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A STUDY ON CLIMATE CHANGE PROJECTION AND CLIMATE ANALOG IN SOUTHEAST ASIA

Major : Climate Change

Code : 9440221

PHD THESIS SUMMARY ON CLIMATE CHANGE

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The PhD thesis is available at:
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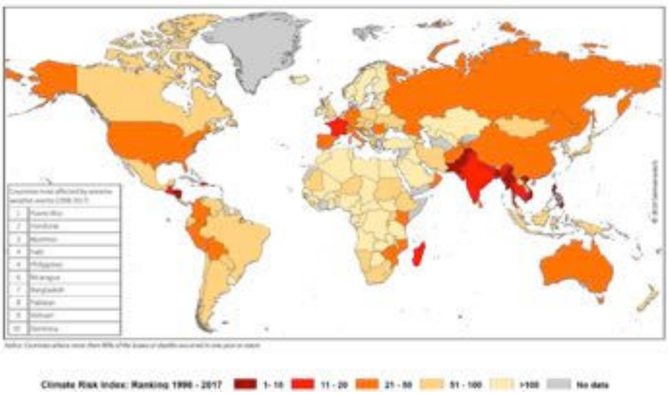
INTRODUCTION

Necessity of the chosen thesis topic "A study on climate change projection and climate analog in Southeast Asia"

In the past years, the term 'climate change' has been intensively used in daily life and in research documents. It has been existent and affecting many aspects of human life. As climate change is a global issue, this phenomenon has attracted great concerns from most countries in the world. Therefore, the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) has been periodically organized since 1995 till the present time. The latest COP 25 has just been held in Madrid, Spain in 2019 with certain results. At the Katowice summit in COP 24, the Global Climate Risk Index 2019 was released and indicated that intense cyclones, excessive rainfall and severe floods have caused some countries in South and Southeast Asia (SEA) to be at most risk by climate change (Figure 0.1).



Source: Climate Risk Index 2019, Germanwatch

Figure 0.1. The World Map of Climate Risk Index 2019.

The SEA region is considered to be one of the most vulnerable areas to climate change impacts as most countries in the region has long coastlines, major economic activities concentrated in coastal areas and their citizens' livelihood heavily depend on agriculture, forestry and fisheries and other natural resources (ADB, 2009).

In the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), the Working Group I (WGI) described that the SEA region had already experienced durable changes in its regional climate (Christensen, 2013). Moreover, the IPCC Working Group II (WGII) also underlined that the SEA region obviously had been impacted by regional climate change (Hijioka et al., 2014). However, through a limited number of recent studies, these reports also demonstrated a substantial lack of regional climate change research and its impact in the SEA region.

In addition, climate analog is used to define locations at which their present climate is similar to the projected future climate of a reference site (Ford et al., 2010; Luedeling and Neufeldt, 2012; Mearns et al., 2001). It is an interesting tool to study climate in spatio-temporal relationship. The approach is relatively comprehensive compared to the one based on only temperature or precipitation or both, as it helps to realize spatio-temporal climatic vision. Though climate analogs have been used relatively widely in studies in the world, there is, to date, no study on this analog approach conducted in SEA.

Therefore, the above-mentioned reasons lead to the author's choice of the thesis topic "Climate change projection in Southeast Asia".

General objective and specific aims

The general objective of the thesis is to grasp future climate change in SEA through climate projection and climate analog.

The specific research aims of the thesis include:

1) To project temperature and rainfall and their changes over the SEA region;
2) To define the best climate analog locations of some cities in SEA and Viet Nam and their common moving tendency;
3) To identify locations and land fractions of novel climate and disappearing climate in SEA and Viet Nam.

Research subjects and research scopes

The research subjects of the thesis are climate projection, climate analog, novel climate and disappearing climate within the research scope of SEA and Viet Nam. The thesis focuses on two important climate variables: 2m temperature and rainfall.

Defending points

The thesis points to be defended consist of:

1. Among 6 global circulation models (GCMs) and 6 regional climate models (RCMs), ensemble mean (ENS) has some advantages in simulating climate over SEA compared to individual experiments;
2. A modified version of an existing formulation to estimate climate distance is appropriate in SEA;
3. Novel climate in SEA is mainly found in coastal areas and islands, especially near equatorial areas and disappearing climate in Viet Nam is located in moutainous area at the end of the 21^{st} century.

New contributions

The thesis' new contributions or key findings include:

1. Evaluation on climate simulation in SEA and Viet Nam by 6

CMIP5 GCMs and 6 RCMs, and generally showing ENS's superior role.

2. Identification of a modified version of an existing formulation to estimate climate distance with weighted parameters for temperature and rainfall, and for ENS and analog climate thresholds
3. Distribution of good-analog, poor-analog, and novel climate over SEA and disappearing climate in Viet Nam under the Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5.

Scientific and practical significance of the PhD thesis

The thesis would provide scientific knowledge on projected temperature and rainfall changes, the appearance of novel climate as well as the disappearance of present climate in the future in the SEA and Viet Nam region.

These results would contribute practical inputs to climate change impact assessment and adaptation studies for scientists and to adaptation planning for policy makers.

Thesis structure

The thesis structure includes:

Introduction

Chapter 1: Literature review on regional climate downscaling and climate analog

Chapter 2: Observed data, numerical experiments and methodology,

Chapter 3: Performance of multi-model experiments in Southeast Asia

Chapter 4: Climate change projection and climate analog in Southeast Asia

Conclusions and Recommendations.

CHAPTER 1 – LITERATURE REVIEW ON REGIONAL CLIMATE DOWNSCALING AND CLIMATE ANALOG

1.1. Related concepts

Climate analog

Climate analog is used to define locations at which their present climate is similar to the projected future climate of a reference site (Mearns et al., 2001). This concept implies the spatio-temporal relationship between the reference site and the analog location (Figure 1.9).

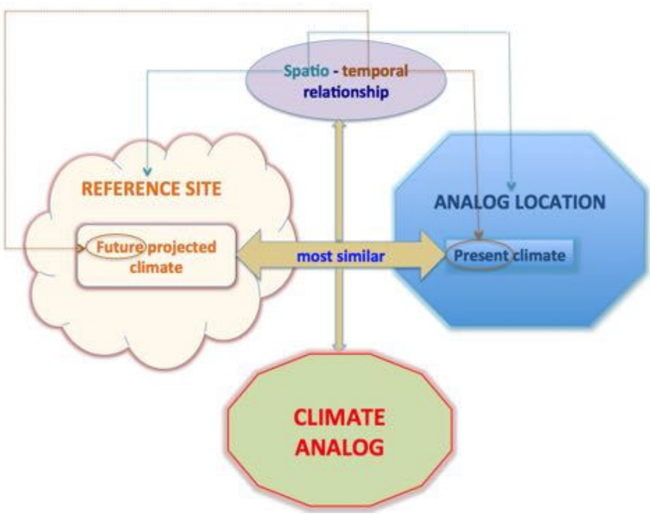


Figure 1.9. Schematic concept of climate analog.

1.2. Literature review

In the world

One of the most typical and comprehensive worldwide reference documents on climate simulation and projection is the AR5 contributed by the WGI of the IPCC (IPCC, 2013). Based on plenty of independent scientific analysis from observations on climate system, paleoclimate archives, theoretical research on climatic processes and simulations using climate models, the AR5 described inclusive pictures of Atmosphere – Ocean General Circulation Models (AOGCMs), Earth System Models (ESMs), Regional Climate Models (RCMs), etc. RCMs are regularly utilized to dynamically downscale global climate models (GCMs) for some particular geographical areas to supply more elaborate information (Laprise, 2008; Rummukainen, 2010).

In Southeast Asia, a number of studies have been conducted at the regional and country level. Aldrian et al. (2004) simulated rainfall in Indonesia using the Max Planck Institute regional climate model REMO. Three lateral boundary forcings were used in the study, including reanalyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA15 and National Center for Atmospheric Research (NCAR), the National Centers for Environmental Prediction (NCEP) and NCAR and the simulations from ECHAM4 climate model. The result showed that REMO generally well reproduced the spatial pattern of monthly and seasonal rainfall over land, but overestimated rainfall over the ocean. It was also shown that the quality of driving data could significantly affect the performance of the REMO experiments.

Loh et al. (2016) projected rainfall and temperature changes in Malaysia by the end of the 21st century using the Providing Regional Climates for Impacts Studies (PRECIS) RCM and the SRES scenarios. The temperature changes were projected to be from 2.5 to 3.9^{o}C, from 2.7 to 4.2^{o}C and from 1.7 to 3.1^{o}C for the A2, A1B and B2 scenarios, respectively. About 20 to 40% decrease of rainfall in the months of December to May was projected over Peninsular

Malaysia and Borneo, while a rainfall increase from ~20 to 40% during the summer months in most Malaysia was shown.

Ratna et al. (2017) used the WRF model and reported an overestimation of boreal summer precipitation in the SEA mainland and an underestimation of boreal winter precipitation in Indonesia.

Tangang et al. (2018) projected changes in annual precipitation extremes over SEA under the global warming of 2^{o}C based on the SEACLID/CORDEX-SEA simulations. Their study showed significant and robust changes in consecutive dry days (CDD) in Indonesia and in intensity of extreme precipitation (RX1day) in Indochina. The significant and robust changes in CDD, frequency of rainfall exceeding 50 mm day^{-1} (R50mm) and RX1day were also projected over the northern Myanmar.

Climate analog

With regard to climate analog, there have been studies in various places in the world.

Williams et al. (2007) projected the distributions of novel and disappearing climates by 2100. The study showed the relationship between novel climates and formation of novel species associations and other ecological surprises. Likewise, the disappearance of some existing climates was able to increase the level of extinction for species with narrow geographic or climatic distributions and disruption of existing communities.

A non-parametric approach was applied to identify climate analogs for 17 cities in Australia by Nakaegawa et al. (2017 with the global research domain. Among the identified climate analog cities in a global search, ten located within Australia while the other seven were in other continents (five in Africa, one in Mexico, and one in

Argentina).

Fabienne et al. (2017) used the climate analog approach to locate novel and disappearing climate across the world. The study showed that 15%, 21% or more than one third of the global land fractions would experience novel climates at the 1.5^{o}C, 2^{o}C or 4^{o}C global warming levels, respectively. These fractions were similar for the case of disappearing climate.

In Viet Nam

In Viet Nam, a number of climate studies in general and climate change studies in particular have been published to date, such as those of Nguyễn Đức Ngữ and Nguyễn Trọng Hiệu (1991), (2004), Nguyễn Viết Lành (2007), Trần Việt Liễn et al. (2007) and Nguyễn Đức Ngữ (2008).

In 2009, MONRE published the Climate Change and Sea Level Rise Scenarios for Viet Nam. It used the MAGICC/SCENGEN 5.3 software (http://www.cgd.ucar.edu/cas/wigley/magicc/) and statistical downscaling method to provide climate change and sea level rise scenarios for seven climatic sub-regions (MONRE, 2009). In 2012, MONRE updated the climate change scenarios through combining the statistical and dynamical downscaling results. The dynamical results were from the Providing REgional Climates for Impacts Studies (PRECIS) RCM developed at Hadley Centre, the United Kingdom (UK) and the MRI GCM of the Japanese Meteorological Research Institute (MONRE, 2012). In 2016, the report continued to be updated. An ensemble of RCMs including RegCM, WRF, Conformal-Cubic Atmospheric Model (CCAM), MRI, and PRECIS was used to dynamically downscale a number of CMIP5 GCMs under different Representative Concentration

Pathways (RCPs) scenarios (MONRE, 2016; Van-vuuren, 2011). This report has been considered as a reference document for supplying the basis for climate change-related studies in various sectors.

In 2015, the Viet Nam Institute of Meteorology, Hydrology and Climate change (IMHEN) coordinated with the United Nations Development Program (UNDP) published the Viet Nam Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IMHEN and UNDP, 2015). The report assessed extreme events and their impacts on the natural environment, socio-economic development and sustainable development of Viet Nam, which aimed to promote adaptation to climate change and management of risks of disaters and extreme events in Viet Nam.

1.3. Chapter 1 summary

Chapter 1 introduced the relevant concepts used in the thesis and the overview of literature on regional climate downscaling and climate analog in the world and in Viet Nam. Although a great effort on conducting researches related to climate simulations and projections using RCMs has been made for the past years, the quantity of studies on these issues over the SEA region is still modest (Aldrian et al., 2004; Phan-Van et al., 2009; 2014; Ngo-Duc et al., 2014).

With regard to climate analog, no studies on this topic over the SEA region and Viet Nam have been conducted up to the present time.

CHAPTER 2 – OBSERVED DATA, NUMERICAL EXPERIMENTS AND METHODOLOGY

2.1. Data

2.1.1. Observation data

In the thesis, daily observation data of rainfall and temperature (mean daily temperature, T2m) were obtained from 365 meteorological stations within the SEA region (Figure 2.1) for the period 1986 - 2005, including 118 stations in Thailand, 70 stations in Viet Nam, 32 stations in the Philippines, 33 stations in Malaysia, 88 stations in Indonesia, 23 stations in Myanmar and one station in Laos.

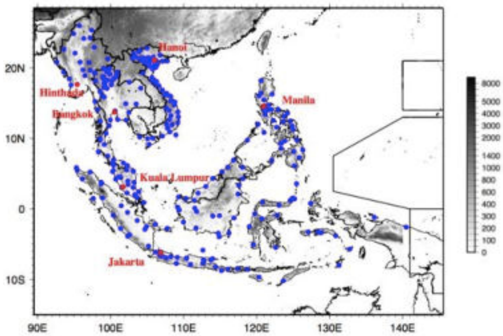


Figure 2.1. The SEA domain with 365 circles showing the station locations in Thailand, Viet Nam, Philippines, Malaysia, Indonesia, Myanmar and Laos where data are used for the analysis in this study. Topography over SEA (shaded, unit is in *m*) is obtained from the Global 30 Arc-Second Elevation (GTOPO30) data set.

2.1.2. Numerical experiments

Temperature and precipitation data used in the thesis are obtained from the regional climate downscaling experiments of the SEACLID/CORDEX-SEA project and from the six respective driving GCMs of the Coupled Model Intercomparison Project Phase 5 (CMIP5).

The 20 - year baseline period is 1986 - 2005 and the future periods to be analyzed is 2046 – 2065 (mid-century) and 2080 – 2099 (far-century) under the RCP4.5 and RCP8.5 scenarios.

2.2. Methodology

2.2.1. Evaluation on performance of multi-model experiments

To evaluate performance of multi-model experiments, seasonal climatological cycles of temperature and precipitation over six cities in SEA (Bangkok, Ha Noi, Jakarta, Kuala Lumpur, Manila and Hinthada) simulated by GCMs and RCMs were compared to the observed data. Taylor diagram and ranking approach are used to evaluate the experiments.

2.2.2. Projection on temperature and precipitation change

The RegCM4.3 was used to downscale projected data from the CMIP5 GCMs. Thus, RCM projected temperature and precipitation originated from CMIP5 GCMs under two GHG scenarios, i.e. RCP4.5 and RCP8.5.

2.2.3. Significance test

In order to determine if there is a significant difference between two independent sample means which are future projected data and baseline data, a t-test is applied. The general test statistic is a function of a comparison of the two sample means, and the real observed difference will be usually some number (not zero). The null hypothesis is often that the actual difference is zero. The alternative hypothesis is that: (1) the true difference is not zero, or (2) one of the two means is bigger than the other [Daniel et al. (2006)]. In the thesis, 5% significance level is applied, which means that only 5% probability that the results from the two datasets happened by chance.

2.2.4. Climate distance formulation

For each numerical experiment, the dissimilarity (dis) between the future climate variable at a reference grid point *f* and the present condition at any grid point p in the research area is calculated as follows:

$$A_{dis} = \frac{1}{12}\sum_{n=1}^{n=12}\sqrt{\frac{(A_{f,n} - A_{p,n})^2}{\sigma_{f,n}{}^2 + \sigma_{p,n}{}^2}} \quad \text{(Eq. 2.4)}$$

where A is the 20-year monthly mean temperature (T_{dis}) or precipitation (P_{dis}) for month n (from January to December), and σ is the internal variability derived from the standard deviation of the monthly values within the 20-year present or future period.

In Section 4.2 and Section 4.4, three grid points with the minimum are marked out as the best analogs (hereinafter *TP-analogs*) to address the issue of good, poor or no-analog for a specific reference point *f*. These three best *TP-analogs* are averaged to identify a standard value S_{TP} for the point *f*.

In the thesis, a reference point *f* is subjectively considered to have a good analog, poor analog, or no-analog if $S_{TP} \leq 1$, $1 < S_{TP} \leq 2$, or $S_{TP} > 2$, respectively. The threshold value of 2 for detecting no-analog matched up with 95% confidence interval if only temperature for a single month, an analog point and a climate model are considered.

2.3. Chapter 2 summary

Chapter 2 introduced the data used in the thesis, including the observation data and model data resulted from six regional climate models of the SEACLID/CORDEX-SEA project in SEA.

The formula of climate distance/ dissimilarity was formulated to define climate analog with various weighting factors for each experiment and for the ensemble.

CHAPTER 3 - PERFORMANCE OF MULTI-MODEL EXPERIMENTS IN SOUTHEAST ASIA

This chapter investigates the performance of the six regional climate downscaling experiments, 6 GCMs and their ensemble average (ENS) in simulating rainfall and temperature for the reference period 1986 – 2005 over SEA and its seven climatic sub-regions in Viet Nam. The best experiments were then chosen to project climate change in the Chapter 4.

3.1. Performance of downscaling experiments in SEA

Figure 3.5 shows the ranking scores of the experiments on their ability to represent observed temperature (Figure 3.5a) and precipitation (Figure 3.5b) based on the *rmsd* values. Figure 3.5a shows that regional downscaling allows a more accurate representation of temperature over SEA, and also displays the relatively better performance of the ensemble mean compared to each individual experiment.

For precipitation (Figure 3.5b), the ensemble mean still outperformed the individual experiments. The G_ENS got the best ranking score in all 14 experiments, while the R_ENS outperformed most RCM experiments, except its score (23) was slightly lower than that of the R_CNRM (25). Figure 3.5b also shows that the GCM experiments ranked higher than the RCM ones.

3.2. Performance of downscaling experiments in Viet Nam

The ensemble mean ENS outperforms each individual experiment in representing temperature and rainfall in seven sub-regions of Viet Nam.

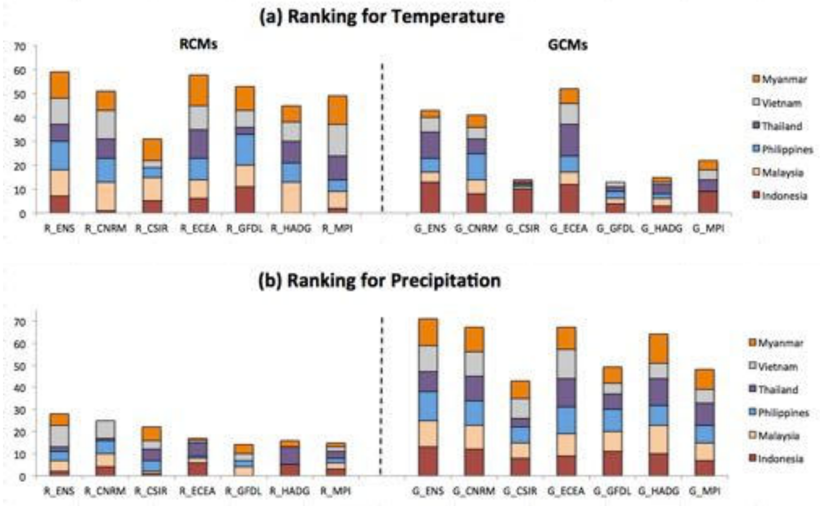


Figure 3.5. The ranking scores of the 7 GCM and 7 RCM experiments based on the centered root mean square difference (*rmsd*) with the observation over the stations of Indonesia, Malaysia, Philippines, Thailand, Viet Nam and Myanmar for (a) temperature and (b) precipitation.

Figure 3.8 shows the seasonal variability of the monthly means of temperature averaged over the seven climatic sub-regions for the period 1986 - 2005. In general, all experiments underestimate T2m. The underestimation of temperature is prominent in the regions NW and SC in the late winter and in CH and SV in spring. The ENS is in a good agreement with the observation, especially in NE, RRD, NC and CH. HADG and CSIRO show a better performance in NW and HADG is better in SC than the other models (Figure 3.8). It should be noted that Phan-Van et al. (2009) also reported the cold bias characteristic of the RegCM model in simulating temperature over the climatic sub-regions of Viet Nam.

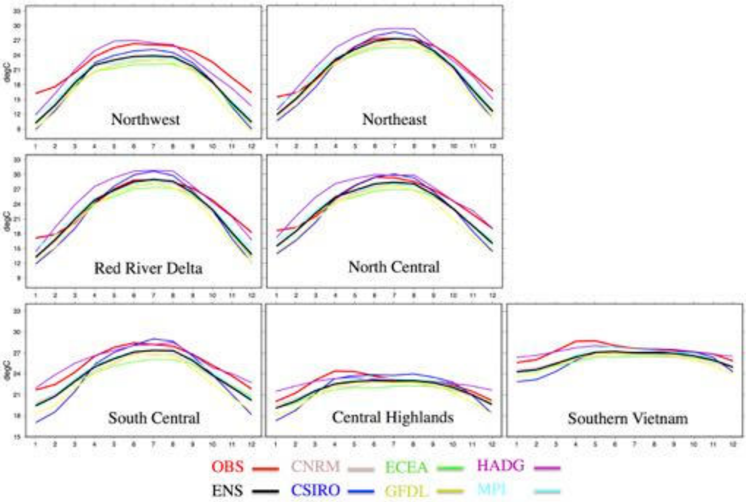


Figure 3.8. Seasonal cycles of T2m observation data and model data. The data are monthly averaged for the period 1986 - 2005 over the stations in seven climatic sub-regions of Viet Nam.

3.3. Chapter 3 summary

Chapter 3 evaluated the performance of six regional and global climate models together with their ensembles over the six countries in SEA, including Indonesia, Malaysia, the Philippines, Thailand, Vietnam and Myanmar. It was shown that regional downscaling allowed a more accurate representation of temperature but displayed a higher variability of rainfall over SEA compared to the results of the GCMs. The ensemble mean experiment had a relatively better performance compared to each individual model in representing the monthly time series of temperature and precipitation.

Chapter 3 also evaluated the performance of six regional downscaling experiments for the period 1986 – 2005 in Viet Nam.

CHAPTER 4 - CLIMATE CHANGE PROJECTION AND CLIMATE ANALOG IN SEA

4.1. Projected changes of temperature and rainfall in SEA

Figure 4.1 shows that temperature increases by 1-2.2^{o}C (1.3-2.8^{o}C) and 1-2.5^{o}C (2.5-4.6^{o}C) under the RCP4.5 (RCP8.5) for the period 2046-2065 and 2080-2099, respectively. The areas with lower temperature (above the latitude 15N) have higher temperature changes, up to 3.7-4.6^{o}C under the RCP8.5. Under two RCPs and for both periods (mid- and far-future), the differences at 5% significance level under t-test are all 100%. These results comply with the apparent temperature changes over the time.

The rainfall changes for both the periods under the RCP4.5 and for the period 2046-2065 under the RCP8.5 are relatively similar (-25 to 30%) (Figure 4.3). The rainfall considerably decreases in most of the SEA region (-30 to 0%) under the RCP8.5 for the period 2080-2099, except for some parts of Thailand, Myanmar and East Malaysia. The difference between the means of future precipitation and baseline one at 5% significance level under t-test are 49% and 56% of the SEA land area under RCP4.5 respectively for the period 2046-2065 and 2080-2099. Under RCP8.5, the difference is 65% and 89% of the SEA land area respectively for the mid- and far-future (areas with diagonal lines in Figure 4.3). At the end of century (2080-2099) under RCP8.5, 89% of the SEA land has significant rainfall difference at 95% confidence level compared to the baseline period while those ratios are smaller for three other cases (RCP4.5 2046-2065, RCP4.5 2080-2099, RCP8.5 2046-2065).

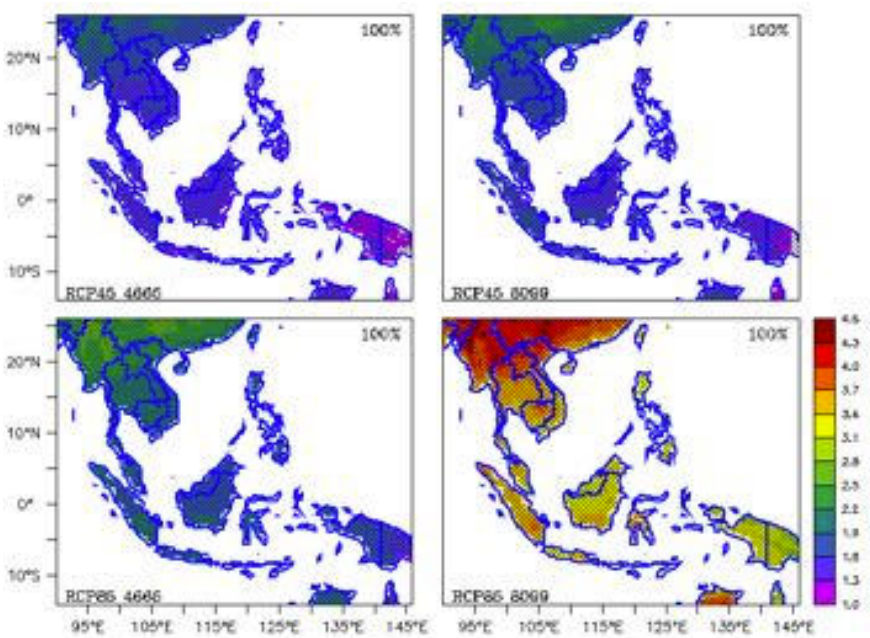


Figure 4.1. Absolute temperature change (º C) in SEA under the RCP4.5 and RCP8.5 scenarios for the period 2046-2065 and 2080-2099 compared to the baseline 1986-2005. Difference at 5% significance level under t-test indicated by diagonal lines and the number in the upper-right corner of each panel shows the percentage of grid points with significant differences.

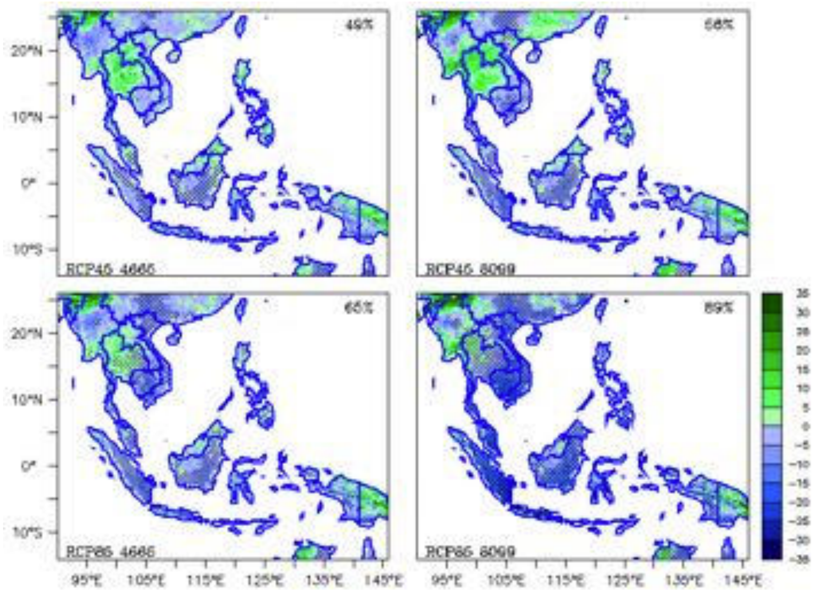


Figure 4.3. As in Figure 4.1 but for relative rainfall change (%).

4.2. Relocation of cities' climate and climate analog in SEA

Figure 4.6 displays the analog locations of six specific big cities in the SEA region based on the minimum climate distance for the R_ENS and G_ENS experiments. In general, when the original cities lie in the northern hemisphere, their best analogs with the R_ENS are usually located southwards, i.e. towards warmer regions.

Figure 4.9 displays the distribution of poor-, good-analog and novel climate locations at the end of the 21st century under the RCP4.5 and RCP8.5 for both the G_ENS and R_ENS experiments.

For the RCP8.5 scenario, the ratio of areas with novel climate and poor-analog significantly increased compared to the RCP4.5. Twenty-four percent (21%) of Southeast Asia is defined as novel climate by the R_ENS (G_ENS).

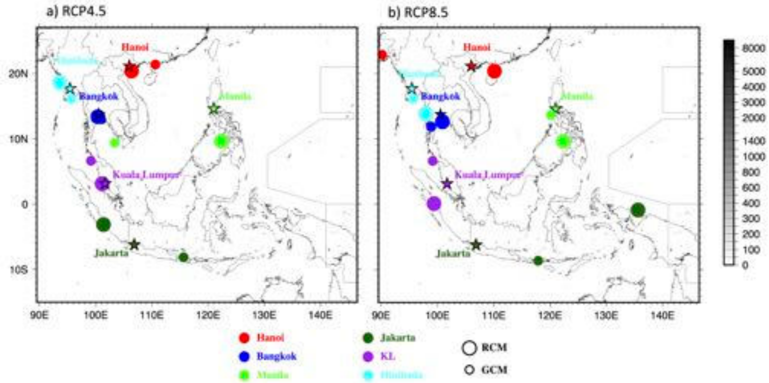


Figure 4.6. Relocation of six cities' climate in SEA at the end of the 21st century under the a) RCP4.5, and b) RCP8.5 scenario. The locations of the six cities are marked with the star symbols. The best analog locations were found with the R_ENS (bigger circles) and G_ENS (smaller circles) experiments.

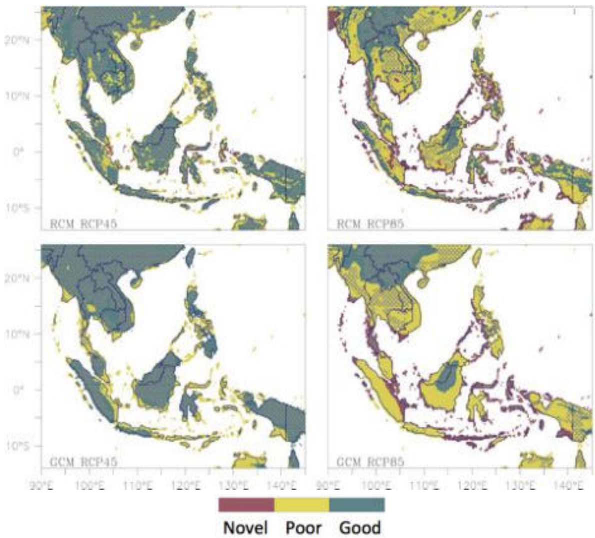


Figure 4.9. Locations of good-analog (green), poor-analog (yellow), and novel climate (red). Results are obtained from the R_ENS (upper) and G_ENS (lower) in the RCP4.5 and RCP8.5 scenario at the end of the 21st century and based on both temperature and precipitation. Cross hatching denotes the agreement of at least two thirds of the individual RCM or GCM experiments.

4.3. Projected changes of temperature and rainfall in Viet Nam

Figure 4.12 depicts the projected temperature change in Viet Nam. Under the RCP8.5 scenario during the 2046-2065 period, the temperature in the whole country rises by 1.8-2.4^{o}C (1.8-2.3^{o}C) by the present study (CC Scenario). By the end of the century under the RCP8.5, the changes of 3.4 - 4.2^{o}C (3.0-3.4^{o}C) are found in the northern (southern) part.

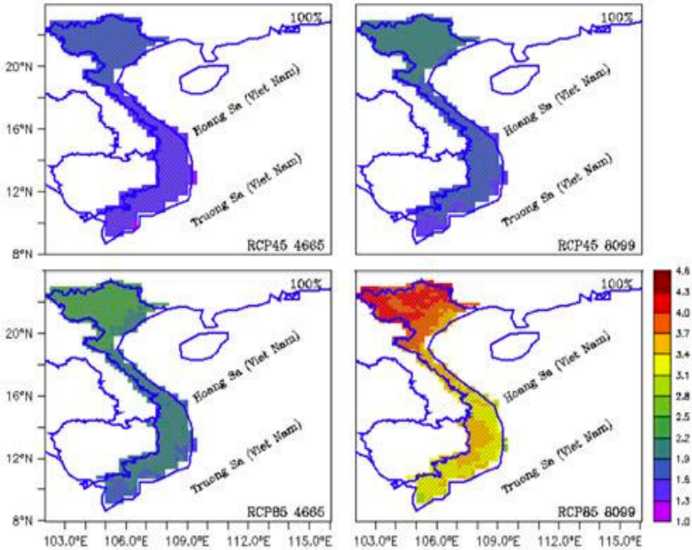


Figure 4.12. Projected temperature changes (ºC) in Viet Nam under the RCP4.5 and RCP8.5 scenarios for the periods 2046-2065 and 2080-2099 compared to the baseline period 1986-2005. Difference at 5% significance level under t-test indicated by diagonal lines and the number in the upper-right corner of each panel shows the percentage of grid points with significant differences.

4.4. Relocation of cities' climate and climate analog in Viet Nam

Figure 4.17 shows the locations of the best climate analog (with minimum climate distance) of the six cities in Viet Nam projected by the CNRM, ECEA and ENS experiments. The best analog locations tend to be located southward from the reference cities. Those of Ha Noi, Hai Phong and Da Nang are close to their original cities except for the RCP8.5 scenario with the ENS experiment while those of Ho Chi Minh and Can Tho are at far distances from their origins. The ECEA future climates of both Ho Chi Minh and Can Tho under the RCP8.5 are similar to the present climate of Illoning, Maluku, Indonesia (131.375E, 4.125S). The ENS future climate of Can Tho is analogous to the present climate of Penang island, Malaysia (100.125E, 6.125N) for both the scenarios. The climate distances under the RCP8.5 are greater than those under the RCP4.5.

Disappearing climate in Viet Nam

The land fractions of disappearing climate in Viet Nam are 0.66%, 1.75% and 2.39% for the CNRM, ECEA and ENS experiments under the RCP8.5, respectively. This means that we can almost find a location within the SEA region at which the projected future climate is close to the present climate of a given place in Viet Nam. The present climate in only a few small parts in the Northern and Southern Central Highlands of Viet Nam (red parts in Figure 4.19) will disappear in SEA in the future. This is in agreement with the results of Williams et al. (2007), which showed that disappearing climate was located in mountainous tropical areas.

4.4. Chapter 4 summary

Chapter 4 presented the projected temperature and rainfall changes, and climate analog in the SEA region in the mid- and far-future periods under the RCP4.5 and RCP8.5 scenarios.

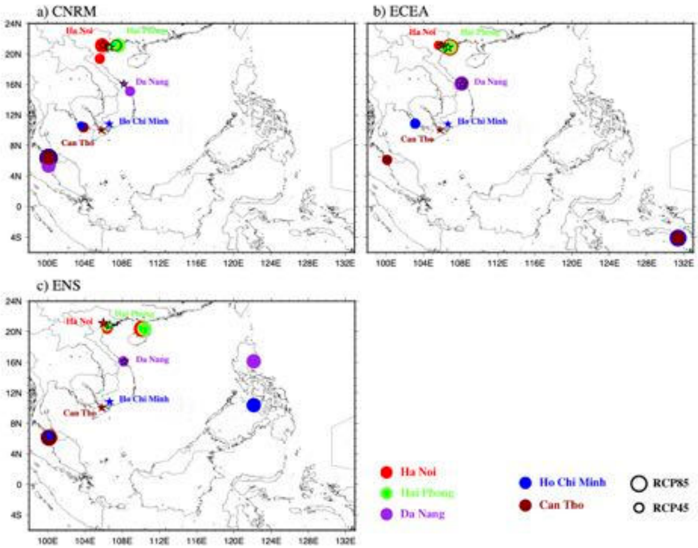


Figure 4.18. Climatic relocation of 5 central cities in Viet Nam at the end of the 21st century under the RCP4.5 (smaller circles) and the RCP8.5 scenario (larger circles) with three experiments. The original locations of the 5 cities are marked with star symbols.

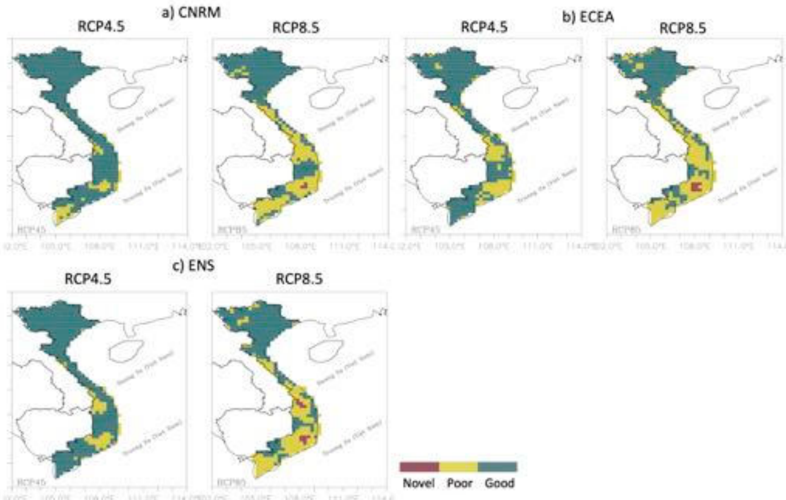


Figure 4.20. Locations of good analog (green), poor analog (yellow), and disappearing climate (red) in Viet Nam. Results are obtained under the RCP4.5 and RCP8.5 scenario at the end of the 21st century.

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

In the thesis, the 2-m temperature and rainfall variables were evaluated and projected over SEA and Viet Nam. Climate analog, disappearing and novel climate analysis over SEA and Viet Nam were also implemented. The RegCM4.3 model was used to downscale six CMIP5 GCMs under the framework of SEACLID/CORDEX-SEA project. The results showed that:

i. Regional downscaling allowed a more accurate representation of temperature but displayed a higher variability of rainfall over SEA compared to the results of the GCMs.
ii. The ENS had advantages in reproducing temperature and rainfall variations compared to the individual GCM and RCM experiments in SEA and Viet Nam.
iii. A modified version of the existing formulation to estimate climate distance was introduced with weighting factors for temperature and precipitation, and for the ensemble.
iv. A common tendency of climatic relocation for the six big cities in SEA including Ha Noi, Manila, Kuala Lumpur, Bangkok, Jakarta and Hinthada towards warmer regions is prominent with the regional ENS experiment.
v. The percentages of novel climate areas in SEA at the end of the 21st century were projected to be 24% (RCM ENS) and 21% (GCM ENS) under the RCP8.5.
vi. Novel climate are mainly located in coastal areas and islands, especially near equatorial areas and disappearing climate are found in mountainous areas.

vii. In Viet Nam, the projection results of this study were also compared to those in the previous study. The results showed a high agreement in the temperature changes but a remarkable uncertainty in rainfall trend.

viii. 2.39% of Viet Nam land, mainly located in the Northern and Southern Central Highlands, was projected to experience disappearing climate by the ENS experiment under the RCP8.5.

The results of the present study would provide worthwhile inputs for climate change impact assessment, adaptation and mitigation research. When conducting climate-related research using multi-models, it is necessary to evaluate their performance before implementing the following analyses. The results of novel climate and disappearing climate in Southeast Asia and Viet Nam could be linked to various sectors such as agriculture, infrastructure, urban, health, immigration, etc. to help people better adapt to and mitigate climate change.

2. Recommendations

Based on the results and findings presented in the thesis, the following issues could be implemented in futher studies:

i. The uncertainty of models should be considered. Thus, bias correction could be applied before implementing the projection over SEA and Viet Nam.

ii. More efforts on understanding the mechanism of future rainfall changes should be made, that could help to better understand the different wetter/drier signals between the results of the previous study and of the thesis.

LIST OF PUBLICATIONS

1. **Nguyen-Thi, T**, Ngo-Duc, T, Tangang, FT, *et al.* Climate analogue and future appearance of novel climate in Southeast Asia. *Int J Climatol*. 2020; 1– 18. https://doi.org/10.1002/joc.6693
2. **Nguyen-Thi, T**, Ngo-Duc, T., Phan-Van, T. (2019), Climate Analog Locations of Cities and Disappearing Climate in Viet Nam. *VNU Journal of Science: Earth and Environmental Sciences*, [S.l.], v. 35, n. 4, dec. 2019. ISSN 2588-1094. doi: https://doi.org/10.25073/2588-1094/vnuees.4409.
3. **Nguyen-Thi, T**, Ngo-Duc, T., Phan-Van, T. (2019), Performance of SEACLID/CORDEX-SEA multi-model experiments in simulating temperature and rainfall in Vietnam. *Vietnam Journal Of Earth Sciences*, [S.l.], v. 41, n. 4, p. 374-387, aug. 2019. ISSN 0866-7187. doi:https://doi.org/10.15625/0866-7187/41/4/14259.
4. **Nguyễn Thị Tuyết**, Ngô Đức Thành, Phan Văn Tân (2019), Biến đổi nhiệt độ và lượng mưa trong thế kỷ 21 trên khu vực Đông Nam Á theo dự tính đa mô hình SEACLID/CORDEX-SEA, *Tạp chí Khoa học Biến đổi khí hậu*, số 11 – Tháng 9/2019. ISSN 2525-2496.
5. **Nguyen-Thi, T**, Ngo-Duc, T., Phan-Van, T. (2017), Sensitivity evaluation of climate analog patterns with varying weighting factor values of rainfall of some capital cities over the Southeast-Asia. The International Conference on Research Development and Cooperation in Geophysics (Viet-Geophys-2017), Viet Nam, *Proceedings*.