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AN EVALUATION OF PRECIPITATION VARIABILITY OVER THE VIETNAMESE MEKONG RIVER DELTA BASED ON CMIP5 MULTI-MODEL ENSEMBLE SIMULATIONS AND 21ST CENTURY PROJECTIONS

Le Van Thien
Hanoi University of Natural Resources and Environment, Vietnam

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Abstract

Vietnamese Mekong River Delta (VMRD) is one of the most bio diverse rivers in the world and is greatly affected by distinct wet and dry seasons. It is also the largest agriculture and aquaculture production region of Vietnam. Precipitation variability has major economic, social and environmental impacts across the globe in general and on VMRD in particular. The historical precipitation variability (1911 - 2005) based on 26 global circulation models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) archive over the 20th century relative to observational data and two future emission scenarios used (representative concentration pathways (RCP) 8.5 and RCP 4.5 referred to the twenty - first century projections of precipitation are evaluated. The results showed that CMIP5 models can reproduce the spatial pattern of precipitation better in winter than in both summer and entire year over the VMRD during the 20th century. However, the models overestimate the magnitude of seasonal and annual precipitation in most regions of the VMRD and underestimate summer precipitation in some parts of Ca Mau province and eastern south of Vietnam. Throughout the 20th century, both the observations and models show a decreasing trend in precipitation in winter over entire the VMRD and some parts of western VMRD. There is poor agreement in annual and summer precipitation trends in eastern VMRD. In general, multi-model means can capture the amplitude of observed multidecadal precipitation variability better in winter than in summer and entire year. In the 21st century, annual and summer precipitation generally increases while winter precipitation decreases over the VMRD under two scenarios. Both the RCP 8.5 and RCP 4.5 scenarios show precipitation trend at a rate of about +24 mm/decade by the end of the century.

Keywords: Precipitation; Mekong River Delta; CMIP5.

Corresponding author. Email: lvthien@hunre.edu.vn

1. Introduction

Precipitation is one of the most important factors in the climate system because of its influences on atmosphere, hydrosphere and biosphere. Precipitation variability and climate change have great impacts on both natural environment and human activities. The Intergovernmental

Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) has shown that the precipitation has likely increased over land area of the Northern Hemisphere [1]. Water availability plays an important role in agricultural and industrial development due to the vulnerability of water resources [2]. Moreover, the hydro - meteorological extreme events such as floods and droughts can lead to high risks of environment and decrease in gross domestic product in each country.

An ensemble of global coupled ocean-atmosphere circulation models forced with projected greenhouse gas and aerosol emissions are the primary tools for estimating trends and variability of future changes in temperature and precipitation extremes [3]. Phase 5 of the Coupled Model Intercomparison Project (CMIP5) [4] was established as a standard experimental protocol to evaluate the atmosphere-ocean general circulation models (GCMs) and to estimate future climate projections under different scenarios. CMIP5 can reproduce summer precipitation with large uncertainties over south China [5]. The CMIP5 historical simulations reasonably capture the climatology of East Asian summer rainfall, associated circulation, moisture and its transport. CMIP5 shows better skill than CMIP3 in capturing the monsoon characteristics both in summer and winter [6, 7].

Recently, there have been two studies conducted in simulating the temperature and rainfall over Vietnam and Ho Chi Minh city [8, 9]. However, no one has evaluated the performance of CMIP5 ensemble multi-models in simulating precipitation in Vietnam. Moreover, a comprehensive assessment relative to historical observations in 20th century and the projected precipitation variability in the 21st century has not yet been performed for over the Vietnamese Mekong River Delta (VMRD).

In this study, we therefore investigate precipitation simulation statistics over the VMRD based on the 26 global circulation models (GCMs) from the CMIP5 archive with simulations for both the 20th and 21st centuries.

2. Study area, data and methods

2.1. Study area

The study region is the area over the VMRD (104E - 110E, 8N - 13N). This region is considered to be one of the most bio diverse rivers in the world and is greatly affected by distinct wet and dry seasons. It is also the largest agriculture and aquaculture production region of Vietnam.

2.2. Data

Three simulations from 26 the Earth System Models (ESMs) coupled the atmosphere, ocean and land surface from the CMIP5 archive (Tab. 1) (one historical experiment and two future emission scenarios) were used. More information on the Coupled Model Intercomparison Project (CMIP5) and the 5th Assessment of the IPCC can be found (https://pcmdi.llnl.gov/mips/cmip5/). The two future scenarios are the representative concentration pathways (RCP) RCP8.5 and RCP4.5 developed for the IPCC AR5. The historical experiment (1911 - 2005) was forced by observed atmospheric composition changes. The RCP 8.5 scenario (2006 - 2300) assumes high population growth and high energy demand without climate change policies. Therefore, it corresponds to the pathway with the highest greenhouse gas emissions, brought about by a radiative forcing of 8.5

W/m^2 in 2100 [10]. RCP 4.5 is a scenario that stabilizes radiative forcing at 4.5 W/m^2 in 2100 without ever exceeding that value [11]. Monthly precipitation output from the 20 GCMs based on the historical and three future scenarios was obtained from the CMIP5 website (https://pcmdi.llnl.gov/mips/cmip5/).

The observational data set of precipitation from the Global Precipitation Climatology Centre (GPCC) version 6 was used to evaluate the GCM's performance. This GPCC data set provides high resolution gridded (0.5 x 0.5) monthly precipitation for global land surface based on a large number of observational station from 1901 - 2010 [12, 13].

2.3. Methods

This section provides an overview of the models analyzed, the historical simulations and the general methodology for evaluating the models. Data from multiple model simulations of the historical scenario from the CMIP5 archive were used. The CMIP5 experiments were carried out by more than 20 modeling groups with the aim of further understanding past and future climate change in key areas of uncertainty. The CMIP5 is improved in several ways compared with the previous phase (CMIP3) experiments. It has a greater number of modeling centers participated, the models run at higher spatial resolution with some models being more comprehensive processes, therefore hopefully resulting in better skill. Table 1 provides an overview of the models used. Model types are atmosphere-ocean coupled, ocean-atmosphere-chemistry coupled, Earth system model and Earth system model chemistry coupled.

Table 1. List of 26 CMIP5 GCMs Used in this Study

Models	**Atmospheric horizontal resolution (lat × lon)**	**No. of model levels**	**Institutions**
ACCESS1.0	1.875 × 1.25	38	Australian Community Climate and Earth-System Simulator, version 1.0
BCC-CSM1.1	2.8 × 2.8	26	Beijing Climate Center, China Meteorological Administration, China
CanCM4	2.8 × 2.8	35	Fourth Generation Canadian Coupled Global Climate Model Canadian Centre for Climate Modeling and Analysis, Canada
CanESM2	2.8 × 2.8	35	Second Generation Canadian Earth System Model Canadian Centre for Climate Modeling and Analysis, Canada
CCSM4	1.25 × 0.94	26	Community Climate System Model, version 4 National Center for Atmospheric Research, United States
CESM1 (CAM5)-1-FV2	1.4 × 1.4	26	Community Earth System Model, version 1 (Community Atmosphere Model, version 5) Community Earth System Model Contributors [National Science Foundation (NSF), DOE and NCAR]
CNRM-CM5.1	1.4 × 1.4	31	Centre National de Recherches Meteorologiques Coupled Global Climate Model, version 5.1 National Centre for Meteorological Research, France

Models	Atmospheric horizontal resolution (lat × lon)	No. of model levels	Institutions
CSIRO Mk3.6.0	1.8 × 1.8	18	Commonwealth Scientific and Industrial Research Organization Mark, version 3.6.0 Commonwealth Scientific and Industrial Research Organization/ Queensland Climate Change Centre of Excellence, Australia
EC-EARTH	1.125 × 1.12	62	EC-Earth Consortium EC-Earth Consortium
FGOALS-g2	2.8 × 1.6	26	Flexible Global Ocean-Atmosphere-Land System Model gridpoint, second spectral version State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences
GFDL-CM3	2.5 × 2.0	48	Geophysical Fluid Dynamics Laboratory Climate Model, version 3NOAA/Geophysical Fluid Dynamics Laboratory, United States
GFDL-ESM2G/M	2.5 × 2.0	48	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component (ESM2G) and with Modular Ocean Model 4 (MOM4) component (ESM2M) NOAA/Geophysical Fluid Dynamics Laboratory, United States
GISS-E2H/ E2-R	2.5 × 2.0	40	Goddard Institute for Space Studies Model E, coupled with the HYCOM ocean model (E2H) and with the Russell ocean model (E2-R) National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies, United StatesChem
HadCM3	3.75 × 2.5	19	Hadley Centre Coupled Model, version 3Met Office Hadley Centre, United Kingdom
HADGEM2-CC	1.875 × 1.25	60	Hadley Centre Global Environment Model, version 2-Carbon CycleMet Office Hadley Centre, United Kingdom
HadGEM2-ES	1.875 × 1.25	60	Hadley Centre Global Environment Model, version 2-Earth SystemMet Office Hadley Centre, United Kingdom ChemESM
INM-CM4.0	2 × 1.5	21	Institute of Numerical Mathematics Coupled Model, version 4.0Institute for Numerical Mathematics, Russia
IPSL-CM5A-LR	3.75 × 1.8	39	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, low resolution L'Institut Pierre-Simon Laplace, France Chem
IPSL-CM5A-MR	2.5 × 1.25	39	L'Institut Pierre-Simon Laplace Coupled Model, version 5, coupled with NEMO, mid resolutionL'Institut Pierre-Simon Laplace, FranceChem

Models	Atmospheric horizontal resolution (lat × lon)	No. of model levels	Institutions
MIROC4h	0.56 × 0.56	56	Model for Interdisciplinary Research on Climate, version 4 (high resolution) Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan
MIROC5	1.4 × 1.4	40	Model for Interdisciplinary Research on Climate, version 5 Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan
MIROC-ESM	2.8 × 2.8	80	Model for Interdisciplinary Research on Climate, Earth System Model Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental Studies
MIROC-ESM-CHEM	2.8 × 2.8	80	Model for Interdisciplinary Research on Climate, Earth System Model, Chemistry Coupled Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo) and National Institute for Environmental StudiesChem
MPI-ESM-LR	1.9 × 1.9	47	Max Planck Institute Earth System Model, low resolution Max Planck Institute for Meteorology, Germany
MRI-CGCM3	1.1 × 1.1	48	Meteorological Research Institute Coupled Atmosphere-Ocean General Circulation Model, version 3Meteorological Research Institute, Japan
NorESM1-M	2.5 × 1.9	26	Norwegian Earth System Model, version 1 (intermediate resolution) Norwegian Climate Center, Norway

The models were chosen to span a diverse set of modeling centers and model types. The historical simulations are run in coupled atmosphere-ocean model forced by historical estimates of changes in atmospheric composition from natural and anthropogenic sources, volcanoes, green house gases (GHGs) and aerosols, as well as changes in solar output and land cover. Note that only anthropogenic GHGs and aerosols are prescribed common forcing to all models and each model differs in the set of other forcing that it uses, such as land - use change. Anthropogenic GHGs and aerosols are common forcing to all models and each model differs in the set of other forcing that it uses such as land use change. Data from the historical CMIP5 scenarios are evaluated in this study. Our evaluations of historical simulations were generally carried out for the period from the start of the industrial revolution to near the present: 1911 - 2005. The early period (1911 - 1956) may potentially bias the assessment of model performance due to shortcomings in the observations. We therefore assess model performance for both the more data-rich period of 1956 - 2005 and 1979 - 2008. Because of the different spatial resolutions among the GCMs, all model output was re-gridded to a uniform resolution of 1.0° × 1.0° through bilinear interpolation, which is a common re-gridding technique [14, 15, 16, 17, 18]. The results are generally shown for the multi - model ensemble mean. Due to heterogeneity in precipitation distribution, linear trends in seasonal and annual precipitation were analyzed for all regions of the Vietnamese Mekong River Delta. In order to quantify the agreement between observations and model simulations, we calculated spatial distribution of mean annual and seasonal precipitation between the observational data set and the CMIP5 data set. We also calculated the absolute differences between the observational data and model simulations.

In order to evaluate precipitation variability during the 20th and 21st centuries, the period 1911 - 2005 was extracted from the historical experiment and the period 2006 - 2100 was extracted from the two emission scenario experiments. Due to heterogeneity in precipitation distribution, linear trends in seasonal and annual precipitation were analyzed for all regions of the Vietnamese Mekong River Delta. In order to quantify the agreement between observations and model simulations, we calculate spatial distribution of mean annual and seasonal precipitation between the observational data set and the CMIP5 data set.

3. Results

3.1. Historical precipitation in the 20th Century

We compare saperately the spatial patterns of the mean annual prescipiation and the winter (December to Febuary, DJF), the summer (June to August, JJA) seasons during 1911 - 2005. Figure 1 shows the spatial distribution of the mean annual and seasonal precipitation during the 20th century from between GPCC and the ensemble averages from CMIP5. There is generally good agreement between the observational data set and simmulation output. The highest annual observational precipitation occurs over provinces in southern VMRD such as Ca Mau, Bac Lieu and Kien Giang. The lowest annual precipitation is observed over the northwestern VMRD, especially in Dong Thap and Long An province (Fig. 1a). Seasonal annual observational precipitation suggests a monsoon-induced pattern, with more precipitation in summer and less during winter (Fig. 1a). In general, CMIP5 can reproduce the spatial distribution of annual and seasonal precipitation reasonably (Fig. 1b).

Figure 2 shows the spatial pattern of the difference between CPCC observation and CMIP5. Compared with the observations, the CMIP5 models exhibit better in the winter than in the summer over 1911 - 2005. There are negative biases in southern VRMD during summer and much larger positive biases in the during both summer and winter. However, it overestimates the precipitation magnitude in many provinces of VMRD. There are larger positive differeneces in the summer than in the winter, likely due to the summer monsoon. Additionally, the models underestimate summer precipitation over southern VMRD.

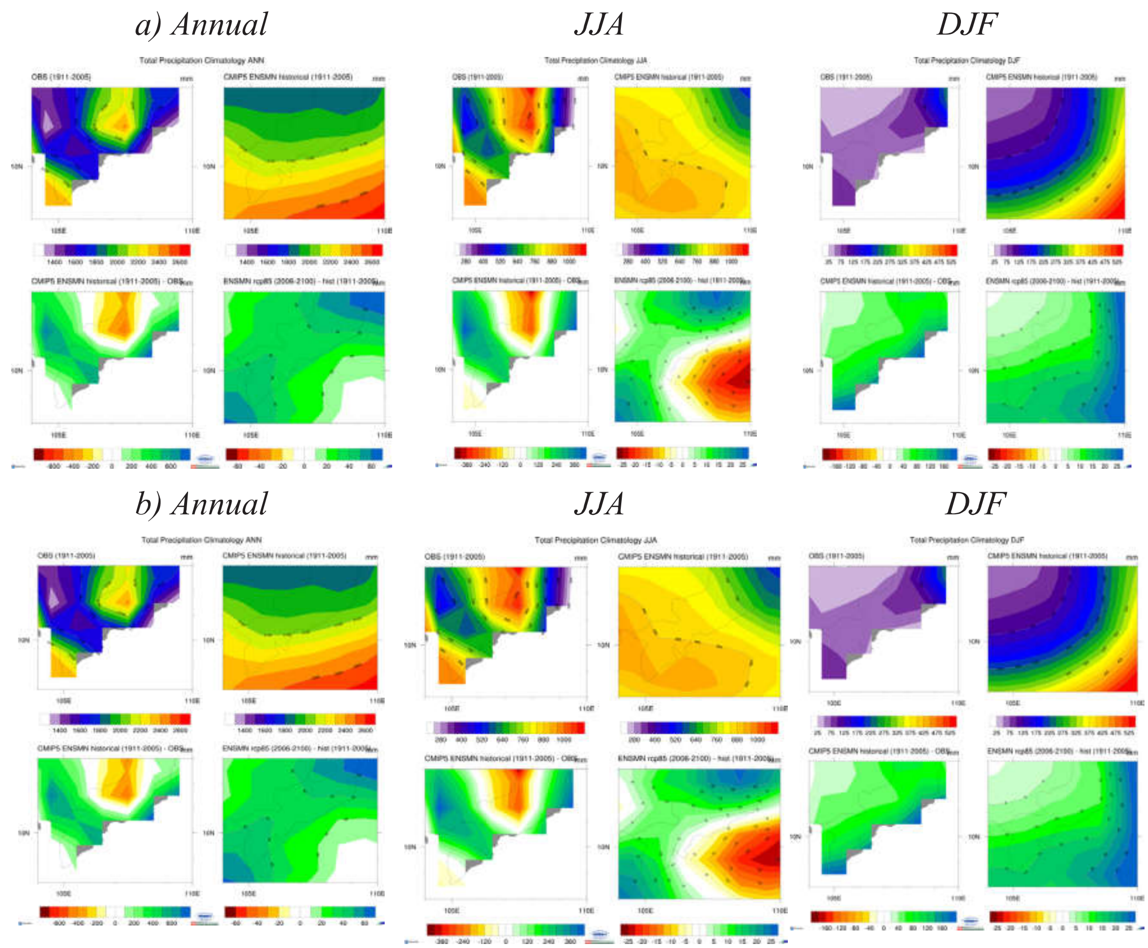

Figure 1: Spatial distribution of mean annual precipitation over the Vietnamese Mekong River Delta during the 20th century generated from (a) GPCC and ensemble averages from (b) CMIP5 (left) Annual precipitation, (middle) summer (JJA) precipitation and (right) winter (DJF) precipitation

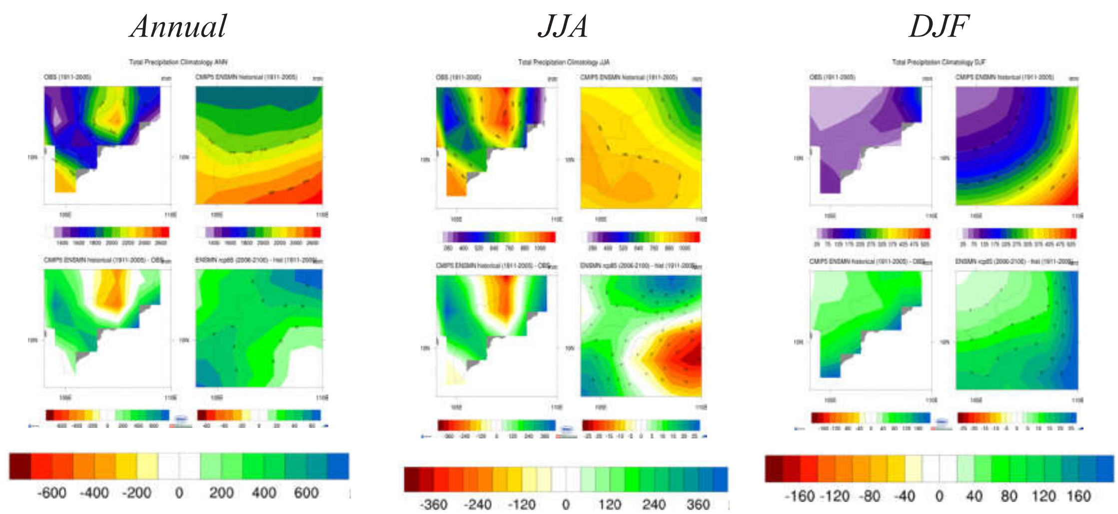

Figure 2: The difference in mean annual precipitation between model simulations and observations: CMIP5 - GPCC (left) Annual precipitation, (middle) summer (JJA) precipitation and (right) winter (DJF) precipitation

We also compare the linear annual precipitation trends over the 20th century based on the GPCC observations and CMIP5 simulations (Fig. 3). The GPCC observations show that precipitation increased significantly over many provinces of the south region (about +14 mm/decade) and decreased significantly over other parts of the north region (about -10 mm/decade), as well as the eastern south region (Fig. 3a). CMIP5 precipitation exhibits a much simpler dipole trend pattern, consisting of significantly decreasing precipitation of -8 mm/decade over the VMRD (Fig. 3b).

a) PCC ***b) CMIP5***

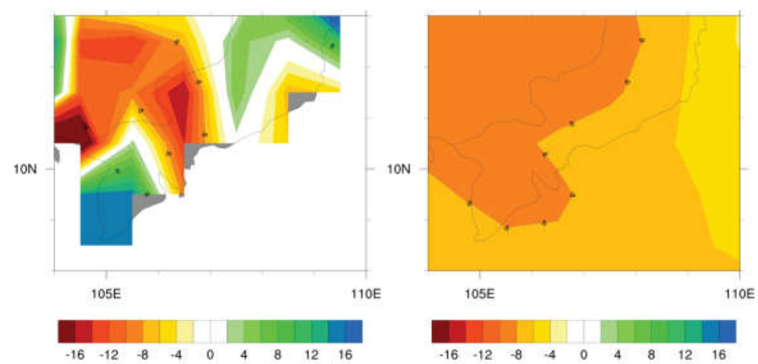

Figure 3: Annual precipitation least squares linear trends over the 20th century. (a) GPCC and (b) CMIP5

a) GPCC ***b) CMIP5***

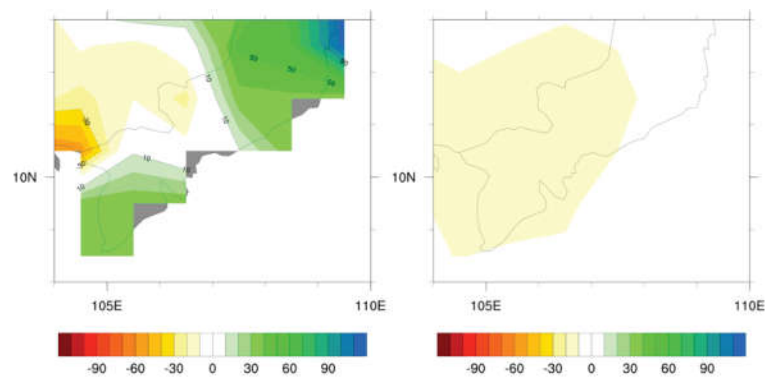

Figure 4: As Figure 3 but for the period 1956 - 2005

a) GPCC ***b) CMIP5***

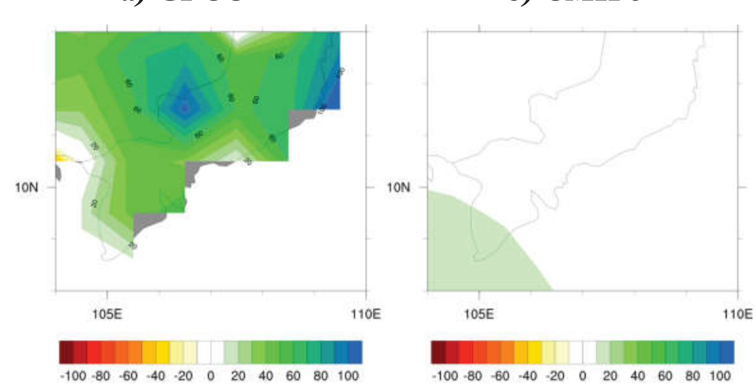

Figure 5: As Figure 3, but for the period 1979 - 2008

3.2. Precipitation projections for the 21st century

Simulated annual precipitation trends averaged for VMRD from 2006 to 2100 is shown in Figure 6. All the emission scenario experiments exhibit significantly increasing precipitation over VMRD during the 21st century. Both the RCP 8.5 and RCP 4.5 scenarios exhibit the increasing trend, at a rate of 24 - 25 mm/decade.

Spatially, precipitation will increase throughout VMRD in the 21st century (Fig. 6). The two emission scenarios reveal the same spatial pattern of future precipitation changes. Under the RCP 8.5 and RCP 4.5 scenarios, there is a relatively high increasing trend over whole VMRD (about 24 - 25 mm/decade), but the RCP 8.5 scinario shows higher increasing trend in the west than the east (Fig. 6b).

Comparing the two periods of 2070 - 2099 versus 1956 - 2005 reveals the same spatial pattern of changes in annual precipitation (Fig. 7). There is a prevailing increase in annual mean precipitation under two scinarios over the VMRD with the greatest annual precipitation increase in the northwest under RCP 4.5 scinario (Fig. 7b).

a) RPC 8.5 ***b) RPC 4.5***

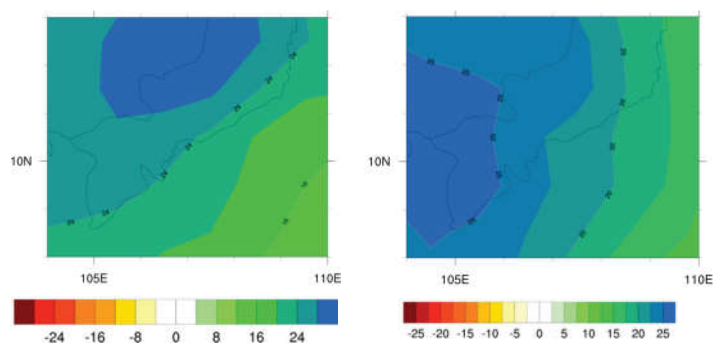

Figure 6: Annual precipitation least squares linear trends in the 21st century for two emission scenarios ((a) RCP 8.5, (b) RCP 4.5)

a) RPC 8.5 ***b) RPC 4.5***

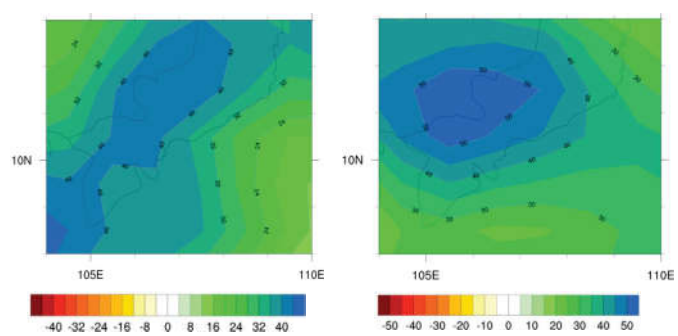

Figure 7: Changes in anuual precipitation (2070 - 2099 versus 1956 - 2005) based on CMIP5 projections ((a) RCP 8.5 and (b) RCP 4.5)

Precipitation projections for the RCP 8.5 and RCP 4.5 scenarios exhibit similar seasonal patterns in different regions of VMRD over the 21st century (Fig. 8). For VMRD as a whole, the largest increase in precipitation will occur in JJA. In winter, the wetting trend is much larger in southeast than in other parts, with relatively large increases under RCP 4.5 scinario.

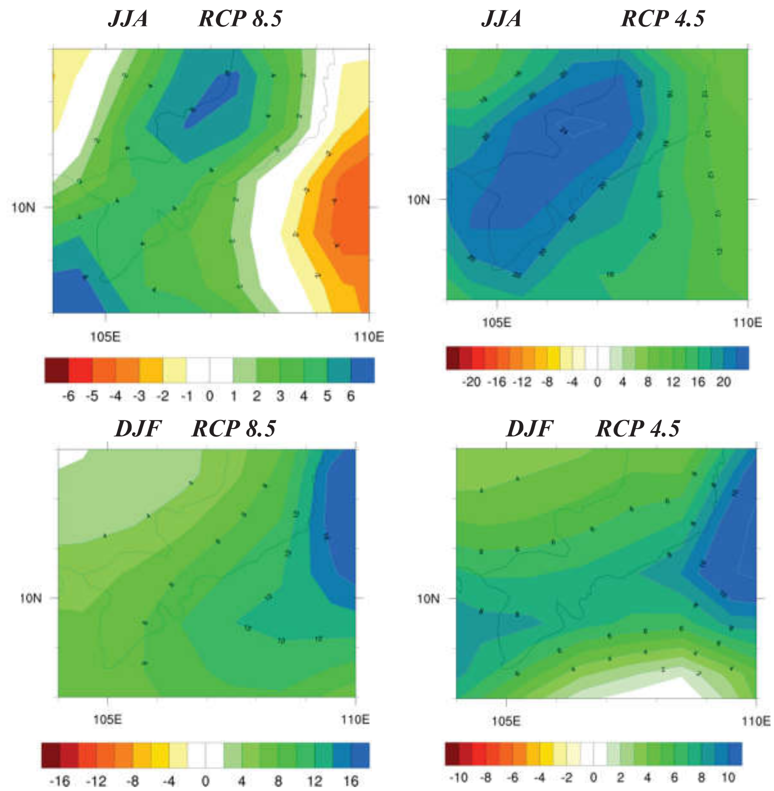

Figure 8: Seasonal precipitation trends over VMRD for the 21st century based on two CMIP5 scenario projections ((left) RCP 8.5 and (right) RCP 4.5)

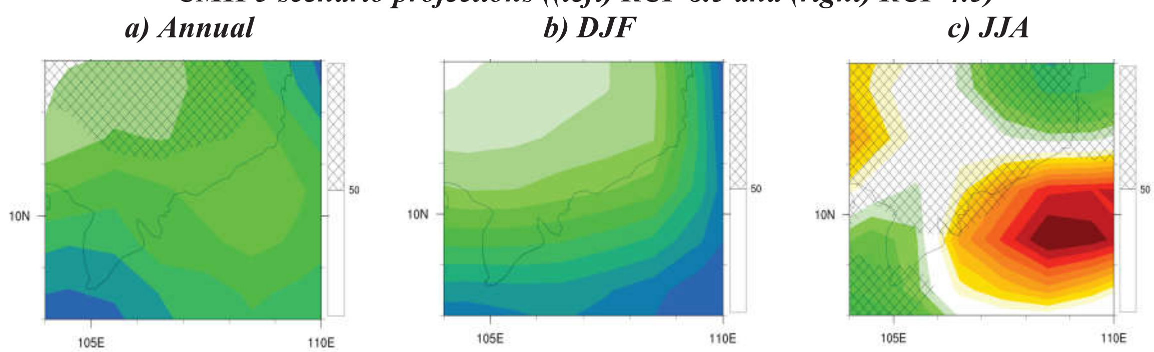

Figure 9: Projected CMIP5 multi model mean change for 2006 - 2100 relative to 1911 - 2005 under RCP 4.5 in annual (a), DJF (b) and JJA(c) rainfall

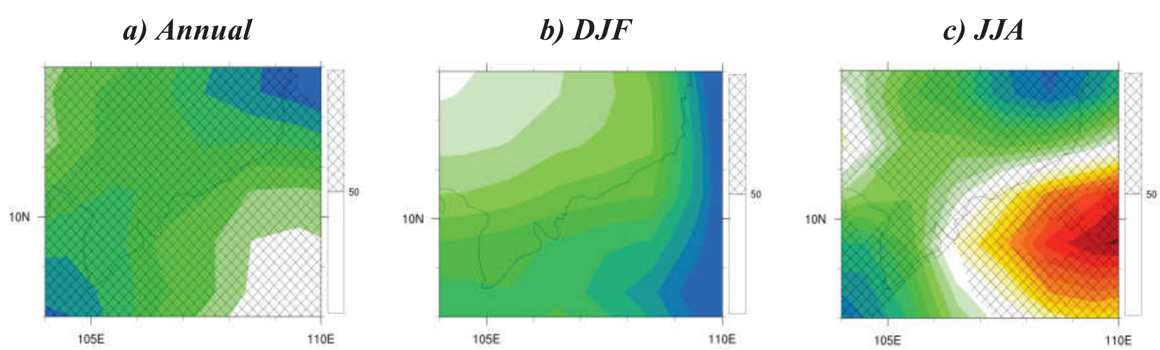

Figure 10: Projected CMIP5 multi model mean change in in annual (a), DJF (b) and JJA(c) rainfall for 2006 - 2100 relative to 1911 - 2005 under RCP 8.5

To assess if a majority of models have significant climate changes according to a T test (95 % level), the Student's T-test is used to make statistically significant tests for precipitation anomalies. Regions where 50 % or more of models agree on the sign of wetter or drier future climate are crossed lines. Figures 9, 10 show the 26 - member model ensemble mean annual, December - February (DJF) and June - August (JJA) precipitation changes during 2006 - 2100 relative to a 1911 - 2005 base period for RCP 4.5 and RCP 8.5. According to a T test, the majority of models have significant precipitation changes found in annual and summer season in the 21st century for two emission.

4. Discussion

In this study, the output of 26 GCMs from CMIP5 was used to evaluate the precipitation variability over Mekong River Delta in Vietnam by using both observational data sets and model simulations and estimates future changes. CMIP5 models well reproduced the spatial pattern of annual and seasonal precipitation over Vietnam Mekong River Delta area. However, there is a large bias over most parts of VMRD, especially in the summer. These biases are likely due to dominance of the East - Asian monsoon in VMRD in which previous studies have suggested GCM's deficiencies in simulating the East Asian monsoon [19, 20]. CMIP5 models overestimate the magnitude of precipitation in most regions of VMRD as a whole and underestimate summer precipitation over Ca Mau province. Also, the disagreement in precipitation may be related with the poor El Nino - Southern Oscillation (ENSO) - monsoon relationship in CMIP5 models [21]. Throughout the 20th century, the observations show an increasing trend in precipitation in the summer and a decreasing trend in the winter over most provinces of VMRD. Both the observations and model show a decreasing trend in the winter precipitation. However, there is poor agreement in the summer and annual precipitation. The differences in precipitation among CMIP5 models are likely due to differences in the forcing, the magnitude of the internal variability and the climate sensitivity of individual models. Song, F., T. Zhou and Y. Qian (2014) [22] showed that forcing from modes of internal interdecadal variability such as the Pacific Decadal Oscillation can not be reproduced in CMIP5.

The spatial resolution may not influence the ability of CMIPP5 in reproducing precipitation variability [23]. Chen, L and O. W. Frauenfeld (2014) [24] indicated that there is no relationship between model performance and their horizontal resolution. For instance, among the four models with the highest skill for both the climatology and ISTD of precipitation (EC-EARTH, HadGEM2 - CC, INM - CM4 and MIROC5), EC - EARTH has a relatively high horizontal resolution (ranking third of all 26 models), while the other three models have medium horizontal resolutions. The NCAR models (CCSM4 and CESM - CAM5) with very high spatial resolution, however, do not exhibit high skill in our analysis.

The spatial pattern of CMIP5 trends over the 20th century corresponds to observational trends, especially in winter. However, there is also significant disagreement in precipitation trends in summer between the CMIP5 and observational data sets over southern VMRD.

Based on projections from the 20 CMIP5 GCMs, there is a generally increasing trend in precipitation over all of VMRD under all the two greenhouse emission scenarios in the 21st century. By the end of the 21st century, annual precipitation will significantly increase by 30 - 50 mm/decade based on the two emission scenarios. Because of continually increased temperature trends, the increased atmospheric moisture content associated with global warming is hypothesized leading to increased precipitation (IPCC, 2007). The greatest increase will occur over most part of VMRD during summer, suggesting future changes in the summer monsoon.

5. Conclusion

This paper investigates the historical precipitation trends over the 20th century by using both observational data sets and model simulations and estimates future changes in the 21st century. Overall, the multi-model ensemble does reasonably well in representing the main features of precipitation variability over the VMRD and the adjoining seas. CMIP5 models well reproduced the spatial pattern of annual and seasonal precipitation over VMRD during the 20th century. However, uncertainties in climate models are still evident. CMIP5 models overestimate the magnitude of precipitation in most regions of VMRD, especially in the northern edge of the delta and underestimate summer precipitation over several provinces in the south of VMRD. Regional performance for precipitation is variable across models. There is large spread among individual models, with the greatest uncertainties in simulating summer precipitation. No particular model performs better than others across all analyses.

Throughout the 20th century, the observations show an increasing trend in annual precipitation over VMRD and models show a decreasing trend in precipitation over most parts of region. Both the observations and models show a decreasing trend in winter precipitation over VMRD. However, there is poor agreement in summer precipitation trend over VMRD. In the 21st century, there is a generally increasing trend in precipitation over all of VMRD under all the two emission scenarios. By the end of the 21st century, annual precipitation will significantly increase by 24 - 25 mm/decade based on both the RCP 8.5 and RCP 4.5 scenarios. The greatest increase will occur over the western part of VMRD during summer.

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