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Future Simulation of Solar Radiation and Cloud Fraction over the Malaysia Region under RCP 4.5 and RCP 8.5 Scenarios

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Abstract: Climate change may be defined as a significant change of weather patterns over a long period of time. It has adverse impacts on developing countries such Malaysia that strongly rely on agriculture and natural resources development and extraction. This present study projected the future average solar radiation and total cloud fraction from 2010-2100 over the Malaysian region based on IPCC Fifth Assessment Report. A global climate model, the Bias-corrected Community Earth System Model (CESM) was used for initial and boundary conditions for Weather Research Forecast (WRF) modelling system. Generally, the model underestimated the reanalysis data for solar radiation and overestimated for cloud fraction over the Malaysia region. The future simulation showed that the averaged solar radiation increased by 12.4 W/m^2 in Winter and 26.2 W/m^2 in Summer season under RCP8.5 scenario, relative to the baseline period. In RCP4.5 scenario, the increment of solar radiation was lower in Winter (7.4 W/m^2) but higher in Summer (45.7 W/m^2) as compared to high emission scenario during Winter and Summer seasons, respectively. At the end of this century, the total cloud fraction decreased over Malaysia domain around-12.9 and 15.9% during Winter and Summer seasons, respectively in RCP 8.5 scenario. Meanwhile, the changes of cloud fraction decreased by -0.9% in January but increased about 27.1% in July under a low emission scenario. Our simulation suggests that climate variability in future scenarios could lead to climate-related risks such as air quality impacts and vulnerability in the region.

Key words: WRF, solar radiation, cloud fraction, Malaysia, RCP 8.5, RCP 4.5

INTRODUCTION

The rapid transformation of Malaysia's economy in the last few decades has been identified as one of the most significant contributors to the countr's increase anthropogenic emissions. The increase in greenhouse gas emissions as well as biogenic emissions from associated with various economic activities such as the conversion of forest into oil palm and other land uses has been found to be significant (Sentian *et al*., 2011; Skiba *et al*., 2012). Based on the socio-economic and environmental settings and landscapes, the country has also been identified as one of the most vulnerable in the regions due to climate change (Kong and Sentian, 2013; Kong *et al*., 2015). Therefore, concern about vulnerability issue due to climate change related risks has been the top priority in Malaysian government policies dealing with climate change.

Recently a number of modelling studies have been conducted in the Southeast Asian (SEA) region that related to the climate change and its impacts (Kong *et al*., 2015; Ueda *et al*., 2006; Sentian and Kong, 2013; Kong and Sentian, 2013). In the studies mentioned, the surface temperature and precipitation are the main climatic variables discussed. Meanwhile, there are some other climatic parameters such as solar radiation and cloud fraction that could play an important role in explaining climate change. A few studies have indicated that solar radiation increased in the future over SEA region (Sentian and Kong, 2013; Sentian *et al*., 2011). Relative to the current period, the mean solar radiation was increased by 5.6 W during DJF (December-January-February) and 4.6W during JJA (June-July-August) under SRES A2. In SRES B2, increased solar radiation was slightly lower than SRES A2, by 3.1 W during DJF and 3.8 W during JJA. In term of cloudiness, the downscaling model suggested that the cloud fraction reduced by 0.07 during DJF and 0.04 during JJA under SRES A2 as relative to baseline scenario. Under the B2 scenario, the total cloud fraction decreased by 0.04 during DJF and 0.05 during

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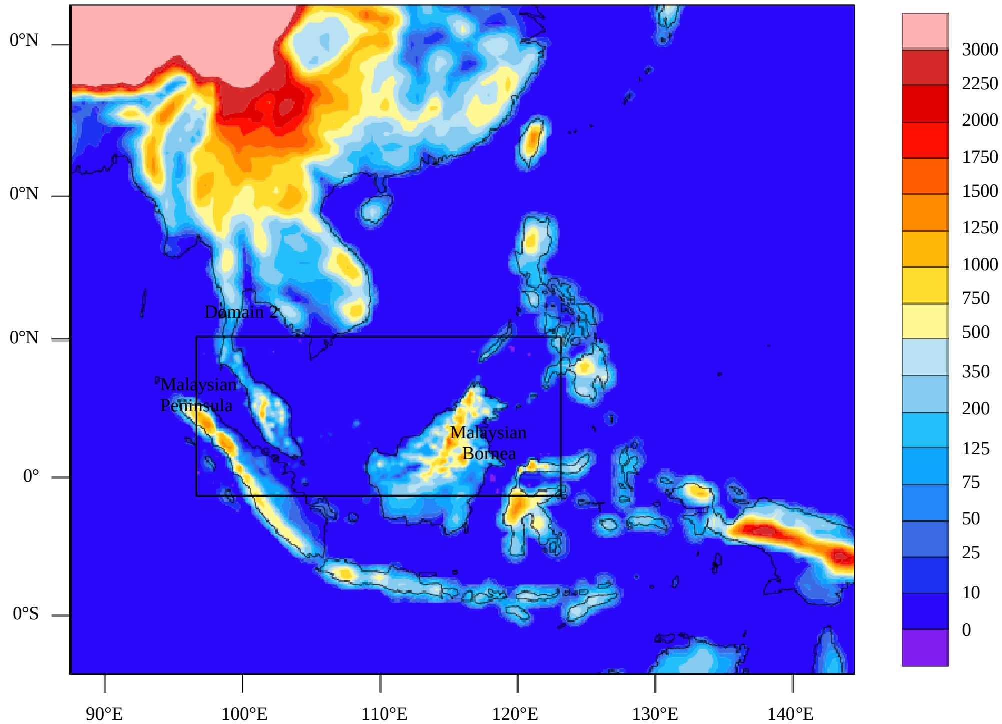

Fig. 1: The study domain (height) with 2 nested, domain 1 and 2

JJA. Moreover, an earlier study also showed that the total cloud fraction in SEA decreased 10% under IS92a scenario.

As mentioned in previous studies, the climatic scientist applied the emission scenarios used for the climate impact studies which are mostly based on IPCC third and fourth assessment reports. The report encompassed the social-economic emission scenarios and seen as more strenuous in terms of exploration as the emission trajectories have 'locked in' options for the changes of socio-economic. Recently, IPCC fifth assessment report, the Representative Concentration Pathways (RCPs) has been introduced for the purpose of gaining scientific advances in understanding the climate system featuring new set of emission scenarios that integrate the latest information on recent historical emissions, climate change impacts, vulnerability, mitigation and adaptation. The present study demonstrates the projection of future solar radiation and cloud fraction over Malaysia simulated via the WRF model, based on newly developed RCP scenarios.

MATERIALS AND METHODS

In the present study, we performed the same modelling method as mentioned by Kong *et al.* (2015). Two-way nesting was used by WRF Model with version 3.5.1 where the simulations were carried out in two nested horizontal domain. The first domain (domain 1) covered the Southeast Asia region with 45 km resolution (124×106 grid points) while the second domain (domain 2) was the Malaysia region, consisting of Peninsula Malaysia and East Malaysia, spaced at 15 km (172×76 grid points) (Fig. 1). The analysis was concentrated on second domain. Meanwhile, 30 vertical levels with the top reaching 10 millibars were used in the model. The spatial resolution of the data was 1×1° and temporal resolution was 6 h of time-step with a sequence of 00, 06, 12 and 18 UTC.

The simulation of surface temperature was generated using Bias-corrected Community Earth System Model (CESM) version 1 as initial and boundary conditions (Gent *et al.*, 2011; Hurrell *et al.*, 2013). CESM is the coupled global climate model that constructed by 4 component models such as atmosphere, land use, sea-ice and ocean. In the support of coupled model intercomparison experiment phase 5 (Taylor *et al.*, 2012) and the intergovernmental on climate change 5th assessment report, the CESM simulations were utilized to produce present-day dataset. The CESM dataset has a strong ability to simulate observed temperature and rainfall globally (Knutti *et al.*, 2013). Moreover, it contains a historical simulation and three future projections.

The future simulations include the Representative Concentration Pathways (RCPs): RCP 4.5, RCP 6.0 and RCP 8.5 (Moss *et al*., 2010) with the time slice 2006-2100. In this study, we focus our investigations on RCP 4.5 and RCP 8.5. The future scenario of RCP 4.5 is a low-to-moderate emission scenario in which Greenhouse Gas (GHG) radioactive forcing will reach 4.5 W/m^2 at the year 2100. Moreover, this represents a scenario in which a variety of adaptive policies has been applied to limit the radioactive forcing (Thomson *et al*., 2011). Meanwhile, RCP 8.5 indicates a high emissions scenario with GHG radioactive forcing will reach 8.5 W/m^2 by 2100. It shows that little has been done to control or limit GHG emissions (Riahi *et al*., 2011).

Two sets of simulation were performed: one is the baseline period (2010) and another one is the future-day period (2100). The time slice for the present-day simulation is selected between 0000 UTC 1 January 2010 and ended at 0000 UTC 1 February, 2010 denoted as Winter or Northeast Monsoon. Moreover, simulations of Summer or Southwest monsoon were run from 0000 UTC 1 July, 2010 and ended at 0000 UTC 1 August, 2010. The initial and boundary conditions for WRF simulation were run for 5 days with the 1st day discarded as model spin-up. The physics schemes of the physics components included within the WRF are the Kain-Fritsch scheme for cumulus parameterization (Kain, 2004); Yonsei University (YSU) scheme for PBL parameterization; Rapid Radiation Transfer Model (RRTM) for Long wave Physics Radiation (Hong and Pan, 1996); WRF single-momentum 6-class scheme (WSM6) for microphysics parameterization (Hong *et al*., 2004); Dudhia short-wave radiation scheme for Short wave Physics Radiation (Dudhia, 1989) and Noah Land Surface Model (LSM) that has been set as four layers of soil and one canopy layer. The reanalysis data used as the main comparison in this study is NCEP FNL (Final) Operational Global Analysis data as obtained from Global Data Assimilation System (GDAS). Global Telecommunications System (GTS) and few sources continuously provides observational data to GDAS. The dataset is in grid format with 1 degree to 1 degree grids and is updated every 6h. The NCEP data consists of surface information with 26 mandatory levels (1000-10 milibars) of surface boundary level. The meteorological parameters included temperature, sea surface temperature, sea level pressure, surface pressure, geopotential height, relative humidity, ice cover, vertical motion, vorticity, ozone, u and v winds. The continuous time series has been updated and extended to a close-present date (NCEP, 2015).

RESULTS AND DISCUSSION

This study of research discusses climate changes corresponding to solar radiation and cloud fraction in Malaysia based on RCP 85 and 45 scenarios developed by Intergovernmental Panel on Climate Change (IPCC) 5th assessment report. The results are presented and concentrated with January denoted as Northeast monsoon (Winter) and July denoted as Southeast monsoon (Summer).

Model evaluation: In this study, high resolution WRF-regional climate model data downscaled from CISL was compared with the RCM data from NCEP-reanalysis data. We assumed that the NCEP data was an unbiased dataset to be compared with baseline scenario of RCP 8.5. Table 1 shows the evaluation and assessment of WRF modeling system relative to reanalysis of the dataset in terms of bias, Normalized Mean Square Error (NMSE), Fractional Bias (FB) and Factor of two (Fa2). Results from Table 1 shows that the NMB of solar radiation between RCP 8.5 and reanalysis dataset were underestimated in the range of 24.9-26.3%. For Fractional Bias, the model performed well but underpredicted by values of -0.30 during JAN and -0.29 during JUL. Also, the relatively small value of NMSE around -0.003 showed high performance for WRF-RCP85. Fa2 between WRF-RCP 85 and WRF-NCEP was relatively high at 0.74 during JAN and 0.75 during JUL. Obviously, the WRF-RCP85 under projected NCEP reanalysis data over most of the research domain except central part of Malaysian Peninsula and Borneo (Fig. 2). Under RCP45 baseline scenario, the bias of solar radiation with reanalysis data were similar with RCP85, underestimated in the range of 24.9-27.4% (Table 2). Fa2 between WRF-RCP45 and WRF-NCEP was consistent with RCP8.5 by 0.73 during JAN and 0.75 during JUL. Figure 3 clearly shows that WRF-RCP85 underprojected the NCEP reanalysis data over most part of research domain. The model however overprojected the reanalysis data across the central and internal region. Figure 4 shows the simulated seasonal mean of total cloud fraction compared to NCEP. The NMB were 34.1% in January and 23.2% in July (Table 1). High FB and NMSE were consistent with high NMB. In terms of Fa2, the WRF-RCP85 was performing well with the observed data by 1.3 and 1.2 under both seasons. WRF-RCP85 overprojected the cloud fraction as relative to WRF-NCEP across the whole research domain. However, both data sets agreed that the cloud fraction was low over high latitude area in January and vice versa in July. As shown in Fig. 4c, the model overprojected the reanalysis data over large part of research domain with highest overestimation across Northern part of Malaysian Borneo.

The simulated seasonal mean of total cloud fraction under RCP4.5 scenario compared to NCEP was shown in Fig. 5. The NMB were 36.4% in January and 5.4% in July (Table 2). Similar to WRF-RCP85, WRF-RCP45 was performing well with the reanalysis data in terms of Fa2 by

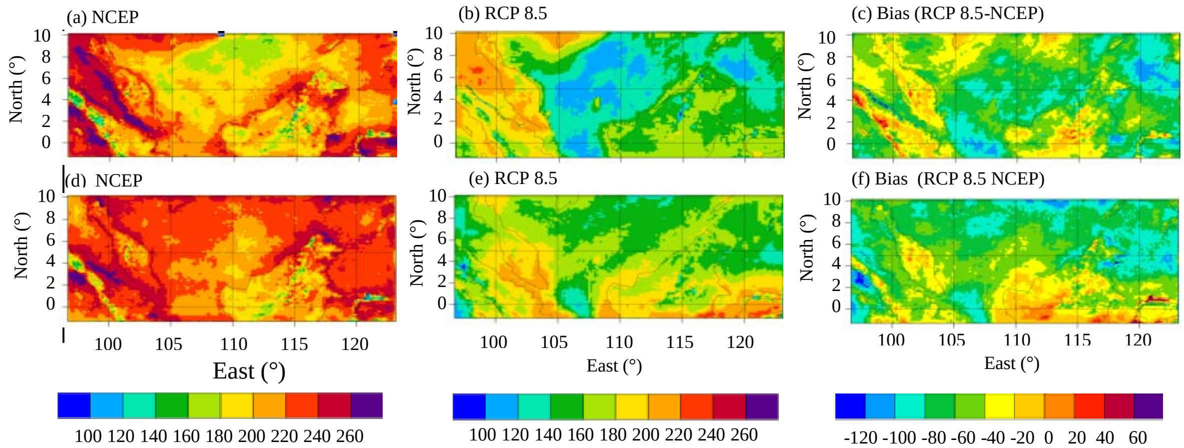

Fig. 2: Averaged solar radiation (W/m^2): a-f) Winter and Summer in RCP8.5 simulation (left), Reanalysis data (NCEP, center) Bias (difference between model and reanalysis, right)

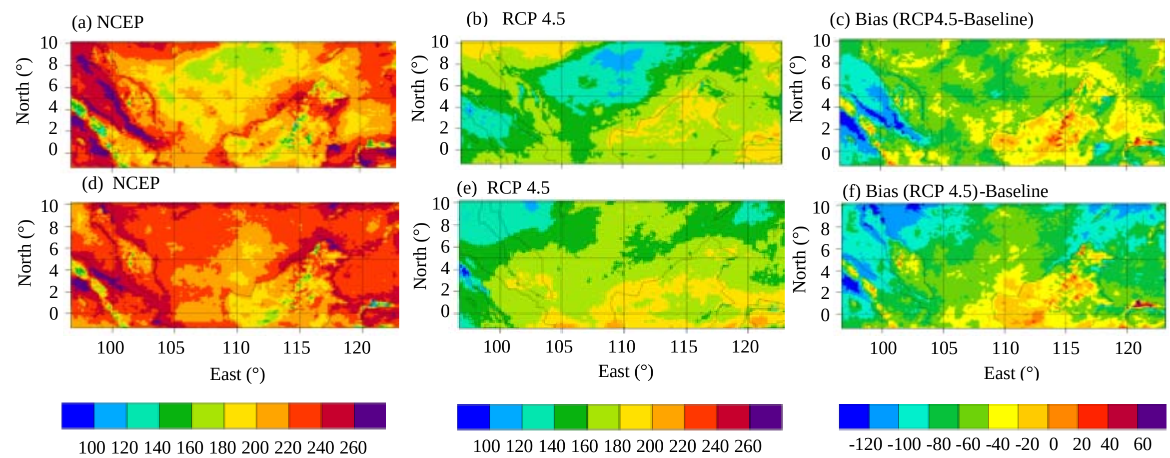

Fig. 3: Averaged solar radiation (W/m^2) for (a-f) Winter and Summer in RCP4.5 simulation (left), Reanalysis data (NCEP, center). Bias (difference between model and reanalysis, right)

Table 1: Comparison of averaged solar radiation in January (Jan) and July (Jul) under RCP 8.5 and 4.5 as relative to observed (CRU) for Normalized Mean Bias (NMB), Fractional Bias (FB), Normalised Mean Square Error (NMSE) and Factor of two (FA2)

Surface temperature	Period RCP 85-Jan.	RCP 45-Jan.	RCP 85-Jul.	RCP 45-Jul.
Model (W/m^2)	156.6000	159.7000	168.9000	163.7000
NCEP (W/m^2)	212.6000	225.8000	212.6000	225.8000
Bias (W/m^2)	-56.0000	-52.9000	-56.3000	-61.8000
NMB (%)	-26.3000	-24.9000	-24.9000	-27.4000
FB	-0.3000	-0.2800	-0.2900	-0.3200
NMSE	-0.0034	-0.0031	-0.0030	-0.0034
Fa2	0.7400	0.7500	0.7500	0.7300

1.4 and 1.1 under both seasons (Fig. 3). Both simulations told us that the cloud fraction was high over low latitude area in January and vice versa in July. As shown in Fig. 5, large overestimation was observed over Malaysian Peninsula in January at >0.30. In JUL, the model bias was generally low.

Table 2: Comparison of cloud fraction in January (Jan) and July (Jul) under RCP 8.5 and 4.5 as relative to observed (CRU) for Normalized Mean Bias (NMB), Fractional Bias (FB), Normalised Mean Square Error (NMSE) and Factor of two (FA2)

Surface temperature	Period RCP 85-Jan.	RCP 45-Jan.	RCP 85-Jul.	RCP 45-Jul.
Model	0.59	0.60	0.69	0.590
NCEP	0.44	0.44	0.56	0.560
Bias	0.15	0.16	0.13	0.030
NMB (%)	34.10	36.40	23.20	5.400
FB	0.29	0.31	0.21	0.052
NMSE	1.20	1.20	0.67	0.180
Fa2	1.30	1.40	1.20	1.100

Future projection of solar radiation: In 2100, the averaged solar radiation was observed to reach 169.0 W/m^2 during Winter and 195.1 W/m^2 during the Summer season under RCP 8.5 scenario (Fig. 6).

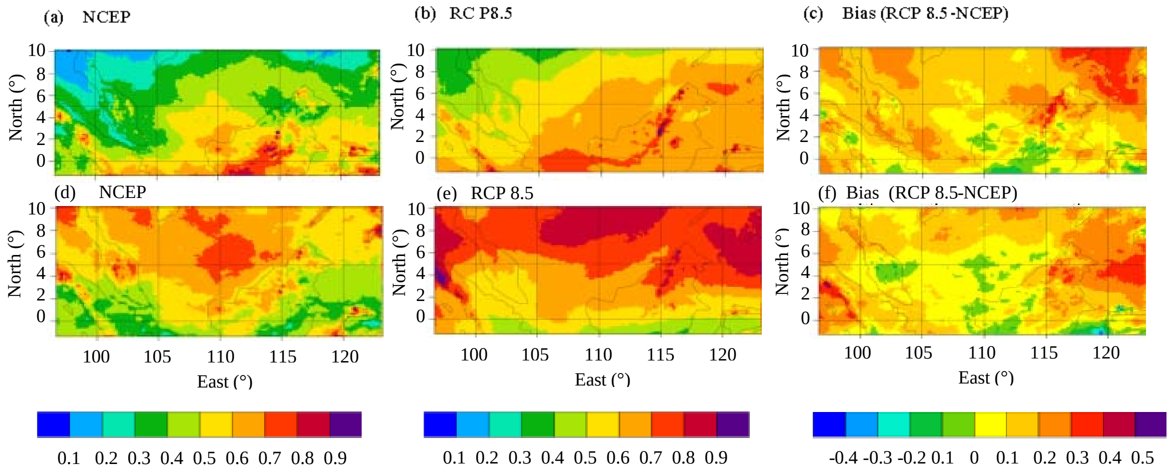

Fig. 4: Cloud fraction for; a-f) Winter and Summer in RCP8.5 simulation (left), Reanalysis data (NCEP, center) Bias (difference between model and reanalysis, right)

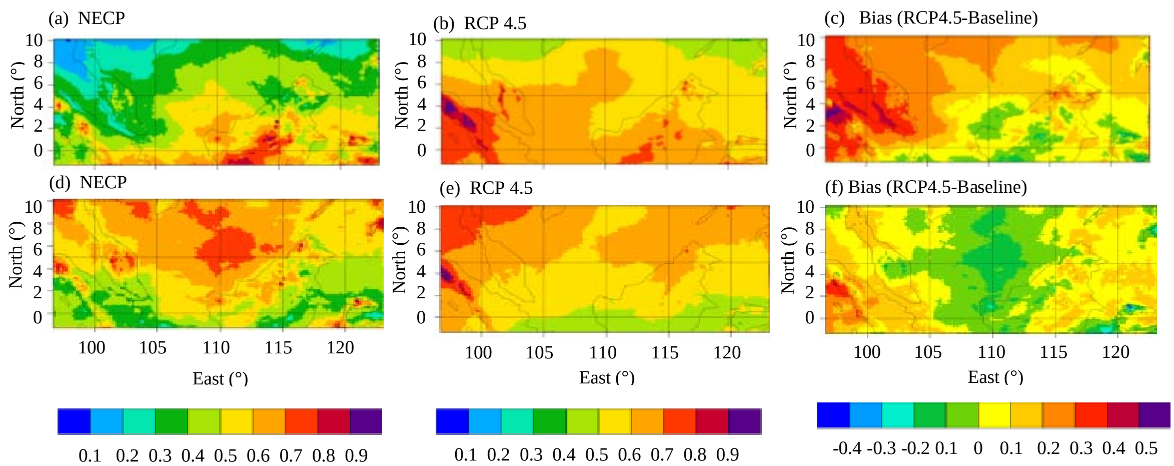

Fig. 5: Cloud fraction for; a-f) Winter and Summer in RCP4.5 simulation (left), Reanalysis data (NCEP, center), Bias (difference between model and reanalysis, right)

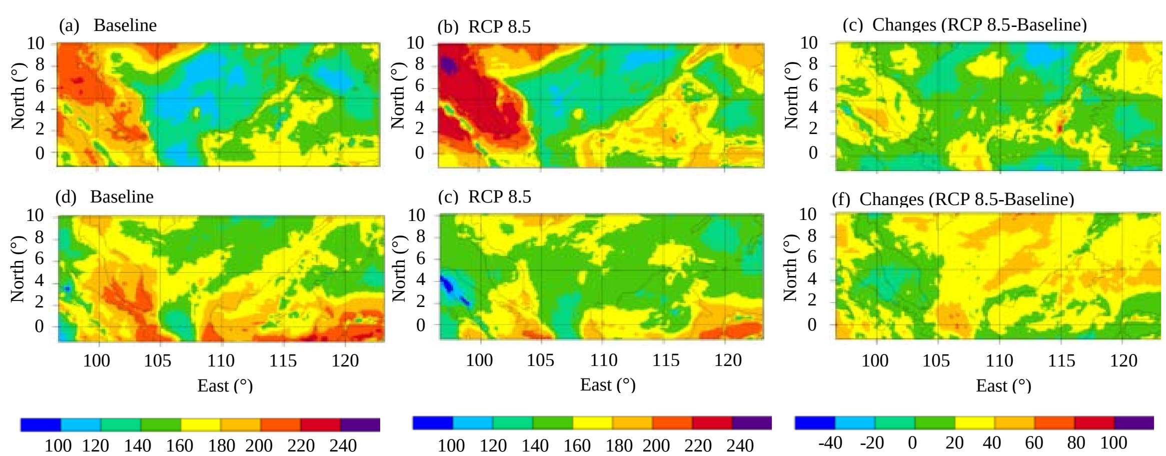

Fig. 6: Mean solar radiation (W/m^2) for; a-f) Winter-January and Summer-July under Baseline (year 2010) (left), RCP8.5 (year 2100) (centre) and Changes between RCP8.5 and Baseline (right)

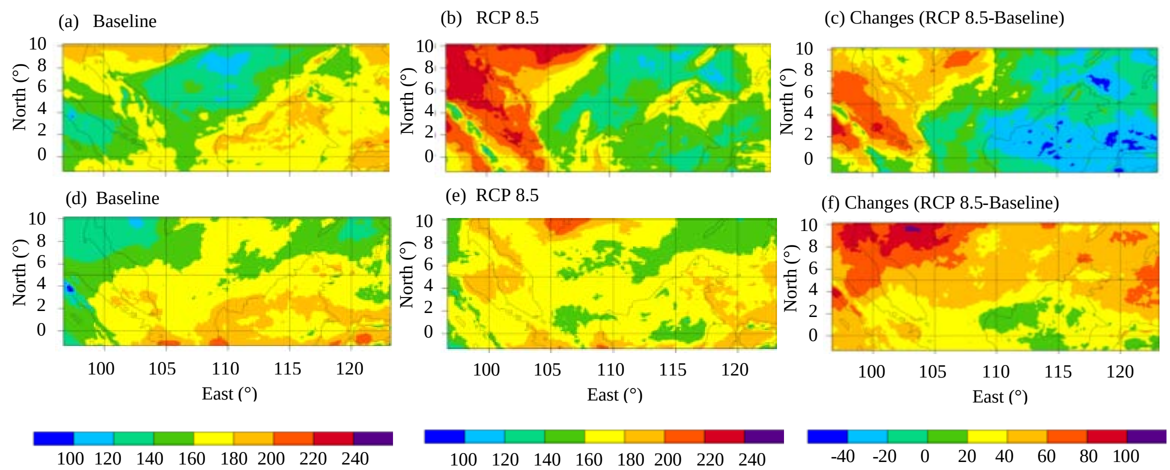

Fig. 7: Mean solar radiation (W/m^2) for; a-c) Winter-January and d-f) Summer-July under Baseline (year 2010) (left), RCP4.5 (year 2100) (centre) and Changes between RCP4.5 and Baseline (right)

Table 3: Mean baseline period and changes in solar radiation and cloud fraction under the RCP8.5 and RCP 4.5 emission scenarios as relative to baseline period

Variables	Period	January	July
Solar radiation (W/m^2)	**RCP 85**		
	Baseline	156.600	168.90
	Future	169.000	195.10
	Changes	12.400	26.20
	RCP 45		
	Baseline	159.800	163.70
	Future	167.100	209.50
	Changes	7.400	45.70
Cloud fraction	**RCP 85**		
	Baseline	0.590	0.69
	Future	0.510	0.58
	Changes	-0.076	-0.11
	RCP 45		
	Baseline	0.600	0.59
	Future	0.540	0.76
	Changes	-0.050	0.16

Relative to Baseline scenario, the changes of solar radiation were increased about 12.4 W/m^2 (7.9%) during January and 26.2 W/m^2 (15.5%) during July under RCP 8.5 scenario. In January, most of the research domain experienced an increment of solar radiation with the highest increment over the interior area of Malaysian Borneo (>60 W/m^2). However, the averaged solar radiation over certain parts of Northern Malaysian Borneo was found to decrease relative to baseline period. Obviously, the solar radiation in Malaysian Borneo underwent larger degree of increment as compared to Malaysian Peninsula during July (Table 3). Refer to Fig. 7, it was observed that the simulated mean solar radiation was 167.1 W/m^2 during January and 209.5 W/m^2 during July under RCP 4.5 scenario at the end of this century. Changes in solar radiation were increased about 7.4 W/m^2 (4.6%) during January and 45.7 W/m^2 (27.9%) during July under the RCP4.5 scenario. In Winter, the simulated solar radiation increased over the Malaysian Peninsula but decreased over Malaysian Borneo. A large change of solar radiation was observed around Straits Malacca and west coast of Malaysian Borneo, increasing >60 W/m^2. Moreover, a large decrease in solar radiation over the middle part of Malaysian Borneo (40 W/m^2) was found. In July, most of the research domain experienced the radiation increment with highest magnitude over Northern Malaysian Peninsula.

The increment of solar radiation over the whole Southeast Asia region at the end of this century were 5.6 W/m^2 during Winter season and 4.6 W/m^2 during Summer season (Sentian *et al*., 2011) which was lower compare to present study as relative to high emission scenario. Relative to B2 scenario, the projected change were 3.1 and 3.8 W/m^2 during Winter and Summer seasons, respectively. Research conducted by Sentian and Kong (2013) indicated that the average increase in solar radiation over the Malaysian region was 5-12 W/m^2 under SRES A2 and 3-10 W/m^2 under SRES B2.

Future projection of cloud fraction: As shown in Fig. 8, the simulated total cloud fraction during January was 0.51 and during July was 0.58 under RCP 8.5 scenario at the end of this century. There were fewer clouds during January but increased during July. Relative to the baseline period, the changes of total cloud fraction over Malaysia showed a reduction about -0.076 (-12.9%) during January and -0.11 (-15.9%) during July. Larger changes (<-0.30) were observed in the interior part of Malaysian Borneo in January. During July, it was obvious that a large area of Malaysian Peninsula and small area of Malaysian Borneo underwent increased cloud fraction but research area above 6°N latitude experienced a large reduction (<-0.1).

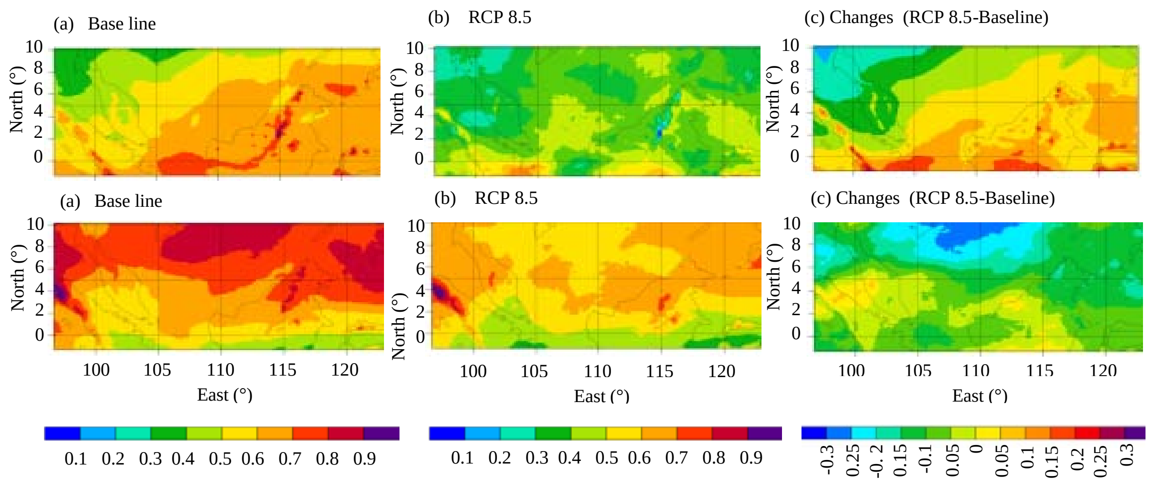

Fig. 8: Total cloud fraction for; a-c) Winter-January and d-f) Summer-July under Baseline (year 2010) (left), RCP8.5 (year 2100) (centre) and Changes between RCP8.5 and Baseline (right)

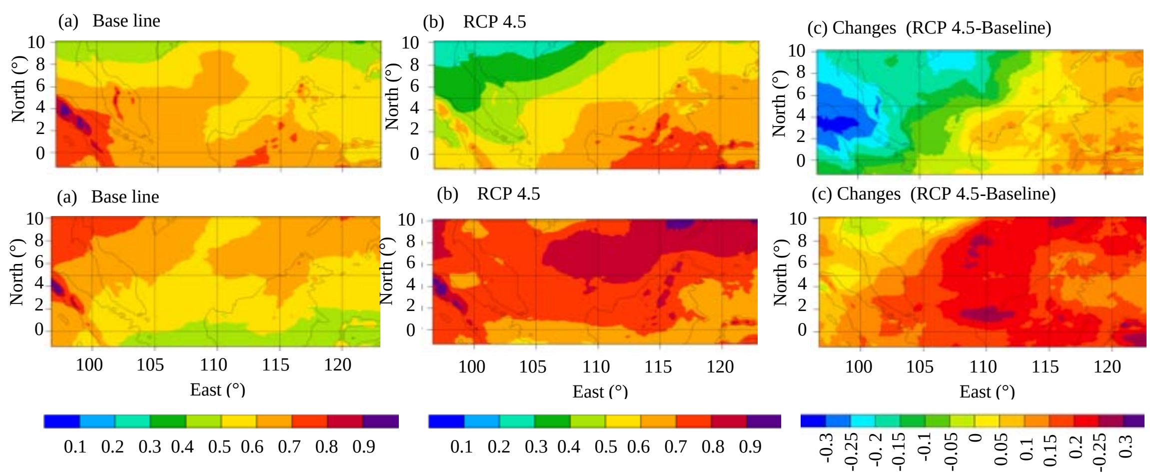

Fig. 9: Total cloud fraction for; a-c) Winter-January and d-f) Summer-July under Baseline (year 2010) (left), RCP4.5 (year 2100) (centre) and Changes between RCP4.5 and Baseline (right)

Under the RCP4.5 scenario, the total cloud fraction was recorded as 0.60 during January and 0.59 during July (Fig. 9). The changes of total cloud fraction showed a decrement of about 0.054 (-0.9%) during January but increased by 0.16 (27.1%) during July. During January, all of Malaysian Borneo including the sea area experienced increased total cloud fraction as relative to baseline scenario. Meanwhile, decreased of cloud fraction was observed over Malaysian Peninsula. The situation was different in July where cloud fraction increments were observed across the whole research domain with a higher increase of cloud fraction over Malaysian Borneo than Peninsula. Besides that we observed a large increment across most parts of South China Sea which might be due to the high intensity of evaporation.

Research conducted by McGregor found that the total cloud fraction in Southeast Asia decreased 10% under IS92a scenario which showed similarity in this study. In this study, mean total cloud fractions showed a reduction within the Malaysian region in the future-day period during 2100 under high emission scenario. Also, a study conducted by Sentian *et al*. (2011) indicated that in the A2 scenario, the total cloud fraction decreased around-0.07 during DJF and -0.04 during JJA as relative to Baseline scenario. For B2, the decrement of total cloud fraction was-0.04 during DJF and -0.05 during JJA. The decrement of total cloud fraction was larger in the current study compared to that by Sentian *et al.* (2011) under high emission scenario. Kong and Sentian (2013) performed a dynamic downscaling over the Malaysian region based on IPCC AR3. The results showed that the projected total cloud fraction was reduced by 0.14-0.032 under SRES A2 and 0.11-0.0057 under SRES B2 compared to the baseline scenario.

CONCLUSION

In the present study a high resolution WRF regional climate model was applied to project the future average solar radiation and total cloud fraction over the Malaysian region under RCP 8.5 and RCP 4.5 scenarios developed by IPCC firth assessment report. Overall, the downscaling model performed well in projecting averaged solar radiation while the model under-projected the reanalysis data throughout most of the research domain. A small over-projection (>20 W/m^2) was distributed over the central region. Meanwhile, the model demonstrates overestimation in simulating the total cloud fraction. In 2100, the averaged solar radiation was increased by about 12.4 W/m^2 during Winter and 26.2 W/m^2 during Summer season under RCP 8.5 scenario, relative to the baseline period. In RCP4.5 scenario, the increment of solar radiation was lower in Winter but higher in Summer compared to RCP 8.5 at around 7.4 and 45.7 W/m^2 during Winter and Summer seasons, respectively. The total cloud fraction decreased over Malaysia at the end of this century by around -12.9 and -15.9% during Winter and Summer seasons, respectively in RCP 8.5 scenario. Under the RCP 4.5 scenario, the changes of cloud fraction decreased by -0.9% in January but increased about 27.1% in July. Increased solar radiation was related to reduced cloudiness as mentioned by Penrod *et al*. (2014) which showed consistency with our simulation under RCP 8.5 scenario. A highly increased cloud fraction in July under RCP 4.5 may be due to the increase of rainfall (Kong *et al*., 2015) and evaporation process over the research domain. This carries the implication that the simulation results from this study are important for climate change impact, risk and vulnerability assessments. Moreover, national policymakers can use the results for the purpose of adaptation and mitigation policy development.

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