Extreme Rainfall Projections for Malaysia at the End of 21st Century
Using the High Resolution Non-Hydrostatic Regional Climate Model (NHRCM)

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Abstract

The Non-Hydrostatic Regional Climate Model (NHRCM) was used in simulating the present and future rainfall climate over Malaysia under the RCP8.5 scenario in this study. Simulation and projection from 1979 to 2002 for present day and 2070 to 2100 for the end of century were conducted over the Malaysia. The 20 km resolution MRI-AGCM3.2 model simulation from Meteorological Research Institute (MRI) was used as boundary conditions. The objective of this study was to estimate the extreme rainfall projections in Malaysia at 5 km of resolution during the November to February period, representing the northeast monsoon season. Overall, the model was capable to simulate the historical rainfall climatology and distribution, but model tended to underestimate high rainfall frequency and mean rainfall intensity in Malaysia. However, compared with simulations at 25 km, added values have been shown at 5 km resolution. Based on the NHRCM05 simulations, a number of hotspots have been identified with significant projected increases up to 80% for the extreme rainfall indices (R20mm, RX1day, R95pTOT and R99pTOT), 30% increases in mean rainfall intensity (SDII) and 20% for consecutive dry days indices (CDD).

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1. Introduction

Malaysia has been experiencing reoccurrences of weather and climate extreme related hazards, e.g., floods, droughts, landslides, storms, which often come with huge socio-economic impacts (Juneng et al. 2007; Tangang et al. 2008; Tangang et al. 2012; Chan 2015; Ramli et al. 2015; Abdul Rahman and Mapjabil 2017; Hai et al. 2017; Ibadullah et al. 2019). Hence, Malaysia is considered highly exposed and vulnerable to these hazards. As weather and climate extremes intensify due to climate change (Field et al. 2012), Malaysia needs to reduce its exposure and build-up its climate resilience for climate change impact in future decades, which is achievable through planned adaptation measures. However, such endeavors require robust knowledge of weather and climate extremes in future periods.

Both the general circulation model (GCM) and regional climate model (RCM) are tools required in generating future climate scenarios at regional and local scales (Giorgi and Mearns 1991; Meehl et al. 2000; Giorgi et al. 2009). While GCM resolves large-scale features of global and regional climate, the RCMs are capable of adding and incorporating the complexities on local and regional scales (Kanamitsu and DeHaan 2011). With the high-resolution nature of RCM products, impacts of climate change at local and regional levels can now be addressed. The high-resolution data can input into impact assessment tools, e.g., hydrology or crop models (Tan et al. 2019). The data would, therefore, help provide much more robust information for impact assessments, leading to the development of climate adaptation strategies, which are local in nature.

The progress of regional climate downscaling study in Southeast Asia is considered at its early stage, as reviewed in Tangang et al. (2020). Most studies relied on a combination of a single GCM and RCM, which does not allow for an estimation of the model’s full ranges of uncertainty (Valle et al. 2009). As part of the global initiative of the Coordinated Regional Climate Downscaling Experiment (CORDEX), the first phase of the CORDEX Southeast Asia (hereafter CORDEX-SEA) was initiated in 2013 and subsequently completed in 2018, and currently providing the multi-model climate projections at 25 km (Tangang et al. 2020). However, even at 25 km, which is the highest recommended resolution in CORDEX, large-biases can still be featured in the simulations, especially in the archipelagic sub-regions of the Maritime Continent (Supari et al. 2020). While the biases can be attributed to multiple factors, inadequacy in the model’s spatial resolution can be an important contributor. In the archipelagic Maritime Continent where landmasses are characterized by many small islands, higher spatial resolution may be needed to reduce model’s biases (Tangang et al. 2020). However, model’s performances in simulating climate in Southeast Asia can be also influenced by the physical parameterization schemes of the models (Manomaphiboorn et al. 2013; Ngo-Duc et al. 2014; Rahmat et al. 2014; Juneng et al. 2016; Cruz et al. 2017; Ngo-Duc et al. 2017; Raghavan et al. 2017; Ratna et al. 2017; Chung et al. 2018; Ge et al. 2019; Kang et al. 2019; Lui et al. 2019; Wang et al. 2020). The effects of different physical schemes are reflected in the inter-model variations in model’s biases (e.g. Tangang et al. 2020). Readers are referred to Tangang et al. (2020) for a complete review on regional climate simulation in Southeast Asia.

The regional climate simulation study at a country level in within the region is also limited, as it is the case in Malaysia (Tangang et al. 2012). There have been a number weather and
climate simulation studies in Malaysia, e.g., focusing on process understanding (Juneng et al. 2007; Salimun et al. 2010; Sow et al. 2011; Ardie et al. 2012; Jamaluddin et al. 2018; Ibadiullah et al. 2019) and climate projection (Kwan et al. 2014; Loh et al. 2016; Ngai et al. 2020). However, the elevated demands in recent years for climate projection data at much higher resolution, e.g., at basin scales, warrants an investigation of added values of regional climate simulations at spatial resolution finer than 25 km. This is the aim of this study, which will be using the Non-Hydrostatic Regional Climate Model (NHRCM) to simulate the present and future climate over Malaysia at 5 km spatial resolution.

The NHRCM has been used for regional climate studies particularly in Japan and Southeast Asia (Murata et al. 2012; Nakano et al. 2012; Murata et al. 2015; Cruz et al. 2016; Cruz and Sasaki 2017; Jamaluddin et al. 2018). Cruz and Sasaki (2017) highlighted that although NHRCM is well reproducing the topographic effect on rainfall over the Southeast Asia, wet (dry) biases in the windward (leeward) side of mountains can be found in results. Tangang et al. (2020) used NHRCM as one of 7 RCMs in CORDEX-SEA multi-model regional climate downscaling in Southeast Asia. Meanwhile, Jamaluddin et al. (2018) showed that NHRCM performed reasonably well in simulating diurnal rainfall cycles over Peninsular Malaysia. In this study, the non-hydrostatic regional climate model (NHRCM) is used to simulate present and future climate in Malaysia with a grid spacing of 5 km. The objective of this study is to estimate the projected changes of extreme rainfall indices based on the representative concentration pathway (RCP 8.5) 8.5 scenarios at the end of the 21st century over Malaysia. The details of the datasets, method and model design are presented in Section 2. Results and discussion are shown in Section 3. The summary and conclusions are presented in Section 4.

2. Data and methods

2.1 NHRCM model and experiment design

The NHRCM is a regional climate model developed by the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA) based on the non-hydrostatic model (Sasaki et al. 2008). The parameterization schemes used in this study followed the configuration described in Nakano et al. (2012) and Cruz et al. (2016). For instance, the modified Kain-Fritsch scheme is used for cumulus convection and Mellor-Yamada for turbulence closure models (Kain and Fritsch 1993; Ohmori and Yamada 2004) and the land surface model is represented by an improved MRI-JMA Simple Biosphere model with Zeng et al. (1998) surface layer flux scheme. The spectral nudging scheme based on the spectral boundary coupling method (Kida et al. 1991; Sasaki et al. 2000) is used to preserve the large-scale field of the boundary condition within the nested domain (Nakano et al. 2012).

In this study, the simulation of 20 km resolution MRI-AGCM3.2s model (Mizuta et al. 2012) is used as boundary conditions for the NHRCM. The simulation was run over a period around 20 years – 1979 to 2002 for historical period and 2079 to 2100 for the far future period based on the RCP 8.5. Similar to Cruz and Sasaki (2017) and Jamaluddin et al. (2018), the NHRCM was run in parallel each year from 1st of September to 31st October of the following year. The results of the first month (September) were discarded as model spin-up. Figure 1 showed the domain (491 × 181 grids points) and topography of this study covering the whole Malaysia from 8.5°N to 0.5°S and 97.8°E to 119.9°E at 5 km resolution (hereafter referred as NHRCM05) with 50 vertical levels. Malaysia has two geographically separated regions, Peninsular Malaysia (or West Malaysia) and the northern part of Borneo (East Malaysia, comprising the states of Sarawak and Sabah). For the analysis, this study focuses on the northeast monsoon season, Nov-Dec-Jan-Feb (NDJF). The time periods considered in this study are – historical period (1979–2002) and end century period (2079–2100). Although the simulation only covers 20 years, previous studies have shown that a 20 years climatology is sufficient for extreme climatology studies (Lelieveld et al. 2016; Tangang et al. 2018). The significance of future changes was determined via a Monte Carlo permutation test (von Storch and Zwiers 1999).

### Table 1. List of extreme rainfall indices together with respective definitions.

| No. | Indices | Definition | Units |
|-----|---------|------------|-------|
| 1   | SDII    | Simple daily intensity index, seasonal total number of wet days ≥ 1 mm/day | mm/day |
| 2   | CDD     | Maximum number of consecutive dry days (dry days < 1 mm/day) | days |
| 3   | RX1day  | Highest one day rainfall amount per time period / Seasonal maximum 1-day rainfall amount | mm |
| 4   | R20mm   | Number of days with rainfall amount ≥ 20 mm/day | days |
| 5   | R95pTOT | Total rainfall amount when daily rainfall amount > 95th percentile of rainfall on wet days in the time period | mm |
| 6   | R99pTOT | Total rainfall amount when daily rainfall amount > 99th percentile of rainfall on wet days in the time period | mm |

2.2 Observational datasets and extreme rainfall indices

The high resolution (0.05°) Climate Hazards Group Infrared Precipitation with Station (CHIRPS) dataset (http://chg.geog.ucsb.edu/data/chirps/) is used to evaluate the performance of NHRCM05 in reproducing spatial pattern of the mean rainfall and probability distribution of extreme rainfall indices. The CHIRPS 5 km precipitation dataset (hereafter CHIRPS5) has been shown as one of reliable gridded data products in Malaysia (Ayoub et al. 2020). The NHRCM05 outputs were re-gridded onto CHIRPS5 grids for spatial consistency.

Table 1 shows the description of six extreme indices selected from the ETCCDI (Joint CCI/CLIVAR/JCOMM Expert Team in Climate Change Detection and Indices, http://etccdi.pacificclimate.org/list_27_indices.shtml). These six extreme rainfall indices (SDII, CDD, RX1day, R20mm, R95pTOT and R99pTOT) were used to examine the possible change of rainfall extreme in future projection.

3. Results and discussion

3.1 Historical rainfall and extreme evaluation

Figure 2 shows the spatial distribution of mean climatology rainfall for observations and NHRCM05, and model biases with respect to the observations over the northeast monsoon (NDJF) over Malaysia. Also shown are the complementary cumulative density functions (ccdf) of daily rainfall of CHIRPS5, NHRCM05 and the NHRCM 25 km resolution of Tangang et al. (2020) (here-
after NHRCM25). During the NDJF season, Malaysia receives high rainfall amount (less rainfall) particularly over the east coast (west coast) of Peninsular Malaysia and East Malaysia due to the influence of the northeast monsoon (Tangang et al. 2012). Generally, the NHRCM05 simulation tends to overestimate NDJF rainfall particularly over the high mountain area (i.e., Titiwangsa mountain range in Peninsular Malaysia and the Crocker and Iran mountain ranges over the East Borneo Malaysia) (Fig. 2b). Dry biases were found mostly in the coastal areas - the northern east of Peninsular Malaysia and East Malaysia. In the mountainous regions, wet biases prevail (Fig. 2e). The quality of CHIRPS data can be relatively low due in remote areas due the absence of meteorological stations (Ayoub et al. 2020). Hence, the biases may reflect inadequacy of CHIRPS data over remote mountainous region. Furthermore, the NHRCM05 was able to capture the east-west rainfall gradient, which is separated by the Titiwangsa mountain range over Peninsular Malaysia. Added values of NHRCM05 can also be seen at local scales as indicated by smaller biases compared with NHRCM25. Also, based on Fig. 2d, although both NHRCM05 and NHRCM25 underestimated the frequency of daily rainfall, the former offered a much better approximation especially at intensity of 18 mm/day and higher.

Figure 3 shows maps of the climatological means of indices together with respective biases with respect to CHIRPS5. Generally, notable biases can be seen for all indices although spatial variation is also depicted. NHRCM05 tends to underestimate the very high rainfall days (R20mm) in East Malaysia and mean rainfall intensity (SDII) over the east coast of Peninsular Malaysia. Wet biases in the peninsula’s west coast (dry biases in east coast peninsular) is indicated for RX1day, R95pTOT and R99pTOT indices representing intensity of extreme rainfall. In East Malaysia’s Crocker and Iran ranges, and Titiwangsa range in Peninsular Malaysia, the tendency for wet biases is indicated, which could be attributed to the relatively low quality of CHIRPS in these areas.

Most of the biases shown in Figs. 2 and 3 are presumably systematic (i.e. resulted from the model’s shortcomings e.g., parameterization schemes) in nature. Hence, considering the anomalies instead (i.e. removing the long-term mean), which is akin to a simple bias correction, and comparing the PDFs of observation and simulations, would give a better account of the model’s skills (Tangang et al. 2018). Figure 4 shows the comparisons of PDFs of anomalies of indices of CHIRPS5 and NHRCM05. Also shown is the respective PDF of NHRCM25. For all indices, the distribution of CHIRPS5 anomalies is well represented by the respective PDFs of NHRCM05. This implies that, by discounting the systematic biases, NHRCM05 gives reasonable approximations of the

Fig. 2. Mean rainfall climatology of (a) CHIRPS5, (b) NHRCM05, (c) NHRCM25. The respective biases are shown in (e) and (f). The complementary cumulative density functions of daily rainfall are shown in (d).
Fig. 3. Mean climatology (first column and third column) and indices biases (second column and fourth column) of six rainfall indices with respect to CHIRPS5 observation from 1979-2002 over Malaysia.

Fig. 4. PDF of the anomalies in CHIRPS observation (red), NHRCM05 (solid black) and NHRCM25 (dotted grey) rainfall indices for historical period: (a) SDII, (b) CDD, (c) RX1day, (d) R20mm, (e) R95pTOT and (f) R99pTOT.
observed indices. However, this is not the case for NHRCM25, especially for CDD (Fig. 4b) and R20mm (Fig. 4d). The broad distribution of CDD and R20mm NHRCM25 suggests over estimation of the tail values.

3.2 Future changes in extremes rainfall

The assumption of systematic biases to persist in future periods justifies the use of the simulations to estimate future changes for each index. Figure 5 shows the percentage changes in the indices for the RCP8.5 scenario, where hatching indicates significance at 90% confidence level. Generally, the NHRCM05 projected increases across all extreme indices. However, some hotspots can be readily identified. For SDII, higher projected changes up to 30% are depicted over the west and east coast of Peninsular Malaysia as well as the coast of Sarawak (Fig. 5a). For R20mm, RX1day, R95pTOT and R99pTOT, the southern part of Sarawak is projected to have higher changes as high as 80% by the end of the 21st century. For the CDD however, the hotspots are located in the west coast and southeastern parts of Peninsular Malaysia, where the projected changes can reach as high as 20−25% compared to historical period (Fig. 5b).

We selected a number of hotspot regions indicated by the boxes in Fig. 5. In Fig. 6 the shifting of the PDF of anomalous changes are indicated for all extreme indices in the selected hotspot regions. For SDII, the index representing extreme rainfall intensity, the PDF of anomalous SDII in east coast of Peninsular Malaysia clearly shifted to the right (Fig. 6a), indicating tendency of intensified rainfall by the end of the 21st century. The same can be concluded in west coast Peninsular and coastal areas of Sarawak where the projected increases can be as high as 35%. For CDD, the duration of consecutive no rainfall days, the PDF of hotspot region in the west coast Peninsular Malaysia also indicates slight shifting to the right with projected increase reaches 25% (Fig. 6b). Similar magnitude of increases are depicted for the southeastern areas of Peninsular Malaysia. For the southern areas of Sarawak, indicators of rainfall intensity (RX1day, R95pTOT, R99pTOT) all are showing shifting of PDFs. In the same areas, the shifting of R20mm PDF, an index for very heavy rainfall frequency, for southern parts of Sarawak is even more pronounced with the percentage of projected increases can reach 80% (Figs. 5d and 6d).

The tendency for projected increases in extreme rainfall frequency and intensity could be due to both atmospheric thermodynamic and dynamic changes in future warmer climate (Emori and Brown 2005). Extreme rainfall is likely to increase in future warmer climate due to increased availability of atmospheric water content as mean temperature increases (Raymond 2000; Bretherton et al. 2004; Muller et al. 2009). However, increasing sea surface temperature under future climate change may also contribute to the increase in extreme rainfall (Muller et al. 2011; Cubasch et al. 2013) and this effect could be important in the maritime continent (Supari et al. 2017). Tangang et al. (2020) also found the enhanced low-level divergence (convergence) is correlated well with decreased (increased) in mean rainfall during future warmer climate in Southeast Asia.
4. Summary and conclusion

The NHRCM05 model is used to project the future changes in extreme rainfall over Malaysia at the end of the 21st century based on the RCP8.5 scenario. Results showed that the NHRCM05 model is capable of simulating the historical rainfall climatology and distribution in Malaysia. However, the model tends to underestimate the very high rainfall days and mean rainfall intensity. Nevertheless, some added values have been shown in NHRCM05 compared to NHRCM25. The projected extreme rainfall showed significant increases (30%−80%) for most of the indices in some areas in Malaysia. A number of hotspots of projected increases of extreme rainfall by the end of the 21st century have been identified. The southern part of Sarawak is considered highly exposed under RCP8.5 scenario as both the frequency of heavy rainfall (R20mm) and intensity of extreme rainfalls (RX1day, R95pTOT, R99pTOT) showed significant increases up to 80%. In the west and east coast of Peninsular Malaysia, both rainfall intensity and dryness are projected to increase. While the findings of this study are useful, especially in demonstrating the added values of simulations at much higher resolution, the highlighted projected changes are absent of uncertainty estimations, both from the GCM and RCM. Multiple GCMs and RCMs must be part of the ensemble for robust future projection (Valle et al. 2009; Tangang et al. 2020).

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