINGV-RCM with explicit representation of convection is able to capture the diurnal cycle of precipitation close to observation (IMERG). While the ERA5 driving model and 9km parameterised runs show earlier diurnal peak than the observed. The results are quite similar for SG domain as well (Figure 6.8b).

High grid resolution runs of 2km and 1.5km have a better diurnal peak timing as well as intensity compared to coarse grid resolution simulations of 9km, 8km and 4.5km, this may be due to the fact that, it takes longer for the system to work up enough energy to lift a larger grid box when having to convect on that grid scale.

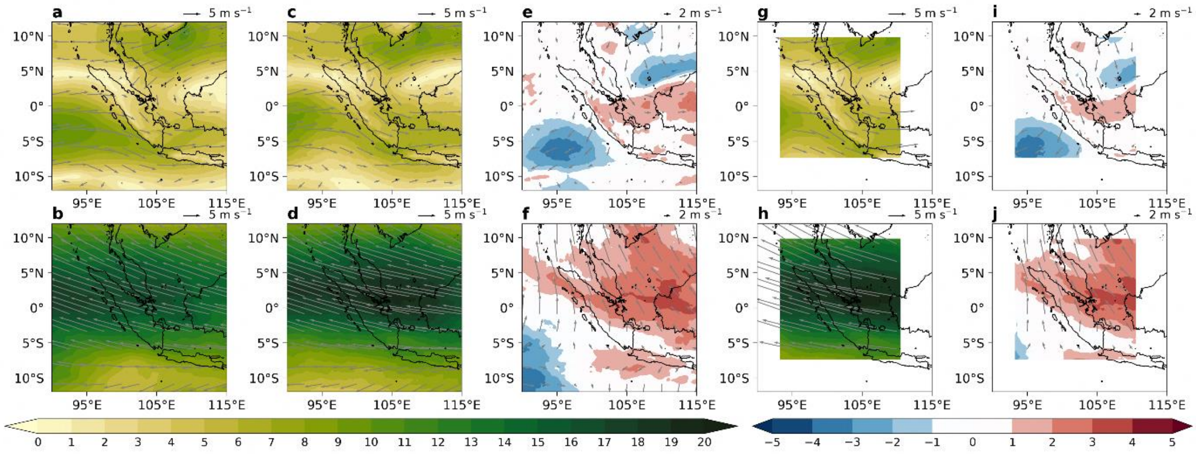

Figure 6.9: Mean simulated Circulation (850hPa and 200hPa) and bias w.r.to ERA5 for SINGV-5.0 version for 8 km & 2km resolutions. Mean circulation (a. ERA5-850hPa winds, b. ERA5-200hPa winds c. 8km-850hPa winds, d. 8km-200hPa winds, g. 2km-850hPa winds, h. 2km-200hPa winds) and bias in the circulation (e. 8km-ERA5 for 850hPa, f. 8km-ERA5 for 200hPa, i. 2km-ERA5 for 850hPa, j. 2km-ERA5 for 200hPa). Units in m/s.

From Figure 6.8, we found that the precipitation features for different resolutions look quite consistent. Meanwhile, we wanted to examine how the circulation features (Two upper levels: 850 hPa and 200 hPa) are simulated after downscaling to 8 km from the driving model (ERA5) and then from 8 km to 2 km resolution. Therefore, we plotted the mean circulation feature changes over the MC domain from 8 km and 2 km simulation with ERA5. We notice from the Figure 6.9 (ERA5, SINGV-RCM and differences at 2 different levels: 850hPa and 200hPa) that SINGV-RCM exhibit negative bias in the 850hPa to the East of Malaysian peninsula and positive bias over regions close to south of Indonesia and Borneo (Figure 6.9e [8km] and Figure 6.9i [2km]). While the SINGV-RCM exhibits positive bias in the 200hPa over the entire region covering more than 50% western maritime continent (Figure 6.9f [8km] and Figure 6.9j [2km]). But nevertheless, the large-scale pattern for 850hPa and 200hPa wind circulation after downscaling from ERA5 to 8km and to 2km looks quite similar to the driving model ERA5 (Figure 6.9 a-d and g, h).

6.4 Evaluation of SINGV-RCM over Southeast Asia

The SINGV-RCM model's ability in simulating the climate realistically arises from the model itself: e.g., dynamical core or physical parameterisations and the skill of the driving model in the region through Lateral Boundary Condition (LBC) and surface condition (SST). Therefore, evaluation of the model simulations of SINGV-RCM shall include diurnal cycles of rainfall, the Probability Distribution Functions (PDFs) of model simulated rainfall with focus on extremes, spatial model biases of mean rainfall and to evaluate the models' performance over two domains, Maritime Continent (MC) domain and Singapore (SG) domain and for different grid resolutions.

6.4.1 Mean precipitation

In terms of the mean precipitation biases, we notice dry bias close to Singapore is large in the parameterised run (Figure 6.10a) compared to the explicit run (Figure 6.10b). For the other explicit runs like 4.5km (Figure 6.10c) and 8km (Figure 6.10d) over the MC domain, the biases are quite similar and the dry bias decreases from coarse grid resolution to high grid resolution around the Singapore-Malaysia region.

The mean precipitation averaged over the MC-domain for GPM-IMERG Precipitation is 0.29 mm/hr. The Mean, Bias, PCC and RMSE with respect to IMERG for each simulation is shown at the top of each figure panel (Figure 6.10a-d). Generally, the Bias value decreases and pattern correlation coefficient (PCC) increases, when moving from Parameterisation to Explicit convection and to higher grid resolution (9km-Param. 9km-explicit and 4.5km-explicit) in SINGV-RCM (Figure 6.10a-c). The Bias becomes slightly positive for the 8km simulation over the MC domain with highest PCC over the MC domain (Figure 6.10d)

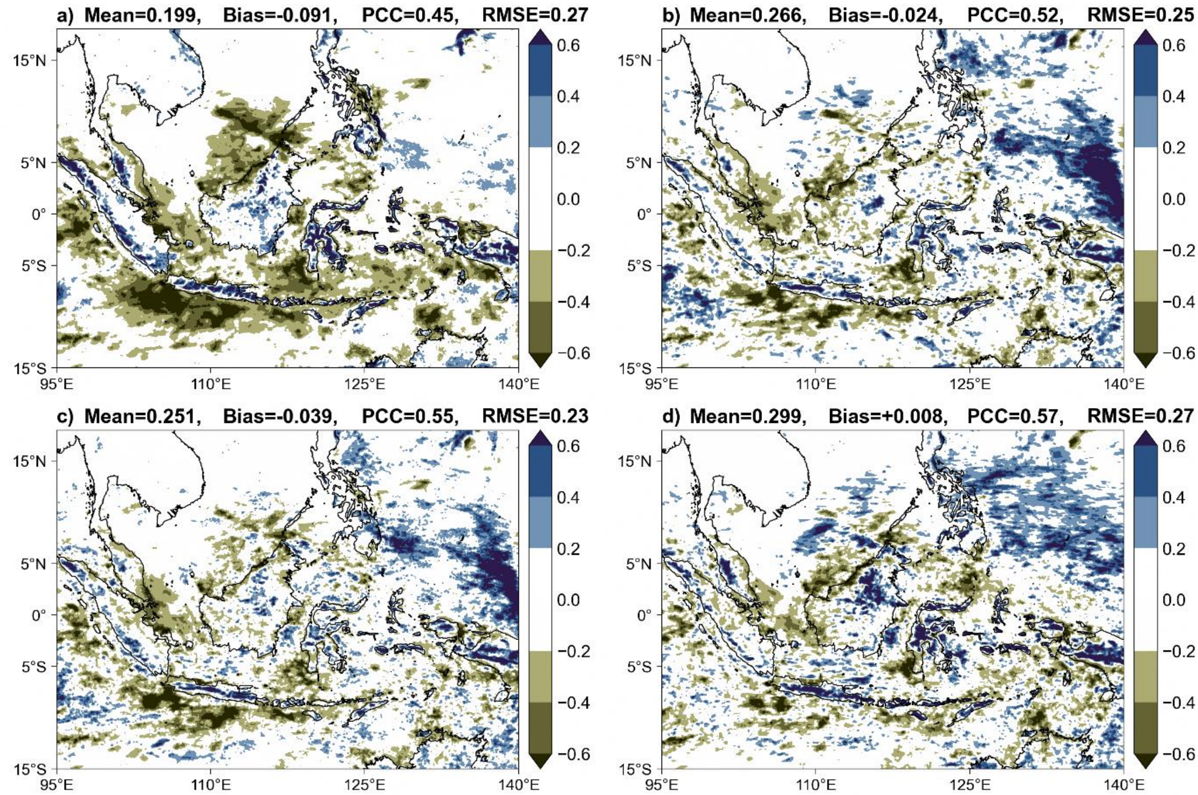

Figure 6.10: Mean simulated Precipitation bias w.r.to GPM-IMERG for SINGV-4.1 version for 9 km (a. Parameterised, b. Explicit), c. 4.5 km (Explicit) and for SINGV-5.0 version d. 8 km (Explicit) simulations over the MC-domain downscaled from ERA5 driving model. Units in mm/hr. GPM-IMERG Precipitation mean for the domain is 0.29 mm/hr.

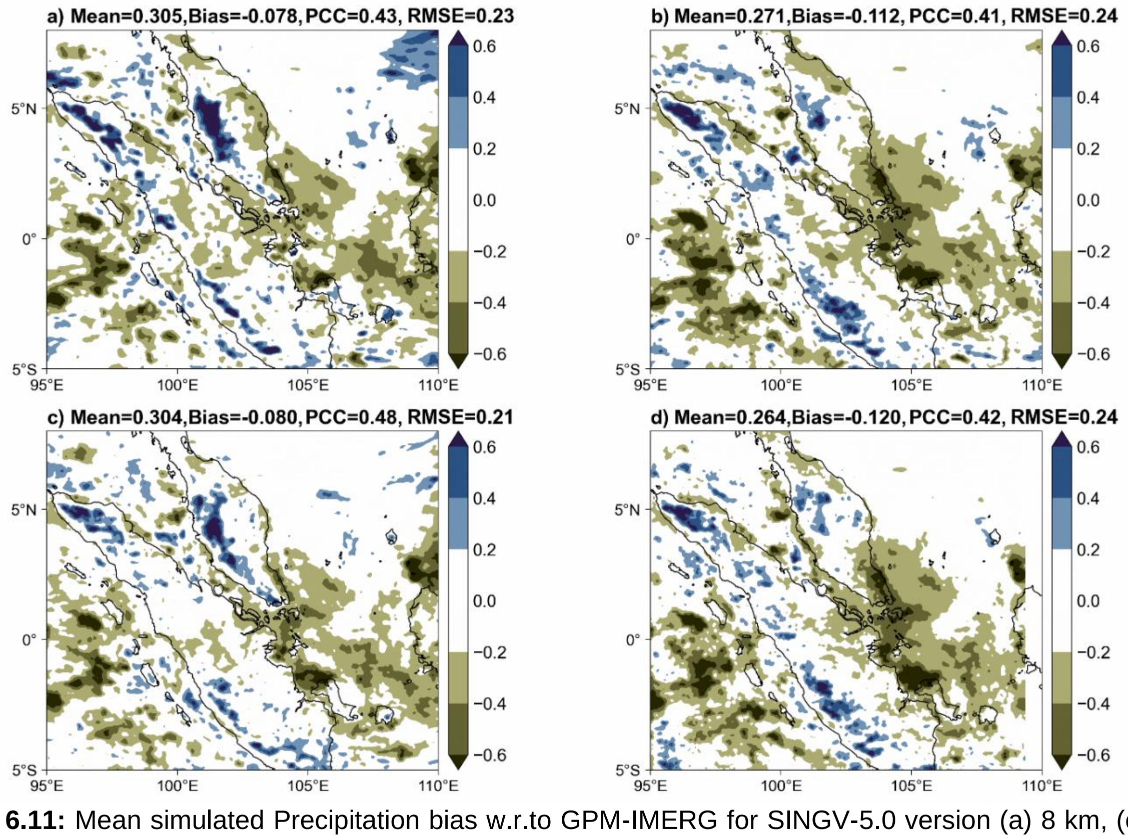

Figure 6.11: Mean simulated Precipitation bias w.r.to GPM-IMERG for SINGV-5.0 version (a) 8 km, (c) 2 km and for SINGV-4.1 version (b) 4.5 km (d) 1.5 km simulations over the SG-domain downscaled from ERA5, 8 km-Explicit, 9 km-Explicit and 4.5 km-Explicit SINGV-RCM simulations, respectively. Units in mm/hr. GPM-IMERG Precipitation mean for the domain is 0.385 mm/hr.

Even the high-grid resolution simulations like 2 km (Figure 6.11c) and 1.5 km (Figure 6.11d) for the smaller domain around Singapore (SG) domain downscaled from 8 km (Figure 6.11a) and 4.5 km (Figure 6.11b) larger MC domain show dry bias close to Singapore (SG) domain. The new version SINGV5.0 has less dry bias around SG domain compared to the older version SINGV4.1, which supports the use of newer version of SINGV-RCM for the V3 study.

The mean precipitation averaged over the SG-domain for GPM-IMERG Precipitation is 0.385mm/hr. The Mean, Bias, PCC and RMSE with respect to IMERG for each simulation is shown at the top of each figure panel (Figure 6.11a-d). Generally, the Bias value does not change much, and pattern correlation coefficient (PCC) increases slightly, when moving from lower grid resolution to higher grid resolution (4.5km-explicit and 1.5km-explicit) in SINGV-RCM (Figure 6.11b and Figure 6.11d) and also for the 8km and 2km simulation over the SG domain (Figure 6.11a and Figure 6.11c)

The biases in simulations using 4.5 km grid resolution SINGV4.1 (Figure 6.10c) and 8 km SINGV 5.0 (Figure 6.10d) are relatively similar compared to that in the parameterised simulation (Figure 6.10a) suggesting that mean features of the rainfall can be captured relatively well even at 8 km grid resolution with explicit treatment of convection, which is computationally less demanding than the 4.5 km resolution, suggesting that there is no major detriment to the rainfall simulation when allowing explicit treatment of convection even at 8km grid resolution.

6.4.2 Diurnal representation of Precipitation

In this section the area-averaged mean diurnal cycle over land-only grid points of area bound by MC and SG domains are discussed in detail. We notice (see Figure 6.12a) a clear advantage of using 8km explicit representation of convection over the Maritime continent (MC) domain in comparison to ERA5 reanalysis, which uses convection parameterisation at 30 km grid resolution".

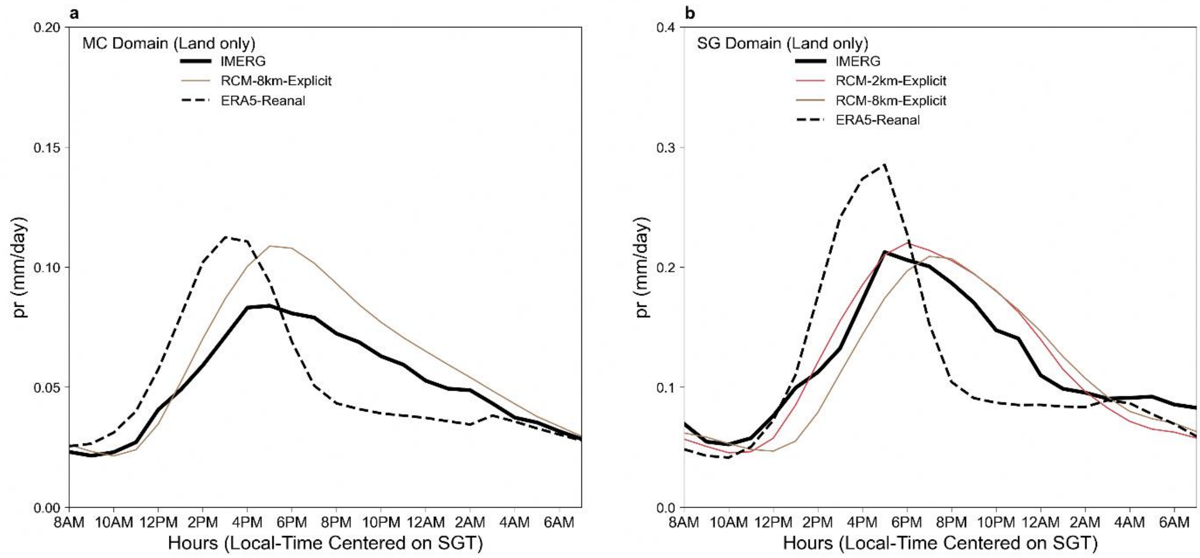

Figure 6.12: Diurnal cycle of Precipitation area averaged over land-only grids for MC and SG domains. Units in mm/hr.

It is noted that that the diurnal peak of precipitation in the ERA5 driving model is at least couple hours earlier than the observed GPM-IMERG over the area averaged over the entire land-points of MC domain, though the precipitation intensity in the SINGV-RCM is higher than the observed, the peak diurnal timing is well captured by the model over the MC domain. Similarly, from Figure 6.12b, we notice that the diurnal precipitation in ERA5 starts vigorously at least a couple hours earlier when compared GPM-IMERG. Even the rainfall intensity in ERA5 is substantially high. In SINGV-RCM, on the other hand, both precipitation intensity and phase are closer to the observation. As expected, this correspondence with observation is better captured at 2 km grid resolution.

Figure 6.13 shows the spatial variation in the timing of the diurnal rainfall peak over SG domain compared to GPM-IMERG data at each grid point. Figure 6.13a shows the time of diurnal peak for each grid from GPM-IMERG for the analysis period, Jan 2001, Figure 6.13b is for the ERA5 reanalysis, we can notice that the diurnal timing over both land and Ocean grids points from the ERA5 reanalysis does not match with the observed IMERG. But there is a marginal improvement in the SINGV-RCM parameterised run at 9km (Figure 6.13c) compared to the driving model ERA5 reanalysis. While the explicit representation of convection run of SINGV-RCM at 9km (Figure 6.13d) is closer to the observed GPM-IMERG Peak timing of diurnal precipitation (Figure 6.13a).

We can also notice gradual improvement in the diurnal peak precipitation timing as we go from coarse-grid resolution to high-grid resolution simulations of SINGV-RCM 8km-explicit (Figure 6.13e), 4.5km-explicit (Figure 6.13f), 2km-explicit (Figure 6.13g) and 1.5km-explicit (Figure 6.13h). It is clear from these experiments that the explicit representation of convection combined with improved grid resolution corrects the diurnal cycle of precipitation over the Singapore domain.

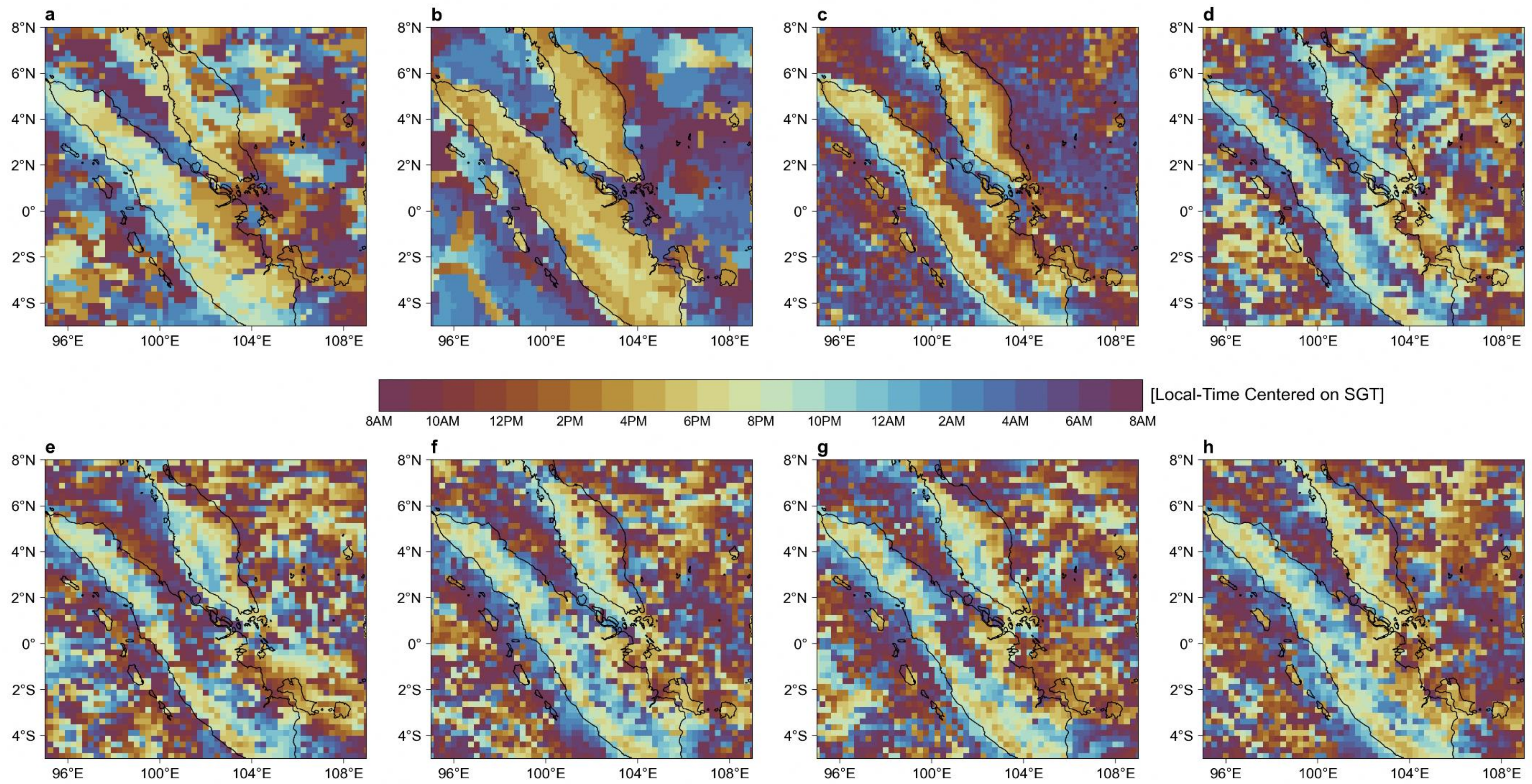

Figure 6.13: Spatial map of Peak Diurnal timing of Precipitation. a) IMERG, b) ERA5-Reanal., c) 9 km-Parameterised, d) 9 km-Explicit, e) 8 km-Explicit, f) 4.5 km-Explicit, g) 2 km-Explicit and h) 1.5 km-Explicit. Units in hour (UTC).

6.4.3 Representation of precipitation extremes

In this section the distribution of 95-percentile extremes at each grid point in the SINGV-RCM simulations for different model grid resolutions.

Figure 6.14a shows the 95-percentile extreme threshold value at each grid point from the observed GPM-IMERG data. Figure 6.14b to 6.14h show the 95-percentile extreme bias value at each grid point with respect to observed GPM-IMERG data. Figure 6.14b shows the bias for ERA5 reanalysis, dry bias is evident at every grid point, which means the driving model ERA5 is not able to get extreme rainfall above the 95 percentile threshold over the Singapore domain, but the SINGV-RCM parameterised run at 9km shows some improvement over a fewer grids (Figure 6.14c), while the SINGV-RCM 9km-explicit run shows positive bias over the majority of grid-points (Figure 6.14d). The positive bias in the 95-percentile extreme rainfall either intensifies or reduces from coarse-grid resolution to higher-grid resolution thereby becoming closer to the observation; SINGV-RCM 8km-explicit (Figure 6.14e), 4.5km-explicit (Figure 6.14f), 2km-explicit (Figure 6.14g) and 1.5km-explicit (Figure 6.14h), which is an added value of downscaling to very-high grid resolution over the Singapore domain. We have regridded the data to the lower resolution (25km), before calculating and differencing the percentiles.

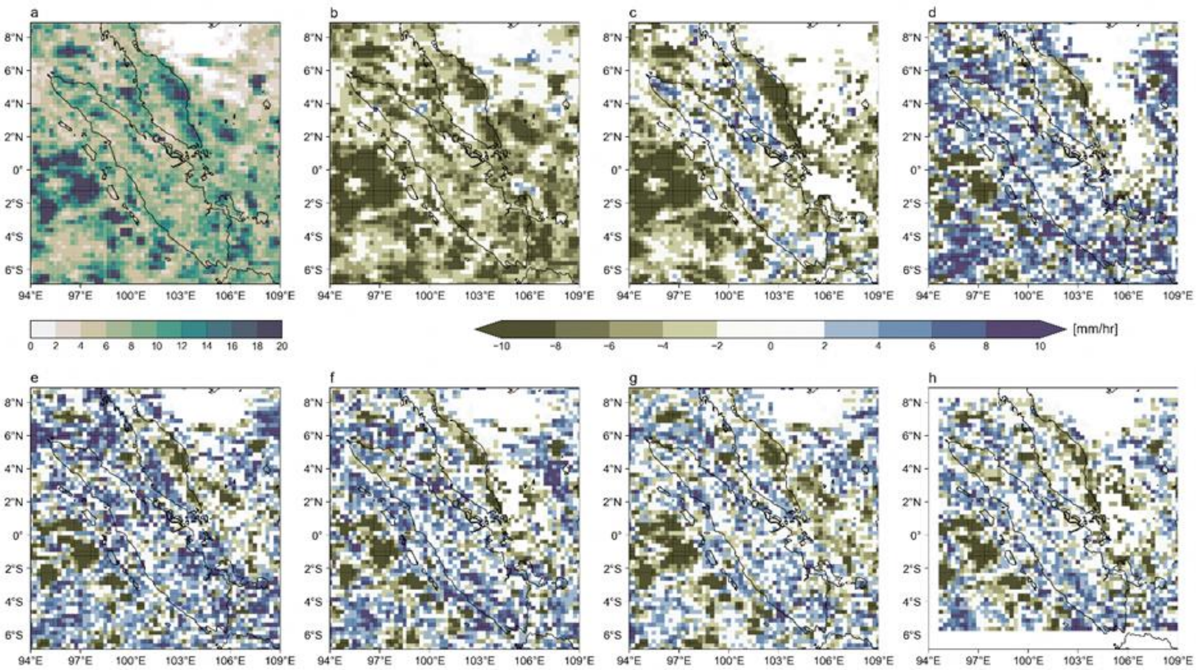

Figure 6.14: Extreme Precipitation a) 95-percentile threshold value for GPM-IMERG and rest are precipitation bias w.r.to IMERG. b) ERA5-Reanal, c) 9 km-Parameterised, d) 9 km-Explicit, e) 8 km-Explicit, f) 4.5 km-Explicit, g) 2 km-Explicit and h) 1.5 km-Explicit. Units in mm/hr.

6.4.4 Frequency Distribution of Precipitation in SINGV-RCM

The frequency distribution of rainfall between the GPM-IMERG observation and the SINGV-RCM simulations over the SG-domain for the entire period is shown in Figure 6.15. The results reveal that SINGV-RCM parameterised convection, though estimates better the light rainfall compared to the GPM-IMERG in the range of 0–1 mm/hr., but underestimates moderate and moderately high rainfalls, in the ranges 5-10 and 10–25 mm/hr., respectively. It is encouraging to see that the SINGV-RCM is close to the GPM-IMERG observation in estimating the 5-10 and 10-25 mm/hr ranges in all explicit-run grid resolutions. Heavy rainfalls in the range of 25-100 mm/hr; model is always lower than GPM-IMERG and no precipitation in the ranges above 100mm/hr. The explicit representation of convection in the model configuration simulates moderate rain rates better than the light rainfall rates, irrespective of model grid resolution and the parameterised convection simulation tend to predict better the light rainfall rates at the expense of heavy rainfall events (under-predicts above 5mm/hr).

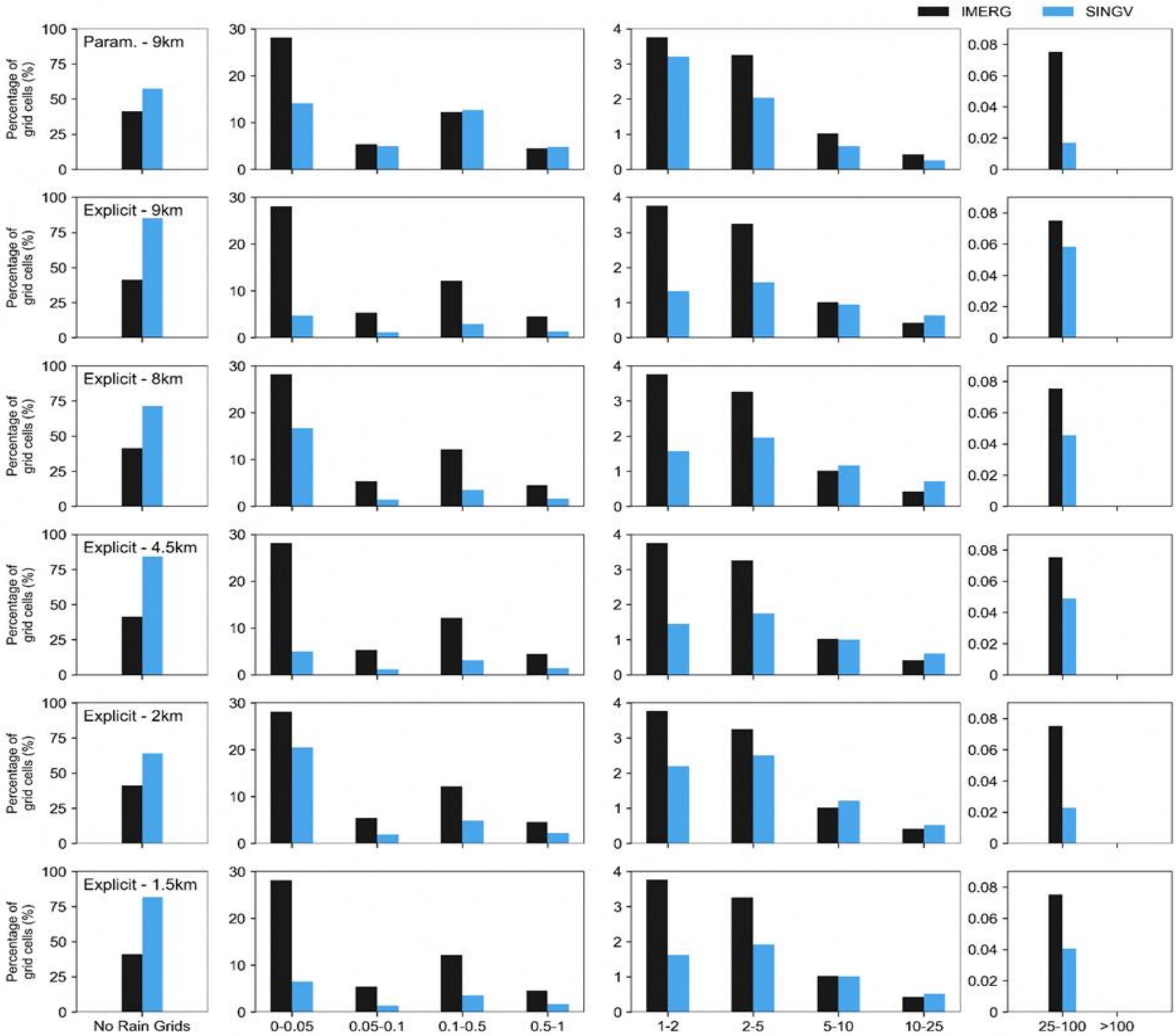

Figure 6.15: Distribution of rain rate over the grids with the older (SINGV-4.1) as well as newer (SINGV-5.0) version of SINGV-RCM with Parameterised vs explicit representation of convection at 9 km and high-grid resolution grids at 8 km, 4.5 km, 2 km and 1.5 km. Units in mm/hr.

6.4.5 Parameterised vs explicit representation of Convection

We performed simulations of both explicit and parameterised representation of convection at 9km grid resolution and we found that the explicit run is able to capture the peak diurnal timing better than the parameterised one in the area averaged profile (Figure 6.8 a, b) and in the spatial diurnal timing map (Figure 6.13c, d) compared to GPM-IMERG (Figure 6.13a). In the mean precipitation bias as well, we see the dry bias close to Singapore is large in the parameterised run (Figure 6.10a) compared to the explicit run (Figure 6.10b). For the extreme precipitation (95 percentile threshold), the parameterised-9km run 95 percentile precipitation bias (Figure 6.14c) shows large dry bias, while the explicit-9km run for 95 percentile precipitation bias (Figure 6.14d) shows reduced dry bias near the Singapore domain. We also found the parameterised one has too much light rain and less moderate and intense rainfall from the distribution analysis (Figure 6.15) compared to the other explicit grid resolutions.

6.5 Summary

We have modified the SINGV NWP model to SINGV-RCM that is fit for purpose to carry out long term climate simulations. In the process we tested SINGV-RCM with different grid resolutions 9km, 8km, 4.5km for MC domain and 2km and 1.5km over the SINGV domain and found the results are robust for both domains in terms of capturing mean and diurnal cycle of precipitation with both earlier and newer version of SINGV-RCM. Multiple experiments performed with SINGV as an RCM proves the suitability of SINGV-RCM for the V3 study as SINGV as benefitted from the development of different SINGV versions developed over the Singapore region (Regional Tropical atmosphere version).

SINGV-RCM at different grid resolutions with explicit representation of convection performed better than the convection parameterised version at 9km grid resolution. We noted the biggest step change in performance when explicit convection is used even at coarse grid resolution. The SINGV-RCM with explicit convection has shown better diurnal cycle timing and intensity compared to the convection parameterised version with respect to GPM-IMERG precipitation data. This result of daily timing of maximum precipitation is better captured when the convection is explicit strongly suggests that even at a very coarse grid resolution of 9km or 8km, the model is already "convection-enabling" and is performing better without the convection parameterisation (Birch et al. 2016) . Furthermore, this result is consistent with other studies for Western Africa using the UM model with a 4.5km horizontal grid resolution (e.g., Berthou et al. 2019) and for the Western maritime Continent using the WRF model (Argueso et al. 2020).

We also noted better distribution of rainfall intensities (less light rain, more heavy rain). 2 km is not statistically different to 8 km-explicit over a large domain (little sensitivity to grid resolution). To balance between very high computation cost and longer/more simulations to capture uncertainty range, we may still need 2 km time slice simulations over the smaller Singapore domain in the future projection simulations for specific agency applications.

Following are some of the key summary points from this study:

1) As part of development of SINGV-RCM, we ingested the SST at a 3-hour cycle to represent the Diurnal cycle of SST over the region.

2) We modified IGBP-LULC to high-grid resolution CCI-LULC for ancillary preparation.

3) Also, we found improvements in precipitation simulation with grid resolution increase and a better representation of Orography over the region with increased grid resolution of the model.

4) We also conducted test runs with Convection parameterisation adopted from GA7 physics and explicit experiments at 9km and found that the explicit run captured the diurnal timing better than the parameterised one, which encouraged us to push the explicit representation of convection to 8km or 9km grid resolution considering the merits of reduced computational requirements.

5) We also performed high-grid resolution simulations of 2km and 1.5km for a smaller domain and found to be consistent with the larger domain simulations, we could notice added value in terms of precipitation simulation with respect to GPM-IMERG observations, which also finds usefulness in other downstream application studies.

6) We found the explicit versions of the SINGV-RCM simulations are able to capture the higher threshold precipitation rates compared to lower precipitation range bins as evidenced from the precipitation distribution analysis.

7) We have clearly shown that the added value of downscaling from the driving model (ERA-5) to 8km and 2km, will augur best possible downscaling setup for simulation with CMIP6 models for V3 studies, which goes into various climate change applications over the Singapore region.

Key findings from this study are:

- Explicit convection setting is better than parameterised due to the fact that the improvement is notable when moving from parameterised to explicit convection in the timing of the diurnal cycle, which has the potential to improve other aspects of the simulation through feedbacks on the radiative fluxes and circulation (Birch et al 2016)
- the gain by switching convection off is more than increasing resolution from 8km to 4.5km
- simulations at 2 km adds value over 8km.

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