Climate Resilience for Provincial Road Improvement Project

Loan 2839-CAM (SF)/ 8254-CAM and Grant 0278-CAM

Climate Modeling Report

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Acronyms and Abbreviations

ADB	Asian Development Bank
ADCP	Asian Disaster Preparedness Center
AusAID	Australian Agency for International Development
CCAM	Conformal Cubic Atmospheric Model
CMIP	Coupled Model Intercomparison Project
CRU	Climatic Research Unit - School of Environmental Sciences, University of East Anglia
CSIRO	Commonwealth Scientific and Industrial Research Organisation
FAO	Food and Agriculture Organization of the United Nations
GCM	Global Climate Model
GPS	Global Positioning System
IDA	International Development Association (Asian Development Bank Group)
IPCC	United Nations Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
MAFF	Ministry of Agriculture Forestry and Fisheries
MOE	Ministry of Environment
MOWRAM	Ministry of Water Resources and Meteorology
MOT	Ministry of Transport
MPWT	Ministry of Public Works and Transport
MRC	Mekong River Commission
MRD	Ministry of Rural Development
NH	National Highway
PMU	Project Management Unit
PRECIS	Providing REgional Climates for Impacts Studies
RCM	Regional Climate Model
RCP	Representative Concentrations Pathway
SEA START	South East Asian SysTem for Analysis and Training
SRES	Special Report on Emissions Scenarios
UNDP	United Nations Development Program
UNEP	United Nations Environment Programme
UNFCC	United Nations Framework Convention on Climate Change
USAID	United States Agency for International Development
USD	United States Dollar

I. INTRODUCTION

This report provides a review of climate modeling that has recently been carried out in Cambodia with a focus on General Circulation Models (GCMs) and methods to provide higher resolution climate projection data for national scale analysis (downscaling). First the general concepts related to climate modeling are reviewed with a focus on the contribution of the United Nations Intergovernmental Panel on Climate Change (IPCC). IPCC emission and representative scenarios are discussed and the Coupled Model Intercomparison Project (CMIP) is briefly reviewed. A literature review of the suitability of GCMs for application to the South East Asian region is presented and suitable GCMs for further downscaling are outlined. The general principles of downscaling GCMs are discussed and previous downscaling efforts for Cambodia are reviewed.

Based on the review, the data models that are most suitable for climate proofing Cambodia roads are recommended.

II. CLIMATE SCENARIOS

IPCC reports have presented a range of scenarios that make projections of possible future climate change. These scenarios are based on assumptions about driving forces such as patterns of economic and population growth, technology development, and other factors. Emissions scenarios describe future releases into the atmosphere of greenhouse gases, aerosols, and other pollutants and, along with information on land use and land cover, provide inputs to climate models.

The Special Report on Emissions Scenarios (SRES), published by the IPCC in 2000, describes the emissions scenarios that have been used to make projections of possible future climate change, for the IPCC Third Assessment Report (TAR), published in 2001, and in the IPCC Fourth Assessment Report (AR4), published in 2007.

A. Special Report on Emissions Scenarios (SRES)

There are 40 different scenarios, each making different assumptions for future greenhouse gas pollution, land-use and other driving forces. These emissions scenarios are organized into four families, which contain scenarios that are similar to each other in some respects. The following are the major families of SRES emissions scenarios:

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
- The A2 storyline and scenario family describes a very heterogeneous world.
- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with an emphasis on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. The scenario is oriented toward environmental protection and social equity.

Climate modeling in South East Asia has been based on a number of scenarios. Typically an A1 scenario (usually A1F1) is used to represent the extreme of a high C02 emission conditions and a B1 or a B2 scenario is used to represent low C02 emission conditions.

B. Representative Concentration Pathways (RCP) Scenarios

The (IPCC) Fifth Assessment Report will begin to use the Representative Concentrations Pathway (RCP) scenarios. Four scenarios have been developed, and named after the radiative forcing (global energy imbalance) caused by human emissions around the year 2100:

- RCP 3-PD represents a very aggressive scenario, with a peak radiative forcing at about 3 Watts per square meter (W/m²) before 2100, declining thereafter. After peaking in 2020, our annual CO2 emissions decline at a rate of around 3.5% per year. In this scenario, our emissions actually become negative after about 2070, meaning we remove more CO2 from the atmosphere than we add.
- RCP 4.5 and RCP 6 represent global energy imbalances of 4.5 and 6.0 W/m², respectively, and stabilization without overshoot after 2100.
- RCP 8.5 represents a rising radiative forcing pathway leading to 8.5 W/m² in 2100, continuing to rise thereafter.

The projected C02 emissions for the three RCP scenarios are shown in Figure 1.

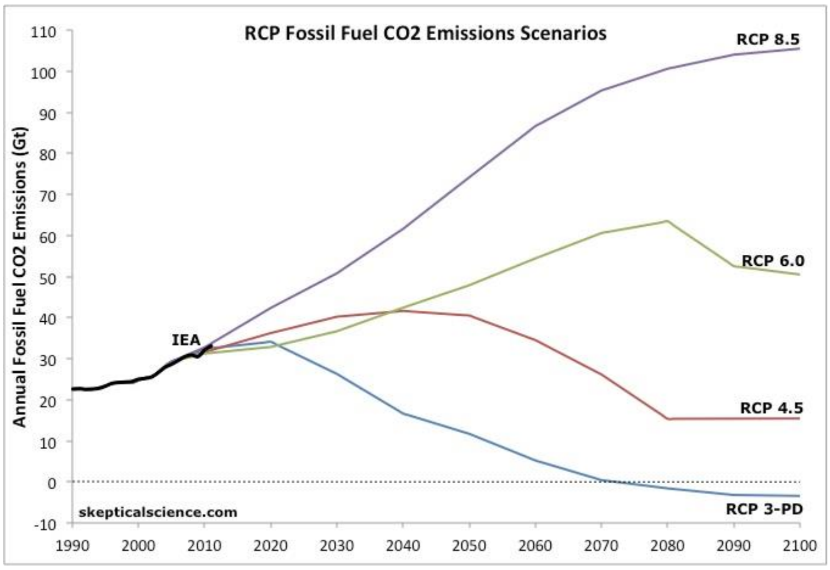


Figure 1 IPCC5 representative concentration pathway scenarios. Source: van Vuuren et al. (2011).

III. GLOBAL CLIMATE MODELS

General Circulation Models, (GCMs), represent physical processes in the atmosphere, ocean, cryosphere and land surface. In GCMs climate is depicted using a three dimensional grid over the globe, typically having a horizontal resolution of anywhere between 100 and 600 km with more recent versions of each GCM having a finer resolution (presently they are in the order of 100 km). GCMs have 10 to 20 vertical layers in the atmosphere and up to 30 layers in the oceans. Climate models are systems of differential equations based on the basic laws of physics, fluid motion, and chemistry. To "run" a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results.

GCM are often a coupling of an atmospheric GCM (AGCM) and an oceanic GCM (OGCM). Atmospheric models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points. Oceanic GCMs model currents and heat transfer in the ocean (with fluxes from the atmosphere imposed) and usually contain a sea ice model.

There are certain physical processes that act at a scale much smaller than the characteristic grid interval (e.g. clouds, convection and turbulence). These processes cannot be eliminated, so simplifying equations are developed to represent the gross effect of the many small-scale processes within a grid cell as accurately as possible. This approach is called parameterization.

Different GCMs handle information in different ways and are generally parameterized to produce results that are representative of the region around the country that produces the model. As a result the various GCMs will produce different output data.

Table 1 List of centers that have produced Global Climate Models that have been used in Cambodia, the name of the model and the approximate resolution.

No.	Originating Group(s), Country	Model	Horizontal grid spacing(km)
1	Bjerknes Centre for Climate Research, Norway	BCCR	~175
2	Canadian Climate Centre, Canada	CCCMA T47	~250
3	Meteo-France, France	CNRM	~175
4	CSIRO, Australia	CSIRO-MK3.5	~175
5	Geophysical Fluid Dynamics Lab, USA	GFDL 2.0	~200
7	Institute Pierre Simon Laplace, France	IPSL	~275
8	Centre for Climate Research, Japan	MIROC-M	~250
9	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, Germany/Korea	MIUB-ECHO-G	~400
10	Max Planck Institute for meteorology DKRZ, Germany	MPI-ECHAM5	~175
11	Meteorological Research Institute, Japan	MRI	~250
12	National Center for Atmospheric Research,	NCAR-	~125

No.	Originating Group(s), Country	Model	Horizontal grid spacing(km)
	USA	CCSM	
13	Canadian Centre for Climate Modelling and Analysis	CanESM2 / CGCM4	~150
14	The Norwegian Earth System Model	NorESM	~120
15	Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, Australia	ACCESS	~145
16	Max Planck Institute for meteorology DKRZ, Germany	MPI-ESM-LR	~100 x 200
17	National Institute of Environmental Studies, at the Centre for Climate System Research (CCSR) at the University of Tokyo	NIESS	~110
18	University of California Los Angeles (UCLA) and Los Alamos National Laboratory (LANL), USA	CGCM	~175
19	NASA Goddard Institute for Space Studies, USA	GISS-AOM	~180
20	Hadley Centre for Climate Prediction and Research, England.	HadGEM2	~60
21	Institute of Atmospheric Physics, Chinese Academy of Sciences	FGOALS	
22	Institute for Numerical Mathematics, Moscow, Russia.	inmcm4	180 x 120

A. The Coupled Model Intercomparison Project (CMIP)

Under the World Climate Research Program (WCRP) the Working Group on Coupled Modeling (WGCM) established the Coupled Model Intercomparison Project (CMIP) as a standard experimental method to study the output of coupled atmosphere-ocean general circulation models. CMIP provides a standard set of model simulations in order to provide projections of future climate change on two time scales, in the near term (out to about 2035) and in the long term (out to 2100). The Program for Climate Model Diagnosis and Intercomparison (PCMDI) archives and makes available the CMIP data and provides other support for CMIP.

As a result of the CMIP model comparisons, the model outputs produced as part of the CMIP process have become the standard for GCM data sources. When describing modeling efforts in various regions it is now common practice to describe the models that were used by the number of the CMIP comparison, e.g. CMIP3 or most recently CMIP5.

The performance of efforts to model the SE Asian monsoon using CMIP3 and CMIP5 were compared by Sperber et al (2012). They found that progress has been made in improving the modeling of aspects of the monsoon between CMIP3 and CMIP5. The CMIP5 models produced better results than the CMIP3 models in terms of the ability to simulate patterns with respect to observations, though there is no single model that best represents all of the aspects of the monsoon. However, Chen and Bordoni (2014) found that the mean of the output of the CMIP5 models still underestimates precipitation compared to standard global rainfall datasets (GPCP and TRMM, see Appendix 1 for a brief summary of international datasets) due to biases in both precipitation intensity and spatial extent.

B. GCM ensembles

Given the current state of scientific understanding and the limitations of GCMs in simulating the complex climate system many modeling studies use the outputs from an ensemble of GCM simulations. A large ensemble of GCM simulations will sample the widest possible range of modeling uncertainties and can provide a spread of possible regional change.

C. Comparison of the performance of GCMs in the South East Asia Region

With more and more detailed GCM data becoming publicly available, including daily time series, it is now possible to produce comparisons of the outputs a large number of GCMs.

The evaluation of observed data and model outputs has shown that the confidence in GCM projected extremes of precipitation is much less than that of temperature. In general, the magnitude of change in precipitation extremes simulated by GCMs has a linear relationship with the global warming trend. GCM-simulated extreme precipitation intensities are generally much lower than the observed data. Chen and Bordoni (2014)

By comparing climate variables output by the models with real data we can get an idea of the most suitable models for Cambodia. A number of studies have made comparisons of GCM outputs for the South East Asian region. An MRC report presented comparisons of CMIP3 models. The SEACLID/ CORDEX alignment have made intensive comparisons and sensitivity of CMIP5 model outputs but this information is not available. The Sperber et al (2012) study found that when modeling the interannual and intraseasonal variability of the South East Asian monsoon the mean value of 25 CMIP5 results outperformed the individual models. The time of monsoon peak and withdrawal is better simulated than that of monsoon onset. The CSIRO's Climate and Adaptation Flagship program carried out a comparison of a number of GCMs with measured values over Southeast Asia for 1975-2004.

a. Measures of GCM accuracy

There are two important measures of GCM accuracy; error and correlation. Ideally the modeled data would provide the same values of rainfall, temperature etc. as local weather data. Any difference in the values can be represented by a measure of the Root Mean Square Error (RMS). A perfect model will have zero errors but realistically errors of 1-2°C or 1-2mm/day is considered to be acceptable.

A second measure of GCM accuracy is the correlation between modeled and measured data. Ideally modeled data should show the same pattern of changes in the values of rainfall, temperature or other variables. A model should at least predict high values of rainfall for rainy days and low values for days when rainfall is low and similarly for temperature and other variables. A perfect model will have a correlation of 1 but realistically a correlation of 0.8 – 0.9 is good.

The RMS and correlation for 24 GCMs is presented for temperature and rainfall in Figure 2 and Figure 3. Observed global surface air temperature data were taken from the ERA-Interim archives and rainfall data is from the Climate Research Unit (CRU) dataset (See Appendix 1 for details of datasets). For temperature, models show good correlations but errors range from 1 – 3 °C. However, for rainfall, models show lower correlations from 0.55 to 0.825. Rainfall errors are generally between 1.5 to 2.5 mm/day. The NASA Godard GISS model showed errors of over 4 mm/day. The Hadley models that are widely used in climate modeling in South East Asia show temperature errors of 1.5 to 2°C but good a correlation for rainfall with errors of less than 1.5 mm/day.

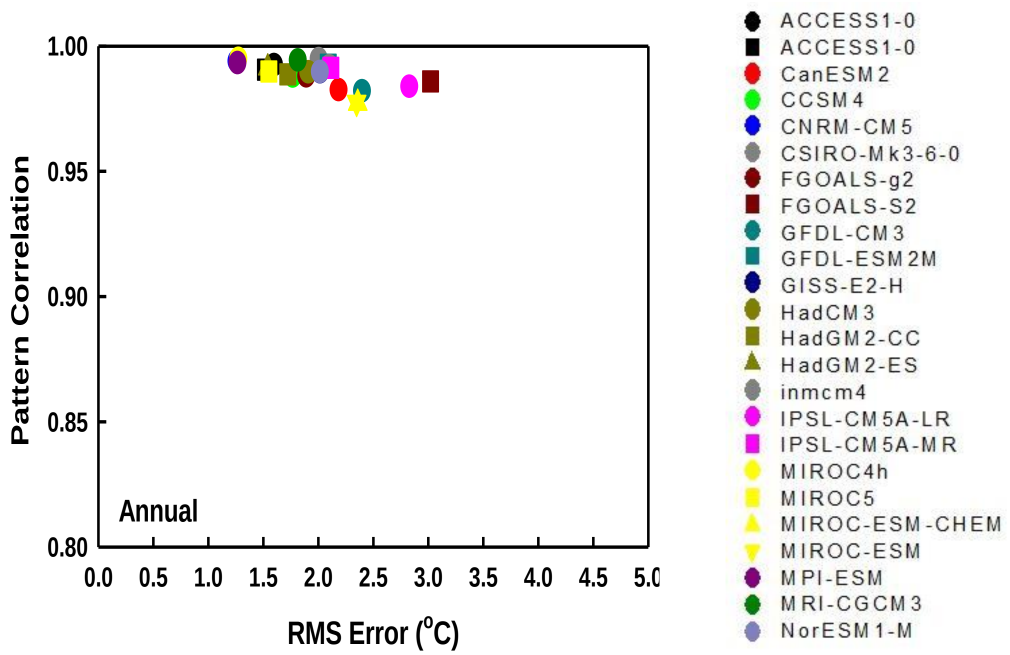


Figure 2 Relationship between RMS error and pattern correlation when comparing modeled temperature with measured values over Southeast Asia for 1975-2004. Source: Katzfey et al. (2013).

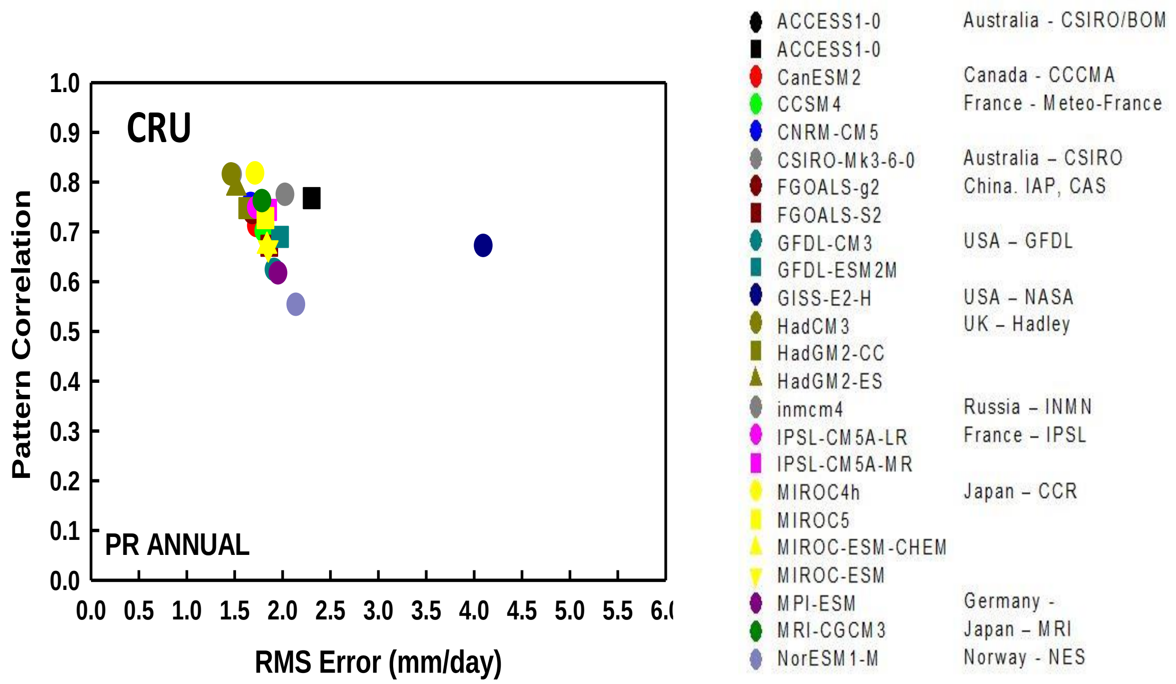


Figure 3 Comparison of modeled rainfall with measured values over Southeast Asia for 1975-2004. Source: Katzfey et al. (2013).

Sperber et al (2012) compared the spatial pattern of the correlation of CMIP5 and CMIP3 with the Global Precipitation Climatology Project (GPCP) data (Huffman et al. 2001) for the wet season monsoon rainfall over the Asian region. The results are presented in Figure 4. They found that the mean CMIP5 modeled rainfall had a higher pattern correlation (0.9) and a smaller root-mean-square error (1.51 mm/day) than the mean of the CMIP3 models (0.86 and 1.69 mm/day). Examination of the RMS of the difference between the standard data set (GPCP) and the mean of each CMIP ensemble over Cambodia shows that both models produce rainfall values that are similar to GPCP in the south east and northwest and both ensemble means underestimate rainfall by 2 to 3 mm per day in the northeast. While the CMIP5 mean simulates similar values to the GPCP data for the mountainous region in the south west, the CMIP3 ensemble mean underestimates rainfall by 1-2 mm per day in this region.

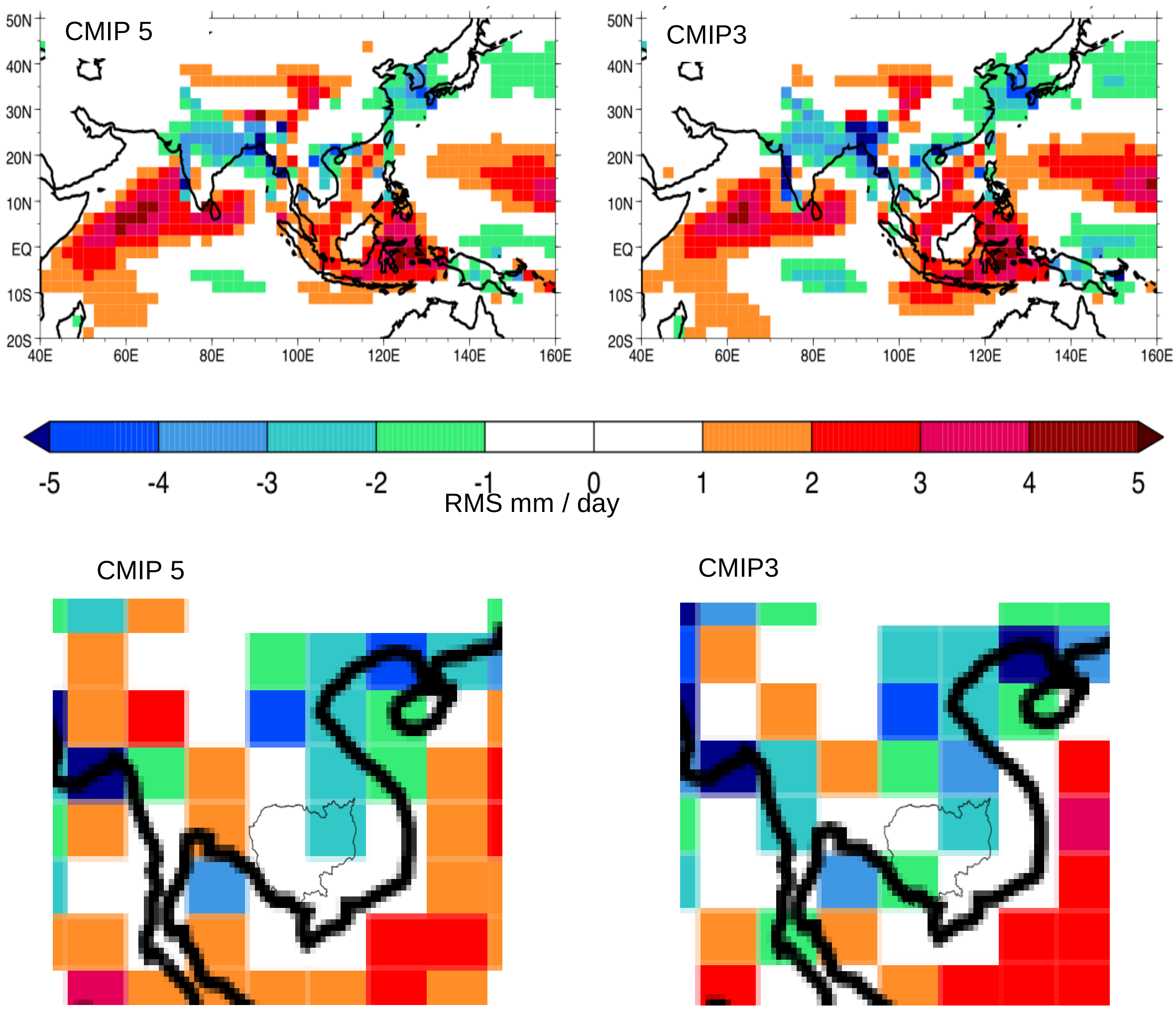


Figure 4 Spatial pattern of the difference between the GPCP data and CMIP5 and CMIP3 ensemble means for the wet season monsoon rainfall (a) over the Asian region and (b) over Cambodia. Source: Sperber et al (2012b).

Chen and Bordoni (2014) compared the intermodel spread within the CMIP5 models for the East Asian summer monsoon simulations. The correlations for three sub regions are displayed in Figure 5. The study found that the simulated South East Asian regional precipitation from 17 climate models shows a wide range, with most models producing an area average of 4.2 – 5.0 mm d^{-1}, and minima and maxima ranging between ~ 3.5 mm d−1 (EC-EARTH) and ~ 6.5 mm d−1 (HadCM3).

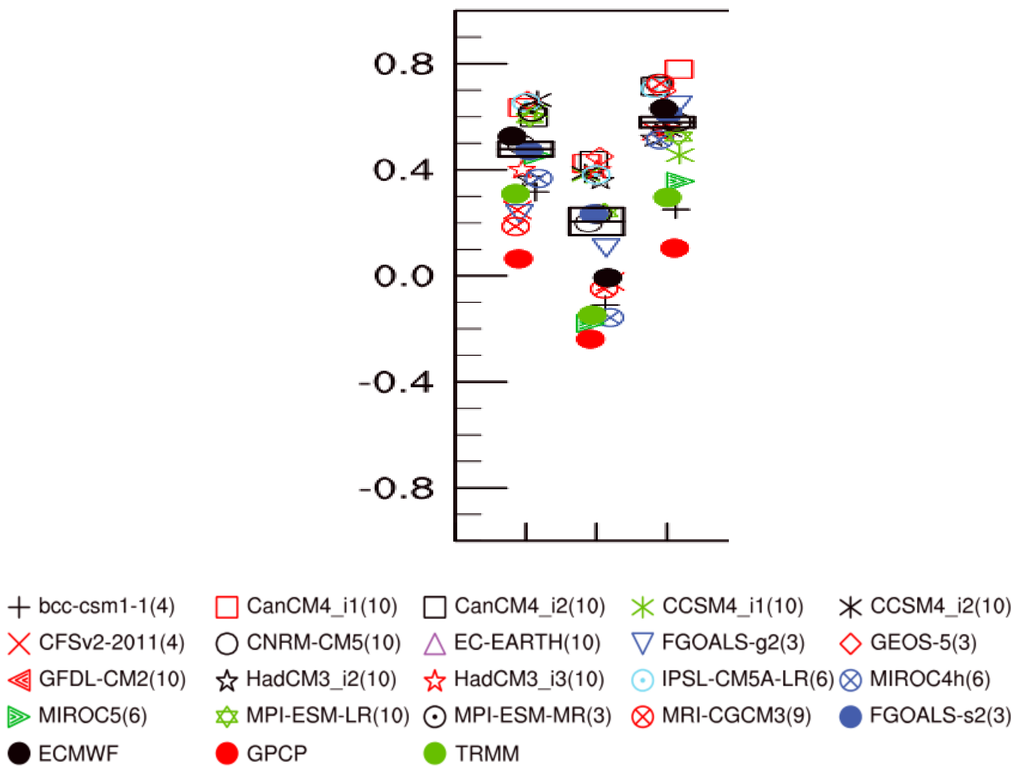


Figure 5 Spatial pattern correlation between the summer monsoon precipitation for East Asia (left), East China (middle), and the northwestern Pacific region (right).

The names of the 17 models and three additional experiments with different initialization method are labeled in the legend, with initialization methods (when necessary) labeled with i# and numbers in parentheses indicating the number of ensembles. Source: Chen and Bordoni (2014).

Annamalai (2013) who has published papers on South Asian Summer Monsoon and its relationship with ENSO found that the GFDL_CM2.1 and the NCAR_CCSM4 showed realistic simulation of monsoon rainfall climatology and its variability in the current climate however a dry bias (less rainfall) was evident over the monsoon region.

Based on their limited set of boreal summer Asian monsoon diagnostics Sperber et al. (2012) selected a number of good performing models:

(1) Nor- ESM1-M and CCSM4, which use the same atmospheric model, are top five finishers in simulating the rainfall climatology, and most aspects of the climatological annual cycle of pentad rainfall. The former model also performs consistently well in representing the interannual variability;

(2) the MIROC5 and MIROC4h models have complimentary skill in representing the climatological annual cycle of pentad rainfall;

(3) the ECHAM based models tend to perform well on intraseasonal time scales.

b. GCMs selected for use by previous studies

Based on an assessment of the performance of CMIP5 models, CSIRO selected 6 models as inputs into a newly developed regional model, (CCAM). The GCMs selected were; CNRM-CM5, CCSM4, NorESM1-M, ACCESS1.0, MPI-ESM-LR and GFDL-CM3. These models were all developed as part of CMIP5.

Based on the assessment of model performance in the South East Asian region by Cai et al. (2009) and Eastham et al. (2008), the USAID funded Mekong Adaptation and Resilience to Climate Change (ARCC) project selected six models; MICROC3 2(hires), CCSM3, CGCM3.1 (T63), GISS-AOM, CNRM-CM3, and ECHAM5/MPI-OM. These models were mostly developed as part of CMIP3.

The models used for the Ministry of Environment (MOE) for the Second National Communication were selected by the Climate Risk Assessment Division, Center for Global Environmental Research, National Institute for Environmental Studies, Japan. The fourteen models selected were; BCCR-BCM2, CCCMA-CGCM3.1, CNRM-CM3, GFDL-CM2.0, GFDL-CM2.1, GISS-ER, INMCM3, IPSL-CM4, MIROC3.2-medres, MIUB-echo-G, MPI-ECHAM5, MRI-CGCM2.3-2a, HadCM3, HadGEM1.

The original models selected for examination in the latest Mekong River Commission (MRC) study are not yet available and the three models selected for downscaling are also not yet available.

The German Research Centre for Geoscience project tested GCMs for their ability to simulate monsoon variability. They selected in order of suitability BCCR-BCM2, HadGEM, HadCM3 and CNCM3.

Table 2 presents an overview of assessments of the performance of GCMs in simulating monsoon rainfall the South East Asian region that has been presented in scientific literature and as part of the background of studies that have been carried out for Cambodia.

The method used by each study to compare models is not consistent across studies. Some studies present a ranking for suitability but others do not. Where no ranking is presented in a study, a rank value was derived for this report from information presented in the study such as correlation or error scores. It should be noted that the presented difference in performance is often minor and where different aspects of performance are measured, different GCMs will perform better in some aspects then others.

The Table presents the list of GCMs in an approximate order of suitability. This rank has been developed for this report and focuses on the suitability of the GCMs for simulating monsoon rainfall in the region. The rank is based on:

- The number of researchers that have selected a model as being a good performing model
- Discussions provided in the relevant research report or scientific paper
- Ranks provided by the authors
- Correlation or other scores presented in the research papers

The latest versions of the top seven listed models can be considered to be the best performing models for simulating wet season rainfall over the South East Asian region. Sperber et al (2012) found that mean of the outputs from an ensemble of GCMs often outperformed individual GCMs. This indicates that downscaling carried out using the mean value of an ensemble of the top performing models should be the most suitable downscaled information. The maximum and minimum values from the ensemble could then be used to provide information on possible variability.

Table 2 Overview of the performance of GCMs in simulating monsoon rainfall the South East Asian region and an outline of the models that have been used by various studies. The GCMs are listed in rank as outlined in the text.

		Project				Research Comparisons			
	Organization	MOE	MRC	USAID	CSIRO				
Model	**Institute** / **Reference**	Not available	Kiem (2014)	Cai et al. (2009)	Katzfey et al. (2013)	Sperber et al (2012)	Annamalai (2013)	Chen & Bordoni (2014)	Delgado et al (2013)
NCAR-CCSM	National Center for Atmospheric Research, USA		5	2	2	2	2	1	
NorESM	The Norwegian Earth System Model		1		3	1			
GFDL CM	Geophysical Fluid Dynamics Lab, USA	4	3		6		1		
CanESM2 / CGCM4	Canadian Centre for Climate Modelling and Analysis		2					4	
BCCR-BCM	Bjerknes Centre for Climate Research, Norway	1							1
CNRM	Meteo-France, France	3	4	5	1				
MIROC-M	Centre for Climate Research, Japan	8	6	1		3			
ECHAM* / MPI-ESM-LR	Max Planck Institute for meteorology DKRZ, Germany	*10		*6	5	*4		5	
IPSL CM5A	Institute Pierre Simon Laplace, France	7						2	
CGCM	University of California Los Angeles (UCLA) and Los Alamos National Laboratory (LANL), USA	2		3					
GISS-AOM	NASA Goddard Institute for Space Studies, USA	5		4					
GEOS	The NASA Center for Climate Simulation							3	
ACCESS	Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology, Australia				4				
BCCR-BCM	Bjerknes Centre for Climate Research, Norway	1							1
INMCM	Institute for Numerical Mathematics, Moscow, Russia.	6							
MIUB echo-G	Meteorological Institute University of Bonn	9							
HadCM3 **HadGEM**	Hadley Centre for Climate Prediction and Research, England.	11							4 2

IV. DOWNSCALING

GCM outputs are still the most reliable source of information for future climate scenario projections. Global models perform best for large spatial scales, a distance of five to six grid boxes and more are often considered to be trustworthy. However, GCMs have relatively poor performance on simulating precipitation at a regional or local scale compared to the historical observed data. This has seriously limited the direct use of GCM precipitation time series in extreme precipitation event analysis.

Downscaling climate data is a strategy for generating locally relevant data from Global Circulation Models (GCMs).The main goal in downscaling is to obtain regional weather phenomena that are influenced by the local topography, land-sea-contrast, and small-scale atmospheric features (e.g. convection). The dynamical downscaling is supposed to retain all the large-scale information which can be resolved well by the global model or reanalysis. It should also add regional information that the coarse-resolution global model could not generate.

Downscaling can be produced from; the output of a single GCM, the average output from a number of GCMs, or from data from a number of GCMs that has been reanalyzed as part of the CMIP process. The latter method is the preferred option.

Downscaling can be carried out using two different methods:

- Using statistical relationships between local weather stations and GCMs
- Nesting a regional climate model into an existing GCM

A. Statistical Methods

Downscaling using statistical methods attempts to establish a relationship between climate variables produced by GCMs and local climate conditions measured by weather stations. Once these relationships have been developed for existing conditions, they can be used to predict what might happen under the different conditions indicated by GCMs. Statistical downscaling can be carried out by establishing either a statistical regressions between GCM data and local weather station data, or by using a Stochastic Weather Generator. The weather generator develops a series of statistical linkages between GCM data and local weather station data.

One type of downscaling that has been recently used by MRC on the Mekong basin is pattern scaling. This method uses linear least squares regressions to downscale GCM data onto a finer grid scale. It is based on 2 assumptions.

1. Climatic variables at different spatial and/or temporal scales are a linear function of the global annual mean temperature change represented by a GCM.

2. A simple climate model can accurately represent the global responses of a GCM, even when the response is non-linear.

In the pattern scaling method a spatial pattern of differences from the global mean temperature output by a GCM run is calculated for each climate variable. This pattern is produced from one GCM emission simulation. The change pattern value for each grid cell is calculated from the chosen GCM simulation using a linear least squares regression of annual mean global temperature change against the local anomaly from the GCM. The local change pattern values are interpolated from the original GCM resolution to a finer scale grid using a bilinear interpolation method. For a given climate variable, its anomaly for a particular grid cell, month and year or period is then used to produce the local climate change based on the annual global mean temperature change.

a. Data Sources

Because statistical downscaling methods do not require large computer resources there are a number of downscaled data sets and software are available freely on the World Wide Web.

The World Bank provides daily downscaled climate data at a resolution of 5° through its data portal. The data were developed by collaborative effort between The WorldBank, The Nature Conservancy, Climate Central, and Santa Clara University (Girvetz et al 2003).

Another web based source of 1km downscaled climate data is WorldClim that was developed by The Museum of Vertebrate Zoology, University of California, Berkeley. (Hijmans et al 2005)

A freely available downscaling software suit MAGICC/SCENGEN (Model for the Assessment of Greenhouse-gas Induced Climate Change / regional climate SCENario GENerator) deleloped by NCAR/UCARs Climate and Global Dynamics combines a GCM (MAGICC) and a stochastic weather generator (SCENGEN).

Statistical downscaling software (SDSM Statistical Down Scaling Model) using a stochastic weather generator to produce high-resolution monthly climate information from an ensemble of GCMs is also freely available from the UNFCCC website.

A pattern scaling ARCGIS based software is available from SIMCLIM.

b. Limitations of statistical downscaling methods

Statistical downscaling methods have much lower computational requirements in comparison to nested limited area regional models. However statistical downscaling methods have been shown to have some limitations and can produce spurious results. These limitations are the result of the use of models that are statistically inadequate due to the assumptions of the underlying probabilistic models not being satisfied. In a study using statistical downscaling in Mexico, Estrada et al. 2013 found that the assumptions of the statistical models did not hold for about 70% of the grid points, leading to errors in the downscaled results.

There are two fundamental sources of error with pattern downscaling related to its underlying theory: 1) Nonlinearity error: the local responses of climate variables, precipitation in particular, may not be inherently linear functions of the global mean temperature change; and 2) Noise due to the internal variability of the GCM will produce spurious local change pattern values.

B. Regional climate models

The more complex method of downscaling is to nest a regional climate model into an existing GCM (see Figure 6). A regional climate model is a fully functioning dynamic model, like a GCM, but it can be thought of as being composed of three layers. One layer uses average data from a number of GCMs, another layer builds on locally specific data, and the third layer uses its own physics based equations to resolve the model based on data from the other two.

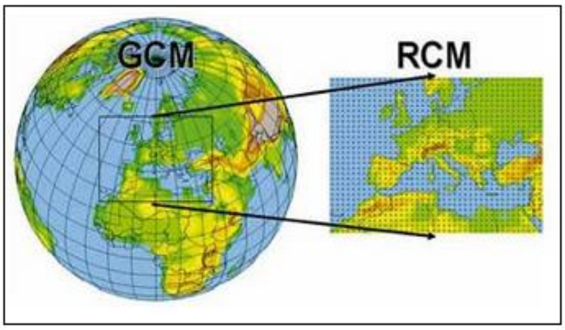


Figure 6 Example of how a regional model sits within a GCM.

a. Limitations of Regional Climate Models

Regional climate models have very large computational requirements and are thus limited to large institutions with super computers and a large research staff. Even with higher resolution than standard GCMs, models simulating regional climate still need parameterizations for sub grid-scale processes. Most regional simulations also require a convection parameterization and these parameterizations are the same or nearly the same as those used in GCMs, however the parameterization required may not be the same especially for convection and cloud microphysics

b. Data Sources

The UK Met Office Hadley Centre for Climate Prediction and Research provides free software for downscaling GCM data. PRECIS (Providing REgional Climates for Impacts Studies) is a regional climate modeling system designed to run on a Linux based PC. The Bangkok based South East Asian SysTem for Analysis and Training (SEA START) provides PRECIS downscaled data and training for the region. PRECIS data has been used by numerous studies in Cambodia as outlined in the next section.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) provides data from a 10km regional model that was developed as part of the High-resolution Climate Projections for Vietnam project, funded by AusAID. The model CCAM, was used in Cambodia for the ADB funded project; Climate Change Impact Modeling for Koh Kong and Mondulkiri, Cambodia, (a component of the TA-7459 REG; Greater Mekong Subregion Biodiversity Conservation Corridors Project – Pilot Program for Climate Resilience Component – Cambodia). This model is described in detail in section VI.C.

V. PREVIOUS HIGH RESOLUTION MODELING IN THE CAMBODIA REGION

There have been a number of previous climate modeling and downscaling efforts in the south-east Asian region with some modeling specifically examining Cambodia.

A. MOE - First National Communication (2002)

Climate modeling to produce climate change projections for Cambodia were produced by the Cambodian Ministry of Environment (Ministry of Environment, 2001) as part of the first national communication to the United Nations Framework Convention on Climate Change (UNFCCC). The communication study used global climate simulations performed for the IPCC Fourth Assessment Report and focused on two GCMs. The first was developed by CSIRO to focus on the Australian

Region (It is not stated which CSIRO-GCM version was used but it is likely that it was mk 3.5), the second GCM that was used was NIES which was developed by the Centre for Climate System Research (CCSR) at the University of Tokyo to focuses on the Japan Region. Two global warming scenarios were used; A2 and B1.

The communication study reported that validation carried out as part of the research for the communication indicated that the two GCM models used were not suitable for use in Cambodia with significant deviations of GCM modeled data from the observed rainfall data particularly in the wet season. The GCM outputs were consistently higher than the observed. The deviation of monthly wet season rainfall was up to 794 mm. In order to overcome this difference, correction factors were developed and used in the subsequent analysis.

The results of the study are shown in Table 3 and

Table 4. Rainfall results for the B1 scenario show a similar pattern to the A2 scenario but of a smaller magnitude.

Table 3 Simulated changes in annual temperature for Cambodia for three time periods by two models for two scenarios. Source MOWRAM (2011).

Scenario	A2		B1	
Variable	CSIRO	NIES	CSIRO	NIES
Annual Temperature Increase 2025	0.3	0.6	0.45	0.6
Annual Temperature Increase 2050	0.7	1.0	0.75	0.9
Annual Temperature Increase 2100	2.0	2.5	1.35	1.6

Table 4 Simulated changes in annual rainfall for Cambodia for three time periods by two models for the A2 scenario. Source MOWRAM (2011).

Scenario	A2	
Value	NIES	CSIRO
Annual Rainfall Increase 2025	6%	5-15%
Lowland Rainfall Increase 2025	4-8%	
Highland Rainfall Increase 2025	0-4%	
Annual Rainfall Increase 2050		5-23%
Lowland Rainfall Increase 2050	8-12%	
Highland Rainfall Increase 2050	-ve	
Annual Rainfall Increase 2100		3-35%
Lowland Rainfall Increase 2100	-ve	
Highland Rainfall Increase 2100	-ve	

B. MRC - Impacts of climate change and development on Mekong flow regimes First assessment (2009)

Future climate projection daily data used by the Mekong River Commission for the two scenarios (A2 and B2) was provided by the SEA START Regional Center. The GCM used was the Max Planck Institute for Meteorology's ECHAM4. Data was downscaled to the Mekong region using the PRECIS system. The PRECIS data for the Baseline 1985 - 2000 were adjusted by comparing them with the available observed data in an effort to calibrate the models to match calculated flow regime outputs. This bias-correction was used to make the downscaled monthly values of the simulated climate for the past period match the observed monthly values.

The PRECIS data were produced by the SEA START Regional Center for 2,225 grid cells covering the entire Mekong River Basin with resolution of 0.2 degree x 0.2 degree (equivalent to about 22 km x 22 km). These data comprise two data sets for ECHAM4 SRES Scenarios A2 and B2. The data set for Scenario A2 is for 1960 – 2004 and 2010 – 2050 while that for Scenario B2 is only for 2010 – 2050 since the data for 1960 – 2004 are identical to those for Scenario A2. Extracted simulated rainfall changes are presented below.

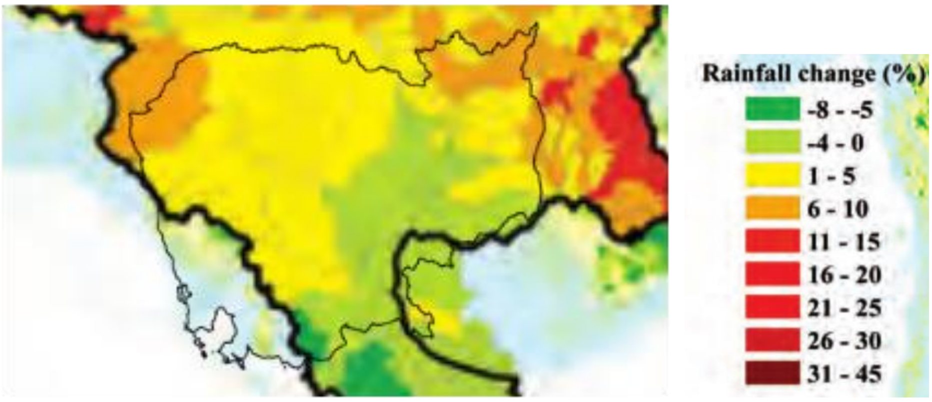


Figure 7 Change in mean annual precipitation (%) during 2010 - 2050 compared to that for 1985–2000 for Scenario A2. Source: Hoanth et al (2009).

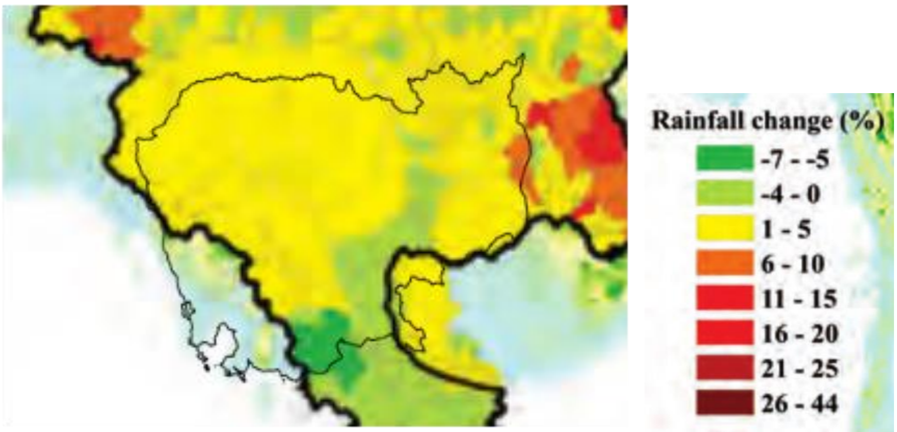


Figure 8 Change in mean annual precipitation (%) during 2010 - 2050 compared to that for 1985–2000 for Scenario B2. Source: Hoanth et al (2009).

Table 5 Modeled precipitation changes for A2 scenario compared with 1985 – 2000 for the lower Mekong Basin. Source: Hoanth et al (2009).

Variable	1985-2000	2010-2025	2026-2041	2042-2050
Mean Annual Precipitation (mm)	1598	1647	1671	1707
Change in Mean Annual Precipitation (mm)		49	73	109
Change in Mean Annual Precipitation (%)		3.0	4.6	6.8
Mean Wet Season Precipitation (mm)	1390	1416	1453	1488
Change in Mean Wet Season Precipitation (mm)		26	63	98
Change in Mean Wet Season Precipitation (%)		1.8	4.5	7.1
Mean Dry Season Precipitation (mm)	208	230	221	219
Change in Mean Dry Season Precipitation (mm)		22	14	11
Change in Mean Dry Season Precipitation (%)		10.6	6.6	5.5

C. MOE - Second National Communication (2010)

The second national communication has not yet been released (due to technical issues). Through informal discussions with Ministry of Environment staff it appears that climate downscaling was carried out by The 3rd National Institute for Environmental Studies (NIES). It appears that two methods were used. The 1° x 1° NIES model from CCRS Tokyo and the CSIRO-GCM model were again used and downscaling was carried out using PRECIS. A second modeling effort was also carried out using 14 GCMs with downscaling carried out using PRECIS to produce a 20 km resolution regional model. The climate change projections were derived from the simulations based on emission scenarios that were produced for the Coupled Model Intercomparison 3 (CMIP3) program and used in the IPCC Fourth Assessment Report.

Three SRES scenarios were used; A1B, A2 and B1 were used.

The consultant's report for the ADB TA No 7665-CAM, Preparing the Provincial Roads Improvement Project presented some results on changes in rainfall from an extract of the Second Nation Communication which are presented below. Source MOWRAM (2011).

Table 6 Projected changes in rainfall for Prey Veng and Svay Rieng. Source MOWRAM (2011).

Month	1960-1979	1980-1999	2000-2019	2020-2039	2040-2059
Jan	0	0	0	0	0
Feb	10	2	2	2	10
Mar	30	30	30	30	30
Apr	70	80	80	80	70
May	150	160	160	160	150
Jun	180	170	170	170	180
Jul	180	170	170	170	180
Aug	210	200	200	200	210
Sep	250	300	300	300	250
Oct	150	290	290	290	150
Nov	10	90	90	90	10
Dec	2	2	2	2	2
Annual	1242	1494	1494	1494	1242
% annual change		20	0	0	-17
% peak rainfall change		20			

Table 7 Projected changes in rainfall for Kampong Chhnang and Kampong Speu. Source MOWRAM (2011).

Month	1960-1979	1980-1999	2000-2019	2020-2039	2040-2059
Jan	0	0	0	0	0
Feb	10	2	10	10	10
Mar	30	30	30	30	30
Apr	70	80	100	100	100
May	150	160	240	240	240
Jun	180	170	180	280	280
Jul	180	170	290	290	290
Aug	210	200	380	380	380
Sep	250	300	400	400	400
Oct	150	290	200	200	200
Nov	10	90	20	20	20
Dec	2	2	2	2	2
Annual	1242	1494	1952	1952	1952
% annual change		20	31	0	0
% peak rainfall change		20	33		

VI. MOWRAM - SUPPORTING POLICY AND INSTITUTIONAL REFORMS AND CAPACITY DEVELOPMENT IN THE WATER SECTOR (2010)

Climate model downscaling was carried out for the ADB project; Supporting Policy and Institutional Reforms and Capacity Development in the Water Sector (TA 7610 – CAM). Two different sets of freely available downscaled data were used. Both modelling efforts used the CMIP3 versions of GCMs. The first data used was dynamically downscaled data from SEA START based on MPI-ECHAM4. The 2.8° GCM data was downscaled to daily data using a regional climate model; PRECIS with a resolution of 0.22° (20 x 20 km).

Two SRES Scenarios A2 and B2 were used and simulations were carried out for a reference of 1970-2000, and for the future; 2010-2100. The percentage change in rainfall during the wettest month at mid-century for the two scenarios are shown in Figure 9.

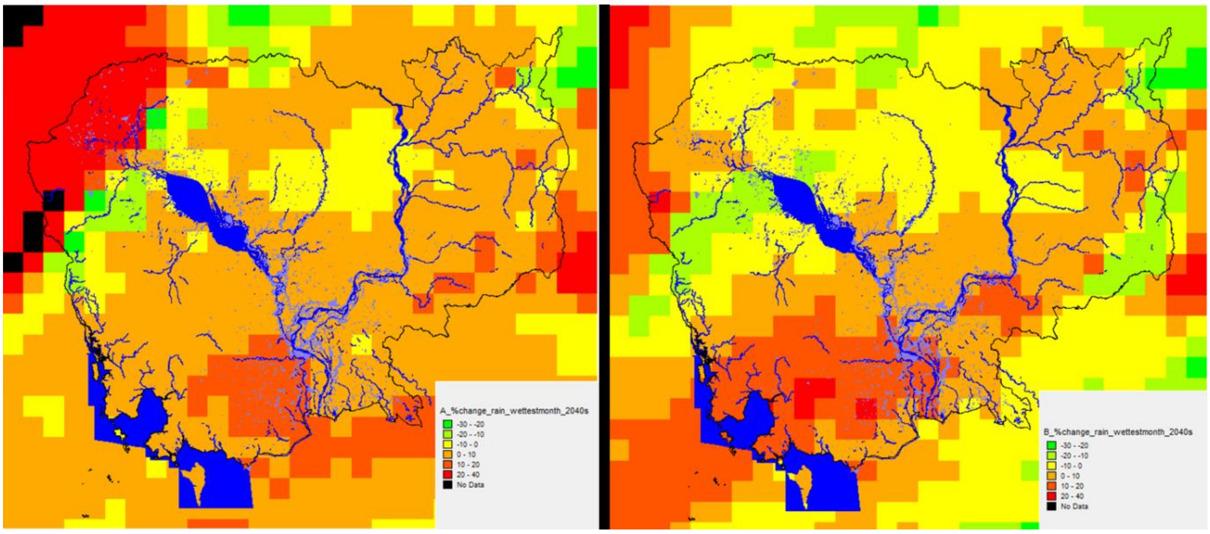


Figure 9 Downscaled ECHAM4 percentage change in rainfall during the wettest month at mid-century for scenarios A2 and Scenario B2. Source MOWRAM 2013.

The study also used statistically downscaled data from the World Bank Data Portal which is available for 9 GCMs to simulate present, mid-century and end-century. The data is described in Girvetz et al (2013). Three SRES scenarios (A2, A1B and B1) were used. Daily data at a spatial resolution of 0.5° or approximately 50 x 50 km is simulated using the method described in Wood et al (2004).

For a given climate variable, each climate model's baseline projection was compared to historic observations to assess the match; then the models were "weighted" in the ensemble average by how well they match historical observations. It is implied that this bias correction was carried out as part of the study, however bias correction is carried out as part of the World Bank Data Portal processing. Statistically downscaled data for annual rainfall change in under Scenario A1B for 2050s is shown in Figure 10.

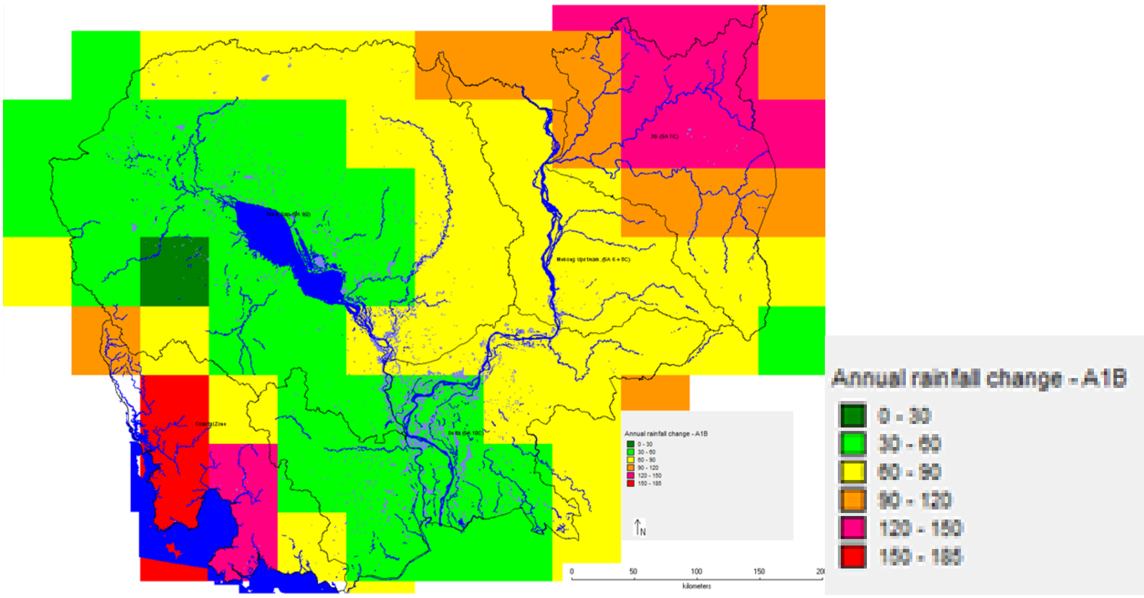


Figure 10 Statistically downscaled data for change in annual rainfall under Scenario A1B for 2050. Source MOWRAM (2013)

Summary of climate change in Cambodia projected by the MOWRAM study.

- Warmer and more occurrences of heat waves
- Warming by an average of up to 1.5°C by mid-century
- Increased total rainfall, but with actually fewer wet days
- More rain occurs as intense precipitation
- Average rainfall on wet days increases
- More accumulated rainfall during wet days
- Fewer number of dry periods, but when a dry spell occurs the duration is longer
- Risk that dry season may become longer and dryer, whereas the wet season may become shorter (onset delayed) but with higher rainfall intensities
- Variability of rainfall may increase, indicating possible increased occurrence of dry periods even during the wet season
- Rainfall in the wettest months could increase by up to 20%, increasing flood risks

The MOWRAM study also derived a comparison measure to examine the agreement among the models' projections, the relative inter-quartile ratio. The relative inter-quartile ratio (RIQR) is computed by taking the difference of the 75th and 25th percentile values, and dividing the result by the median value. It measures the agreement among the multi-model projections, and is similar in concept to standard deviation. The lower the IRQR value, the better the agreement among the models. The IRQR value of projected change in number of consecutive dry days per year is shown in Figure 11.

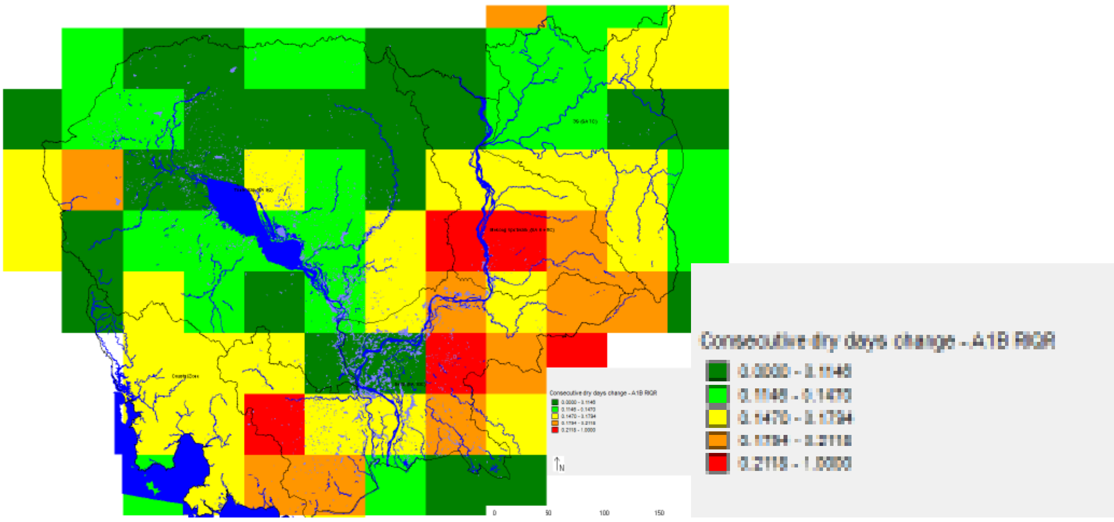


Figure 11 IRQR value of projected change in number of consecutive dry days per year. Source: MOWRAM (2013).

The MOWRAM IRQR assessment showed that the models selected had good agreement in the north but produce varied outputs in the east and southwest.

A. United Nations Development Program report (2009)

High-resolution climate change projections for Cambodia for the A2 and B1 emission scenarios produced by the Center for Climate Systems Research (CCSR) and Commonwealth Scientific and Industrial Research Organisation (CSIRO) were presented in a United Nations Development Program report (2009). Projected increases in temperature ranged from 1.35 to 2.5°C and increases in annual rainfall ranged from 3 to 35% by 2100.

B. USAID Mekong Adaptation and Resilience to Climate Change (2014)

This Mekong basin wide study carried out by ICEM compared the output of 12 GCMs and chose the six that most accurately replicated historical data across the basin for the period of 1980 – 2005. Downscaled projections for the A1 scenario were derived using in house developed statistical downscaling based on the Delta method developed by Lauri et al. (2012). Six GCMs were selected based on studies by Cai et al. (2009) and Eastham et al. (2008); MICROC3 2(hires), CCSM3, CGCM3.1 (T63), GISS-AOM, CNRM-CM3, and ECHAM5/MPI-OM. These models were mostly developed as part of CMIP3. The results are presented in Figure 12 and Figure 13 below.

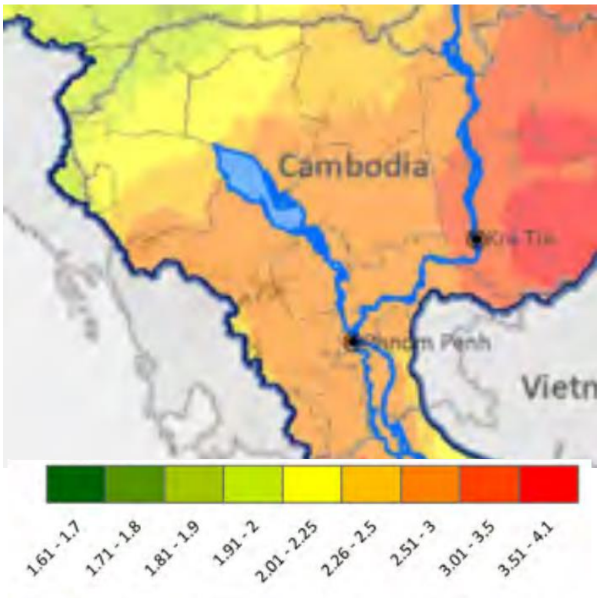


Figure 12 Projected Annual Average Maximum Daily Temperature Changes (C°) in the Lower Mekong Basin between 2005 and 2050 for the A1 scenario. Source Hatman et al (2014).

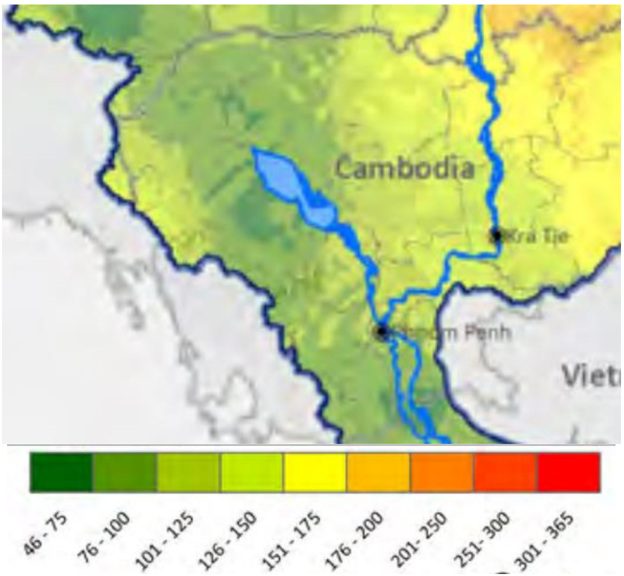


Figure 13 Projected Annual Precipitation Changes (mm) in the Lower Mekong Basin between 2005 and 2050 for the A1 scenario. Source: Hatman et al (2014).

The Mekong Adaptation and Resilience to Climate Change (ARCC) study showed that annual rainfall is projected to increase across Cambodia by 50-100 mm in the central flatlands and by up to 150 mm in the east.

C. CSIRO's Conformal Cubic Atmospheric Model (2013)

Created as part of the High-resolution Climate Projections for Vietnam project, funded by AusAID, the model was used in Cambodia for the ADB funded project; Climate Change Impact Modeling for Koh Kong and Mondulkiri, Cambodia. This project was a component of the TA-7459 REG; Greater

Mekong Subregion Biodiversity Conservation Corridors Project – Pilot Program for Climate Resilience Component – Cambodia.

The study developed projections using bias-corrected sea surface temperatures from six CMIP5 GCMs to drive a global atmosphere-only model at 50 km horizontal resolution (CCAM). Downscaling was carried out by using the 50 km simulations to drive a regional model at a 10 km grid spacing. Two emissions scenarios were considered: RCP 4.5 (lower greenhouse gas concentrations) and RCP 8.5 (higher greenhouse gas concentrations).

The report indicated that temperatures are projected to increase by about 0.7 by 2025 for RCP 4.5 and to increase by 1.0°C by 2025 for RCP 8.5 with small seasonal differences.

Rainfall change projections show both increases and decreases in rainfall in the future. Simulated annual rainfall changes for RCP 8.5 by the end of the century projected annual rainfall increases of up to 10% over Cambodia by the end of this century for RCP 8.5. CCAM generally simulates increases in rainfall in all seasons, except during the Southwest Monsoon, which shows a slight decrease in some parts of Cambodia. The study presented extreme rainfall as the maximum projected rainfall over one day and 5 day periods. The model projected increases of more than 10-20 mm/day over Cambodia by 2055.

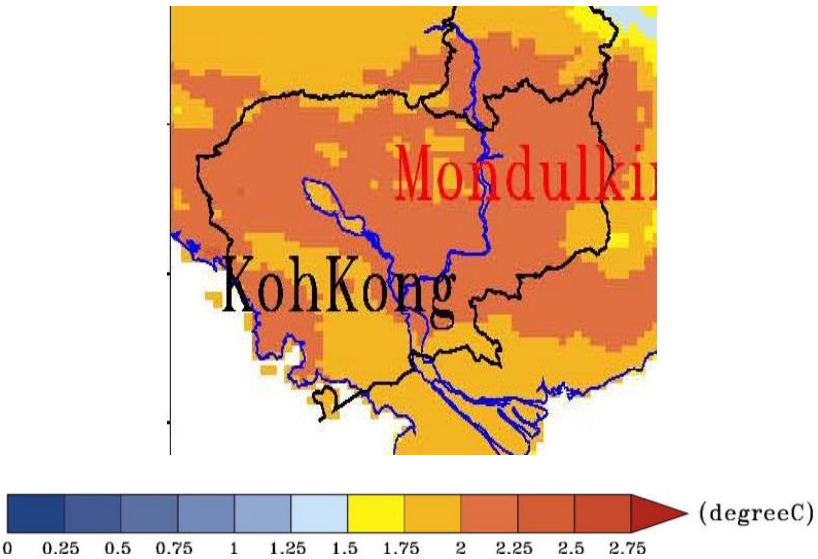


Figure 14 CCAM-simulated maximum dry season temperature increases (°C) for the period centered on 2055 for RCP8.5. Source: Katzfey (2013).

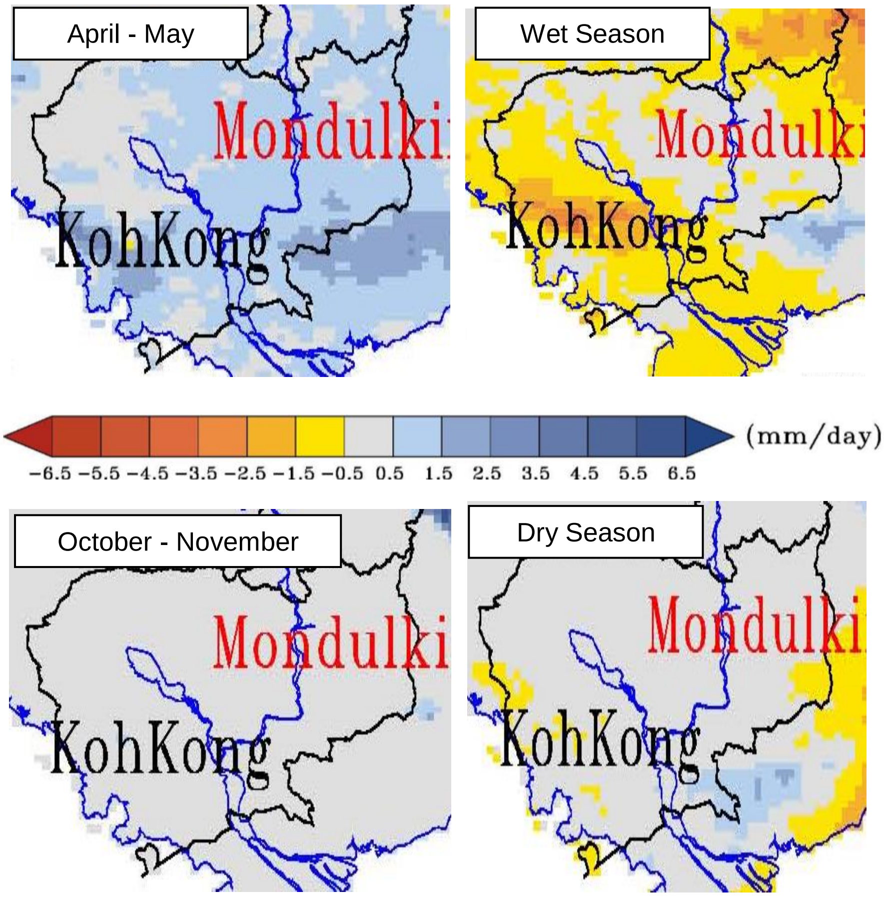


Figure 15 CCAM simulated seasonal rainfall (mm/day) over Cambodia for the period 2055 for RCP 8.5. Source: Katzfey (2013).

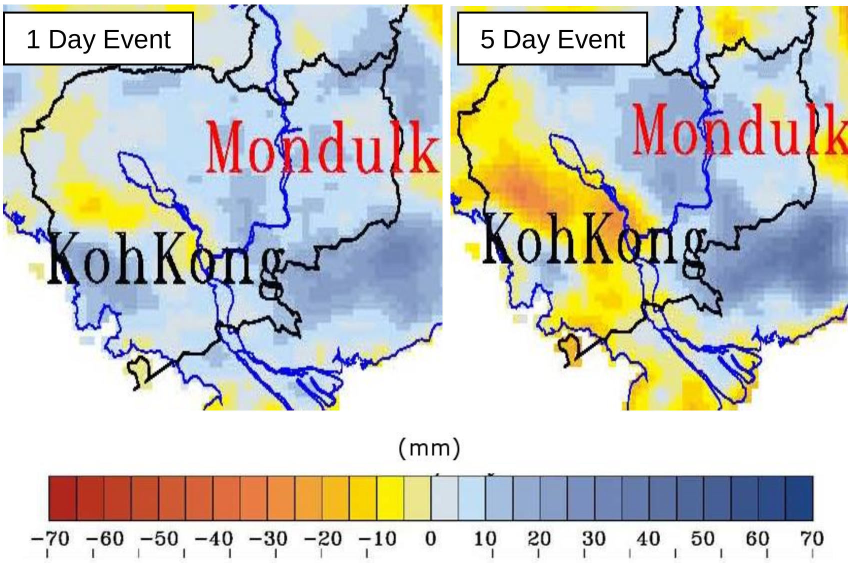


Figure 16 Projected CCAM change in mean extreme rainfall by 2055 for RCP 8.5. Source: Katzfey (2013).

D. Research Modeling Efforts

A large number of research projects have used regional models to look at various climate aspects in the south East Asian region. The models are often modified and run for specific purposes and often do not apply standard climate scenarios and the data is not generally available. Some of the more relevant studies are briefly described below.

a. Institute for Coastal Research, GKSS Research Centre, Germany 2007

This study used an Atmospheric regional climate model; RCM CLM the Climate version of the operational of the German Weather Service weather forecast model Lokal Model. For this study, reanalysis data from the National Center for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR) were downscaled dynamically using a regional model. The reanalyzed data output by the GCM were downscaled in a double-nesting approach first to a 50 km grid and then to a 18 km grid (Feser et al. 2008).

b. National Climate Center of China

Another study using reanalysis data as input for a regional model was presented by Chan et al. (2004). They modified the Regional Climate Model of the National Climate Center of China to simulate the summer monsoon rainfall over South China and the South China Sea (Chan et al. 2004).

c. Chiang Mai University, Thailand

This study was carried out for the South East Asian region using the ECHAM5 atmospheric model coupled to the Max-Planck-Institute ocean model (MPIOM) on a 1.9° x 1.9° grid. The A1B scenario is used for future climate projection. Downscaling was carried out using the WRF model, developed by the National Center for Atmospheric Research (NCAR, 2008). The WRF regional climate model was run using one-way nesting at a 60-km grid spacing.

Over the region the largest increase in maximum temperature warming over the domain is 1.37° C in January and the smallest is 0.77° C in November. The largest increase in dry season minimum temperature of 2°C was found for eastern Cambodia. The model found precipitation changes of less than 1mm/day over the SE Asia mainland.

d. Japans KAKUSHIN Program

High resolution modeling has been carried out as part of Japans KAKUSHIN Program - Innovative Program of Climate Change Projection for the 21st Century funded by the Ministry of Education, Culture, Sports, Science and Technology. A large group of Japanese institutes pooled their resources to develop a 20km resolution GCM (MIROC-ER very high res) and regional models of 5km, 2km and 1km resolution for southern Japan to study investigate changes in heavy precipitation. However data from the model is only available for research purposes Kondo, H. (2014).

e. Mekong Challenge Program on Water and Food

A group of institutions carried out downscaling in 2011 as part of the Mekong Challenge Program on Water and Food. The group; Chulalongkorn University (Bangkok), Aalto University (Finland) and VU University (Amsterdam) downscaled six global models as inputs for hydrological modeling for the Mekong River basin. The models used were; CGCM3.1 (CCCMA) (3.75 x 3.75), CM3 (CNRM) (2.8 x 2.8), CCSM3 (NCA) (1.4 x 1.4), MIROC3.2Hires (1.1 x 1.1), GISS-AOM (3 x 4), ECHAM5 (1.9 x 1.9).

E. Review of Modeling Carried out in the Region

The results from the widely distributed modeling that has been carried out in the region are presented in Table 8 and Table 9. The various models presented all show warming occurring, with the early studies generally projecting warming in the order of 0.01°C to 0.03°C, and later models projecting warming of 0.03°C to 0.06°C. The projections for rainfall are much more varied and are also presented in different ways. Many models project no or small changes in annual rainfall. The earlier studies projected seasonal changes of a later onset of the wet season, a wetter wet season and a dryer dry season.

From Table 9 it can be seen that more recent studies present varied results. The regional models generally show wetter wet seasons except the draft 2nd national communication which projects increasing wet season rainfall in the near future with decreasing rainfall after 2025. The recent CSIRO CCAM modeling presents downscaling information at the highest resolution and while it projects no change to the rainfall during the wet season, it does project an increase in rainfall at the start of wet season.

Table 8 Comparison of projected climate change from different studies up to 2008 (Source: Modified from Hoanh et al. 2009).

Institution	MoE(2002)	IUCN (2003)	IWMI, MRC, FW, IoES * (2003)	Finnish Environment Institute (2003)	START (2008)	MRC CSIRO (2008)	UNDP (2008)
Authors/ Reference	1st National Communication	Snidvongs et al. (2003)	Hoanh et al. (2003)	Ruosteenoja et al. (2003)	WGRG** & START (2008)	Eastham et al. (2008)	Mac Sweeney et al. (2008)
Location	Cambodia	Lower Mekong catchment	Mekong Basin	Southeast Asia	Lower Mekong catchment	Lower Mekong catchment	Cambodia, Viet Nam
Models	CSIRO-GCM Mk3.5, NIES	CSIRO-GCM	HADC	7 GCMs	ECHAM4	11 GCMs	15 GCMs
Downscaling					PRECIS	Statistical	
Scenarios	A2, B1	No specific	A2, B2	A1F1, A2, B1, B2	A2	A1B	A2, A1B, B1
Period	1990 -2025, 2050, 2100	From [1xCO2] to [2xCO2]	1960-2099	1961-2095	1960-2099	1951-2000 and 2030	1970-2090
Projected changes in annual rainfall	1990-2025: 0-+4% in highlands; +4-8% in lowlands 2050: +8-12% in lowlands, -ve in highlands 2100: -ve	Not explicitly quantified	-1.64 to +4.36 mm/y	Either >0 or <0, depends on models and scenarios. Almost always insignificant	Increase (not explicitly quantified)	+0.1 to +9.9 mm/y	+0.3 to +0.6 mm/y
Changed in seasonal rainfall pattern		1-month delayed wet season Dry season drier and longer		1-month delayed wet season Dry season drier and longer	1-month delayed wet season Dry season drier and longer	Wetter wet season (+1.7 to +6.1 mm/y) Drier dry season (-0.3 mm/y – not significant)	Cambodia Wetter wet season: +0.8 to +1.5 mm/y (C); Drier dry season: -0.7 to -0.1 mm/y (C);
Temperature	+0.0135 to +0.025 °C/y	+0.01 to 0.03°C/y	+0.026 to +0.036 °C/y	+0.01 to +0.05 °C/y	Increase (not explicitly quantified)	+0.012 to +0.014 °C/y	0.00 to +0.06 °C/y

*IWMI, MRC, FW,IoES - International Water Management Institute, Mekong River Commission, Future Water, Institute of Environmental Studies.

**WGRG - Water Development & Research Group of Helsinki University

Table 9 Comparison of projected climate change from different studies after 2009

Institution	ADB (2009)	SIDA (2009)	MRC (2009)	MOWRAM (2010)	MoE (2010) Not yet published	USAID (2014)	CSIRO (2013)
Authors		Johnston et al. (2009)	Hoanh et al. (2009)-MRC IM No4	MOWRAM (2013)	2nd National Communication	USAID Mekong ARCC (2014)	Katzfey et al. (2013)
Location	Thailand, Viet Nam	Greater Mekong Subregion	Mekong Basin	Cambodia	Cambodia	Mekong Basin	Cambodia
Models	MAGICC	ECHAM4	ECHAM4	ECHAM4 & 9 GCMs	14 GCMs	6 GCMs	6 GCMs
Downscaling		PRECIS	PRECIS	PRECIS & Statistical	PRECIS	Statistical	CCAM
Scenarios	A1F1, B2	A2, B2	A2, B2	A2, A1B and B1	A1b, A2, B1	A1	RCP 4.5, 8.5
Period	1990-2100	1960-2049	1985-2050	1970-2100	1990- 2080	2005-2050	2025, 2055
Projected changes in annual rainfall	1990-2050: +1.26 to -1.62 mm/y (B2); 0.66 to -1.14 mm/y (A1F1) 1990-2100: +3.27 to +4.91 mm/y (A1F1) and -1.63 to -2.45 mm/y (B2)	No significant change at the whole GMS scale	+ 1.2 (B2) to +2 (A2) mm/y	Increased total rainfall, fewer wet days. 0 – 2.75 mm/y by 2050	1990-2025: decrease 2025-2080: increase	+1.6 to 3.5 mm/yr	
Changes in seasonal rainfall pattern		Wetter wet season in Gulf of Thailand (From +0.2 to +0.6 mm/y) Drier dry season on both sides of Gulf of Thailand (-2.5 to -2.8 mm/y)	Wetter wet season: +1.2 (B2) to +1.5 (A2) mm/y Wetter dry season in UMB +0.9 mm/y and insignificant change in LMB	Shorter but wetter wet season increased dry season	Increase until 2040-2050. Then dryer wet season; -7 mm/yr Dryer dry season -3mm/yr		RPC 8.5; central lowlands; Dryer wet season -8.4 mm/yr in North of C; no change to wet season Increase at start of wet season +1.2 mm/yr Dry season no change
Temperature	+0.03 to +0.06 °C/y	+0.03 to +0.06 °C/y	+0.020 to +0.023 °C/y	+0.03 °C/y	0.013 - 0.036 °C/y to 2099	+0.043 to +0.045 °C/y	+0.045 to +0.056 °C/y

VII. COMMENTS ON RAINFALL DATA IN CAMBODIA

A. Meteorological data availability

In Cambodia meteorological data collection is still poor. From the 1910s until the early 1970s data for hydrological and meteorological stations were recorded daily at 50 hydrological stations on the Mekong, the Tonle Sap and the tributaries. Only about twenty hydrological stations have been repaired since the mid-eighties.

Systematic observation involving the recording of hydrological and meteorological data is the responsibility of the Ministry of Water Resources and Meteorology (MOWRAM). The Department of Meteorology (DoM) of MOWRAM has 38 meteorological stations that record rainfall, 23 that record evaporation, and 14 stations that record wind speed. As is the situation with the hydrological stations, the meteorological stations were destroyed during the war. Various proposals have been developed for the rehabilitation and modernization of these stations. For forecasting purposes, key stations send data (weather forecast) daily to DoM. Rainfall, air temperature, wind speed, wind direction and relative humidity are observed by only two main stations (Pochentong and Sihanoukville).The MRC maintains 12 stations in Cambodia and these 12 stations are considered to be the only reliable stations.

B. Rainfall Maps

A number of rainfall maps have been developed for Cambodia at a variety of scales and using a number of different methods. From an analysis of the know determinants of the spatial spread of rainfall, it can be considered that a suitable map would reflect both the overall regional scale rainfall pattern and the influence of local topography.

The two major influences on the rainfall pattern of Cambodia are; the south-westerly direction of the major rain bearing monsoon winds and the effect that topography has on these winds with higher areas inducing higher rainfall due to orographic effects and the resultant rain shadows with reduced rainfall falling on the flat central area in the lee of the mountains. Topography will also affect thunderstorm activity. The resultant rainfall is a combination of three influences; a pattern of decrease in rainfall from the southwest to the northeast would be expected across the country, rainfall will increase with elevation and a rain shadow would be expected in the lea of the mountainous area of Koh Kong District. The southwestern side of the Koh Kong mountains would have higher rainfall, the peaks will have the highest values and the increase in elevation in the NE would lead to an increase in rainfall in the far northeast part of the country.

There are a number of other influences in local rainfall patterns; landuse (particularly forest cover), surface water availability, large water bodies and importantly the random nature of storm paths. However, rainfall station data in Cambodia is sketchy at best, with poor spatial and intermittent temporal coverage and interpolation based on expert opinion or modeling are required to estimate the spatial pattern at high resolution. The suitability of some of the available rainfall maps is discussed below.

a. Asian Disaster Preparedness Center - ADCP rainfall map

Comparison of ADCP rainfall map with the location of the highland areas is shown below. The map does not appear to reflect the influence of elevation on rainfall, and while it does show a southwest to northeast gradient at the SW coast, it shows a northwest to southeast gradient over the rest of the country.

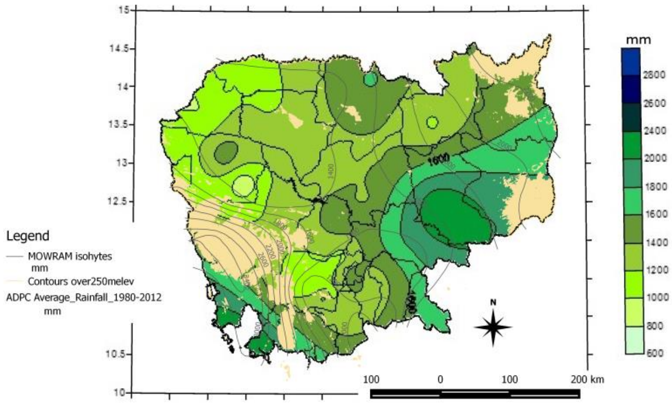


Figure 17 Comparison of ADCP rainfall map and the location of highland areas. Source ADPC (2014).

b. FAO - CRU CL 1.0 (1999)

The Food and Agriculture Organization of the United Nations FAO in partnership with the Climatic Research Unit at the School of Environmental Sciences, University of East Anglia (CRU) developed a monthly and annual global rainfall dataset that covers Cambodia. This CRU CL 1.0 global map of monthly precipitation is based on 1961-1990 climatology is a global grid with a spatial resolution of approximately 0.1 degrees. The station data were interpolated as a function of latitude, longitude and elevation using thin-plate splines. The accuracy of the interpolations are assessed using cross-validation and by comparison with other datasets. Monthly images are created as an average of three decadal images and annual rainfall images have been computed as the sum of twelve monthly images.

The rainfall extracted from the CRU dataset shows the influence of topography in both the SW coastal area and the rain shadow in the central flatlands. Higher rainfall is also indicated for the northeast elevated areas.

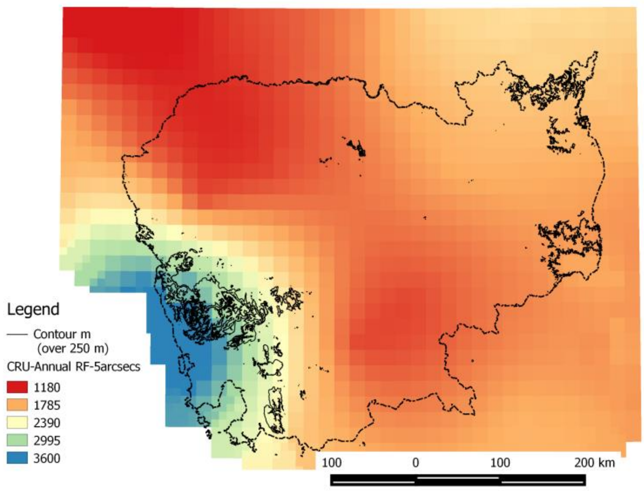


Figure 18 Comparison of FAO CRU CL 1.0 with elevations above 250m. Source New et al (1999).

c. The MOWRAM map

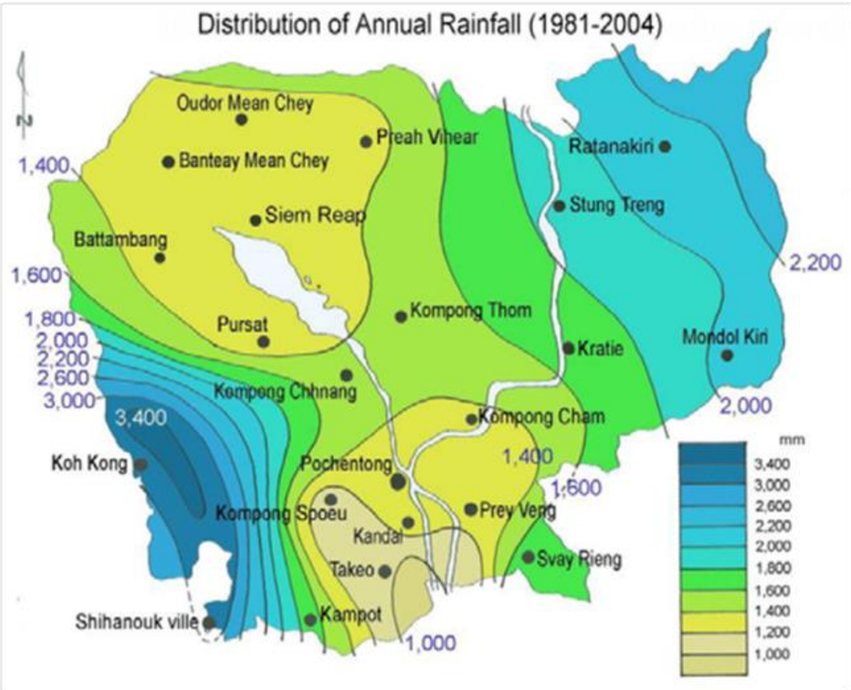


Figure 19 MOWRAM rainfall map. Source Sao 2009.

This map is listed in Hatfield Synthesis report as (MOWRAM 2005, presented in UNEP 2010). It was also presented in Sao 2009

The MOWRAM map labeled as the distribution of average annual rainfall (1981-2004) has an accurate reflection of the influence of topography and shows similarities to the CRU rainfall map. It does however show a more pronounced rainfall shadow with lower values between the central flatlands and the mountain in the sw. It also presents an increase in rainfall towards the north of the country of higher values than in the CRU map.

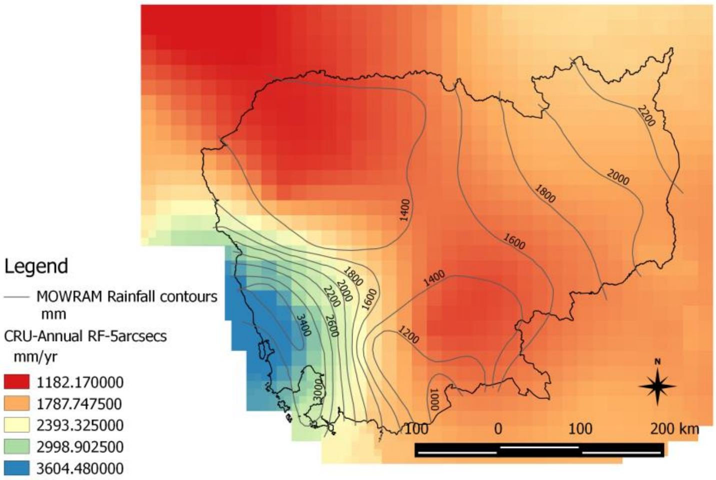


Figure 20 Comparison of MOWRAM and CRU CL 1.0 maps.

d. MRC

The MRC rainfall isohyets in comparison with the elevation and with the CRU global data set are shown below. The MRC rainfall isohyets present a southwest to northeast trend and has a rain shadow in the central flatland. However the MRC map shows little change in the north east and does not indicate increased rainfall in the higher elevations in this area.

In the western half of the country the MRC contours show a close fit with the CRU rainfall map but this is not the case for the eastern half. It is possible that the rainfall isohyets provided had some missing and incorrectly placed isohyets in this part of the map.

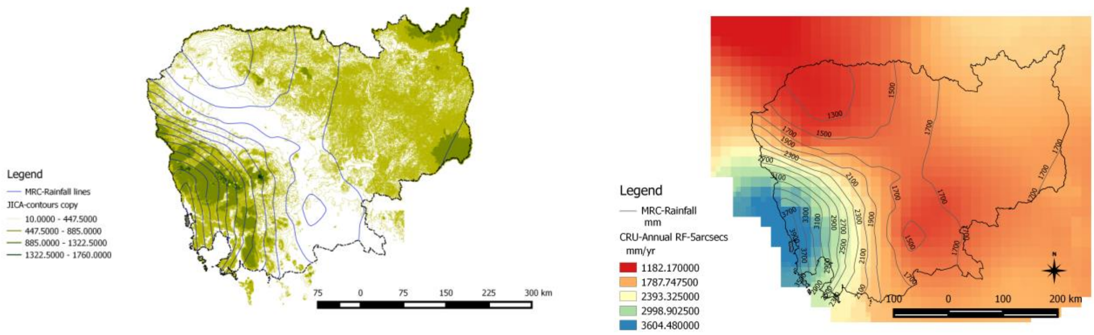


Figure 21 The MRC rainfall contours in comparison with the elevation and CRU CL 1.0 (New et al 1999) rainfall.

A Comparison of MOWRAM and MRC rainfall maps is shown below. The two maps have generally similar features with similar minimum and maximum rainfall values. The major differences are that the MOWRAM map shows a much steeper gradient from the high rainfall areas in the SW down to the central flatland and also shows an increasing trend in the north east.

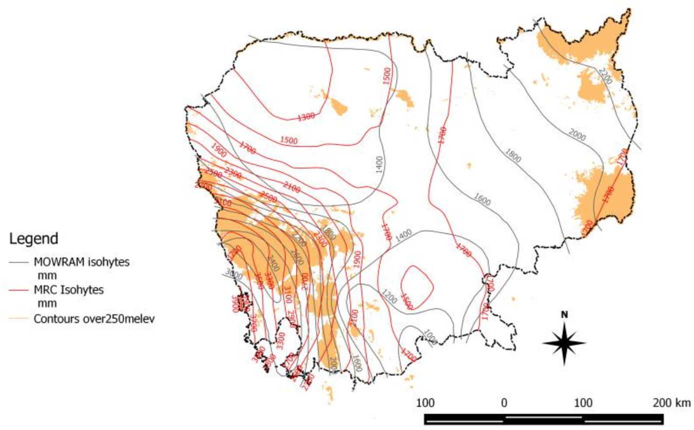


Figure 22 Comparison of MOWRAM and MRC rainfall maps with elevation.

e. Rainfall data for MRC modeling

Rainfall data was also developed by the MRC for use in flood modeling using SWAT and IQQM. The spatial and temporal gaps in rainfall were estimated using MQUAD. In a report to MRC Decision Support Framework by Halcrow Group Limited, (2004) it was recommended that *given the poor coverage of rainfall stations in mountainous regions this may be improved by using a spline approach adjusted for elevation. The splines could be determined for each month and then disaggregated to daily by using the nearest rainfall station.*

The rainfall used in the MRC modeling does not cover the high rainfall area on the southwest coastal area and adjacent mountains. It has a more complicated pattern than the isohyets in the NE of the country.

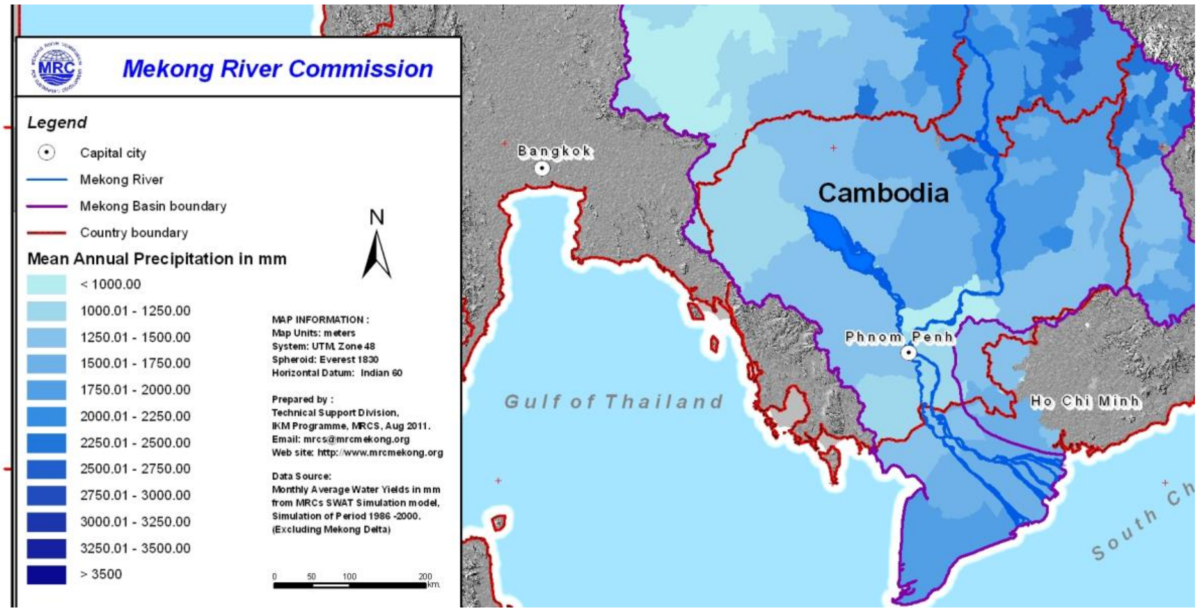


Figure 23 The rainfall used in the MRC SWAT and IQQM modeling Source MRC (2004).

VIII. DATA & MODELS SELECTED FOR CR-PRIP

A. Climate change model

Global Climate Model (GCM) outputs are still the most reliable source of information for future climate scenario projections. However, global models perform best for large spatial scales and have relatively poor performance on simulating precipitation at a regional or local scale. The output from a 100 km resolution GCM over Cambodia produces a grid of approximately 6 by 6 cells. This is much too coarse to determine local scale climate variations and has seriously limited the direct use of GCM precipitation time series in precipitation analysis.

Downscaling climate data is therefore a strategy for generating locally relevant climate data from GCMs. The main goal in downscaling is to obtain regional weather phenomena that are influenced by the local topography, land-sea-contrast, and small-scale atmospheric features (e.g. convection). Downscaling will retain all the large-scale information which can be resolved by the global model and adds regional information that the coarse-resolution global model could not generate.

The important downscaling models used in Cambodia are outlined in the table below.

Table 10 Review of Climate Downscaling Models developed for Cambodia

Modeling	Comments
MOE for the 2nd National Communication (draft) *Carried out with assistance from* National Institute of Environmental Studies (NIES), at the Centre for Climate System Research (CCSR) at the University of Tokyo.	The modeling was carried out in 2009-10 Data from 14 GCMs (pixels ~250 km) was downscaled to smaller pixels Using statistical downscaling Final pixel size 20km Older generation IPCC models
MOWRAM *Carried out by* TA 7610 – CAM Supporting Policy and Institutional Reforms and Capacity	The modeling was carried out in 2010 Data from 9 GCMs (pixels 125-400 km) was downscaled to smaller pixels (Data from World Bank Web Portal) Using statistical downscaling

Modeling	Comments
Development in the Water Sector Project	Final pixel size 50 km Older generation IPCC models
Mekong River Commission *Carried out with assistance from* The Commonwealth Scientific and Industrial Research Organisation (CSIRO) and The South East Asia SysTem for Analysis, Research and Training Regional Center (SEA START).	The modeling was carried out in 2012 Data from 1 GCMs - Max Planck Institute for Meteorology's ECHAM4 (pixels ~250 km) was downscaled to smaller pixels Using a Regional Climate Model Final pixel size of 50 km Older generation IPCC models
ADB TA 7459-REG Greater Mekong Subregion Biodiversity Conservation Corridors Project – Pilot Program for Climate Resilience Component – Cambodia *Carried out by* The Commonwealth Scientific and Industrial Research Organisation (CSIRO)	The model was developed and run in 2012. CCAM - This is a regional model that was run specifically for South East Asia. It uses 6 GCMs selected for best performance in South East Asia The model has a pixel size of 10 km It uses the latest IPCC standard set of model simulations

Projected Temperature change

All these models presented show warming occurring over Cambodia in the future, with the early studies generally projecting warming of 0.01 degrees C to 0.03 degrees C per year, and later models projecting warming of 0.03 degrees C to 0.06 degrees C per year. This equates to a warming of 0.35 to 2 degrees C by 2050 and 1 to 5 degrees C by 2100. The projected change in temperature output by the CSIRO's CCAM model is assumed to be reliable since it is very similar to the one produced by the MOWRAM modeling carried out in 2010 but is slightly higher than that produced by the MOE modeling carried out for the second national communication in 2010.

Projected Rainfall Change

Climate in Cambodia is traditionally described with reference to two seasons, the wet season, when rain bearing monsoon winds from the southwest predominate and the dry season, when dry northeast monsoon occur. Climate change could result in changes in the total amount of rain in each season and a change in the onset or end of the wet season.

Early climate change studies projected a shorter wet season in the future with a later start and a longer drier dry season. The results of these recent studies for rainfall change are much more varied than those for temperature. Many models project no or small changes in annual rainfall and some studies project a decrease in rainfall. For both provinces a change in 1% represents about 17mm so the maximum projected change of -17% represents a decrease of approximately 290 mm spread across the wet season. This amount is less than the inter-annual variability that is found in both provinces.

The recent CSIRO modeling presents downscaling information at the highest resolution and while it projects a decrease in rainfall during the wet season, it does project an increase in rainfall at the start of the wet season. The CSIRO modeling also projects an increase in the amount of rain that falls in extreme events (i.e. is conservative for flood prediction purpose).

Rainfall Intensity

All of the recent climate change studies have projected an increase in rainfall intensity during rainy days by 2055. A decrease in the total yearly rainfall that is projected for some locations is a result of a decrease in the number of rainy days not a reduction in intensity. The CSIRO's CCAM model projected an increase of daily rainfall of 10 to 20mm.

Model selection

The large number of climate modeling and downscaling efforts that have previously been carried out indicates that there is little need for more climate change modeling and downscaling. The primary requirement is for the outputs of past efforts to be more widely disseminated.

However, many of the recent modeling efforts carried in Cambodia have used unsophisticated statistical downscaled data or freely available software that can be downloaded from the World Wide Web and run on personal computers. These efforts also use the older versions of GCMs that were developed and disseminated for the older IPCC reports.

For example the report presenting the details of the downscaling carried out by the Climate Change Unit in MOE for the Second National Communication has not been officially released. This Modelling was carried out in 2010 using older generation GCMs and was produced using statistical methods. The MRD Rural Roads Improvement Project – Climate Change Adaptation project proposed using this model in order to maintain national consistency. However it is difficult to justify using older modelling outputs particularly considering that they have not been described in any published document and therefore cannot be considered official.

Given the paucity of long term measurement stations in Cambodia it is also unlikely that statistical downscaling based on local station data would produce sufficiently accurate high resolution information. The scant rainfall record and poor topographically coverage of weather stations in Cambodia was reflected in early results of MRD consultant to produce rainfall and projected rainfall change maps based entirely on Cambodian rainfall station data. These maps did not reflect the current scientific understanding of the relationship between topography and rainfall distribution and were therefore not used in CR-PRIP.

The use of outdated GCM outputs and the use of relatively unsophisticated downscaling techniques in past downscaling efforts would also reduce the suitability of other previously published results. However a high resolution regional model can overcome the lack of detailed observational data to some extent by incorporating local scale topographic effects within the model.

Therefore the preferred source of downscaled data should be from a recent high resolution regional model.

The most recent high resolution modeling/downscaling outputs that cover Cambodia (that are readily available) are the results of the Commonwealth Scientific and Industrial Research Organization (CSIRO) regional model - Conformal Cubic Atmospheric Model (CCAM). These were produced for the High-resolution Climate Projections for Vietnam project, and used for the climate modeling that was part of the Greater Mekong Sub-region Biodiversity Conservation Corridors Project – Pilot Program for Climate Resilience Component – Cambodia.

B. Climate Change data provided for Road Risk Analysis

As no high resolution rainfall data was available at the time this study was commenced, it was decided that four rainfall datasets would be extracted from a published report for use in the analysis. The data was digitized from maps presented in published reports and is listed below.

- Current 1 day extreme rainfall output from the CSIRO CCAM model for the period 1980 - 2000
- Projected 1 day extreme rainfall for the two decade period centered on 2055 for a RCP of 8.5
- Current 5 day extreme rainfall output from the CSIRO CCAM model for the period 1980 - 2000
- Projected 5 day extreme rainfall for the two decade period centered on 2055 for a RCP of 8.5

Current 1 Day Extreme Rainfall

The 1 day extreme rainfall map presents results from the CSIRO CCAM model runs that were used to verify the model against current measurements. The CCAM output was used in preference to other available data sets in order to maintain consistency between current and projected rainfall data sets. 1 day extreme rainfall is an average of the results of six CCAM model runs based on inputs from six different GCMs. It is defined as the maximum total daily rainfall from a 20 year CCAM model run. The current 1 day extreme rainfall represents the maximum rainfall output by the models for a 20 year period centered on 1990.

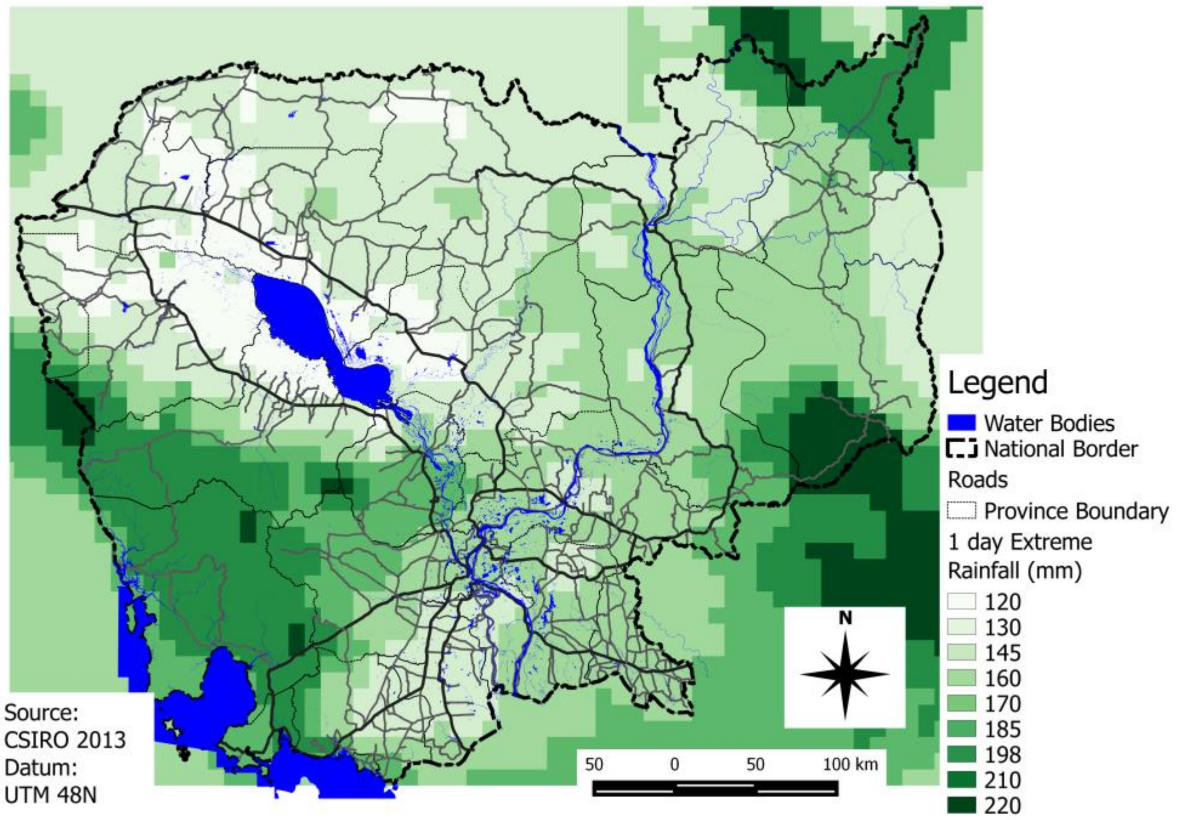


Figure 24 Current 1 day extreme rainfall from the CCAM model.

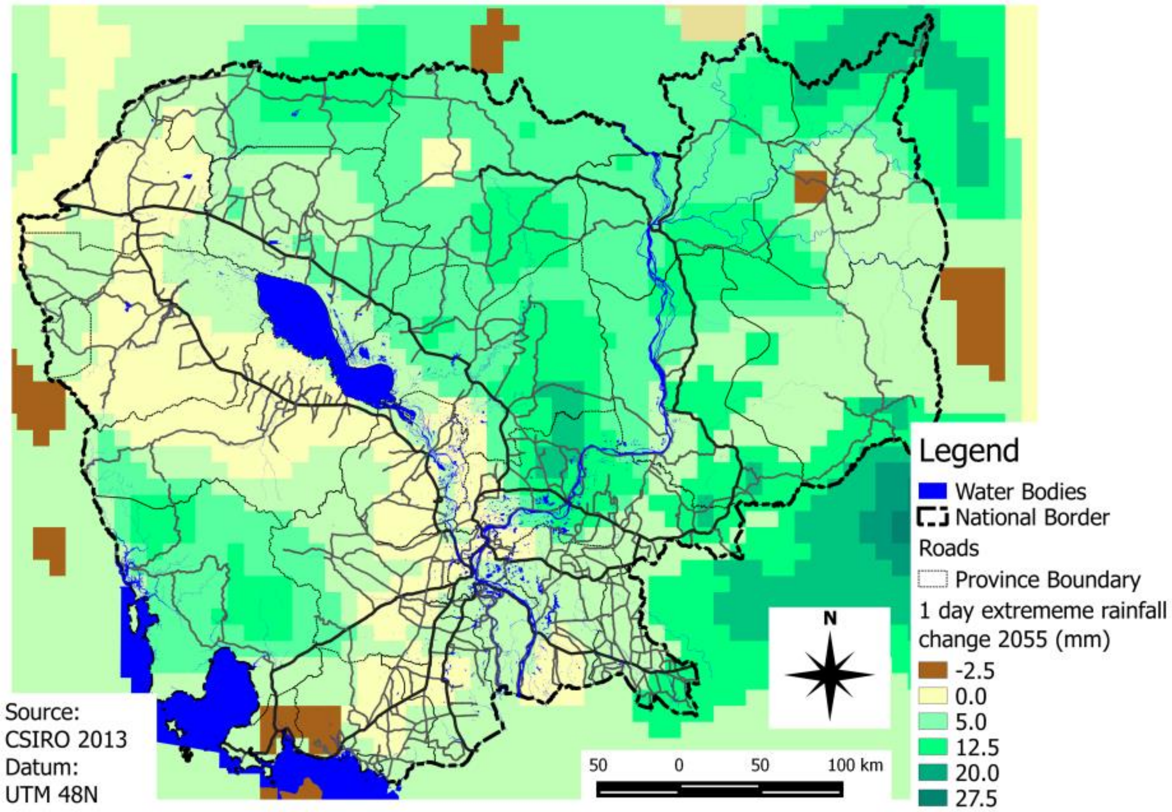


Figure 25 Projected change in 1 day extreme rainfall for 2055 for RCP of 8.5 from CCAM.

The distribution of 1 day extreme rainfall shown in Figure 24 reflects the spatial distribution of annual rainfall with high values of around 200mm in the mountainous region near the coast and in Mondul Kiri and in the far north east. Smaller 1 day extreme events of 100 – 145 mm occur in the central flat lands and hilly regions in the north. The model shows the lowest values around Tonle Sap.

Projected 1 day extreme rainfall for 2055 with RCP of 8.5

The projected 1 day extreme rainfall is the average results from the six CSIRO CCAM model runs for a 20 year period centered on 2055 using an RCP of 8.5. The projected change in 1 day extreme rainfall is the difference between current and projected 2055 values and the map is presented in

Figure 25.

The model projects an increase in 1 day extreme rainfall over the coastal mountains and over the hilly regions in the north of the country. There is no change or only a small change projected for the central flat areas, except for a small area north east of Phnom Penh.

Current 5 day Extreme Rainfall

The 5 day extreme rainfall map (Figure 26) presents results from the CSIRO CCAM model runs that were used to verify the model against current measurements. The CCAM output was used in preference to other available data sets in order to maintain consistency between current and projected rainfall data sets. 5 day extreme rainfall is an average of the results of six CCAM model runs based on inputs from six different GCMs. It is defined as the maximum total rainfall recorded over a 5 day period from a 20 year CCAM model run. The current 5 day extreme rainfall represents the average maximum rainfall output by the model for a 20 year period centered on 1990.

The distribution of 1 day extreme rainfall reflects the spatial distribution of annual rainfall with high values of 300mm or more in the mountainous region near the coast and in Mondul Kiri and in the far north east. Smaller 5 day extreme events of 150 – 180 mm occur in the central flat lands and hilly regions in the north. The model shows the lowest values around Tonle Sap.

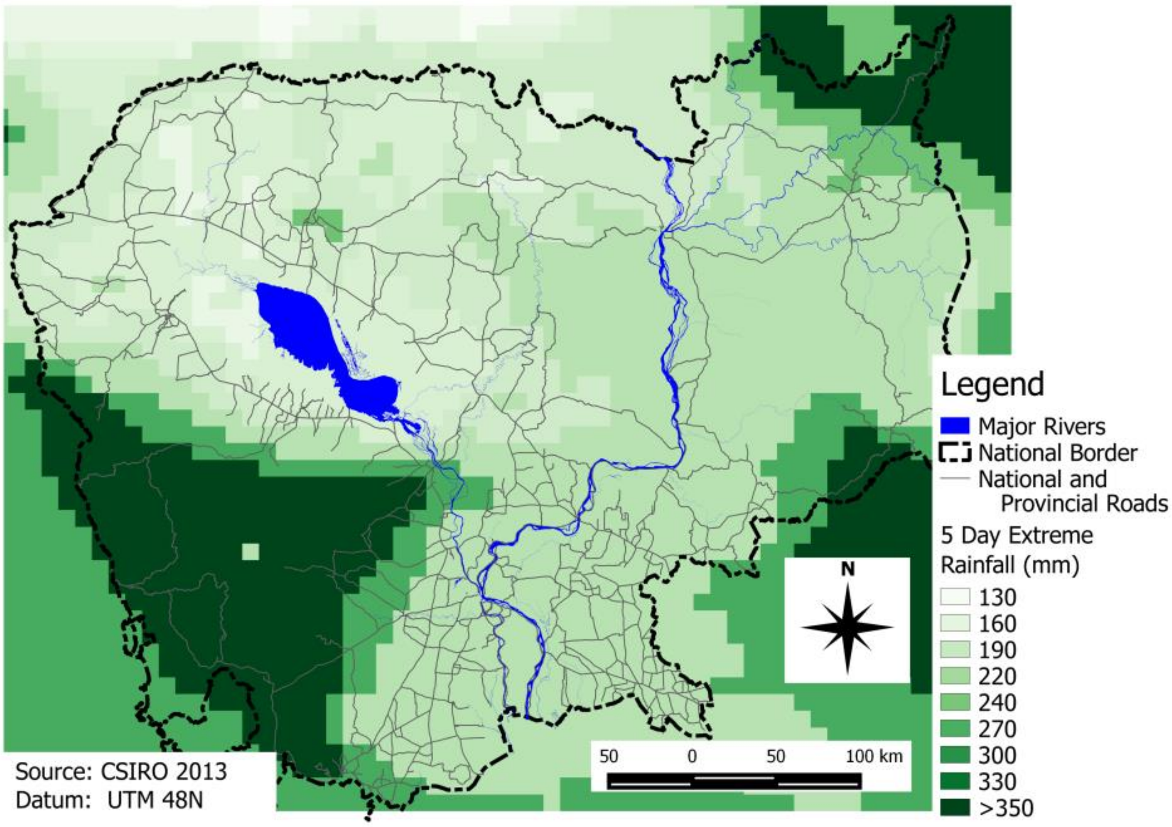


Figure 26 Current 5 day extreme rainfall from CCAM

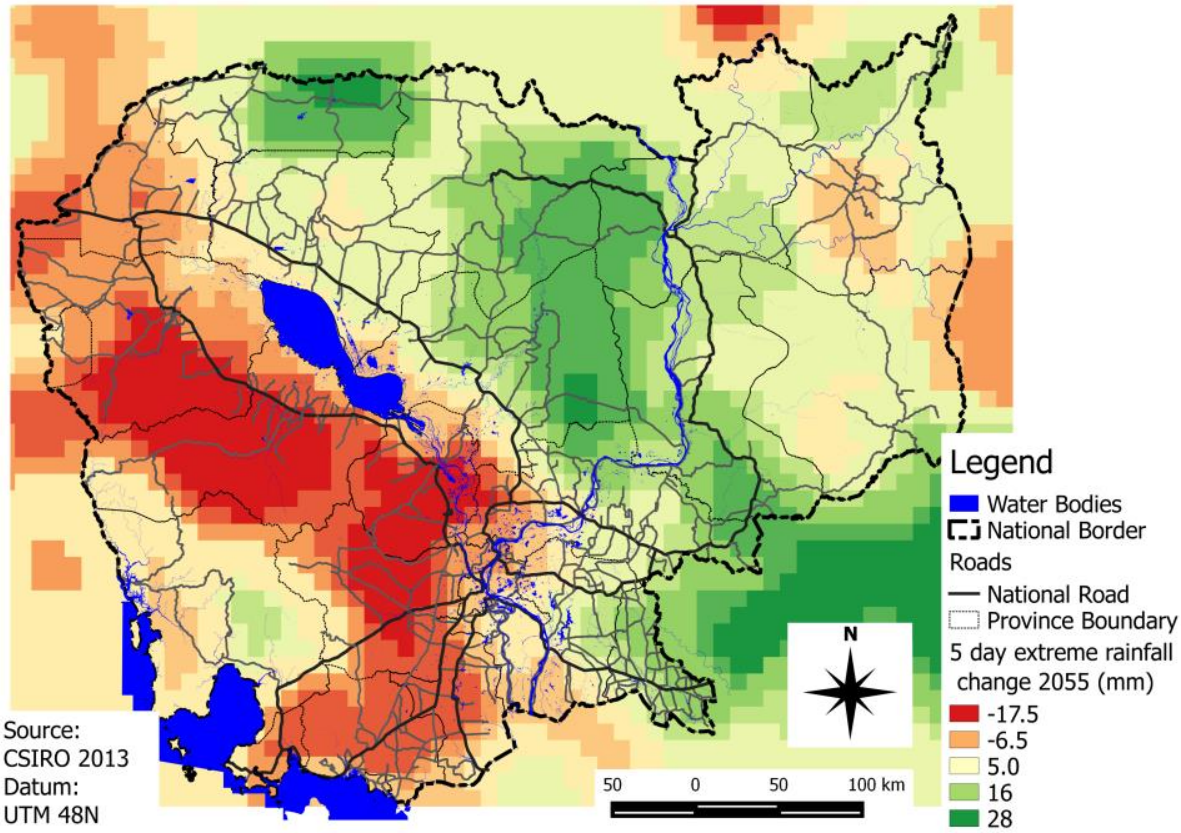


Figure 27 Projected change in 5 day extreme rainfall for 2055 for a RCP of 8.5 from CCAM.

Projected 5 day extreme rainfall for 2055 with RCP of 8.5

The projected 5 day extreme rainfall is the average results from the six CSIRO CCAM model runs for a 20 year period centered on 2055 using an RCP of 8.5. The 5 day extreme rainfall represents the maximum output from a 5 day period. The projected change in 5 day extreme rainfall is the difference between current and projected 2055 values and is presented in Figure 27.

The model projects a small increase in 5 day extreme rainfall over the coastal and other high mountains but a more pronounced increase of 16-20 mm per day for the hilly regions to the west of the Mekong in the north of the country. Little change or a slight decrease is projected to occur in the lower hilly areas east of the Mekong. The most pronounced change is a projected decrease of 5 day precipitation of over 17 mm per day for the flat areas south and southwest of Tonle Sap. 5 day extreme rainfall is projected to increase in Svay Rieng.

Limitations of the model

Studies comparing model performance with global climate data have shown that accuracy can be improved if the results are produced as an average of a suit of GCMs that are chosen for good performance in the region. The process of averaging projections from six simulations based on different GCMs may however mask the extreme cases (such as those projecting substantial increases). On the other hand it must be noted that using results from a single extreme model may also be misleading.

With respect to temperature all of the GCMs are projecting increases in temperature for every season across Cambodia. And any differences between models by mid-century (e.g., 2055) are not projected to be large, so that averages are not misleading. The range of minimum and maximum temperature changes during the hot season projected to occur by 2050 are in the order of 0.5 to 1.2 for RCP4.5 and 0.6 to 1.4 for RCP8.5.

With respect to averaging precipitation projections, all of the GCMs simulations agree on the direction and approximate magnitude of change (Katzfey et al 2013), giving good confidence in the results. For example, in Koh Kong, the wettest province, the projected change in rainfall for the six simulations for 2025 for the wettest three months ranges from -5 to -7.5% for an RCP of 8.5 and from -10 to 4 % for an RCP of 4.5. The use of extreme rainfall (the average of the highest values output by each model for a 20 year model run) for vulnerability mapping ensures that a best guess value for the maximum projected rainfall is used. In some other locations, larger changes in rainfall can however be expected but a full country wide comparative analysis was not possible within the scope of this study.

In summary, the effect of extreme cases is partially taken into account by using rainfall intensities from the highest carbon future, in this case RCP8.5 but it is advised that at the detailed design stage, the latest local rainfall data be investigated and appropriate factors be applied if large variations between rainfall predictions models are found.

C. Climate Assessment of Kampong Leaeng and Tuek Phos

This section presents a review of the current climate for Kampong Leaeng and Tuek Phos and presents a number of indicators that represent projected climate changes. The climate assessment was carried out as part of a watershed and hydrology assessment component of an integrated management plan for the two selected areas. Current monthly climate data for Kampong Chhnang for two 20 year time periods was extracted from the MOWRAM climate data (from MOE 2010), however, as only one province wide value is available, the same current values were used for both Kampong Leaeng and Tuek Phos. Climate change data from the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) Conformal Cubic Atmospheric Model (CCAM) regional climate model was obtained by the consultant. Projected rainfall changes for a 10 year period centered on 2055 under a Representative Concentration Pathway (RCP) of 8.5 were used.

a. General climate parameters

The average annual mean temperature is 25°C +/- 3°C. Maximum temperatures of higher than 32°C are common, however, and just before the start of the rainy season, they may rise to more than 38°C. Minimum temperatures rarely fall below 10°C. January is the coolest month, and April is the warmest. Tropical cyclones that often devastate coastal Vietnam rarely cause damage in Cambodia but can form tropical depressions that result in high rainfall for a 3-4 day period.

Between 1960 and 2010 annual rainfall has ranged between 1200 and 2000 mm, concentrated between May and October. Over 80% of annual rainfall occurs in these six months, with peak rainfall occurring in September.

Relative humidity is lowest in March and highest in September. Daily evaporation values range from 3.1 mm in October to 6.7 mm in March, and the sunshine duration ranges from 6.0 hours a day in August to 9.3 hours a day in January.

b. Projected Temperature change

Projected temperature change for the short term and to 2055 are shown below. When considering changes over the next 10 to 15 years, changes are projected to be 0.5 to 1°C for the low CO_2 scenario and 0.6 to 1.4 for the higher CO_2 scenario with maximum temperatures expected to increase more than minimum temperatures. By midcentury, under the high emission scenario, maximum temperatures are projected to rise by up to 2.1 °C during the early part of the dry season (December – March) but only by 1.6 °C during the latter part of the dry season.

Projected temperature change for the short term and to 2055 are shown below. When considering changes over the next 10 to 15 years, changes are projected to be 0.5 to 1°C for the low CO2 scenario and 0.6 to 1.4 for the higher CO2 scenario with maximum temperatures expected to increase more than minimum temperatures. By midcentury, under the high emission scenario, maximum temperatures are projected to rise by up to 2.1 °C during the early part of the dry season (December – March) but only by 1.6 °C during the latter part of the dry season.

Table 11 CCAM Projected temperature change for the period 2025 to 2030 for two CO_2 scenarios.

	2025:RCP4.5			2025:RCP8.5		
Season	Minimum	Mean	Maximum	Minimum	Mean	Maximum
April-May	0.5 – 1.1	0.5 – 1.0	0.4 – 1.1	0.7 – 1.3	0.7 – 1.3	0.65 – 1.3
June-September	0.5 – 1.1	0.5 – 1.1	0.6 – 1.1	0.7 – 1.4	0.8 – 1.4	0.9 – 1.4
October-November	0.5 – 1.0	0.6 – 1.0	0.7 – 1.2	0.6 – 1.4	0.8 – 1.4	0.8 – 1.4
December-March	0.6 – 1.1	0.6 – 1.1	0.7 – 1.2	0.8 – 1.3	0.9 – 1.3	0.95 – 1.4
Annual	0.5 – 1.1	0.6 – 1.1	0.8 – 1.2	0.7 – 1.3	0.8 – 1.4	0.9 – 1.4

Table 12 CCAM Maximum projected temperature rise for the high CO_2 scenario (RCP 8.5) for the 10-year period centered on 2055.

Season	Temperature increase °C
April-May	1.6
June-September	1.8
October-November	1.8
December-March	2.1

c. Droughts

Droughts occur regularly in the region. The current values and projected values for the period centered on 2055 of two measures of drought, the occurrence of dry periods and the maximum number of consecutive dry days, are presented in the tables below.

i. Kampong Leaeng

Both the average frequency (no of events in a 20 year period) and duration (months) of dry periods are expected to decrease by 2050. The number of consecutive dry days is also projected to decrease.

Table 13 Frequency (no of events in a 20 year period) and duration (months) of dry periods >3 months and number of consecutive dry days.

	Current	2055
Frequency	8	6.5
Duration	6	5.5

Consecutive dry days	28	27

ii. Tuek Phos

The average frequency (no of events in a 20 year period) is projected to stay the same but the average duration (months) of dry periods is expected to increase slightly by 2050. The number of consecutive dry days is projected to decrease.

Table 14 Frequency (no of events in a 20 year period) and duration (months) of dry periods >3 months and number of consecutive dry days.

	Current	2055
Frequency	10	10
Duration	6.25	6.75
Consecutive dry days	35	32

d. Projected Rainfall change

The monthly rainfall from MOWRAM records for Kampong Chhnang for the two 20 year periods between 1960 and 2000 are shown below. The projected changes for each location for the high CO_2 scenario (RCP 8.5) for 2055 presented in Katzfey et al 2013 were used to modify the derived current rainfall (See Table 15 and Table 16).

i. Kampong Leaeng

Rainfall is projected to decrease for the four wettest months of the wet season (June to September), resulting in a decrease in annual rainfall of 8%.

Table 15 Monthly rainfall for Kampong Leaeng for 20 year periods and projected rainfall for the high CO_2 scenario for the period centered on 2055.

Month	1960-1979	1980-1999	2050-2060
Source	MOWRAM	MOWRAM	Katzfey et al 2013
Jan	0	0	0
Feb	10	2	2
Mar	30	30	30
Apr	70	80	80
May	150	160	160
Jun	180	170	140
Jul	180	170	140
Aug	210	200	170
Sep	250	300	270
Oct	150	290	290
Nov	10	90	90
Dec	2	2	2
Annual	1242	1494	1374
% annual change		20	-8

ii. Tuek Phos

Annual rainfall for the area around Tuek Phos is projected to decrease by 10% compared to the average rainfall for 1980 to 2000. Monthly rainfall is projected to increase in the early months of the wet season but is projected to decrease for the remainder of the wet season, resulting in the overall decrease in the annual rainfall.

Table 16 Average monthly rainfall (mm) for Tuek Phos for 20 year periods and projected rainfall for the high CO_2 scenario for the period centered on 2055.

Month	1960-1979	1980-1999	2050-2060
Source	MOWRAM	MOWRAM	Katzfey et al 2013
Jan	0	0	0
Feb	10	2	2
Mar	30	30	30
Apr	70	80	95
May	150	160	175
Jun	180	170	125
Jul	180	170	125
Aug	210	200	155
Sep	250	300	255
Oct	150	290	290
Nov	10	90	90
Dec	2	2	2
Annual	1242	1494	1314
% annual change		20	-10

e. Changes in extreme rainfall indicators

Current values of three measures of rainfall intensity and the projected changes for the high CO_2 scenario (RCP 8.5) from the CCAM model for the period centered around 2055 are shown below. The model indicates that the rainfall intensity during 5 day extreme events is projected to decrease in both locations but the average number of consecutive wet days is projected to decrease in Kampong Leaeng and to increase in Tuek Phos.

i. Kampong Leaeng

Table 17 Current rainfall intensity indicator values and as projected for the high CO_2 scenario (RCP 8.5) for the period centered around 2055.

Indicator	Current (mm)	2055 (mm)
1 day extreme rainfall events	160	160
5 day extreme rainfall events	180	170
Consecutive wet days (wet day > 1mm)	37	32

ii. Tuek Phos

Table 18 Current rainfall intensity indicator values and as projected for the high CO_2 scenario (RCP 8.5) for the period centered around 2055.

Indicator	Current (mm)	2055 (mm)
1 day extreme rainfall events	120	120
5 day extreme rainfall events	250	230
Consecutive wet days (wet day > 1mm)	50	55

f. Conclusion

i. Kampong Leaeng

The climate of Kampong Leaeng is a typical monsoon climate with heavy rainfall confined to the six month wet season. The average annual mean temperature is 25°C with temperatures of up to 38 °C towards the end of the dry season. Temperatures are projected to rise by 0.4 to 1.4 °C by 2055. The frequency and duration of dry periods is projected to decrease by 2055 and the average number of consecutive dry days is also projected to decrease slightly. Rainfall is projected to decrease over the four months when the heaviest falls occur (June to September), resulting in an 8% decrease in the annual rainfall compared to the average rainfall over the period 1980 to 1999. The amount of rainfall in 5-day events and the number of consecutive wet days is projected to decrease. The projected rise in temperature will increase evapotranspiration. Potential problems caused by this increase will be offset to some extent by the decrease in the frequency and duration of dry periods. The decrease in rainfall will contribute to the reduction in the water budget but the overall effect is likely to be small given that the reduction is projected to occur in the wettest months and the annual rainfall is still projected to be over 1370 mm.

ii. Tuek Phos

The climate of Tuek Phos is also a typical monsoon climate with heavy rainfall confined to the six month wet season. The average annual mean temperature is 25°C with temperatures of up to 38 °C towards the end of the dry season. Temperatures are projected to rise by 0.5 to 1.5 °C by 2055. The duration of dry periods is projected to increase by 2055 but the average number of consecutive dry days is projected to decrease. Rainfall is projected to increase at the start of the wet season but decrease over the four months when the heaviest falls occur, resulting in a 10% decrease in the average annual rainfall compared to the average rainfall over the period 1980 to 1999. The number of consecutive wet days is projected to increase but the amount of rainfall in 5-day extreme events is projected to decrease. The projected rise in temperature will increase evapotranspiration as will the increase in duration of dry events. The effects of this increased evapotranspiration will be offset to some extent by the decrease in the number of consecutive dry days and increase in the number of consecutive wet days. The 10% decrease in average annual rainfall will contribute to the reduction in the water budget due to higher temperatures. The overall effect of the reduced water budget is likely to be small given that rainfall is projected to increase at the end of the dry season / start of the wet season and the annual rainfall is still projected to be over 1300 mm.

D. Projected changes in wind speed - National

a. Average Wind Speed

Projected changes in seasonal mean wind speed for the Mekong Delta for the B2 scenario are shown in Table 19 below. Average wind speed is projected to increase in winter, spring and autumn months, but to decrease in the summer months. (Monre 2011).

Table 19 Change in Seasonal Mean Wind Speed (m/s), Scenario B2.

	2030	2050
Winter (Dec-Feb)	0.3	0.2
Spring (Mar-May)	0.1	0.1
Summer (Jun-Aug)	-0.2	-0.2
Autumn (Sep-Nov)	0.2	0.2
Average	-0.1	-0.1

b. Typhoons

Typhoons and tropical cyclones are classified depending on the speed of their winds. An example of the classification is provided in Table 20.

Table 20 Beaufort scale of Typhoon Classification.

Beaufort Scale	knots	km/h	m/sec	SW Pacific (FMS)	NW Pacific (JMA)
0–6	<28	<52	<14	Tropical Depression	Tropical Depression
7	28-29	52-56	14-15		
	30-33	56-63	15-17		
8–9	34–47	63-89	17-24	Tropical Cyclone (1)	Tropical Storm
10	48–55	89-104	24-29	Tropical Cyclone (2)	Severe Tropical Storm
11	56–63	104-119	29-33		
12	64–72	119-135	33-37	Severe Tropical Cyclone (3)	Strong Typhoon
13	73–85	135-159	37-44		
14	86–89	159-167	44-46	Severe Tropical Cyclone (4)	Very Strong Typhoon
15	90–99	167-185	46-51		
16	100–106	185-198	51-55		
17	107-114	198-213	55-59	Severe Tropical Cyclone (5)	Intense Typhoon
	115–119	213-222	59-61		
	>120	>222	>61		

i. Exposure to Typhoons in Cambodia

Figure 28 shows the pattern of typhoon paths in the region in past history. Since the 1950s, over 200 typhoons have affected Vietnam and some continued towards Cambodia. In an average typhoon season, about 30 typhoons usually develop in the northwest Pacific, of which around 10 are based in the South China Sea. Of this number, on average 4–6 will make landfall on or near Vietnam, although there have been years when 10 or more have hit, such as in 1964, 1973, 1978, 1989, and 1996 (CCSFC 1999).

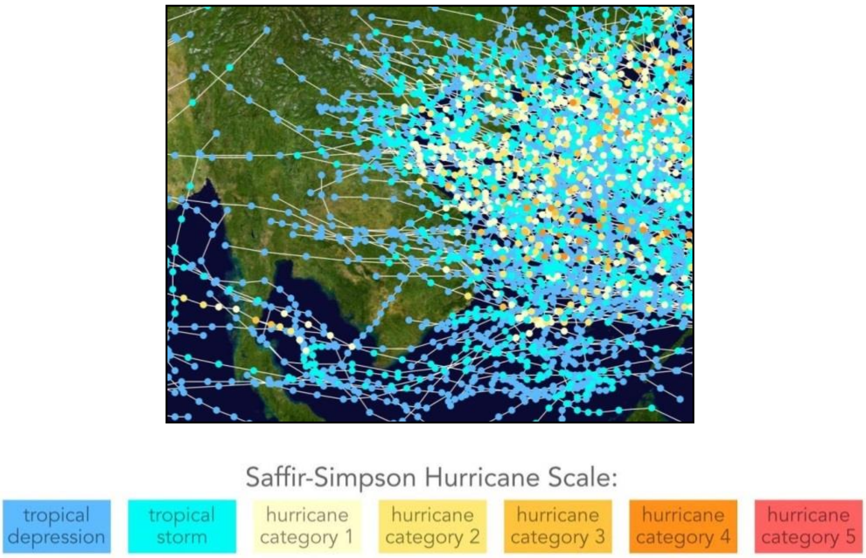


Figure 28 Regional tropical cyclone tracks from 1980 – 2005, coded by Saffir-Simpson category. The points show the locations of the storms at six-hourly intervals. Source: Wikipedia.

The typhoons that make landfall on the coast of Vietnam rapidly lose energy and become tropical depressions and the speed of the maximum wind gust quickly reduces to below 17 m/s. The tropical depression systems continue on their westerly course across Cambodia, gradually loosing energy. As a result the eastern provinces have in a higher frequency of tropical storms. In the case of large typhoons, this weakening may take some time, resulting in tropical depressions with energy levels at or near the energy levels of a category 1 typhoon penetrating into Cambodia. This is illustrated in Figure 30 that indicates that Ratanak Kiri has experienced the remnants of over 13 typhoons since the 1950s generally as tropical storms with winds of up to 17 m/s.

ii. Coastal Typhoons in the Gulf of Thailand.

The Gulf of Thailand is at the southerly limit for typhoons and many of the storms that cross Vietnam and continue into the Gulf are at the lower end of the intensity scale. However, in 1997 Typhoon Linda did cross Southern Vietnam and re-intensified into a category 1 Typhoon (see Figure 29). Linda was considered to be the worst storm to hit Vietnam this century, killing over 4,000 in southern Vietnam and the total damages were estimated to be $600 million (ANRC 1997).

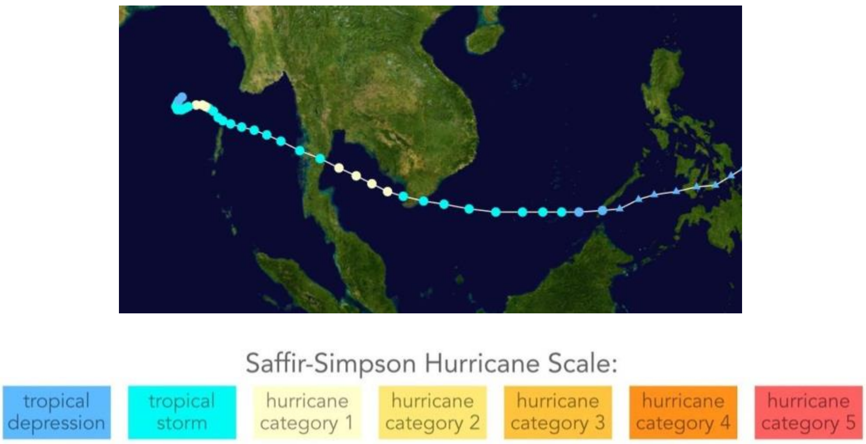


Figure 29 Path of Typhoon Linda, coded by Saffir-Simpson category. Source: Wikipedia 2011.

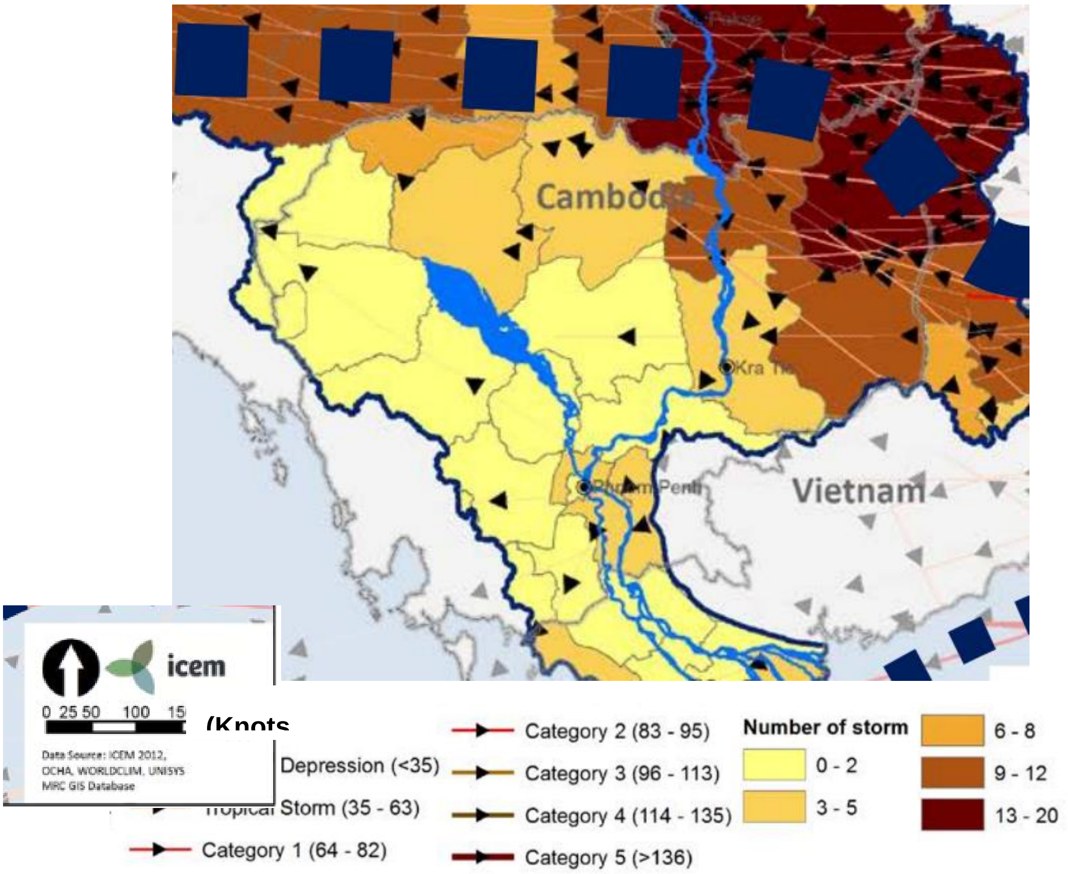


Figure 30 Details of tropical depression occurrence in Cambodia.

c. Climate Change and Typhoons

Uncertainty in historical records, incomplete understanding of the physical mechanisms linking typhoons to climate, and their natural variability means it is hard to attribute changes in typhoon activity to anthropogenic influences (IPCC 2012). Based on historic records and future modeling, early studies projected a 5% increase in typhoon intensity for each °C increase in global surface temperatures. However recent modelling studies have shown that the situation is more complicated.

Oouchi et al 2006 looked into the future of typhoons on a warming planet for the time period 2080-99 for the A1B scenario, using the atmospheric 20km grid. They found that the number of tropical depression is projected to decrease globally by about 30%, and the modelling suggests that the accumulated tropical storm days in South East Asia are expected to decrease from 90 to 55 days. Over Cambodia a slight decrease in frequency is projected to occur (See Figure 31). However, the average strength of maximum winds in tropical depressions will increase from 16 km/hr to 17 km/hr (Matsuno 3013). The Oouchi et al 2006 study projected that the most intense tropical cyclones in the future tend to become much stronger than those in the present-day experiment. In particular, in the Northern Hemisphere, the increase is projected to be 7.3 m/s at the statistical significance level of more than 95%.

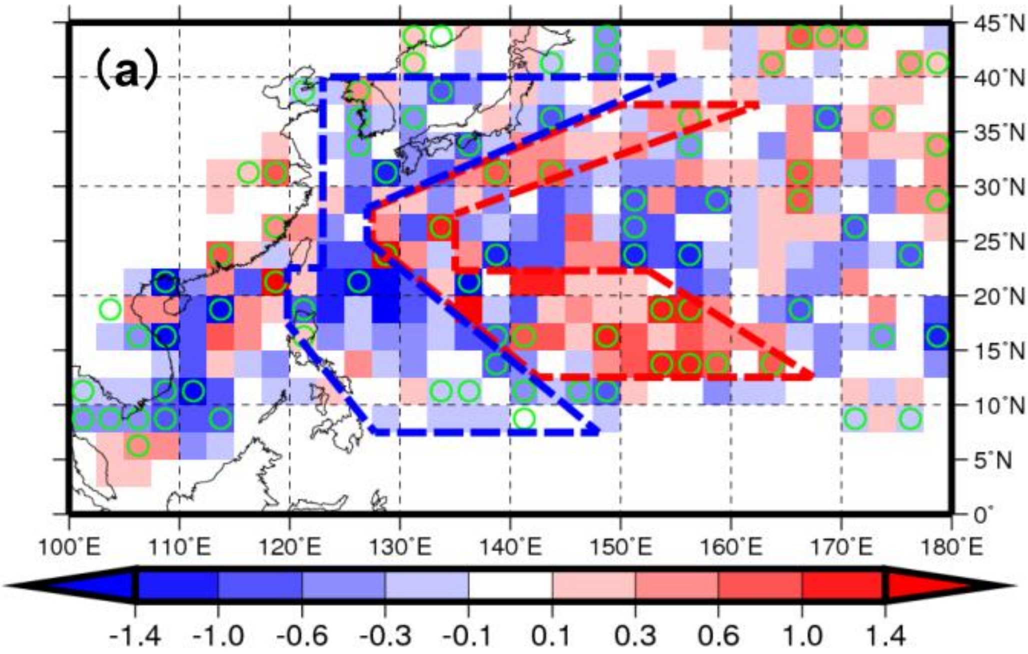


Figure 31 Projected change in typhoon frequency of Occurrence in July – October for 2075-2099 compared to 1979-2003.

d. Summary findings

In terms of determining if a change to the wind parameters of the road design standards is required the following points need to be considered.

- Increases in average wind speed increases due to climate change for the region are not expected to exceed 1 m/s.
- Storm events in Cambodia to date have been limited to tropical depressions with wind speeds of less than 17 m/s.
- In the north east of Cambodia the strength is close to that of a category 1 typhoon with winds in the order of 17 m/s.
- The largest recorded storm in the Gulf of Thailand was the Category 1 Typhoon Linda in 1997 with wind speeds of up to 24 m/s
- Typhoon strength is projected to increase by up to 7.3 m/s by the end of the century.
- Tropical depressions that travel across Vietnam and strike Cambodia can be expected to increase to no more than 23.3 m/s.
- Typhoons in the Gulf of Thailand may increase to up to 31.3 m/s. This represents an increase from Category 1 to the upper end of category 2.

The projected changes are within the values presented in the Cambodian Bridge Design Standard and therefore no changes are required.

E. Projected changes in temperature - National

The existing Amendments to the Bridge Design Standard provide a Table of Shade Air Temperatures that replaces “Table 2.9.2 (a)”. This table presents maximum and minimum shade air temperatures for two climate regions in Cambodia – Coastal Land, and Flat Land and High Land.

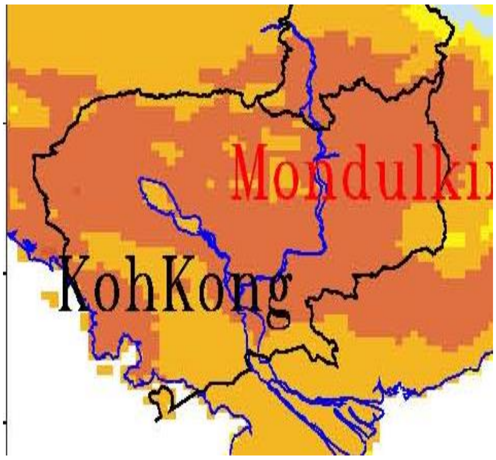
A large number of recent studies have modeled the projected increase in temperature due to climate change. The results from the studies for the maximum projected increase in average air temperature in Cambodia are shown in the following table. These climate change modeling studies indicate that the projected maximum temperature change due to climate change in Cambodia is 2 to 4 degrees C.

Table 21 Maximum temperature increase projected to occur by 2100 for high CO2 climate scenarios by recent studies in Cambodia.

Study	Projected Temperature Rise (degrees C)
MOE (2002)	2.5
MRC (2009)	2.1
UNDP (2009)	2.5
MOE (2010)	3.24
MOWRAM (2010)	2.7
MekongARCC (2013)	3.8
CSIRO (2013)	3.75

The figure below shows the spatial extent of the maximum projected temperature change for the region for 2050 for an extreme CO2 scenario represented by an RCP of 8.5 W m-2 (Katzfey et al 2013). The map is from a recent modeling study that examined projected temperature change for Cambodia simulated by 6 GCMs that was carried out as part of the TA-7459 REG; Greater Mekong Subregion Biodiversity Conservation Corridors Project – Pilot Program for Climate Resilience Component – Cambodia. This recent high resolution climate change mapping indicates that the projected changes are fairly uniform over Cambodia with slightly less increase projected for the flat lands south of Tonle Sap and west of Phnom Penh.

All of the studies indicate that average and maximum temperatures will increase within the next 100 years. Given that bridges have a design life of over 50 years; it would be prudent to ensure that users of the Cambodian Design Standard are aware that maximum temperatures in terms of bridge design may increase and that this increase should be allowed for. As the MOE 2010 study is the official Cambodian submission to the UNFCC the value presented in that report is selected as the projected maximum temperature increase.



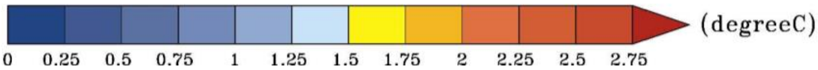


Figure 32 CCAM-simulated maximum dry season temperature increases (°C) for the period centered on 2055 for RCP8.5. Source: Katzfey (2013).

Therefore it is proposed that the Bridge Design Standard is updated to reflect the projected increase in maximum temperature due to climate change as follows:

Table 22 New version of Bridge Design Standard "Table 2.9.2".

CLIMATIC REGION[1]	SHADE AIR TEMPERATURES (^{0}C)	
	Maximum	Minimum
Coastal[2]	43	11
Flat Land and High Land [3]	45	8

Notes:

1) For the extent of climatic regions refer to Figure 2.9.2
2) For locations less than 20 km from the sea coast the maximum temperature may be reduced by 2 ^{0}C and the minimum temperature increased by 3 ^{0}C
3) For locations with altitude greater than 1000 m above the sea level the maximum temperature shall be reduced by 10 ^{0}C and the minimum temperature shall be reduced by 5 ^{0}C.

Recent climate change modeling in Cambodia carried out by The Ministry of Environment for the UNFCC 2nd National Communication indicates that temperatures will increase in the future and that this increase is likely to be a maximum of 3.2 degrees Celsius for a high CO2 scenario. Therefore the historical maximum shade air temperatures for bridge design have been increased by 3 degrees C.

IX. CONCLUSION

Rainfall station data in Cambodia is sketchy at best, with poor spatial and intermittent temporal coverage so interpolation based on expert opinion and/or modeling is required to estimate the spatial pattern of rainfall at high resolution.

Comparisons of the performance of GCMs (Global Climate Models) over South East Asia shows that the most recent versions of GCMs that were developed for the 5th Coupled Model Intercomparison Project (CMIP5) produce better results than the older versions of models that were developed for CMIP3. Comparison studies also show that some GCMs performed better than others in representing rainfall during the South East Asian monsoon. This study identified seven GCMs considered the best performing models for simulating wet season rainfall over the South East Asian region.

However GCMs perform best for large spatial scales and have relatively poor performance on simulating precipitation at a regional or local scale. Downscaling carried out using the mean value of an ensemble of the top performing models provide the most suitable high spatial resolution information. The maximum and minimum values from the ensemble can then be used to provide information on possible variability.

There have been numerous studies that have produced high resolution climate change information using downscaling for Cambodia, with six of these studies produced since 2009. However, many of the recent modeling efforts carried in Cambodia have used either a single GCM or have used unsophisticated statistical downscaled data or models. These efforts also use the older versions of GCMs that were developed and disseminated for the older IPCC reports e.g. CMIP3. Most of these previous studies have used PRECIS for downscaling. Given the paucity of long term measurement stations in Cambodia it is unlikely that statistical downscaling based on local station data would produce sufficiently accurate high resolution information.

A number of rainfall maps have also been developed for Cambodia with the MOWRAM and MRC maps showing the closest match to the FAOs standard rainfall dataset CRU CL 1.0.

In order to ensure that the most recent up to date climate change information was used in the assessment of climate change impacts, data from the CCAM regional model was chosen because it used an ensemble of GCMs that were a) selected as being suitable for predicting rainfall in South East Asia, and b) were the versions developed for CMIP5 and because it is a high resolution regional model that can overcome the lack of detailed observational data by incorporating local scale topographic effects within the model. Four CCAM rainfall datasets were extracted from a published report for use in the flood risk analysis. That analysis uses Current 1 day and 5 day extreme rainfalls output from the CCAM model for current climate conditions and the projected 1 day and 5 day extreme rainfalls for the decade centered on 2055 for a RCP of 8.5 from CCAM. The values extracted are the average values from 6 runs of CCAM with each different GCM.

Potential changes to the hydrology of Kampong Leaeng and Tuek Phos based on current climate data from MOWRAM and using climate change projections from the CCAM regional climate change model, are analyzed and presented.

A review of current observed wind speeds and occurrence of typhoons and tropical depressions in Cambodia coupled with recent modeling studies on the effects of climate change on wind strength and temperature at a national scale were used to propose minor changes to the Bridge Design Standard.

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XI. APPENDIX 1

Title	producer	Years	Source	Resolution	Reference
ERA-40 and ERA-Interim reanalysis	European Centre for Medium-range weather Forecasts (ECMWF)	September 1957 to August 2002	Succession of satellite-borne instruments from the 1970s onwards, supplemented by increasing numbers of observations from aircraft, ocean buoys and other surface platforms		Uppala et al. (2005)
NCEP	National Centre for Environmental Prediction (NCEP) and the National Center for Atmospheric Research	From 1948 to the present	Reanalysis dataset using an analysis/forecast system that performs data assimilation of past data	2.5 x 2.5 degree horizontal grid	Kalnay et al. (1996)
CRU	The Climatic Research Unit - available through the IPCC Data Distribution Center	mean climatology for the period 1901-2000	Mean monthly climatology (including precipitation and wet-day frequency) for global land areas, excluding Antarctica.	0.5° latitude by 0.5° longitude resolution	New et al. (1999) and Mitchell and Jones (2005)
GPCP	Global Precipitation Climatology Project created by the NASA Goddard Space Flight Center	from 1979 to the present	Measurements from over 6,000 rain gauge stations, as well as satellite geostationary and low-orbit infrared, passive microwave, and sounding observations.	Merged precipitation data on a 2.5-degree global grid	Alder et al. (2003).
APHRODITE: Asian Precipitation — Highly Resolved Observational Data Integration Towards Evaluation of Water Resources.	Environment Research & Technology Development Fund of the Ministry of the Environment, Japan.	from 1951 to 2008	Station data from Asia and Europe, by subregions. This dataset has higher resolution that captures the effect of topography over the complex mountainous regions	0.25 latitude by 0.25 longitude grid resolution	Yatagai et al. (2012)
TRMM Tropical Rainfall Measurement Mission	NASA and the Japan Aerospace Exploration Agency (JAXA)	From 1997 to present	TRMM is a research satellite designed to improve our understanding of the distribution and variability of precipitation within the tropics	0.5° latitude by 0.5° longitude resolution	Huffman et al., 2007