Dynamically Downscaled NARCCAP Climate Model Simulations: An Evaluation Analysis over Louisiana

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Dynamically Downscaled NARCCAP Climate Model Simulations: An Evaluation Analysis over Louisiana

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Dedication

I would like to dedicate this thesis to my parents.

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I would like to express my gratefulness to Allah, the most graceful, the most merciful. I would like to thank Allah for giving me the strength and patience to accomplish this achievement.

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LIST OF ABBREVIATIONS

AOGCM	Atmosphere–Ocean Global Climate Model
CCCma	Canadian Centre for Climate Modeling and Analysis
CDF	Cumulative Distribution Function
CGCM	Canadian Coupled Global Climate Model
CPRA	Coastal Protection and Restoration Authority
GCM	Global Circulation Model
CP	Chenier Plain
IPCC	Intergovernmental Panel on Climate Change
NARCCAP	North American Regional Climate Change Assessment Program
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NEXRAD	Next-Generation Radar
ppm	parts per million
ppt	parts per thousand
RCM	Regional Climate Model
SDM	Statistical Downscaling Model
SRES	Special Report on Emissions Scenarios

CHAPTER 1 INTRODUCTION

1.1 Background

In response to awareness of the potential impacts of climate variability and change on natural and human systems, scientists from various disciplines and stakeholders with a wide range of interests are undertaking climate impact assessments. For the most part, these assessments target a particular activity, phenomenon, or system. Also, these assessments are constrained to limited geographic areas. Climate change scenarios are employed by an assessment team for analyses and modeling efforts unique to the specific assessment and by stakeholders to inform decision making (Winkler et al. 2011). Climate scenarios are the traditional starting point for a local/regional climate change impact assessment that links the scenarios in a sequential manner starting from natural models (e.g., hydrologic and ecological), to economic models, to decision-making and policy frameworks (Figure 1).

Figure 1 Schematic of an end-to-end assessment strategy, also referred to as a ‘feed forward approach’, for a local/regional climate change impact assessment. (Source: Winkler et al. 2011)

In order to prepare for future climate change, land and water resource managers need to know how the key climate variables – precipitation and temperature – may change in the future relative to the present. Atmosphere-Ocean General Circulation Models (AOGCMs, or GCMs), typically used within global climate modeling studies, are the principal tools for investigating potential future climate changes on global to regional scales. GCMs are computer models that represent how the different constituents of the Earth System – mainly the atmosphere, oceans, land surface, ice sheets, and sea ice – interact to generate weather and climate. Usually, GCM outputs have relatively coarse spatial resolution (100-300 km). That is why many user applications of GCM climate projections require processing of the GCM output for getting the effective scale of the data to a more local level by using a process called *downscaling* (Cozzetto et al. 2011; Winkler et al. 2011). Downscaling is a process that aims to increase the spatial resolution of global-scale climate model projections. Dynamic downscaling can be achieved using Regional Climate Models (RCM).

Even though there is some level of disagreement among climate models, these models are based on well-established physical principles either directly for simulated processes, or indirectly for parameterized processes. The results of these experiments are comprehensively used by a large community of modelers and researchers around the globe (for instance, as part of the Intergovernmental Panel on Climate Change, IPCC) to provide projections of future climate change due to expected increases in CO_2 emissions (Foster et al. 2009). In addition, climate models produce simulations of current and past climate conditions (hindcasts).

Climate models agree on certain aspects of future climate change. For instance, they all demonstrate rising global temperatures with amplified warming in the Arctic, enrichment of the hydrologic cycle (wet places becoming wetter and dry places becoming dryer), and rising sea level (e.g., Morris et al. 2002; Milliman et al. 1989; Michener et al. 1997). Many of these aspects affect each other and could be considerably altered in an already changing climate. Climate models are designed to reduce the uncertainty of simulated climate change impacts, which aids in adaptation. Generally, more confidence is placed in simulations that are at larger scales because of the agreement in global averages and patterns.

Among many climate variables, precipitation is one of the most critical to model formulation due to its strong dependence on parameterization schemes and their interaction with the resolved model dynamics (Maraun et al. 2010). When assessing climate change impacts, precipitation is a crucial variable, due to its direct influence on many aspects of our natural-human ecosystems, such as freshwater resources, agriculture and energy production, and health and infrastructure (Soares et al. 2012). However precipitation is considerably more challenging to model than other climate variables (e.g., temperature) mostly due to its nonlinear nature and high spatial and temporal variability (Maraun et al. 2010). As such, it is important to evaluate the reliability of precipitation simulations provided by the climate models and assess their regional representativeness before being used for scientific and engineering applications, as well as by decision and policy makers.

1.2 Research Objectives

The current study performs an evaluation analysis of precipitation simulations produced by a set of dynamically downscaled climate models provided by the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2012). NARCCAP is an international program that produces high resolution simulations of past (1971-2000) and future (2041-2070) climate for use in impacts research. The NARCCAP simulations are produced using a set of regional climate models (RCMs) driven by (or nested within) a set of atmosphere-ocean general circulation models (AOGCMs) over a domain covering the United States and most of Canada. All the RCMs are run at a spatial resolution of 50 km.

The goal of this study is to perform an evaluation analysis by implementing a direct assessment where the hindcast, historical NARCCAP simulations are compared against actual precipitation observations over the same historical period. The Assessment analysis will be implemented for a period that covers 20 to 30 years (1970-1999), depending on joint availability of both the observational and the NARCCAP datasets. In addition to direct comparison versus observations, the hindcast NARCCAP simulations will be used within a hydrologic modeling analysis for a regional ecosystem in coastal Louisiana (Chenier Plain). The results of the hydrologic simulations, namely water level and salinity, will be used to assess whether the NARCCAP simulations can reproduce some basic hydrologic characteristics within the ecosystem.

The following is a list of research objectives addressed throughout the chapters of this thesis:

1. To analyze the levels of uncertainties in precipitation fields produced by the dynamically downscaled climate models of the North American Regional Climate Change Assessment Program (NARCCAP).
2. To examine how the NARCCAP precipitation simulations compare to the observations in terms of spatial and temporal characteristics at various temporal scales that range from daily, monthly, seasonal and annual scale, as well as spatial scales that range from a pixel-scale to climate division.
3. To assess whether the NARCCAP simulations can reproduce fundamental hydrologic characteristics in a regional ecosystem of Coastal Louisiana (Chenier Plain).

4. To provide guidelines on the use of dynamically-downscaled precipitation simulations for the purposes of hydrologic ecosystem impact assessment studies.

1.3 Thesis Outline

The thesis includes 6 chapters. Chapter 1 introduces the overall background, objectives, and research questions, with a brief outline of the research methodology. Chapter 2 provides an overview of Climate Modeling techniques. Chapter 3 reviews previous studies on NARCCAP climate models. Chapter 4 describes the methodology for the assessment and application of NARCCAP climate models. Chapter 5 represents the main results and discussions on the Assessment and Application analyses. Finally, Chapter 6 summarizes the thesis, discusses its conclusions and contributions, and suggests some directions for future research.

CHAPTER 2 AN OVERVIEW OF CLIMATE MODELING

2.1 GCMs and RCMs

General Circulation Models (GCMs) are sophisticated computer models that mathematically represent how the different constituents of the Earth System – mainly the atmosphere, oceans, land surface, ice sheets and sea ice – interact to generate weather and climate. GCMs divide the earth's surface into a three-dimensional grid in the atmosphere and the ocean and create thousands of grid cells. This allows to effectively simulate the global circulations and spatial complexities of the climate system (Figure 2).

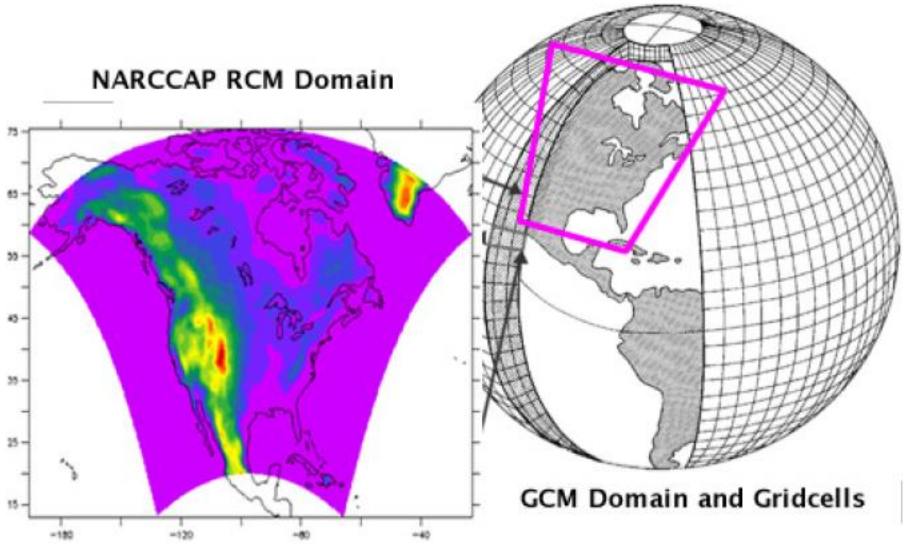


Figure 2 The model grid for the atmosphere component of a typical GCM (right) and the domain and topography of the NARCCAP RCMs (left) that were run "nseted" within a GCM. (Sources: NOAA and NCAR)

During the running phase of GCMs, standard physical equations for the transfer of heat, water, and wind speed (i.e., momentum) are solved for each grid cell. Many relevant processes such as large-scale westerly flow of moisture from the Pacific Ocean are well represented at the scale of these grid cells. Other processes which occur at a spatial scale much smaller than the grid cells, for instance, the formation of individual clouds, are parameterized. This means, they are characterized by values which reflect the observed relationships among climate variables. For example, even when it is not possible to model the individual clouds, a parameterization can determine the coverage of clouds and their total water content in a grid cell based on the water vapor, temperature and winds (Cozzetto et al. 2011).

Over a dozen research groups have developed GCMs around the world. The most recent Intergovernmental Panel on Climate Change (IPCC) assessment report made use of projections from 24 different GCMs. The archive of these projections is named Coupled Model Intercomparison Project (CMIP). The size of the GCM grid cells, and the spatial resolution of the climate projections, is restricted by the massive computing power required to solve the equations for all of the grid cells at hourly (or shorter) time steps for runs which might span 100 years or more. So, the output produced by the climate models at the time of the latest IPCC report (2007) has spatial scales of roughly 200-300 km (120-180 miles) (Cozzetto et al. 2011).

In order to increase the spatial resolution of global-scale climate model projections, dynamic downscaling with Regional Climate Models (RCM) is commonly used. The choice of boundary forcing applied to RCMs is one of the uncertainties in creating these projections (Wang and Kotamarthi 2013). When forced with different atmosphere–ocean coupled global climate models (AOGCMs) for the current or historical period, the skill of the RCMs depends largely on the skill of the forcing or “parent” AOGCM. As such, the AOGCMs have a large effect on the RCMs. In-depth analysis of parent GCM and RCM scenarios can identify a meaningful subset of models that can develop credible simulations of the North American monsoon precipitation (Bukovsky et al. 2013).

The use of RCMs implies a limited area model (LAM) that runs for an integration time greater than nearly two weeks, so that the sensitivity to initial atmospheric conditions is lost (Castro et al. 2005). An RCM is very similar to a GCM but covers a smaller spatial domain (e.g., North America), at a higher resolution (Figure 2) than a GCM. The GCM provides the environmental conditions, usually for every 3 or 6 hours, at the boundaries of the RCM domain. RCMs provide better topographical representations and local to regional scale atmospheric dynamics than GCMs. For example, RCMs can improve the simulation of warm-season convective precipitation (Cozzetto et al. 2011). Figure 3 illustrates how an RCM portrays individual mountain ranges that are not typically captured by GCMs.

In order to assess the impact of climate change at regional and local scales, Regional Climate Models (RCMs) are increasingly used whereas Global Climate Models (GCMs) are fit for the study of global atmospheric properties and global warming. Through regional climate modeling, the regional or local effects can be directly identified (Soares et al. 2012). It must be noted that the RCM does not substitute GCMs, but it is an influential tool to be used together with the GCMs for adding fine-scale detail to their broad-scale projections (Jones et al. 2004).

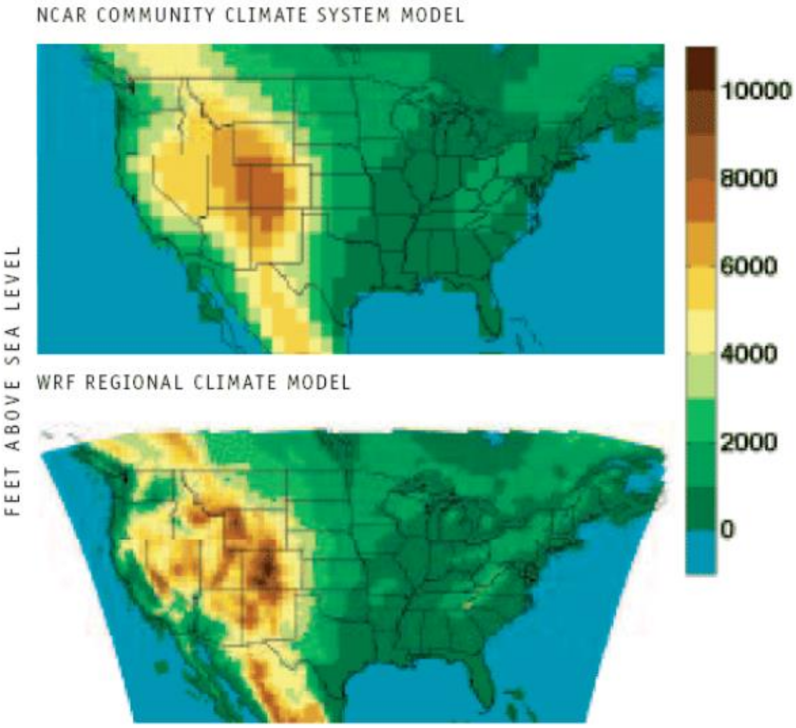


Figure 3 The spatial resolution and the representation of topography across the US of a typical GCM (top; NCAR CCSM 3.0) and a typical RCM (bottom; WRF Model). (Source: NCAR)

2.2 Review of Downscaling Techniques

The term ‘‘downscaling’’ refers to the use of either fine spatial-scale numerical atmospheric models, or statistical relationship in order to achieve detailed regional and local atmospheric data. Typically a larger-scale atmospheric or coupled oceanic-atmospheric model that runs globally is the starting point for downscaling. Then the downscaled high-resolution data can be inserted into other forms of simulation and management tools (e.g., hydrological and ecological models) (Castro et al. 2005).

Global climate models (GCMs) are the principal tools to understand how the global climate might change in the future. But, these presently do not provide information on scales below about 200 km (for an illustration, see Figure 4). Hydrological processes usually happen on finer scales. Particularly, GCMs cannot resolve circulation patterns leading to hydrological extreme events. To reliably assess hydrological impacts of climate change, higher-resolution scenarios are essential for the most relevant meteorological variables. Downscaling tries to resolve the scale inconsistency between climate change scenarios and the resolution needed for impact evaluation. It is based on the statement that large-scale weather exhibits a strong impact on local scale weather but it disregards any reverse effects from local scales upon global scales.

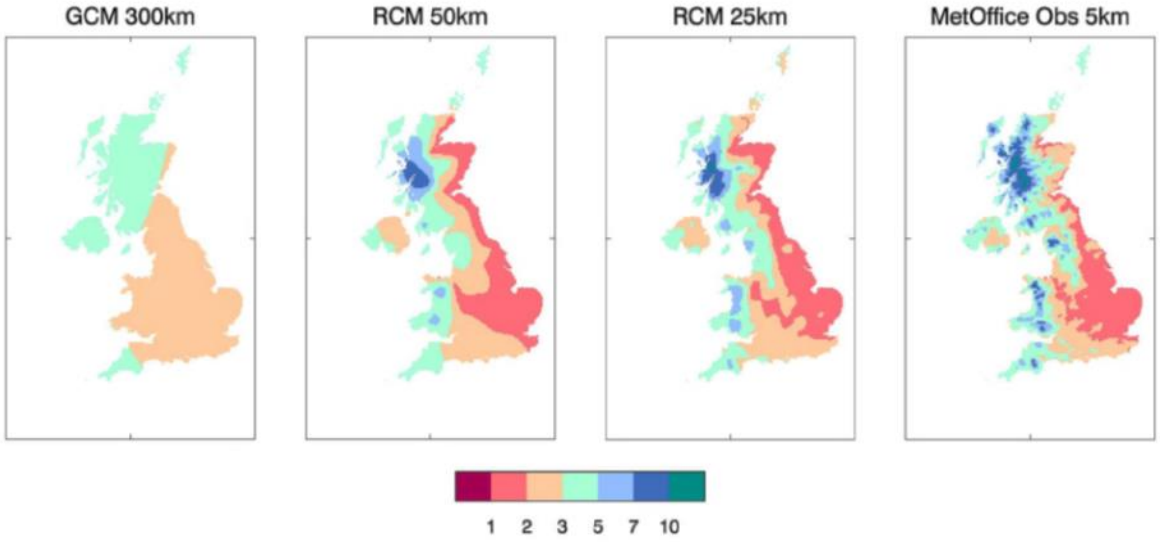


Figure 4 Average UK winter precipitation (mm/d) for a time period of 1961–2000 simulated by the GCM, HadCM3 and the RCM, HadRM3 at 50 and 25 km resolutions compared with gridded observations. (Source: Maraun et al. 2010)

The coarse resolution and poor representation of precipitation in global climate models is improved by precipitation downscaling. Downscaling also helps end users to measure the possible hydrological impacts of climate change. End users demand a reliable and dependable representation of precipitation intensities including temporal and spatial variability, along with physical consistency, independent of region and season. In addition the downscaling technique adds considerable value to projections from global climate models (Maraun et al. 2010).

Winkler et al. (2011) used a three category classification of downscaling methods, namely dynamic downscaling, empirical-dynamic downscaling and disaggregation approaches to downscaling. Dynamic downscaling contains the use of numerical models, for instance global models with variable spatial resolution, high-resolution global models, or, more frequently, regional climate models (RCMs) driven by coarse-scale GCM output, for simulating climate fields with a comparatively fine spatial resolution. Even though the term ‘empirical-dynamic,’ or alternatively ‘statistical-dynamic,’ has been used before in the study of Najac et al. (2011), this terminology traditionally refers to those downscaling methods that uses circulation ⁄ airflow patterns for the estimation of local or regional surface climate variables. Contrary to empirical-dynamic downscaling, disaggregation downscaling methods start with coarse-scale fields of a climate variable and conclude higher spatial and temporal resolution for that variable. Overall, disaggregation methods need fewer resources than either dynamic or empirical-dynamic downscaling. For better visualization of the different downscaling approaches, a schematic of the outputs when the methods are applied to GCM simulations is shown in Figure 5.

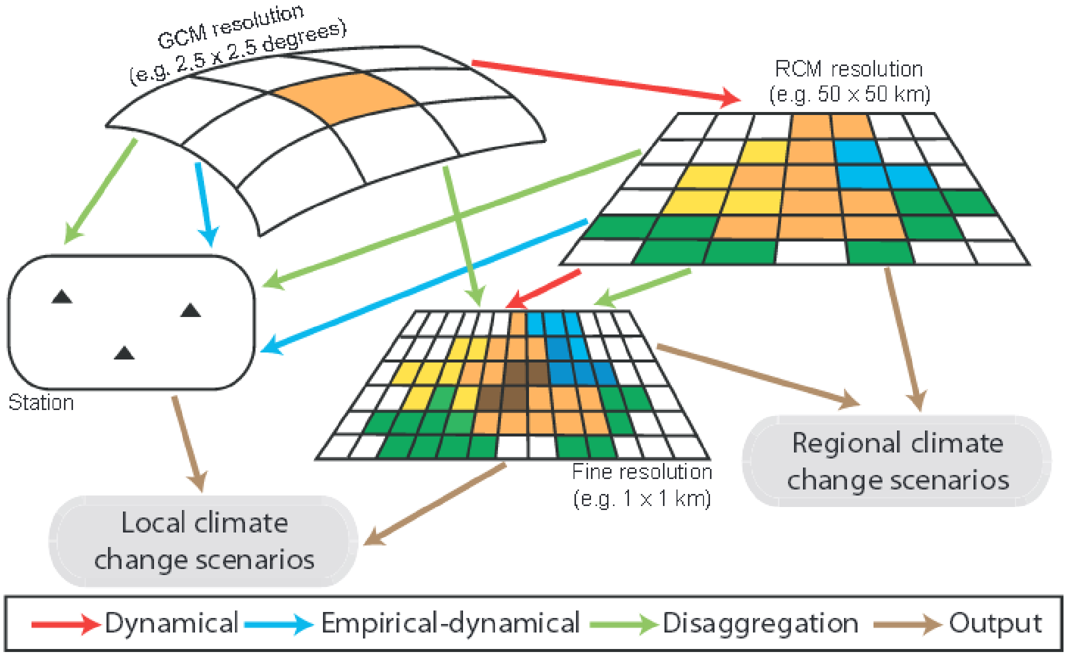


Figure 5 Schematic of the outputs of dynamic downscaling, empirical-dynamic downscaling and disaggregation downscaling methods when applied to GCM simulations. (Source: Winkler et al. 2011)

One should consider a range of projections rather than one or two while making use of downscaled climate projections, as with the underlying GCM output. In case of statistical downscaling, a group of GCM projections are typically downscaled using the same method. Similarly with dynamical downscaling, it is vital to consider projections produced by multiple RCM-GCM combinations. Each RCM, like each GCM, differs in how it represents climate processes. Moreover, there are important differences among RCMs in how they interact with the specific GCMs that provide their boundary conditions. The reason behind this is that each model has strong points and flaws, there is no one best RCM, nor one best RCM-GCM combination (Cozzetto et al. 2011).

Downscaling techniques are needed for most user applications in order to increase the spatial resolution of the GCM output. Dynamically downscaled projections can be generated at a variety of spatial scales, sometimes as small as 1 km. Still, these efforts are generally limited to the 25-50 km range due to computational constrains. A major shortcoming of dynamical downscaling is that, as with GCMs, the process is computationally intensive and there are systematic errors or biases in the simulation of the present-day climate. If modelers of water and ecosystem impacts want data at a finer spatial resolution than is provided by the RCMs, then they might still need to use the statistical methods for further downscaling of the data.

One of the main advantages of dynamical downscaling over statistical downscaling is that the former represents the physical processes of climate. Consequently the dynamical downscaling links spatial scales of climate in a manner that can vary as the future climate changes. On the other hand, statistical downscaling is based on fixed historically-based assumptions regarding the spatial relationships of climate variables. Additionally, a greater number of output climate variables from these RCMs relevant to resource managers, are being archived at sub-daily timescales. The RCMs simulate the individual terms in the water and energy budgets at the Earth’s surface, so that projected trends in solar radiation, evapotranspiration, and snowcover can be investigated at sub-GCM scales (Cozzetto et al. 2011).

CHAPTER 3 LITERATURE REVIEW ON NARCCAP CLIMATE MODELS

This study performs an evaluation analysis of the NARCCAP dynamically downscaled climate simulations. In this chapter, an overview of the NARCCAP models and their applications is presented.

3.1 NARCCAP Program

The North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2012) is an international program that produces high resolution simulations of future climate for use in impacts research. The NARCCAP simulations are produced using a set of regional climate models (RCMs) driven by (or nested within) a set of atmosphere-ocean general circulation models (AOGCMs) over a domain covering the United States and most of Canada. The AOGCMs climate change simulations are forced with the SRES A2 emissions scenario for the 21st century (2041-2070). The same sets of models were also used to produce simulations for the current (historical) period (1971-2000). The NARCCAP program also includes a set of simulations where the RCMS are driven with NCEP Reanalysis II data for the historical period 1979-2004. All the RCMs are run at a spatial resolution of 50 km. These simulation results are beneficial for further downscaling experiments, impacts analysis, and analysis of model performance and uncertainty in regional scale projections of future climate.

Due to limited funding for NARCCAP, it was decided to focus on the uncertainty across different AOGCMs and RCMs and run one emissions scenario (A2) for all simulations. The A2 emissions scenario was chosen as it was one of the 'marker' scenarios developed through the IPCC and was a common one used at the time NARCCAP was being planned. The scenario is described in Nakicenovic et al. (2000) in the Special Report on Emissions Scenarios (SRES) commissioned by the IPCC. In the fifth IPCC WGII AR5 report (Climate Change 2014: Impacts, Adaptation, and Vulnerability), the SRES scenarios were replaced with Representative Concentration Pathways (RCP) scenarios. In both the IPCC 2001 and 2007 reports, some of the scenarios described in that volume have been used in the climate model simulations assessment.

The A2 scenario is at the higher end of the SRES emissions scenarios (but not the highest). This was preferred because, from an impact and adaptation perspective, if one can adapt to a greater climate change, then the minor climate changes of the lower end scenarios can also be adapted too. A low emissions scenario potentially gives less information from an impacts and adaptation viewpoint. Besides, the current actual trajectory of emissions (1990 to present) relates to a comparatively high emissions scenario (Nakicenovic et al. 2000).

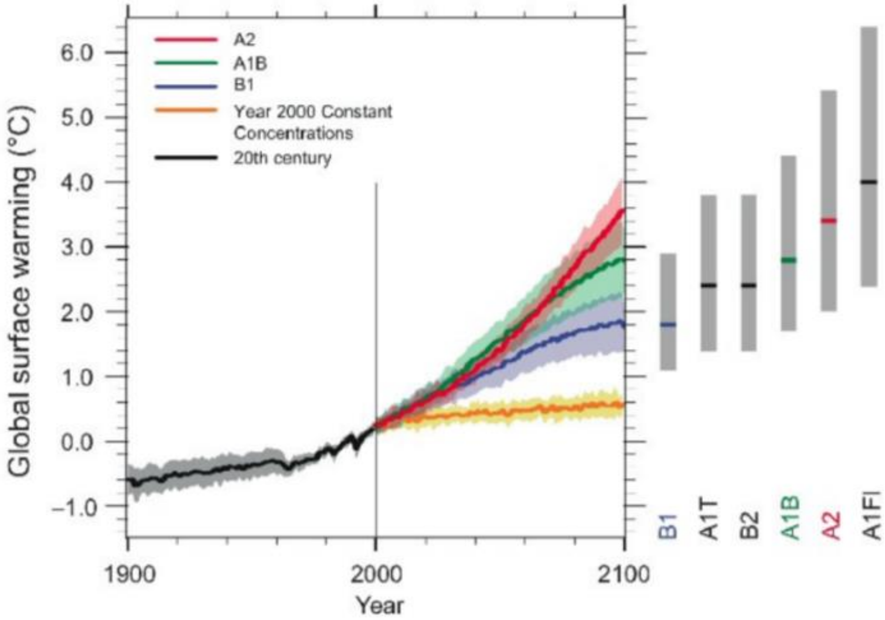


Figure 6 Multi-model Averages and Assessed Ranges for Surface Warming.
(Source: Nakicenovic et al. 2000)

A brief summary of the major characteristics of the scenario is presented here. The SRES scenarios were developed by considering various possible futures of world development in the 21st century. It includes some factors such as population change, economic development, technological development, energy use and land-use change. The 4 major story lines were established, which were quantified into 4 scenario families. A total of 40 different scenarios across the 4 story lines/families were built. It is assumed by the authors of the SRES scenarios that all scenarios will be equally plausible and they did not assign any probabilities to them.

Heterogeneity is the characteristic of the A2 story line. Self-sufficiency and local identities are emphasized, and population growth increases continuously. By 2050, population reaches over 10 billion. Economic and technological development is relatively slow, compared to the other story lines and economic development is regionally oriented. Based on these major factors, and by means of Integrated Assessment Models (IAMs), emissions of the major greenhouse gases were determined for the 21st century. Cumulative CO_2 emissions by the middle and end of the 21st century are projected to be about 600 and 1850 GtC, respectively. Projected CO_2 concentrations (ppm) for the middle and end of the 21st century in this scenario are about 575 and 870 ppm, respectively. To put these values in perspective, the current concentration of CO_2 is about 380 ppm. Generation of methane and nitrous oxide increases rapidly in the 21st century. Sulfur dioxide production increases to a maximum value (105 MtS/yr) just before 2050 and then drops in the second half of the century (60 MtS/yr by 2100) (Nakicenovic et al. 2000).

3.2 NARCCAP models

3.2.1 RCMs

The names of the 6 regional models participating in NARCCAP are listed in Table 1. Major characteristics of RCMs participating in NARCCAP are presented in Table 2.

Table 1 Regional Models (Source: Official Website of NARCCAP, UCAR 2007)

Model	Aliases	Modeling Group	Full Name
CRCM	MRCC	OURANOS / UQAM	Canadian Regional Climate Model / le Modèle Règional Canadien du Climat
ECPC	RSM	UC San Diego / Scripps	Experimental Climate Prediction Center Regional Spectral Model
HRM3	PRECIS, HadRM3	Hadley Centre	Hadley Regional Model 3 / Providing REgional Climates for Impact Studies
MM5I	MM5, MM5P	Iowa State University	MM5 – PSU/NCAR mesoscale model
RCM3	RegCM3	UC Santa Cruz	Regional Climate Model version 3
WRFP	WRF	Pacific Northwest Nat'l Lab	Weather Research & Forecasting Model

Table 2 Major characteristics of RCMs participating in NARCCAP (Source: Official Website of NARCCAP, UCAR 2007)

	CRCM	**ECPC/ECP2**	**HRM3**	**MM5I**	**RCM3**	**WRFP/WRFG**

	CRCM	ECPC/ECP2	HRM3	MM5I	RCM3	WRFP/WRFG
Dynamics	Nonhydrostatic, Compressible	Hydrostatic, Incompressible	Hydrostatic, Compressible	Nonhydrostatic, Compressible	Hydrostatic, Compressible	Nonhydrostatic, Compressible
Lateral Boundary Treatment	9 points (Davies 1976); spectral nudging of horizontal wind.	Perturbations relaxed at boundaries; spectral filter	4 points (Davies and Turner 1977)	4 points (linear relaxation)	12 points (exponential relaxation)	15 grid points (exponential relaxation)
Land Surface	CLASS	NOAH	MOSES	NOAH	BATS	NOAH
Vegetation Types	21 vegetation classes	13 classes	53 classes (Wilson and Henderson-Sellers 1985)	16 classes from USGS SiB model	19 classes	24 classes from USGS
Original Grid Size*	160 x 135	193 x 152	171 x 146	154 x 129	160 x 130	155 x 130
Length of Timestep	900 Seconds	100 seconds	300 Seconds	120 seconds	150 Seconds	150 seconds
tasmin/tasmax Calculation***	timestep	timestep	timestep	timestep	3-hourly	hourly

The CRCM is a limited-area nested model. Originally it was developed at Université du Québec à Montréal, based on the fully elastic nonhydrostatic Euler equations. Noncentered semi-implicit and semi-Lagrangian numerical algorithm had been used to solve these equations. The horizontal grid of CRCM is uniform in a polar stereographic projection, with a typical 45-km grid mesh (true at 60°N). In contrast, its vertical resolution is variable using a Gal-Chen scaled height terrain-following coordinate. Two versions of the CRCM are named CRCM_V3.6 and CRCM_V4.0. The CRCM_V3.6 includes most of the subgrid-scale physical parameterization package of the second generation Canadian Coupled General Circulation Model. The updated version of the CRCM model (CRCM_V4.0) is a significant evolution from the former version. The parameterization package of the updated

CRCM_V4.0 takes account of changes to the treatment of cloud cover, the radiation scheme, boundary layer mixing scheme, and land surface parameterization scheme (Music and Caya 2007).

Yulaeva et al. (2008) presents a new Experimental Climate Prediction Center (ECPC) Coupled Prediction Model (ECPM). The Jet Propulsion Laboratory (JPL) version of the Massachusetts Institute of Technology (MIT) ocean model coupled to the ECPC version of the National Centers for Environmental Prediction (NCEP) Atmospheric Global Spectral Model (GSM) is included in the ECPM. For ocean state assimilation, the adjoint and forward versions of the MIT model forced with the NCEP atmospheric analyses are routinely used at JPL. A former version of the GSM has been used for the NCEP–Department of Energy reanalysis-2 project and for operational seasonal forecasts at NCEP. In comparison to the observations and reanalysis data, the ECPM climatology and internal variability derived from a 56-yr-long coupled integration are used. However, the ECPM exhibits climatological biases, but these biases are relatively small and equivalent to the systematic errors produced by other common coupled models, including the latest NCEP Climate Forecast System. The internal variability of the model is similar to the observations. ECPM can simulate both the seasonal and interannual variability in the tropical Pacific well. The model is capable to reproduce the mechanism of ENSO evolution along with ENSO teleconnection patterns (including the Indian monsoon–ENSO relationship). The ability of the ECPM in predicting 1994–2006 sea surface temperature anomalies over the Niño-3.4 region is proved to be comparable to other coupled models. Currently ECPC produces and displays a modeled climatology for real-time seasonal forecasts derived by using those retrospective forecasts.

From the official website of ‘The PRECIS Regional Climate Modelling System,’ it has been found that PRECIS is based on the Met Office Hadley Centre's regional climate modeling system. For easy setup of experiments over any region, PRECIS has been ported to run on a PC (under Linux) with a simple user interface.

The new regional modeling system PRECIS is sponsored by the UK Department for International Development (DFID), the UK Department for Environment, Food and Rural Affairs (DEFRA), and the United Nations Development Programme (UNDP). The modeling system has these components:

1. An RCM which can be applied to any area of the globe to generate thorough climate change projections,
2. A simple user interface in order to allow the user to set up and run the RCM,
3. A visualization and data-processing package to permit display and manipulation of RCM output.

The Hadley Centre’s current version of the RCM (HadRM3P) is based on HadAM3H. HadAM3H is an upgraded version of the atmospheric component of the most recent Hadley Centre coupled AOGCM, HadCM3. Horizontal resolutions of 50 km and 25 km with 19 levels in the atmosphere (from the surface to 30 km in the stratosphere) and 4 levels in the soil have been used with HadRM3P (Jones et al. 2004).

MM5 (The PSU/NCAR mesoscale model) is designed to simulate or predict mesoscale atmospheric circulation. It is a non-hydrostatic, terrain-following sigma-coordinate and limited-area model. The numerous pre- and post-processing programs that provide support to the model are referred to collectively as the MM5 modeling system. The MM5 modeling system software is written in Fortran. It has been developed at Penn State and NCAR as a community mesoscale model with contributions from users worldwide. The Mesoscale Prediction Group in the Mesoscale and Microscale Meteorology Division of NCAR freely provides and supports the MM5 modeling system software.

A state-of-the-science regional climate model called the ICTP Regional Climate Model version 3 (RegCM3) is maintained and distributed by the Earth Systems Physics group of the Abdus Salam International Centre for Theoretical Physics. Presently, RegCM3 is a flexible, convenient, and user-friendly system that can be applied to an extensive range of scientific problems, from process studies to seasonal forecast and climate change applications. In RegCM3, the formation of precipitation is represented in two forms, resolvable (or large scale) and convective (or subgrid). (Pal et al. 2007)

The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system. It is designed to serve both atmospheric research and operational forecasting necessities. The two dynamical cores featured by this model are (a) a data assimilation system and (b) a software architecture facilitating parallel computation and system extensibility. The model aids a varied range of meteorological applications across scales from tens of meters to thousands of kilometers. The endeavor to develop WRF began in the latter part of the 1990's and was a collaborative partnership primarily among the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (represented by the National Centers for Environmental Prediction (NCEP) and the (then) Forecast Systems Laboratory, the Air Force Weather Agency, the Naval Research Laboratory, the Federal Aviation Administration (FAA) and the University of Oklahoma (UCAR 2006).

3.2.2 AOGCMs

The names of the 4 driving AOGCM Models are presented in Table 3. Major characteristics of AOGCMs participating in NARCCAP are presented in Table 4.

Table 3 Names of driving AOGCMs participating in NARCCAP (Source: Official Website of NARCCAP, UCAR 2007)

Driver	Full Name
CCSM	Community Climate System Model
CGCM3	Third Generation Coupled Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory GCM
HadCM3	Hadley Centre Coupled Model, version 3
NCEP	NCEP / DOE AMIP-II Reanalysis

Note: NCEP is not a GCM, but a reanalysis, a restrospective model of the atmosphere based on observed data. NARCCAP uses NCEP-DOE Reanalysis 2, sometimes referred to as “NCEP-2”.

Table 4 Major characteristics of AOGCMs participating in NARCCAP (Source: Official Website of NARCCAP, UCAR 2007)

Model	**Sponsor**	**Atmosphere Top Resolution**	**Ocean Resolution**	**Sea Ice**	**Coupling / Adjustments**	**Land Surface**
CCSM3	NCAR	Top = 2.2 hPa T85 (1.4x1.4°) L=26	0.3-1° L40	Rheology, leads	No adjustments	Layers, canopy, routing
CGCM3.1	CCCMA	Top = 1 hPa T47 (1.9°x1.9°) L31	0.9 x 1.4° L29	Rheology, leads	Heat, fresh water	Layers, canopy, routing
GFDL CM 2.1, 2005	NOAA-GFDL	Top = 3 hPa 2.0°x 2.5°	0.3-1.0°	Rheology, leads	No adjustments	Bucket, canopy, routing
UKMO HadCM3	Hadley Centre	Top = 5 hPa 2.5°x3.75° L19	1.25°x1.25° L20	Free drifts, leads	No adjustments	Layers, canopy, routing

The available RCM-GCM combinations are presented in Table 5.

Table 5 RCM-GCM combinations (Source: Official Website of NARCCAP, UCAR 2007)

	Phase II					Phase I
	GFDL	HADCM3	CGCM3	CCSM		NCEP
RegCM3	X		X			X
ECPC	X	X				X
PRECIS	X	X				X
CRCM			X	X		X
WRF			X	X		X
MM5		X		X		X

(Note: Planned model combinations were changed in late 2008 to improve the experiment's statistical design.)

For the simulation of past, present, and future climates, a coupled model named The Community Climate System Model (CCSM) has been developed. In its present form, CCSM is made up of 4 components such as the atmosphere, sea ice, ocean, and land surface linked through a coupler that exchanges fluxes and state information among these components. An international community of students and scientists from universities, various institutions, and national laboratories are contributing in the developement of this model. This model can be applied to the studies of interannual and interdecadal variability, projections of future anthropogenic climate change and simulations of paleoclimate regimes. In 1996, the first generation, the Climate System Model version 1 (CSM1), was released. Then in 2002, as an improvement over the version 1, the second generation, the Community Climate System Model version 2 (CCSM2), was released (Collins et al. 2006). The third generation, the Community Climate System Model version 3 (CCSM3) was released in June 2004. One of the worst features of the CCSM3 climate was the El Niño – Southern Oscillation (ENSO) period, which was controlled by variability at 2 year, rather than the 3–7-year period from observations. Improving ENSO was the uppermost priority in the fourth generation, the Community Climate System Model version 4 (CCSM4) developments, and a substantial improvement has been achieved (Gent et al. 2011).

As a continuation in the development of global climate models at the Canadian Centre for Climate Modelling and Analysis (CCCma), the first version, CGCM1, has been developed to include a complete three-dimensional ocean component. Previous models have focused on the atmosphere with either specified ocean temperatures or a 50 m mixed-layer ocean. This model is intended for use in long (multi-century) climate experiments. Its resolution is similar to other coupled models of this type, for instance more recent models in the Coupled Model Intercomparison Project (Flato et al. 2000). The second version of the Canadian Centre for Climate Modelling and Analysis (CCCma) Coupled Global Climate Model (CGCM2) is an improvement based on the earlier CGCM1. CGCM2 differs from CGCM1 by having a background horizontal diffusivity of 1/10 the isopycnal value, and a vertical diffusivity of 5×10^{-5} m^2/s. CGCM2 uses the cavitating fluid sea-ice dynamics scheme in place of the thermodynamic-only sea ice in CGCM1 (Flato and Boer 2001). The third version of Canadian coupled atmosphere–ocean Global Climate Model (CGCM3) is the latest AOGCM version used in the IPCC 4th assessment report (i.e. IPCC 2007). It was established based on the same ocean component as the earlier CGCM2, but it makes use of the substantially updated atmospheric component AGCM3 (Version 3 of Atmospheric Canadian GCM) (Jeong et al. 2012).

A multi-level, global, spectral transform model of the atmosphere has been developed at Geophysical Fluid Dynamics Laboratory (GFDL). The model is based upon spherical harmonics. The GFDL spectral model has been commonly utilized at GFDL for a wide range of weather prediction experiments. Additionally, it has been adapted and applied to 4-dimensional data assimilation experiments, climate studies, and even to the atmosphere of Venus (Gordon and Stern 1982). These models improve our understanding and make projections of the behavior of the atmosphere, the oceans, and climate by using state-of-the-art supercomputer and data storage resources. They have become key tools to understand the physical and biogeochemical processes and the interactions amongst them that control the earth's climate. Models are used to investigate the extent to which observed climate changes may be due to natural causes or may be attributable to human activities. GFDL has had a central role in each assessment of the Intergovernmental Panel on Climate Change (IPCC) since 1990. For the assessment issued in 2007, GFDL contributed in the development of two of the models used for climate assessments (CM2.0 and CM2.1).

The latest version of the Hadley Centre Coupled Model (HadCM3) is an AOGCM developed at the Hadley Centre in the United Kingdom (Gordon et al. 2000). In the IPCC Third Assessment Report (2001), HadCM3 was one of the major models that had been used (Megdal et al. 2012). Flux adjustment is required by the earlier version of the Hadley Centre Coupled Model (HadCM2) but the latest version (HadCM3) does not require flux adjustments to prevent large climate drifts in the simulation (Gordon et al. 2000). Simulations from the HadCM3 run for periods of over a thousand years show little drift in its surface climate (Saelthun and Barkved 2003). The main two components of HadCM3 are the atmospheric model HadAM3 and the ocean model (Jana and Majumder 2010).

3.2.3 NCEP Reanalysis II

Reanalysis datasets are originally developed for climate monitoring and weather-related research. But these are often used when evaluating GCM and ⁄or RCM simulations. These gridded fields, which can be considered a ‘blend’ of observations and model output, are constructed using a multi-part data assimilation system that includes an operational weather forecasting model; complex algorithms for quality control of raw observations from balloon soundings, ships, buoys, aircraft, satellites, and surface observing stations; and space and time interpolation schemes (Kalnay et al. 1996; Saha et al. 2010).

In order to remove discontinuities introduced by changes over time in forecast models and assimilation systems, the same forecast model and assimilation system are used for the entire period of the reanalysis. But discontinuities may still exist due to changes in the quantity and quality of atmospheric observations. Reanalyses can be categorized in terms of their spatial coverage as either ‘global’ or ‘regional’. The National Center for Environmental Prediction (NCEP)⁄National Center for Atmospheric Research (NCAR) Reanalysis (available for 1948–present), and ERA-40 (available for 1957–2002 and produced by the European Center for Medium Range Weather Forecasting) are two of the earliest and most commonly used global reanalysis datasets.

It is important to keep in mind that the reanalyses are unlikely to have the same grid spacing as corresponding GCM or RCM fields while using either global or regional reanalyses for evaluating the inputs to, and outputs from, climate downscaling techniques. And often regridding of either the reanalysis or model fields is necessary. Another important issue is that reanalysis fields are affected by biases and limitations (e.g. resolution) of the operational weather forecasting model used to produce the reanalysis and as a result, the reanalysis fields can deviate from observations (Winkler et al. 2011). Stefanova et al. (2012) found that dynamically downscaled reanalyses are in good agreement with station and gridded observations in terms of both the relative seasonal distribution and the diurnal structure of precipitation, even though total precipitation quantities tend to be systematically overestimated.

The NCEP–DOE Atmospheric Model Intercomparison Project (AMIP-II) reanalysis is based on the broadly used 50-year (1948-present) NCEP-NCAR Reanalysis Project. The Reanalysis-2 is an improvement upon the NCEP/NCAR Reanalysis by fixing the errors and by updating the parameterizations of the physical processes. NCEP–DOE AMIP-II reanalysis covers the “20-year” satellite period of 1979 to the present and uses an updated data assimilation system, updated forecast model, upgraded diagnostic outputs, and settles the known processing problems of the NCEP-NCAR reanalysis. Merely minor differences are found in the primary analysis variables such as winds in the Northern Hemisphere extratropics and free atmospheric geopotential height, while significant improvements upon NCEP-NCAR reanalysis are prepared in land surface parameters and land-ocean fluxes. Where the original analysis has problems, this analysis can be used as a supplement to the NCEP-NCAR reanalysis. The variances between the two analyses provide a measure of uncertainty in current analyses.

Despite the fact that Reanalysis-2 is considered better, it should not be considered the "next generation" of reanalysis. Improvements such as direct assimilation of radiances, higher horizontal and vertical resolution, proper use of SSM/I data, assimilation of rainfall data, need to be integrated (Kanamitsu et al. 2002).

3.3 Assessment and Application Studies of NARCCAP

The Regional Climate Model Evaluation System (RCMES) has been used for the evaluation of precipitation over the conterminous United States region using the NARCCAP RCM hindcast simulations (Kim et al. 2013). It was found that all RCMs simulate the observed climatology of the variables. RCM skill varies more widely in case of the magnitude of spatial variability than the pattern. The multimodel ensemble gave the best performance for precipitation. The key point from the systematic variations in biases for regions, seasons, variables, and metrics is that, the bias correction in applying climate model data to assess the climate impact on various sectors must be performed accordingly. From precipitation evaluation with multiple observations, it can be stated that the observational data can be a significant source of uncertainties in the evaluation of model. So, in order to evaluate the models, cross examination of observational data is essential. After comparing the multimodel mean of the NARCCAP simulations to observations a weighting scheme is applied on the basis of the reliability ensemble averaging approach developed by Giorgi and Mearns (2003) that combines an additional measure on the basis of the model skill score (Perkins et al. 2007). Weights are applied at each 50 km grid cell over the study area. Moreover, an additional weighting criterion is added based on each model’s ability to match the probability density function (pdf) of the observations. These weights are applied to the present-day NARCCAP output in order to illustrate present day bias reduction and future change in precipitation and temperature. Application of the weighting scheme contributes a considerable decrease in magnitude and percent area displaying significant bias in all seasons for precipitation. The weighting scheme can then extend to evaluate future change (Sobolowski and Pavelsky 2012).

In order to reproduce the North American monsoon system, the 17 dynamically downscaled simulations produced as part of NARCCAP were examined by Bukovsky et al. (2013). The concentration is on precipitation and the factors responsible for the precipitation biases seen in the simulations of the current climate. So, in order to help assess confidence in this suite of simulations, a process-based approach to the question of model reliability is considered. The RCMs, forced with a reanalysis product and atmosphere-only global climate model (AGCM) time-slice simulations, do sensibly well over the core Mexican and southwest United States regions.

The precipitation climatology of the Intermountain Region (IR), produced by the 6 regional climate models of NARCCAP, has been assessed (Wang et al. 2009). The existence of a complex combination of the precipitation annual and semiannual cycles with their different phases form 4 major climate regimes over the IR were examined. Systematic biases are produced in the central IR where these different climate regimes encounter. The simulated winter precipitation is too large and the annual cycles are universally too strong. Instead, the semiannual cycles are relatively well produced. Consequently, proper attention is advised while interpreting the simulated NARCCAP precipitation for the IR.

In order to analyze the ability of the NARCCAP ensemble of regional climate models for the simulation of extreme monthly precipitation and its supporting circulation for regions of North America, 18 years of simulations driven by the National Centers for Environmental Prediction (NCEP) reanalysis have been compared with observations. The main concern was on the wettest 10% of months during the cold half of the year (October–March), when it is expected that resolved synoptic circulation governs precipitation. For a coastal California region, the models independently and jointly reproduce well the monthly occurrence of extremes and the quantity of extreme precipitation. The statistics of the interannual variability of occurrences of extremes are also reproduced very well by the models. In the region of upper Mississippi River basin, the models agree with observations in both monthly frequency and magnitude, while not as closely as for coastal California. Furthermore, observations are similar to the simulated circulation anomalies for extreme months. All regions have significant seasonally varying precipitation processes that rule the occurrence of extremes in the observations, and the models can show those variations (Gutowski Jr. et al. 2010).

Kawazoe and Gutowski Jr. (2013) analyzed the ability of NARCCAP's ensemble of climate models to simulate very heavy daily precipitation and its supporting processes, by means of comparing simulations that used observation-based boundary conditions with observations. The study takes account of regional climate models and a time-slice global climate model that all used approximately 0.5° resolution. Analysis focuses on an upper Mississippi River region for winter (December to February), when it is anticipated that resolved synoptic circulation governs precipitation. All models usually replicate the precipitation-versus-intensity spectrum seen in observations well, with a slight tendency toward generating overly strong precipitation at high-intensity thresholds, for example the 95th, 99th, and 99.5th percentiles. Other analysis focuses on precipitation events higher than the 99.5th percentile that occur concurrently at a number of points in the region, yielding so-called “widespread events”. Investigation of additional fields indicates that the models produce very heavy precipitation events for the similar physical conditions seen in the observations.

Takle et al. (2010) used Soil and Water Assessment Tool (SWAT) driven by observations and outputs of climate models to assess hydrological measures, including streamflow, in the Upper Mississippi River Basin (UMRB) for a time period of 1981–2003 in comparison to observed streamflow. Daily meteorological conditions are used as input to SWAT. They are taken from three sources: (a) observations at weather stations in the basin, (b) daily meteorological conditions simulated by a group of regional climate models (RCMs) driven by reanalysis boundary conditions, and (c) daily meteorological conditions simulated by a group of GCMs. The Variable Infiltration Capacity (VIC) model was used to assess the hydrologic response of the trans-state Oologah Lake watershed to climate change by means of both statistically and dynamically downscaled multiple climate projections. The hydrologic model has been forced by the simulated historical and projected climate data from NARCCAP and Bias-Corrected and Spatially Downscaled–Coupled Model Intercomparison Phase 3 (BCSD-CMIP3). Moreover, for a higher VIC model performance, different river network upscaling methods are also compared. The results from the evaluation and comparison are that, from the hydrologic perspective, the dynamically downscaled NARCCAP projection gave better performance, and is most likely in capturing a greater percentage of meso scale-driven convective rainfall in comparison to the statistically downscaled CMIP3 projections. The VIC model produced higher seasonal streamflow amplitudes that match closely to observations. In addition, though their precipitation and temperature are bias corrected to be more favorably than the NARCCAP simulations, the statistically downscaled GCMs are not able to capture the hydrological simulation properly due to missing integration of climate variables of wind, solar radiation and others. The results from both NARCCAP and BCSD-CMIP3 show that the future water availability (rainfall, runoff, and base flow) in the watershed would increase annually by 3-4 %. NARCCAP results indicate seasonal variability of rainfall and other water fluxes that are 2-3 times higher than the results from BCSD-CMIP3 models. Since the land surface and atmosphere processes are considered integrally, the hydrologic performance could be used as a potential metric to comparatively differentiate climate models (Qiao et al. 2014).

Mailhot et al. (2012) performed an analysis of annual maxima (AM) series of precipitation from 15 simulations of NARCCAP for grid points covering Canada and the northern part of United States. Three groups of NARCCAP Regional Climate Models' simulations have been used: (1) NCEP (6 simulations); (2) GCM-historical (5 simulations); and (3) GCM-future (4 simulations). Historical simulations are used to represent 1968-2000 period and future simulations cover 2041-2070 period. Comparison of results from NCEP and GCM-historical groups indicates good agreement in terms of spatial distribution of AM intensities. The 14 Canadian climatic regions have been used to define regional projections. Uncertainties on these regional values, resulting from inter-model inconsistency, were also assessed. Results suggest that inland regions will experience the largest relative increases in AM intensities while coastal regions will experience the smallest ones. These projections are most important inputs for the evaluation of future impact of climate change on water infrastructure and the formulation of more efficient adaptation strategies.

Seasonal extreme daily precipitation is analyzed by Wehner (2013) of the ensemble of NARCAPP regional climate models. It was found that the models’ abilities are significantly different to reproduce observed precipitation extremes over the contiguous United States. Model performance metrics are introduced to portray overall biases, seasonality, spatial extent and the shape of the precipitation distribution. Comparison of models to gridded observations including an elevation correction is found to be better than to gridded observations devoid of this correction.

Mearns et al. (2013) investigated major results of the NARCCAP multiple RCM experiments driven by multiple GCMs regarding the climate change for seasonal temperature and precipitation over North America. From the study it was found that the RCMs tend to produce robust climate changes for precipitation: greater increases in the northern part of the domain in winter and larger declines across a swath of the central part during summer, in comparison to the 4 GCMs driving the regional models along with the full set of CMIP3 GCM results. The GCMs explain more variance for winter precipitation and the RCMs for summer precipitation. Thus, it is recommended that future RCM-GCM experiments over this region include a balanced number of GCMs and RCMs.

Weller et al. (2013) introduced novel methodology to inspect the capacity of 6 RCMs in the NARCCAP ensemble to simulate past extreme precipitation events seen in the observational record over two different regions and seasons. Their main concern was to examine the strength of daily correspondence of extreme precipitation events between the output of both the RCMs and the driving reanalysis product and observations. Daily precipitation in a West Coast region of North America is analyzed in two seasons. The analysis shows that the simulated extreme events from the reanalysis-driven NARCCAP models show strong daily correspondence to extreme events in the observational record. The examination of precipitation over a central region of the United States shows some daily correspondence between winter extremes simulated by reanalysis-driven NARCCAP models and those seen in observations; on the other hand, no such correspondence is found for summer extremes. Moreover, greater discrepancies were found among the NARCCAP models in the tail characteristics of the distribution of daily summer precipitation over this region than seen in the precipitation over the West Coast region.

CHAPTER 4 RESEARCH METHODOLOGY

4.1 Datasets

The North American Regional Climate Change Assessment Program (NARCCAP) is an international program to produce high resolution climate change simulations. The main goal of NARCCAP is to study the uncertainties in regional scale projections of future climate. It is used to generate climate change scenarios for future study. RCM output is stored for more than 50 variables at 3-hourly resolution in standards-compliant, GIS-compatible Network Common Data Form (NetCDF) format. The files are organized similarly to the CMIP archive and distributed for free (registration required) via the Earth System Grid data portal. We performed an analysis of the daily, monthly, seasonal and annual variability of precipitation downloaded from the official NARCCAP website (http://narccap.ucar.edu) for the state of Louisiana, USA at 50 km resolution.

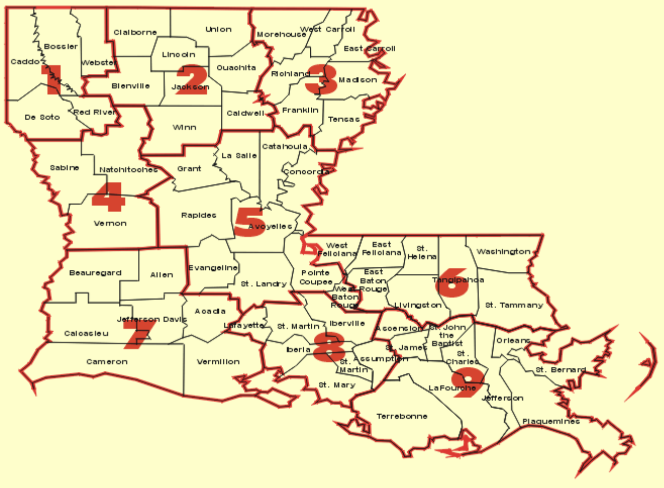


Figure 7 Louisiana Climate Divisions (Source: NWS/Climate Prediction Center)

In order to fulfill the study objectives, daily precipitation data from NARCCAP climate models have been used. These models are dynamically downscaled. Two groups of NARCCAP Regional Climate Models' simulations based on the driving data used at the RCMs boundaries have been used:

1. GCM-historical (11 simulations), which cover a 30-year (1970-1999) time period
2. NCEP (6 simulations), which cover a period of 20 years (1980-1999)

Python scripts have been used for pre-processing of the downloaded precipitation data. Python 2.7, ArcGIS 10.2 and MATLAB 2010 are used for the analysis of the processed data and to create maps and graphs.

4.2 Study Area

Our study area (for the application section) comprises the Louisiana Chenier Plain. Two major hydrologic basins, the Mermentau and the Calcasieu-Sabine, constitute the Louisiana Chenier Plain (Figure 8). Chenier Plain extends from the western bank of the Freshwater Bayou Canal westward to the Louisiana-Texas border in Sabine Lake, and from the marsh areas just north of the Gulf Intracoastal Waterway (GIWW) south to the Gulf of Mexico in Vermilion, Cameron, and Calcasieu parishes (Figure 8). It consists of approximately 2,402 square mile of marsh, open water, and Chenier habitats. Marsh types, their associated land cover across the region, and the percent of total marsh coverage represented by each type are: fresh marsh, 554 square mile (47%); intermediate marsh, 264 square mile (22%); brackish marsh, 310 square mile (26%); and saline marsh, 52 square mile (4%); Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority [LCWCRTF/WRCA 1998] (LCWCRTF 2002).

Figure 8 Louisiana’s Chenier Plain (Source: LCWCRTF 2002)

The study area for Louisiana is divided into a grid by points at 12.5 km x 12.5 km resolution similar to the resolution of the observed dataset. For the application section of this study, cell-wise precipitation data are required. The method of Voronoi polygons is used to get the precipitation of all the grid points that make up an individual eco-hydrology model cell. In this system the contributing fraction of all the Voronoi polygons within a cell are calculated. The weightage of precipitation is estimated based on the fraction of participating Voronoi areas. Then all the weighted precipitation values are summed up to get the total precipitation within that cell.

4.3 Precipitation Reference Observations

A dataset of daily gridded observations of precipitation of a rectangular boundary covering Louisiana extending from 28.8125°N to 33.0625°N and from 94.1875°W to 88.6875°W (Figure 7) is used to assess the validity of 11 RCM-AOGCM and 6 RCM-NCEP simulations for the periods of 1970–1999 and 1980-1999 respectively. Observations are essential for the development and evaluation of climate models, and satellite measurements provide exceptionally comprehensive data for both purposes (Gleckler et al. 2011). The objective of the Observations for Model Intercomparison Projects (Obs4MIPs) is to provide observational data to the climate science community, which is analogous (in respect of variables, spatial and temporal frequency, and periods) to output from the 5th phase of the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project (CMIP5) climate model simulations. The important aspect of the Obs4MIPs methodology is that it firmly follows the CMIP5 protocol document when selecting the observational datasets (Teixeira et al. 2014).

Maurer et al. (2002) studied a model-derived dataset of land surface states and fluxes. The domain covers all of the conterminous United States plus a bounding area that covers parts of Canada and Mexico (specifically latitudes 25°–53°N and longitudes 67°–125°W). Also it is consistent with the domain and resolution of the Land Data Assimilation System (LDAS)–North America project. The time period of the dataset was 1950–2000 at a 3-h time step with a spatial resolution of 1/8°. These sets of data were different from reanalysis because gridded precipitation and temperature were derived directly from observations. Furthermore, both the land surface water and energy budgets balanced at every time step. Surface forcing for the dataset were: precipitation, air temperature derived downward solar and long wave radiation, vapor pressure deficit, and wind. Simulated runoff matched well with the observations in large river basins. This set of data included physically based model parameterizations. All these characteristics made this dataset useful for different studies. The data are archived in NetCDF format.

4.4 The Eco-Hydrology Model

In order to examine how the downloaded daily precipitation data from NARCCAP simulations influence the overall hydrology of coastal Louisiana, an Eco-Hydrology model has been used. A time period of 10 years (1990-1999) is considered for this hydrologic analysis. This model has been developed by a group of experts as a part of the 2012 Coastal Master Plan (master plan) initiated by the Louisiana Coastal Protection and Restoration Authority (CPRA). The CPRA initiated an extensive numerical modeling effort in order to build the 2012 Coastal Master Plan. The goal of the master plan was the evaluation of the performance of potential protection and restoration projects on Louisiana Coast for the next 50 years. This numerical modeling effort was unprecedented in such a way that it endeavored to create an intricate chain of model outputs that could be used as input for additional models, where the ultimate stage presented an overall “outlook” of the coast after implementing proposed projects for 50 years. This project “outlook” would then be compared to a similar undisturbed “outlook” representing nature being left to its own devices, also known as future without action (FWOA).

The Eco-Hydrology model (Meselhe et al. 2012) included three main regions along the Louisiana Coast: Lake Pontchartrain/Barataria Basin (PB), Atchafalaya Basin (AA), and Chenier Plain (CP) region. Our study focuses on the Chenier Plain (CP) for the application section.

A number of assumptions were made to effectively model the hydrodynamics and water quality of the coastal domains. Some of these assumptions are as follows (Meselhe et al. 2013):

1. All variables were uniform in space within a compartment but they changed with respect to time.
2. The cross-sections of the links were presented by an equivalent rectangular shape.
3. The calibrated roughness coefficients and the diffusivities were kept constants for each link.

Usually a mass-balance compartment model is a 0-dimensional grid. Within this grid, the compartment centroids are connected with one another and with the boundary by way of links. Typically the links run from centroid to centroid or mid-point to mid-point, depending on the compartments being connected.

The models were designed to calculate hydrodynamic and water quality processes. They considered some features such as water and constituents entering and exiting the domains, atmospheric processes, like precipitation and evapotranspiration and exchange between the compartments. Stage, flow rate, and velocities were the constituents of the hydrodynamics included in the models.

The CP compartments were obviously separated into 3 (three) types: channel, open water, and marsh, where either compartment type could exchange with the other two types through links. A percentage of land was applied to each compartment in order to account for the water inside a marsh compartment, where 100% related to all land/marsh and 0% related to water. As a result, all channel, water, and offshore compartments had 0% land. The compartments exchange water with the atmosphere through precipitation (P), and evaporation/evapotranspiration (ET), and with one another through exchange flows (Q).

In order to setup the model and boundary conditions of the Eco-Hydrology models, numerous data were required including geometry data such as bathymetry, topography, dimensions of hydraulic structures, etc.; boundary conditions such as riverine inflows, open water tide and salinity time-series records, rainfall records, and ET records; initial conditions such as initial water depth and concentrations of the various water constituents; structure operation schedules; and system parameters like roughness, diffusion coefficients, and other physical and numerical parameters.

The exchange flows of the links, Q_i, between compartments were calculated using a variation of the Manning's equation (Equation (1)) (Chow 1959).

$$Q_i = A_i \left\{ \frac{2g\left| \left(E_j + \frac{d_i SAL_j}{1000}\right) - \left(E_{j+1} + \frac{d_i SAL_{j+1}}{1000}\right) \right|}{\left(\sum k_{im} + 2gn_i^2 \frac{L_i}{R_i^{4/3}} \right)} \right\}^{\frac{1}{2}} (3600.24) \tag{1}$$

Where,

i = link identifier

j = upstream compartment model

$j+1$ = downstream compartment identifier

Q_i = water flow rate in link i, m^3/day

A_i = cross sectional water flow area for link i, m^2

g = gravitational constant, 9.81 m/s^2

Ej = water surface elevation of compartment j, m

d_i = centroidal water depth for link i, m

SAL_j = concentration of salinity in compartment j, ppt or kg/m^3

k_{im} = minor loss coefficient for link i, 1/s^{2}m$^{2/3}$

n_i = Manning's roughness coefficient

L_i = length for link i, m

R_i = hydraulic radius for link i, m

Equation (2) shows the formulation for the change in depth as a function of exchange flows and atmospheric exchanges.

$$\frac{dH_j}{dt} = \left(\frac{\sum Q_{j,i} + \sum Q_{j,trib} + \sum Q_{j,div} + \sum Q_{j,run}}{As_j}\right) + \left(P_j - ET_j\right) \qquad (2)$$

Where,

dH_j /dt = rate of change in water depth for compartment j, m/day

$Q_{j,I}$ = flow to compartment j from all links i, m^3/day

$Q_{j,trib}$ = flow to compartment j from all tributaries, m^3/day

$Q_{j,div}$ = flow to compartment j from all diversions and distributaries, m^3/day

$Q_{j,run}$ = flow to compartment j from all runoff contributions, m^3/day

P_{j} = precipitation on compartment j, m/day

ET_j = evapotranspiration from compartment j, m/day

As_j = water surface area of compartment j, m^2

The mass-balance-based, reactive transport equation for each water quality constituent (salinity) solved within each computational compartment can be stated as showed in Equation (3):

$$\frac{dC_{k,j}}{dt} = -\frac{C_{k,j}V_j'}{V_j} + \frac{\sum C_{k,j,s}Q_{j,s}}{V_j} - \frac{k_{dis}}{V_j}\sum_i \frac{A_i}{L_i}\left(C_{k,j} - C_{k,jn}\right) + \frac{\sum Ss_{k,j,l}}{V_j} + \frac{1000 L_k As_j}{V_j} \quad (3)$$

Where,

$\frac{dC_{k,j}}{dt}$ = rate of change of concentration of constituent *k* in compartment *j*, g/m^3 or mg/L

s = water source via a tributary, a diversion/distributary, or runoff

$C_{k,j,i,s}$ = concentration of constituent *k* flowing into or out of compartment *j* via link *i* or a source *s*, g/m^3 or mg/L

$Q_{j,s}$ = water flow rate entering or exiting compartment *j* via link *i* or a source *s*, m^3/day

A_i = cross-sectional water flow area for link *i*, m^2

V_j = water volume of compartment *j*, m^3

V_j' = change in water volume with respect to time for compartment *j*, m^3/day

t = time, days

k_{dis} = dispersion coefficient, m^2/day

L_i = length of link *i*, m

$C_{k,jn}$ = concentration of constituent *k* in compartment *jn* adjacent to compartment *j* g/m^3 or mg/L

$Ss_{k,j,l}$ = rate of change of mass of constituent *k* in compartment *j* due to source/sink *l* associated with kinetic processes including transformations/reactions and settling, g/day

As_j = water surface area for compartment *j*, m^2

L_k = regional atmospheric deposition rate (for water compartments) or local loading flux (such as marsh/wetland delivery) for constituent k, kg/m^2/day

4.5 Assessment Methods

In order to assess the representativeness of the NARCCAP downscaled simulations for regional precipitation characteristics for our study area, the following set of statistical metrics are used. The metrics will be evaluated for the observational dataset and the 11 RCM-AOGCM simulations and 6 RCM-NCEP simulations over the 30-year (1970-1999) and the 20-year (1980-1999) historical period respectively.

1. The analysis of daily, monthly, seasonal and annual variability of precipitation is performed for the assessment of precipitation data for Louisiana. For seasonal analysis, the consideration of month is followed by the study of Maurer et al. (2002) and Mearns et al. (2012). June-July-August (JJA) is considered as summer, September-October-November (SON) is defined as fall, December-January-February (DJF) is assumed as winter, and March-April-May (MAM) is thought as spring.
2. The mean and standard deviation of daily precipitation are computed over 30 and 20 years using the observation data and NARCCAP simulations. A measure of variability simulated by each model is computed as the ratio of its standard deviation, in both space and time, to the corresponding standard deviation of the observation data.
3. The mean monthly precipitation, area-averaged percentage of summer (JJA) days with precipitation exceeding the specific thresholds, quantiles of daily precipitation in wet days (>0.1 mm)

4. Percentages of model relative to observation of days with precipitation greater than 1 mm are estimated for 9 climate divisions of Louisiana.
5. Spatial dependence using correlation distance: Maps of correlation distance (km) for daily, monthly and seasonal (summer, fall, winter and spring) precipitation of models and observation are produced. The grid-based precipitation values are used to derive correlation decay lengths in the form of

   $$r = e^{-x/d} \tag{3}$$

   Where, r is the correlation between adjacent grids, x is the distance between the grid centers, and d is the characteristic correlation decay length. Values of d are estimated for each grid using daily, monthly, and seasonal (daily summer, fall, winter and spring) data. The entire study area was used in the estimation of d (Jones et al. 1997).
6. Statistical assessment at climate division scale:

   For the purpose of regional evaluation of precipitation data of NARCCAP simulations, 9 climate divisions of the state of Louisiana are considered (Table 6). Whether the NARCCAP models are able to reproduce characteristics of observed precipitation in the individual climate divisions is important for evaluating their relevance for water resources management studies (Soares et al. 2012). Therefore, similar statistical analysis is performed at the scale of individual climate divisions.

Table 6 Climate Divisions of Louisiana

1	Northwest
2	North Central
3	Northeast
4	West Central
5	Central
6	East Central
7	Southwest
8	South Central

9	Southeast

7. Hydrologic Metrics:

The effect of precipitation on hydrology (salinity and water level) is the basis for the application-driven evaluation of NARCCAP model simulations. The hydrologic response of the Chenier Plain ecosystem to the use of NARCCAP simulations is analyzed by examining the water level and salinity predictions provided by the Eco-hydrology model. Maps of models to observation average and standard deviation of daily precipitation, salinity and water level are produced.

CHAPTER 5 RESULTS

In this study, precipitation data over Louisiana have been used to assess the skill of 11 RCM-AOGCM and 6 RCM-NCEP simulations for the periods of 1970-1999 and 1980-1999, respectively from NARCCAP projections. Spatial and temporal characteristics and variability of NARCCAP precipitation have been analyzed in terms of different time scales (daily, seasonal) and spatial scales (grid and climate division).

5.1 Biases and Variability in Precipitation Simulations

The mean, bias, and standard deviation of daily precipitation are calculated and presented in Figure 9, Figure 10, and Figure 11, respectively. In order to assess seasonal dependencies, the means and standard deviations of daily precipitation were calculated for different seasons: summer – June, July, and August (JJA) and winter – November, December and January (NDJ) and presented in Figure 12, Figure 13, Figure 14, and Figure 15. To facilitate the interpretation of the comparison of NARCCAP versus observations, the results of the standard deviations are presented using ratios of the two standard deviations (i.e., standard deviation of model divided by that of the observation).

Let us first examine the precipitation mean field. Figure 9 shows a comparison of the geographical distribution of the average daily precipitation of Louisiana of NARCCAP simulations with respect to observation data. The southeast-northwest precipitation gradient is recognized in the observations and in most of the models. All the RCM-NCEP simulations show an underestimation of observed average daily precipitation. This statement matches with the result found on the NARCCAP website (http://www.narccap.ucar.edu/results/ncep-results.html).

In case of the 11 RCM-AOGCM simulations, for some models, e.g., ECP2_GFDL, RCM3_CGCM3 and RCM3_GFDL, the average daily precipitation map is very similar to observations. However, most of the models show a slightly more heterogeneous spatial pattern than the observational grids, with underestimation of the northwest average daily precipitation particularly by CRCM_CCSM, MM5I_CCSM, WRFG_CCSM and WRFG_NCEP.

As the models are not bias corrected; therefore, it is expected to find some level of disparity in average daily precipitation between models and observation. The bias is calculated by taking the difference between model and observation data. From Figure 10, it is noticed that, both NARCCAP simulations types show a dry bias over the entire spatial domain when average daily precipitation is compared to the observed data. It means that, in general, the NARCCAP simulations underestimate the observed average daily precipitation.

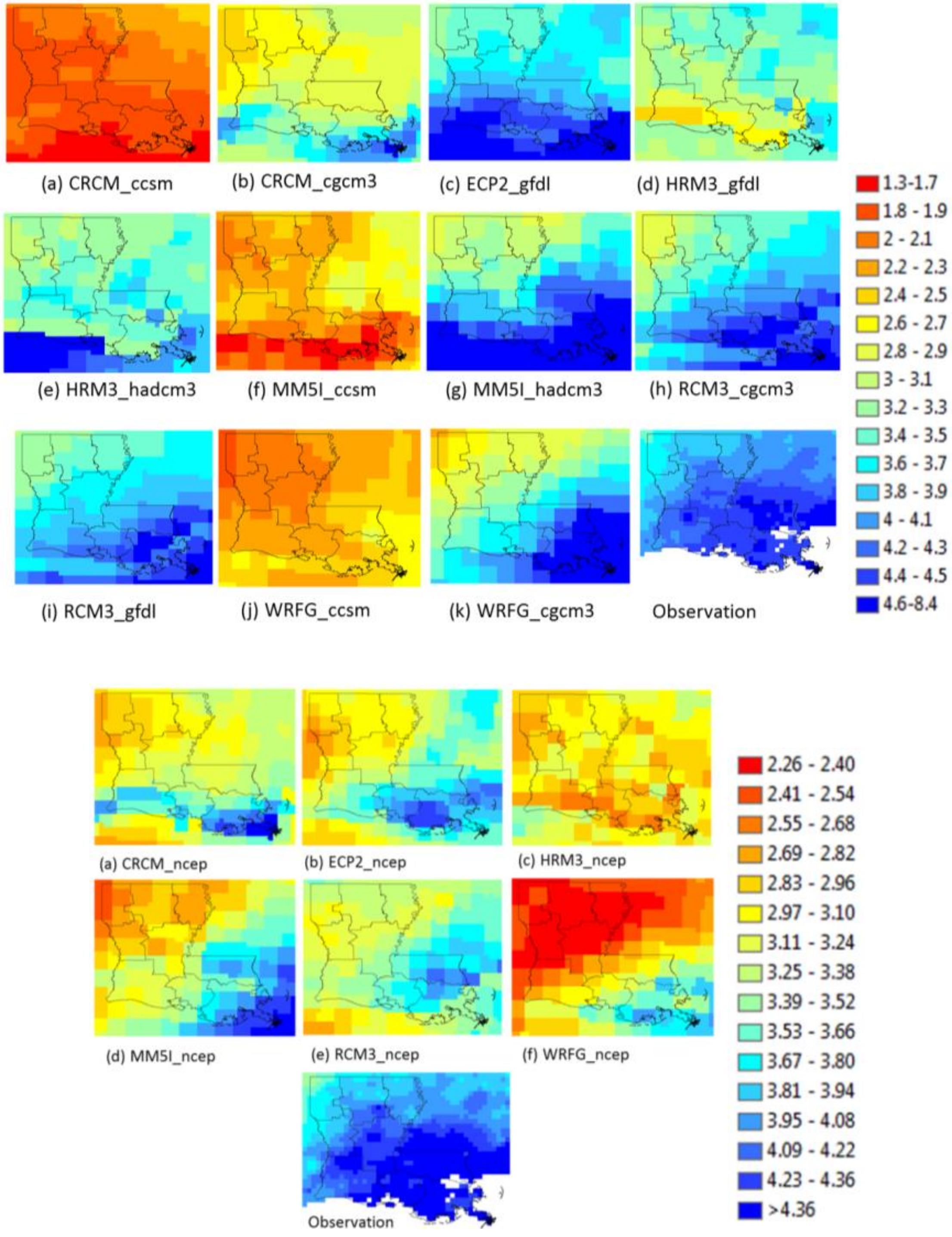


Figure 9 Average daily precipitation rate (mm/day) of NARCCAP simulations; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

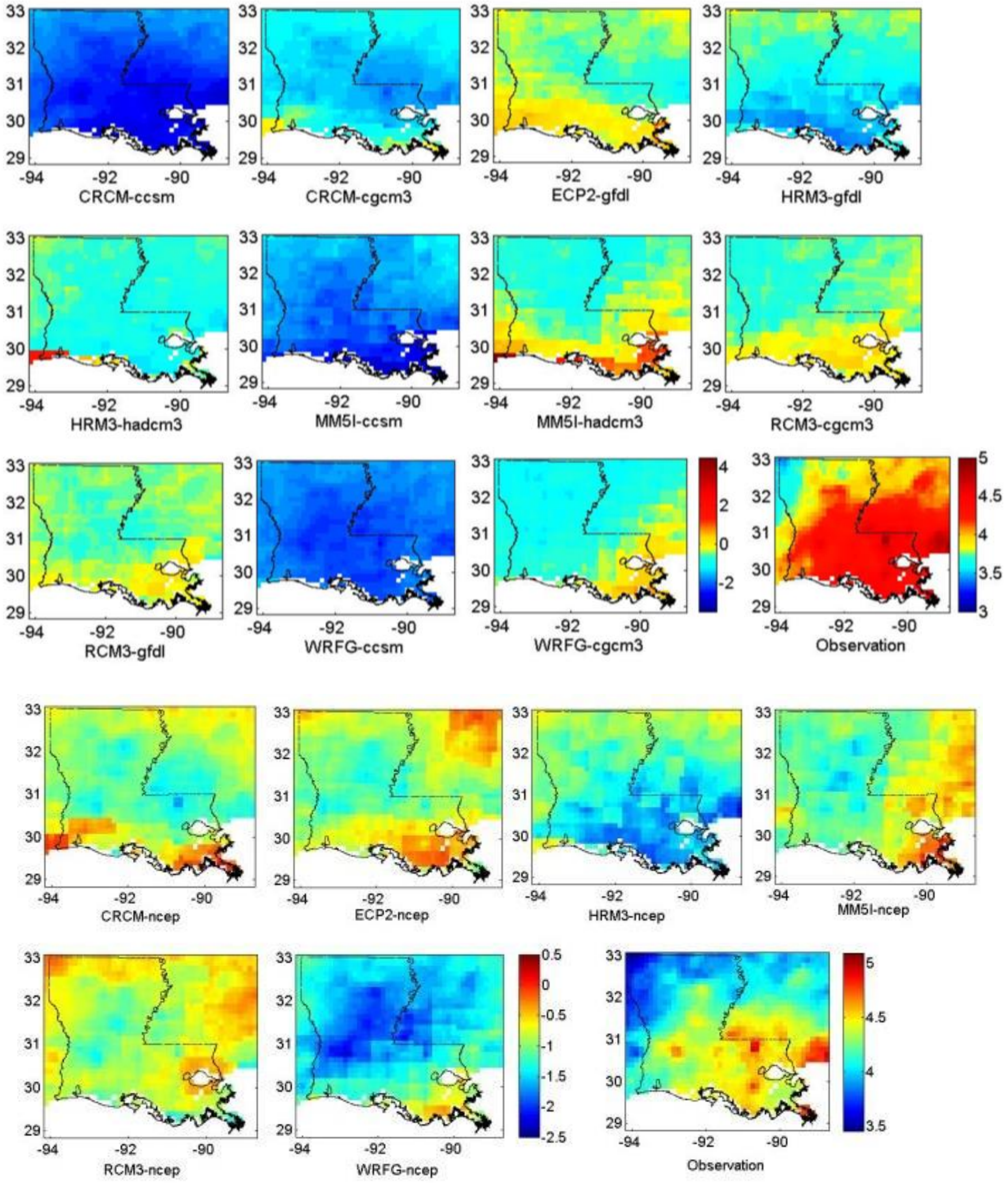


Figure 10 Bias in daily precipitation rate (mm/day) of NARCCAP simulations; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP [Note: The ‘Observation’ map shows the average precipitation rate in mm/day]

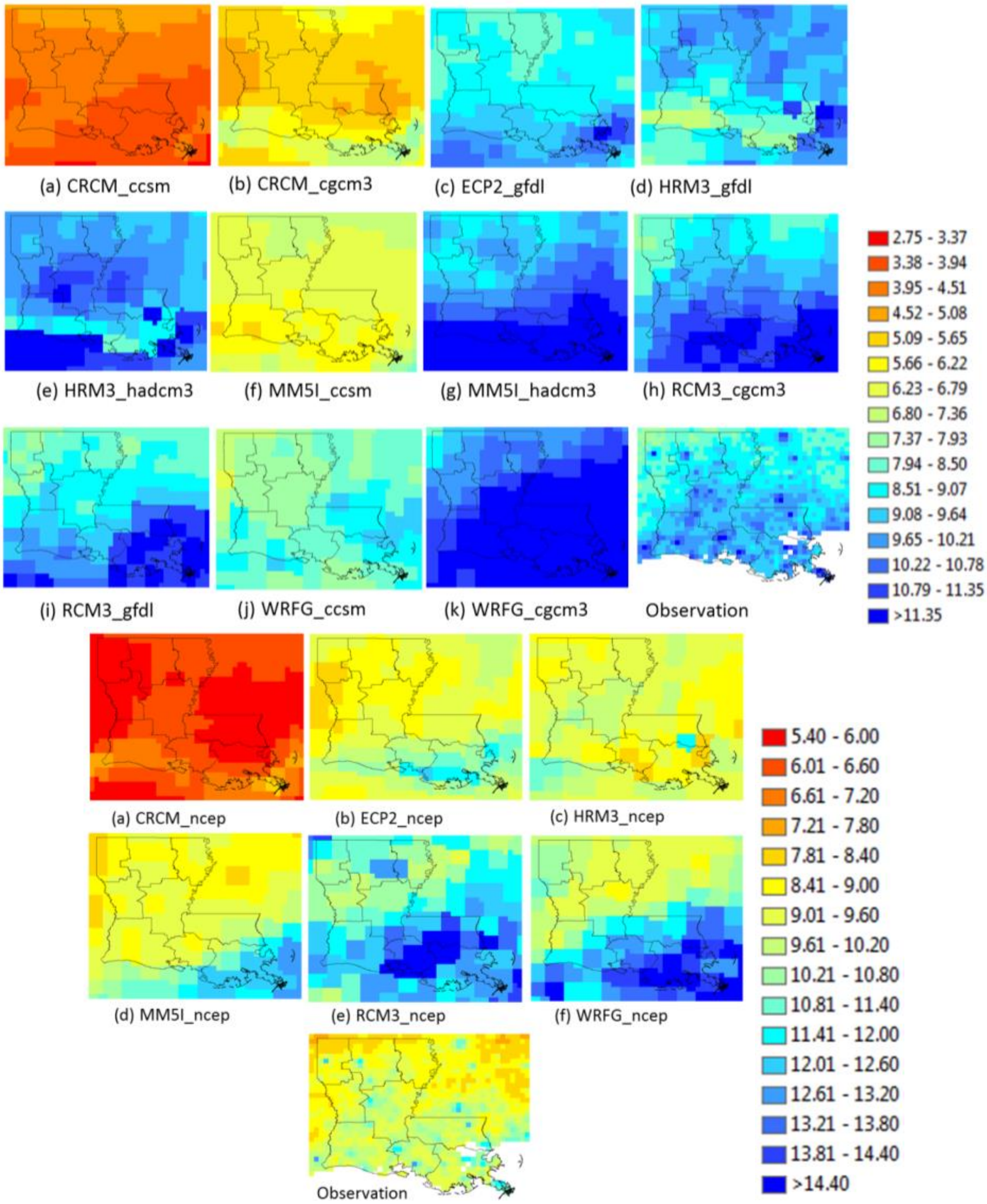


Figure 11 Standard deviation of daily precipitation rate (mm/day) of NARCCAP simulations; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

Next, consider the maps that show the spatial distribution of daily precipitation standard deviation, which is a measure of temporal variability at each grid pixel (Figure 11). The standard deviation maps show the variation of precipitation over 20 or 30 years in the whole spatial domain. In some models, e.g., CRCM_CCSM, CRCM_CGCM3, and MM5I_CCSM the standard deviation of daily precipitation maps show very low values compared to observations. The remaining models show a slightly more homogeneous spatial pattern. Among all the 6 NCEP simulations, CRCM_NCEP displays considerable underestimation of the observations. ECP2_NCEP, HRM3_NCEP and MM5I_NCEP contain close similarity with observation in terms of both magnitude and spatial distribution of standard deviation of daily precipitation. Also RCM3_NCEP and WRFG_NCEP respond similarly in capturing the spatial variability of daily precipitation all over the study domain.

Seasonal maps are presented to assess the model ability in reproducing seasonal variation in the mean and standard deviation of daily precipitation. Figure 12 shows the geographical distribution of the average daily summer precipitation of Louisiana. As the models are not bias corrected, it is expected to find some level of dissimilarity in the scenario of average daily summer precipitation between models and observations. In some models, e.g., HRM3_HadCM3, RCM3_CGCM3, and RCM3_GFDL, the average daily summer precipitation map is noticeably similar to observations. However, other models show a slightly more heterogeneous spatial pattern than the observational grids. Among all the 6 NCEP simulations, HRM3_NCEP and WRFG_NCEP exhibit substantial underestimation of the observation data.

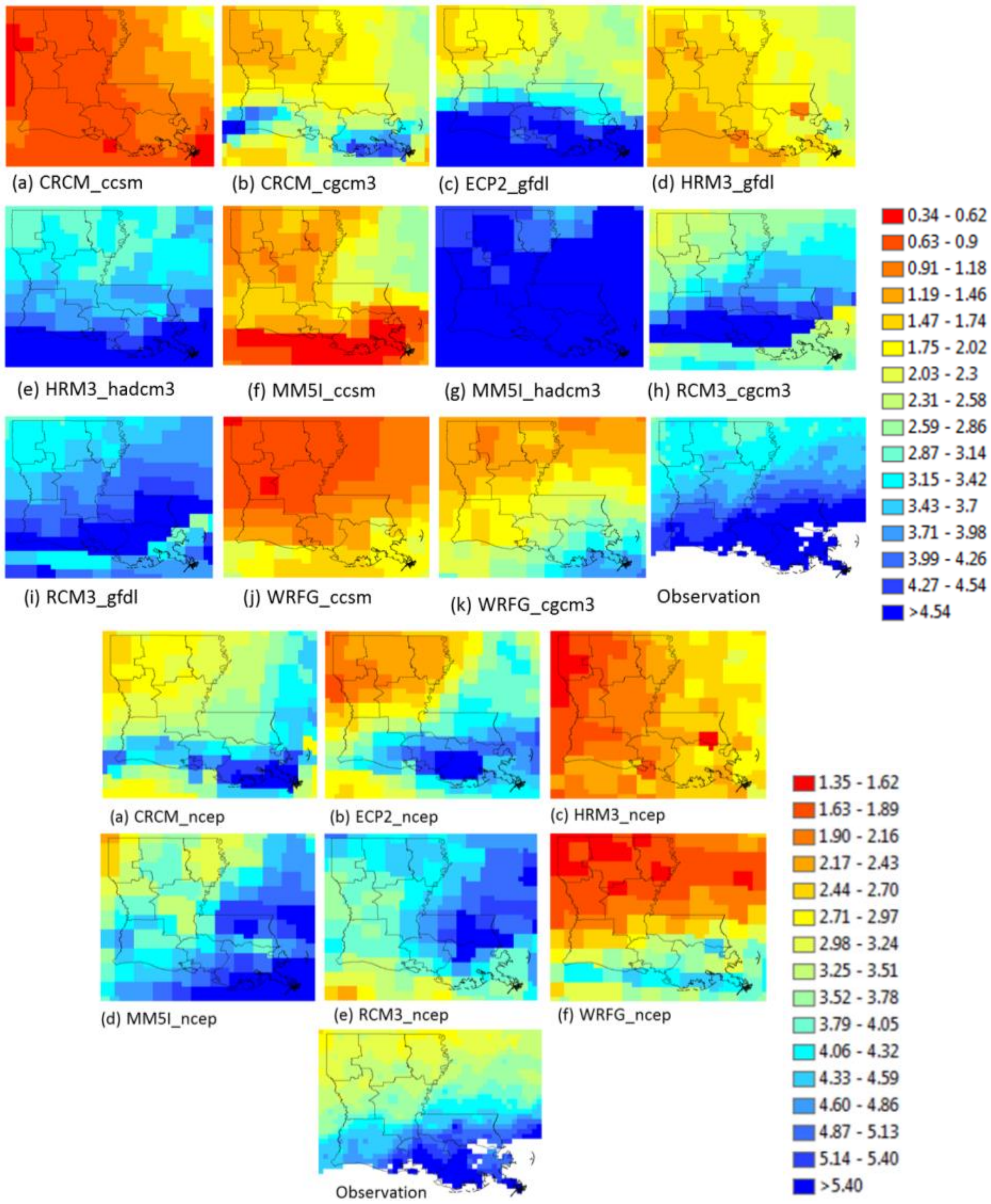


Figure 12 Average daily summer (JJA) precipitation (mm/day) of NARCCAP simulations; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

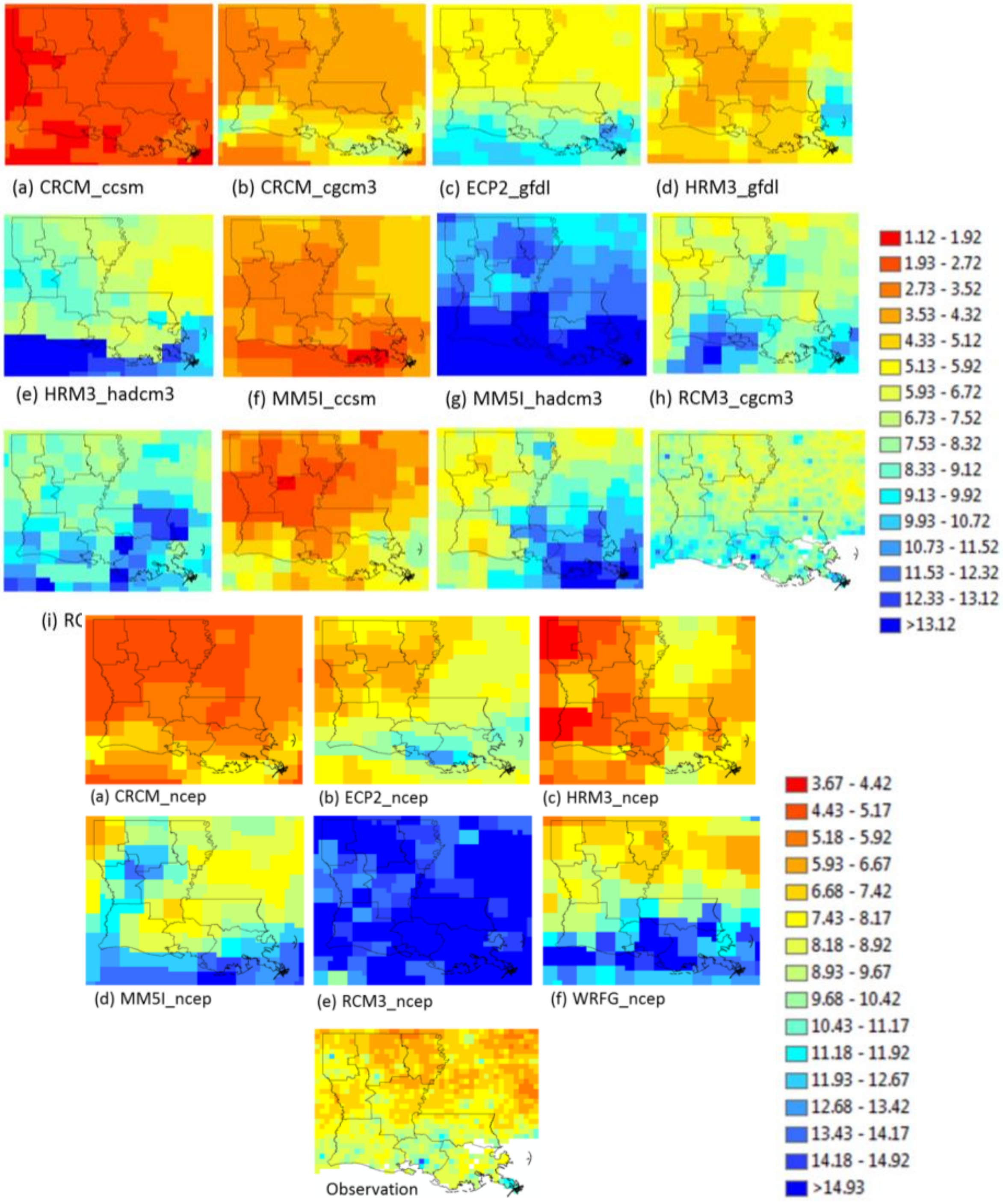


Figure 13 Standard deviation of daily summer (JJA) precipitation (mm/day) of NARCCAP simulations; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

Figure 13 shows the spatial distribution of the standard deviation of daily summer (JJA) precipitation. For ECP2_GFDL, HRM3_HadCM3, RCM3_CGCM3, and RCM3_GFDL, the standard deviation of daily summer precipitation map is very similar to observations. Among all the NCEP simulations, RCM3_NCEP significantly overestimates the observed standard deviation. WRFG_NCEP can capture the observed magnitude and spatial distribution of standard deviation of daily summer precipitation in the northeast portion of study domain well.

As the models are not bias corrected, it is expected to find some level of difference in the scenario of average daily winter precipitation between models and observation. In Figure 14, most of the models show a more heterogeneous spatial pattern than the observational grids in case of average daily winter precipitation. ECP2_GFDL and ECP2_NCEP show the most similar average pattern compared to observations while MM5I_HadCM3, MM5I_NCEP and RCM3_NCEP show significant underestimation of the observed average daily winter precipitation.

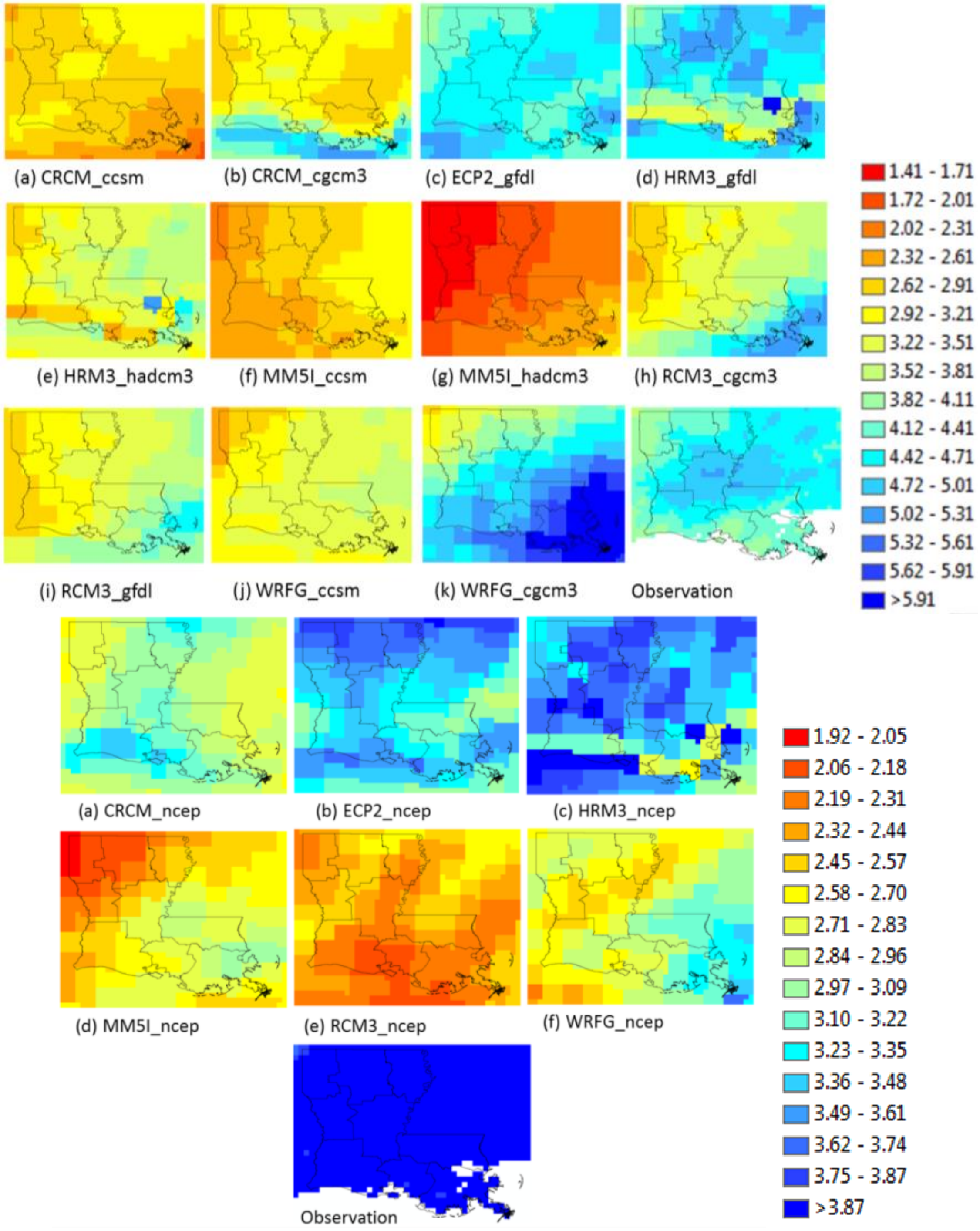


Figure 14 Average daily winter (NDJ) precipitation (mm/day) of NARCCAP simulations; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

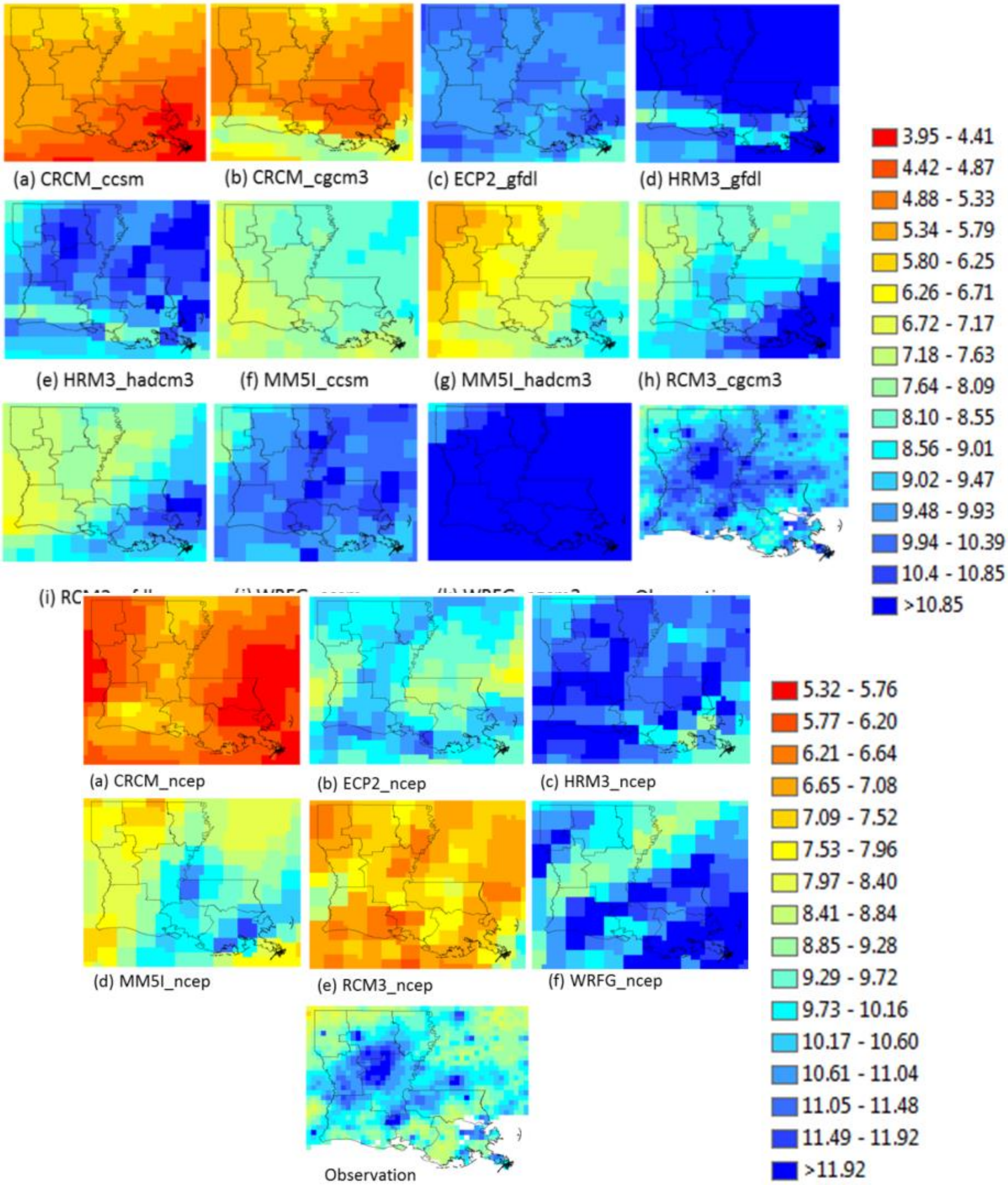


Figure 15 Standard deviation of daily winter (NDJ) precipitation (mm/day) of NARCCAP simulations; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

In Figure 15, HRM3_HadCM3 and WRFG_CCSM show a quite similar standard deviation pattern of daily winter (NDJ) precipitation to observations while CRCM_CCSM, CRCM_CGCM3, and MM5I_HadCM3 simulates the least range of standard deviation relative to the observations. Among the 6 NCEP simulations, CRCM_NCEP and RCM3_NCEP present considerable underestimation of the observations. ECP2_NCEP behaves quite similarly to observations. From Figure 13 and Figure 15, it is clear that, during winter the variation in precipitation is less than that of summer, so the models can capture the standard deviation of winter better than that of summer.

For a better comparison between the simulations and the observations, the results are re-presented in the form of rations of mean and standard deviation for daily summer (JJA) and winter (NDJ) precipitation (Figure 16 through Figure 19).

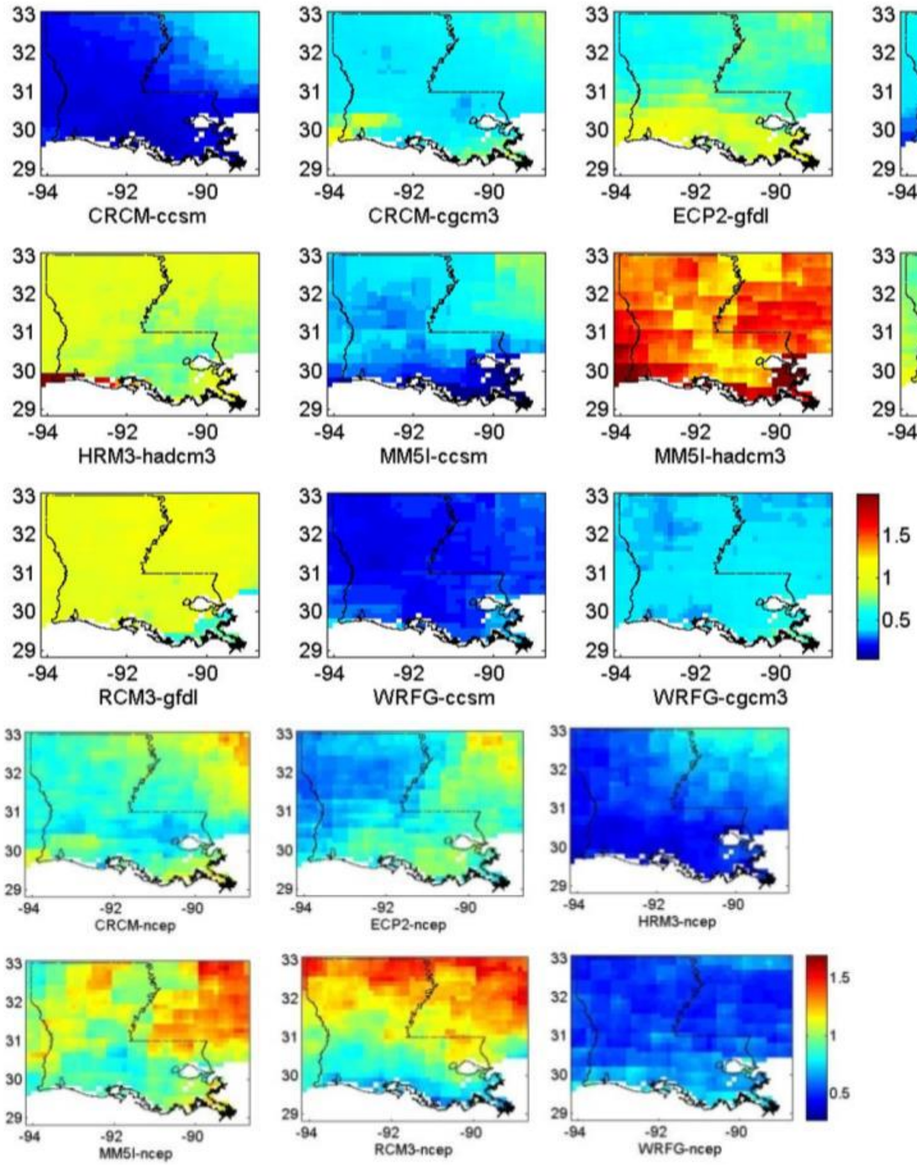


Figure 16 Ratio of average of NARCCAP models to average of observation for daily summer (JJA) precipitation rate (mm/day); [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

If the ratio is closer to 1, it means that, the value of daily summer precipitation of model is very close to that of observation. Figure 16 gives an indication that HRM3_HadCM3, RCM3_CGCM3 and RCM3_GFDL have a ratio close to 1. MM5I_hadcm3 has a ratio greater than 1 while CRCM_CCSM and WRFG_CCSM have ratios less than 1 like within a range between 0.2 and 0.3. Among the NCEP simulations, HRM3_NCEP and WRFG_NCEP have ratios less than 1 like 0.4. CRCM_NCEP has a ratio very close to 1.

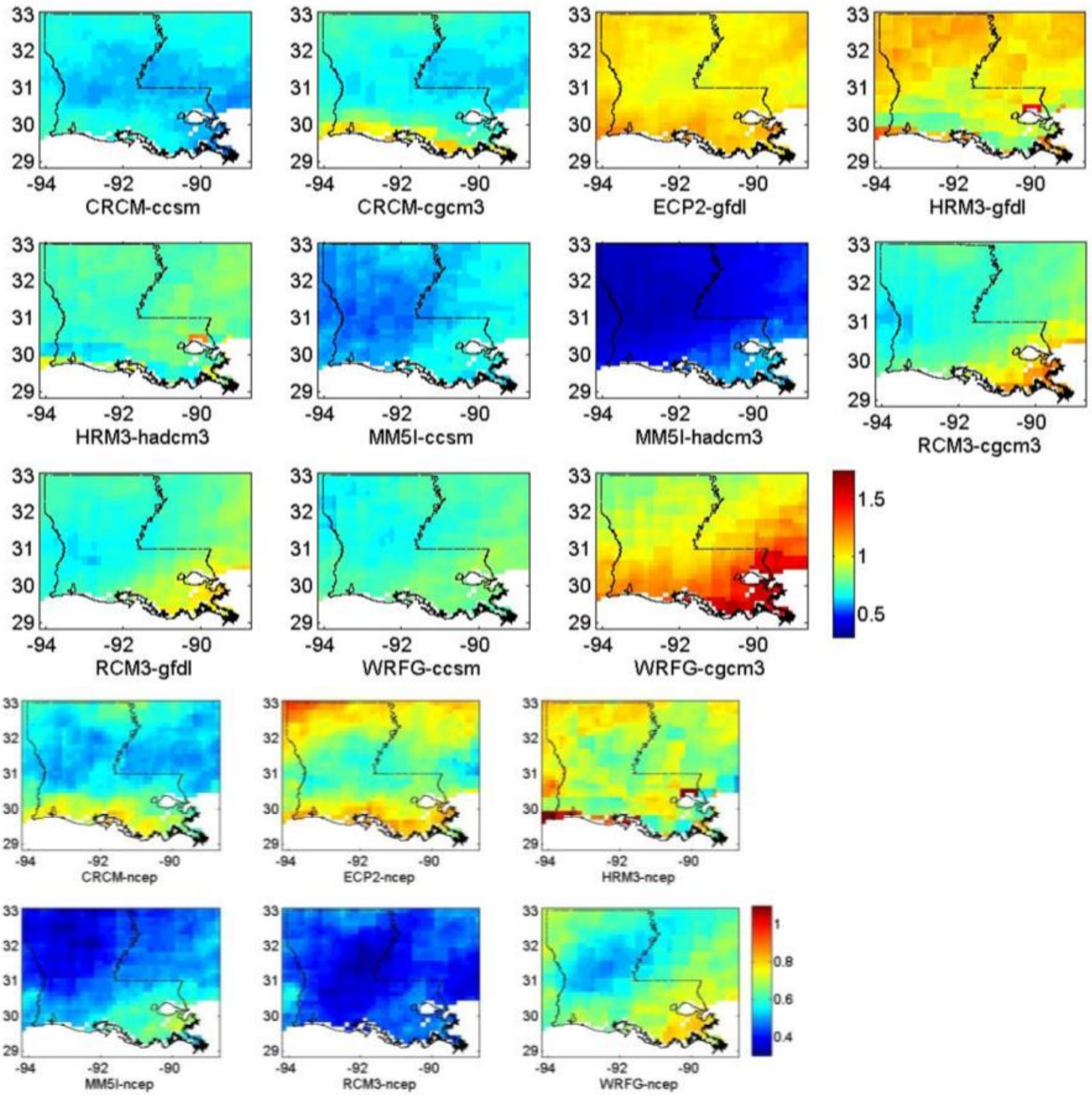


Figure 17 Ratio of average of NARCCAP models to average of observation for daily winter (NDJ) precipitation rate (mm/day); [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

If the ratio is closer to 1, it means that, the value of daily winter precipitation of model is very close to that of observation. Figure 17 indicates that, among the AOGCM driven RCM simulations, ECP2_GFDL, HRM3_GFDL, and WRFG_CGCM3 have a ratio close to 1 whereas in comparison to other simulations, MM5I_HadCM3 displays a ratio less than 1 like 0.3. It is noticeable that, overall the NCEP simulations have a ratio lower than the perfect value.

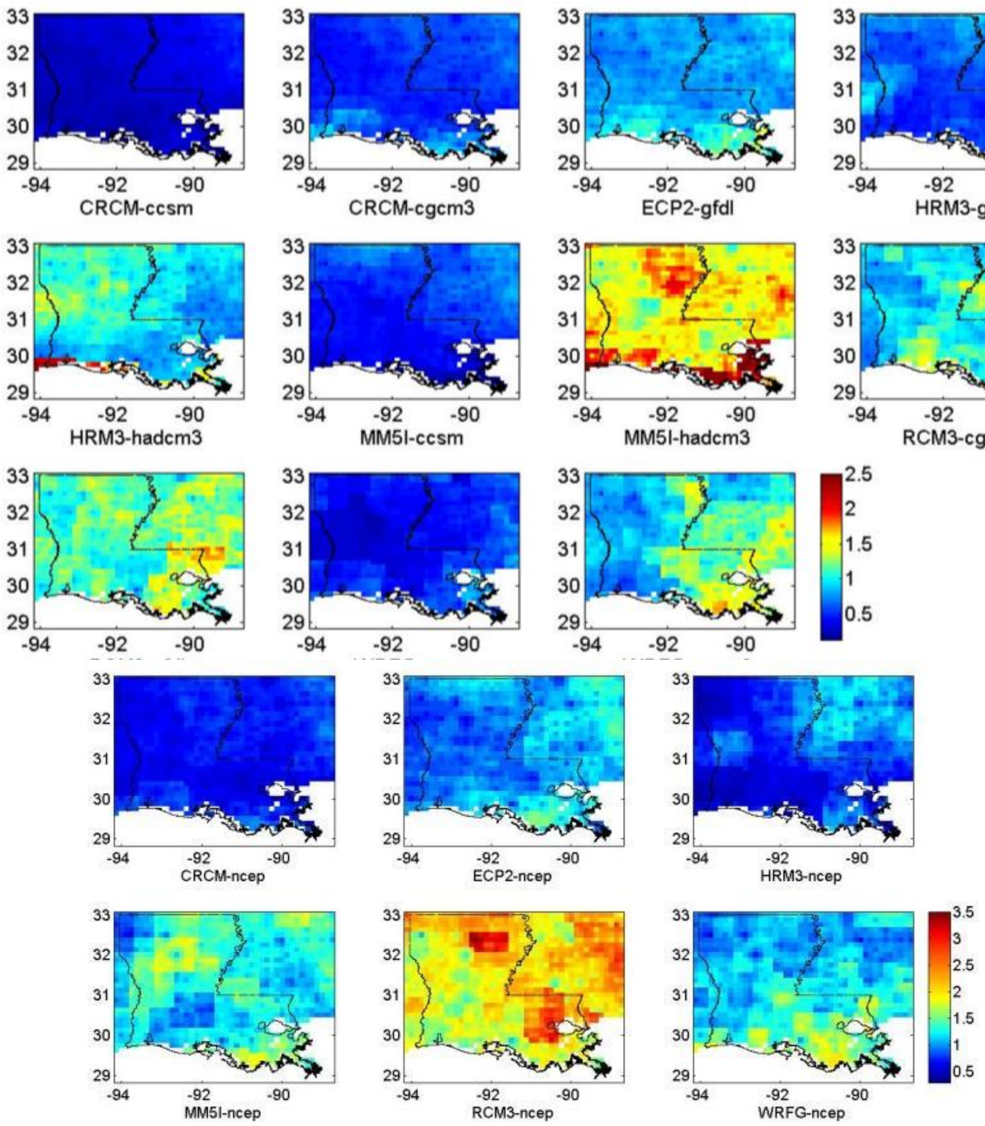


Figure 18 Ratio of standard deviation of NARCCAP models to standard deviation of observation for daily summer (JJA) precipitation rate (mm/day); [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

Figure 18 shows that HRM3_HadCM3, RCM3_CGCM3 and RCM3_GFDL have a ratio close to 1 in terms of standard deviation of daily summer (JJA) precipitation rate (mm/day). On the other hand, CRCM_CCSM, CRCM_CGCM3, MM5I_CCSM and WRFG_CCSM have ratios less than 1 like within a range between 0.2 and 0.3. Among the NCEP simulations, CRCM_NCEP, ECP2-NCEP and HRM3_NCEP have ratios less than 1 like almost 0.6 while RCM3_NCEP certainly overestimates the observed standard deviation of daily summer (JJA) precipitation with a ratio greater than 1 like within a range between 1.5 and 2.5.

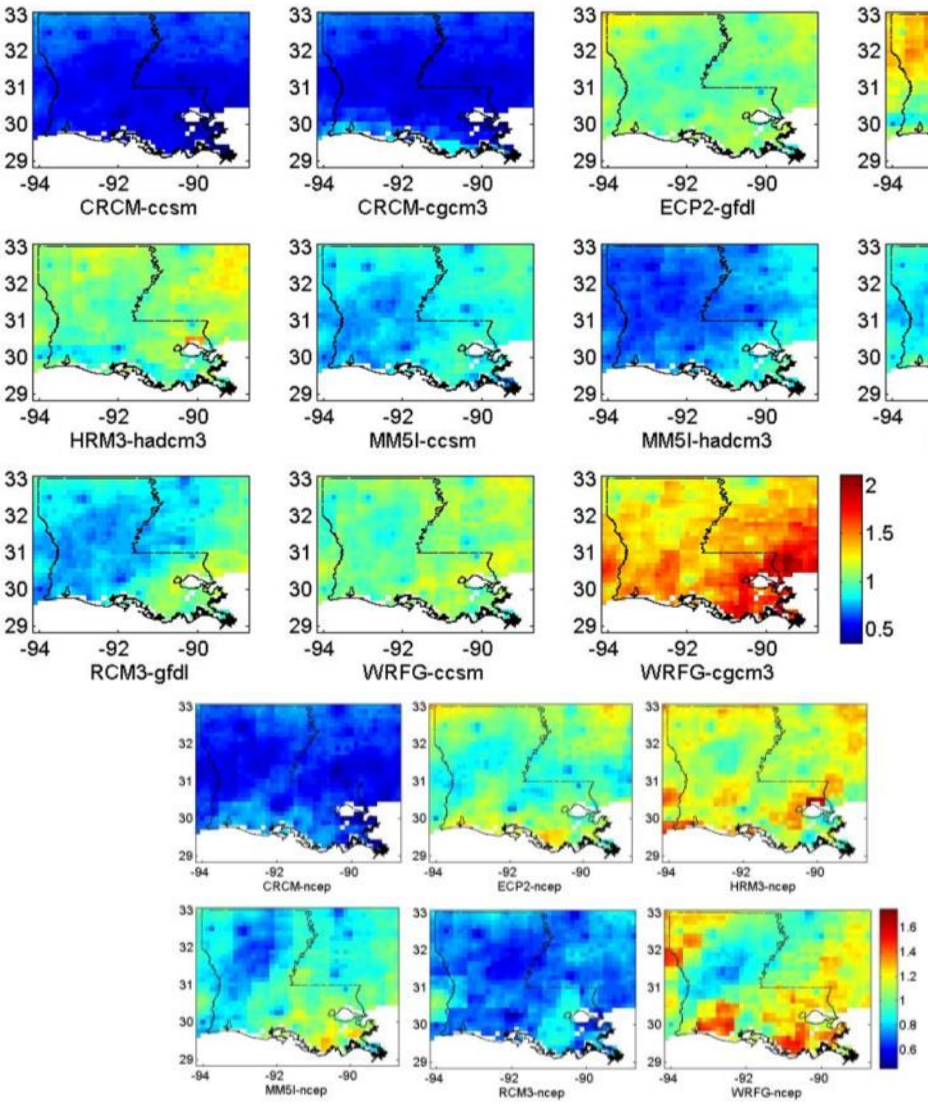


Figure 19 Ratio of standard deviation of NARCCAP models to standard deviation of observation for daily winter (NDJ) precipitation rate (mm/day); [left] 11 RCM-AOGCM and [right] 6 RCM-NCEP

It is noticed from Figure 19 that ECP2_GFDL, HRM3_HadCM3, RCM3_CGCM3 and WRFG_CCSM have a ratio close to 1. WRFG_CGCM3 has a ratio larger than 1 (about 1.5) and CRCM_CCSM and CRCM_CGCM3 have ratios less than 1 (approximately 0.5). Among the NCEP simulations, CRCM_NCEP and RCM3_NCEP have ratios less than 1 while ECP2_NCEP has a ratio quite close to 1.

5.2 Precipitation Spatial Dependence

Székely et al. (2007) stated that, correlation distance is a measure of spatial dependence between random variables. Correlation distance is zero only if the random vectors are independent. Maps of the correlation distance of the observational dataset and the NARCCAP simulations are calculated using the isotropic correlation function as defined in the methodology section of this study. The estimation assumes an isotropic reduction in the correlation with distance (Jones et al. 1997). Maps of correlation distance (km) for daily, monthly and seasonal (summer, fall, winter and spring) precipitation of the observation dataset and the NARCCAP simulations are shown in Figure 20 through Figure 23. Note that the correlation distance (*d* in Equation (4)) is a characteristic correlation decay length that represents the separation distance at which spatial correlation drops to a value of 1/e (0.367).

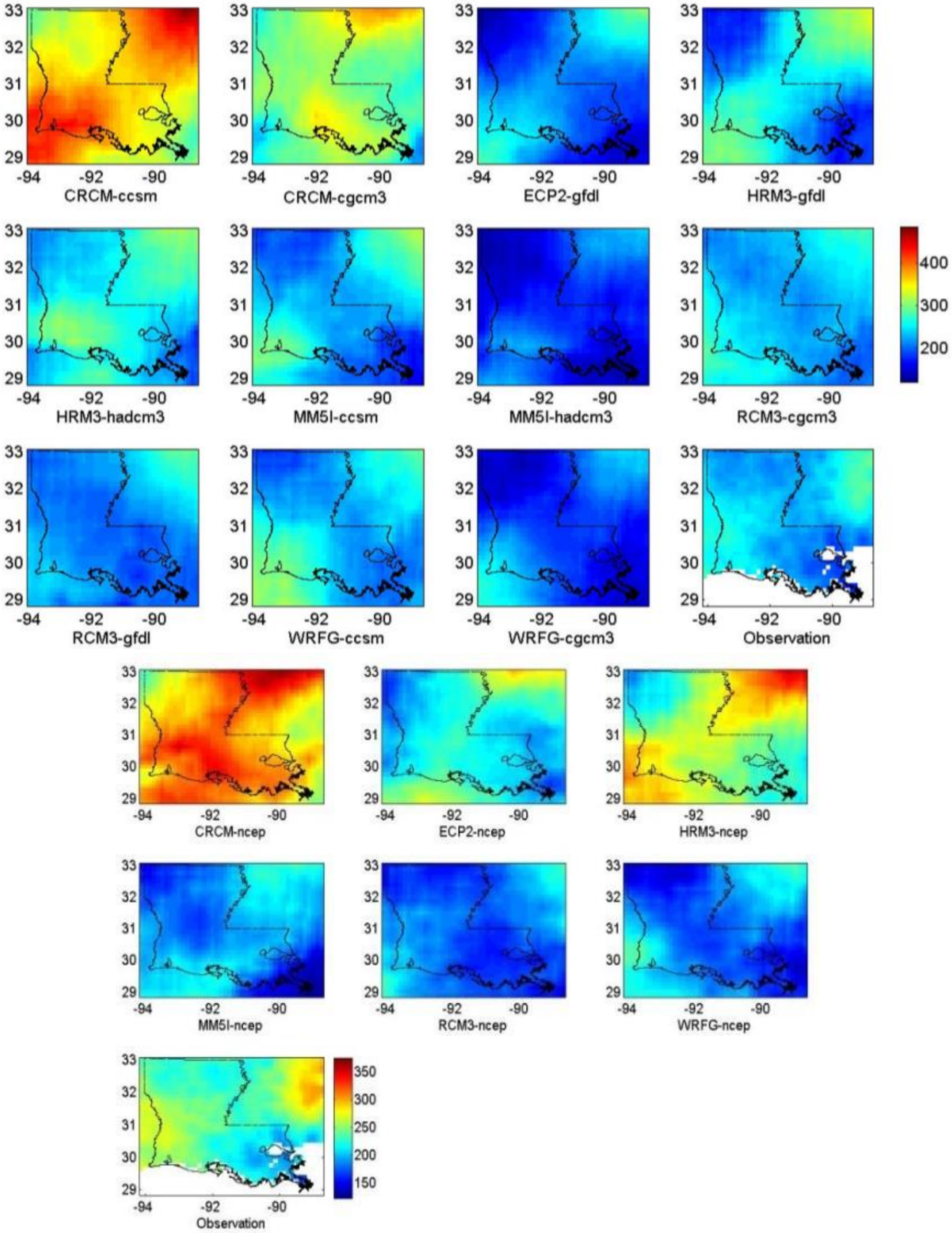


Figure 20 Map of correlation distance (km) for daily precipitation; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

Figure 20 and Figure 21 show the maps of correlation distance for daily and monthly scales respectively. These maps represent the spatial dependence of grid wise precipitation themselves. In these maps, the distance at which the correlation of grid point to grid point corresponds to 0.367 is calculated for daily and monthly scales. All models except CRCM_CCSM, CRCM_CGCM3 are close to observations in a range of 100-300 km for the daily scale. However, most of the NCEP simulations show an overall heterogeneous spatial pattern for the daily scale compared to the observational grids. CRCM_CCSM, CRCM_CGCM3, HRM3_GFDL are the least close to observations for the monthly scale. Others models closely match with observations with a range of 100-600 km. Here, an increase of the maximum range from daily to monthly scale is noticed. CRCM_NCEP and HRM3_NCEP present quite high correlation distance compared to the observations in both the daily and monthly scales.

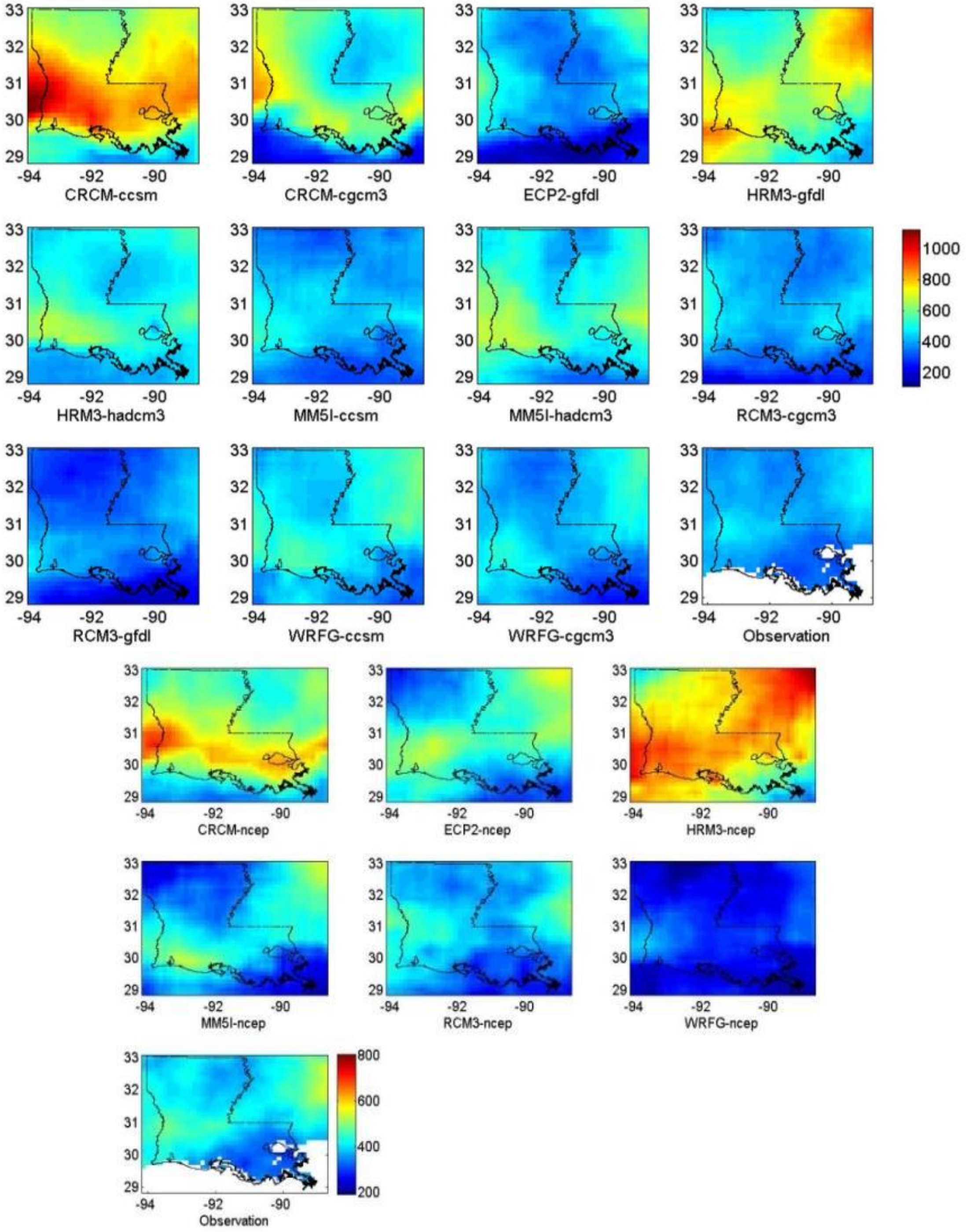
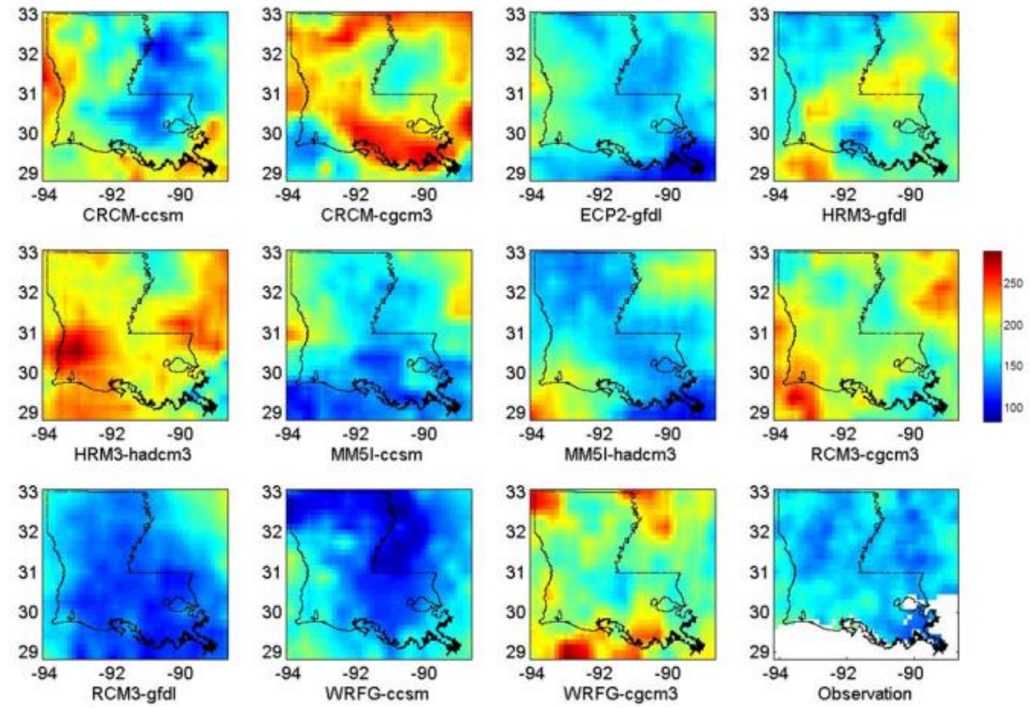
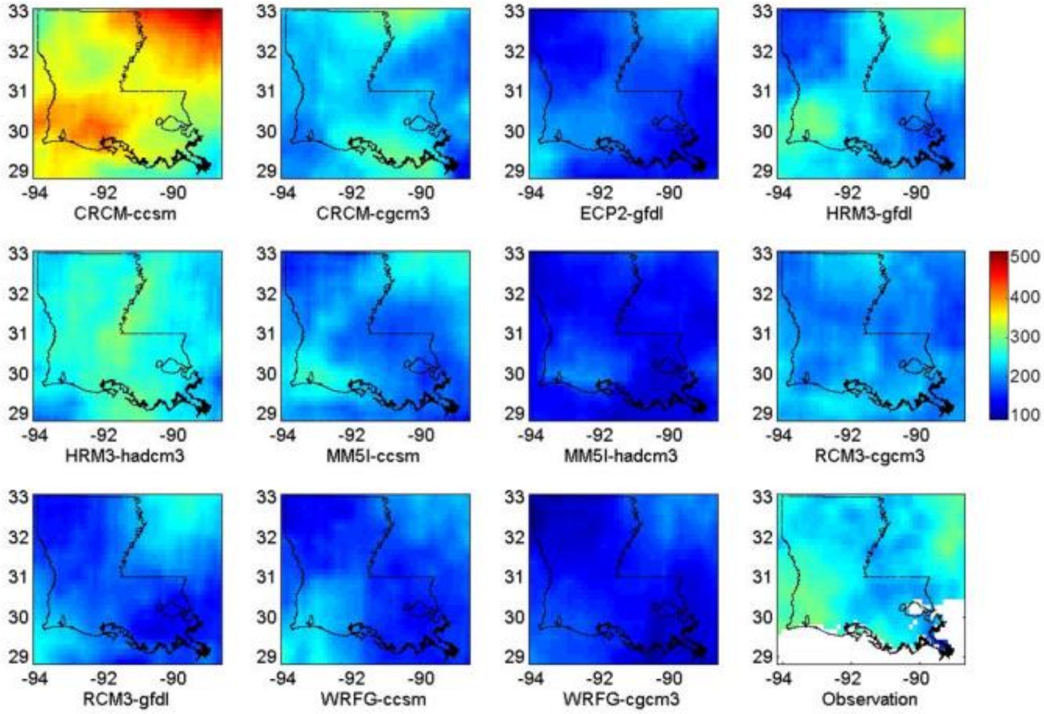


Figure 21 Map of correlation distance (km) for monthly precipitation; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP


33
32
31
30
29
-94
-92
-90
CRCM-ccsm
CRCM-cgcm3
ECP2-gfdl
HRM3-gfdl
HRM3-hadcm3
MM5I-ccsm
MM5I-hadcm3
RCM3-cgcm3
RCM3-gfdl
WRFG-ccsm
WRFG-cgcm3
Observation
250
200
150
100


33
32
31
30
29
-94
-92
-90
CRCM-ccsm
CRCM-cgcm3
ECP2-gfdl
HRM3-gfdl
HRM3-hadcm3
MM5I-ccsm
MM5I-hadcm3
RCM3-cgcm3
RCM3-gfdl
WRFG-ccsm
WRFG-cgcm3
Observation
500
400
300
200
100

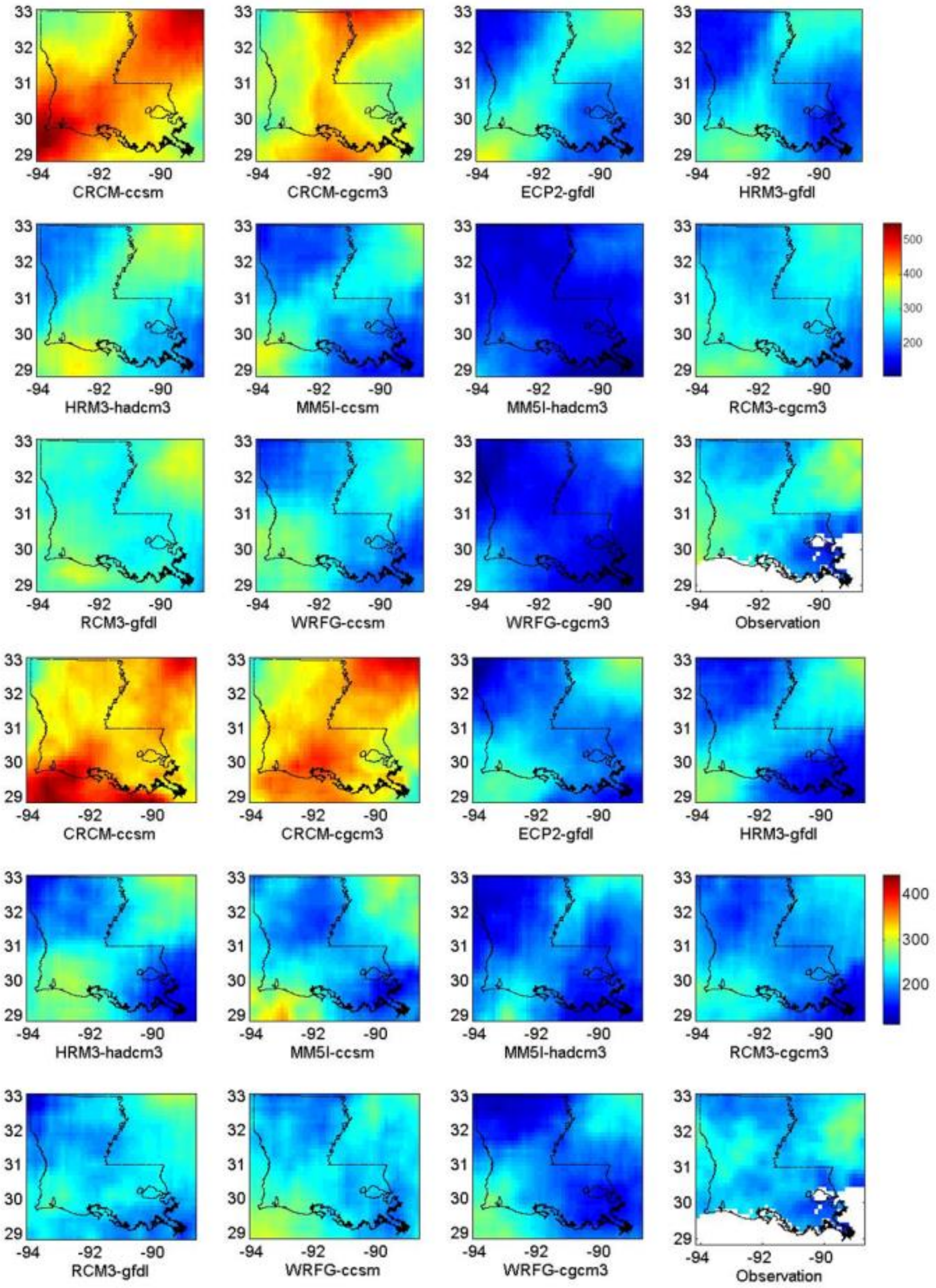
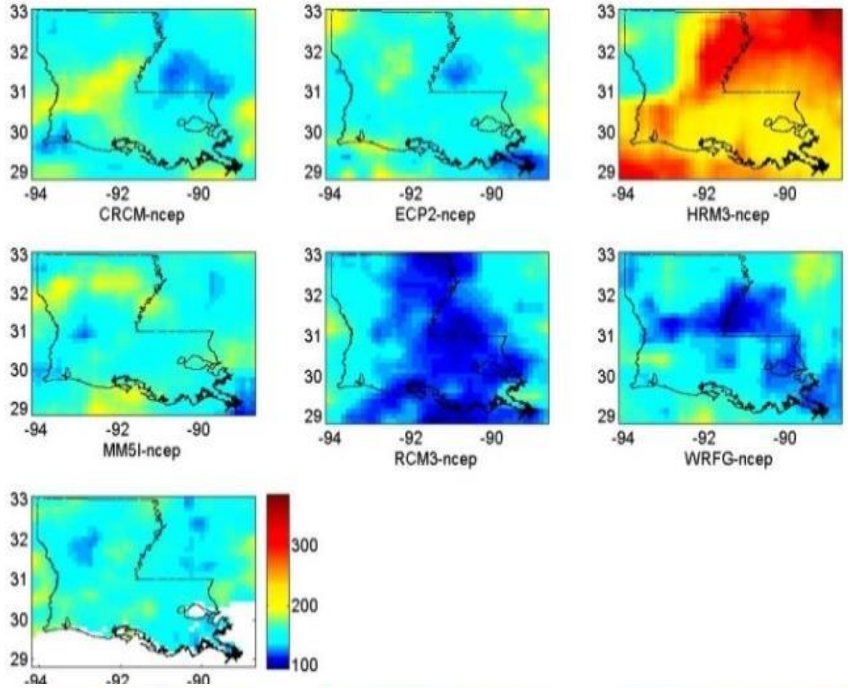


Figure 22 Maps of correlation distance (km) for (a) summer (JJA), (b) fall (SON), (c) winter (DJF), and (d) spring (MAM) precipitation of NARCCAP_RCM-AOGCM simulations

Figure 22 shows the maps of correlation distance for the seasonal scale of the AOGCM driven RCM simulations. For summer, RCM3_GFDL, WRFG_CCSM match with observation having a range from 80 km to 160 km. Higher values belong to CRCM_CGCM3 and HRM3_HadCM3 (about 200-300 km). For fall season, HRM3_HadCM3 is almost similar to observation with a range of 100-300 km whereas CRCM_CCSM shows very high value compared to observation. ECP2_GFDL, MM5I_HadCM3, WRFG_CCSM and WRFG_CGCM3 exhibit comparatively low values than the observation. For winter, all the models except CRCM_CCSM and CRCM_CGCM3 (higher than observation), MM5I_HadCM3 and WRFG_CGCM3 (lower than observation) match with observation. For spring most of the models have a similar range as observation except CRCM_CCSM and CRCM_ CGCM3, which contain higher values.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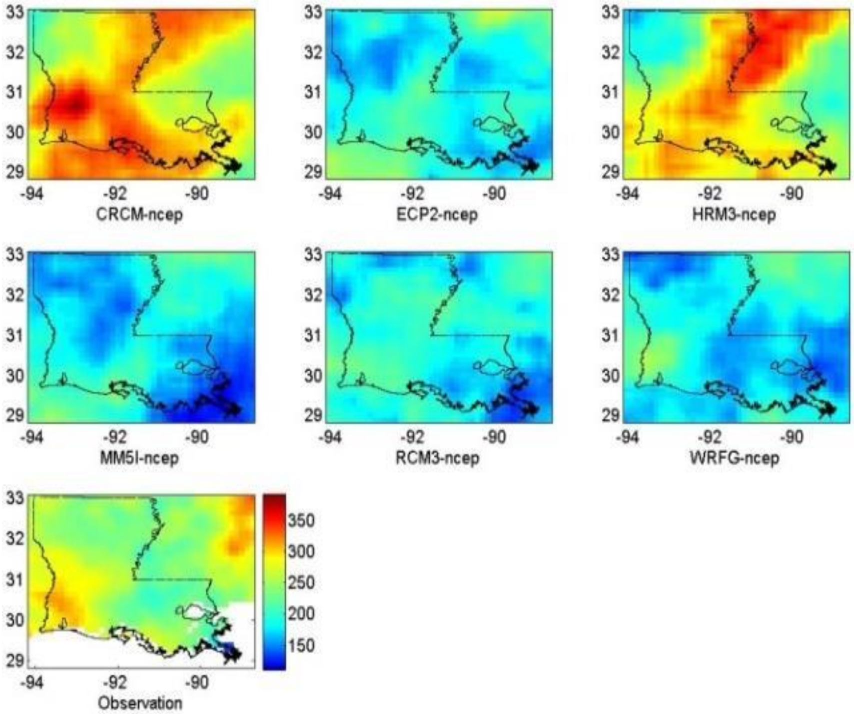
32
31
30
29
-94
-92
-90
CRCM-ncep
ECP2-ncep
HRM3-ncep
MM5I-ncep
RCM3-ncep
WRFG-ncep
300
200
100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32
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29
-94
-92
-90
CRCM-ncep
ECP2-ncep
HRM3-ncep
MM5I-ncep
RCM3-ncep
WRFG-ncep
Observation
350
300
250
200
150

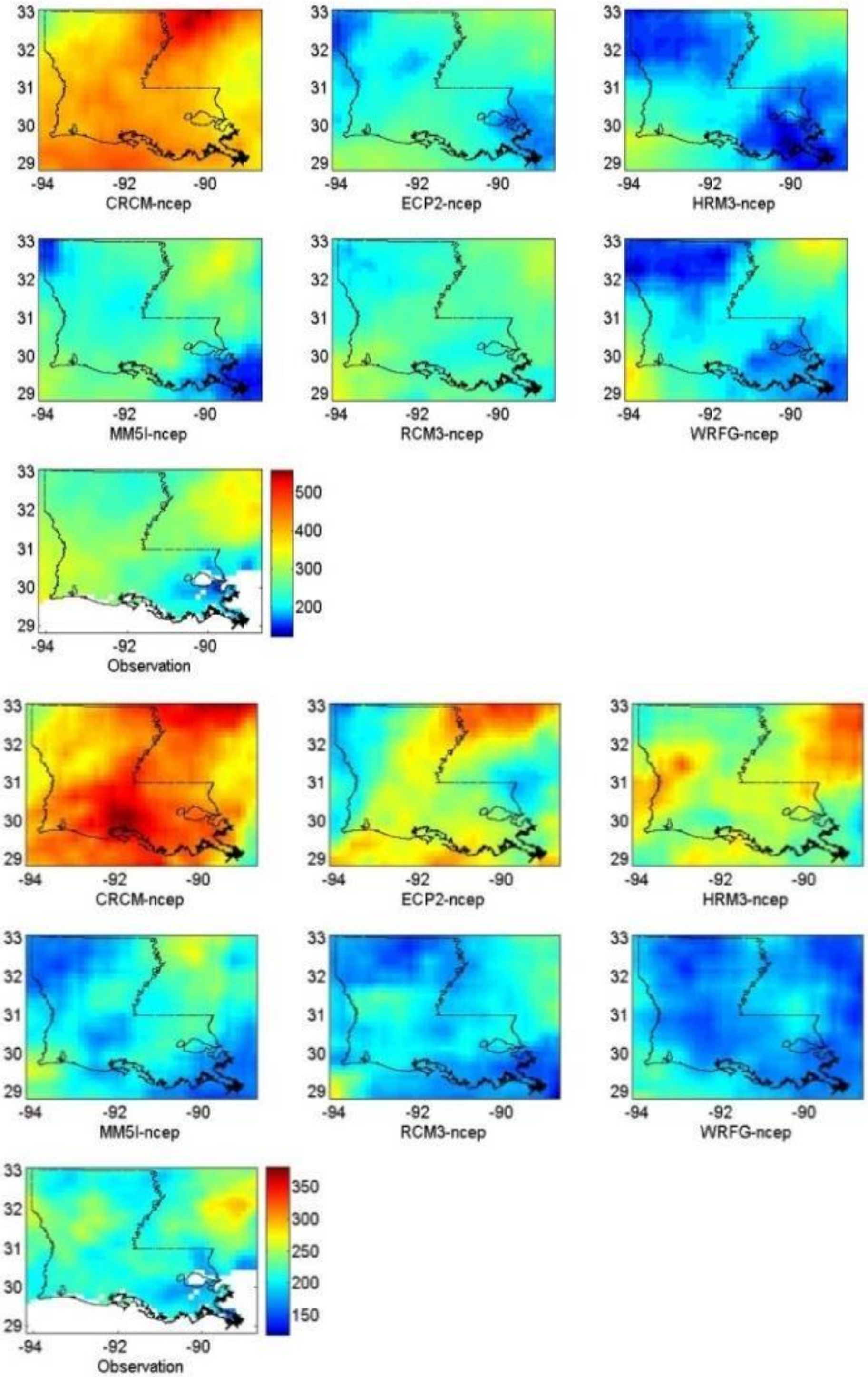


Figure 23 Maps of correlation distance (km) for (a) summer (JJA), (b) fall (SON), (c) winter (DJF), and (d) spring (MAM) precipitation of NARCCAP - NCEP simulations

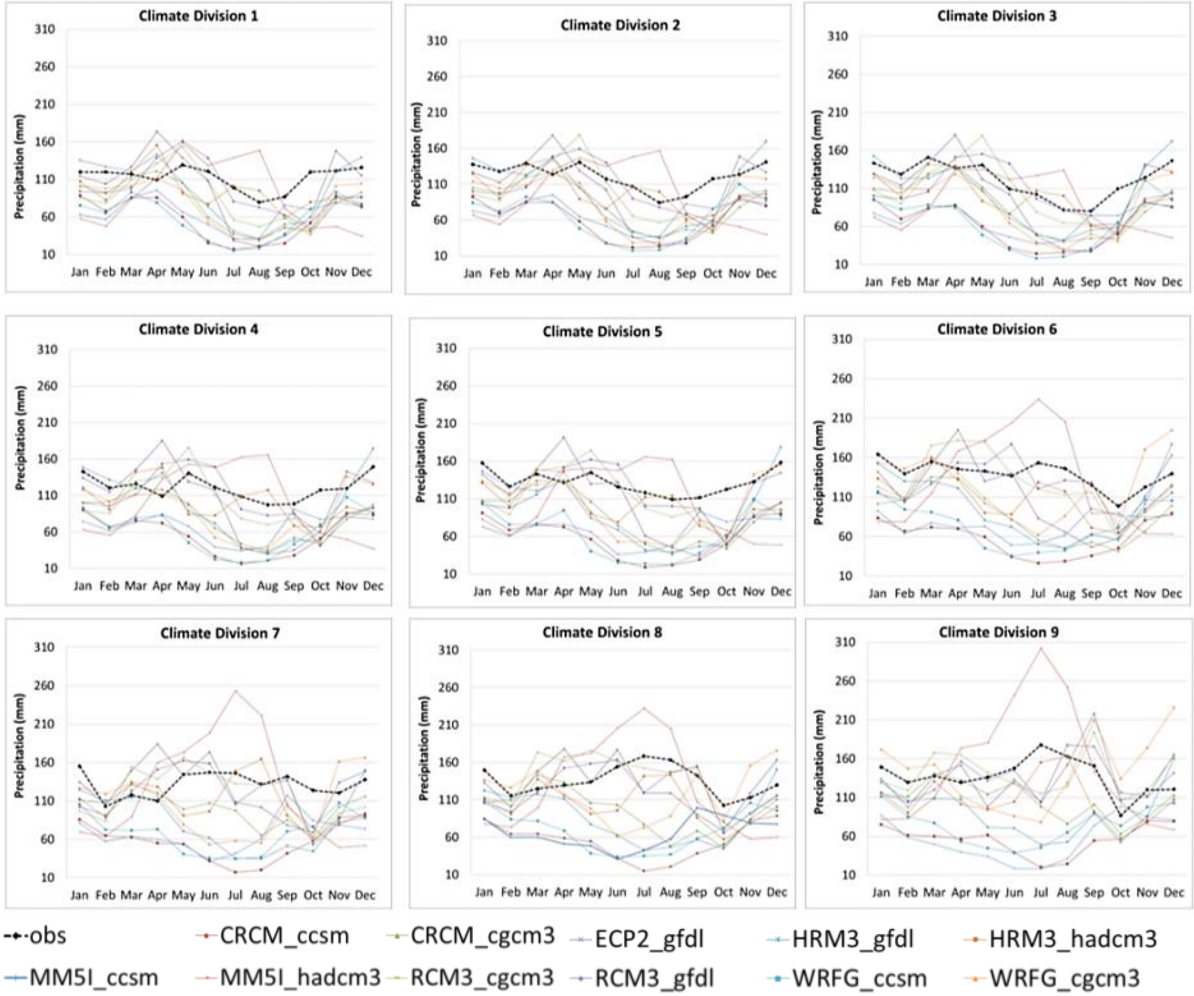
Figure 23 shows the maps of correlation distance for the seasonal scale of the NCEP driven RCM simulations. For summer, HRM3_NCEP has higher values than the observation while RCM3_NCEP has lower values than the observation. The rest of the models almost match with observation. For fall, in general, all the models display more heterogeneous spatial patterns than the observation. CRCM_NCEP and HRM3_NCEP have relatively higher values than the observation. For winter, MM5I_NCEP and RCM3_NCEP closely match with the observed correlation distance range (approximately 200-350 km). CRCM_NCEP shows higher range (approximately 400-500 km) than the observed one. For spring, in general, all the models demonstrate more heterogeneous spatial pattern than the observation. CRCM_NCEP represents quite higher range than the observed one in case of the fall and winter season.

After analyzing Figure 22 and Figure 23, it can be stated that, the map of correlation distance for summer season shows the lowest range of correlation distance (km) compared to other seasons. This means, the specified correlation (0.367) between the grid to grid daily summer precipitations is found within a relatively small boundary (domain) when compared to other seasonal precipitation. So this small boundary indicates that the value of daily summer precipitation is comparatively similar in the grids.

5.3 Precipitation Seasonal Cycles

Next, the models are assessed at the scale of climate divisions (Figure 7). Simulated and observed mean monthly precipitation aggregated according to the 9 climate divisions of Louisiana are presented in Figure 24. The ability of NARCCAP models to reproduce precipitation at climate division level is important to assess how these models may be used to assist, for example, on water management. Monthly climate division wise precipitation averages, observed and simulated, for the nine (9) divisions, can be seen in Figure 24.

From Figure 7 it is found that, climate division 1, 2 and 3 belong to comparatively dry zone and climate division 7, 8 and 9 fall in a relatively wet zone along the coast. And this spatial pattern is well captured by the NARCCAP simulations in Figure 24. As a result, there is an increase of monthly precipitation starting from the climate division 6 and finally the climate division 9 shows the largest precipitation in case of both types of NARCCAP simulations. MM5I_HadCM3 overestimates the July precipitation in all the climate divisions. All the other RCM_AOGCM models generally underestimate monthly precipitation in all climate divisions. Among the 6 NCEP simulations, overall RCM3_NCEP overestimates the observed monthly precipitation in all the climate divisions.


Climate Division 1
Climate Division 2
Climate Division 3
Climate Division 4
Climate Division 5
Climate Division 6
Climate Division 7
Climate Division 8
Climate Division 9
Precipitation (mm)
310
260
210
160
110
60
10
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
obs
CRCM_ccsm
CRCM_cgcm3
ECP2_gfdl
HRM3_gfdl
HRM3_hadcm3
MM5I_ccsm
MM5I_hadcm3
RCM3_cgcm3
RCM3_gfdl
WRFG_ccsm
WRFG_cgcm3

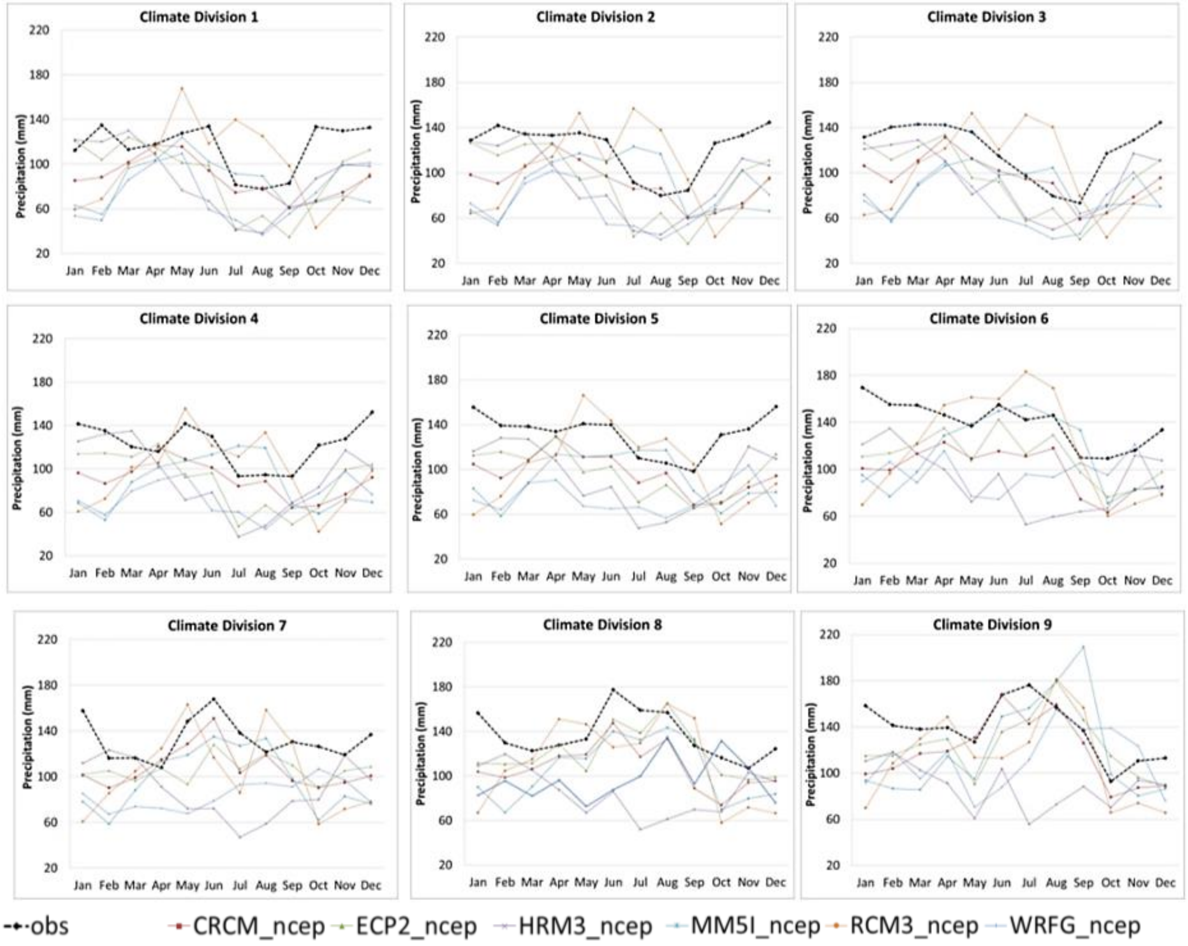
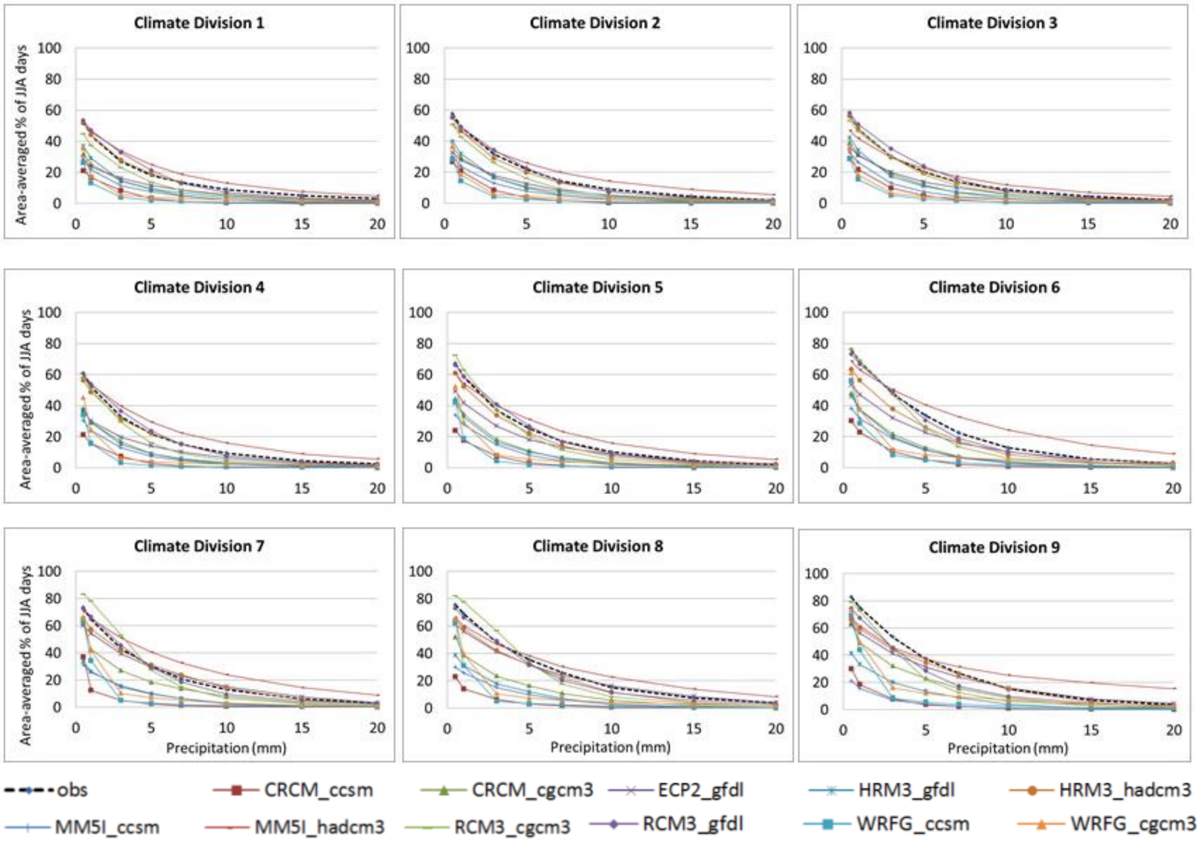


Figure 24 Mean monthly precipitation for each climate division; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP


Climate Division 1
Climate Division 2
Climate Division 3
Climate Division 4
Climate Division 5
Climate Division 6
Climate Division 7
Climate Division 8
Climate Division 9
Area-averaged % of JJA days
100
80
60
40
20
0
0
5
10
15
20
Precipitation (mm)
obs
CRCM_ccsm
CRCM_cgcm3
ECP2_gfdl
HRM3_gfdl
HRM3_hadcm3
MM5I_ccsm
MM5I_hadcm3
RCM3_cgcm3
RCM3_gfdl
WRFG_ccsm
WRFG_cgcm3

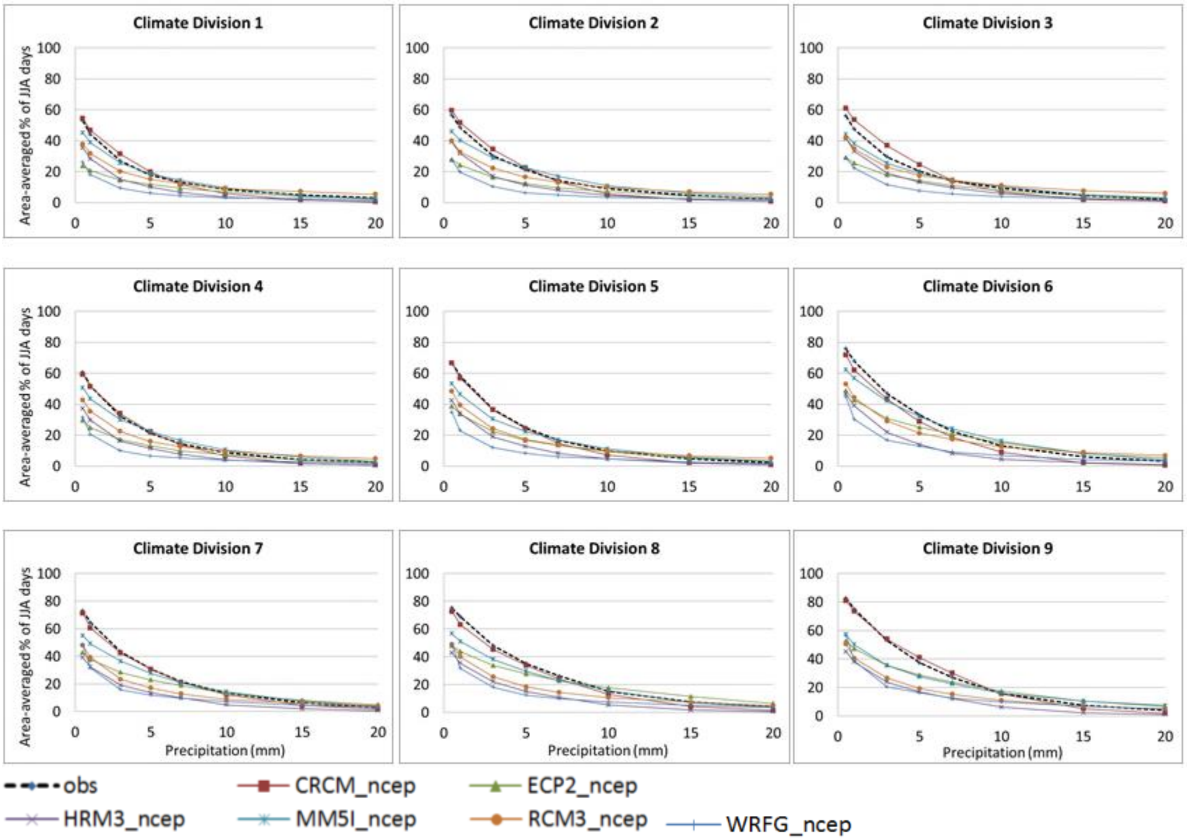
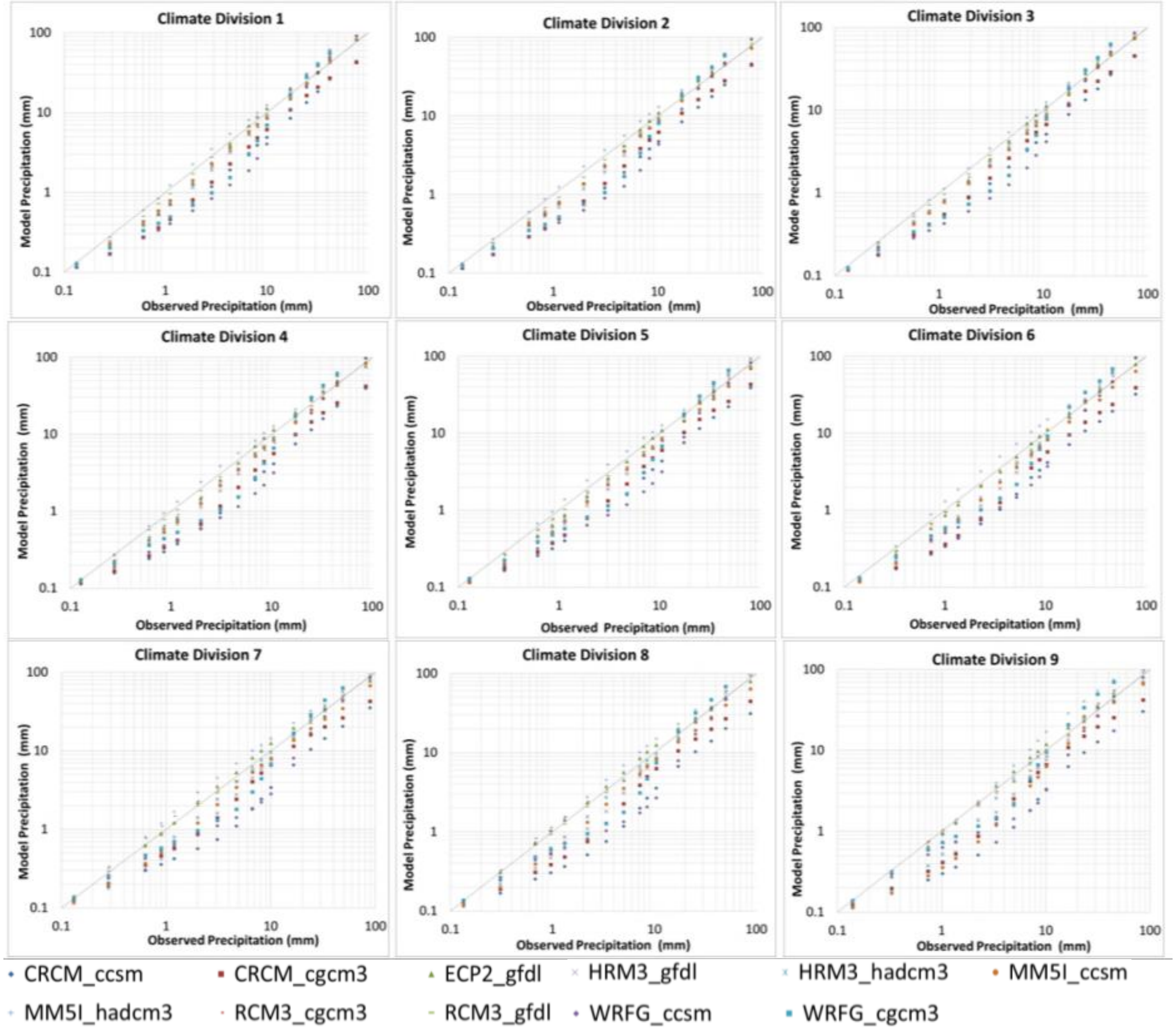


Figure 25 Area-averaged percentage of JJA days with precipitation exceeding the threshold indicated on the x-axis (mm); [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

Next, we calculated the average percentage of days in JJA with precipitation exceeding thresholds of 0.5, 1, 3, 5, 7, 10, 15, and 20 mm for the models and observation. This calculation was done to investigate whether excess precipitation in the downscaled models occur due to an increased number of rainy days or an increased frequency of intense precipitation events. For all nine climate divisions of the domain, the models overall underestimate the probability of precipitation exceeding all the threshold values in case of both RCM_AOGCM and RCM_NCEP combinations. MM5I_HadCM3 overestimates the observed value in all the climate divisions (Figure 25). Among the NCEP simulations, only CRCM_NCEP behaves comparatively different: it overestimates the observations from climate division 1 to 3, then almost merges with the line of observation in climate division 4 and 5, after that it starts underestimation from climate division 6 to 8 and finally it again starts overestimation in climate division 9.

A more detailed understanding of the skills of RCMs in reproducing the precipitation regimes is given by the distribution of the daily precipitation quantiles for wet days (> 0.1 mm), in a logarithm scale. Figure 26 shows the precipitation quantiles in the 9 climate divisions pooling together all the grid points. All the models underestimate the observed quantiles bellow quantile 20, with a tendency to overestimate above quantile 20. Wet days may be defined as days with daily precipitation above 0.1 mm (including very light precipitation) or above 1 mm (including light precipitation) (Soares et al. 2012). In Figure 27, the relative difference of wet days between models and observations, for the 9 climate divisions, indicates that models RCM3_CGCM3, RCM3_GFDL, CRCM_NCEP underestimate (below the line of 100%) the frequency of light precipitation, with a tendency to slightly overestimate starting from climate division 7. In general, all the RCM and NCEP simulations except RCM3_CGCM3, RCM3_GFDL and CRCM_NCEP underestimate the observed percentage of wet days


Climate Division 1
Climate Division 2
Climate Division 3
Climate Division 4
Climate Division 5
Climate Division 6
Climate Division 7
Climate Division 8
Climate Division 9
Model Precipitation (mm)
Mode Precipitation (mm)
Observed Precipitation (mm)
0.1
1
10
100
CRCM_ccsm
CRCM_cgcm3
ECP2_gfdl
HRM3_gfdl
HRM3_hadcm3
MM5I_ccsm
MM5I_hadcm3
RCM3_cgcm3
RCM3_gfdl
WRFG_ccsm
WRFG_cgcm3

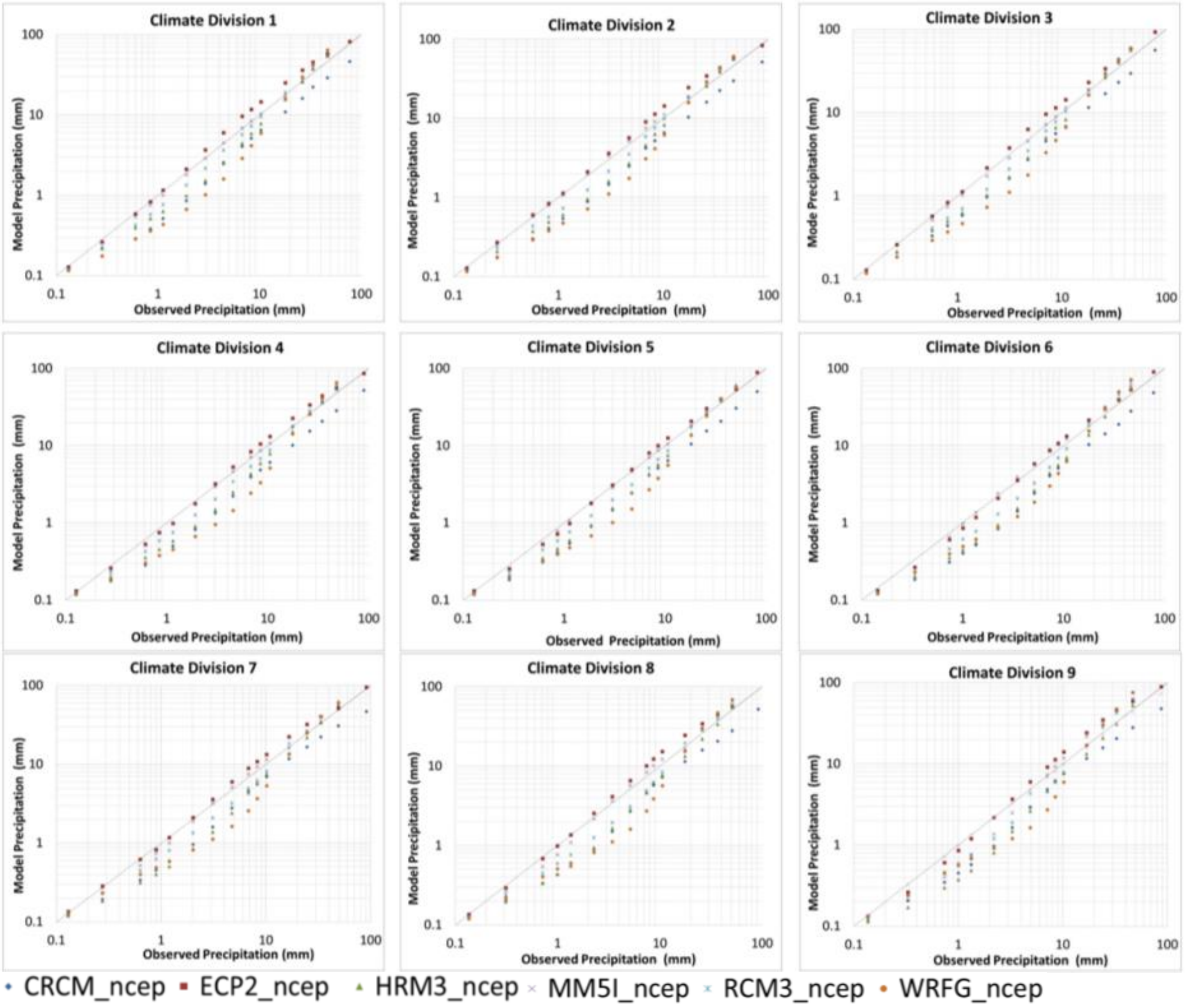


Figure 26 Quantiles of daily precipitation in wet days (>0.1 mm); [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

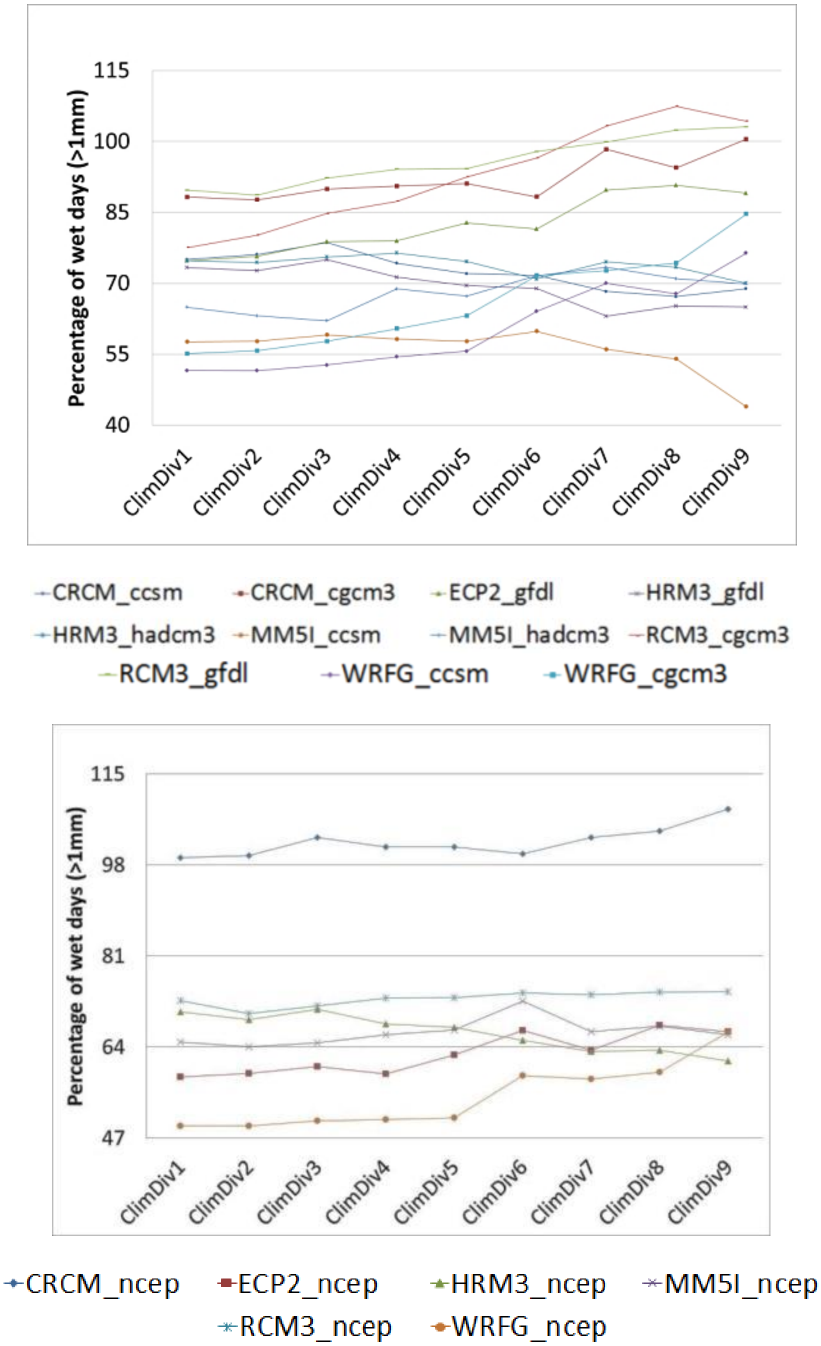


Figure 27 Percentage of model relative to observation of days with precipitation >1 mm; [top] 11 RCM-AOGCM and [bottom] 6 RCM-NCEP

5.4 Impact on Water Level and Salinity

Next, let us consider the effect of NARCCAP precipitation on the hydrologic regime in the Chenier Plain by examining the predictions of the Eco-Hydrology model over the 10-year simulation period (1990-1999) in terms of two direct output variables:

1. Daily Water Level
2. Daily Salinity

Figure 9 presents the maps of the average daily precipitation over the 30 years (1970-1999) and the 20 years (1980-1999) for the RCM-AOGCM and RCM-NCEP simulations respectively, while Figure 28 presents the maps of the ratio of model to observation for the average daily precipitation over the 10 years (1990-1999) for both simulations. But the pattern is similar, where CRCM_CCSM, MM5I_CCSM, HRM3_NCEP and WRFG_NCEP belong to lower average daily precipitation range. The more the ratio of model to observation is closer to 1 the more the better representation of observed average daily precipitation by the model. When the ratio is less than 1 then is means the model underestimates the observed average daily precipitation. When the ratio is greater than 1 then it means the model overestimates the observed average daily precipitation. Among the RCM-AOGCM simulations, the ratio of average daily precipitation for CRCM_CCSM, MM5I_CCSM and the other 9 models are approximately 0.42 to 0.31 (too low) and 0.65 to 1.3 respectively. In case of RCM-NCEP simulations, the ratio of average daily precipitation for HRM3_NCEP, WRFG_NCEP and the other 4 models are approximately 0.51 to 0.68 (too low) and 0.73 to 1.00 respectively.

Similarly, Figure 11 presents the maps of the standard deviation of daily precipitation over the 30 years (1970-1999) and the 20 years (1980-1999) for the RCM-AOGCM and RCM-NCEP simulations respectively while, Figure 29 presents the maps of the ratio of model to observation for standard deviation of daily precipitation over the 10 years (1990-1999) for both simulations. But the pattern is similar, where CRCM_CCSM, CRCM_CGCM3, MM5I_CCSM, and CRCM_NCEP belong to lower standard deviation of daily precipitation range. Among the RCM-AOGCM simulations, the ratio of standard deviation of daily precipitation for CRCM_CCSM, CRCM_CGCM3, MM5I_CCSM and the other 8 models are approximately 0.27 to 0.58 (too low) and 0.70 to 1.5 respectively. In case of RCM-NCEP simulations, the ratio of standard deviation of daily precipitation for CRCM_NCEP, HRM3_NCEP and the other 4 models are approximately 0.55 to 0.95 and 1.00 to 1.50 respectively.

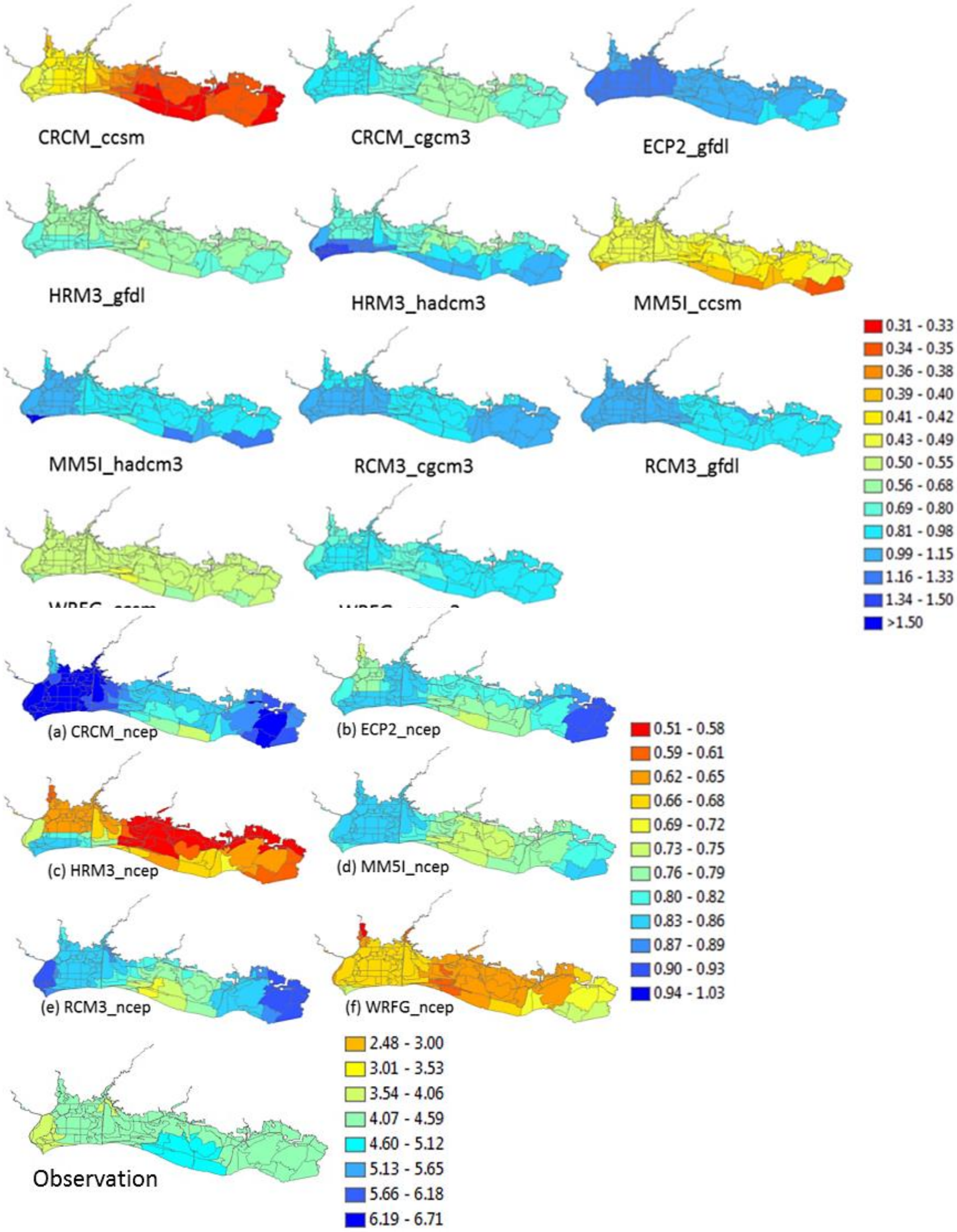


Figure 28 Bottom panel: Average daily precipitation (mm) based on observation. Panels (top & middle): ratios of average daily precipitation simulated using RCM-AOGCM & RCM-NCEP models relative to observation (simulation period is 1990-1999)

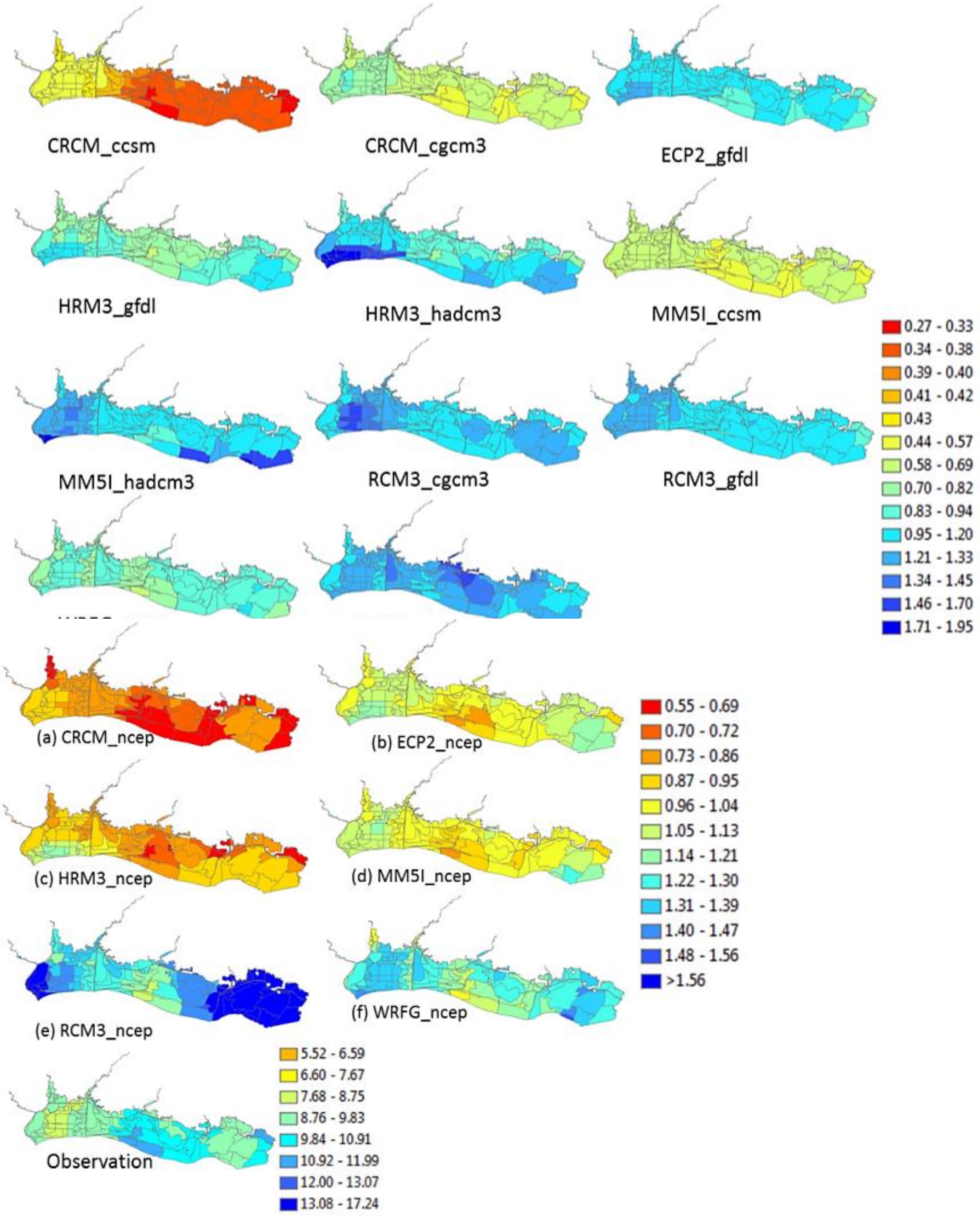


Figure 29 Bottom panel: Standard deviation of daily precipitation (mm) based on observation. Panels (top & middle): ratios of standard deviation of daily precipitation simulated using RCM-AOGCM & RCM-NCEP models relative to observation (simulation period is 1990-1999)

The more the ratio of model to observation is closer to 1 the better representation of observed average daily water level by the model. In Figure 30, among the RCM-AOGCM simulations, the ratio of average daily water level for CRCM_CCSM, MM5I_CCSM, WRFG_CCSM and the other 8 models are approximately 0.46 to 0.93 and 0.87 to 1.05 respectively. In case of RCM-NCEP simulations, the ratio of average daily water level for all the 6 models is approximately 0.88 to 0.99. In Figure 31, among the RCM-AOGCM simulations, the ratio of standard deviation of daily water level for CRCM_CCSM, MM5I_CCSM, MM5I_HadCM3, WRFG_CCSM, RCM3_GFDL and the other 6 models are approximately 0.36 to 0.88 and 0.89 to 1.8 respectively. In case of RCM-NCEP simulations, the ratio of standard deviation of daily water level for all the 6 models is approximately 0.58 to 1.04.

From Figure 30 and Figure 31, in general, a common trend is found in all the simulations for both RCM-AOGCM and RCM-NCEP. The ratio of model to observation for both the average and the standard deviation of daily water level are comparatively low in the area between Calcasieu Lake and White Lake than the remaining study domain.

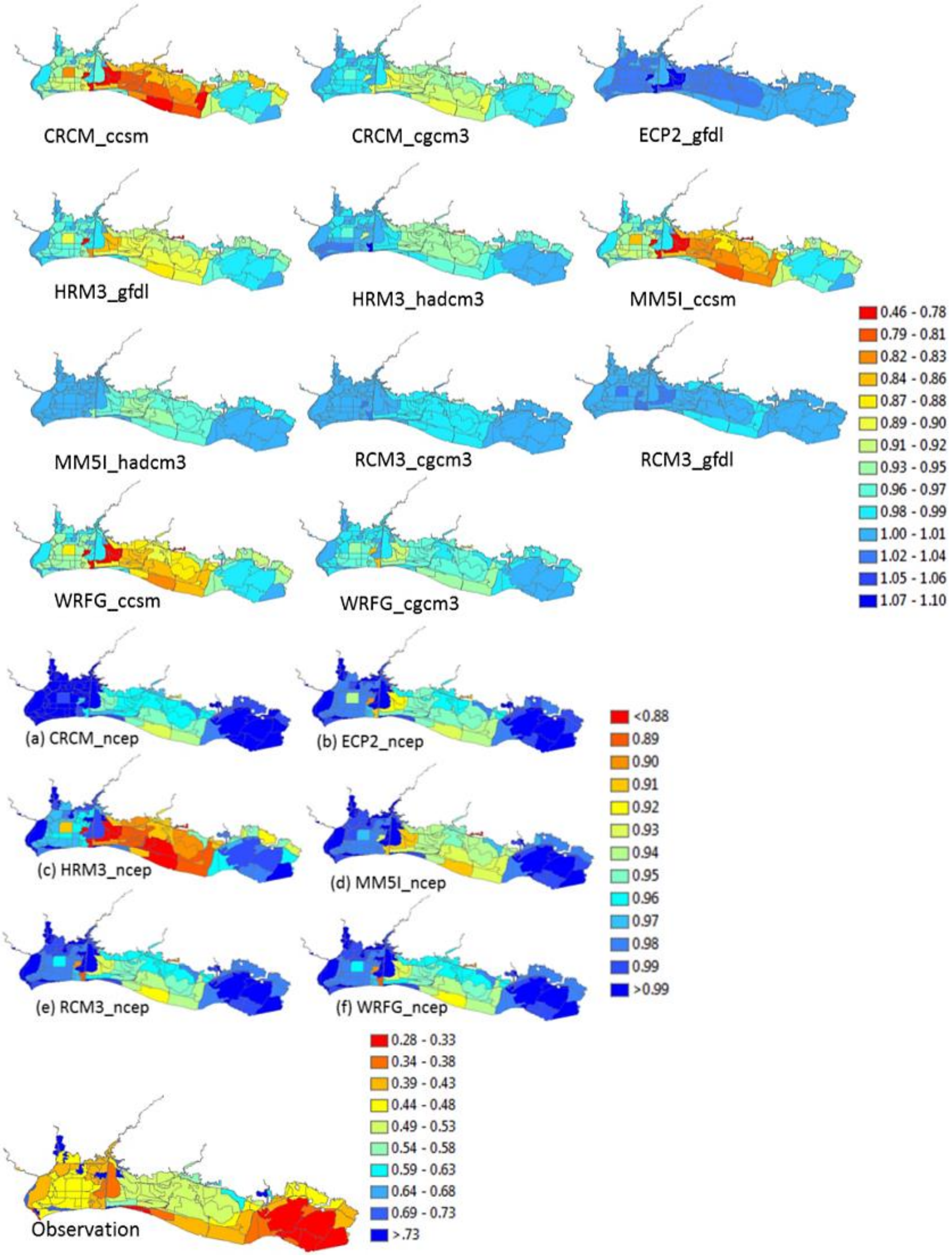


Figure 30 Bottom panel: Average daily water level (m) based on observation. Panels (top & middle): ratios of average daily water level simulated using RCM-AOGCM & RCM-NCEP models relative to observation (simulation period is 1990-1999)

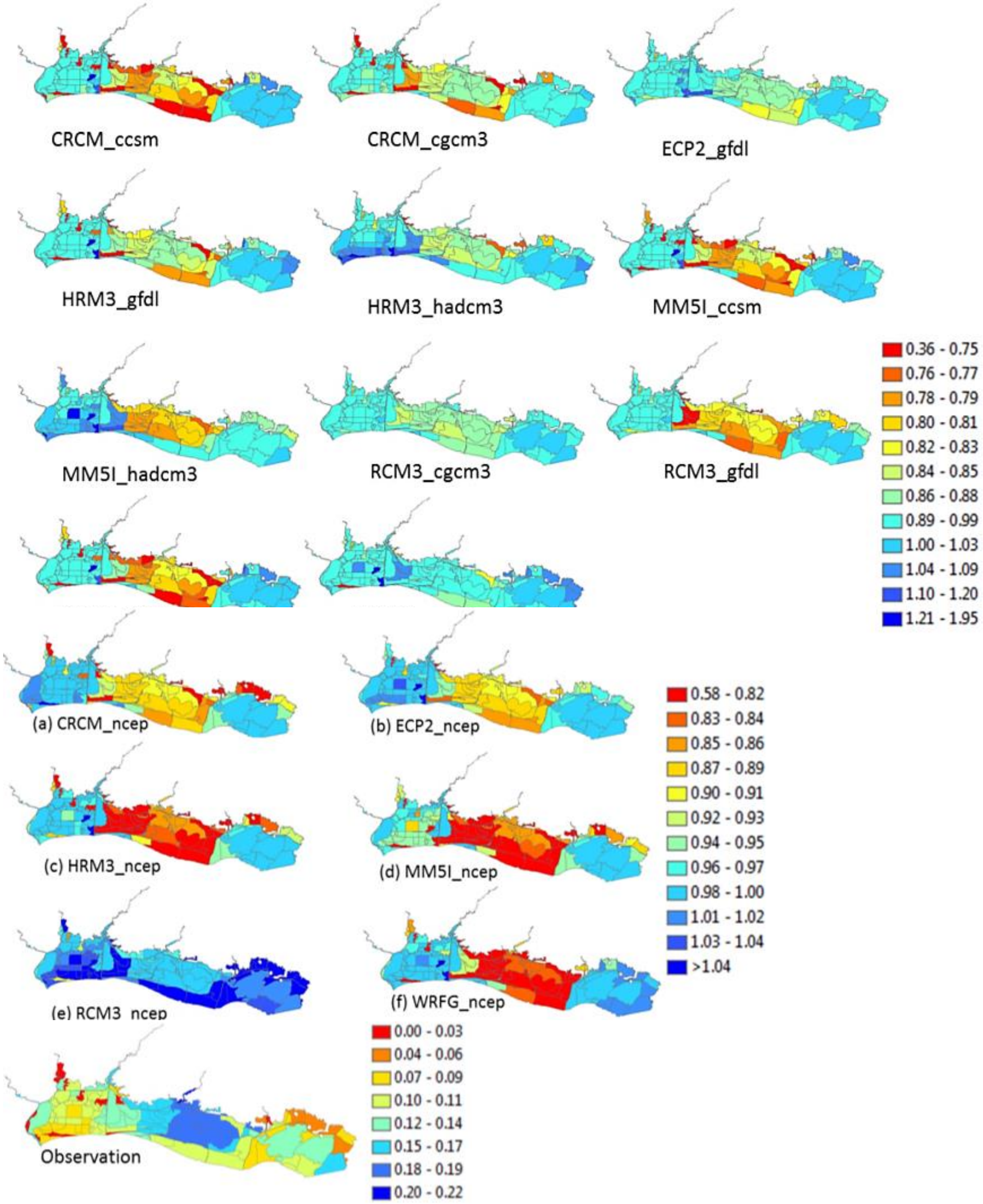


Figure 31 Bottom panel: Standard deviation of daily water level (ppt) based on observation. Panels (top & middle): ratios of standard deviation of daily water level simulated using RCM-AOGCM & RCM-NCEP models relative to observation (simulation period is 1990-1999)

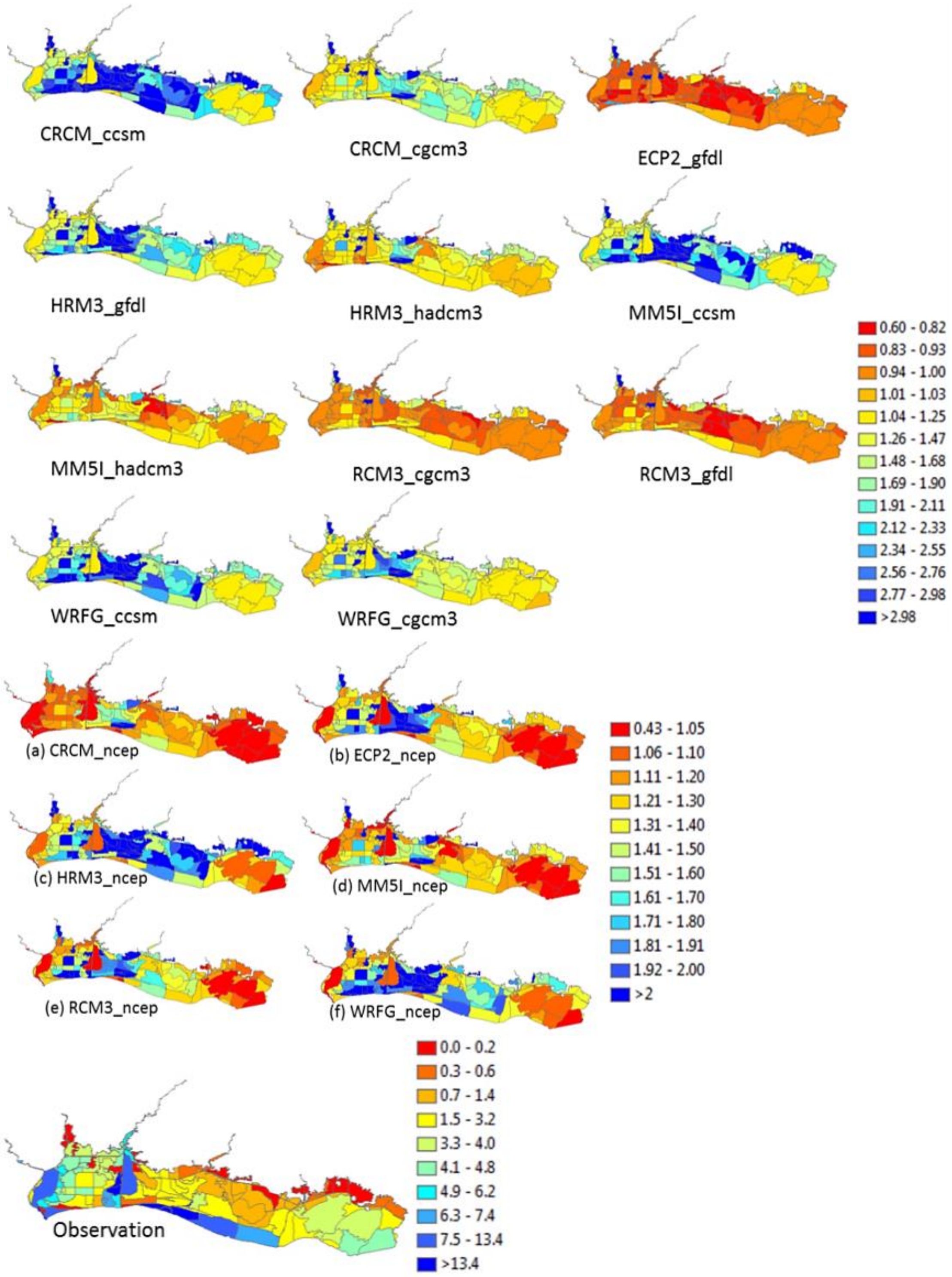


Figure 32 Bottom panel: Average daily salinity (ppt) based on observation. Panels (top & middle): ratios of average daily salinity simulated using RCM-AOGCM & RCM-NCEP models relative to observation (simulation period is 1990-1999)

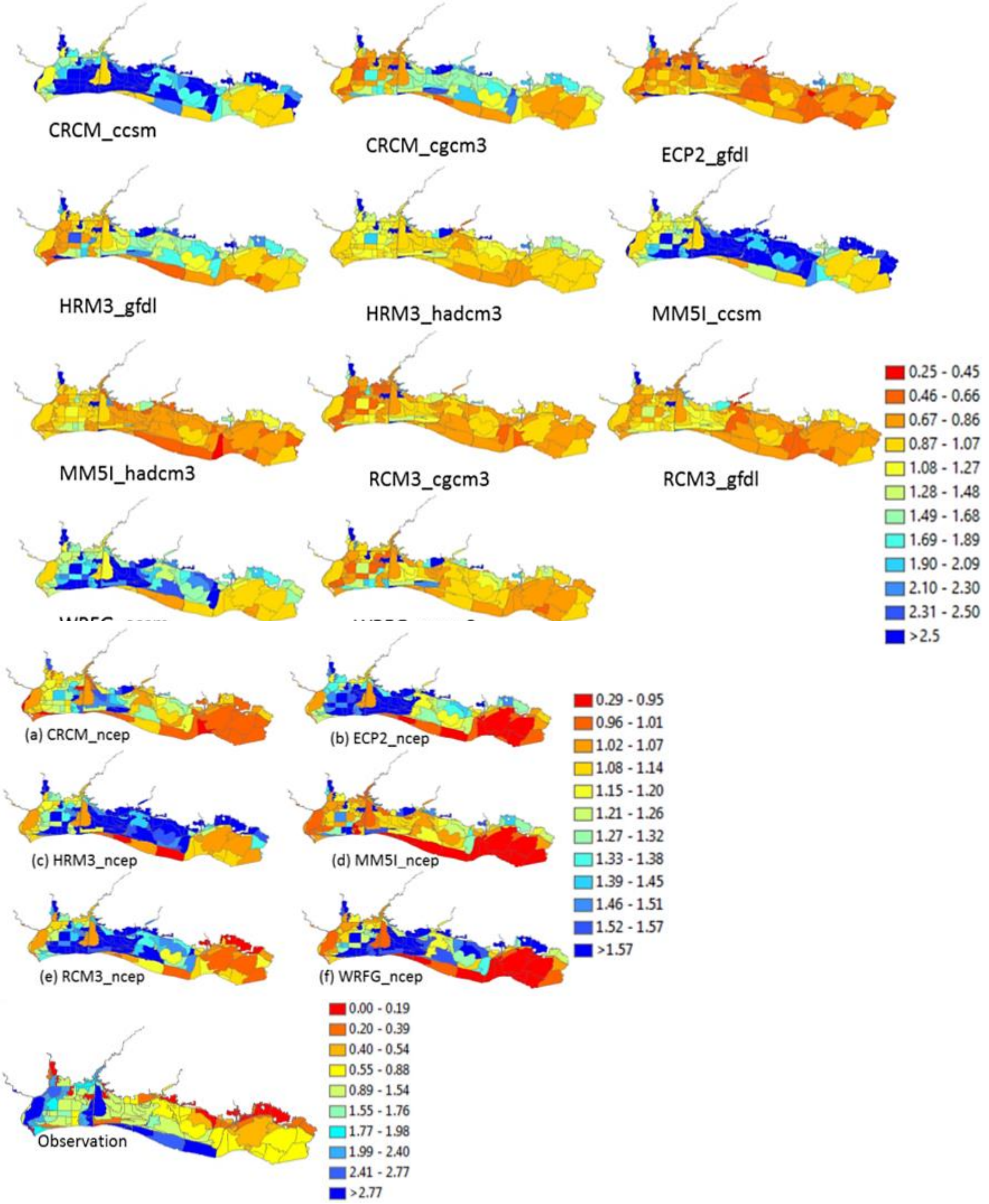


Figure 33 Bottom panel: Standard deviation of daily salinity (ppt) based on observation. Panels (top & middle): ratios of standard deviation of daily salinity simulated using RCM-AOGCM & RCM-NCEP models relative to observation (simulation period is 1990-1999)

The more the ratio of model to observation is closer to 1 the better representation of observed average daily salinity by the model. In Figure 32, among the RCM-AOGCM simulations, the ratio of average daily salinity for ECP2_GFDL, MM5I_HadCM3, RCM3_CGCM3, RCM3_GFDL and the other 7 models are approximately 0.60 to 1.03 and 1.04 to 2.7 respectively. In case of RCM-NCEP simulations, the ratio of average daily salinity for all the 6 models is approximately 0.43 to 1.9. In Figure 33, among the RCM-AOGCM simulations, the ratio of standard deviation of daily salinity for CRCM_CCSM, MM5I_CCSM, WRFG_CCSM and the other 8 models are approximately 0.87 to 2.4 and 0.25 to 1.27 respectively. In case of RCM-NCEP simulations, the ratio of standard deviation of daily salinity for all the 6 models is approximately 0.29 to 1.50.

Since water level and salinity depend on the precipitation quantity, the maps of ratio of model to observation for average and standard deviation of these two variables are produced to see how they respond to the different precipitation quantity over the spatial domain compared to observation. From Figure 30 and Figure 31, it is understood that the average and standard deviation of water level remain quite similar in all the models and observation. Water level is relatively low along the coast in all the models and observation. From Figure 32, it is seen that the average daily salinity is the same for all the models and observation but the standard deviation of daily salinity (Figure 33) in all the models vary from the observation. Since the water level is low along the coast, as a result the salinity concentration is high along the coast. From Figure 29 and Figure 33, it can be stated that, where the ratio of model to observation for the standard deviation of daily precipitation is low there the ratio of model to observation for standard deviation of daily salinity becomes high particularly the case of CRCM_CCSM and MM5I_CCSM simulations clarify this scenario sharply.

CHAPTER 6 CONCLUSIONS

6.1 Conclusion

Climate simulations and projections of future climate change scenarios are highly sought for impact assessment and resource management applications. At present, global-scale Atmosphere-Ocean General Circulation Models (AOGCMs or GCMs) are the principal tools for investigating potential future climate changes on global to regional scales. However, GCMs do not provide climate simulations at scales over which impact assessment are most desired. In order to make up-to-date judgments in response to future climate change, researchers, policy-makers and the public need climate projections at the scale of tens of kilometers, rather than the scales provided by GCMs. The North American Regional Climate Change Assessment Program (NARCCAP) is such a recent effort that addresses this necessity.

As the climate models contain various levels of uncertainty, it is essential to evaluate the performance their representativeness of regional climate characteristics. This study performed an evaluation analysis of the NARCCAP dataset by examining hindcast, historical simulations against actual precipitation observations over the same historical period. This type of evaluation analysis was implemented for a period that covers 20 to 30 years, depending on joint availability of both the observational and the NARCCAP datasets. The evaluation also included an analysis where the hindcast NARCCAP simulations were used to drive a hydrologic model of a regional ecosystem (coastal Louisiana). The hydrologic outputs of the model were used to judge whether the NARCCAP simulations can reproduce some of the basic hydrologic characteristics within the selected region. The Application analysis was implemented for a period that covers 10 years (1990-1999) that overlap with the simulation period of the hydrologic model. The hydrology model provides simulations of various eco-hydrological variables, with the focus herein on salinity and water level.

The following set of conclusions can be made based on the results of this study:

1) The NARCCAP simulations, driven by NCEP or by the GCMs, are characterized with systematic biases when compared against actual observations. The biases vary in magnitudes and patterns by season (winter or summer) and for the different combinations of the NARCCAP models.
2) Systematic biases in NARCCAP simulations are probably the result of model deficiencies in simulating precipitation physical processes; therefore, a bias correction scheme is needed to improve the performance of such models and before they can be used in any subsequent hydrologic analysis.
3) The NARCCAP models showed mixed performance in terms of re-producing the temporal variability of precipitation over Louisiana. Some models were able to show standard deviations that are comparable to observations; however, some of the models resulted in simulations that are much smoother and less variable than the observations. Because winter precipitation is less variable than the summer, the simulations could capture the standard deviation of daily winter precipitation better than that of summer.
4) The correlation distance was used as a measure of the spatial dependence in the NARCCAP downscaled precipitation simulations and how they compare to

observations. Except for few models, the NARCCAP simulations showed correlation distances that are comparable to the observations at most temporal scales (daily, monthly or seasonal). This indicates the ability of the NARCCAP models to represent spatial variability in precipitation over Louisiana.

5) The study indicated that, overall, NARCCAP regional models can properly simulate the seasonal cycle of precipitation within different climate divisions in Louisiana. Most models were able to reproduce both the timing and amplitude of the seasonal cycle of precipitation in each of the nine climate divisions.
6) From this study it is clear that the different regional climate models differ in how they represent climate processes. Moreover, there are important differences among RCMs in how they interact with the specific GCMs that provide their boundary conditions. The results didn’t indicate the presence of a certain model as being the “best” RCM-GCM combination.

   The biases present in the NARCCAP precipitation fields have led into corresponding biases and pronounced variability in the hydrologic simulations of water level and salinity in the study area. Such biases are alarming since they may undermine the utility of the models for regional applications.

The above findings are the main contributions of this study for the future users.

6.2 Future Work

Based on the results of the current study, a number of follow-up research questions can be proposed for future investigations:

1) The most difficulty the study faced was to pre-process the downloaded precipitation data from the official NARCCAP website. The reason behind this is the heterogeneous coordinate system, time step, and availability of data for the different RCM and GCM of NARCCAP. Since the reliability of the results depends upon the accuracy of the selected data, special attention should be given to the pre-processing of data by applying several verification approaches. In the current study several verification approaches have been applied for the accuracy of the output, for example after the completion of processing of each model dataset (either in NetCDF format or ASCII format), random precipitation data was selected for different time period and location, then that particular value was calculated manually and verified with the processed value.
2) A viable approach to reducing the systematic biases in NARCCAP simulations is to apply a weighting scheme. Such a scheme can result in a considerable decrease in magnitude and percent area containing significant bias in all seasons for precipitation. Weights can be applied at each 50 km grid cell over the study area, or in a more regional sense. Additional weighting criterion can be based on model's ability to match the probability density function (pdf) of the observations. The weights can be applied to the present-day NARCCAP output in order to inform and evaluate future change in precipitation.
3) The current study used the observation data Obs4MIPs for the simplicity of the analysis (this observational data has been used in one of our previous studies, so it is was ready to use for analysis). The NARCCAP performs all their research work based on UDEL (University of Delaware) observed data. So in future the current study can

be done based on the observed data provided by UDEL in order to examine if the model performance can improve compared to the present state.

4) The spatial resolution of NARCCAP dataset is converted from 0.5° to 1/8$^{\text{th}\circ}$ to make it compatible to the spatial resolution of observation. In future, this approach can be avoided and the observation with a spatial resolution similar to the NARCCAP models can be used for the study to maintain the original model resolution.
5) In future the current work can be combined with the focus on evapotranspiration along with the precipitation, because evapotranspiration/evaporation is another key factor affecting ecosystem hydrology.

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ABSTRACT

In order to make informed decisions in response to future climate change, researchers, policy-makers, and the public need climate projections at the scale of few kilometers, rather than the scales provided by Global Climate Models. The North American Regional Climate Change Assessment Program (NARCCAP) is such a recent effort that addresses this necessity. As the climate models contain various levels of uncertainty, it is essential to evaluate the performance of such models and their representativeness of regional climate characteristics. When assessing climate change impacts, precipitation is a crucial variable, due to its direct influence on many aspects of our natural-human ecosystems such as freshwater resources, agriculture and energy production, and health and infrastructure. The current study performs an evaluation analysis of precipitation simulations produced by a set of dynamically downscaled climate models provided by the NARCCAP program. The Assessment analysis is implemented for a period that covers 20 to 30 years (1970-1999), depending on joint availability of both the observational and the NARCCAP datasets. In addition to direct comparison versus observations, the hindcast NARCCAP simulations are used within a hydrologic modeling analysis for a regional ecosystem in coastal Louisiana (Chenier Plain). The study concludes the NARCCAP simulations have systematic biases in representing average precipitation amounts, but are successful at capturing some of the

characteristics on spatial and temporal variability. The study also reveals the effect of precipitation on salinity concentrations in the Chenier Plain as a result of using different precipitation forcing fields. In the future, special efforts should be made to reduce biases in the NARCCAP simulations, which can then lead to a better presentation of regional climate scenarios for use by decision makers and resource managers.

BIOGRAPHICAL SKETCH

Marzia Tamanna was born on September 05, 1988 in Bangladesh. She received a Bachelor of Science in Civil Engineering from Bangladesh University of Engineering and Technology in 2011. She joined SMEC Bangladesh Limited (South Asia Regional Office) of SMEC International Pty Ltd as Assistant Engineer, Water & Environment in January 2011 and worked there until November 2011. Then she joined Center for Environmental and Geographic Information Services (CEGIS) as Professional, Water Resources Division and worked there for more than one and a half years, until July 2013. Marzia has studied in the Master’s program in Engineering with concentration in Civil Engineering at the University of Louisiana at Lafayette since August 2013 and graduated in summer 2015.