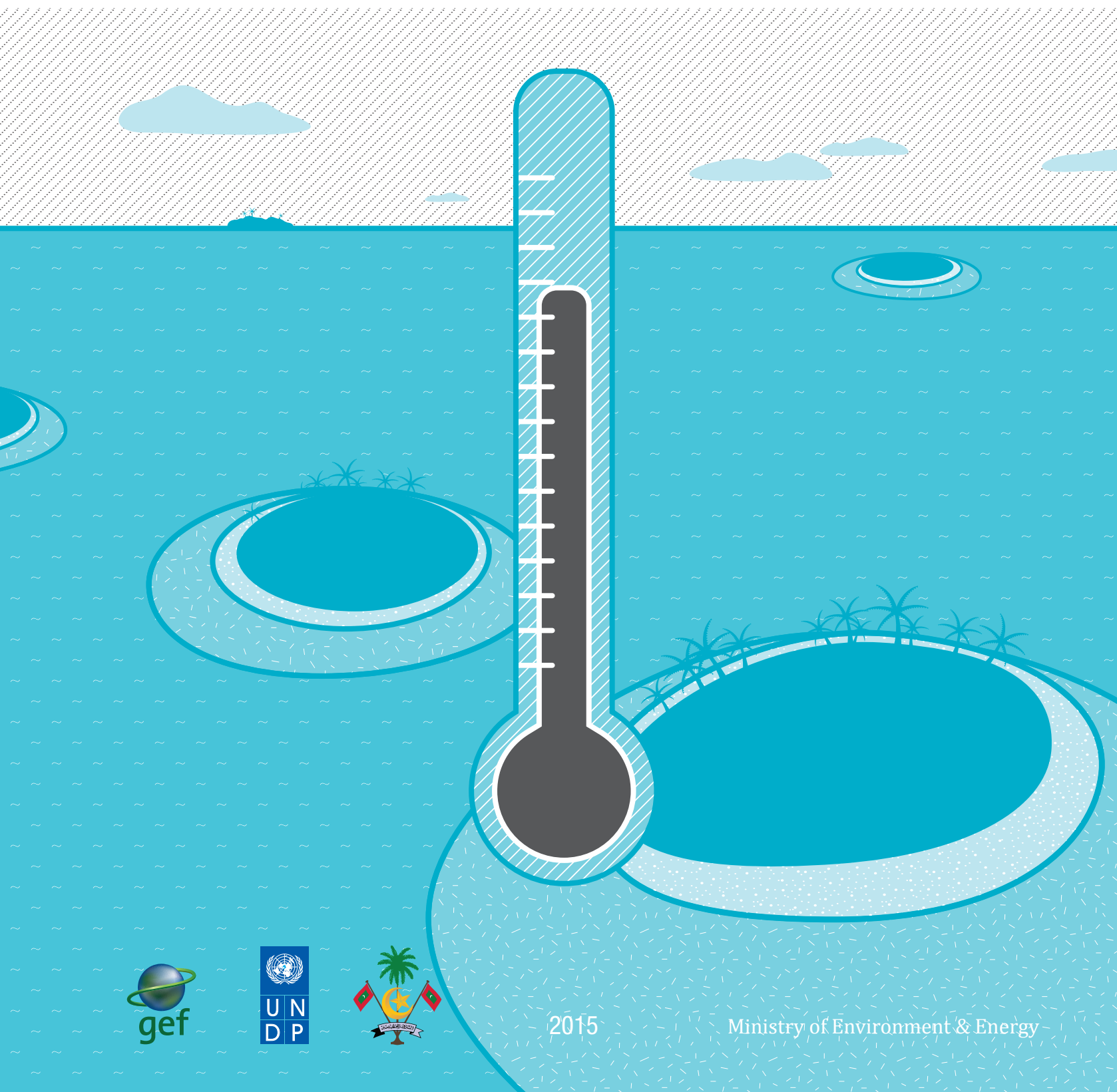


Development of High-resolution Regional Climate Model for the Maldives

Integrating Climate Change Risks into Resilient Island Planning in the Maldives Project



2015

Ministry of Environment & Energy

High-resolution Regional Climate Model for the Maldives

Through statistical & dynamic downscaling of global climate models to provide projections for national & local planning

2015



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Foreword

Natural disasters of recent years have evidenced that climate change is the greatest threat faced by mankind. The United Nations Secretary-General Ban Ki-moon has described climate change as the “the defining issue of our time”. Affected by all, the Intergovernmental Panel on Climate Change (IPCC) has stated that “the poorest of the poor will be the hardest hit by climate change”.

Being one of the most vulnerable countries to climate change, we are compelled to employ every means possible to understand the behavior and long term projections.

Global climate models (GCMs) are important tools for climate study and research and even more so for making projections for the future. These models provide realistic representation of large-scale aspects of climate but generally lack interpretations at regional and local levels. GCMs therefore need to be downscaled and fine-tuned to cater for the Maldives. This climate downscaling is the first of its kind carried out for the Maldivian domain. Given the data sparseness and smaller size of the islands this, such an assessment is challenging however, useful for the country.

This report establishes climatic variability and the associated vulnerability for different regions of the Maldives. The projection of sea level rise of 82 to 95 mm across the various atolls by 2080s, though startling, is an important piece of the puzzle that was not known before. Using this finding and further research, steps must be taken now to protect infrastructure, livelihoods and human lives across the geographic regions of the Maldives.

A handwritten signature in blue ink, appearing to read 'Thoriq Ibrahim', with a horizontal line underneath.

Thoriq Ibrahim
Minister

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Acronyms

20C3M	20th Century Climate in Coupled Models	MRC	Marine Research Center
AR4	Fourth Assessment Report, IPCC	MRI CGCM	Meteorological Research Institute, Coupled General Circulation Model, Japan
CGCM	Canadian Centre for Climate Modelling and Analysis Coupled General Circulation Model, Canada	MTL	Mean Tide Level
CMIP3	Coupled Model Inter-comparison Project phase 3	NAPA	National Adaption Programme for Action
CRU	Climate Research Unit, UK	NAR	National Assessment Report
DIRAM	Detailed Island Risk Assessment in Maldives	NASA	National Aeronautics and Space Administration, USA
DNP	Department of National Planning	NCAR	National Center for Atmospheric Research, USA
ECMWF	European Centre for Medium-Range Weather Forecasts	NCEP	National Center for Environment Protection, USA
EEIO	Eastern Equatorial Indian Ocean	NDMC	National Disaster Management Council
ERA	ECMWF reanalysis	NOAA	National Climatic Data Center, USA
ERA-40	40-year ECMWF reanalysis	NOC	National Oceanography Centre
ESRL PSD	Earth System Research Laboratory Physical Sciences Division	NRA-50	50-year NCEP reanalysis
FNCM	First National Communication from Maldives to UNFCCC	OAR	Office of Oceanic and Atmospheric Research, NOAA
GCM	General Circulation Models	OND	Northeast monsoon months (October, November and December)
GCOS	Global Climate Observing System	ppm	Parts per million
GEWEX	Global Energy and Water Cycle Experiment	PSMSL	Permanent Service for Mean Sea Level
GFDL	Geophysical Fluid Dynamics Lab	RegCM	Regional Climate Models
GHCN	Global Historical Climatology Network	RCM	Regional Climate Models
GHG	Greenhouse gas	RIMES	Regional Integrated Multi-Hazard Early Warning System for Africa and Asia
GMSL	Global Mean Sea Level	RMSD	Root mean square difference
GPCP	Global Precipitation Climatology Project	SAARC	South Asian Association for Regional Cooperation
GSN	GCOS Surface Network	SDSM	Statistical Down Scaling Model
HadCM3	Hadley Centre Coupled Model, Version 3, United Kingdom	SMRC	SAARC Meteorological Research Centre
IPCC	Intergovernmental Panel on Climate Change	SOI	Southern Oscillation Index
IPRC	International Pacific Research Center	SRES	Special Report on Emission Scenarios, IPCC
ISM	Indian Summer Monsoon	SST	Sea Surface Temperature
JJAS	Southwest monsoon months (June, July, August and September)	TRMM	Tropical Rainfall Measuring Mission
MHAHE	Ministry of Home Affairs, Housing and Environment	UNDP	United Nations Development Programme
MHE	Ministry of Housing and Environment	WCRP	World Climate Research Programme
MMS	Maldives Meteorological Service	WDCC	World Data Center for Climate
MPI ECHAM	Max Planck Institute for Meteorology (MPI), European Centre/Hamburg Model (ECHAM), Germany	WMO	World Meteorological Organization
		WNPM	Western North Pacific Monsoon
		ZOS	Sea surface height





**REVIEW OF EXISTING CLIMATE
CHANGE MODELING INFORMATION**

CHAPTER. 1

1. INTRODUCTION

1.1 Background

Under the National Adaptation Programme of Action for Maldives, the Ministry of Housing and Environment (MHE), Government of Maldives, in collaboration with the United Nations Development Programme (UNDP), is implementing the first climate change adaptation project entitled “Integrating Climate Change Risks into Resilient Island Planning in the Maldives”. Generation of better information on potential climate change effects on atoll and island level risks is one of the key outputs of the project. This involves review of past climate change studies and data analysis, and production of downscaled climate change scenarios for the Maldives, to guide national and local planning. The Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES) is implementing this component of the project.

RIMES component of the project, i.e. the development of high-resolution regional climate change model for the Maldives through statistical and dynamical downscaling of global climate change models to provide projections for use in national and local planning, aims to: a) identify appropriate global climate change models, based on their relative veracity to simulate the climatology of the Indian Ocean region centered over the Maldives; and b) downscale climate change projections, and enable interpretation of impacts for use in national and local planning. Work shall be undertaken in three stages: 1) Review of existing information on climate change modeling and observed climate data and trends pertaining to the Maldives; 2) Identification of a suitable set of global climate models, and downscaling, using appropriate dynamical and statistical downscaling techniques, based on the unique geographical and climatological context of the Maldives; and 3) Interpretation of the climate change scenarios into climate change impact outlook and disaster risk profiles, and communication of results through technical report, meetings and workshop.

This chapter presents a critical review of the climatological and modeling information available from previous studies carried out in the Maldives. It begins with a brief introductory chapter giving a background of the project, and presents the review approach and the unique climate context of the Maldives. The next two main chapters provide a review of available information on observed trends of climate variables, including sea-level rise, and the climate change projections from climate models. The concluding chapter briefly outlines the strategy in proceeding further.

1.2 Approach for the Review

The review involved:

1. Examination of important publications of the Maldives government that consider future climate change projections (Table 1.1), and identification of the extent of climate change modeling information available, data used, quality of results obtained, and projected or interpreted impacts.
2. Preliminary assessment of the climate data sets provided by the Maldives Meteorological Services to RIMES, and identification of datasets needed and available for downscaling.
3. Data quality check, and identification of data gaps and recommendations.

Figure 1.1 Documents reviewed for climate change modeling study

S. No	Report	Published Year	Agency Responsible
	First National Communication of the Republic of Maldives to the United Nations Framework Convention on Climate Change (MHAHE, 2001)	2001	Ministry of Home Affairs, Housing and Environment, Maldives
	National Assessment Report (MHTE,2010)	2010	Department of Climate Change and Energy, Ministry of Housing, Transport and Environment, Maldives
	National Adaptation Programme of Action (MEEW, 2007).	2007	Ministry of Environment, Energy and Water
	Detailed Island Risk Assessment in Maldives	2010	Disaster Risk Management Programme, UNDP Maldives

1.3 Maldives – A Unique Geographical Setting

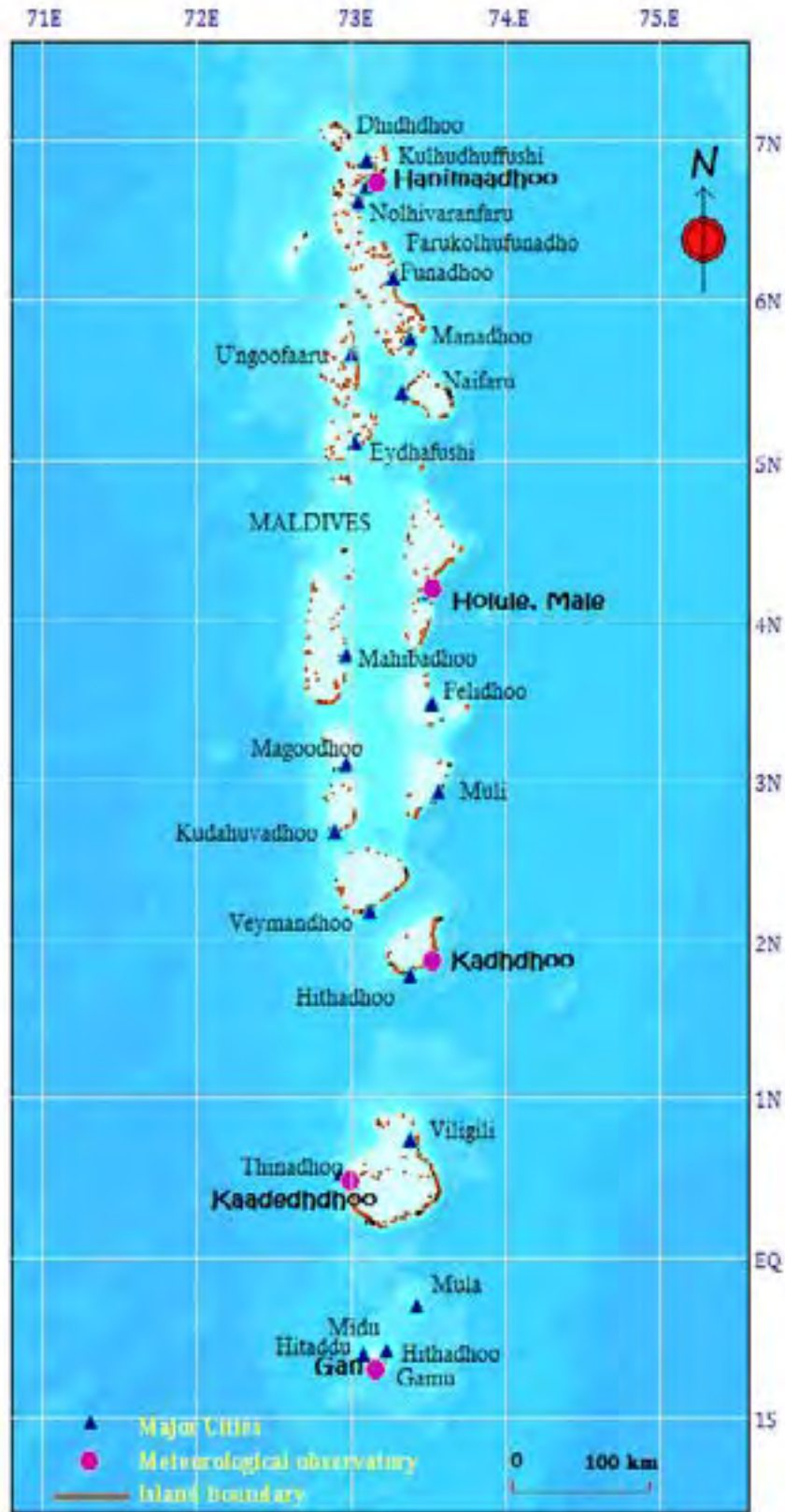
Maldives, an archipelago of 1,190 islands, grouped into 26 atolls, is located in the Indian Ocean, to the southwest of the Indian sub-continent. The islands stretch 860km from latitude 7o6'35"N, crossing the Equator to 0o42'24"S, and lying between 72o33'19"E and 73o46'13"E longitude (Figure 1.1). The islands are very low-lying, with more than 80% having an elevation of less than 1m above mean sea level; none exceeds an elevation of 3m (MHAHE, 1999). Coral reefs surrounding the islands protect the inhabitants from adverse impacts of strong waves. Only 200 of the total number of islands are inhabited, with combined population of 395,000 (July 2011 estimates, The World Factbook). The main contributors to the economy are the tourism, fisheries, construction, and commercial sectors. The tourism and fisheries sectors are very much dependent on the coastal environment of Maldives.

The islands' geophysical characteristics predispose the country's propensity to natural hazards. Its geographic location near the equator in the Indian Ocean exposes Maldives to tropical storms and storm surges, swell waves, gale-force winds, heavy rainfall, drought, as well as tsunamis and earthquakes. Floods occur from heavy rainfall, storm surges, or from swells generated by storms from the far south. The small size of the islands and their low elevation make human settlements defenseless against severe weather events, as well as tsunamis, as retreat inland or to

higher grounds would be impossible (MHTE, 2010). Also, accelerated sea level rise due to climate change will have devastating effects on the islands, and can threaten their very existence (MHAHE, 2001). Combined with high waves, increase in sea level increases flood risks and rate of erosion that would lead to alteration of beaches (Tariq, et.al, 2002). The powerful swell that occurred from 15-19 May 2007, during high tide, caused substantial flooding and soil erosion in many islands (NDMC, 2007).

Maldives has a warm and humid tropical climate, dominated by two monsoon periods: the southwest monsoon (wet period, from May to November); and the northeast monsoon (dry period, from January to March) (MEEW, 2007). Annual average rainfall is 2,124mm. The southern atolls receive, on average, 2,277mm of rainfall annually, while the relatively drier northern atolls receive 1,786mm (MHTE, 2010). No significant long term trends are evident in the observed daily, monthly, annual or maximum daily rainfall. Analysis of past daily rainfall data revealed that 160mm of rainfall in a day is a relatively rare event at Hulhul , with a return period of 17 years, while an extreme daily rainfall of 180mm is a 100-year event.

Figure 1.2 Geographic location of the Maldives



The islands and associated bottom topography influence circulation patterns in the Maldives. Ramamirtham's (1979) study of the ocean circulation patterns in the region 71° to 80°E and the equator to 8°N revealed that a large cyclonic gyre exists in the northern regions and an anticyclonic one in the southern region, mainly in the subsurface layers. The monsoon current and equatorial counter-currents join and attain high speed, south of the Indian peninsula; the reflection of equatorial counter-currents is due to the bottom configuration in this area. Thus the large cyclonic and anticyclonic gyres observed can, in all probabilities, be the extended patterns of the monsoon currents in this area.

The ENSO influence often propagates across the tropical Indian Ocean from Africa to Indonesia, modulating the troposphere moisture flux over the Indian Ocean and rainfall

in surrounding continents. The eastern 'node' is confined near Sumatra, while the western center of action extends from the Maldives to the Seychelles Islands. Studies have been conducted to understand the relation between Southern Oscillation Index (SOI) and Sea-Surface Temperatures (SST) around the Maldives. Correlations indicate that the strength of ENSO in the Indian Ocean region has decreased in recent decades, while large scale, spatial and temporal patterns suggest independent variations of the Indian Ocean. Apart from annual variations of the monsoon and year-to-year fluctuations of climate, short-term weather events have a dramatic impact on countries around the Indian Ocean. Such relationships could be valuable for evolving statistical downscaling methods. More details of ENSO studies are mentioned under chapter 2.4.

2. OBSERVED TRENDS AND VARIATIONS

Observed climate datasets are key input for downscaling climate change scenarios. Observed data from surface observatory and satellite-based estimates shall be used in this project. Table 2 details the available climate datasets.

Climatology studies have been carried out with long time series data, available from Male and Gan stations, to understand the northern and southern climate characteristics of Maldives. Seasonal and annual characteristics are explained under chapter 1.3. Daily characteristics are as follows: daily temperature varies between 31°C and 23°C; mean daily maximum temperature is 30.4°C, and mean daily minimum temperature is 25.7°C. Humidity ranges from 73 to 85%.

these are considered as unreliable, as they have not yet been validated by the Maldives Meteorological Service. Presently, Maldives has 20 Automatic Weather Stations throughout the country; ten were recently installed in 2009. Observation stations are located in various atolls, which might help to analyze the climatology over every two degree of the grid boxes.

2.1 Availability of Observed Datasets

The current observatory network for Maldives is very sparse. Historical data are available for five meteorological stations: Hanimaadhoo, Male, Kadhdhoo, Kaadedhdhoo and Gan. Though some data are available from few more stations,

Table 1.1 Available observed climate datasets and their sources

S. No	Observational dataset	Data type	Parameter	Period	Source
1	Global surface summary of day data (GHCN)	Station	Tmean, Tmax, Tmin, Prec, SLP, WS (daily)	1973 to 2011	NOAA National Climatic Data Center, USA
2	GSN monthly climate data	Station	Tmean, Tmax, Tmin, Prec (monthly)	1966 to 1992	NOAA National Climatic Data Center, USA (97.5% data available)
3	CRU monthly climate data	Grid at 0.5X0.5 deg	Tmean, Precipitation (monthly)	1901 to 2006	Climate Research Unit, UK
4	NCEP reanalysis data	Grid	Ua, Va, MSLp, Rhur, Shur	1961 to 1990	Canadian Institute for Climate Studies and NCEP
5	Terrestrial air temperature and precipitation	Grid at 0.5X0.5deg	Prec, Tmean (Monthly)	1950 - 1999	University of Delaware
6	Global precipitation climatology project (GPCP)	Grid at 0.25X0.25deg	Prec (Monthly)	1975 to 2010	Global Energy and Water Cycle Experiment (GEWEX),
7	Tropical rainfall measuring mission	Grid at 0.25X0.25deg	Prec	1998 to 2010	NASA - Goddard Earth Sciences (GES) Data and Information Services Center (DISC).
8	Surface observatory parameters		Prec, Tmax, Tmin, Tmean (daily)	1975 to 2010	Maldives Meteorological Service

Base data for the period 1960 to 1990 is widely used in downscaling climate scenarios. Maldives, however, lacks historical information from 1960; hence, this project considers a base period of 1975 to 2005. Since available observation data is insufficient in terms of spatial and

temporal requirements, it is proposed to use various global observed climate datasets, such as CRU and TRMM, to the maximum possible extent. Data quality checks have been performed on observation data from the Maldives Meteorological Service (Table 3).

Table 1.2 Data quality checks for collected observatory data from MMS

Station	No of Missing Cells		% data available	
	Rainfall	Temperature	Rainfall	Temperature
Hulhule	0	0	100.00	100.00
Gan	1203	1228	90.85	90.66
Kadhoo	5479	5485	58.33	58.29
Hanimaadhoo	6209	6209	52.78	52.78
Kaadeddhoo	6940	6942	47.22	47.21

From the data quality checks, two stations (Hulhule and Gan) have been identified as useful in correlating long term record (>80% data available) to a global climate model grid, which might lead to achieve statistically significant result relevant for the Maldives context. All stations have continuous datasets, except for three stations (Kadhdhoo, Hanimaadhoo and Kaadedhdhoo) which have observations only from 1990, 1991, and 1994, respectively. Data issues shall be resolved through spatial statistics of inter-relating station data, to build a climate surface for at least five locations.

2.2 Trends and Patterns in Climate Parameters

Annual and monthly climatology plots for precipitation and maximum and minimum temperatures have been prepared, using observed climate data received from Maldives Meteorological Services for the period 1975 to 2010, to understand the annual and monthly variation and trends over the Maldives region. Annual anomaly of climate parameters is estimated and plotted to understand the historical trend.

Trend analysis in previous studies (MHAHE, 2001) used climate datasets from 1969 to 1997. The current study used a decade of additional data, hence should give a better trend analysis. The MHAHE study (2001) indicated a rate of change in total annual rainfall per decade of -2.7mm and -7.6 mm in Male and Gan stations, respectively. Our preliminary analysis shows a rate of change of -0.43mm and -3.6mm in Hulhule and Gan, respectively (Figure 1.2). Monthly rainfall deviates from -200mm to 300mm, with very few anomalies close to or more than 400mm.

In terms of long-term annual maximum and minimum temperatures, the MHAHE study (2001) showed a rising trend for the Male station, with annual maximum temperature increase of 0.17°C every 10 years, and annual minimum temperature increase of 0.07°C every 10 years. Our preliminary analysis (Figure 1.3) shows an increasing trend in mean and minimum temperatures in both northern and southern parts of the Maldives. Maximum temperature shows an increasing trend in the northern part of the Maldives, but a decreasing trend in the southern part. Further detailed trend analysis will be carried out to understand the climate variations to be used in statistical downscaling and in evaluating model fit.

Attempts have been made to identify the correlation between SOI and climate parameters in Maldives. Tariq, et.al (2002) found that SOI leads the monthly maximum temperature anomaly. In Male, maximum temperature anomaly shows out-of-phase relationship with SOI, except in 1973-1974, 1982-83, 1986-87, earlier nineties, and 1997-98, when

the maximum temperature showed delayed response to SOI. This pattern was also found evident at Gan, with the exception of 1982-83 when a spontaneous response in temperature to SOI was observed. It has to be noted that the relationship is not a simple one. Many other parameters, like sea surface temperature, cloudiness, and rainfall distribution, also play very vital roles interactively. SOI has been identified as one of the key parameters in understanding climate variability. Further analysis is in progress to understand these links from a statistical downscaling predictant context.

Monthly climatology from the observed datasets (1975 to 2010) has been derived and represented in Figure 1.4. This helped to identify rainfall peaks, which are the months May and September. These peaks have been well marked in all other stations, illustrating the strong signal of the two monsoon seasons in the rainfall climatology of the islands. Gan and Male/ Hulhule stations, having continuous and longer-term data, will be considered for further evaluation, for use in model validation.

Rainfall in Maldives varies from north to south, with the amount of rainfall increasing towards the south. This difference in rainfall pattern is primarily due to the northeast monsoon, and April being much drier in the north than in the south (Edwards, 1989). This pattern is captured in the monthly climatology chart (Figure 4).

Figure 1.3 Monthly rainfall series trend chart for Maldives from 1975 to 2010

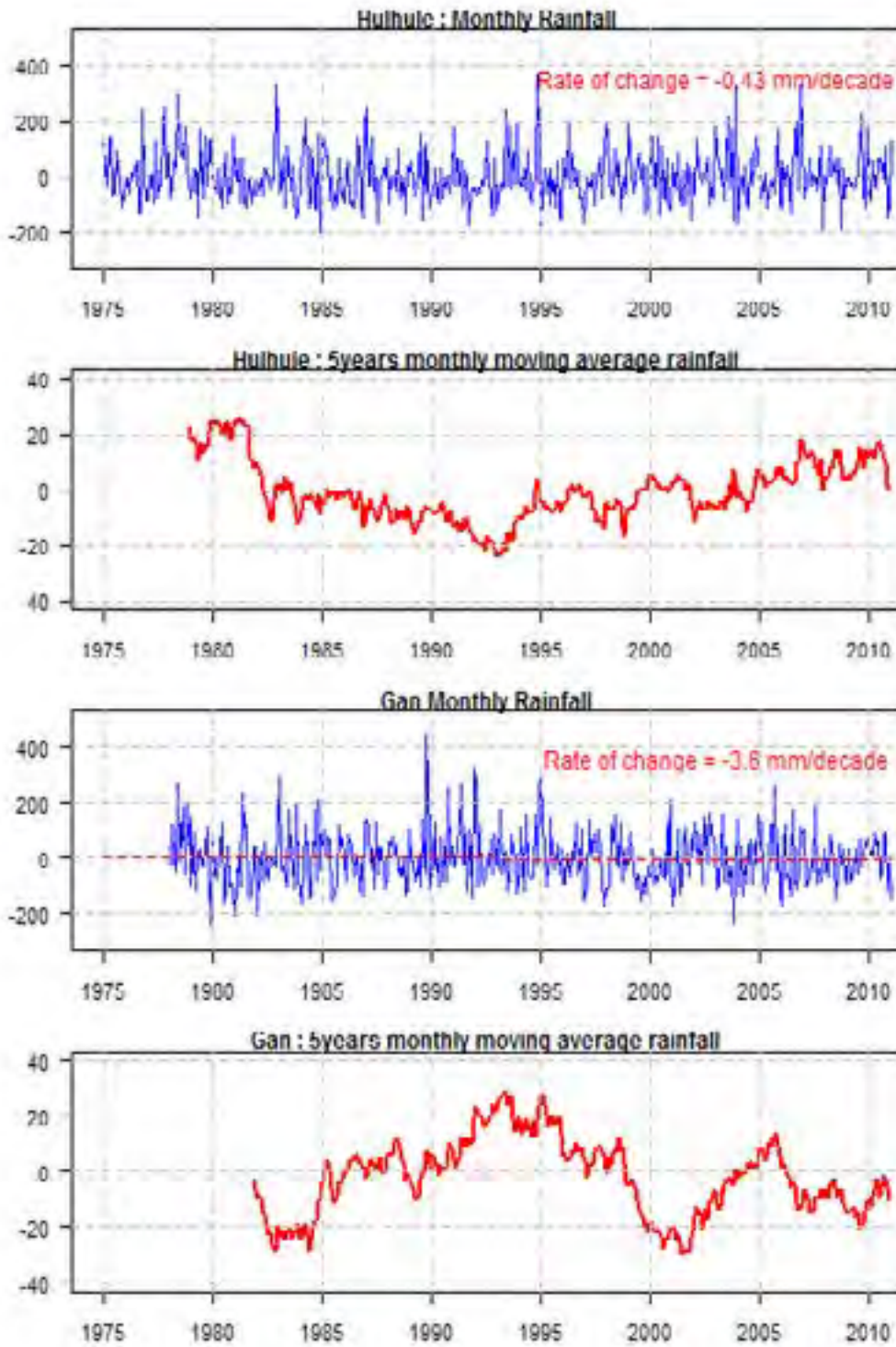


Figure 1.4 Maximum and minimum temperature anomalies in Maldives from 1975 to 2010

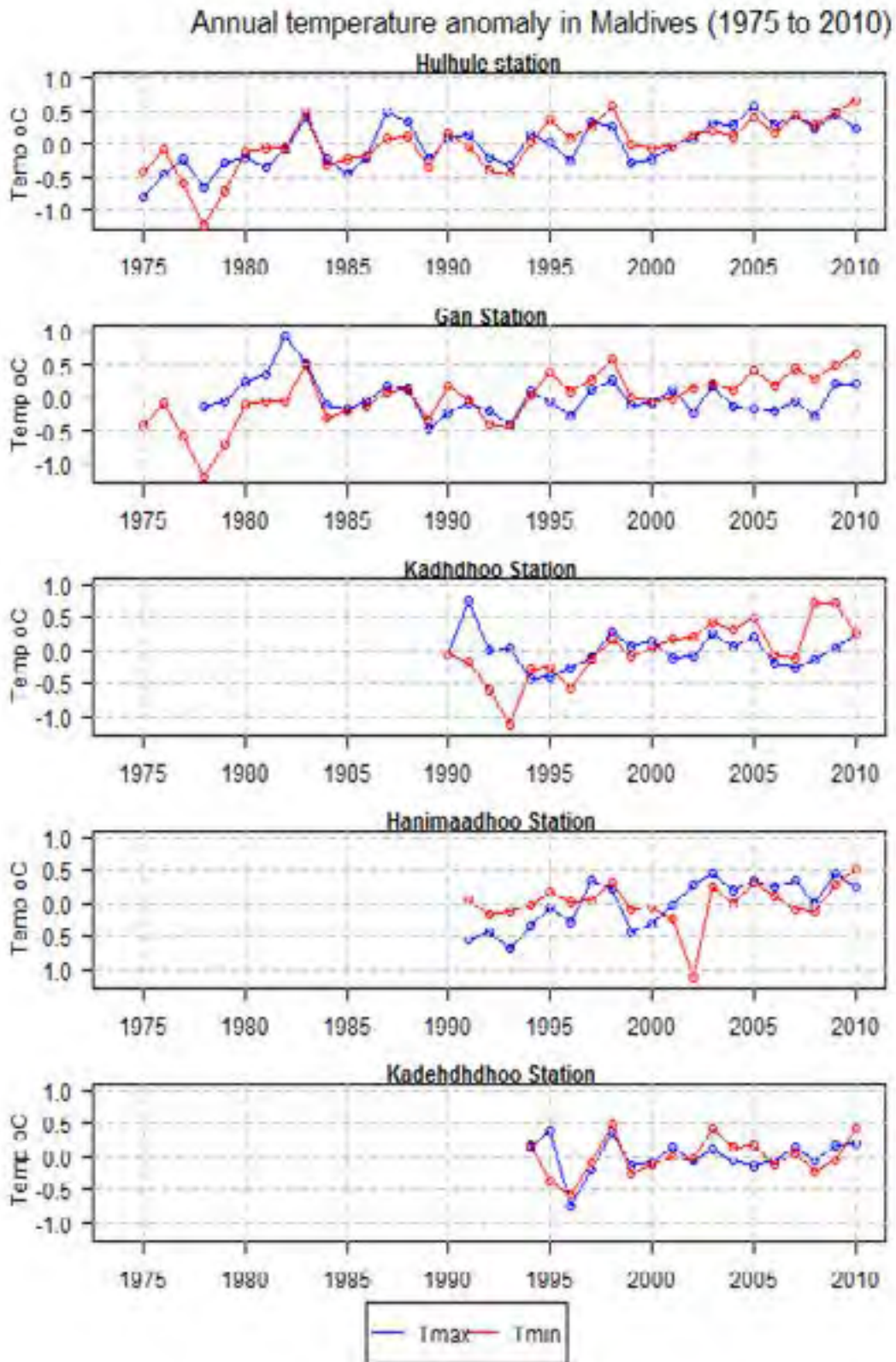
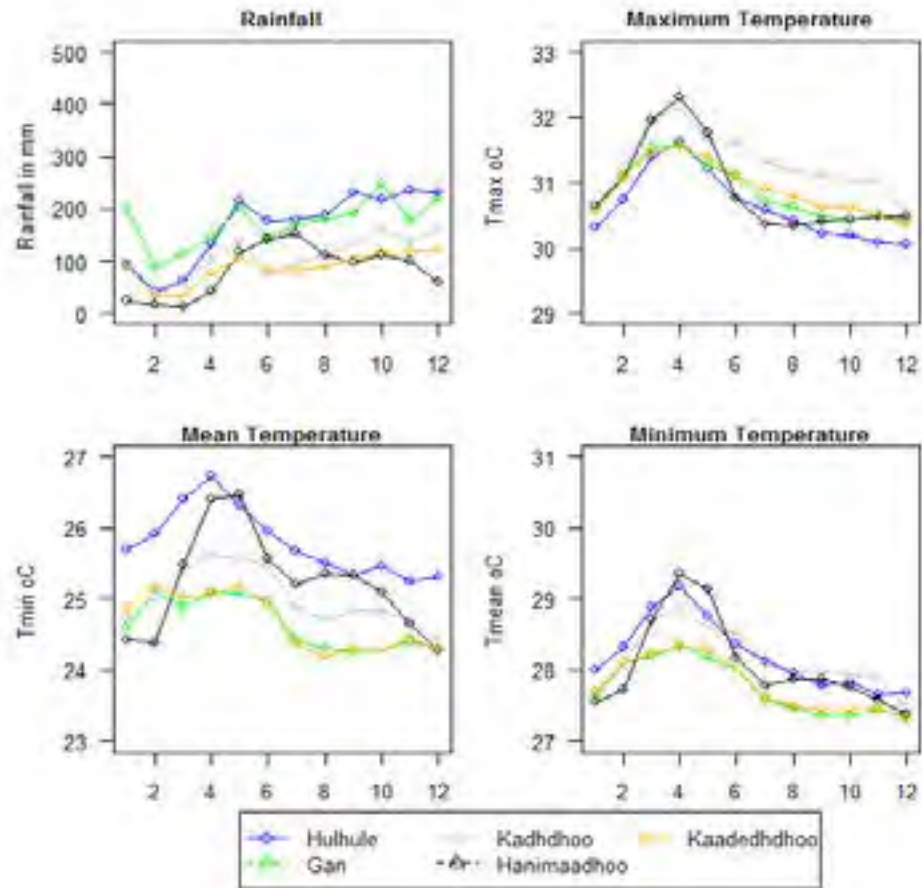
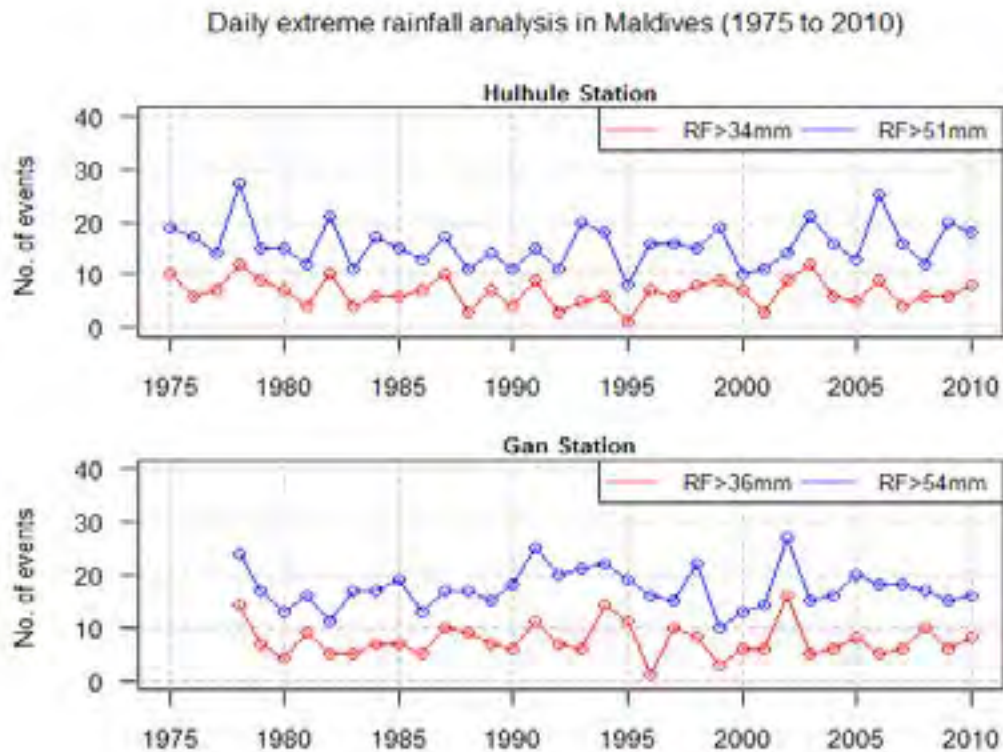


Figure 1.5 Monthly variations of climate parameters in Maldives



The occurrence of extreme rainfall events in a year are represented in Figure 1.5, estimated using the standard deviation of recorded rainfall. From analysis of available data, the trend in the number of extreme event days with rainfall > 34mm and rainfall > 51mm for Hulhule is -0.01 and -0.29, and for Gan, with rainfall > 36mm and rainfall > 54mm, is 0.04 and -0.14. Further analysis, including the use of satellite-derived data sets, will be made to cross-check and establish suitable connections for undertaking statistical downscaling and evaluating dynamically downscaled output.

Figure 1.6 Extreme rainfall analysis in Maldives from 1975 to 2010



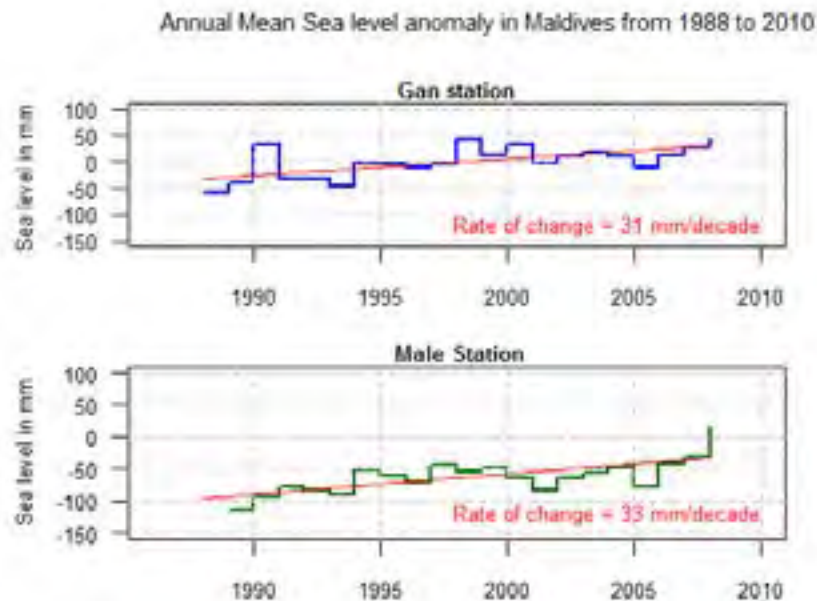
2.3 Sea Level

Maldives, being an island nation, is more vulnerable to sea-level rise and associated impacts of climate change. The National Assessment Report II (2010) states that a slight increase in sea level is threatening to the Maldives, since 80% of the country's land area is less than a meter above mean sea level. This is further complicated by tide variation. Many islands are already suffering from inundation and shoreline erosion because of their low elevation. Maldives uses the Intergovernmental Panel on Climate Change (IPCC) fourth assessment report estimate of a 0.18 to 0.59 meter sea level rise by the mid-2090s for adaptation planning. This estimate is based on projections from 17 different global climate models, for six different future emission scenarios.

Understanding the historical trend of sea level change from available data and appropriate estimation of sea level changes are among the key activities in this study. Review of existing literature and examination of datasets from the Permanent Service for Mean Sea Level (PSMSL) was undertaken. Morner (2004) recently reported on sea level change in the Maldives and its vulnerability to this change.

The study showed that there had been a 30cm fall in sea level in the Maldives over the last 50 years. Woodworth & Player (2003) and Church et al. (2004), however, using PSMSL data sets for Gan, Male and Hanimaadhoo, and calculating and analyzing the annual mean sea level, reported an increase in sea level of 30.7mm and 35.2mm in a decade for Gan and Male stations, respectively. This increasing trend was also reported by Singh et al. (2001) and DIRAM (2010), with rates of sea-level rise projected at 8.4mm/yr, 3.7mm/yr, and 4.4mm/yr for Gan, Male and Hanimaadhoo stations, respectively. PSMSL records for these three stations are, however, short, having started only in 1988 (Figure 1.6), and, therefore, cannot represent longer-term trends. No attempt has been made for evaluating the records using datum correction, error estimation, etc.

Figure 1.7 Annual mean sea level variations in Maldives from 1988 to 2008



Errors in the above-mentioned sea level projections could be less than 2mm/year, and are likely to be underestimated because the record is so short that it is not possible to reliably estimate an integral time scale. The above reports argue that these gauges may be significantly affected by vertical land motion. The rates over the 52-year period from the reconstruction are 1.0, 1.0 and 1.2mm in a year at the three sites, respectively.

Sea level changes are generally local in nature, being affected by a complex combination of local, regional, and global processes, which operate on different time and space scales. SST is one of the most important climatic parameters affecting sea level variations (Tariq, et.al, 2002). However, reconciling this analysis with satellite-based information and sea surface elevation parameter from GCM might give a better understanding of the trend and projection, which is planned to be carried out under this project. Results of the review indicate that there is a need for very careful interpretation in order to arrive at realistic risk estimates for sensitive coastal zones.

2.4 Sea Surface Temperature

Average monthly Sea Surface Temperature (SST) ranges from 28°C to 29°C. An increasing trend in SST has been observed. Annual mean SST trends at Hulhule and Gan are -0.2 to 0.2 and 1.1 to 1.6 per decade, respectively (MEEW, 2007).

The study by Tariq, et.al (2002) on the relationship of Mean Tide Level (MTL) with SST along the Maldives coast showed a strong linear relationship. The relationship was found to be stronger when smoothed data were used. The correlation coefficient (r) values for actual and smoothed data are, respectively, 0.65 and 0.83 for Male, 0.53 and 0.59 for Gan. The possible influence of ENSO on SST and sea level within the Maldives has been studied previously (Tariq, et.al, 2002). SST is an important parameter because of its change might affect Maldives' coral reefs (coastal eco system). Understanding SST historical change and projection is, therefore, essential for coastal ecosystem impact assessment.

CLIMATE CHANGE SCENARIO RESULTS

2.5 General Circulation Models

A General Circulation Model is a mathematical model of the general circulation of a planetary atmosphere or ocean, used for simulating the atmosphere or ocean of the Earth. GCMs are widely applied for weather forecasting and projecting climate change.

Two reports provide significant information on climate change and modeling information for the Maldives: 1) First National Communication to UNFCCC and 2) DIRAM report. It is noted, however, that both these studies did not attempt to validate climate models or undertake site-specific assessments, as time and resources were limited. This project, therefore, has strategic importance in generating downscaled climate information, with adequate validation. The first national communication report to UNFCCC, prepared by Maldives in 2001, analyzed the historical rainfall, temperature, and wind speed trends for Male and Gan, where datasets are available from 1969 to 1999. Climate change projections, based on IPCC's (AR3) emission scenarios IS92a and IS92e for GCMs CSIRO-MK2 and HadCM2, have been used and summarized in Table 4. These, however, need to be updated with AR4 scenarios. Also, a limited number of model results have been used.

An extreme three-hourly rainfall of 100mm is currently a 25-year event. It will likely become at least twice as common, on average, by 2050. Previous studies emphasized the likely climate change impacts, such as changes in weather patterns

(temperature, winds, precipitation, etc), sea-level rise, coastal erosion, and changes in the frequency of extreme events.

Sea level data (tidal data) from the University of Hawaii Sea Level Center for the three tidal stations (Hanimadhoo, Male and Gan) are used to analyze the historical sea level trend.

In the present downscaling study for Maldives, a subset of eight GCMs (Table 5), from the World Climate Research Programme's (WCRP's) Coupled Model Inter-comparison Project phase 3 (CMIP3) that were used in the IPCC Fourth Assessment Report (2007), would be considered. Maldives' geographical extent is captured by approximately four to five grid boxes in GCMs, depending on their respective resolutions. Firstly, the historical base period climate information will be constructed for five locations, then this information shall be used to determine correlations with the model grid boxes to understand its relationship with the model control, as well as with other regions where observed data is not available. These statistics will be used also to identify the most suitable GCMs for further downscaling, depending on their capability to simulate the observed climatological features over the Maldives region, particularly the monsoon circulation.

Table 1.3 Climate change scenarios from Maldives First National Communication to UNFCCC

Year Model /Scenario	2025			2050			2100		
	Temp (°c)	Rainfall (%)	Sea level (cm)	Temp (°c)	Rainfall (%)	Sea level (cm)	Temp (°c)	Rainfall (%)	Sea level (cm)
CSIRO.MK2 IS92a(mid)	0.4	1.6		0.9	3.0		2.0	5.9	
CSIRO.MK2 IS92e(high)	0.6	2.5		1.4	3.6		2.8	8.1	
Hadcm2 IS92a(mid)	0.7	12.1	9.3	1.4	23.0	19.9	2.6	44.3	48.9
HADCM2 IS92a(high)	1.0	18.9	19.7	1.7	38.6	39.7	3.8	77.4	94.1

Table 1.4 Summary of available GCMs

S.No	Model Name/ horizontal res.	Grid details specific for Maldives	Source	Available Climate variables
1	CSIRO (200 X200Km ²)	5 grid points	Commonwealth Scientific and Industrial Research Organization, Australia	Tmean, Prec, (control & model)
2	GFDL CM (400X400 km ²)	5 grid points	Geophysical Fluid Dynamics Laboratory Climate Model, USA	Tmean, Prec, (control & model)
3	NCAR (280 X280 Km ²)	4 grid points	National Center for Atmospheric Research, USA	:Tmean, Prec, (control & model)
4	HadCM3 (417X278Km ²)	8 grid points	Hadley Centre Coupled Model, Version 3, United Kingdom	Monthly data :Tmean, Prec, (control & model)
5	BCCR BCM (300X300 Km ²)	4 grid points	Bjerknes Centre for Climate Research (BCCR) Bergen Climate Model (BCM), Norway	Monthly data :Tmean, Prec, (control & model)
6	CGCM (280X280 Km ²)	4 grid points	Canadian Centre for Climate Modelling and Analysis Coupled General Circulation Model, Canada	Monthly data :Tmean, Prec, (control & model)
7	CNRM (300X300 Km ²)	4 grid points	Centre National de Recherches Météorologiques, France	Monthly data :Tmean, Prec, (control & model)
8	MPI ECHAM (140x210 Km ²)	5 grid points	Max Planck Institute for Meteorology (MPI), European Centre/Hamburg Model (ECHAM), Germany	Monthly data :Tmean, Prec, (control & model)

2.6 Regional Downscaling Results

Global climate models represent physiographic features, such as terrain and coastlines, much more smoothly than the real world, and it cannot properly include many atmospheric processes because of its coarse resolution (Raymond, 2009). Regional downscaling methods allow us to derive the finer resolution information from larger-scale weather and climate model output from global climate models. Regional downscaling involves the development of climate information for a point, or small area, from coarse resolution climate model scenarios (Wilby & Miller, 2009). Regional climate downscaling techniques, including both dynamical and statistical methods, are increasingly being used to produce regional climate information to carry out site-specific climate change impact and adaptation studies. None of the past studies reviewed use regional downscaling methods for climate change assessment studies in the Maldives. To address this significant gap, dynamical and statistical downscaling of GCMs will be carried out in this project.

Dynamical downscaling methods involve dynamical models of the atmosphere, nested within the grids of the large-scale

climate models. Typically, one-way nested regional climate models are implemented to produce finer-resolution gridded information for applications, with coarse-resolution models providing initial and lateral boundary conditions. The advantage of using dynamical downscaling is that the physics of the models provide justification for their application under a variety of weather and climate conditions in a changing climate, especially for situations with strong boundary forcing, such as mountainous terrain, land-sea interfaces, etc. For dynamical downscaling, appropriate GCM and emission scenarios for the Maldives, with suitable set of proven diagnostic climate variables, will be chosen. Dynamically downscaled results will be obtained by forcing one of the GCMs identified, using a Regional Climate Model that has been validated over the Indian Ocean region. Regional model runs for the spatial domain covering Maldives (Lat 10N–5S and Lon 70E–75E) for all the standard climate variables control and emission scenarios would be used. The dynamical downscaling scenarios generated would cover three typical time horizons, representing medium- and long-term changes, corresponding to 2030-50s, 2050-2080s and

2081-2100s. These gridded dynamically downscaled results, with higher resolution than GCMs, shall provide the regional scenario for most of the atolls in the Maldives.

Statistical downscaling involves developing quantitative relationships between large-scale atmospheric variables (predictors) and local surface variables (predictands). SDSM is a user-friendly software package designed to implement statistical downscaling methods to produce high-resolution monthly climate information from coarse-resolution climate model (GCM) simulations. The software also uses weather generator methods to produce multiple realizations (ensembles) of synthetic daily weather sequences (Wilby et.al, 2007). For statistical downscaling, SDSM and other statistical tools will be used to downscale the results. This technique derives statistical relationships between observed small-scale (often station level) variables and larger-scale (GCM) variables, using analogue (circulation typing), regression analysis, or neural network methods. Future values of the large-scale variables obtained from GCM projections of future climate are then used to drive the statistical relationships, and so estimate the smaller-scale details of future climate (weather generators). This will be able to provide location-specific climate change scenarios, wherever we have long-term observed datasets.

2.7 Data Validation and Significant Gaps

Historical datasets. Data quality checks were made for five observatory station data in Maldives; of these, two stations have more than 80% of data for the period 1975-2010. Observed datasets from Male and Gan stations will be used for statistical downscaling of GCMs.

Regional modeling results. Regional downscaled products, either dynamical or statistical downscaled climate change scenarios, have not been used in the existing climate change impact assessment studies. Hence, the present work will enable better characterization of the changes. However, the non-availability of long-term data for the main locations would impose limits to the confidence of the regionally downscaled estimates from both the approaches. With accumulating data from the newly established automatic weather station network, it would be possible to improve the confidence of the regional projections in future, beyond the project period.

Predictors and predictands. Observed and scenario data for predictand parameters, such as precipitation and temperature data, are available easily; however, the observed predictor parameters are few. NCEP predictor parameter, as observed values, has to be used. This will restrict the

applicability of the statistical downscaling method, which is expected to be overcome to a certain extent, using satellite-derived data sets.

Satellite-based products. Climate Research Unit observed grid data were checked, and found to have value for only two grid locations, based on the observed station data from Male and Gan. Tropical Rainfall Measuring Mission (TRMM) data has been checked, available for Maldives region with resolution of 0.25 X 0.25 degree. These datasets can be used for substantiation of the observed data over the Maldives. This is, however, limited by the availability of data, which starts from year 1997, so it is possible to use 13 years of datasets in this study.

Table 1.6 summarizes the gaps identified in this study.

Table 1.5 Summary of gaps identified

Items	Existing	Gaps Identified
Observed climate datasets	Data available for limited years	Lacking Spatial and temporal distribution of datasets.
Global Climate Models	IPCC AR3 scenario has been used for two models.	More recent AR4 scenarios not used. Only two models were used Multi-model ensembles not yet tried. No model verification carried out.
Regional Climate Models	No regional model results available	Dynamically downscaled model products not available. Lacking statistically significant downscaled climate information
Climate change Impacts	Projected extreme events and impacts, like sea level rise, etc., available without appropriate climate change base.	No appropriate climate change information used in interpreting impacts Location-specific impacts are not yet done No proper evaluation of sea level rise

3. CONCLUSIONS AND RECOMMENDATIONS

Climate change scenarios used in existing studies are of coarse resolution and without adequate evaluation against observed data. This severely limits the confidence level of the results, for use in risk management strategies. Currently, there are three types of emission scenarios available for eight GCMs, which will be analyzed and the most suitable will be identified. These will be used for generating climate change scenarios through statistical techniques.

From the data quality checks, only two stations are identified to be useful for establishing linkages with long-term records from a global climate model grid. Statistical methods would be incorporated in this study to resolve data issues through spatial statistics of correlating station data, to build a climate series for at least five locations.

Location-specific climate change scenarios will be generated using statistical and dynamical downscaling techniques, with proper validation and evaluation techniques, to fit for the country's specific needs.

Appropriate sea level rise and sea surface temperature projections will be identified through extensive analysis of available information from observations and satellite-based estimates.

Interpretation of climate change scenarios will be carried out with the downscaled climate change scenarios to help in refining the DIRAM results, as well as for N\national and local planning.

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**GLOBAL CLIMATE MODEL AND
EMISSION SCENARIO SELECTION**

CHAPTER. 2

1. INTRODUCTION

This chapter presents a critical review of data quality issues and the process of selection of appropriate general circulation models (GCMs) and greenhouse gas (GHG) emission scenarios for climate downscaling. The chapter is organized under three sub-chapters, as follows:

1. Datasets: Brief on collected data, data quality, and gaps and their impact on downscaling results.
2. Evaluation of GCMs and Emission Scenarios: Screening of emission scenarios, models, variables, and predictors
3. Summary: Highlighting data issues and selection of GCMs and emission scenarios.

2. DATASETS

2.1 Observed Datasets

Observed datasets include surface climate observatory records, sea level, sea surface temperature, past severe weather events, and geographical elements database.

Data collection was carried out, with support from MHE, from various agencies, such as the Department of National Planning (DNP), National Disaster Management Center (NDMC), Marine Research Center (MRC), and United Nations Development Programme (UNDP). Maldives Meteorological Service (MMS) shared extensive information on observed climate datasets for available surface observatories, as well as useful climate reports.

2.1.1 Data availability

An initial data list was prepared and circulated to partner agencies, through MHE, for feedback. The stakeholders meeting, held at MHE on 14 June 2011, discussed data availability and quality issues. Based on these, the data list was finalized, as presented in Table 1.

Table 2.1 Data list and availability

SN	Parameter	Description	Source	Status
A Observed Weather Parameters				
1	Precipitation	24 hours accumulated rainfall for as many stations available	MMS	Data from 5 stations from 1975 to 2010 Discontinuous data for the period 1969 to 1974 for Male and Gan stations
2	Maximum/ Minimum Temperature	Daily observed maximum/ minimum temperature for all stations		
3	Wind Speed	Daily observed wind speed		
B Ocean Parameter				
1	Sea Level	Daily observed mean sea level (from tide gauges)	PSMSL	Data for 2 stations from 1988 to 2010
2	Sea Surface Temperature	Daily observed mean sea surface temperature (satellite-derived or observed information)	NOAA/OAR/ESRL PSD, Boulder, Colorado, USA	Data for the period 1961 to 1990
C Severe Weather Events				
1	Cyclone, Storm Surge, Flood, Extreme Rainfall	Historical disaster and impacts database	NDMC, UNDP	NDMA data not available. DIRAM data for the period 2000 to 2010
D Topography/ Bathymetry				
1	Digital Elevation Model	High resolution datasets for whole Maldives	Maldives Coast Guard	Available, but limited to Male Island
2	Topography / Bathymetry Charts	Scanned copies of topography/ bathymetry charts for areas where digital data is not available		Not available
E Geographical datasets				
1	Administrative Boundary	Island boundary, Atoll boundary maps	MHE	Available
2	Land Use	Land use shows settlement areas, agricultural lands, water bodies, forest, etc.,	MHE	Available
3	Houses/ Infrastructure Locations	House and infrastructure digital data (GIS files) for 10 pilot islands, generated from DIRAM project	DNP, UNDP	Households by island (2010) Location of houses, details, for DIRAM's 10 pilot islands
4	Population	Latest year population by islands/ atoll	DNP	2010 population data
5	Coral reef	Latest year coral reef available locations, characteristics map in and around Maldives	MRC	Reef database from World Fish Center-Reef Base Project MRC reports

2.1.2 Analysis

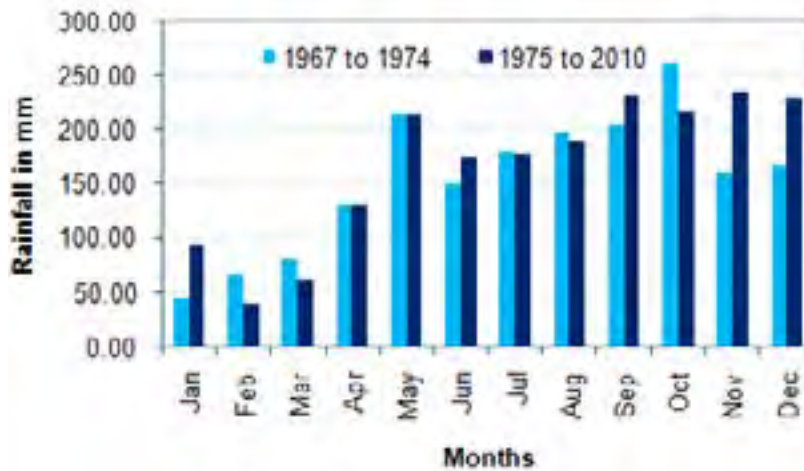
This chapter analyzes datasets acquired from June 2011 to August 2011, as supplement to the first report.

Precipitation. Additional precipitation data for the period 1967 to 1974 was acquired for Male station. These supplement historical climate data, earlier acquired, for the period 1975-2010 for five meteorological stations:

Hanimaadhoo, Male, Kadhdhoo, Kaadeddhoo and Gan.

Before extending the rainfall time series with the additional data obtained for Male, monthly precipitation data for these two periods were compared to establish homogeneity (Figure 2.1). Results show a close agreement amongst the two segments, enabling them to be collated for further use in statistical downscaling.

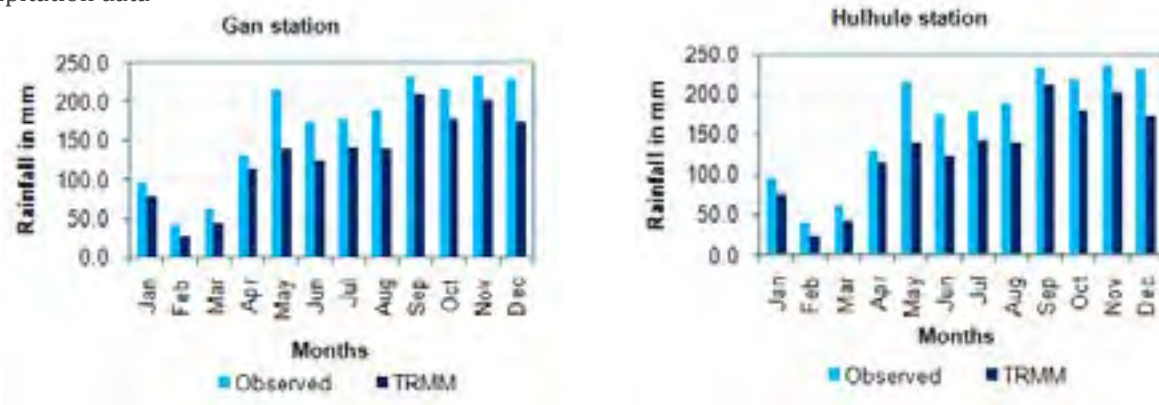
Figure 2.1 Monthly climatology comparison for Hulhule station



Tropical Rainfall Measuring Mission (TRMM) datasets are available at 0.25X0.25 degree resolution from 1998 to present. Datasets have been extracted for Maldives domain for a decade period (1998 to 2007) to compare with observed datasets at Hulhule and Gan station (Figure 2.2). Figure 2 illustrates a good agreement between TRMM rainfall

estimates and the observed rainfall at both the stations in terms of the seasonal climatology. This relationship between TRMM and station rainfall provides an opportunity to overcome the gaps in observed rainfall datasets to some extent. We will use such linkages to leverage improved statistical downscaling for Maldives.

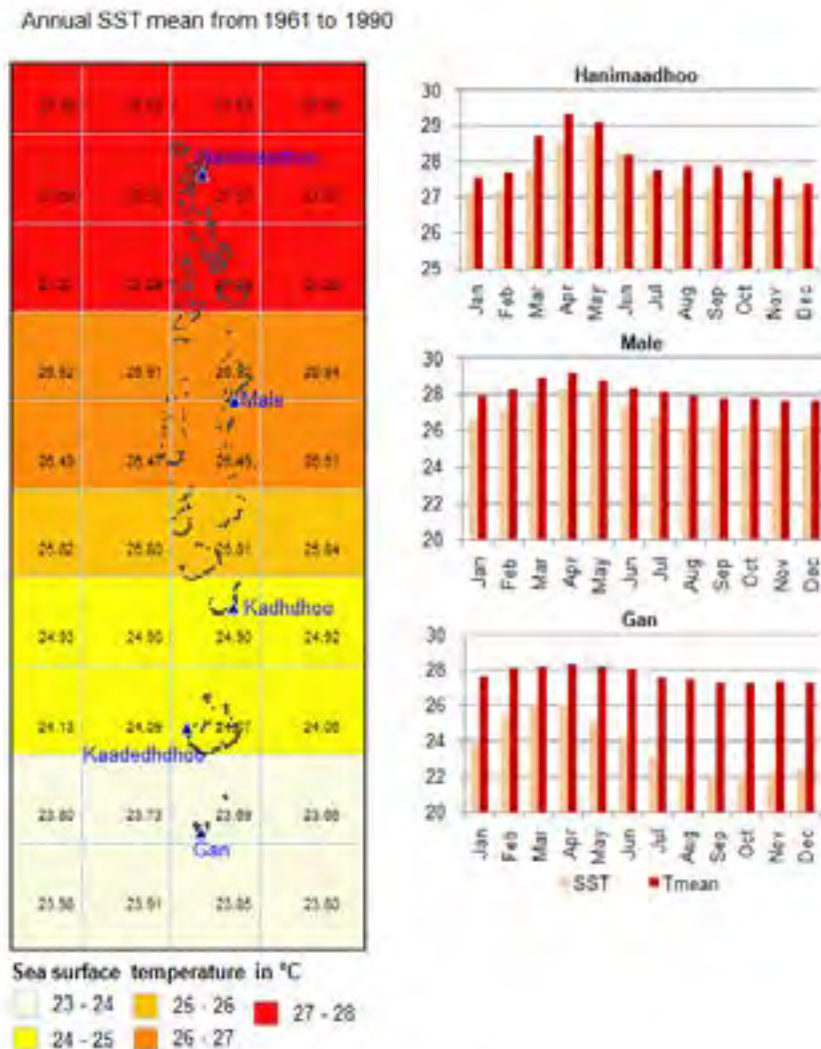
Figure 2.2 Comparison of TRMM and surface observatory precipitation data



Sea surface temperature. NOAA Global Optimum Interpolation (OI) Sea Surface Temperature (SST) Analysis dataset is available for the period 1982 to 2010 at 1degreeX1degree resolution for the entire globe. This data was processed by NOAA from monthly ship and buoy SST data, satellite SST retrievals, and SSTs simulated by sea ice cover. Monthly mean for Maldives region is extracted and plotted to obtain a baseline data for validating GCMs. NOAA_

OI_SST_V2 datasets from NOAA/OAR/ESRL/PSD, Boulder, Colorado, USA, has been downloaded from <http://www.esrl.noaa.gov/psd/> Figure 3, which provides the monthly and annual mean SSTs for Maldives, shows that SST and Tmean has the same pattern over three different zones of Maldives, providing an opportunity to explore more and use sea surface temperature data instead of Tmean for downscaling.

Figure 2.3 Monthly and annual mean sea surface temperature of Maldives



In addition to NOAA datasets, Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) from Met Office Hadley Centre for Climate Change, United Kingdom, will also be used to define baseline SST, for grids over the Maldives region (Rayner et al., 2003).

2.1.3 Data gaps

Normally, the World Meteorological Organization (WMO) recommends a 30-year average to define the climate of a location. The Intergovernmental Panel on Climate Change

(IPCC) uses 1960-1990 to define baseline climate to make comparisons and estimate climate change. For Maldives, however, long period of data is not available, making it necessary to use alternative approaches that employ reanalysis data, which are available for longer periods. Additional global datasets and satellite-derived estimates, such as TRMM rainfall data, will be used to address gaps in observational data. This approach would require a clear understanding of the links between climate parameters at particular location and the large-scale circulation features from the reanalysis fields.

Four key parameters were prioritized and chosen for Maldives region, based on relevance and importance to the country (Table 2.2). GCM outputs are available through data centers, such as the Coupled Model Inter-comparison Project (CMIP3) and World Data Center for Climate (WDCC). However, none of these data centers shares gridded sea level projection datasets, with the required accuracy, assumption, and sensitivity. Topography and bathymetry datasets that are available with the Maldives Coast Guard are only for Male Island, and not for the whole country.

Table 2.2 Data gaps and remarks

SN	Data	Gaps	Remarks
1	Surface observatory climate data	Non-availability of weather data from 1960 to 1975	Affects statistical downscaling, screening predictors
2	Satellite-derived climate data	Non-availability of high resolution data (TRMM/ other source) before 1990s	
3	GCM outputs		
	Sea level (Zostoga)	Detailed gridded global sea level projection is not available	Using GMSL value alone will have uncertainties for Maldives region
	Sea surface temperature (zos)	No observation data available for validation	
	Precipitation flux (pr)	Extensive temporal and spatial resolution is lacking	
	Surface Temperature (tas)	Extensive temporal and spatial resolution is lacking	
4	Topography/ bathymetry	Field survey derived datasets are not available	Affects modeling of sea level rise and inundation area

2.2 GCM Outputs

Observed and projected predictor datasets for the Maldives region were obtained from the data portal maintained by the Canadian Climate Impacts Scenarios Group (CISC, 2011). Predictor grid boxes covering the Maldives region were extracted for the available GCMs (currently HadCM3 and CGCM2). Predictor from NCEP reanalyses and GCM outputs were re-gridded and standardized by the Canadian Climate Impacts Scenarios Group (ibid). Re-gridding was necessary because the grid-spacing (i.e. horizontal resolution) and/ or coordinate systems of the reanalysis datasets used for statistical downscaling model calibration do not generally correspond to the grid spacing of the GCM outputs. For example, the NCEP/ NCAR reanalyses have a grid spacing of 2.5° latitude by 2.5° longitude, whereas the CGCM1 has a coarser resolution of 3.7° latitude by 3.7° longitude and the HadCM3 a resolution of 2.5° latitude by 3.75° longitude (Kalnay, et al., 1996). All the predictor variables (NCEP and GCM) were normalized using their respective 1961–1990

means and standard deviations and, hence, the result is that each predictor variable is dimensionless, and will typically vary between –5 and +5 (Wilby & Dawson, 2007).

2.3 Other Global Datasets

Global reanalysis datasets (Table 3) are used for screening variables and identifying predictors for statistical downscaling. NRA-50 and ERA-40 reanalyses data are widely used datasets. NRA-50 is NCEP/ NCAR 50-year reanalysis of meteorological observations from 1948-1998, while ERA-40 is a re-analysis for the period September 1957 to August 2002 by the European Centre for Medium-Range Weather Forecasts (ECMWF).

In this project, the NCEP reanalysis dataset, available through the Canadian Climate Impacts Scenarios Group, is used for screening the predictors. This dataset was re-gridded to conform to the grid system of HadCM3, and all predictors were normalized with respect to the 1961 to 1990 average.

Table 2.3 List of global reanalysis datasets

Data Source	Source	Period	Model Resolution	Model Output Resolution
Arctic System Reanalysis (ASR)	Polar Met Group	2000-2010	10-20km	10-30km
ECMWF Interim Reanalysis (ERA Interim)	ECMWF	1979-present	T255L60	125 km
ECMWF 40 year Reanalysis (ERA-40)	ECMWF	1958-2001	T159L60	80 km
Japanese Reanalysis (JRA-25)	Japan Meteorological Agency	1979-2004	T106L40	1.125x1.125/2.5x2.5
NASA MERRA	NASA	1979-2010	1/2x1/2 deg	1/2x1/2 deg
NCEP Climate Forecast System Reanalysis (CFSR)	NCEP	1979-2010	T382 L64	.5x.5 and 2.5x2.5
NCEP/DOE Reanalysis AMIP-II (R2)	NCEP/DOE	1979-present	T62 L28	2.5x2.5
NCEP/NCAR Reanalysis I (R1)	NCEP/NCAR	1948-present	T62 L28	2.5x2.5 and 2x2 Gaussian
NCEP North American Regional Reanalysis (NARR)	NCEP	1979-present	32km	32km
NOAA-CIRES 20th Century Reanalysis (20CR)	NOAA/ESRL PSD	1871-2008	T62 L28	2x2

Source: (Reanalysis.org, 2011)

3. EVALUATION AND SELECTION OF GCMS AND EMISSION SCENARIOS

The following chapters present the process of GCM and emission scenario selection for dynamic and statistical downscaling. GCM selection is based on model performance over the Maldives, while emission scenario selection is based on the scenario's relevance for the Maldives.

3.1 General Circulation Models

3.1.1 Available GCMs

The IPCC Data Distribution Centre facilitates the timely distribution of a consistent set of up-to-date scenarios of changes in climate and related environmental and socio-economic factors, for use in climate impact and adaptation assessment. A major advance of the fourth assessment results is the large number of simulations available from a broader range of models, compared with those from the Third Assessment Report (TAR). Model simulations cover a range of possible futures, including idealized emission or concentration assumptions. These include SRES14

illustrative marker scenarios for 2000 to 2100 period, and model experiments with greenhouse gases and aerosol concentrations held constant after year 2000 or 2100 (IPCC, 2007).

Table 4 lists the GCMs available through CMIP3 project from the IPCC Data Distribution Center.

Table 2.4 List of GCMs available under AR4/CMIP3 project

CMIP3 Model ID	Originating Group(s)	Country
BCC-CM1	Beijing Climate Center	China
BCCR-BCM2.0	Bjerknes Centre for Climate Research	Norway
CCSM3	National Center for Atmospheric Research	USA
CGCM2	Canadian Centre for Climate Modeling & Analysis	Canada
CGCM3.1(T47 &63)	Canadian Centre for Climate Modeling & Analysis	Canada
CNRM-CM3	Meteo-France/ Centre National de Recherches Meteorologiques	France
CSIRO-Mk3.0	CSIRO Atmospheric Research	Australia
CSIRO-Mk3.5	CSIRO Atmospheric Research	Australia
ECHAM5/MPI-OM	Max Planck Institute for Meteorology	Germany
ECHO-G	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data group	Germany / Korea
FGOALS-g1.0	LASG / Institute of Atmospheric Physics	China
GFDL-CM2.0	US Dept. of Commerce/ NOAA/ Geophysical Fluid Dynamics Laboratory	USA
GFDL-CM2.1	US Dept. of Commerce/ NOAA/ Geophysical Fluid Dynamics Laboratory	USA
GISS-AOM	NASA / Goddard Institute for Space Studies	USA
GISS-EH	NASA / Goddard Institute for Space Studies	USA
GISS-ER	NASA / Goddard Institute for Space Studies	USA
INGV-SXG	Instituto Nazionale di Geofisica e Vulcanologia	Italy
INM-CM3.0	Institute for Numerical Mathematics	Russia
IPSL-CM4	Institut Pierre Simon Laplace	France
MIROC3.2(hires)	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
MIROC3.2(medres)	Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC)	Japan
MRI-CGCM2.3.2	Meteorological Research Institute	Japan
PCM	National Center for Atmospheric Research	USA
UKMO-HadCM3	Hadley Centre for Climate Prediction and Research/ Met Office	UK
UKMO-HadGEM1	Hadley Centre for Climate Prediction and Research/ Met Office	UK

3.1.2 Model performance evaluation

Model performance is evaluated based on how well the model simulates monsoon precipitation climatology. This benchmark is chosen due to the fact that monsoonal circulation is one of the main factors that influence climate and rainfall over the Maldives. The methodology used follows Annamalai et al. (2007) and Sperber and Annamalai (2008).

Outputs of 18 models, used to simulate the climate of the 20th century (20c3m) as part of the IPCC AR4, were examined. The 20c3m simulations attempt to replicate the overall climate variations during the period ~1850-present, by imposing each modeling group’s best estimates of natural (e.g. solar irradiance, volcanic aerosols) and anthropogenic (e.g. greenhouse gases, sulfate aerosols, ozone) climate forcing during this period. For each model, June-September rainfall climatology of the last 30 years from the 20c3m simulations was constructed and compared with observations.

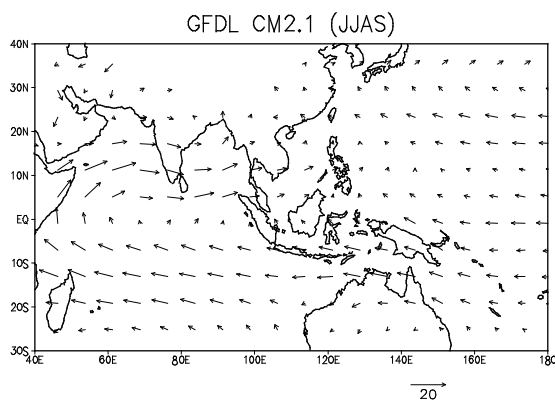
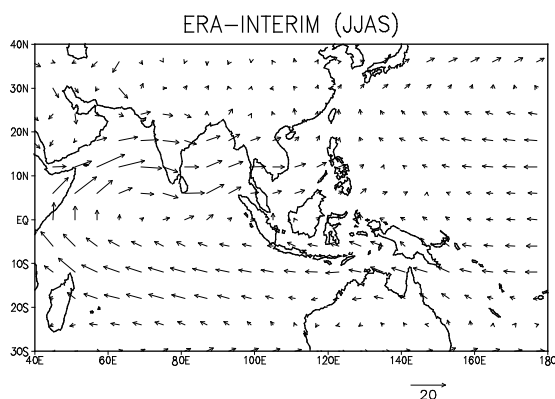
To check the models’ relative abilities to capture the summer monsoon rainfall, simulations of June-September rainfall climatology over both India and the larger monsoon domain (40°E-180°E, 25°S-40°N) were used. GCM selection metrics were based on pattern correlations between simulated and observed rainfall estimates and their root mean square differences (RMSDs) for the period. These values reflect the “present status” of monsoon precipitation simulation by these state-of-the-art climate models. Table 2.5 below gives the pattern correlation and the root-mean-square difference (RMSD) between the model and CMAP observations over the Asian Summer Monsoon domain. The June-September rainfall simulations significantly correlated to observations at 95% confidence level in 6 of the 18 models examined, with GFDL showing the highest correlation and lowest RMSD.

Table 2.5 Pattern correlations and Root Mean Square Differences (RMSD) between GCMs and CMAP rainfall observations

SN	Model	Pattern Correlation	RMSD
1	GFDL-2.1	0.83	2.0
2	GFDL-2.0	0.80	2.3
3	MPI_ECHAM5	0.80	5.6
4	MRI_CGCM	0.80	5.6
5	HadCM3	0.80	5.6
6	NCAR_PCM	0.72	3.2

The capability of GCMs to capture tropical rainfall climatology, particularly those associated with the Asian monsoon is one of the toughest tests. However, it is important to ascertain if the rainfall simulations captured by a particular GCM is a result of right circulation features, for example the unique cross-equatorial flow produced during the monsoon seasons. To examine these aspects, comparison of GFDL 2.1 GCM wind circulation fields (1981-2000 averages) and the ERA reanalysis fields that are used as surrogates for observations (1989-2000 averages), were undertaken for JJAS months. The circulation features for the same period were also evaluated with regional dynamical downscaling using the IPRC REGCM run at 25km spatial resolution for the period (1989-2008) forced with ERA reanalysis boundary conditions. The results of this comparison are given at Figure 2.4 below.

Figure 2.4 Monsoon circulation fields (wind vectors at 850 hpa) averaged during the June, July, August, September (JJAS) period. The top panel is ERA, middle-GFDL CM 2.1, IPRC REGCM with ERA lateral boundary conditions.



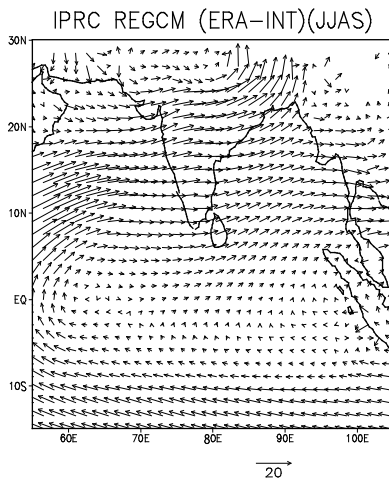


Figure 4 shows clearly that GFDL 2.1 GCM picks out the monsoon circulations very well and the IPRC REGCM enhances the regional circulations further. Diagnostic efforts are being undertaken to isolate factors that are specific to Maldives climate.

Further relationships between GCM control climatology and station climatology was then investigated to determine which model control exhibits the characteristic features of the local climate. Results are presented in Figure 5, for temperature and rainfall. The lack of a clear agreement between station climatology and model fields underlines the need for using large-scale monsoon features to identify suitable GCMs for downscaling, rather than station level climatology. Table 2.6 lists the GCMs selected based on the performance evaluation.

Figure 2.5 Monthly temperature and precipitation correlation between GCM and station data

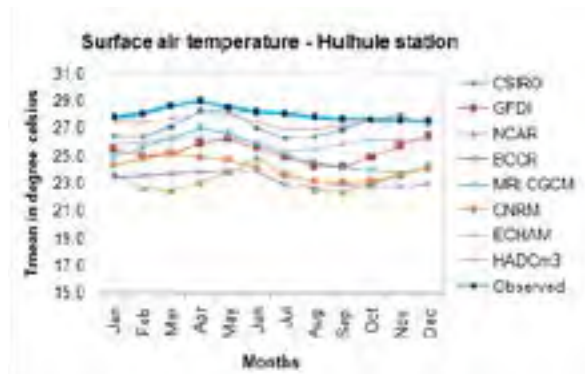
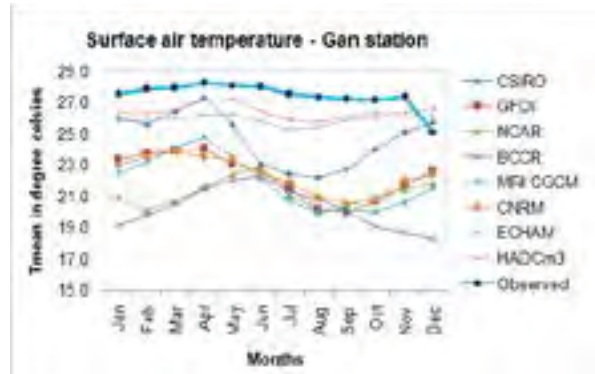
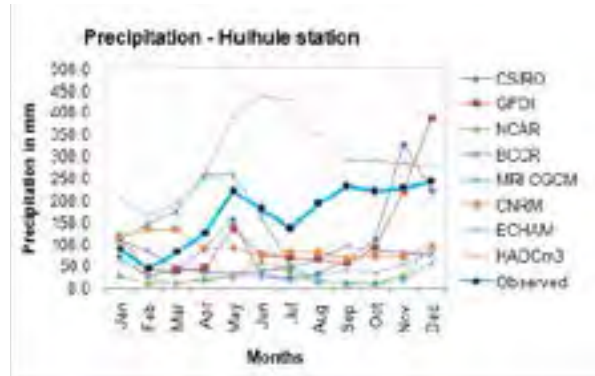


Table 2.6 List of Global Climate Models chosen

SN	Purpose/ Process	Global Climate Models	Remarks
1	Grids over Maldives region	HadCM3, ECHAM, MRI CGCM, GFDL	Good simulation of Asian summer monsoon circulation with low RMSD
2	Statistical downscaling	HadCM3	Standardized qualitative datasets available for SDSM
3	Dynamic Downscaling	GFDL	Captures monsoonal characteristics well in Indian Ocean region

3.1.3 Selection of predictants

Relevant variables from out of 110 variables available for most GCMs are listed in Appendix 1. Table 2.7 lists the variables considered in this project. These predictants were re-gridded for consistency with the HadCM3 and CGCM1 grid spacing, and normalized using their respective 1961-1990 means and standard deviations.

Table 2.7 List of variables considered

Daily variable	Code	NCEP	HadCM2 GG	HadCM3 SRES	CGCM2 SRES	CSIRO SRES
		1961-2000	1961-2009	1961-2099	1961-2099	1961-2099
Precipitation (mm)	prec		Y	Y	Y	Y
Maximum temperature (K)	tmax		Y	Y	Y	Y
Minimum temperature (K)	tmin		Y	Y	Y	Y
Mean temperature	temp	Y		Y	Y	Y
Mean sea level pressure	mslp	Y		Y	Y	Y
500 hPa geopotential height	p500	Y		Y	Y	Y
850 hPa geopotential height	p850	Y		Y	Y	Y
Near surface relative humidity	rhum	Y		Y	Y	Y
Relative humidity at 500 hPa height	r500	Y		Y	Y	Y
Relative humidity at 850 hPa height	r850	Y		Y	Y	Y
Near surface specific humidity	shum	Y		Y	Y	Y
Geostrophic airflow velocity	**f	Y	Y	Y	Y	Y
Vorticity	**z	Y	Y	Y	Y	Y
Zonal velocity component	**u	Y	Y	Y	Y	Y
Meridional velocity component	**v	Y	Y	Y	Y	Y
Wind direction	**th	Y	Y	Y	Y	Y
Divergence	**zh	Y	Y	Y	Y	Y

Notes: Y parameter available; ** fields available at surface, 500 and 850 hPa

Source: Wilby & Dawson, 2007

3.2 Emission Scenarios

IPCC's special report on GHG emission scenarios (SRES) describes a family of six emission scenarios (Table 2.8) to condition global climate models (IPCC, 2007). Each scenario represents different mixes of population changes, economic output, land use, energy and technology use on a global scale. Each of them can be then characterized by maxima in terms of atmospheric CO₂ concentrations. A2 represents the worst-

case scenario with CO₂ concentration increasing from 350 to 850 ppm. In the B1 scenario environmental protection is emphasized and world population increases relatively slowly. In this conservative scenario concentrations of CO₂ stabilize at 550 ppm.

Table 2.8 List of emission scenarios

Family	A1			A2	B1	B2
Scenarios	A1F1	A1B	A1T	A2	B1	B2
Population	~7billion	~7billion	~7billion	~15billion	~7billion	~10 billion
Economic growth	Very high	Very high	Very high	Medium	High	Medium
Per capita Income	Very high	Very high	Very high	Low	High	Medium
Primary energy use	Mainly fossil fuels	Balanced mix of energy sources	Emphasis on non- fossil energy	High	Low	Medium
Hydrocarbon resource use	Low	Low	Low	Very low to Medium	Very low to High	Low to Medium
Land use change	Low	Low	Low	Medium	High	Medium
Temperature change (°C at 2090-2099 relative to 1980-1999)	4.0	2.8	2.4		1.8	2.4
Sea level rise (m at 2090-2099 relative to 1980-1999)	0.26 to 0.59	0.21 to 0.48	0.20 to 0.45	0.23 to 0.51	0.18 to 0.38	0.20 to 0.43

Source: IPCC, 2007 & IPCC, 2000

3.2.1 Emission scenario selection

Among the six scenarios, three were selected to represent extreme and medium scenarios that are most appropriate for the Maldives: A2 (high), A1B (medium), and B1 (low). For choice of emission scenarios we wanted to use representative global emission scenarios for worst case (high emission A2), a mid-level emission scenario represented by A1B and low by B1 to project a full range of possible future climate change. This approach allows better appreciation of risks like for example some sensitive sectors development plans could be based on low emission scenario thresholds; and for others that can tolerate higher risks, one may use higher thresholds provided by the high emission scenario. IPCC/AR4 CMIP3 multi-model GCM projections driven by these three scenarios were chosen for the study. Of these, the extreme scenarios A2 and B1 were selected for statistical downscaling to have a more complete understanding of the risks, while A1B was selected for dynamic downscaling (Table 2.9).

Table 2.9 List of emission scenarios selected

SN	Purpose/ Process	Emission Scenarios	Remarks
1	Grids over Maldives region	A1B, A2, B1	Present the global model projections and scenarios available to Maldives region
2	Statistical downscaling for two locations	A2 and B1	Understand risk by knowing both the extremes over a location
3	Dynamic downscaling for whole of Maldives	A1B	

Summary

Lack of climate data, both in terms of spatial coverage and temporal extent, restricts characterization of the baseline climate, as well as applicability for statistical downscaling. Some of these data gaps can be overcome by using satellite-derived estimates, and use of reanalysis data and global datasets, such as Sea-Surface Temperature fields. Our present analysis has brought out some clear linkages between station level observations and TRMM and SST fields, for rainfall and temperatures respectively. Our further approach will explore these linkages further, to enable meaningful statistical and dynamical downscaling for providing indication of future climate change.

GCM selection was based on the capability of the model to simulate monsoon precipitation climatology, with monsoon circulation being one of the primary factors that influence climate and rainfall over the Maldives. Of the 18 models used to simulate 20th century climate, 6 resulted to June-September rainfall simulation outputs over the region having significant correlations with observations. GFDL showed the highest correlation and lowest RMSD, hence was selected for dynamic downscaling over the region. GCM control climatology and station climatology are at variance, which could be due to both inadequate characterization of the observed climate, as well as uncertainties in GCMs at finer spatial scales. Given this situation, the performance of GCMs with respect to large-scale monsoon circulation has been employed as a benchmark for the choice of GCMs for statistical downscaling. With standardized datasets available, HadCM3 was selected for statistical downscaling.

Selection of emission scenarios was based on the relevance of the scenarios for the Maldives. Of the six IPCC scenarios, three were selected to represent extreme and medium scenarios: A2 (high), A1B (medium), and B1 (low). The extreme scenarios A2 and B1 were selected for statistical downscaling to have a more complete understanding of risks, while A1B was selected for dynamic downscaling.

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The resilient island planning
is perhaps the single
most influential policy in
ensuring climate change
.....knowledge

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Appendix 1

Variable	Long Name	Standard Name
cdd	Maximum Number of Consecutive Dry Days	N/A
cl	Cloud Fraction	cloud_area_fraction_in_atmosphere_layer
clt	Total Cloud Fraction	cloud_area_fraction
clwvi	Column Integrated Cloud Water Content	atmosphere_cloud_condensed_water_content
etr	Intra-Annual Extreme Temperature Range	N/A
gsl	Growing Season Length	N/A
hfls	Surface Latent Heat Flux	surface_upward_latent_heat_flux
hfogo	Northward Ocean Heat Transport	northward_ocean_heat_transport
hfss	Surface Sensible Heat Flux	surface_upward_sensible_heat_flux
htovdiff	Northward Diffusive Heat Transport by Ocean	northward_ocean_heat_transport_due_to_diffusion
htovgyre	Northward Gyre Heat Transport by Ocean	northward_ocean_heat_transport_due_to_gyre
htovovrt	Northward Ocean Heat Transport by Overturning	northward_ocean_heat_transport_due_to_overturning
hur	Relative Humidity	relative_humidity
hus	Specific Humidity	specific_humidity
huss	Surface Specific Humidity	specific_humidity
hwdi	Heat Wave Duration Index	N/A
mrro	Surface and Subsurface Runoff	runoff_flux
mrros	Surface Runoff	surface_runoff_flux
mrso	Total Soil Moisture Content	soil_moisture_content
orog	Surface Altitude	surface_altitude
pr	Precipitation	precipitation_flux
prc	Convective Precipitation	convective_precipitation_flux
prw	Precipitable Water	atmosphere_water_vapor_content
ps	Surface Pressure	surface_air_pressure
psl	Sea Level Pressure	air_pressure_at_sea_level
r10	Number of Days for which Precipitation Rate Exceeds 10 mm/day	N/A
r5d	Maximum 5-day Precipitation Total	N/A
r95t	Percent of Annual Total Precipitation due to Events Exceeding the 1961-1990 95th Percentile	N/A
rlds	Surface Downwelling Longwave Radiation	surface_downwelling_longwave_flux_in_air

Variable	Long Name	Standard Name
rldscs	Downwelling Surface Clear-Sky Longwave	surface_downwelling_longwave_flux_in_air_assuming_clear_sky
rlntp	Net Upward Longwave Flux at 200 hPa	net_upward_longwave_flux_in_air
rlntpcs	Net Upward Clear-Sky Longwave Flux at 200 hPa	net_upward_longwave_flux_in_air_assuming_clear_sky
rlus	Surface Upwelling Longwave Radiation	surface_upwelling_longwave_flux_in_air
rlut	Outgoing Longwave Radiation	toa_outgoing_longwave_flux
rlutcs	Outgoing Clear-Sky Longwave	toa_outgoing_longwave_flux_assuming_clear_sky
rsds	Surface Downwelling Shortwave Radiation	surface_downwelling_shortwave_flux_in_air
rsdscs	Incident Surface Clear-Sky Shortwave	surface_downwelling_shortwave_flux_in_air_assuming_clear_sky
rsdt	TOA Incident Shortwave Radiation	toa_incoming_shortwave_flux
rsntp	Net Downward Shortwave Flux at 200 hPa	net_downward_shortwave_flux_in_air
rsntpcs	Net Downward Clear-Sky Shortwave Flux at 200 hPa	net_downward_shortwave_flux_in_air_assuming_clear_sky
rsus	Surface Upwelling Shortwave Radiation	surface_upwelling_shortwave_flux_in_air
rsuscs	Reflected Surface Clear-Sky Shortwave	surface_upwelling_shortwave_flux_in_air_assuming_clear_sky
rsut	TOA Reflected Shortwave Radiation	toa_outgoing_shortwave_flux
rsutcs	Reflected Clear-Sky Shortwave	toa_outgoing_shortwave_flux_assuming_clear_sky
rtmt	Net Flux at Top of Model	net_downward_radiative_flux_at_top_of_atmosphere_model
sdi	Simple Daily Precipitation Index	N/A
sftlf	Land Area Fraction	land_area_fraction
sltovdiff	Northward Diffusive Salt Transport by Ocean	northward_ocean_salt_transport_due_to_diffusion
sltovgyre	Northward Gyre Salt Transport by Ocean	northward_ocean_salt_transport_due_to_gyre
sltovovrt	Northward Ocean Salt Transport by Overturning	northward_ocean_salt_transport_due_to_overturning
so	Salinity	sea_water_salinity
stfbarot	Ocean Barotropic Streamfunction	ocean_barotropic_streamfunction
stfmmc	Meridional Overturning Streamfunction	ocean_meridional_overturning_streamfunction
ta	Temperature	air_temperature
tas	Surface Air Temperature	air_temperature
tasmax	Maximum Daily Surface Air Temperature	air_temperature
tasmin	Minimum Daily Surface Air Temperature	air_temperature
tauu	Zonal Surface Wind Stress	surface_downward_eastward_stress
taucorr	Eastward Momentum Flux Correction	eastward_momentum_flux_correction_where_ocean
tauv	Meridional Surface Wind Stress	surface_downward_northward_stress

Variable	Long Name	Standard Name
taucorr	Northward Momentum Flux Correction	northward_momentum_flux_correction_where_ocean
thetao	Potential Temperature	sea_water_potential_temperature
tn90	Percent of time Tmin > the 90th percentile value of daily minimum temperature	N/A
tos	Sea Surface Temperature	sea_surface_temperature
ua	Zonal Wind Component	eastward_wind
uas	Zonal Surface Wind Speed	eastward_wind
uo	Eastward Sea Water Velocity	eastward_sea_water_velocity
va	Meridional Wind Component	northward_wind
vas	Meridional Surface Wind Speed	northward_wind
vo	Northward Sea Water Velocity	northward_sea_water_velocity
wap	Omega (=dp/dt)	lagrangian_tendency_of_air_pressure
wfcorr	Water Flux Correction	water_flux_correction_where_ocean
wfo	Water Flux Into Ocean	water_flux_into_ocean
wo	Upward Sea Water Velocity	upward_sea_water_velocity
zg	Geopotential Height	geopotential_height
zmla	Atmospheric Boundary Layer Thickness	atmosphere_boundary_layer_thickness
zmlo	Mixed Layer Thickness	ocean_mixed_layer_thickness
zobt	Sea Floor Depth	sea_floor_depth_below_geoid
zos	Sea Surface Elevation	sea_surface_height_above_geoid
zosga	Global Mean Sea Level Change	global_average_sea_level_change
zostoga	Global Mean Thermosteric Sea Level Change	global_average_thermosteric_sea_level_change

List of selected variables to be scanned for possible use in statistical downscaling

Source: ESG, 2011







**DOWNSCALING PROCESS, RESULTS
AND UNCERTAINTIES**

CHAPTER. 3

1. BACKGROUND

1.1 Progress and Status

This chapter presents about downscaling process, criteria for reliable downscaling, downscaled climate change information and inherent uncertainties.

The chapter is organized under three sub-chapters, as follows:

- i. Inferences from GCMs: Inferences of climate change scenarios from selected GCM products on precipitation, sea surface temperature and surface air temperature.
- ii. Downscaled process, products and uncertainties: Dynamical and Statistical downscaled products for Maldives and its uncertainties
- iii. Conclusion and summary: Issues in the downscaled products, reliability of climate products while using and recommendation.

1.2 Climate Risk Profile

The unique nature of the geography of Maldives exposes it to a range of climate risks. Climatology of the Indian Ocean, particularly variations and changes in sea-levels and the sea-surface temperatures are most important factors, as the climate of the atolls are hardly distinguishable from the surrounding ocean. The nation's capital Male', with around 2.5 sq km of total land area has over a quarter of the entire population of 298,968, while approximately 71 percent of the rest of the 193 inhabited islands have less than 1000 inhabitants according to the 2006 Census information. Life in these inhabited areas is exposed to risks from extreme events such as warmer temperatures, high waves and rainfall, affecting water resources and agriculture. The concentration of population on the larger islands has also led to their vulnerability to climate risks. For example vector and water borne disease outbreaks supported by favorable climate pose risks in populated areas.

The Maldivian economy is heavily dependent on fisheries and tourism, which are the major sources of foreign exchange earnings and government revenue, and which together directly account for about 40 percent of gross domestic product, while indirectly accounting for a much larger proportion of GDP. With only 30 sq km of cultivable land, the Maldives depends heavily on food imports, mostly funded by revenues from fisheries and tourism sectors. The fisheries sector, in addition to its role as an export industry, is an important source of local livelihoods, supporting 20% of the

population and providing a primary source of dietary protein. Tourism, employing 6% of the population, also provides critical revenue for government expenditures. In summary, Sea-levels and sea temperatures are important for the fishing industry and as is perhaps favorable climate for tourism. Extreme climate events, rainfall amounts and its seasonality, high temperature spells are important for livelihoods and human well being.

1.3 Approach for Climate Change Scenario generation

The approach for climate change scenario generation for Maldives involves GCM inference, dynamical downscaling and point level statistical downscaling. Global climate models (GCMs) have resolutions of hundreds of kilometers, whilst regional climate models (RCMs) are available at 20-50km resolution. Statistical downscaling products fulfill the requirement of point-specific climate projections in order to capture fine-scale climate variations, particularly in regions with complex topography, coastal or island locations (Timbal et al., 2008). Under this project, climate change information's were inferred from GCMs, dynamically downscaled models (RCM) and statistical models (SDSM). The models chosen and criteria's involved has been explained in detail in Report-2. Mainly performance of the models with respect to summer monsoon over South Asia, availability of normalized GCMs results and availability of selected scenario runs. Following the brief discussion on climate risks profile presented in chapter 1.2 above, the priority of climate parameters for Maldives are identified as, in the following order Sea-level, Sea Surface Temperature (SST), precipitation and surface air temperature. The details of climate information products and its purpose are presented in Table -1.

Regional modeling support was provided by our collaborating research partner the International Pacific Research Center (IPRC), University of Hawaii. RIMES jointly works with IPRC on the areas of climate research, in particular climate variability through diagnostic approaches. IPRC's regional climate model was used for the dynamical downscaling study, and all the model data analyses were undertaken by IPRC and RIMES scientists collaboratively.

Table 3.1 Climate change projections products and utility

Products	Purpose
Global Mean sea level change and Regional changes in 2030s, 2050s and 2080s for A1B scenario	Understand sea level change at atoll level
GCMs products for GFDL2.1, HadCM3, ECHAM5, MRI CGCM2.3.2a (Changes in 2030s, 2050s & 2080s for A1B, A2, B1 scenarios) Precipitation Surface air temperature Sea surface temperature	Coarse resolution for understanding climate change at regional level
Dynamical downscaled products for GFDL model Precipitation Mean temperature	Medium and high resolution for understanding climate change over the Maldives, with more specific indications for atoll level risks
Statistical downscaled products for HadCM3 model (Changes in 2030s, 2050s and 2080s for A2 and B1 scenarios) Precipitation Mean temperature	High resolution for understanding climate change at specific locations and other defined spatial aggregation

2. INFERENCES FROM GCMS

2.1 Sea Level

Oceans capacity to absorb heat is almost thousand times greater than the atmosphere, and most of this gets stored in the upper layers affecting not only sea-levels and ocean circulations, but also the atmospheric circulation and climate on a variety of time-scales. The changes in oceanic heat storage and distribution of ocean salinity cause the ocean to expand or contract resulting in changes in the sea level both regionally and globally. On long time scales, global mean sea level change results from two major processes that alter the volume of water in the global ocean: i) thermal expansion, and ii) water flow from other sources such as melting of glaciers and ice caps, ice sheets, other land water reservoirs. All these processes cause geographically non-uniform sea level change. Some oceanographic factors like changes in ocean circulation or atmospheric pressure also affect sea level at the regional scale. Local sea level measurements

are influenced strongly by vertical land movements due to tectonics, subsidence (caused by earthquakes for example) and sedimentation influence, hence factoring in these changes are important while detecting long term trends.

For this study the observed sea level data is available through Permanent Service for Mean Sea Level (PSMSL) has been used. PSMSL located in the United Kingdom at the National Oceanography Centre (NOC) is responsible for the collection, publication, analysis and interpretation of sea level data from the global network of tide gauges. PSMSL observed sea level monthly records has been downloaded for the available period for the location Male and Gan. This monthly series data is available from 1988 to 2010, while 1991 to 2000 is considered for comparison as the latter period has fewer missing values.

WCRP-CMIP3 webportal shows that following two parameters are sea level related parameters, 1. zosga - Global Mean Sea Level Change (global_average_sea_level_change), 2.zostoga - Global Mean Thermosteric Sea Level Change (global_average_thermosteric_sea_level_change). Unfortunately zosga and zostoga are not available to public. No sea-level related parameters are currently available from the IPCC AR4 for any of the GCMs. For the sea-level analysis we have used sea-surface heights (zos) data from the Geophysical Fluid Dynamics Lab (GFDL) model version

GFDL CM2.1 which is one of the GCMs used in the IPCC AR4 assessment. The model has been integrated following standard procedures using initial conditions taken from 1st January 2001 of the climate of the 20th century experiment (1860 to 2000). Time varying forcing agents used during the first 100 years (2001 to 2100) experiment were based on SRES A1B emission scenarios. Five model realizations (or ensembles) for the control or base-line and three realizations for the SRES A1B projection scenarios were used for this analysis. Using multiple model runs in the form of ensemble members gives higher confidence in model projections. For this experiment volcanic aerosols were zero, land surface cover types were time invariant, and solar irradiance varied seasonally based upon late 20th century averages. All forcing agents were held constant after year 2100. The horizontal resolution is 0.5 degree and vertical resolution varies from 0.4 to 0.6 degree.

The available zos parameter is sea surface height (in meters) above geoid, which under the base-line conditions is approximately the MSL. Local sea-level change, also known as “Relative sea-level change” is due a variety of causes including regional vertical land motion, coastal hydrodynamics, atmospheric and ocean circulation. The zos parameter being used in our analysis is mainly influenced by the following two factors –

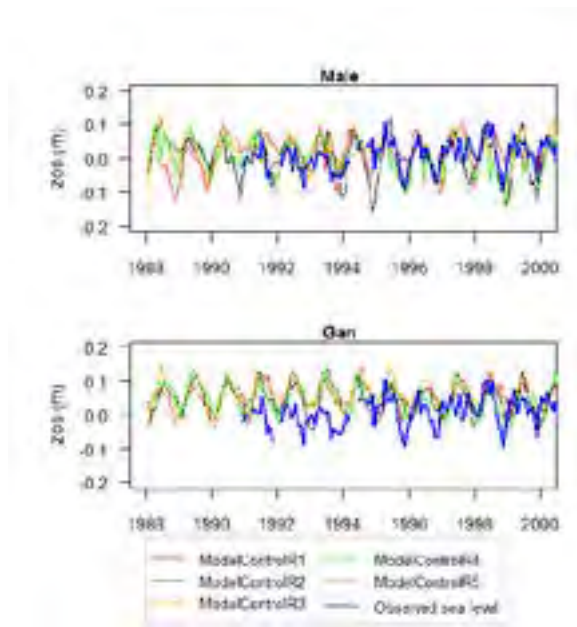
- i. thermal expansion of water leads to sea level rise (global warming on planetary scales) caused by the increase in SST
- ii. local wind forcing that results in leads to deepening of the tropical thermocline (local increase in sea surface height or local sea level rise) or shoaling of the thermocline (local decrease in sea surface height or local sea level decrease)

Regarding (ii) - in a warmer climate, most climate models suggest deepening of thermocline over the western Arabian Sea - i.e., increase in sea level. In the context of Maldives, both (i) and (ii) may act in phase to increase sea level. Due to the fact that the zos parameter represents more localized processes, it was considered as variable to infer possible local sea-level change scenarios in the Maldives context. These changes however need to interpreted closely with global sea-level change scenarios.

The monthly time series of tide data (1991 to 2000) available from PSMSL and GFDL model control runs of sea surface heights have been compared to estimate bias. The systematic bias between monthly series of PSMSL and model control has

been identified as 0.348 and 0.333 for Male and Gan station respectively. This bias correction is carried out in GFDL (zos) model control of five realizations and presented in Figure 3.1 along with observed PSMSL data series.

Figure 3.1 Comparison between model base-line (sea-surface height anomalies) and tide gauge records for Male and Gan location



Comparison between generated base-line sea-surface heights and observed monthly sea level records in Maldives shows good agreement of the seasonal and inter-annual changes (Figure 3.1). Correlations for Male and Gan stations are 0.6 and 0.4 respectively. This encouraging correlation provides confidence on using this GCM to estimate the projected changes for Maldives region at Atoll level.

The change in sea surface height for time slice 2080s from the present (1961-1990) has been estimated and presented the results in Table 3.3. 2030s and 2050s time slices are ignored because of the uncertainties and model inconsistency performance. From Table 3.3, it can be inferred that sea-surface heights changes fluctuates from 8.2 to 9.5 cm with an uncertainty range 4.6 to 11.6cm. These values need to be interpreted in conjunction with global sea-level change scenarios to characterize impacts. This will be taken up in the chapter 4.

Table 3.2 Projected sea-surface height changes for Maldives

Atolls	Longitude	Latitude	Mean Sea surface height change in 2080s N* (Unit: cm)	Max Sea level change in 2080s N** (Unit: cm)
Haa Alifu	73.5	7.06	0.8	8.4 (5.5 to 11.5)
Haa Dhaalu	73.5	6.44	1.3	8.9 (5.9 to 11.6)
Shaviyani	73.5	6.44	1.3	8.9 (5.9 to 11.6)
Raa	72.5	5.84	1.6	9.1 (6.8 to 11.1)
Noonu	73.5	5.84	1.7	9.1 (6.1 to 11.3)
Lhaviyani	73.5	5.27	2.0	8.9 (6.3 to 10.9)
Baa	72.5	5.27	1.9	8.9 (6.7 to 10.6)
Kaafu North	73.5	4.72	2.3	8.7 (6.4 to 10.4)
Kaafu South	73.5	4.19	2.5	8.6 (6.3 to 10.3)
Alifu Alifu	72.5	4.19	2.5	8.3 (6.2 to 9.8)
Alifu Dhaalu	72.5	3.69	2.8	8.2 (6 to 9.7)
Vaavu	73.5	3.69	2.9	8.6 (6.1 to 10.3)
Faafu	72.5	3.22	3.1	8.2 (5.8 to 9.7)
Meemu	73.5	2.77	3.4	8.9 (5.8 to 10.6)
Dhaalu	72.5	2.77	3.4	8.3 (5.5 to 9.7)
Thaa	72.5	2.34	3.6	8.3 (5.2 to 9.9)
Laamu	73.5	1.94	3.9	9.2 (5.6 to 11)
Gaafu Alifu	73.5	0.84	4.2	9.4 (5.2 to 11.3)
Gaafu Dhaalu	73.5	0.17	4.4	9.5 (4.9 to 11.5)
Gnaviyani	73.5	-0.17	4.4	9.5 (4.8 to 11.5)
Seenu	73.5	-0.5	4.4	9.4 (4.6 to 11.4)

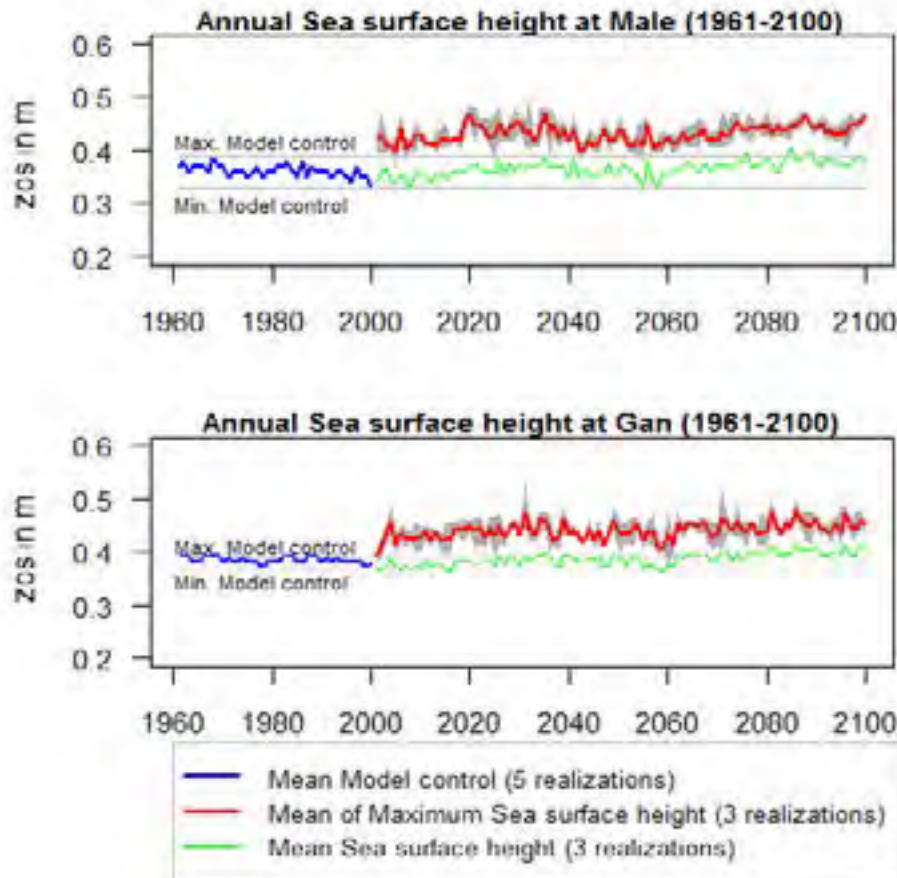
N* - Annual average for every control realization is calculated and then **AVERAGE** among these five realizations is taken for a year for every grid.

N** - Annual Maximum for each realization of SRES scenario is calculated and then **AVERAGE** among these three realizations is taken for a year for every grid.

Annual mean sea surface height from 1961 to 2100 for Male and Gan location has been analyzed and presented in Figure 2. The minimum and maximum of model control (1961 to 2000) for the location Male is 0.33 to 0.39m and Gan is 0.37 to 0.39m. The maximum sea surface height changes for Male during 2001 to 2100 fluctuates from 0.4 to 0.48m with an uncertainty range 0.36 to 0.5m. The maximum sea surface

height for Gan from 2001 to 2100 fluctuates from 0.39 to 0.48m with an uncertainty range 0.37 to 0.53m. The mean sea-surface heights are seen to be within the current range of fluctuations during most of the future period until about 2070s in both locations. The variations are comparatively much more at the northern location than in the south. The maximum sea-surface heights are significantly higher than the mean values at both locations and show very gradual trends. As noted in earlier chapters, projections of sea-surface heights and sea-level at the level of atolls have several uncertainties.

Figure 3.2 Sea surface height above MSL time series plot for Male and Gan location. Units of zos are in meters. Grey color shaded area represents the range of uncertainty of maximum sea level over the island locations.

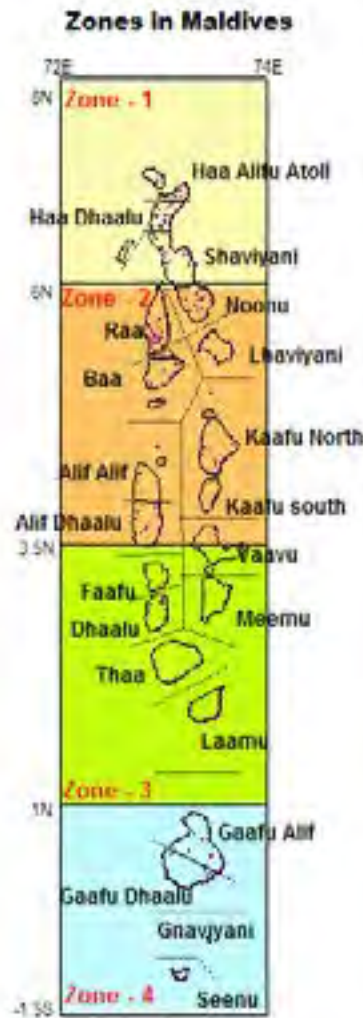


2.2 Climate Variables

Hunter (2010) identified two inherent uncertainties involved in sea level projection. The first is ‘scenario uncertainty’ arises from the fact that the future social, economic and technological development of the world, and the consequent greenhouse-gas emissions, are poorly known. A range of plausible futures, or scenarios, have been used to describe the way in which emissions may change in the future. The second uncertainty ‘model uncertainty’ is related to shortcomings in the present knowledge of the science of climate change, partly due to fact that we do not know exactly the present climate state (the ‘initial conditions’), and partly due to the fact that no model gives a perfect representation of the real world.

As mentioned in Chapter 2, HadCM3, MPI ECHAM 5, MRI CGCM 2.3.2a, GFDL CM2.1 model outputs has been selected for Maldives region, since these models shows good simulation of Asian summer monsoon circulation. Model controls (20C3M) and projection scenarios (SRES A1B, A2, B1) datasets has been extracted, to estimate the changes in three times slices 2030s, 2050s and 2080s. Over Maldives domain, GCM grid location and spacing varies for each model, hence regridding of these datasets has been carried out for four major zones or grids as shown in Figure 3.3 for better spatial visualization and representation.

Figure 3.3 Zone classification of Maldives



2.2.1 Monthly precipitation changes

Over South Asia, warming is likely to be above the global mean, precipitation in summer is likely to increase (IPCC, 2007). These changes will very likely be associated with fewer very cold days, increase in the frequency of intense precipitation events, extreme rainfall and winds associated with tropical cyclones (Christensen, et. al 2007). The above inferences are made for South Asia region, here in this chapter detailed climate change information over grid boxes of Maldives (shown in Figure-3) are examined from GCMs.

Observed annual rainfall based on Maldives station data for the period (1975-2010) ranges from 1750 to 2250mm, while the future projections from the set of GCMs examined show a range of 1250 to 3185mm. This implies both an increasing tendency in the rainfall amounts as well as enhanced variability of rainfall. These aspects however need to be examined further. GCMs annual rainfall projection shows increasing trend over years in all the models.

+ The resilient island planning is perhaps the single most influential policy in ensuring climate changeknowledge

Figure 3.4 Annual precipitation from 2001 to 2100 (X Axis – Year, Y Axis - Precipitation in millimeters)

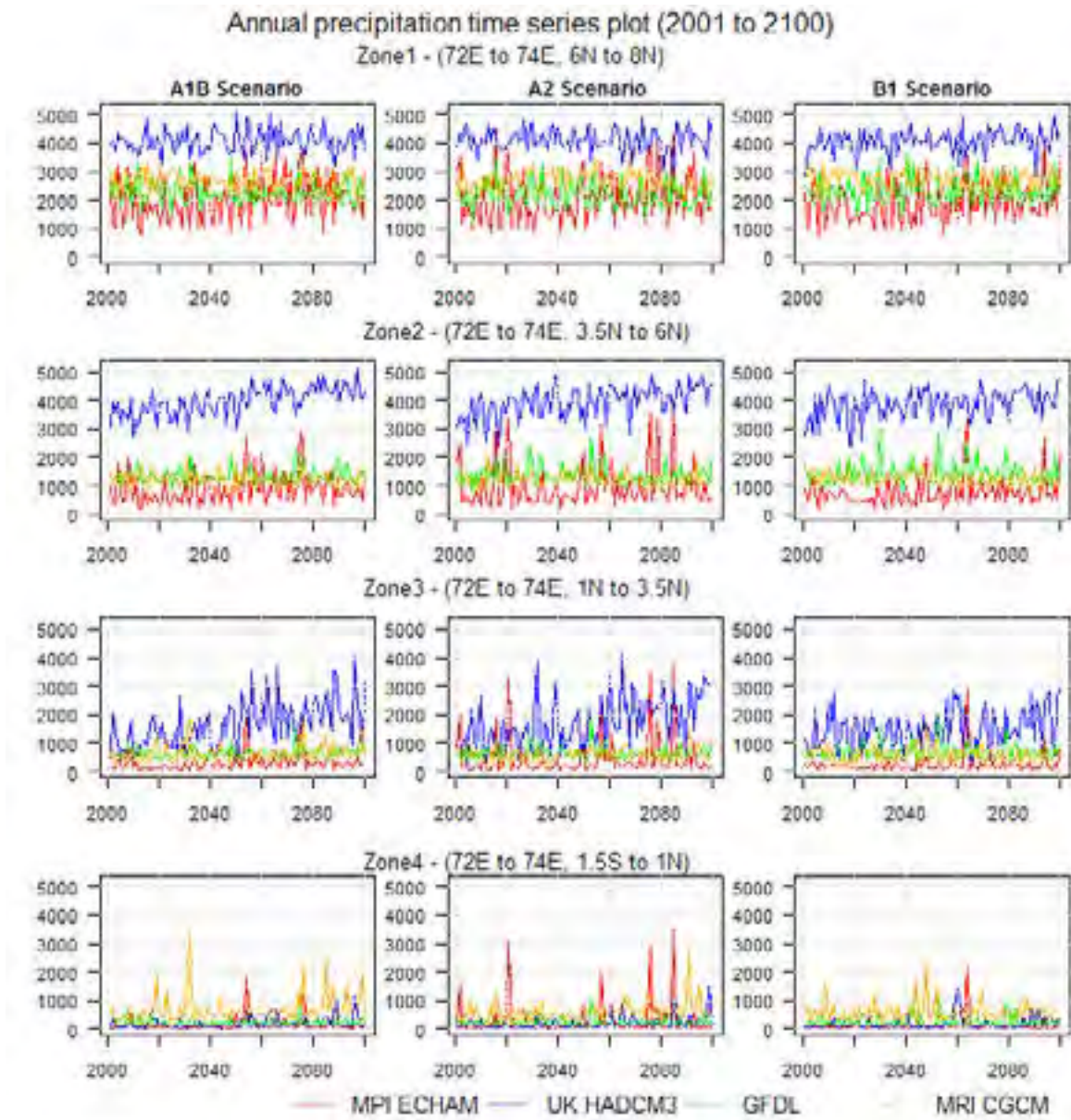


Table 3.3 Precipitation change

Zone	Model	2030s (%)			2050s (%)			2080s (%)		
		A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
Z1	MPI ECHAM	11.4	18.2	9.3	31.9	25.1	21.7	35.1	44.9	26.4
Z2	MPI ECHAM	142.8	44.8	12.8	67.5	57.8	47.6	70.6	98.5	38.9
Z3	MPI ECHAM	32.7	102.5	8.9	137.0	130.4	86.4	125.3	229.1	30.8
Z4	MPI ECHAM	-8.3	143.1	-12.2	137.6	160.3	90.6	103.6	312.0	-9.8
Z1	UK HADCM3	183.2	6.9	4.2	7.2	26.7	4.0	4.3	4.8	7.5
Z2	UK HADCM3	295.4	13.7	11.0	17.7	10.2	13.9	25.3	23.5	16.9
Z3	UK HADCM3	169.1	28.4	18.1	63.0	35.7	33.3	94.5	108.3	55.0
Z4	UK HADCM3	-2.0	2.4	7.9	67.3	50.7	60.8	103.3	131.6	63.5
Z1	GFDL	18.7	-0.9	2.4	-3.6	-4.8	4.7	-0.5	-7.4	0.5
Z2	GFDL	-86.5	2.0	4.2	-6.8	-3.1	6.8	0.8	-9.5	0.0
Z3	GFDL	-45.2	-0.3	3.7	-5.8	-1.7	3.8	5.6	-5.1	2.4
Z4	GFDL	-43.9	-1.4	4.6	-20.3	-6.9	15.1	0.7	-13.3	4.4
Z1	MRI CGCM	40.4	4.3	2.3	0.0	6.4	1.4	-0.2	-2.4	1.1
Z2	MRI CGCM	-3.0	1.7	4.7	-3.4	5.6	3.3	-24.2	-8.2	-4.7
Z3	MRI CGCM	200.8	19.2	47.6	28.0	46.7	52.8	327.7	49.9	24.5
Z4	MRI CGCM	275.8	27.3	67.7	42.9	52.9	75.2	500.3	92.8	53.9

Z1- Zone 1, Z2- Zone 2, Z3-Zone3, Z4- Zone4

Table 3 shows the change of precipitation of three time slices 2030s, 2050s and 2080s from thirty years mean 1961-1990 annual rainfall. Although there are variations on both positive and negative side of the mean climate, there is a tendency for higher than normal rainfall to occur more frequently. The changes do not exhibit any pattern of increase in rainfall over all zones. Even for the same zone, different models show various changes in rainfall. ECHAM and HadCM3 exhibits positive changes in 2050s and 2080s for zone1 and 2, while GFDL and CGCM shows negative changes in rainfall for time slices 2050s and 2080s. HadCM3 shows a much higher range for precipitation variations as compared to the other models, except in the case of zone four. These scenario results illustrate a tendency for both increased rainfall amounts and higher variability across the country, with chances of higher than normal cumulative seasonal rainfall amounts becoming more frequent. The large dispersion among the models examined shows that we cannot make confident conclusions about future rainfall climate of Maldives. With this caveat in mind more detailed analysis to in terms of active break cycles during monsoon season are being examined using the regionally downscaled data.

2.2.2 Surface Air Temperature (TAS)

Surface air temperature (tas) is near-surface (usually, 2 meters) air temperature changes over Maldives is presented in Figure 3.5.

Table 3.4 Surface air temperature change

Zone	Model	2030s (°C)			2050s (°C)			2080s (°C)		
		A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
Z1	MPI ECHAM	1.01	0.94	0.94	1.84	1.63	1.43	2.85	3.27	2.11
Z2	MPI ECHAM	0.98	1.00	0.93	1.93	1.70	1.50	2.94	3.34	2.22
Z3	MPI ECHAM	0.99	1.12	0.95	2.15	1.84	1.64	3.15	3.56	2.37
Z4	MPI ECHAM	1.00	1.18	0.96	2.25	1.88	1.71	3.28	3.72	2.43
Z1	UK HADCM3	1.06	0.99	0.90	1.55	1.60	1.20	2.49	2.79	1.71
Z2	UK HADCM3	1.06	0.98	0.90	1.53	1.57	1.19	2.43	2.71	1.71
Z3	UK HADCM3	1.13	1.08	0.98	1.70	1.72	1.32	2.70	2.99	1.88
Z4	UK HADCM3	1.34	1.25	1.11	2.04	1.99	1.61	3.18	3.52	2.18
Z1	GFDL	1.04	1.05	1.54	1.47	1.45	1.59	2.09	2.37	1.80
Z2	GFDL	0.99	1.06	1.57	1.42	1.45	1.61	2.12	2.37	1.83
Z3	GFDL	0.97	1.05	1.63	1.45	1.47	1.65	2.22	2.46	1.91
Z4	GFDL	0.87	1.03	1.60	1.35	1.45	1.67	2.20	2.44	1.92
Z1	MRI CGCM	1.15	1.00	0.97	1.60	1.58	1.22	2.27	2.43	1.67
Z2	MRI CGCM	1.31	1.17	1.10	1.74	1.82	1.39	2.49	2.62	1.82
Z3	MRI CGCM	1.49	1.27	1.27	1.86	2.02	1.57	2.83	2.88	1.97
Z4	MRI CGCM	1.60	1.24	1.34	1.97	2.06	1.64	3.12	3.11	2.10

Z1- Zone 1, Z2- Zone 2, Z3-Zone3, Z4- Zone4

Figure 3.5 Annual mean surface air temperature from 2001 to 2100 (X Axis – Year, Y Axis – Surface air temperature in degree celsius)

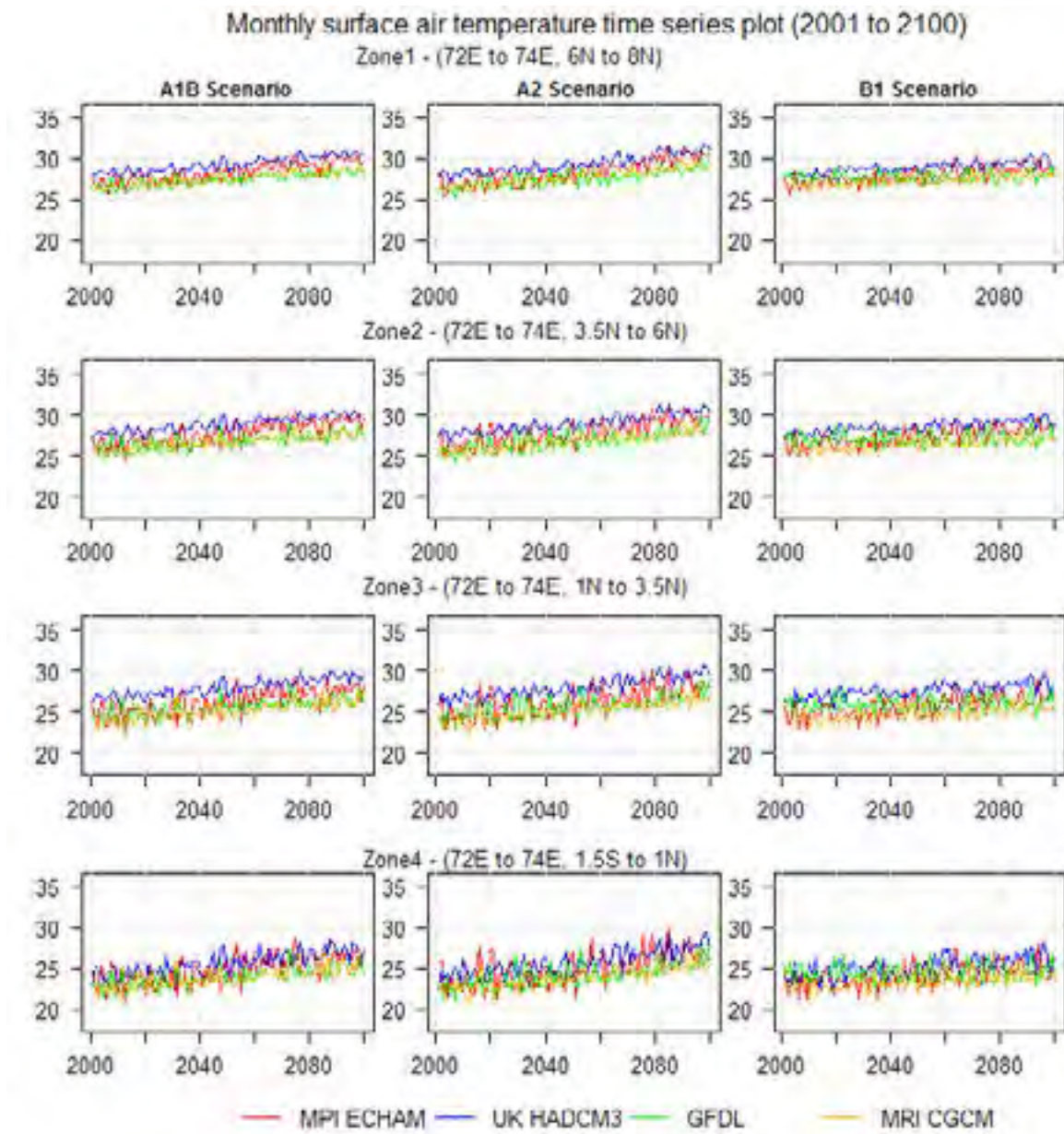


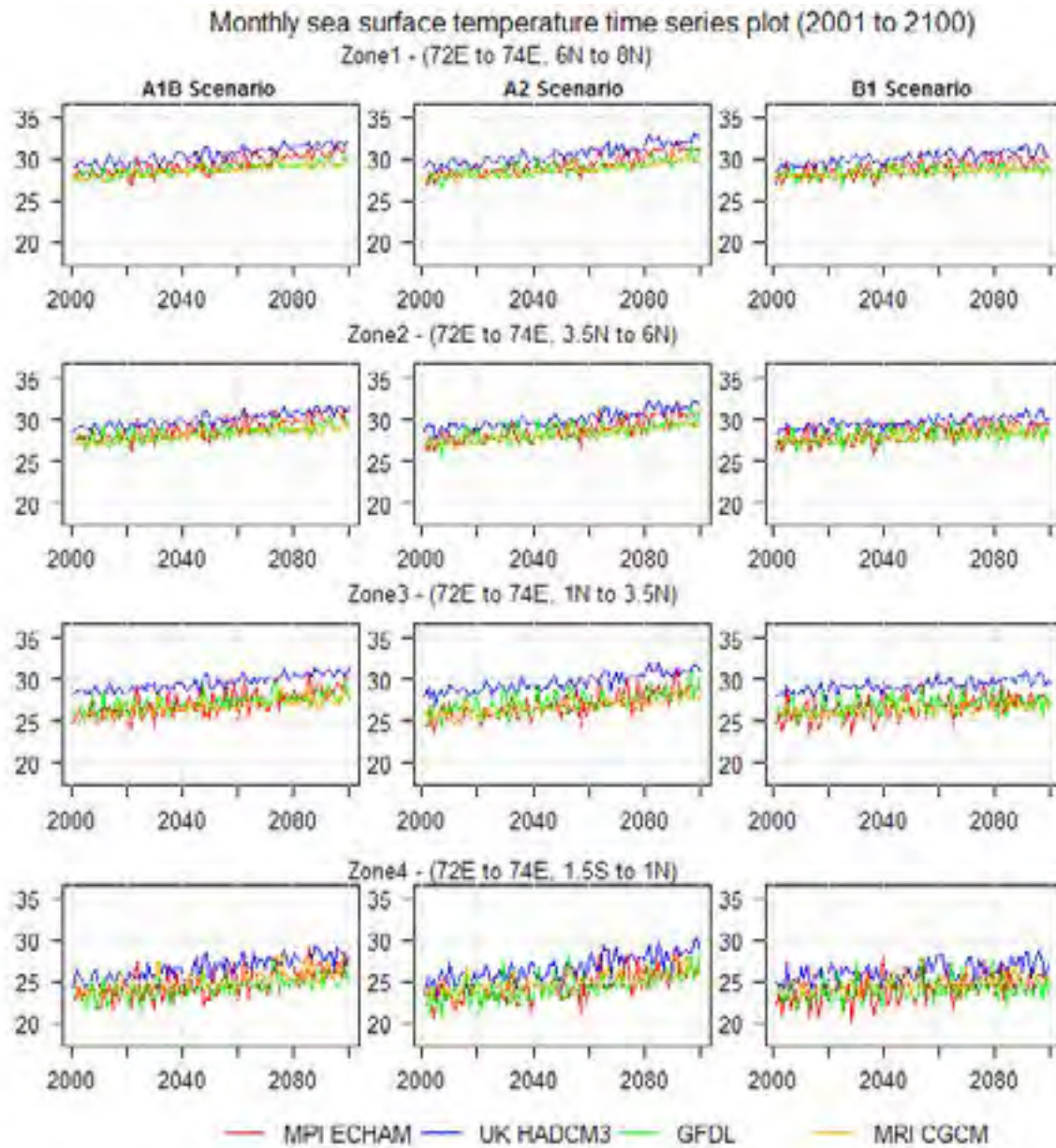
Figure 5 shows there is a steady increase in temperature despite year-to-year variations. There is a remarkable agreement among the four different models which lends greater confidence to the temperature projections. Table 3.4 shows the change of temperature of three time slices 2030s, 2050s and 2080s from thirty years mean 1961-1990 annual mean temperature. The changes exhibit a pattern of steady increase in temperature over all zones. For whole of the Maldives, the range of surface air temperature change for three time slices are as follows 2030s (0.87°C to 1.63°C), 2050s (1.19°C to 2.25°C) and 2080s (1.67°C to 3.72°C). It also seen that the different emission scenarios do not result in very different temperature changes, at least during the time horizons till 2050s. This is perhaps due to the vast expanse of

the oceans that damps out the warming signal that is known to be prominent over the land.

2.2.3 Sea surface temperature (SST)

Sea Surface temperature (SST) is very important parameter for Maldives unique geographical context. SST changes over different zones of Maldives are presented in Figure-6.

Figure 3.6 Annual Sea Surface temperature from 2001 to 2100 (X Axis – Year, Y Axis – Sea surface temperature in degree celsius)



The projected changes for surface air temperature and sea surface temperature is more or less similar because of its unique geographical context (less land mass). Table 3.5 shows the change of sea surface temperature of three time

slices 2030s, 2050s and 2080s from thirty years mean 1961-1990 annual mean temperature. For whole of the Maldives, the range sea surface temperature change for three time slices are as follows 2030s (0.76°C to 1.33°C), 2050s (1.01°C to 1.93°C) and 2080s (1.27°C to 3.40°C).

Table 3.5 Sea surface temperature change

Zone	Model	2030s (°C)			2050s (°C)			2080s (°C)		
		A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
Z1	MPI ECHAM	1.01	0.95	0.76	1.67	1.46	1.37	2.68	2.87	1.88
Z2	MPI ECHAM	1.07	0.97	0.79	1.74	1.48	1.43	2.77	2.92	1.93
Z3	MPI ECHAM	1.16	0.98	0.86	1.86	1.59	1.50	3.02	3.14	2.06
Z4	MPI ECHAM	1.17	0.95	0.94	1.87	1.67	1.55	3.21	3.33	2.08
Z1	UK HADCM3	0.98	0.93	0.86	1.48	1.55	1.15	2.50	2.76	1.67
Z2	UK HADCM3	0.94	0.85	0.79	1.38	1.42	1.05	2.25	2.50	1.56
Z3	UK HADCM3	0.88	0.85	0.78	1.33	1.41	1.02	2.24	2.50	1.56
Z4	UK HADCM3	1.20	1.15	1.04	1.93	1.93	1.48	3.07	3.40	2.08
Z1	GFDL	1.02	1.01	0.82	1.41	1.36	1.16	1.98	2.21	1.27
Z2	GFDL	1.02	1.06	0.85	1.38	1.39	1.24	2.01	2.21	1.32
Z3	GFDL	1.17	1.19	1.02	1.58	1.57	1.44	2.34	2.49	1.53
Z4	GFDL	1.18	1.33	1.17	1.63	1.77	1.65	2.53	2.71	1.67
Z1	MRI CGCM	0.96	0.82	0.84	1.37	1.33	1.02	1.97	2.11	1.44
Z2	MRI CGCM	0.96	0.87	0.80	1.32	1.36	1.01	1.92	2.02	1.38
Z3	MRI CGCM	1.16	1.01	1.03	1.43	1.60	1.23	2.22	2.25	1.51
Z4	MRI CGCM	1.37	1.05	1.17	1.61	1.71	1.38	2.69	2.61	1.76

Z1- Zone 1, Z2- Zone 2, Z3-Zone3, Z4- Zone4

2.3 Circulation features

Some of the circulation features of the GFDL 2.1 model used for further dynamical downscaling was examined. Monsoon circulation patterns of winds at the 850hpa during June, July, August, September (JJAS) months, agree well with those of the reanalysis (ERA-INT) fields, particularly in terms of direction (see Annex 1 Figure A). There is however, a slight decrease in the velocity in GCM which is attributed to its coarser spatial resolution. The GCM is also able to simulate the North East monsoon pattern during the October, November, December (OND) period to a large extent, but the zonal wind components seem to be stronger in model as compared to the reanalysis fields (Annex 1 Figure B). It is also clear from similar analyses that the GFDL coupled model (CM2.1) could capture the seasonal precipitation features quite well over the Maldivian Islands for both JJAS and OND (Figure 8 & 9). The model could simulate both from Southwest monsoon (JJAS) and NE Monsoon (OND) realistically as reported by Annamalai et al. (2007)

Extending the analysis further other diagnostics to isolate active zones responsible for rainfall over Maldives were carried out. Maldives precipitation index (MPI) defined as rainfall averaged over the box bound by latitude/ longitudes (Lon=70°E to 75°E, Lat=5°S to 10°N) representing the entire Maldives Islands using precipitation data from the ERA-INT reanalysis data (1989-2008). It is evident that JJAS precipitation, covering the core monsoon months over the Maldivian Island is due to the moisture convergence of south westerly flow. Whereas for the OND season the moisture flux is from the North easterlies (Annex 1 Figures C & D). Despite some similarities of this diagnostic structure in the GFDL model there are indications of some biases, which are rectified in the regionally downscaled results from the IPRC RegCM.

3. DYNAMICAL DOWNSCALING

3.1 The Regional climate modeling framework

The model implemented for dynamical downscaling in this project is IPRC RegCM. The IPRC-RegCM uses hydrostatic, primitive equations in spherical coordinates with sigma (pressure normalized by surface pressure) as the vertical coordinate. The model equations are solved with a fourth-order conservative horizontal finite-difference scheme on an unstaggered longitude/latitude grid system. The model physics include the cloud microphysics scheme of Wang (2001); a mass flux scheme for sub-grid shallow convection, midlevel convection, and deep convection developed by Tiedtke(1989); the radiation package developed by Edwards and Slingo (1996); the Biosphere-Atmosphere-Transfer Scheme (BATS) for land surface processes.. A one-way nesting is used to update the model time integration in a buffer zone near the lateral boundaries within which the model prognostic variables are nudged to the output of the GFDL_CM_2.1 simulations with an exponential nudging coefficient.. The buffer zone in this experimental setup is 5° in extent. More model details can be found in Wang et al. (2003, 2004).

The version of the IPRC-RegCM used in this study has 28 vertical levels with high-resolution in the planetary boundary layer. The lowest model level is roughly 25 m above the surface. The model domain extends from 50°S to 55°N, 5°E to 170°E with a grid spacing of 0.25° (approximately 30 km horizontal resolution), in both zonal and meridional directions. The IPRC-RegCM has been used to simulate climate over different monsoon regions, particularly over the south and the south east Asia. (Sen et al. 2004; Stowasser et al. 2009) and tropical Pacific (Wang et al. 2004). Typically, at this resolution, a one-year model run takes 24 hrs for on a high-performance computer system.

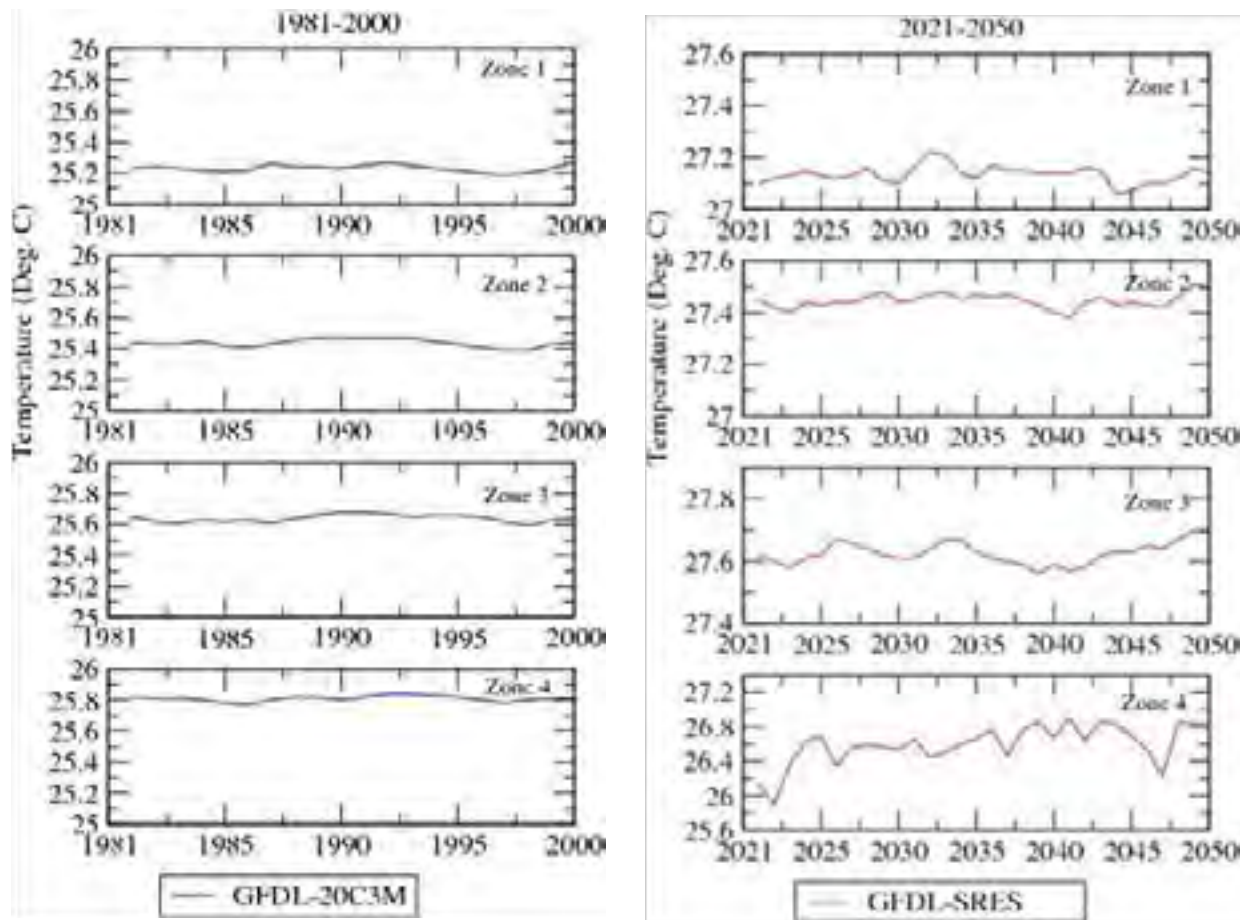
3.2 Scenarios of climate change – preliminary results

Two parameters, mean temperature and precipitation have been examined at daily scales for entire Maldives domain. Further, this daily IPRC-RegCM scenario data sets have been processed into monthly and annual time scales. The results are presented under chapter 3.2.1 and 3.2.2.

3.2.1 Temperature

Mean Temperature plot over Maldives for time slices 1981 to 2000 and 2021-2050 are presented in Figure 3.7. Surface temperature has an increasing trend as seen from the time slices experiments (1981-2000) and (2021-2050) (for the higher CO₂ scenario runs compared to baseline) scenario over the different zones of Maldives. Mean annual temperature during 2021 to 2050 is about 27°C, which is higher than the observed mean (based on 1981-2000) about 25.2°C". The resulting difference 2°C which in-line with the range of temperature change from the GCM projections presented in the earlier chapter. Zone 4, exhibits more rapid increase in temperatures as compared to the other zone during the 2021 to 2050 period under the A1B scenario (~0.8°C). More detailed analysis guided by these preliminary results on warm temperature spells and extremes will be presented in the chapter 4.

Figure 3.7 IPRC RegCM annual mean temperature projection for Maldives (2021-2050) X-Axis: Year, Y-Axis: Temperature in degree celsius



3.2.2 Rainfall

The rainfall simulations by the IPRC RegCM as well as the forcing GCM – the GFDL (CM2.1) for JJAS (core southwest monsoon season and OND months) are illustrated in Figures 3.8 & 3.9 below. The downscaled results are able to resolve minor features in a better manner, however these results are being further examined with additional model runs. There are some large gradients and anomalies noted at the model boundaries particularly south of the equator in the RegCM runs, which is being investigated further. There general tendency of the strengthening of the monsoon currents in both the seasons is clearly indicated. This analysis is being pursued further to make more clear and confident inferences of the projections of rainfall in the monsoon season.

Figure 3.8 Spatial patterns of Precipitation over a larger domain around Maldivian Islands from observations, reanalysis and model simulations. First column shows rainfall features from Observation (TRMM), Reanalysis (ERA-INTERIM) and Model GCM (GFDL Coupled GCM – CM 2.1 model). Second column shows precipitation from downscaled scenarios of IPRC REGCM for 20C3M simulation, SRES A1B simulation and the difference (SRES A1B-20C3M) in mm/day for the season JJAS. (Unit for precipitation is given in mm/day)

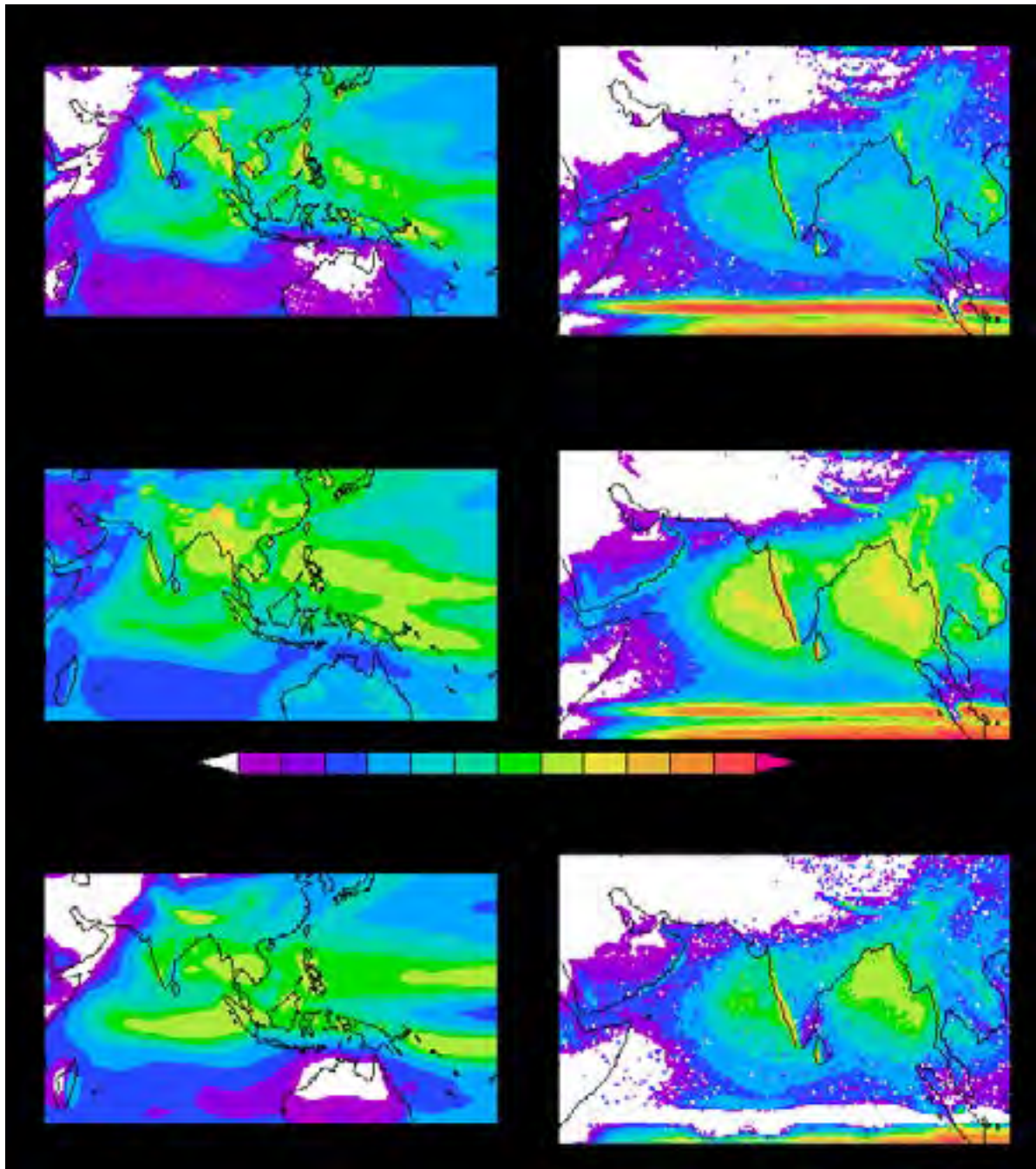


Figure 3.9 Spatial patterns of Precipitation over a larger domain around Maldivian Islands from observations, reanalysis and model simulations. First column shows rainfall features from Observation (TRMM), Reanalysis (ERA-INTERIM) and Model GCM (GFDL Coupled GCM – CM 2.1 model). Second column shows precipitation from downscaled scenarios of IPRC REGCM for 20C3M simulation, SRES A1B simulation and the difference (SRES A1B-20C3M) in mm/day for the season OND. (Unit for precipitation is given in mm/day)

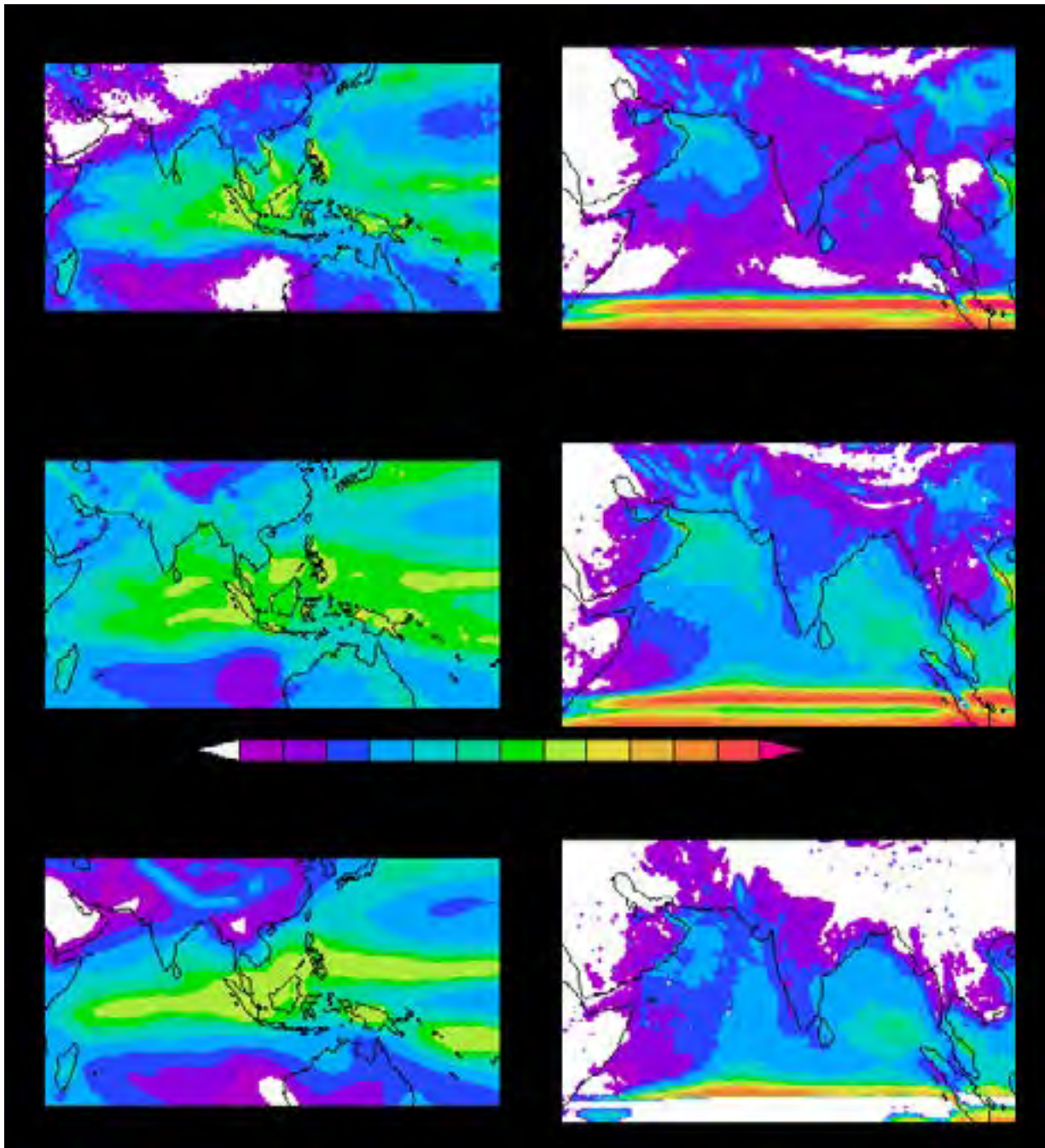


Figure 3.10 Rainfall Climatology over zones of Maldives

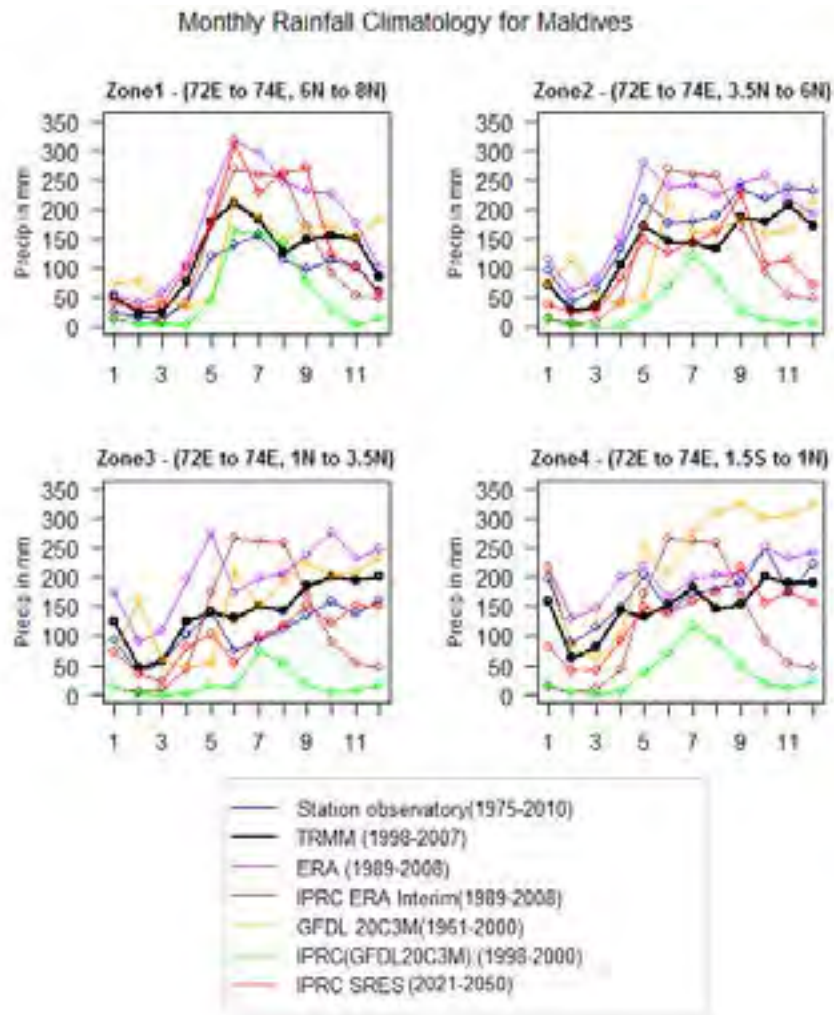


Figure 10 shows the climatological features of various zones in Maldives. The regional model projection climatological cycle shows that it simulates the precipitation cycle quite similarly though the model control is not able to pick well with the cycle. The precipitation projection over each zone is characterized by an increase in the climatological seasonal cycle (20C3M: orange curve; SRES A1B: red curve). It shows that a decrease in the precipitation is evident in the zone 4 during the JJAS season.

The regional model could simulate the precipitation characteristics over different zones as observed (Figure 11). The interesting aspect of this study is the increase in precipitation over most of the zones (Zone 1, 2, 3) except Zone 4 in the IPRC REGCM simulations forced by the GFDL CM2.1 simulation. As we can notice the decrease in the future projected precipitation is clearly seen in the parent (GFDL CM2.1) GCM over the Maldives during JJAS (Figure 11; bottom panel) showing a departure of 25% of the present

value. The regional model projected an increase in the projected precipitation for the northern zones compared to the southern zones. This is an important result of our study and supports our argument that the GCM grids are coarse and cannot capture the regional characteristics over the Maldivian Islands. When the regional model forced by GFDL with the same forcing fields simulate a different result. Further, the reasons for an increase in the projected precipitation over the Maldives in the IPRC RegCM are examined thoroughly. Figure-12 shows the simulated precipitation for 20C3M and SRES A1B scenarios for JJAS and OND months and the projected increase in the precipitation. It is clear from the IPRC RegCM that the decrease in the precipitation is confined only to a few degrees in the equator and largely a greater increase in the precipitation to the north of it, encompassing zones 1, 2 and 3.

Figure 3.11 Spatial patterns of Precipitation in the parent GCM (GFDL Coupled GCM - model). Top panels show precipitation for 20C3M simulation, middle panels show precipitation for SRES A1B simulation and the bottom panel show difference (SRES A1B- 20C3M) in percentage departure. (Unit for precipitation is given in mm/day)

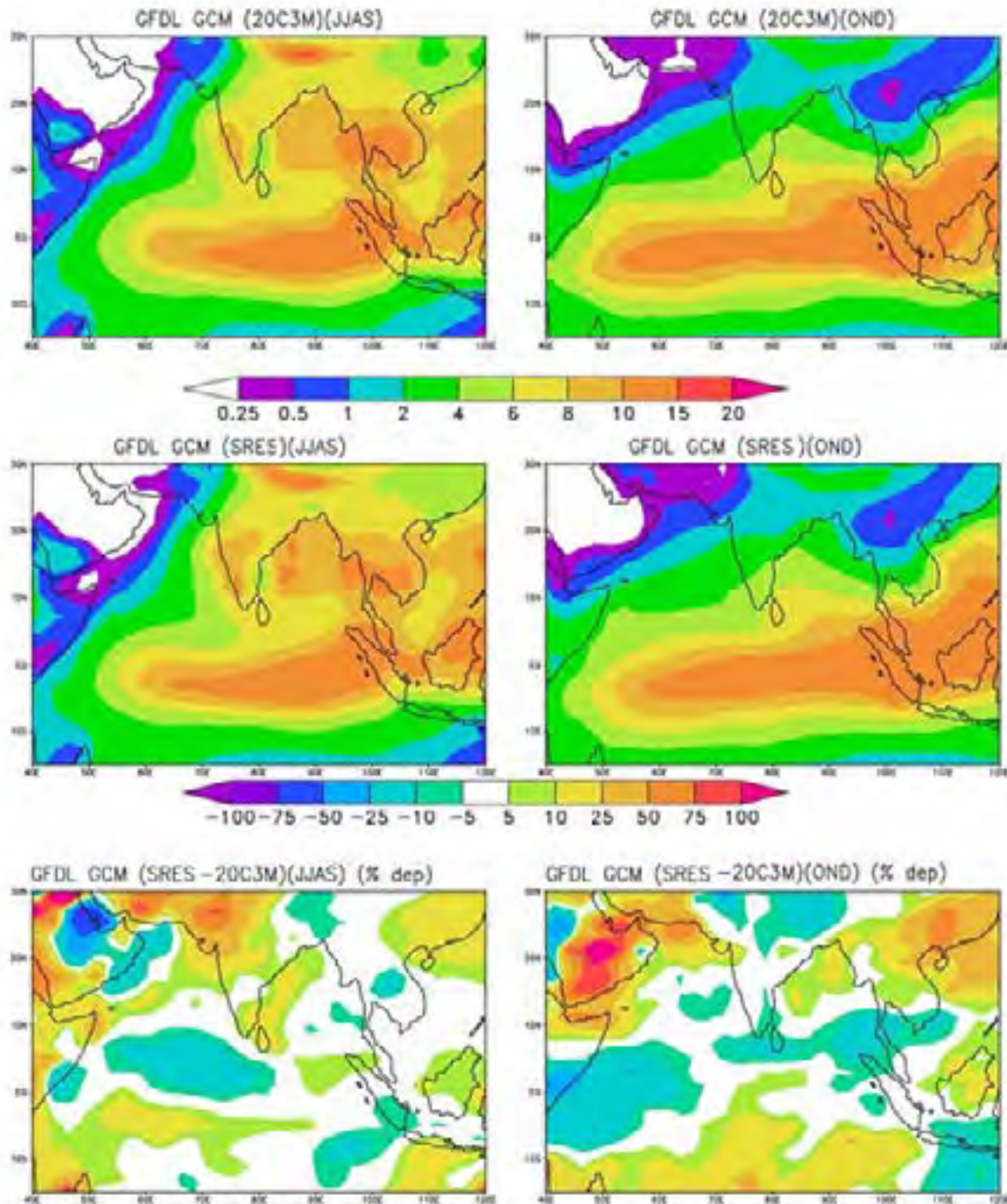


Figure 3.12 Spatial patterns of Precipitation in the IPRC REGCM (downscaled from GFDL CGCM - model forcing). Top panels show precipitation for 20C3M simulation, middle panels show precipitation for SRES A1B simulation and the bottom panel show difference (SRES A1B - 20C3M) in percentage departure. (Unit for precipitation is given in mm/day)

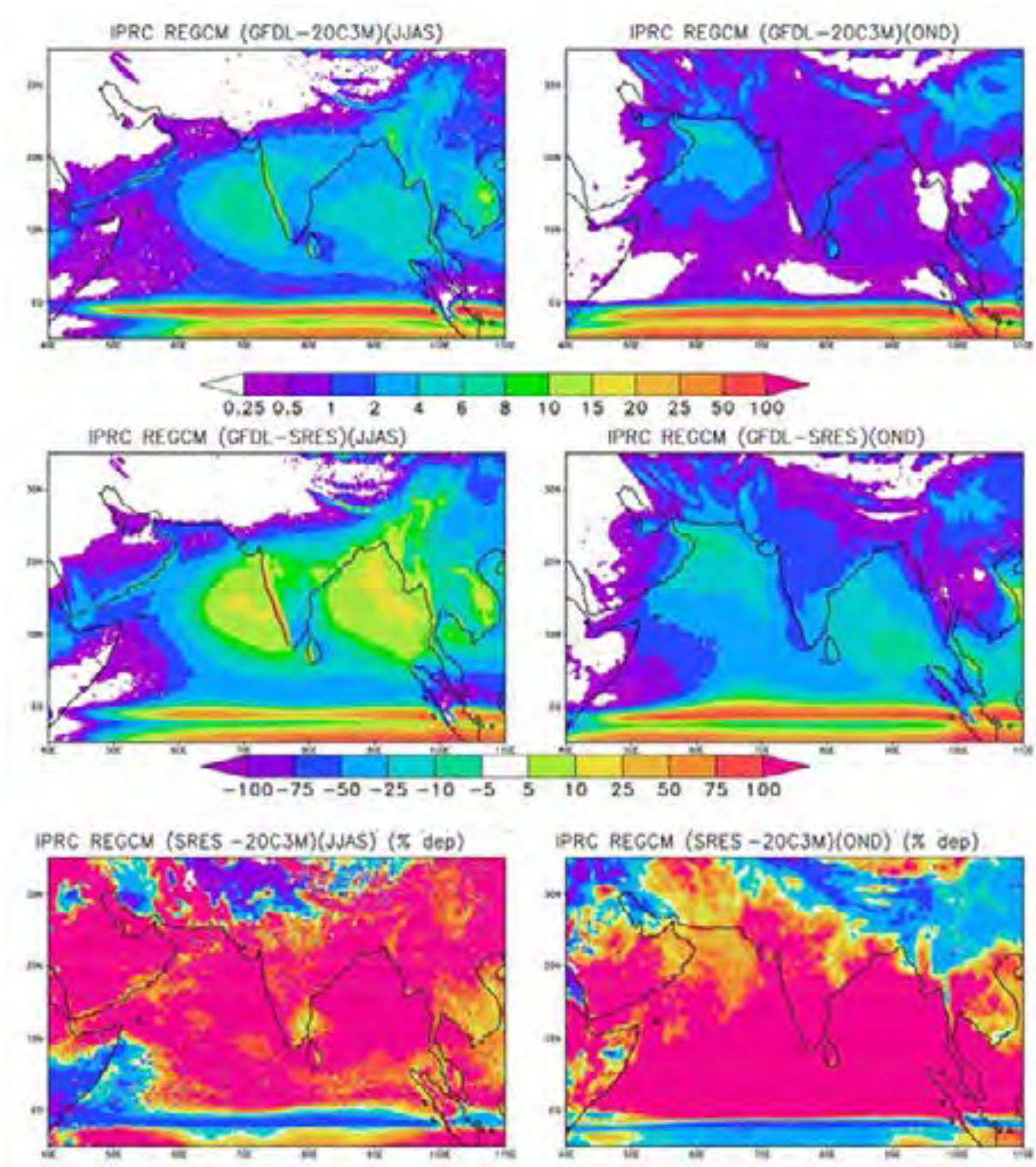


Figure 3.13 Annual precipitation projection for Maldives (2021-2050) X-Axis: Year, Y-Axis: Precipitation in mm/day

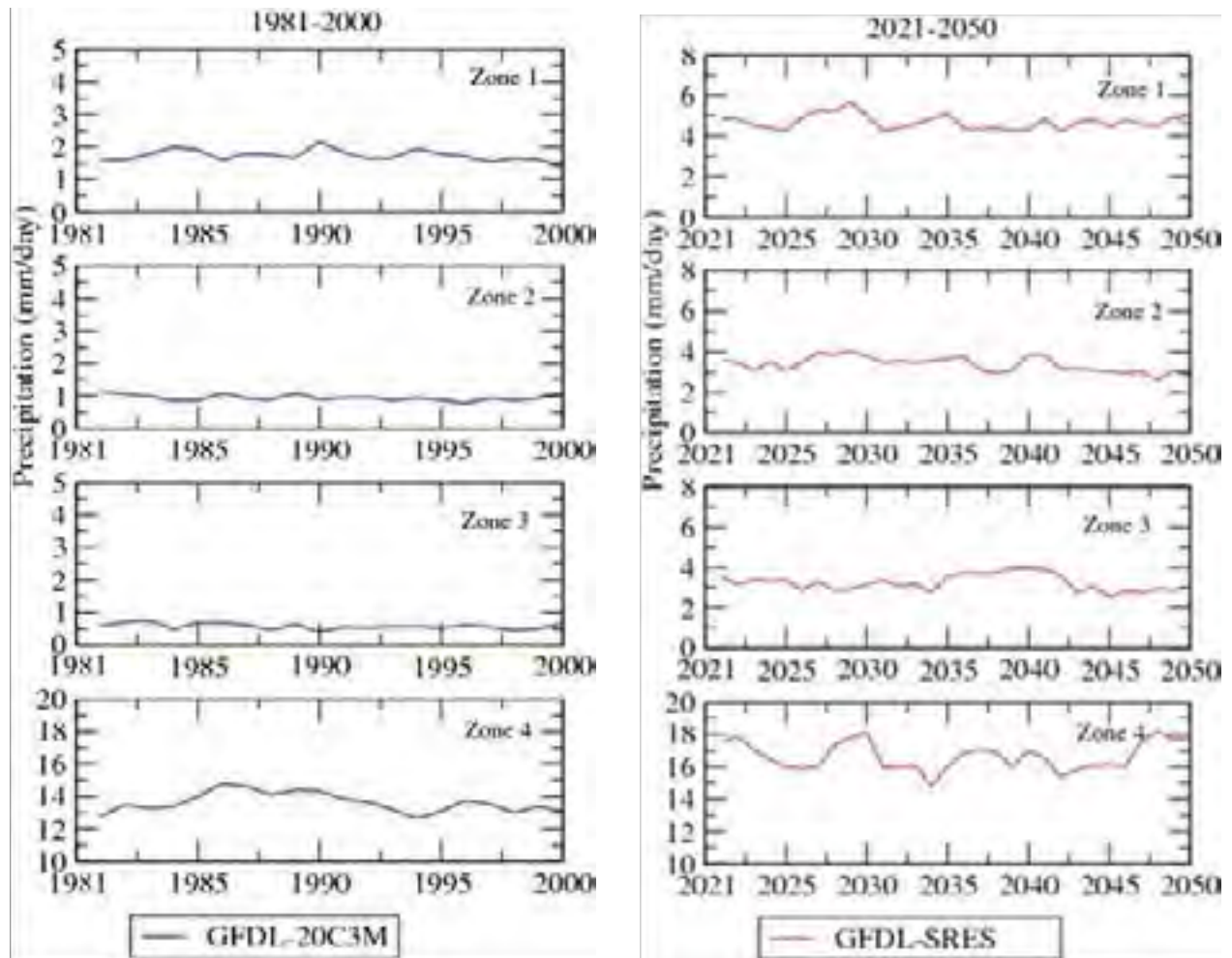


Figure 3.13 shows the annual rainfall time series plot for two time slices (1981-2000) and (2021-2050) over the zones of Maldives. Dynamical downscaled products shows increasing trend in precipitation amount through all the zones over the years, while southern zones has more increasing rainfall in future

3.2.3 Circulation features

The increase in the precipitation is well supported by an increase in the vertically integrated moisture flux in the SRES B1 Scenario (Figure 3.14). The increase is largely due to the increase in the westerly flow of moisture flux over the Maldivian region.

Figure 3.14 Spatial patterns of vertically integrated moisture flux vectors from surface to top of the atmosphere in the IPRC REGCM (downscaled from GFDL CGCM - model forcing). Top panels are for 20C3M simulation, middle panel is for SRES A1B simulation and the bottom panel shows difference (SRES A1B- 20C3M) (Unit for moisture flux vectors are given in kgms^{-1})

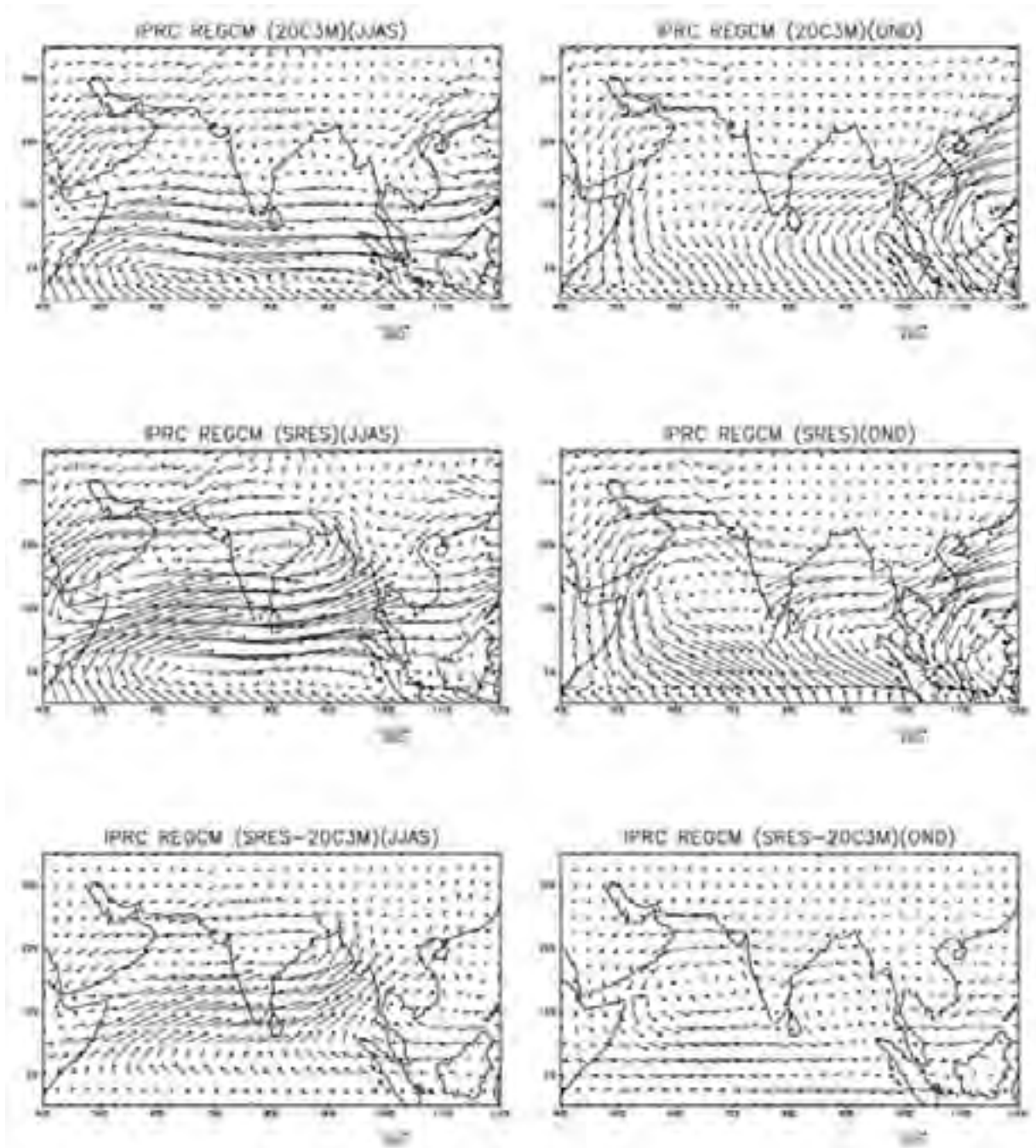
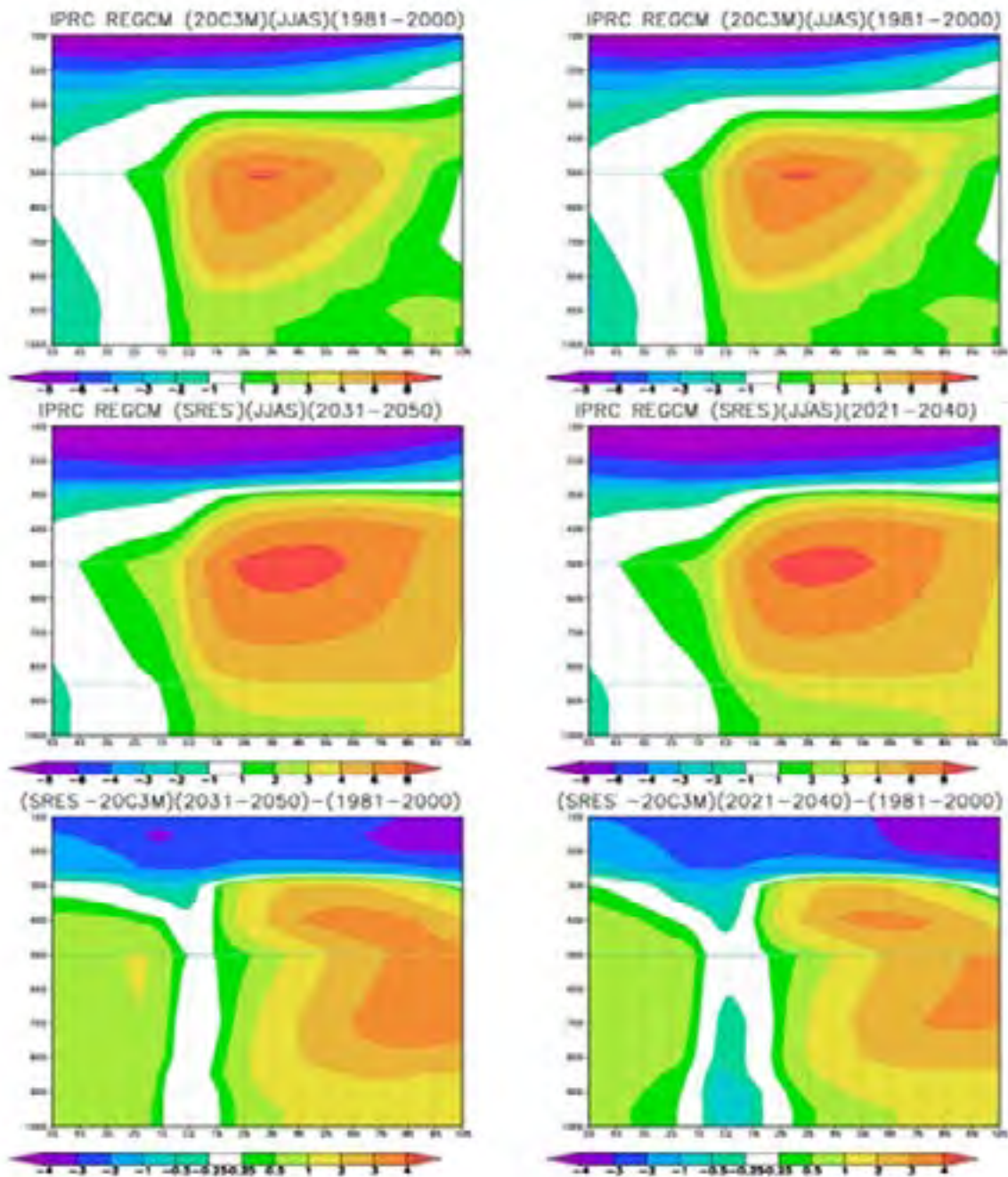


Figure-15 shows the vertical cross section of zonal wind averaged over 70E-75E across 5S-10N, the zonal wind component (U) as simulated for 20C3M forcing and SRES A1B forcing for two time slices (2031-2050) and (2021-2040) and the difference. This clearly shows that increase in the

zonal wind component plays a major role in the bringing moist air over the Maldivian Island and subsequent increase in precipitation. A possible mechanism for explaining the increase in the projected precipitation change in 2021-2050.

Figure 3.15 Vertical cross section across 5S-10N showing the zonal winds averaged over 70E-75E, for 20C3M forcing and SRES



3.2.4 Uncertainties

It must be reiterated that there exist large sources of uncertainty in constructing and applying climate models. These can be classified into initial conditions, boundary conditions, parameterizations and model structure. Initial conditions are often dismissed as a source of uncertainty in climate projections since the results from model runs are usually averaged over decades. Man-made influences for climate change studies are primarily greenhouse gas emissions, whose future behavior depend on unpredictable socio-economic and technological factors. Given the uncertainty for future human activities, simulations of future climate are termed projections rather than predictions to denote their dependence on a particular scenario of human activity.

Uncertainty due to model construction Structural uncertainty is introduced by scientific choices of model design and development. Formal statistical analysis of model output, either coming from multi-model ensembles such as CMIP3 or from PPE experiments is crucial to quantifying the uncertainties caused by models approximations.

3.3 Further Analysis

More detailed analysis on daily rainfall pattern to determine active and break phases of the monsoon current will be also analyzed. Further, diagnostics will be carried out and time series analysis of key islands locations will be analyzed and presented in the chapter 4. Extreme events and their frequencies, incidences of rainfall episodes beyond pre-defined thresholds etc. will be analyzed.

4. STATISTICAL DOWNSCALING

4.1 SDSM Method and Approach

Statistical downscaling is justified whenever GCM (or RCM) simulations of variable(s) modeling are expected to be not clearly applicable for the unique context of the location, based on know deficiencies of the models. . Downscaling may also be used to generate scenarios for context specific variables (such as urban heat island intensity) that cannot be obtained directly from GCMs and RCMs. However, the host GCM must have demonstrable skill for large- scale variables that are strongly correlated with local processes. In practice, the choice of downscaling technique is also governed by the availability of archived observational and GCM data because both are needed to produce future climate scenarios. (Wilby and Christian, 2007)

Statistical downscaling is a two step-process consisting of i) development of statistical relationships between local climate variables and large scale predictors ii) the application of such relationships to the output of Global Climate Model (GCM) experiments to simulate local climate characteristics in the future (Tim H. and Doug N., 2008). SDSM is the tool used for statistical downscaling of precipitation and temperature products from GCMs. In detail, the steps carried out in statistical downscaling are listed below.

- Quality control and data transformation - Enable the identification of gross data errors, specification of missing data codes and outliers prior to model calibration.
- Screening of predictor variables - Identifying empirical relationships between gridded predictors (such as mean sea level pressure) and single site predictands (such as station precipitation)
- Model calibration - operation takes a User-specified predictand along with a set of predictor variables, and computes the parameters of multiple regression equations via an optimisation algorithm (either dual simplex or ordinary least squares).
- Weather generation (using observed predictors) - generates ensembles of synthetic daily weather series given observed (or NCEP re-analysis) atmospheric predictor variables. The procedure enables the verification of calibrated models (using independent data) and the synthesis of artificial time series for present climate conditions.
- Statistical analyses - means of interrogating both downscaled scenarios and observed
- climate data with the Summary Statistics and Frequency Analysis screens.

- Graphing model output - Three options for graphical analysis are provided by SDSM 4.2 through the Frequency Analysis, Compare Results, and the Time Series Analysis screens.
- Scenario generation (using climate model predictors) - the Scenario Generator operation produces ensembles of synthetic daily weather series given atmospheric predictor variables supplied by a climate model (either for present or future climate experiments), rather than observed predictors.

4.2 Downscaling results

4.2.1 Temperature

Mean daily temperature for Male and Gan location is considered for statistical downscaling, since long term observed data is available compare to other stations in Maldives. The details of predictors considered and its correlation with predictands are as follows

Selecting the appropriate predictor variables is viewed as the most challenging aspect of the entire downscaling procedure, because the choice of predictors largely determines the character of the downscaled climate. The predictor variables are meteorological variables generated from HadCM3 model runs for the selected grid square. The process is carried out by using the predictand (i.e., either the observed precipitation or temperature) to screen all the 26 predictor variables for SDSM use, as provided by CICS. Monthly regressions of the predictors with the predictand variable are run, a correlation matrix and explained variance produced, and the predictor variables that are the most correlated with the predictand (and are statistically significant, high correlation value, low p-value, $p < 0.05$) are selected (Table-6).

Table 2 Correlation between predictors and predictands

Predictors	Predictor symbol	Mean Temperature @ Male	Mean Temperature @ Gan
500 hPa geopotential height	ncepp500as	0.34	0.22
Relative humidity at 500 hPa height	Ncepr500as	-0.30	-0.20
Relative humidity at 850 hPa height	ncepr850as	X	-0.23

Figure 3.16 Downscaled HadCM3 A2&B1 Scenario Mean Temperature for Male and Gan location

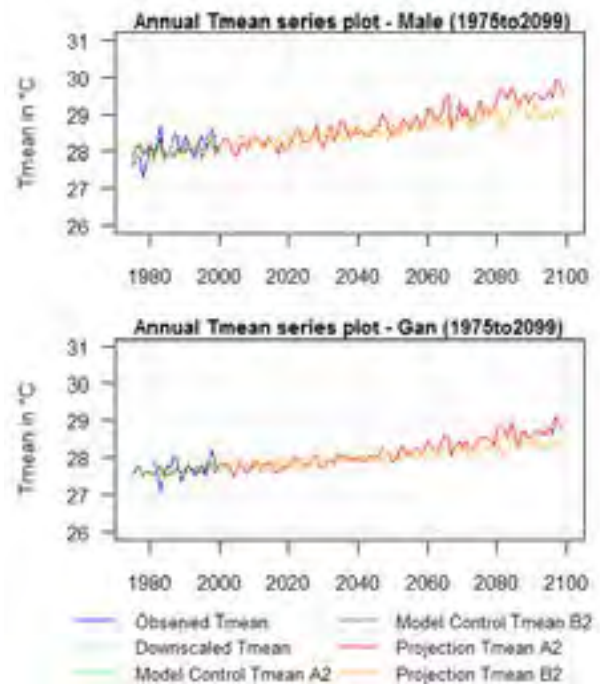


Figure-16 shows the time series annual mean temperature plot from 1975 to 2100. The change of temperature in Male is as follows 2030s (0.4°C to 0.5°C), 2050s (0.6°C to 0.8°C) and 2080s (1.0°C to 1.3°C), where in Gan, these are the changes 2030s (0.3°C), 2050s (0.4°C to 0.6°C), 2080s (0.7°C to 1.0°C).

Figure 3.17 Temperature climatology change over Male Island

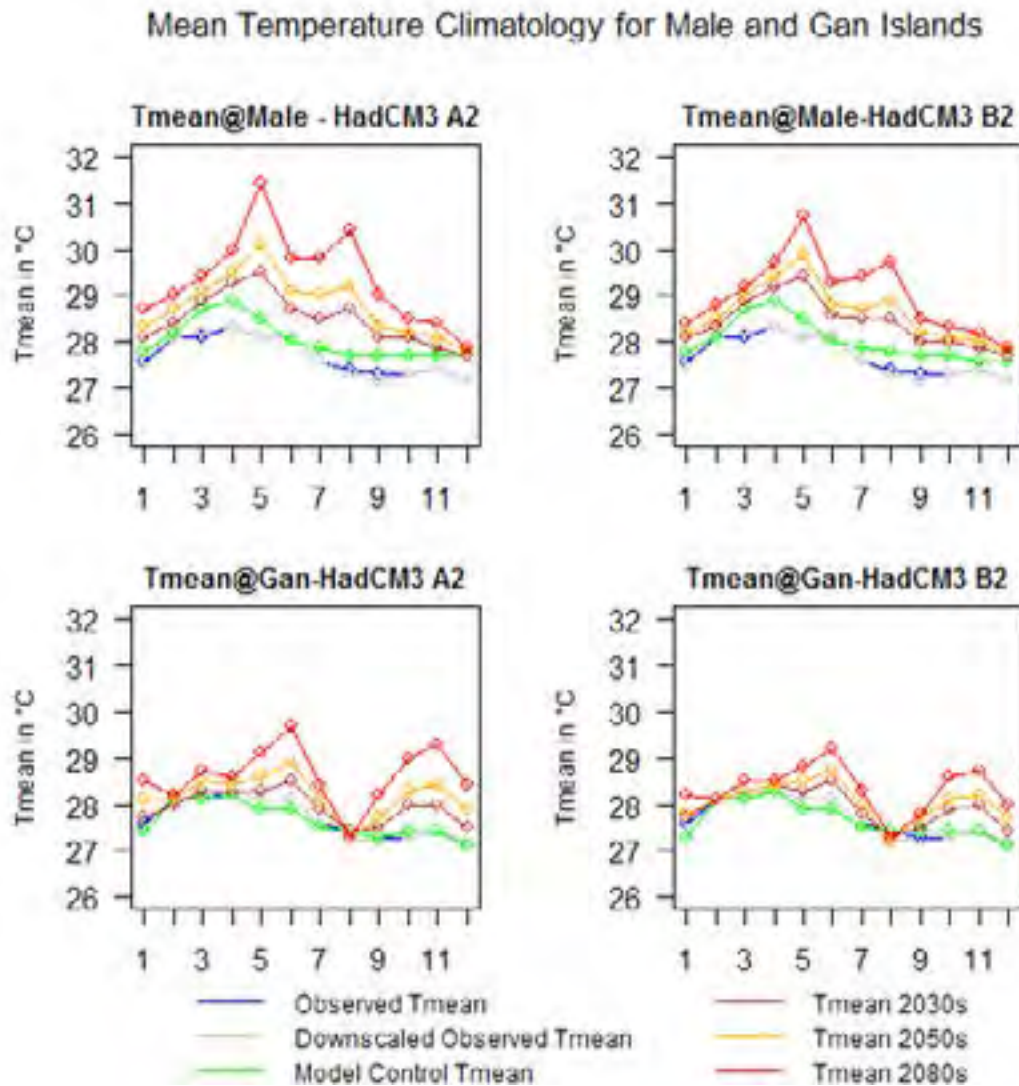


Figure-17 shows the climatology of observed and projected temperature at various time slices for two locations. This analysis shows the temperature raise is steadily increasing over time period. The maximum of 1.5°C raise is observed.

4.2.2 Precipitation

Precipitation downscaling through statistical downscaling techniques were found to be not reliable because of its very poor correlation between predictands and predictors (maximum 0.03). The observed daily precipitation record at station level is not capturing the climate characteristics of the larger domain represented by the GCM. This is mostly attributable to non-availability of long-term rainfall measurement that are able to adequately capture rainfall climate of the region. As observed earlier, rainfall data is only available for two stations, for a limited period (1975 to 2010). However, attempts are still ongoing to identify suitable predictors from the region or globally.

4.3 Uncertainties

Wilby & Christian (2007) strongly cautions that the statistical tools such as SDSM, should be used after establishing physically based relations between predictors and local climate. This is a very real danger when employing regression-based modeling techniques. Rather, the downscaling should be based upon physically sensible linkages between large-scale forcing and local meteorological response. Therefore, good practice demands rigorous

evaluation of candidate predictor–predictands relationships using independent data. Furthermore, the local knowledge base is an invaluable source of information when determining sensible combinations of predictors.

Daily precipitation amounts at individual stations continue to be the most problematic variable to downscale, and research is ongoing to address this limitation. This arises because of the generally low predictability of daily precipitation amounts at local scales by regional forcing factors. The unexplained behavior is currently modeled stochastically within SDSM by artificially inflating the variance of the downscaled series to accord better with daily observations. Even so, the model can produce unrealistic behavior if the stochastic component is not properly handled. This, again, underlines the importance of independent testing of all model parameters against data withheld from model calibration.

Ultimately, all statistically downscaled scenarios depend on the realism of the climate model forcing. Systematic biases in the mean and variance of GCM predictors can be reduced through normalization with respect to a control period (as in the present case where we have used pre-prepared SDSM predictors). Biases in large–scale patterns of atmospheric circulation in GCMs (e.g. shifts in the dominant storm track relative to observed data) or unrealistic inter–variable relationships pose more difficult problems. It is therefore advisable to use multiple GCMs, which however requires pre-preparation of the data

SUMMARY

Based on the analysis, sea level, sea surface temperature, precipitation and temperature pose climate risks for Maldives, in that order of their respective priorities. Chapter we have attempted to present a preliminary analysis of the climate change scenarios for the above mentioned parameters were generated using different approaches ranging from inference from GCMs, dynamical downscaled products, statistical downscaled products.

Sea surface height projection from GFDL-CM2.1 has been extracted for all atoll locations. It is inferred that the observed tide gauge records and model control for Male and Gan location has good correlation and hence the projected data from this model is suppose to have reliable projected data. Maximum sea surface height change has been prepared for 2080s for atolls to guide the worst case scenario in the region. More data for global sea-levels are being procured for analysis which will have to be combined with the present analysis of sea-surface heights to make inundation maps

to guide risks from SLR. This analysis will be available in chapter 4. Sea-surface heights cannot be used directly for these purposes.

Sea surface temperature parameter has been inferred directly from GCMs, neither statistical downscaling nor dynamical downscaling techniques carried out because of lacking observational records. The sea surface temperature changes over years have steady increment. For whole of the Maldives, the range sea surface temperature change for three time slices are as follows 2030s (0.76°C to 1.33°C), 2050s (1.01°C to 1.93°C) and 2080s (1.27°C to 3.40°C).

Generation of precipitation change scenario involves inference from GCMs, dynamical downscaling techniques, statistical downscaling techniques. Statistical downscaling results were not considered because of the unrealistic values and poor correlation with predictors. Precipitation results from dynamical downscaling techniques are to be considered for interpreting impacts and further planning activities needed at atoll levels. Over the zones of Maldives, average annual rainfall from 2021 to 2050 increases by 3 to 8mm/day from twenty years average rainfall. Dynamical downscaled products shows increasing trend in precipitation amount through all the zones over the years, while southern zones has more increasing rainfall in future. This is supported by the corresponding strengthening of the monsoon currents evidenced by the circulation diagnostics from both the regional and global model inferences.

Generation of temperature change scenario involves inference from GCMs, dynamical downscaling techniques, statistical downscaling techniques. All three techniques are considered. Mean annual temperature from 2021 to 2050 increases by 1.5°C to 1.85°C from the observed mean, which is still under the range of temperature change observed in GCMs that (1.19° to 2.25°). Statistical downscaling shows the change of temperature in Male is as follows 2030s (0.4°C to 0.5°C), 2050s (0.6°C to 0.8°C) and 2080s (1.0°C to 1.3°C), where in Gan, these are the changes 2030s (0.3°C), 2050s (0.4°C to 0.6°C), 2080s (0.7°C to 1.0°C). From all the above results, it is clear that downscaled temperature scenarios increase is likely to be from 0.4° C to 1.85°C. In this project we have simultaneously pursued two different approaches and model data acquisition and its quality control has taken significantly more time and effort. The unique context of the Maldives and non-availability of local data has been a major barrier. The analyses presented here are being pursued expeditiously for making relevant climate risk conclusions and evolution of tools for use of the data sets generated. The forthcoming chapter will be presenting all these aspects in complete details.

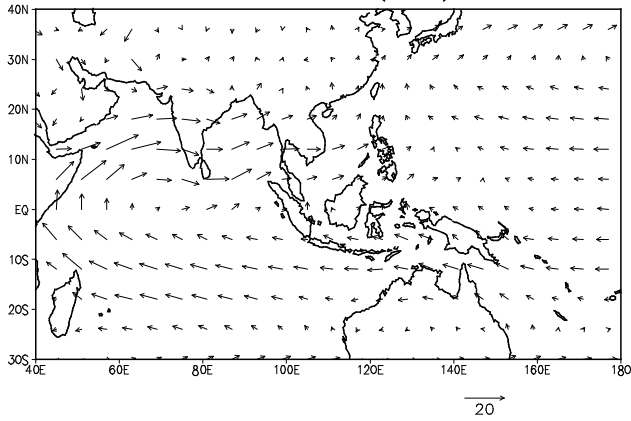
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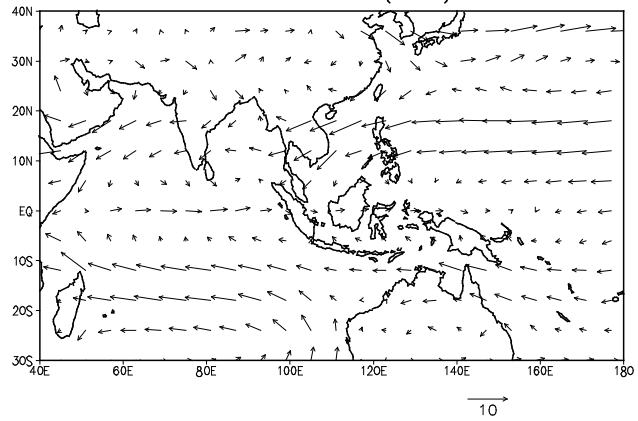
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ANNEXES

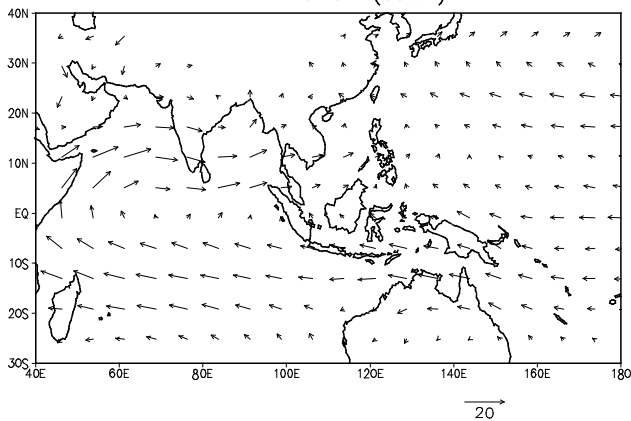
ERA-INTERIM (JJAS)



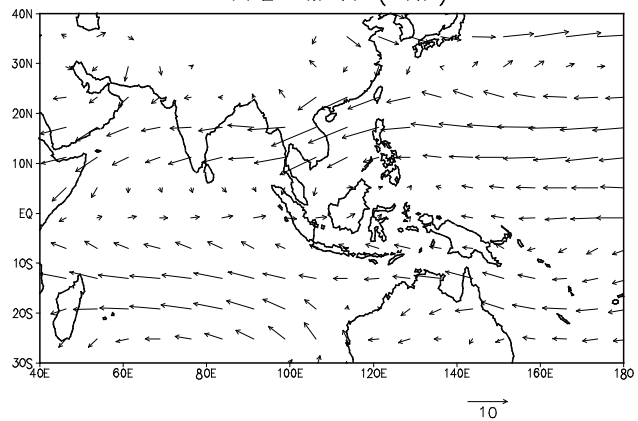
ERA-INTERIM (OND)



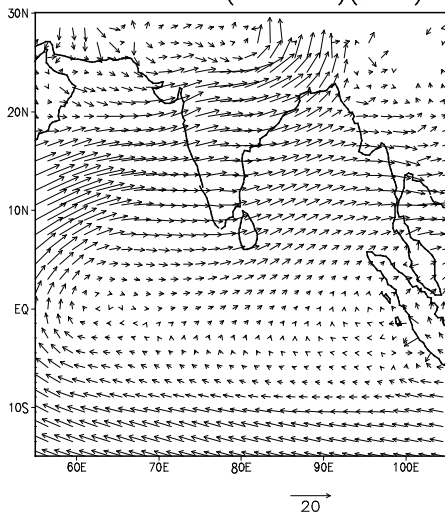
GFDL CM2.1 (JJAS)



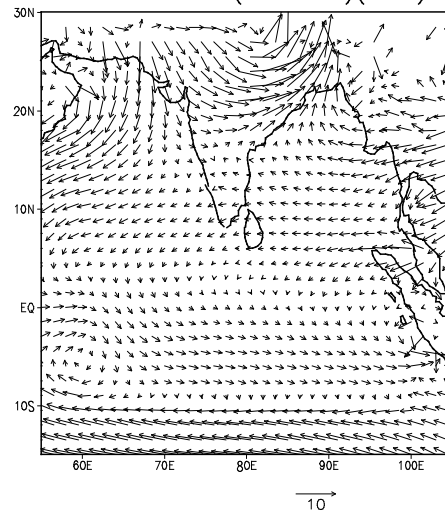
GFDL CM2.1 (OND)



IPRC REGCM (ERA-INT)(JJAS)



IPRC REGCM (ERA-INT)(OND)



Annex 1- Figure A: Climatology (JJAS) 850hpa wind from ERA-Interim, GFDL CM2.1, IPRC REGCM

Figure B: Climatology (OND) 850hpa wind from ERA-Interim, GFDL CM2.1, IPRC REGCM

Figure C: ERA Interim reanalysis regression maps based on Maldives Island precipitation index with a) Precipitation and b) moisture convergence (shaded) and moisture flux vectors (vectors) during JJAS and c) Precipitation and d) moisture convergence (shaded) and moisture flux vectors (vectors) during OND. Maldives Island encompassing 5o S - 10o N; 70o E - 75o E is shown as box in in panels a and c . Shades and arrow indicate regression coefficients. Unit for Precipitation : mm day-1; Unit for Moisture convergence: mm day-1; Unit for Moist. flux vectors: kg m-1 s-1)

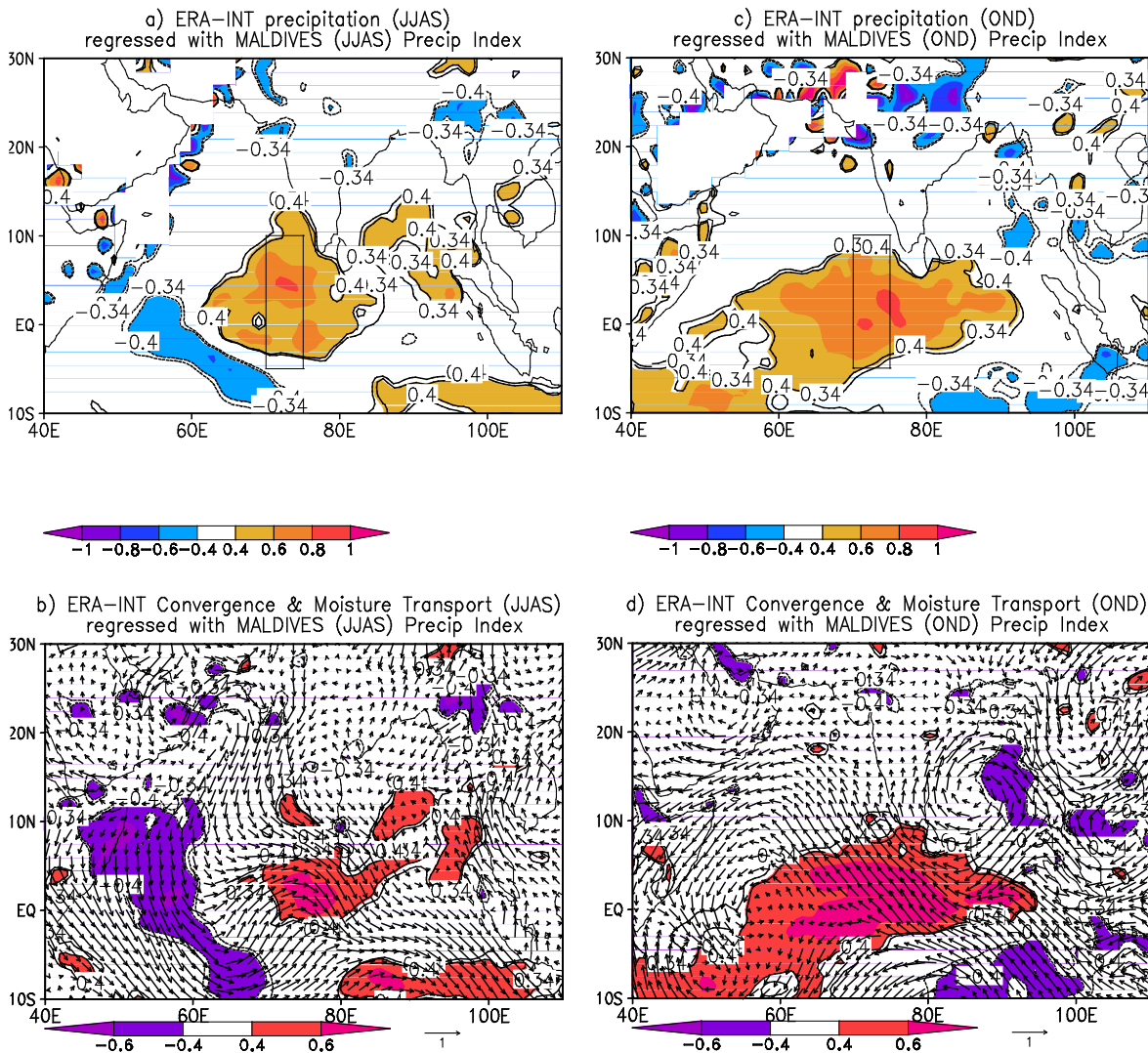
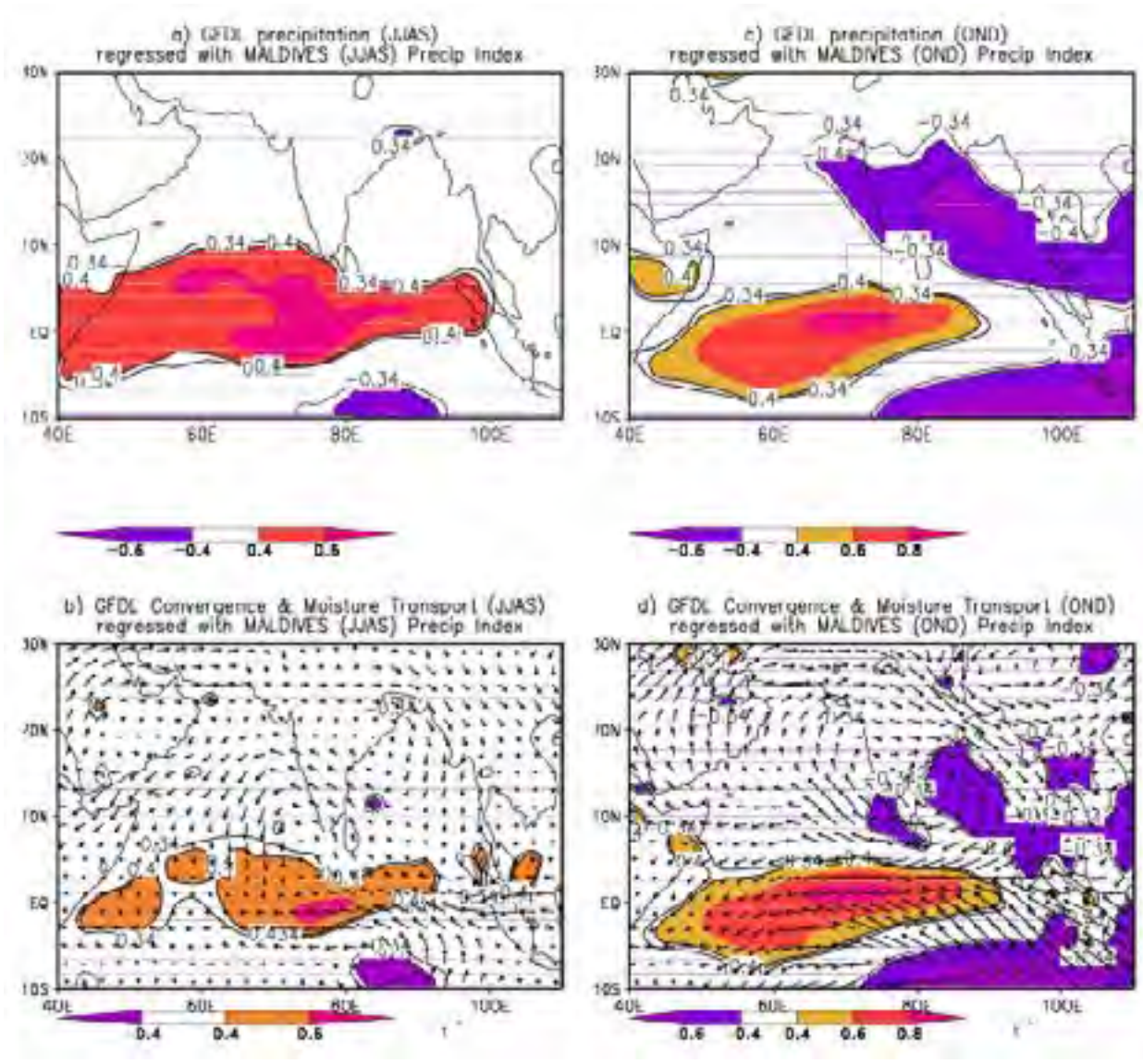


Figure D: GFDL CM2.1 GCM regression maps based on Maldives Island precipitation index with a) Precipitation and b) moisture convergence (shaded) and moisture flux vectors (vectors) during JJAS and c) Precipitation and d) moisture convergence (shaded) and moisture flux vectors (vectors) during OND. Maldives Island encompassing 5o S - 10o N; 70o E - 75o E is shown as box in in panels a and c . Shades and arrow indicate regression coefficients. Unit for Precipitation: mm day-1; Unit for Moisture convergence: mm day-1; Unit for Moist. flux vectors: kg m-1 s-1)

during OND. Maldives Island encompassing 5o S - 10o N; 70o E - 75o E is shown as box in in panels a and c . Shades and arrow indicate regression coefficients. Unit for Precipitation: mm day-1; Unit for Moisture convergence: mm day-1; Unit for Moist. flux vectors: kg m-1 s-1)



ANNEX 2 – EMISSION SCENARIOS

IPCC SRES (Special Report on Emissions Scenarios - SRES) scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The IPCC SRES scenarios contain various driving forces of climate change, including population growth and socio-economic development. These drivers encompass

various future scenarios that might influence greenhouse gas (GHG) sources and sinks, such as the energy system and land use change. The evolution of driving forces underlying climate change is highly uncertain. This results in a very wide range of possible emissions paths of greenhouse gases.

The SRES team defined four narrative storylines, labeled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways.

A1: globalization, emphasis on human wealth Globalized, intensive (market forces). 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. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI),

non-fossil energy sources (A1T), or a balance across all sources.

A2: regionalization, emphasis on human wealth Regional, intensive (clash of civilizations). The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally

oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

B1: globalization, emphasis on sustainability and equity Globalized, extensive (sustainable development). The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.


B2: regionalization, emphasis on sustainability and equity Regional, extensive (mixed green bag) The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Source: IPCC, 2000, Special Report on Emission Scenarios

ANNEX 3 – LIST OF EMISSION SCENARIOS CONSIDERED

Approach	SRES Scenarios considered		
	A2	A1B	B1
Direct GCM output (HadCM3, ECHAM, MRI CGCM, GFDL)	Y	Y	Y
Sea-level analysis (GFDL)	-	Y (5 realization for control and 3 realizations for projection data)	-
Statistical downscaling (HadCM3)	Y	-	Y
IPRC RegCM (GFDL)	-	Y (2082-2100)	Y(2021-2050) Special 1% Co2 increase





**CLIMATE CHANGE SCENARIOS AND
THEIR INTERPRETATION FOR MALDIVES**

CHAPTER. 4

CHAPTER SUMMARY

The project on “Integrating Climate Change Risks into Resilient Island Planning in the Maldives”, the Regional Integrated Multi-Hazard Early Warning System (RIMES) was commissioned in March 2011 by the Maldives’ Ministry of Housing and Environment (MHE) to develop high-resolution regional climate model for the Maldives, through statistical and dynamical downscaling of global models, to provide projections for use in national and local planning.

Global climate models (GCMs) are important tools for studying climate change and making projections for the future. Although GCMs provide realistic representations of large-scale aspects of climate, they generally do not give good descriptions at regional and local scales. Their results need to be downscaled to finer spatial scales to better interpret the scenarios of future climate change at local scale for various sectors. In this project RIMES undertook review of past work, understanding the base-line climate and inferences from future climate projections from GCMs, as well as generating dynamically and statistically downscaled products. Future climate change scenarios inherently represent a set of likely climate futures. Sea surface temperature and Sea Surface height parameters were inferred directly from GCMs. The Maldives region was divided into four zones covering the atolls from north to the south. In all these zones similar increasing trends in temperatures are revealed in the future climate change scenarios examined.

As evidenced by prior reports on climate change concerns over Maldives, the present work also illustrates that sea level, sea surface temperature, rainfall and its variations pose future climate risks for Maldives. Their specific relevance depends on particular sector level activity that the risks are being interpreted for. This short research work should be regarded as preliminary steps in understanding the climate change scenarios over the Maldives geographical domain.

The high resolution RegCM results show consistent increases in rainfall over all the four zones during May to October extended rainy months. This is accompanied by the extreme events such as maximum one day rainfall and no. of consecutive wet days are also increasing over all zones of Maldives. The increased rainfall has positive and negative impacts for various sectors. Increased rainy days may

pose concerns for the tourism sector, where as agriculture and water resource sectors might possibly be benefited in terms of their accumulated water needs if effective water harvesting and management practices are built-in through targeted adaptation projects. There is very clear indication of increases in night time temperatures, which has relevance to human comfort and health issues for the local population as well as the tourism sector. The sea surface temperature changes over years have also steadily incremented and this rise in sea water temperatures may have a profound impact on the important fisheries sector and the rich and unique ocean biology of atolls. Maximum sea surface heights, representing the worst case scenarios based on three realizations of one GCM indicate increases ranging from 8.2 to 9.5 cm across the various atolls for 2080s. The long term risks for Maldives are SSH rise combined with high tides, which occurs for a day or two at times.

One of the important components of this project was a workshop to share the downscaled model scenario results with key stakeholders and also provide training sessions on analysis of extreme climate events. The training events built the capacity of participants from stakeholder department and the Maldives Meteorological on using GIS based tools to visualize future climate change scenarios and statistical tools to examine extreme climate events linked to temperature and rainfall changes.



This work also illustrates that sea level, sea surface temperature, rainfall and its variations pose future climate risks for Maldives

1. INTRODUCTION

Under the National Adaptation Programme of Action for Maldives, the Ministry of Housing and Environment (MHE), Government of Maldives, in collaboration with the United Nations Development Programme (UNDP), implementing the first climate change adaptation project entitled “Integrating Climate Change Risks into Resilient Island Planning in the Maldives”. Generation of better information on potential climate change effects on atoll and island level risks is one of the key outputs of the project. This involves review of past climate change studies and data analysis, and production of downscaled climate change scenarios for the Maldives, to guide national and local planning, Regional Integrated Multi-Hazard Early Warning System for Africa and Asia (RIMES) implemented this component of the project from March 2011 to Feb 2012.

RIMES component of the project, i.e. the development of high-resolution regional climate change model for the Maldives through statistical and dynamical downscaling of global climate change models to provide projections for use in national and local planning, aims to: a) identify appropriate global climate change models, based on their relative veracity to simulate the climatology of the Indian Ocean region centered over the Maldives; and b) downscale climate change projections, and enable interpretation of impacts for use in national and local planning. Work shall be undertaken in three stages: 1) Review of existing information on climate change modeling and observed climate data and trends pertaining to the Maldives; 2) Identification of a suitable set of global climate models, and downscaling, using appropriate dynamical and statistical downscaling techniques, based on the unique geographical and climatological context of the Maldives; and 3) Interpretation of the climate change scenarios into climate change impact outlook and disaster risk profiles, and communication of results through technical report, meetings and workshop.

This chapter, which is the fourth and final presents the baseline climate, future climate (average time series, maps, etc.), interpretation of climate change results and summary of capacity building activities. It begins with a brief introductory chapter giving a background of the project, and presents the unique climate context of the Maldives. The second chapter provides the baseline climate of Maldives which includes, trends and extremities etc., The third chapter presents the climate change results from GCMs, RegCMs and Statistical models; along with validation and limitation of the model results. The fourth chapter explains more on interpretation of the generated climate change scenarios for sector specific in Maldives as well as capacity building activities carried out under this project. The final chapter concluding chapter briefly outlines the conclusion and future recommendations. Stakeholder training and workshop briefing reports are provided in appendix 2 and 3 respectively.

1.1 Geographical uniqueness of Maldives

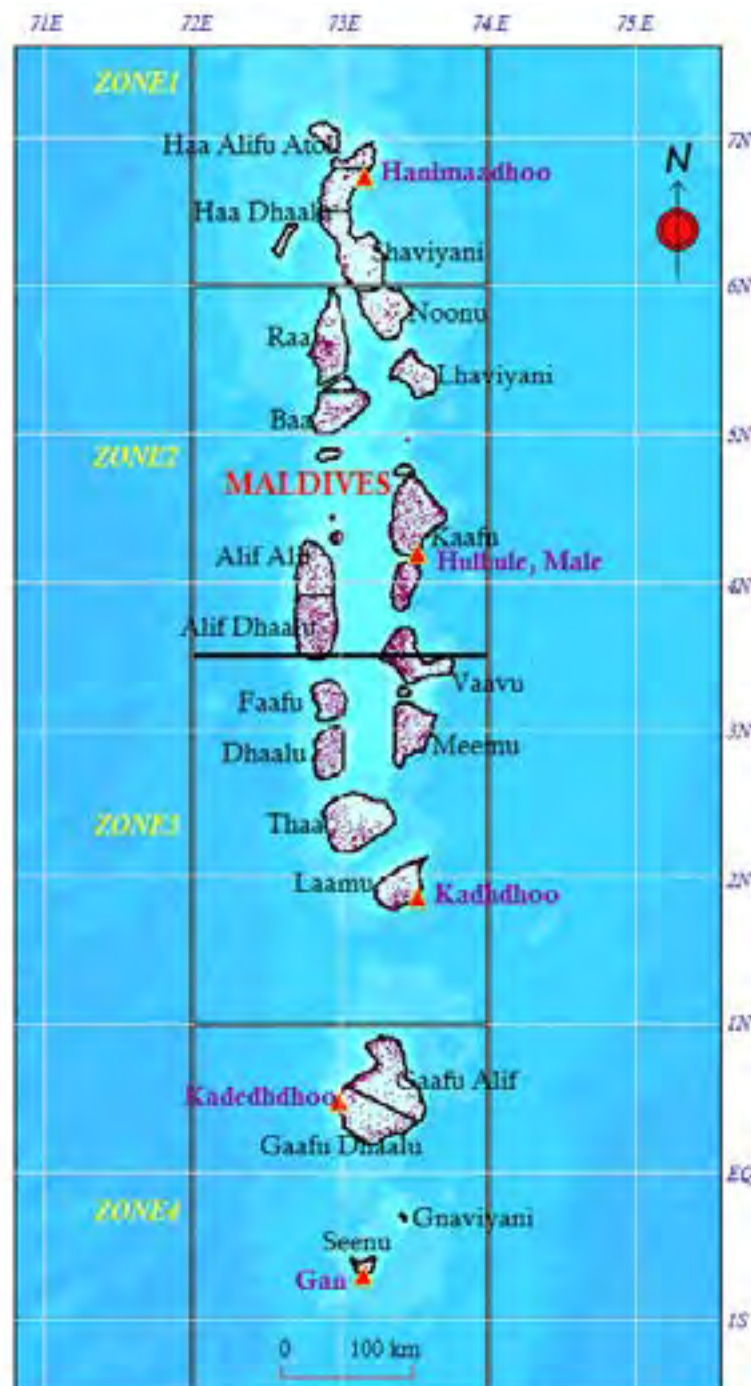
Maldives, an archipelago of 1,190 islands, grouped into 26 atolls, is located in the Indian Ocean, to the southwest of the Indian sub-continent. The islands stretch 860km from latitude 7°6'35"N, crossing the Equator to 0°42'24"S, and lying between 72°33'19"E and 73°46'13"E longitude (Figure 1). The islands are very low-lying, with more than 80% having an elevation of less than 1m above mean sea level; none exceeds an elevation of 3m (MHAHE, 1999). Coral reefs surrounding the islands protect the inhabitants from adverse impacts of strong waves. Only 193 of the total number of islands are inhabited, with combined population of 298,968. The main contributors to the economy are the tourism,

fisheries, construction, and commercial sectors. The tourism and fisheries sectors are very much dependent on the coastal environment of Maldives.

The islands' geophysical characteristics predispose the country's propensity to natural hazards. Its geographic location near the equator in the Indian Ocean exposes Maldives to tropical storms and storm surges, swell waves, gale-force winds, heavy rainfall, drought, as well as tsunami

and earthquakes. Floods occur from heavy rainfall, storm surges, or from swells generated by storms from the far south. The small size of the islands and their low elevation make human settlements defenseless against severe weather events, as well as tsunami, as retreat inland or to higher grounds would be impossible (MHTE, 2010). Also, accelerated sea level rise due to climate change will have devastating effects on the islands, and can threaten their very existence (MHAHE, 2001).

Figure 4.1 Geographical map of Maldives showing the four zones demarcated for interpreting future climate change scenarios



Combined with high waves, increase in sea level enhances flood risks and rate of erosion that would lead to alteration of beaches (Tariq, et.al, 2002). The powerful swell that occurred from 15-19 May 2007, during high tide, caused substantial flooding and soil erosion in many islands (NDMC, 2007). The corals which made up this archipelago are also dying because of the sea surface warming, a problem commonly known as coral reef bleaching. The episodes of coral bleaching over the past decades have been associated with several causes, including increased ocean temperature (Shrestha & Quadir, 2001). Coral reefs in the Maldives were severely impacted by the 1998 coral bleaching event, with subsequent bleaching-induced mortality reducing coral cover from about 42% to 2% (Zahir, 2000). Maldives is made entirely of coral reefs, the climate change and its predicted outcomes of increased sea-surface temperature and associated oceanographic changes, increased rainfall and increased incidence and severity of tropical storms are critical for fishery sector vulnerability assessments. Corals reefs sustain the fisheries and livelihoods of Maldivians including the economically most important tourism sector for the Maldives (Adam, 2006).

For Maldivians, groundwater and rainwater were the traditional sources of fresh water. There are no streams or rivers in any of the islands, except for a few wetlands and freshwater bodies. Groundwater in aquifers, vary seasonally, depending on rainfall and extraction across the islands. Of late, the problem of depletion of fresh water aquifers has been also experienced and threatens the fresh water availability in Maldives.

Maldives has a warm and humid tropical climate, dominated by two monsoon periods: the southwest monsoon (wet period, from May to November); and the northeast monsoon (from January to March) (MMS, 2006; Ramiz, 2007). Annual average rainfall is 2,124mm. The southern atolls receive, on average, 2,277mm of rainfall annually, while the relatively drier northern atolls receive 1,786mm (MMS, 2006). No significant long term trends are evident in the observed daily, monthly, annual or maximum daily rainfall. Analysis of past daily rainfall data revealed that 160mm of rainfall in a day is a relatively rare event at Hulhule, with a return period of 17 years, while an extreme daily rainfall of 180mm is a 100-year event.

The islands and associated bottom topography influence circulation patterns in the Maldives. Ramamirtham's (1979) study of the ocean circulation patterns in the region 71° to 80°E and the equator to 8°N revealed that a large cyclonic gyre exists in the northern regions and an anticyclonic one in the southern region, mainly in the subsurface layers. The monsoon current and equatorial counter-currents join and attain high speed, south of the Indian peninsula; the reflection of equatorial counter-currents is due to the

bottom configuration in this area. Thus the large cyclonic and anticyclonic gyres observed can, in all probabilities, be the extended patterns of the monsoon currents in this area.

The ENSO influence often propagates across the tropical Indian Ocean from Africa to Indonesia, modulating the troposphere moisture flux over the Indian Ocean and rainfall in surrounding continents. The eastern 'node' is confined near Sumatra, while the western center of action extends from the Maldives to the Seychelles Islands. Studies have been conducted to understand the relation between Southern Oscillation Index (SOI) and Sea-Surface Temperatures (SST) around the Maldives. Correlations indicate that the strength of ENSO in the Indian Ocean region has decreased in recent decades, while large scale, spatial and temporal patterns suggest independent variations of the Indian Ocean. Apart from annual variations of the monsoon and year-to-year fluctuations of climate, short-term weather events have a dramatic impact on countries around the Indian Ocean. Such relationships could be valuable for evolving statistical downscaling methods.

Shrestha & Quadir, (2001) study of various meteorological parameters shows a good relationship with ENSO. Temperatures including maximum, minimum and mean show an out-of-phase relationship with SOI with few months lag. SOI leads the temperature data. During the negative phases of SOI when the positive pressure anomalies prevail over Darwin region, with the Maldives region also experiencing positive pressure anomalies. This positive pressure anomaly coincides with the positive rainfall anomaly over Maldives and few months later SOI attains the lowest negative value. Fisheries industry is highly vulnerable to climate change as tuna is highly attuned to the biophysical conditions of the pelagic environment, particularly ENSO and associated changes in SST. During the 1997/1998 El Nino the Indian Ocean purse seine fishery was shifted to the east, unlike other years owing to the elevated depth of the 20°C isotherm (Adam, 2006). In the Maldives during the El Nino years, catch rates of skipjack tuna are depressed while catches of yellowfin tuna are elevated and the effect is reversed in La Nina years (Adam and Anderson 1996a; Adam and Anderson, 1996b). Tuna movement and abundance in the Indian Ocean is closely linked to the climate driven ocean productivity (Adam, 2006).

1.2 Climate risk profile and Socio economic context

The unique nature of the geography of Maldives exposes it to a range of climate risks. Climatology of the Indian Ocean, particularly variations and changes in sea-levels and the sea-surface temperatures are critical factors, as the climate of the atolls are hardly distinguishable from the surrounding ocean. Lives in inhabited islands are exposed to risks from extreme events such as warmer temperatures, high waves and rainfall, affecting tourism, water resources, agriculture and fisheries. The concentration of population on the larger islands has also led to their vulnerability to climate risks. For example vector and water borne disease outbreaks supported by favorable climate pose risks in populated areas.

The Maldivian economy is heavily dependent on fisheries and tourism, which are the major sources of foreign exchange earnings and government revenue, and which together directly account for about 40 percent of gross domestic product, while indirectly accounting for a much larger proportion of GDP. With only 30 sq km of cultivable land, the Maldives depends heavily on food imports, mostly funded by revenues from fisheries and tourism sectors. The fisheries sector, in addition to its role as an export industry, is an important source of local livelihoods, supporting 20% of the population and providing a primary source of dietary protein. Tourism, employing 6% of the population, also provides critical revenue for government expenditures. In summary, Sea-levels and sea temperatures are important for the fishing industry and as is perhaps favorable climate for tourism. Extreme climate events, rainfall amounts and its seasonality, high temperature spells are important for livelihoods and human well being.

1.3 Status of the existing work done and role of present project

Two reports provide significant information on climate change and modeling information for the Maldives: 1) First National Communication to UNFCCC and 2) DIRAM report. It is noted, however, that both these studies did not attempt to validate climate models or undertake site-specific assessments, as time and resources were limited. The first national communication report to UNFCCC, prepared by Maldives in 2001, analyzed the historical rainfall, temperature, and wind speed trends for Male and Gan, where datasets are available from 1969 to 1999. Climate change projections, based on IPCC's (AR3) emission scenarios IS92a

and IS92e for GCMs CSIRO-MK2 and HadCM2, have been used and summarized in Table 4. These, however, need to be updated with AR4 scenarios. Also, a limited number of model results have been used. None of the past studies reviewed use regional downscaling methods for climate change assessment studies in the Maldives.

Regional downscaled products, either dynamical or statistical downscaled climate change scenarios, have not been used in the existing climate change impact assessment studies. Hence, the present work enabled better characterization of the changes. However, the non-availability of long-term data for the main locations imposed limits to the confidence of the regionally downscaled estimates from both the approaches. With accumulating data from the newly established automatic weather station network, it would be possible to improve the confidence of the regional projections in future, beyond the project period.



Sea-levels and sea temperatures are important for the fishing industry and as is perhaps favourable climate for tourism

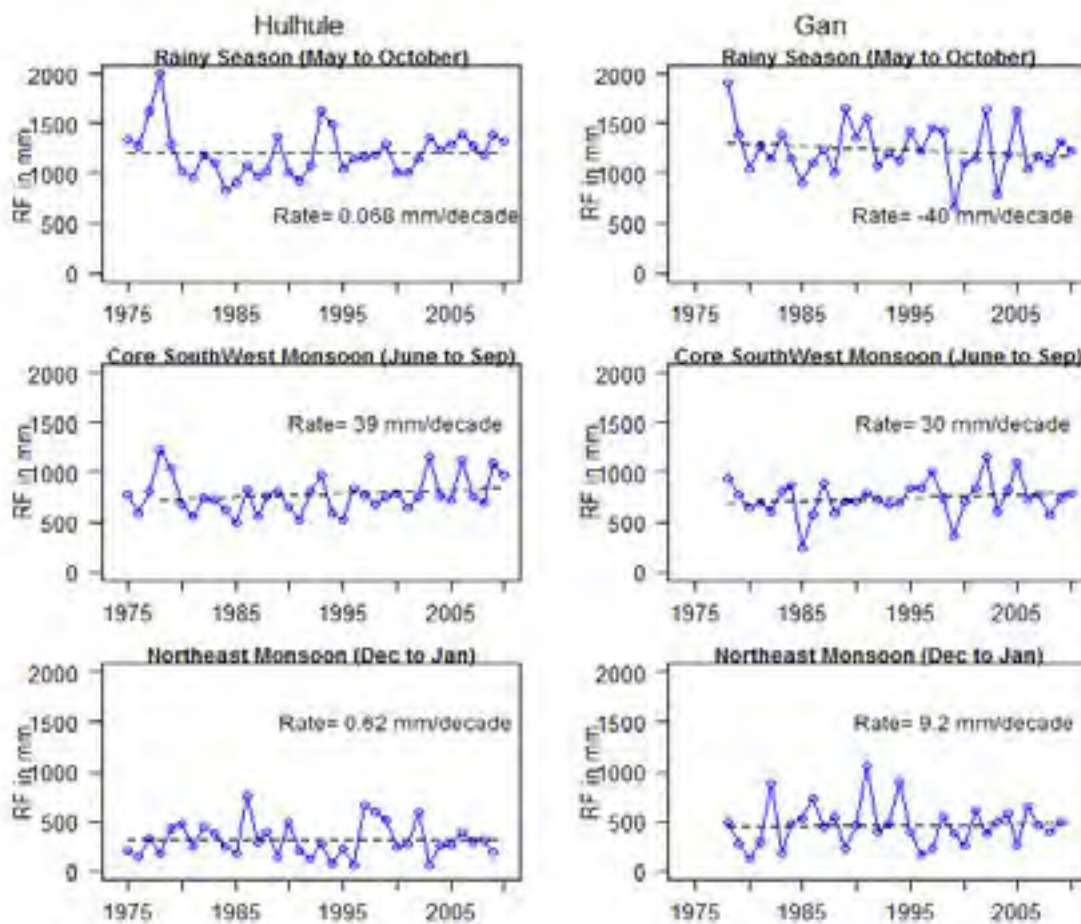
2. BASELINE CLIMATE OF MALDIVES

2.1 Observed trends in temperature and rainfall

Annual and monthly climatology plots for rainfall and maximum and minimum temperatures have been prepared, using observed climate data received from Maldives Meteorological Services for the period 1975 to 2010, to understand the annual and monthly variation and trends

over the Maldives region. The seasonal rainfall time series trend plots for longest available data series station Male' and Gan are presented in Figure 4.2 for the period 1975 to 2010.

Figure 4.2 Accumulated rainfall during various seasons for Male and Gan (1975 to 2010)



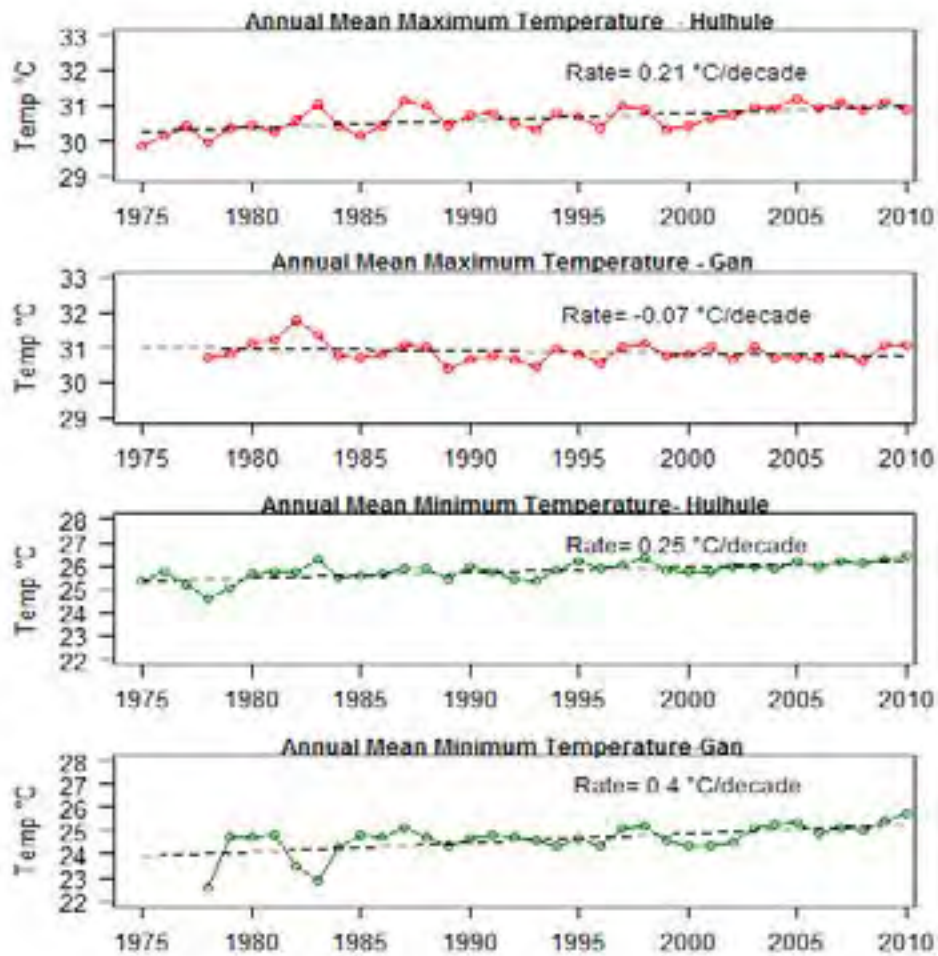
From the present analysis of rainfall trends, indicates overall positive trend in all the seasons except rainy season in Gan (May to October). Rainfall during the core southwest monsoon months (JJAS) and northeast monsoon months (DJ) shows increasing trend for both the locations. The rainfall trend of Gan for MJJASO season is decreasing but has increasing trend during core southwest monsoon season.

Annual TRMM rainfall analysis from 1998 to 2007 shows that zone4 receives more rainfall than other three zones (1, 2 & 3); also the fluctuation of annual rainfall is inferred between 1162 to 2503mm. It is observed that monthly rainfall amounts range from -200mm to 300mm, with very few anomalies that are greater than 400mm. No other long-term rainfall data is available from other stations.

In terms of long-term annual maximum and minimum temperature analysis, our result shows rising trend for both Male and Gan station. Figure-3 shows trend plot of maximum and minimum temperatures in both northern (Hulhule) and southern (Gan) parts of the Maldives. Maximum temperature shows an increasing trend in the northern part of the Maldives (0.21°C/decade), but a decreasing trend in the southern part

(-0.06°C/). Looking at the minimum temperature, there is an increase trend observed in northern parts (0.25°C/) and steep increase in southern part (0.4°C/). However Gan's maximum temperature decreasing trend is overcome by higher rise of minimum temperature. Overall Maldives is experiencing steady increasing temperature over the years.

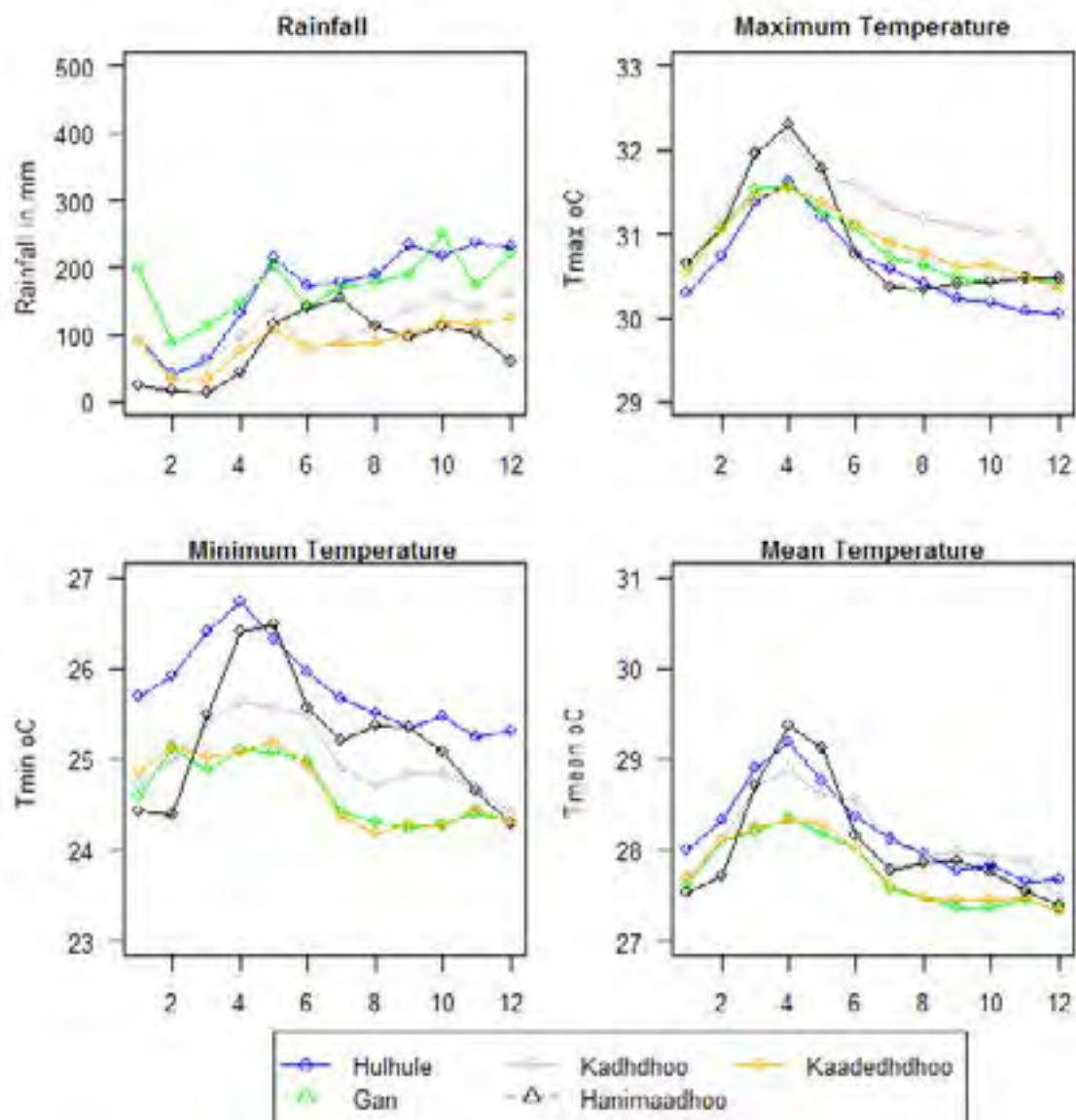
Figure 4.3 Variations in annual mean maximum and minimum temperature for Male and Gan (1975 to 2010)



Monthly climatology from the observed datasets (1975 to 2010) has been shown in Figure 4. This helped to identify the main rainfall months as well as peaks, which are the months May and September. These peaks have been well marked in other stations also, illustrating the strong signal of the two monsoon seasons in the rainfall climatology of the islands. Rainfall in Maldives varies from north to south, with the amount of rainfall increasing towards the south. This

difference in rainfall pattern is primarily due to the northeast monsoon, and April being much drier in the north than in the south (Edwards, 1989). This pattern is captured in the monthly climatology chart (Figure 4.4).

Figure 4.4 Seasonal cycles of climate parameters



2.2 Influence of monsoon

Maldives has a warm and humid tropical climate, dominated by two monsoon periods: the southwest monsoon (wet period, from May to November); and the northeast monsoon (from January to March) (MMS, 2006; Ramiz, 2007). Annual average rainfall is 2,124mm. The southern atolls receive, on average, 2,277mm of rainfall annually, while the relatively drier northern atolls receive 1,786mm (MMS, 2006). The understanding of monsoon is important, since all aspects of societal and economic activities in the monsoon Asia region are critically dependent on the monsoon climate. It has direct impacts on water resources, occurrence of climate-related disasters, agriculture, health, and coastal ecosystem services.

Liu et. Al 2010 study demonstrates the factors influencing Asian rainfall, from the large-scale seasonal monsoon driven by continent-ocean contrast, to regional modifications by orography, and possible human activities. As the south west monsoon system is controlled by continental scale circulations, local geography of Maldives does not influence the climatology significantly. During the summer monsoon, from May to November, moisture is transported from the Arabian Sea and transported out to the Bay of Bengal. The transport is reversed for the rest of the year, with low activity in all segments between February and May, as expected. This produces a slightly longer rainfall season over southern Maldives.

2.3 Extreme climate events

- The extreme climate event analysis has been performed for Hulhule and Gan location using RCLimdex package. The following extremities have been examined to understand the behavior of extreme characteristics of climate over Maldives.
- Cool nights: Percentage of days when TN<10th percentile – Unit in days
- Cool days: Percentage of days when TX<10th percentile – Unit in days
- Warm nights: Percentage of days when TN>90th percentile – Unit in days
- Warm days: Percentage of days when TX>90th percentile – Unit in days
- Max daily rainfall: Max 1-day rainfall amount in a year – Unit in mm

No. of days in a year when daily rainfall ≥ 30 and ≥ 50 mm – Unit in mm

Figure 5 and 6 shows the extremes of the climate observed in Male and Gan from 1975 to 2010. In both Male and Gan station, cool days and cool nights shows decreasing trend over the years, at the same time number of warm days and warm nights are increasing. This confirms the signal of temperature rise in Maldives region, and the results for the Indian ocean reported in Caesar et al (2011) The daily maximum fluctuates between 54mm to 176mm in Hulhule and 63mm to 188mm in Gan station. No. of days having rainfall more than 50mm fluctuates between 2 to 12 days in Hulhule and 2 to 19 days in Gan. Characteristics of rainfall fluctuate a lot in both the stations for the longest available period 1975 to 2010.

Although there is an increasing trend in seasonal rainfall amounts, the daily rainfall amounts or its extremes do not show any increasing trends. However number of Analysis of past daily rainfall data revealed that 160mm of rainfall in a day is a relatively rare event at Hulhule, with a return period of 17 years, while an extreme daily rainfall of 180mm is a 100-year event.

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Although there is an increasing trend in seasonal rainfall amounts, the daily rainfall amounts or its extremes do not show any increasing trend

Figure 4.5 Extreme Climate analysis for Hulhule location a) Warm days and nights b) Cool days and nights c) Maximum daily rainfall occurred in a year d) No. of days which has rainfall more than 30 and 50mm

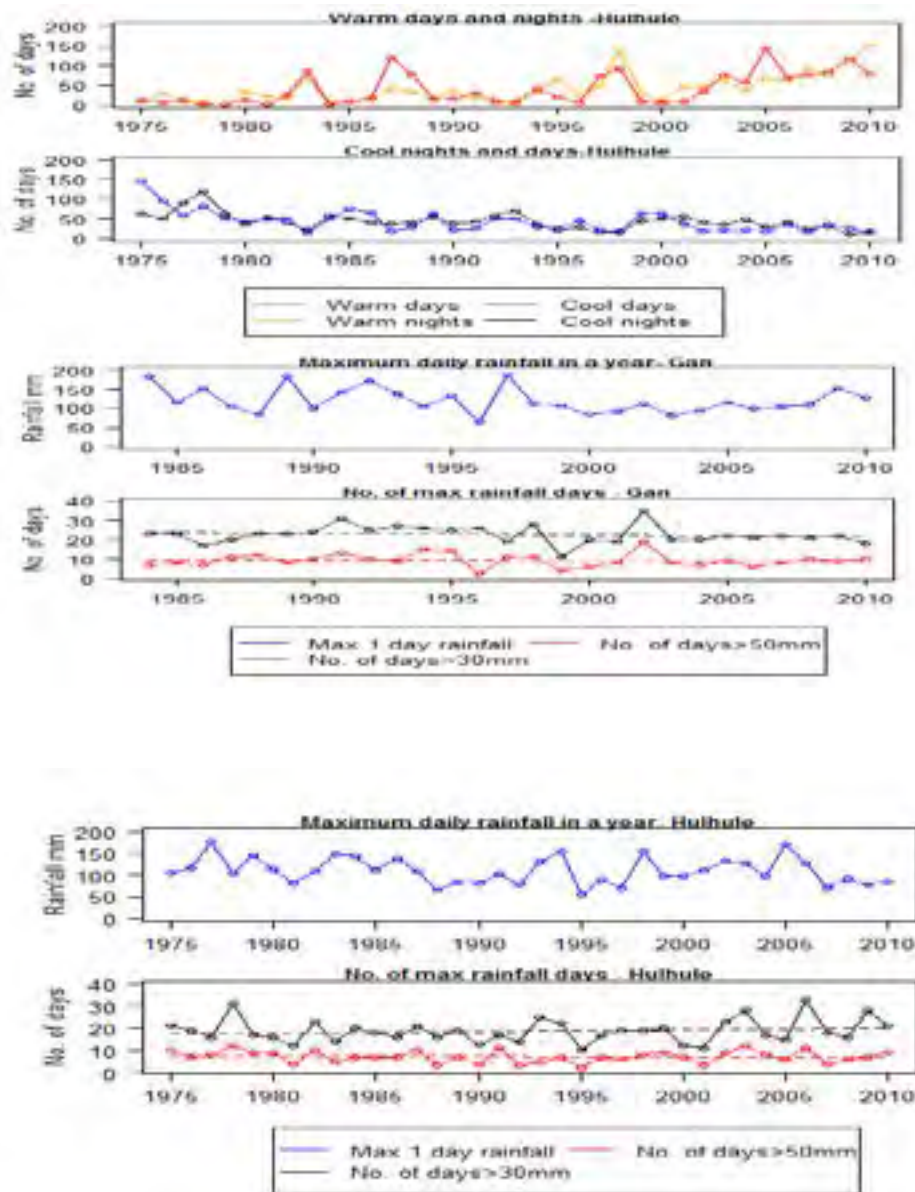
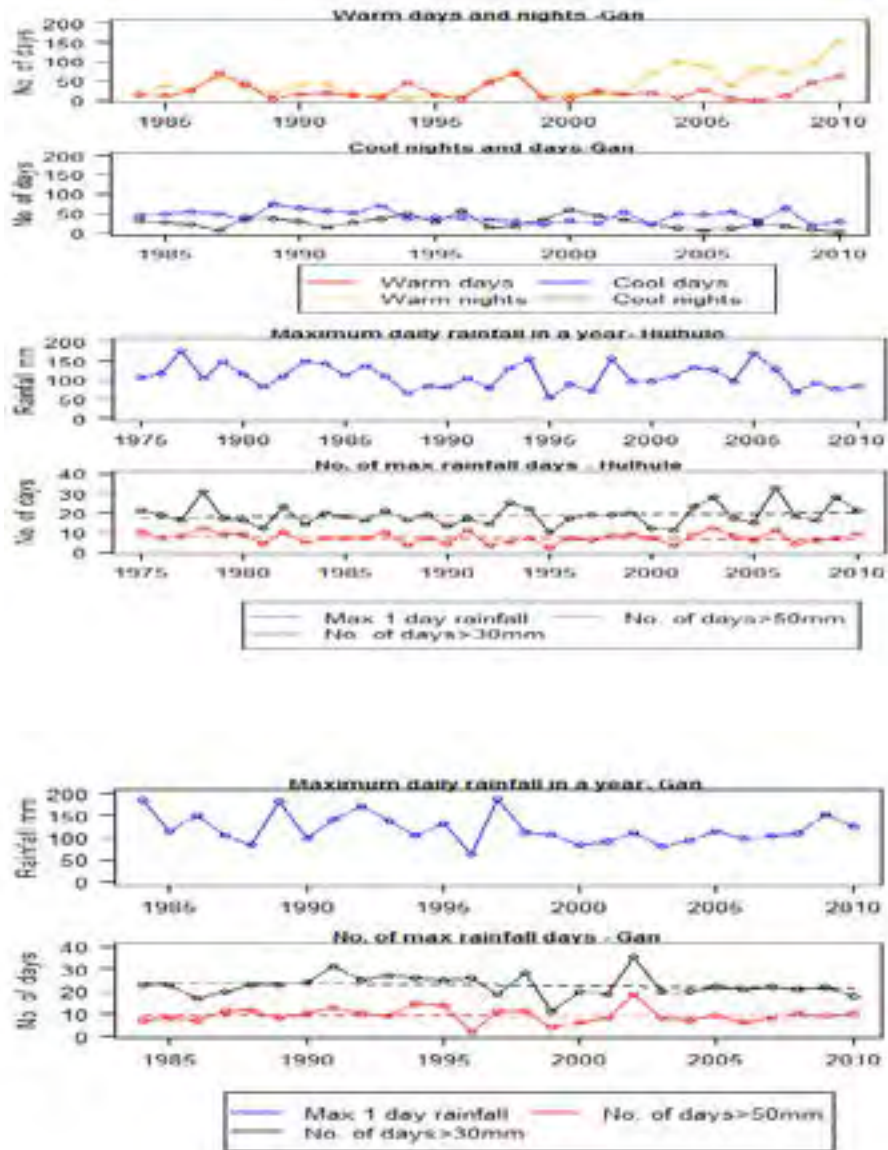


Figure 4.6 Extreme Climate analysis for Gan location a) Warm days and nights b) Cool days and nights c) Maximum daily rainfall occurred in a year d) No. of days which has rainfall more than 30 and 50mm



2.4 Observed Sea level characteristics

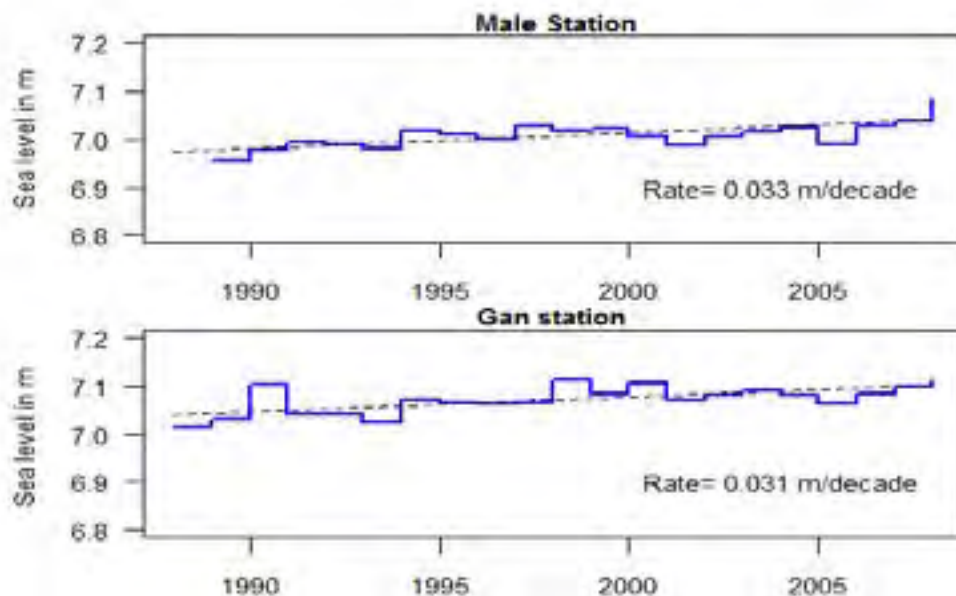
Maldives, being an island nation, is more vulnerable to sea-level rise and associated impacts of climate change. The National Assessment Report II (2010) states that a slight increase in sea level is threatening to the Maldives, since 80% of the country's land area is less than a meter above mean sea level. This is further complicated by tide variation

Understanding the historical trend of sea level change from available data and appropriate estimation of sea level changes are among the key activities in this study. Review of existing literature and examination of datasets from the Permanent Service for Mean Sea Level (PSMSL) was undertaken. Morner (2004) recently reported on sea level change in the Maldives and its vulnerability to this change. The study showed that there had been a 30cm fall in sea level in the Maldives over the last 50 years. Woodworth & Player (2003) and Church et al. (2004), however, using PSMSL datasets for Gan, Male and Hanimaadhoo, and calculating and

analyzing the annual mean sea level, reported an increase in sea level of 30.7mm and 35.2mm in a decade for Gan and Male stations, respectively. This increasing trend was also reported by Singh et al. (2001) and DIRAM (2010), with rates of sea-level rise projected at 8.4mm/yr, 3.7mm/yr, and 4.4mm/yr for Gan, Male and Hanimaadhoo stations, respectively. PSMSL records for these three stations are, however, short, having started only in 1988 (Figure 4.6), and, therefore, cannot represent longer-term trends. No attempt has been made for evaluating the records using datum correction, error estimation, etc.

Figure 4.7 shows the trend plot of sea level for Male and Gan location, which are representing northern and southern zones of Maldives. The sea level analysis shows there is an increasing tendency of 0.033m/decade (3.3mm/yr) at Male and 0.031m/decade (3.1mm/yr) at Gan.

Figure 4.7 Annual mean sea level variations in Maldives from 1988 to 2008



2.5 Sea surface Temperature

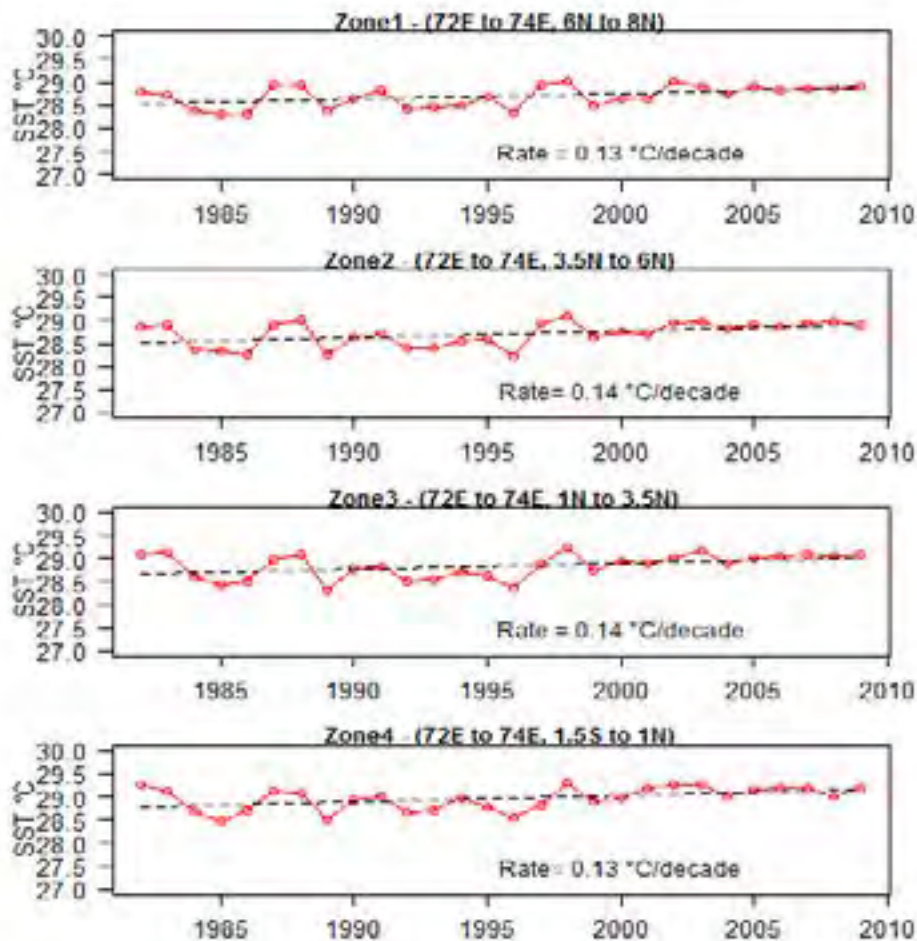
SST is an important parameter because of its change might affect Maldives' coral reefs (coastal eco system) and fisheries sector. Understanding SST historical change and projection is, therefore, essential for coastal ecosystem impact assessment.

NOAA Global Optimum Interpolation (OI) Sea Surface Temperature (SST) Analysis dataset is available for the period 1982 to 2010 at 1degreeX1degree resolution for the entire

globe. This data was processed by NOAA from monthly ship and buoy SST data, satellite SST retrievals, and SSTs simulated by sea ice cover. NOAA_OI_SST_V2 datasets from NOAA/OAR/ESRL/PSD, Boulder, Colorado, USA, has been downloaded from <http://www.esrl.noaa.gov/psd/>

Figure-8 shows four different zones of Maldives. The SST has the same increasing tendency as that of the air temperature recorded at two meteorological stations of Maldives. Average monthly Sea Surface Temperature (SST) ranges from 28.2°C to 29.3°C.

Figure 4.8 Variations of annual mean sea surface temperature fluctuation for four zones in Maldives (1982 to 2009)



2.6 Inferences

Climate of Maldives is largely dictated by the climate of the Indian Ocean, as the atoll clusters do not seem to produce a detectable land-sea contrast to create a clearly distinguishable island climatology. The existing long-term observational records show that the temperatures changes closely correlate with the sea surface temperatures and the rainfall data at the daily scale is very noisy, which is indicative of a preponderance of sporadic convective phenomena. On a seasonal scale there is increasing trend that could perhaps be linked to the rising trends in temperature. Better observational coverage will enable a more precise description of the climatology of the Maldivian atolls, particularly the north-south variations that are seen to some extent in the present analysis.

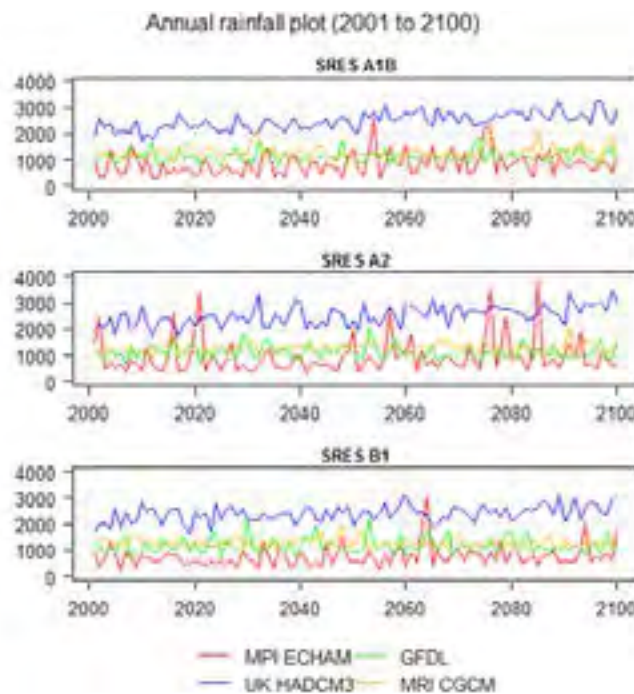
There is very clear indication of increases in night time temperatures, which has relevance to human comfort and health issues for the local population as well as the tourism sector. Rise in sea water temperatures have a profound impact on the important fisheries sector and the rich and unique ocean biology of atolls.

3. FUTURE PROJECTIONS

3.1 Global Climate Model

The results from the GCMs represent the driving source for all downscaled information, it is therefore important to consider their future projections over the region as a background. For this project the HadCM3, MPI ECHAM 5, MRI CGCM 2.3.2a and, GFDL CM2.1 GCMs, were chosen because of their good simulation of Asian summer monsoon circulation. The changes in three times slices 2030s, 2050s and 2080s for climate variables between model controls (20C3M) and projection scenarios (SRES A1B, A2, B1) were analyzed for four zones of Maldives domain. A summary for these results is presented in this chapter and table containing changes in climate parameters over four different zones is available in Appendix 1.

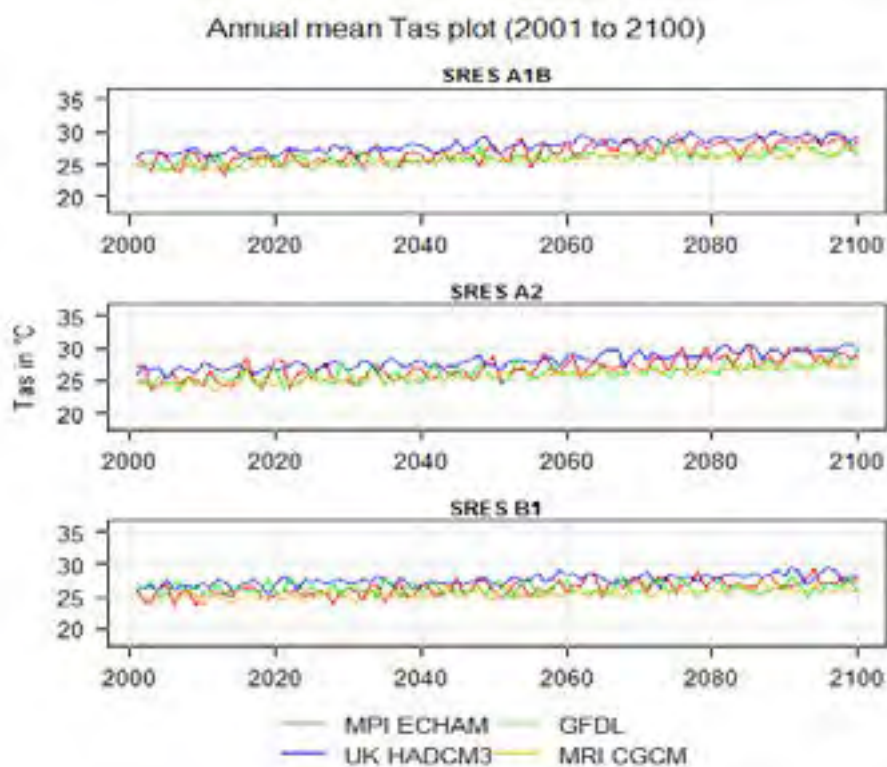
Figure 4.9 Variation in annual rainfall from 2001 to 2100 (X Axis – Year, Y Axis - rainfall in millimeters)



Observed annual rainfall based on Maldives station data for the period (1975-2010) ranges from 1750 to 2250mm, while the future projections from the set of GCMs examined show a range of 1250 to 3185mm. This implies an overall increasing trend of annual rainfall in GCM projections for the future. Figure-9 indicates the long term variation and trends in rainfall from the set of GCMs for the three different emission scenarios. The changes do not exhibit any pattern of increase in rainfall over all zones. Even for the same zone, different models show various changes in rainfall. ECHAM and HadCM3 exhibits positive changes in 2050s and 2080s for zone1 and 2, while GFDL and CGCM shows negative changes in rainfall for time slices 2050s and 2080s.

Time series plot of rainfall from 2000 to 2100 (Figure-9) exhibits increasing trend in rainfall. It is observed that there are variations on both positive and negative side of the mean climate; there is a tendency for higher than normal rainfall to occur more frequently. Even for the same zone, different models show various quantity of rainfall. HadCM3 shows a much higher range for rainfall variations as compared to the other models. These scenario results illustrate a tendency for both increased rainfall amounts and variability across the country, with chances of higher than normal cumulative seasonal rainfall amounts becoming more frequent. The large dispersion among the models examined shows that we cannot make confident conclusions about future rainfall climate of Maldives, except that there is a possibility of enhanced rainfall during the monsoon season

Figure 4.10 Annual mean surface air temperature from 2001 to 2100 (X Axis – Year, Y Axis – Surface air temperature in degree celsius)

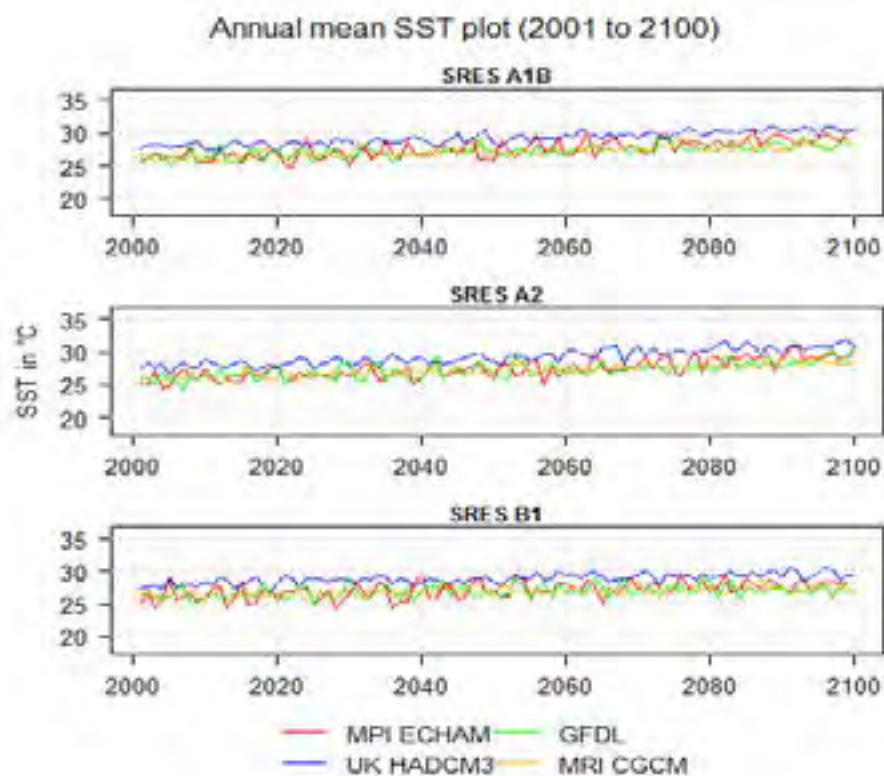


Surface air temperature (tas) is near-surface (usually, 2 meters) air temperature changes over Maldives (Figure 10), shows there is a steady increase in temperature despite year-to-year variations. There is a remarkable agreement among the four different models which lends greater confidence to the temperature projections. The changes exhibit a pattern of steady increase in temperature over all zones. For whole of the Maldives, the range of surface air temperature change for three time slices are as follows 2030s (0.87°C to 1.63°C), 2050s (1.19°C to 2.25°C) and 2080s (1.67°C to 3.72°C). It also seen that the different emission scenarios do not result in very different temperature changes, at least during the time horizons till 2050s. This is perhaps due to the vast expanse of the oceans that damps out the warming signal known to be prominent over the land.

Sea Surface temperature (SST) is very important parameter for Maldives unique geographical context considering their linkages with fisheries, tourism and the rich biodiversity of the lagoons. SST changes over Maldives are presented in Figure-11.

The projected changes for surface air temperature and sea surface temperature are quite similar as the oceanic influence dominates the atoll climatology. Figure-11 shows the change of sea surface temperature of Maldives domain for difference scenarios from models. For whole of the Maldives, the range sea surface temperature change for three time slices are as follows 2030s (0.76°C to 1.33°C), 2050s (1.01°C to 1.93°C) and 2080s (1.27°C to 3.40°C).

Figure 4.11 Annual Sea Surface temperature from 2001 to 2100 (X Axis – Year, Y Axis – Sea surface temperature in degree celsius)



3.2 Regional Climate Model

Regional modeling results were provided by our collaborating research partner the International Pacific Research Center (IPRC), University of Hawaii. RIMES jointly works with IPRC on the areas of climate research, in particular climate variability and change through diagnostic approaches. IPRC's regional climate model was used for the dynamical downscaling study, and all the model data analyses were undertaken by IPRC and RIMES scientists collaboratively.

The model implemented for dynamical downscaling in this project is IPRC RegCM. The version of the IPRC-RegCM used in this study has 28 vertical levels with high-resolution in the planetary boundary layer. The lowest model level is roughly 25 m above the surface. The model domain extends from 50°S to 55°N, 5°E to 170°E with a grid spacing of 0.25° (approximately 30 km horizontal resolution), in both zonal and meridional directions.

Large scale climatological features simulated by IPRC RegCM

The rainfall simulations by the IPRC RegCM as well as the forcing GCM – the GFDL (CM2.1) for JJAS (core southwest monsoon season and OND months) are illustrated in Figures 4.12 & 4.13 below. The downscaled results are able to reproduce the large scale features of the monsoon remarkably well. The simulation also resolves regional scale features like the rainfall variations associated with the western coast of India. The general tendency of the strengthening of the monsoon currents in both the seasons is however clearly indicated. There are however some large anomalies noted at the model boundaries particularly south of the equator in the RegCM runs, which is possibly due to inconsistencies between the parameterization schemes of the driving GCM (GFDL2.1) and the IPRC RegCM. Resolving this problem is only possible through regional model runs with boundary conditions using multiple GCMs.

Figure 4.12 Spatial patterns of rainfall over a larger domain around Maldivian Islands from observations, reanalysis and model simulations. First column shows rainfall features from Observation (TRMM), Reanalysis (ERA-INTERIM) and Model GCM (GFDL Coupled GCM – CM 2.1 model). Second column shows rainfall from downscaled scenarios of IPRC REGCM for 20C3M simulation, SRES A1B simulation and the difference (SRES A1B-20C3M) in mm/day for the season JJAS. (Unit for rainfall is given in mm/day)

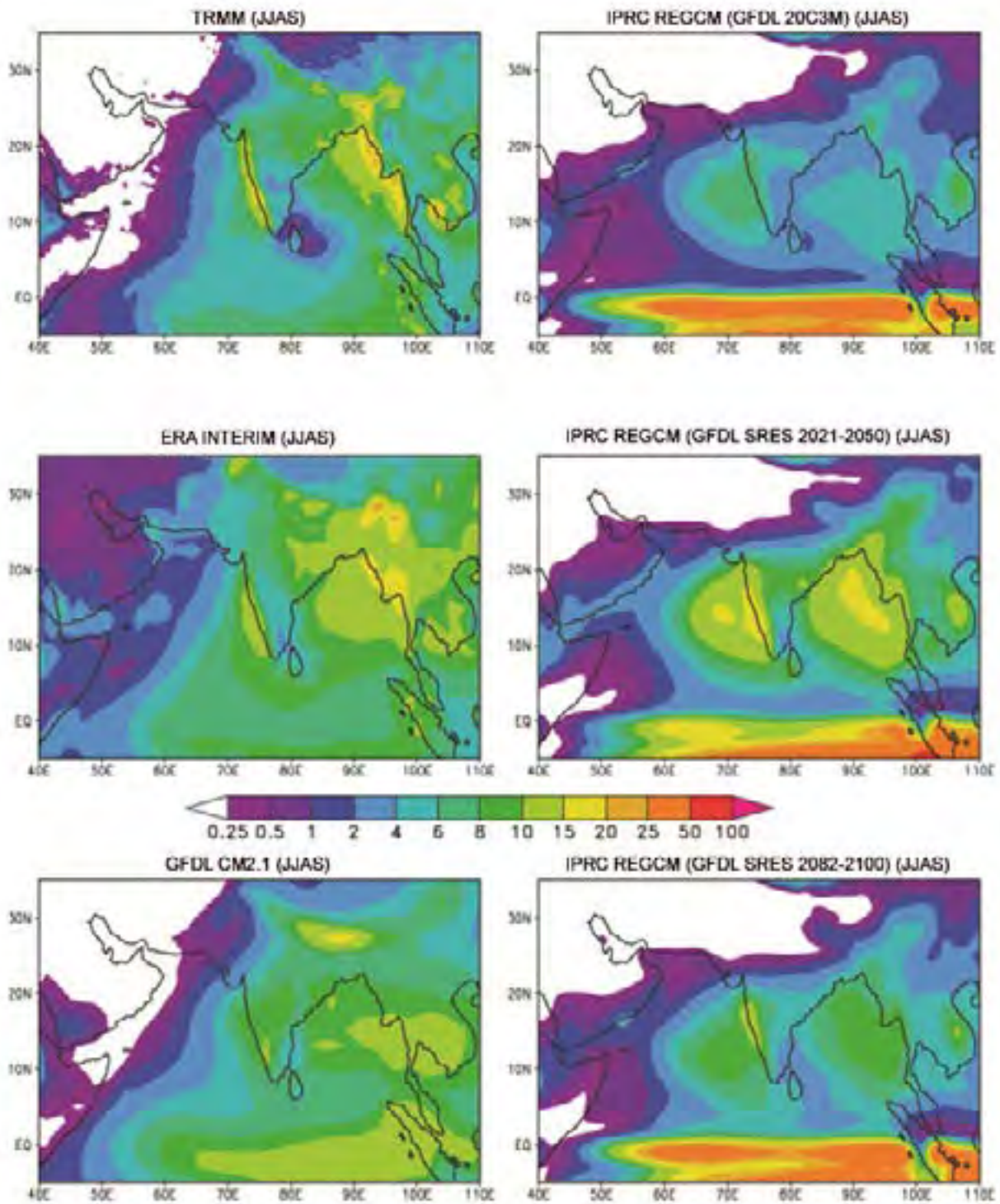
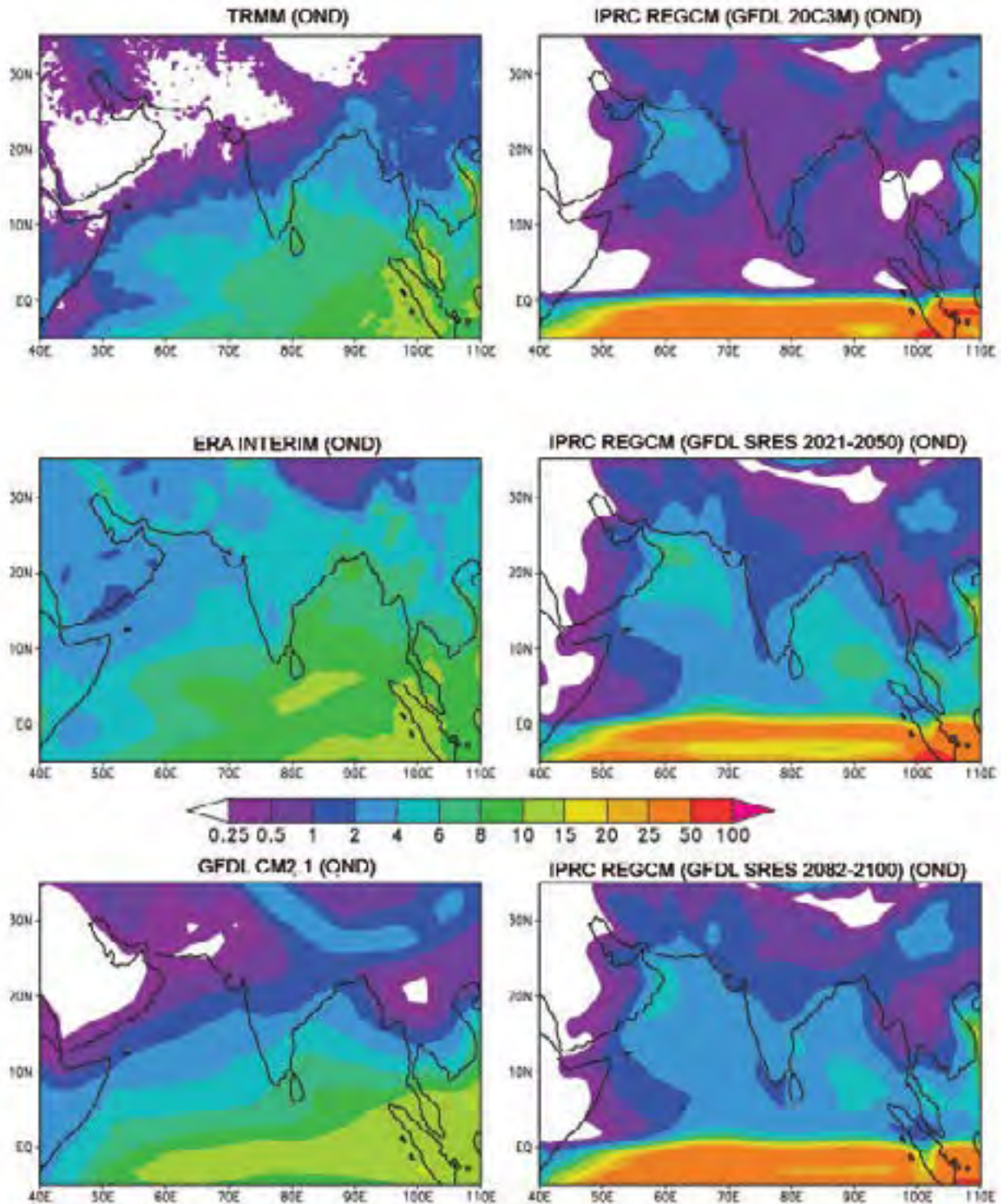


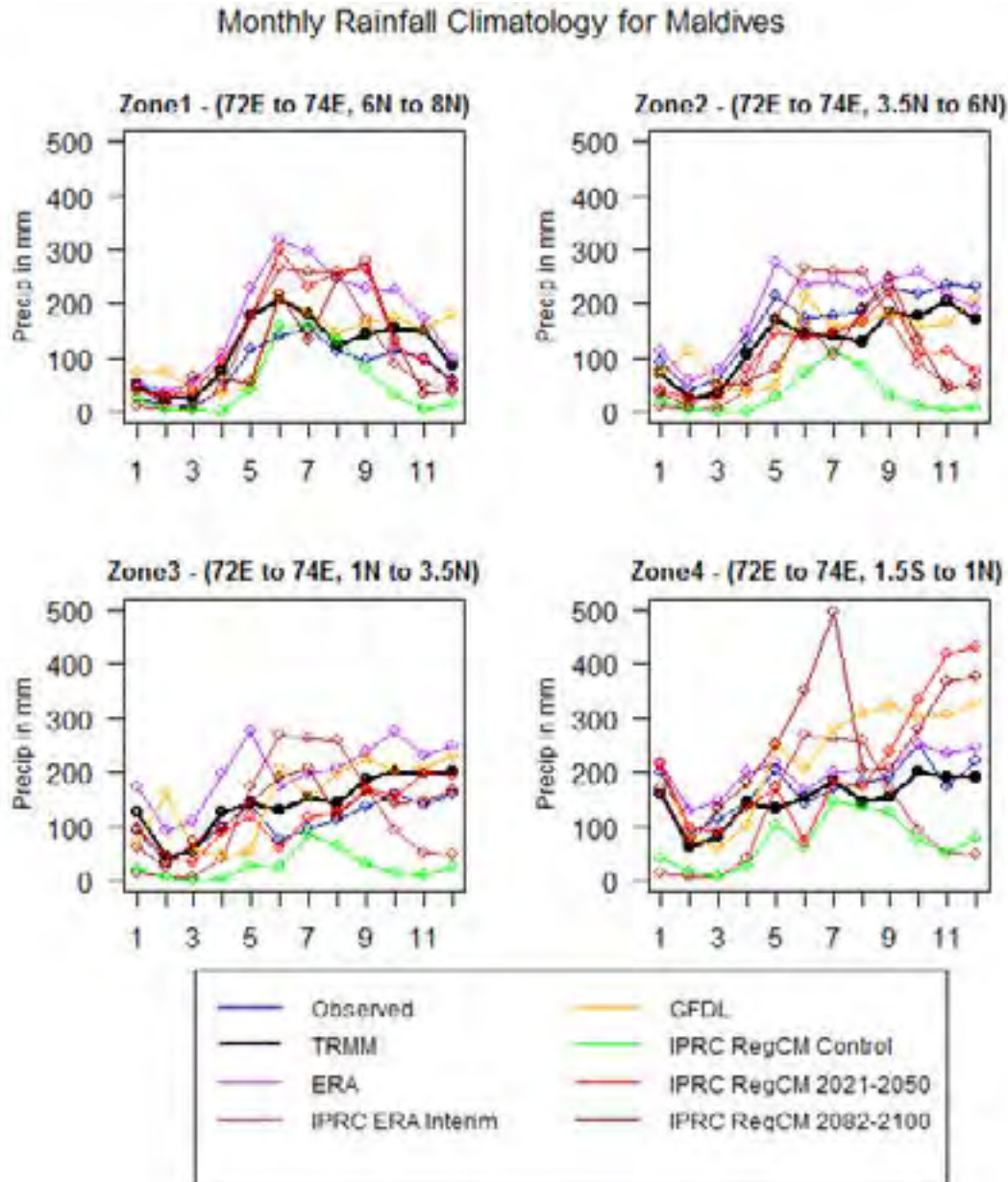
Figure 4.13 Spatial patterns of Rainfall over a larger domain around Maldivian Islands from observations, reanalysis and model simulations. First column shows rainfall features from Observation (TRMM), Reanalysis (ERA-INTERIM) and Model GCM (GFDL Coupled GCM – CM 2.1 model). Second column shows rainfall from downscaled scenarios of IPRC REGCM for 20C3M simulation, SRES A1B simulation and the difference (SRES A1B-20C3M) in mm/day for the season OND. (Unit for rainfall is given in mm/day)



High resolution scenarios generated by IPRC RegCM

The downscaled products (IPRC baseline 1981-2000, 2021to2050, 2082to2100) climatology was compared with GFDL 20C3M, TRMM, ERA and surface observatory data and the results are presented in Figure 4.14. Figure 4.14 shows the climatological features of various zones in Maldives

Figure 4.14 Rainfall Climatology over zones of Maldives

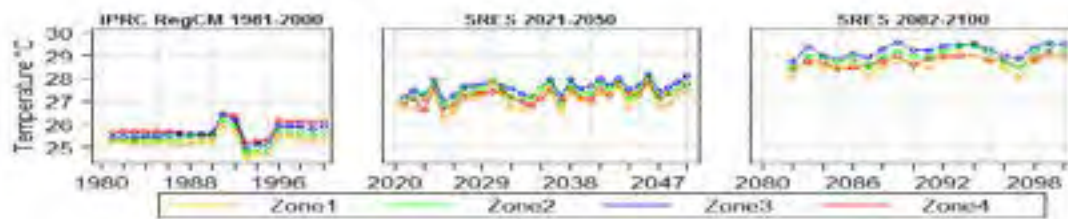


The regional model projection climatological cycle shows that it simulates the rainfall cycle quite well in zone-1, and to a reasonable extent in zone-2 & 3. For zone-4, the similarity is limited which perhaps due to the problems anomalous gradients below equator.

Mean Temperature plot over Maldives for time slices 1981- 2000, 2021-2050, 2082-2100 are presented in Figure 15. Surface temperature has an increasing trend as seen from the time slices experiments (2021-

2050) and (2082-2100) (for the higher CO2 scenario runs compared to baseline) scenario over the different zones of Maldives. Mean annual temperature during 2021 to 2050 is about 27°C, which is higher than the baseline climate (1981-2000) by about 1.8°C. This difference is in-line with the range of temperature change from the GCM projections presented in the earlier chapter. Zone 4, exhibits more rapid increase in temperatures as compared to the other zones during the 2021 to 2050 period (~0.8°C).

Figure 4.15 IPRC RegCM annual mean temperature projection for Maldives (SRES A1B: 2021-2050 & 2082-2100)
 X-Axis: Year, Y-Axis: Temperature in degree Celsius



The regional model could simulate the rainfall characteristics over different zones (Figure 4.16). These results show an increase in rainfall over most of the zones (Zone 1, 2, 3) except Zone 4 in the IPRC REGCM simulations forced by the GFDL CM2.1 simulation.

Figure 4.16 IPRC RegCM annual daily rainfall projection for Maldives (SRES A1B: 2021-2050 & 2082-2100)
 X-Axis: Year, Y-Axis: Rainfall (mm/day)

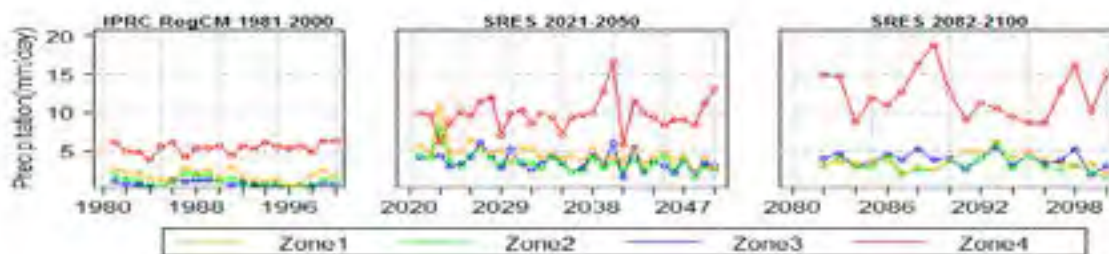
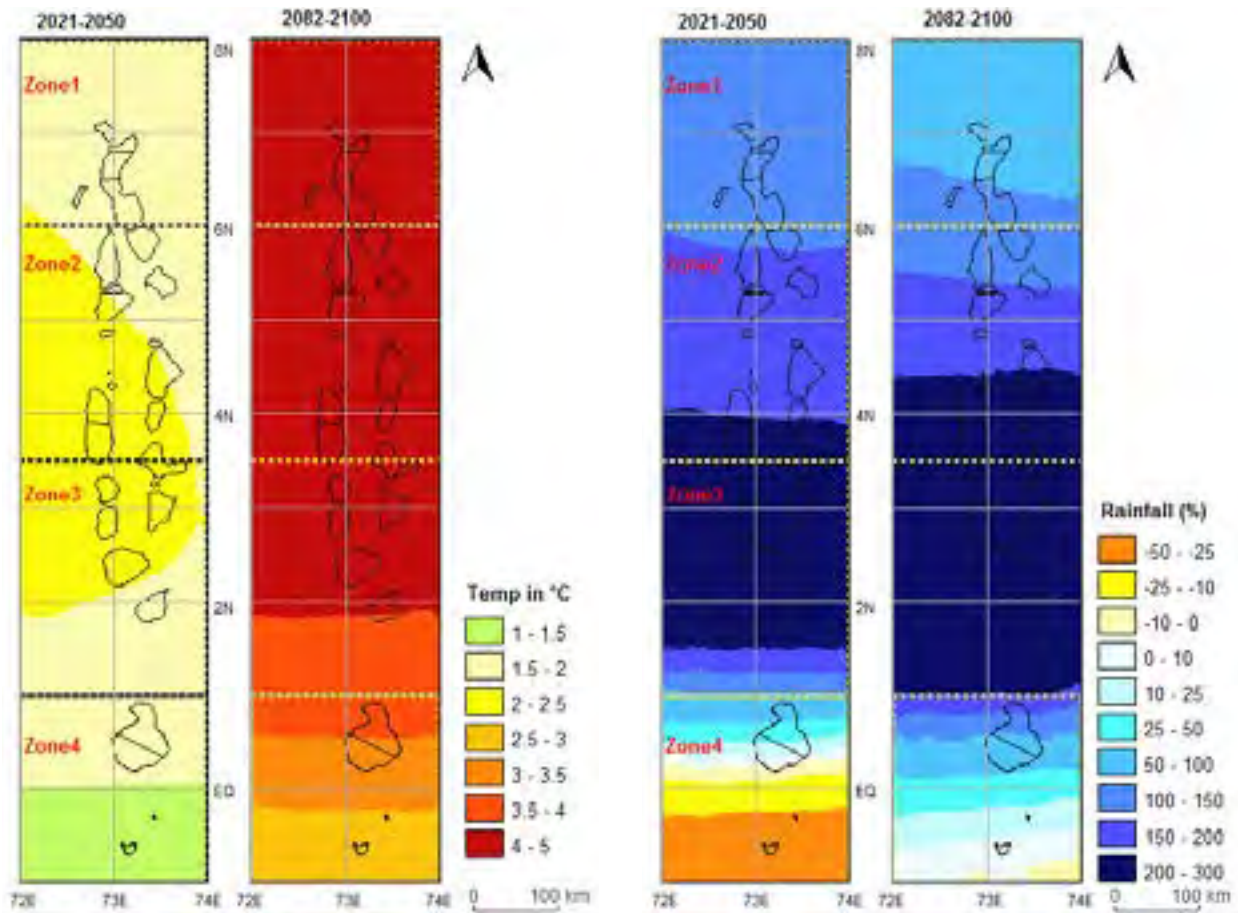


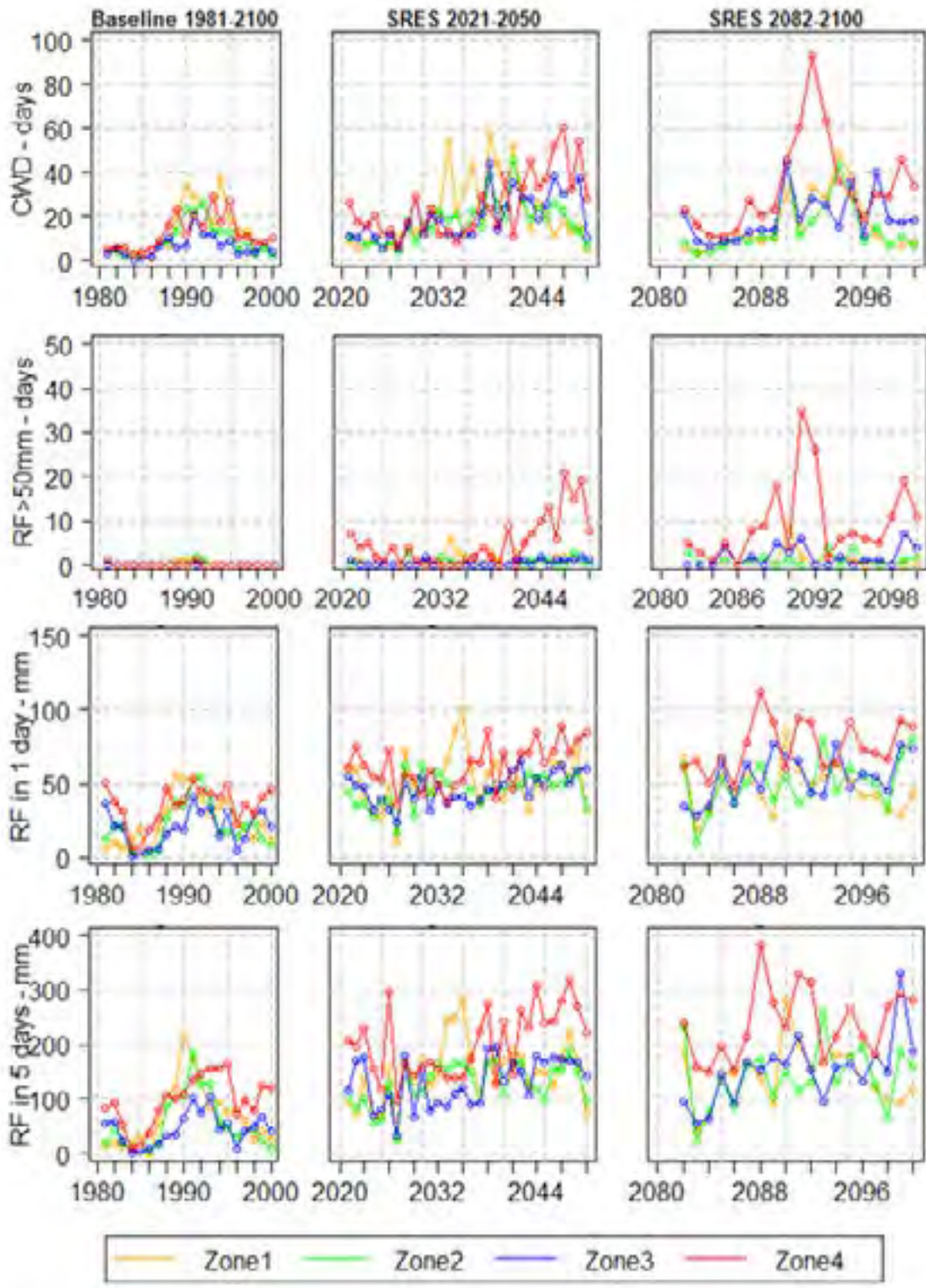
Figure 4.17 Temperature and rainfall changes over Maldives domain from IPRC RegCM scenario time slices (2021-2050) and (2082-2100) from baseline (1980-2000). Unit – Temperature change in degree Celsius and Rainfall change for MJJASO are in %.



The GFDL GCM projects a decrease in rainfall during the period 2030s and 2050s. However, the regional model results using this forcing project an increase in rainfall for northern zones compared to the southern zones. Figure 4.17 shows the simulated rainfall changes through SRES A1B scenarios from 20C3M for MJJASO months. It is clear from the IPRC RegCM that the decrease in the rainfall is confined only to a few degrees in the equator for the time slice (2021-2050), while time slice of 2082-2100 shows increased rainfall overall. A greater increase in the rainfall from the north to south during MJJASO is observed encompassing zones 1, 2 and 3.

The extreme analysis of downscaled projected data has been carried out using Rclimindex package. Keeping 1981-2000 as baseline, indices were calculated for future time slices (2021-2050) & (2082-2100) and results are presented in Figure 4.18

Figure 4.18 Extreme climate analysis of IPRC RegCM downscaled projections A) Maximum number of consecutive wet days in a year – Unit (days) B) Number of days receiving rainfall more than 30mm in a year – Unit (days) C) Maximum daily rainfall in a year – Unit(mm) D) Accumulated 5 days rainfall in a year – Unit (mm)



Extreme events, maximum rainfall in a day or consecutive five days over all zones in Maldives has increasing trend over the projected period. The baseline maximum daily rainfall 55 mm over Maldives region reaches 100mm in 2021-2050 and 112mm in 2082-2100. Similarly, baseline consecutive maximum five days rainfall 217 mm over Maldives region reaches 318mm in 2021-2050 and 382mm in 2082-2100. Rainy days with more than 30mm show an increasing trend in both the time slices as compared to the baseline period. Maximum number of consecutive wet days in a year also show an increasing trend in the projected scenarios. Zone-4 shows some abnormalities which might be the result of errors in model boundaries below equator, as mentioned above.

3.3 Statistical downscaling

Mean daily temperature for Male and Gan location is considered for statistical downscaling, since long term observed data is available compare to other stations in Maldives

Figure 4.19 Downscaled HadCM3 A2&B1 Scenario Mean Temperature for Male and Gan location

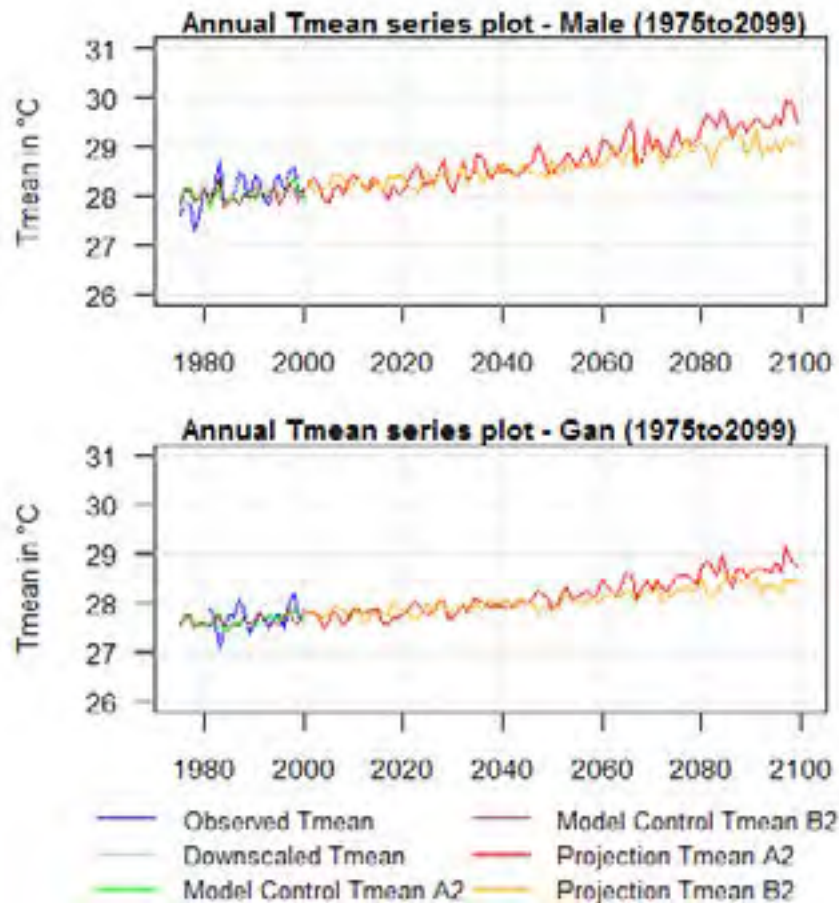


Figure 4.19 shows the time series annual mean temperature plot from 1975 to 2100. The change of temperature in Male is as follows 2030s (0.4°C to 0.5°C), 2050s (0.6°C to 0.8°C) and 2080s (1.0°C to 1.3°C), where in Gan, these are the changes 2030s (0.3°C), 2050s (0.4°C to 0.6°C), 2080s (0.7°C to 1.0°C).

Figure 4.20 Temperature climatology change over Male Island

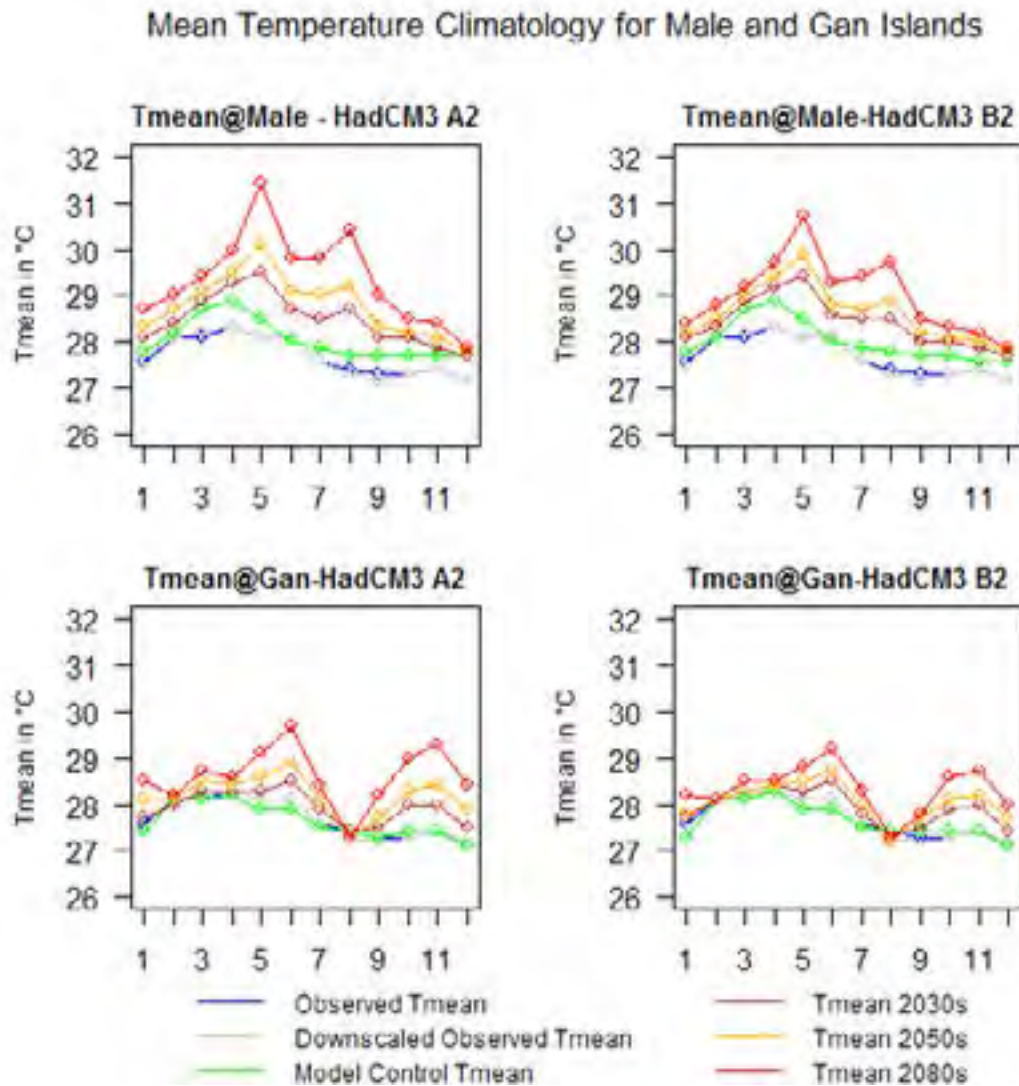


Figure-20 shows the climatology of observed and projected temperature at various time slices for two locations. This analysis shows the temperature is steadily increasing over time period. The maximum of 1.5°C rise is observed.

Rainfall downscaling through statistical downscaling techniques was found to be not reliable because of its very poor correlation between predictands and predictors (maximum 0.03). The observed daily rainfall record at station level is not capturing the climate characteristics of the larger domain represented by the GCM. This could be due to non-availability of long-term rainfall measurement that is to adequately capture rainfall characteristics of the region. As observed earlier, rainfall data is only available for two stations, for a limited period (1975 to 2010). In this study, we have used the statistical downscaling package SDSM which restricts the search of predictors to the available normalized GCM datasets within the package. A wider search of predictors using all available GCMs results

would have perhaps lead to better statistical downscaling results. However the limited time period of the project did not allow this kind of the study to be undertaken. In future, exclusive statistical downscaling projects could perhaps be commissioned for Maldives.

3.4 Sea level change

The change in sea surface height for time slice 2080s from the present (1961-1990) has been estimated and presented the results in Table-1. 2030s and 2050s time slices are ignored because of the uncertainties and model inconsistency performance. From Table-1, it can be inferred that sea-surface heights changes fluctuates from 8.2 to 9.5 cm with an uncertainty range 4.6 to 11.6cm. These values need to be interpreted in conjunction with global sea-level change scenarios to characterize impacts.

Table 4.1 Projected sea-surface height changes for Maldives

Atolls	Longitude	Latitude	Mean Sea surface height change in 2080s N* (Unit: cm)	Max Sea level change in 2080s N** (Unit: cm)
Haa Alifu	73.5	7.06	0.8	8.4 (5.5 to 11.5)
Haa Dhaalu	73.5	6.44	1.3	8.9 (5.9 to 11.6)
Shaviyani	73.5	6.44	1.3	8.9 (5.9 to 11.6)
Raa	72.5	5.84	1.6	9.1 (6.8 to 11.1)
Noonu	73.5	5.84	1.7	9.1 (6.1 to 11.3)
Lhaviyani	73.5	5.27	2.0	8.9 (6.3 to 10.9)
Baa	72.5	5.27	1.9	8.9 (6.7 to 10.6)
Kaafu North	73.5	4.72	2.3	8.7 (6.4 to 10.4)
Kaafu South	73.5	4.19	2.5	8.6 (6.3 to 10.3)
Alifu Alifu	72.5	4.19	2.5	8.3 (6.2 to 9.8)
Alifu Dhaalu	72.5	3.69	2.8	8.2 (6 to 9.7)
Vaavu	73.5	3.69	2.9	8.6 (6.1 to 10.3)
Faafu	72.5	3.22	3.1	8.2 (5.8 to 9.7)
Meemu	73.5	2.77	3.4	8.9 (5.8 to 10.6)
Dhaalu	72.5	2.77	3.4	8.3 (5.5 to 9.7)
Thaa	72.5	2.34	3.6	8.3 (5.2 to 9.9)
Laamu	73.5	1.94	3.9	9.2 (5.6 to 11)
Gaafu Alifu	73.5	0.84	4.2	9.4 (5.2 to 11.3)
Gaafu Dhaalu	73.5	0.17	4.4	9.5 (4.9 to 11.5)
Gnaviyani	73.5	-0.17	4.4	9.5 (4.8 to 11.5)
Seenu	73.5	-0.5	4.4	9.4 (4.6 to 11.4)

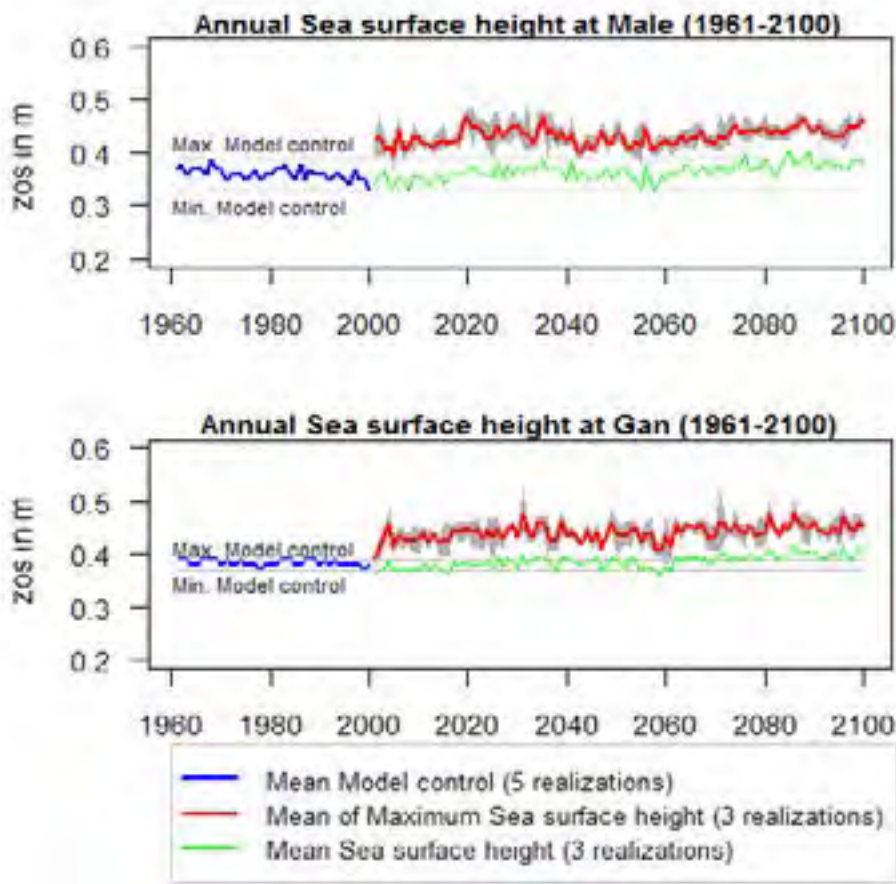
N* - Annual average for every control realization is calculated and then **AVERAGE** among these five realizations is taken for a year for every grid.

N** - Annual Maximum for each realization of SRES scenario is calculated and then **AVERAGE** among these three realizations is taken for a year for every grid.

Annual mean sea surface height from 1961 to 2100 for Male and Gan location has been analyzed and presented in Figure 21. The minimum and maximum of model control (1961 to 2000) for the location Male is 0.33 to 0.39m and Gan is 0.37 to 0.39m. The maximum sea surface height changes for Male during 2001 to 2100 fluctuates from 0.4 to 0.48m with an uncertainty range 0.36 to 0.5m. The maximum sea surface height for Gan from 2001 to 2100 fluctuates from 0.39 to 0.48m with an uncertainty range 0.37 to 0.53m. The mean sea-surface heights are seen to be within the current range of fluctuations during most of the future period until about 2070s in both locations. The variations are comparatively

much more at the northern location than in the south. The maximum sea-surface heights are significantly higher than the mean values at both locations and show very gradual trends. As noted in earlier chapters, projections of sea-surface heights and sea-level at the level of atolls have several uncertainties.

Figure 4.21 Sea surface height above MSL time series plot for Male and Gan location. Units of zos are in meters. Grey color shaded area represents the range of uncertainty of maximum sea level over the island locations.



Hunter (2010) identified two inherent uncertainties involved in sea level projection. The first is ‘scenario uncertainty’ arises from the fact that the future social, economic and technological development of the world, and the consequent greenhouse-gas emissions, are poorly known. A range of plausible futures, or scenarios, have been used to describe the way in which emissions may change in the future. The second uncertainty ‘model uncertainty’ is related to shortcomings in the present knowledge of the science of climate change, partly due to fact that we do not know exactly the present climate state (the ‘initial conditions’), and partly due to the fact that no model gives a perfect representation of the real world.

3.5 References

The results from GCMs as well as from RegCM show clearly increases in temperatures during the future climate change scenarios for Maldives. The trends of temperature increase are similar to the surrounding oceans. There is a detectable

decrease in the number of cold nights and cold days and increase in the number of warm days and warm nights. There is an agreement between different models and across GCMs and the regional model results. As stated sea surface temperatures also show increasing trends. For whole of the Maldives, the range sea surface temperature change for three time slices are as follows 2030s (0.76°C to 1.33°C), 2050s (1.01°C to 1.93°C) and 2080s (1.27°C to 3.40°C). Coarse resolution GCMs show positive as well as negative trends for future rainfall projection over Maldives. The high resolution RegCM results show consistent increases in rainfall over all the four zones during MJJASO. This is accompanied by the extreme events such as maximum one day rainfall and no. of consecutive wet days are also increasing over all zones of Maldives.

Maximum sea surface heights, representing the worst case scenarios based on three realizations of one GCM indicate increases ranging from 8.2 to 9.5 cm across the various atolls for 2080s. 2030s and 2050s time slices are ignored because of the uncertainties and model inconsistency performance.

4. INTERPRETATION AND TRANSLATION OF CLIMATE CHANGE INFORMATION

4.1 Potential impacts of projected climate change scenarios

The future climate parameter projection and its likely impacts over the sectors were identified through participatory way from the stakeholders during the training program and are presented in Table-2.

Table 4.2 Climate parameter and its likely impact in Maldives

Priority. No	Climate parameter	Sectors likely to get affected	Likely impacts
1	Sea-surface temperatures	Livelihood and Fisheries	Sea surface temperature raising trend affecting coral health and fish availability in the region is greater threat for livelihood activity.
2	Rainfall (distribution)	Tourism, Water resources, Transportation and Agriculture	Increased rainfall trend shows positive sign for rainwater harvesting and agriculture activity. But this will have impact on tourism also on water transportation
3	Sea-surface heights or sea-level (on long-term)	Disaster management, Transportation and Infrastructure	Increasing sea level is threat for lives, infrastructure, and existence of few low lying islands.
4	Temperature	Health	Disease outbreaks like Malaria, Dengue, however it is already eradicated in Maldives.

4.2 Likely impacts of sea-level rise scenario

Sea level rise is particularly important for Maldives for risks from inundation. The land inundation from sea surface height change in Maldives is assessed by the comparison of land elevation and future sea surface height scenarios.

Inundation analysis requires land elevation data of high resolution, which is lacking in Maldives and it's a major drawback in assessing the risk with higher confidence. For the present study, the SRTM 90m Digital Elevation data and the General Bathymetric Chart of the Oceans (GEBCO-approx.1km) were combined to generate 10m Digital Elevation Model (DEM) for land inundation assessment. This was done due to limitation of availability of surveyed topographic and bathymetric data in Maldives. All data layers were converted to WGS 1984 & UTM Zone43S, thereafter, the elevation points and zero elevation line assumed from the island boundary are merged and interpolated by the natural

neighbor method for DEMs generation. Island boundary layer is used to clip and generate land elevation grid for the entire country. Further land elevation grids are considered by atolls for the detailed analysis.

Inundation assessment has been carried out using the following methodology. Projected Sea Surface Height (SSH – 2080s) from different GCM scenarios extracted for Maldivian atoll sites were subtracted from the land elevation (grid location) to determine inundation depths. Tide condition (mean tide and high tide at +0.65 m) is also considered for the analysis as shown by equation (1). SHH, Tide and Land elevation are all referred to mean sea level.

$$\text{Potential Inundation depth (m)} = \text{SSH} + \text{Tide} - \text{Land Elevation} \quad (1)$$

To quantify the inundated areas of each scenario, the number of dry and wet grid cells was counted to estimate the submerged areas and percentage of the current dry land at mean tide condition. The summary is presented in Table-3. Only long term SSH projections (2080s) are considered as the projections for time horizons for 2030s and 2050s are uncertain as mentioned in the earlier chapter.

Table 4.3 Projected percentage of inundation for SSH raise in 2080 (m) during mean tide condition in Maldives region

Atoll Names	Projected percentage of inundation for SSH raise in 2080		
	MaxMin_SSH	MaxMean_SSH	MaxMax_SSH
Haa Alifu	0.19	0.29	0.41
Haa Dhaalu	0.17	0.23	0.33
Shaviyani	0.27	0.36	0.51
Raa	0.40	0.51	0.63
Noonu	0.25	0.39	0.47
Lhaviyani	0.87	0.97	1.23
Baa	0.42	0.48	0.60
Kaafu (North and South)	1.15	1.31	1.63
Alifu Alifu	0.60	0.67	0.74
Alifu Dhaalu	0.44	0.59	0.69
Vaavu	0.42	0.49	0.65
Faafu	0.22	0.33	0.38
Meemu	0.66	0.74	0.98
Dhaalu	0.28	0.41	0.48
Thaa	0.35	0.52	0.58
Laamu	0.22	0.31	0.39
Gaafu Alifu	0.31	0.46	0.59
Gaafu Dhaalu	0.40	0.56	0.70
Gnaviyani	0.04	0.05	0.06
Seenu	0.46	0.64	0.81

One of the long term risks for Maldives is SSH rise combined with high tides, which occurs for a day or two at times. However +0.65m observed high tide in the history of Maldives is considered as extreme case and inundation scenarios has been computed and presented in Table 4

Table 4.4 Projected percentage of inundation for SSH raise in 2080 during high tide condition in Maldives region

Atoll Names	Projected percentage of inundation for SSH raise in 2080		
	MaxMin_SSH	MaxMean_SSH	MaxMax_SSH
Haa Alifu	3.04	3.20	3.33
Haa Dhaalu	2.67	2.76	2.91
Shaviyani	3.65	3.78	3.95
Raa	4.79	4.95	5.11
Noonu	3.51	3.69	3.82
Lhaviyani	8.92	9.07	9.33
Baa	4.65	4.72	4.86
Kaafu (North and South)	11.09	11.25	11.57
Alifu Alifu	6.52	6.66	6.76
Alifu Dhaalu	5.22	5.36	5.44
Vaavu	6.85	6.91	7.10
Faafu	3.26	3.39	3.45
Meemu	10.64	10.70	10.81
Dhaalu	4.68	4.84	4.92
Thaa	5.09	5.23	5.32
Laamu	3.13	3.23	3.33
Gaafu Alifu	5.13	5.29	5.48
Gaafu Dhaalu	6.07	6.26	6.45
Gnaviyani	0.81	0.86	0.90
Seenu	6.53	6.76	7.00

4.3 Sea surface temperature and linkages with coral reefs and fishery sector

Maldives is a country abundant with coral reefs, with the very existence and livelihoods directly and indirectly connected to the health of coral reef systems. Therefore, it is fair to assume that the fishery sector of the Maldives is entirely dependent upon how the reef system as a whole is going to respond to the climate change (Adam, 2006). It is known that seawater warming, thermal bleaching, ocean acidification might occur due global warming and it might impacts the coral reef. The impacts on coral reefs from two recent events have shown what might happen in the predicted climate change

scenario. The first was the unprecedented El Niño warming event of 1998 that killed most of the shallow water coral communities. It was reported that over 90% of coral died as a results of bleaching (Zahir et al., 2005)

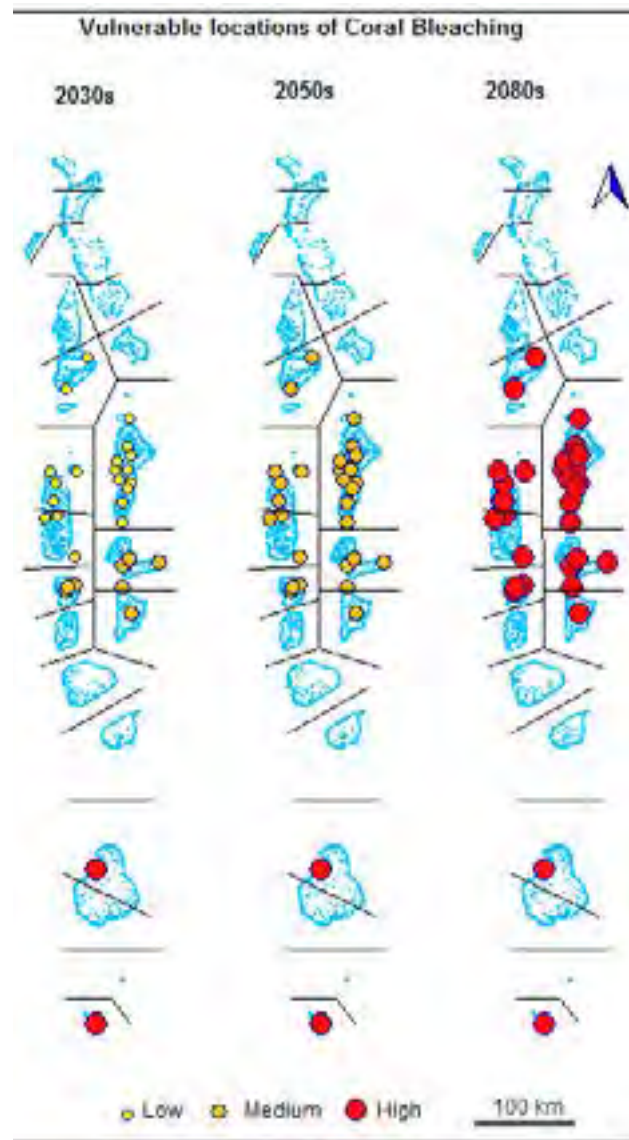
Fisheries account for 6% of GDP, around 12% of employment and 98% of the country’s physical export commodities (DPND, 2009). More than 15,000 fishermen are directly involved in fishing and it is estimated that more than 20% of the population is dependent on income related to the fisheries sector. Total export revenue from fisheries is more than US\$100 million. Corals reefs sustain the fisheries and livelihoods of Maldivians including the economically most important tourism sector for the Maldives. (Adam, 2006). Anecdotal evidence indicates that a large number of medium and small fishermen have installed cold storage boxes in their fishing vessels in the recent five years or so. This can

perhaps be viewed as an autonomous adaptation practice by the fishermen to protect the fish catch from the damage due to high day time temperatures. As most of the small fishermen operate during mornings and by the time they return it is late afternoon, they may be experiencing the day time temperature increase directly. This evidence needs to be examined further and cross checked with temperature and fish catch damage information to formulate a adaptation project around livelihood of small scale fishermen.

Coral bleaching records available through Reef Base Data Center, were analyzed from 1998 to 2008 and found that bleaching occurred in the months of January, February, April, May, August, September. Month May is found to be severe, since most of the higher severity bleaching occurred during

this month from North to Southern zones of Maldives. In depth analysis has been carried out for the month May. Dataset shows water temperature was observed from 29°C to 33°C during coral bleaching. Most of the high severity coral bleaching occurred when SST temperatures touch 33°C. Average SST during month of May is around 28°C, using this benchmark a raise in 1.5°-2°C causes low impact; 2° to 3°C causes medium impact and 3°C to 5°C causes high impact. This criteria has been used to estimate coral bleaching impacts for the temperature changes projected in the SST in the Maldivian region. Figure 22 below illustrates these results which are indicative of the possible damage to coral reefs. These impacts are however based on general indicators and will have to be interpreted carefully for specific locations.

Figure 4.22 Vulnerable spots for coral bleaching based on historical coral bleaching locations and SST projection.



4.4 Rainfall and water harvesting

The Maldives has very little in terms of freshwater resources. Rainwater harvesting is the primary source of drinking water in 90% of the outer islands with groundwater used for washing, agriculture and other domestic uses. Groundwater accumulates in rainwater recharged aquifers which lie at a depth of 1-1.5 meters below the surface where they are highly vulnerable to: (i) contamination from inadequate sanitation facilities and other human activities; (ii) solid waste run-off; (iii) over exploitation; and (iv) saline intrusion through soil erosion and flooding (storms, tsunami etc). Prior to the tsunami, only 39 of the inhabited islands had groundwater that was suitable for drinking. Following the tsunami groundwater on most of the islands showed a high degree of saline and faecal contamination (ADB, 2007).

Groundwater is a scarce resource because of the hydrogeology of the country. The freshwater aquifer lying beneath the islands is a shallow lens, 1 to 1.5m below the surface and no more than a few meters thick. Surface freshwater is lacking throughout the country with the exception of a few swampy areas in some islands. Traditionally people depended on shallow wells to get access to the groundwater lens for drinking water. However, 90% of the atoll households now use rainwater as the principal source of drinking water. In Male', 100% of the population has access to piped desalinated water. (MHAHE, 2009)

The above discussed issues shows the increasing dependency of rain water harvesting for the water needs in islands except Male, since Male depends on bottled water for drinking. The increased rainfall signal might be a good sign for the water resources and agricultural sector.

4.5 Capacity building for interpretation of results

Training component of this project is to share the climate change modeling results and project outcomes with stakeholders through training sessions on understanding the climate change scenario results through simple tools developed for visualization and interpretation of the climate data. In addition, MMS staff's were trained on analyzing extreme climates from the climate datasets. A larger goal was to provide a perspective for climate information from the sector climate risks point of view. The workshop was conducted during 22-26 January 2012 with 13 participants from Maldives Meteorological Services (MMS), Ministry of Housing and Environment. Detailed training report can be found from Appendix 2.

The workshop was targeted through achieving the following aspects

- A freeware GIS tool called SAVGIS was introduced along with climate database, available for visualization of climate change scenarios over the Maldives region, and its interpretation.
- Provided hands on experience with specialized statistical tools used for analysis of climate variability and extremes, like RClimDex, using available climate datasets from Maldives.
- Training made the participants familiar to identify indices and indicators of climate change and variability, with particular emphasis on the creation of indices of daily to seasonal extremes at national level using the standardized software package, popularized by the World Meteorological Organization (WMO).

Overall, the training served to enhance participant's awareness and skill in analysis of climate variables, derivation of climate extremes and statistical techniques of downscaling. More on the training activity can be found in Appendix-2

A half a day high level workshop is organized on 25Jan2012 to brief the outcomes from the project with participants from presence of various sectors such as Agriculture, Tourism, Infrastructure, Environment, and Energy. More on this activity can be found on Appendix-3.



**Increased rainfall
might be a good sign
for water resources and
agricultural sector**

5. CONCLUSION AND FUTURE WORK REQUIRED

From this study, climate parameters such as sea surface temperature, rainfall, temperature and sea level pose different level of threats to various sectors such as tourism, biodiversity, fisheries, infrastructure, transportation and agriculture. In this chapter, we present the baseline climate and climate change scenarios using different approaches ranging from inference from GCMs, dynamical downscaled products, statistical downscaled products.

Maximum sea surface heights, representing the worst case scenarios based on three realizations of one GCM indicate increases ranging from 8.2 to 9.5 cm across the various atolls for 2080s. 2030s and 2050s time slices are ignored because of the uncertainties and model inconsistency performance. From inundation analysis for the projected SSH (2080s) shows that likely inundated area during mean tide level is 0.04 to 1.8%, whereas during extreme high tide (0.65m) leads to inundation of 0.8 to 11.6% lands over different atolls in Maldives. One of the long term risks for Maldives is SSH rise combined with high tides, which occurs for a day or two at times. These findings need to be regarded as very preliminary, as interpreting sea-level changes at individual atoll levels requires detailed understanding of the hydrodynamics within the lagoons and land movement on long time scales. A physical oceanographic study to understand these changes during present-day and with possible changes in sea-surface projected by a range of GCMs will be required.

The sea surface temperature changes over years have steady increment. For whole of the Maldives, the range sea surface temperature change for three time slices are as follows 2030s (0.76°C to 1.33°C), 2050s (1.01°C to 1.93°C) and 2080s (1.27°C to 3.40°C). This increment might be a threat for corals and fisheries sector. Though some attempts of finding links between SST and coral bleaching is carried out with limited datasets, this has to be further examined through detailed study which might help in designing adaptation projects.

Rainfall change scenario has been generated from GCMs, dynamical downscaling techniques and statistical downscaling techniques. Rainfall results from dynamical downscaling techniques are to be considered for interpreting impacts and further planning activities needed at atoll levels. Over the zones of Maldives, average annual rainfall from 2021 to 2050 increases by 3 to 8mm/day from twenty years average rainfall. Dynamical downscaled products shows increasing trend in rainfall amount through all the zones over the years. Coarse resolution GCMs show positive as well as negative trends for future rainfall projection over Maldives. The high resolution RegCM results show consistent increases in rainfall over all the four zones during MJJASO. This is accompanied by the extreme events such as maximum

one day rainfall and no. of consecutive wet days are also increasing over all zones of Maldives. This is supported by the corresponding strengthening of the monsoon currents evidenced by the circulation diagnostics from both the regional and global model inferences. The increased rainfall has positive and negative impacts for various sectors. Tourism sector might be affected because of increased rainy days, where as agriculture and water resource sectors might be benefited for their adequate water needs.

Generation of temperature change scenario involves inference from GCMs, dynamical downscaling techniques, statistical downscaling techniques. All three techniques are considered. Mean annual temperature from 2021 to 2050 increases by 1.5°C to 1.85° C from the observed mean, which is still under the range of temperature change observed in GCMs that (1.19° to 2.25°). Statistical downscaling shows the change of temperature in Male is as follows 2030s (0.4°C to 0.5°C), 2050s (0.6°C to 0.8°C) and 2080s (1.0°C to 1.3°C), where in Gan, these are the changes 2030s (0.3°C), 2050s (0.4°C to 0.6°C), 2080s (0.7°C to 1.0°C). From all the above results, it is clear that downscaled temperature scenarios increase is likely to be from 0.4° C to 1.85°C. In this project we have simultaneously pursued two different approaches and model data acquisition and its quality control has taken significantly more time and effort. Also it is evident that warm days & nights are increasing and cold days & nights are decreasing. There clear indication has relevance to human comfort and health issues for the local population as well as the tourism sector

Summary of key findings

- Increasing temperature trends, manifesting in both sea-surface and surface air temperatures is observed, which might be threat for coral health and fisheries sector. A detailed study of linkages between SST and coral health and fisheries would give a better picture of the likely increase of SST over years.
- Increasing tendencies in rainfall in all zones of Maldives, ranging north to south. Extremities also follows the increasing tendency.
- Mean sea-surface heights, increase in long-term during 2080s time-horizon; Increase combined with high season and tides are more important in the near term, which raises the need for a more in-depth research study.
- This work be regarded as first step in trying to understand the changes happening over a unique geographical setting and it can be used as a broad guidance
- Interpretation context will determine use of the climate change projection information. Sectoral knowledge of current and future climate information is key to understand and links this information for adaptation projects.

Recommendations

- More focused research specific climate change variables of importance – like sea surface heights, rainfall and SSTs
- Climate data is base for all climate change studies, it emphasis the need of better observational network for data recording.
- Incorporation of MMS observational data from the network of climate stations into the GIS visualization tool with some basic querying facility for extremes/ outliers etc. which could be used to quality check and get preliminary climate information from the data. (this will be implemented within this project). We will be also using the updated GIS data provided by Ali Shareef, MHE.
- RIMES to consider conducting regular training workshops on analysis of climate extremes, interpretation of climate change scenarios and similar topics. This could be done biannually or yearly depending on needs. The topics should be of current and of relevance to National climate applications.
- Preparation of pilot adaptation projects in the Maldivian context based on the interpretation of the high resolution climate change scenarios and other supporting analyses undertaken within the current project.
- Long-term project proposal (2-year time-frame) for conducting a detailed analysis of sea-level rise at medium and long- time horizons. This will go into detailed coastal hydro-dynamics of the major atolls, and lead to creation of a oceanographic institute in Maldives for sustained studies of monitoring and analysis of sea-level changes in the IO islands.

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7. APPENDIX

A-1 GCM projected climate changes over different zones of Maldives

Table 1.1 Rainfall change

Zone	Model	2030s (%)			2050s (%)			2080s (%)		
		A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
Z1	MPI ECHAM	11.4	18.2	9.3	31.9	25.1	21.7	35.1	44.9	26.4
Z2	MPI ECHAM	142.8	44.8	12.8	67.5	57.8	47.6	70.6	98.5	38.9
Z3	MPI ECHAM	32.7	102.5	8.9	137.0	130.4	86.4	125.3	229.1	30.8
Z4	MPI ECHAM	-8.3	143.1	-12.2	137.6	160.3	90.6	103.6	312.0	-9.8
Z1	UK HADCM3	183.2	6.9	4.2	7.2	26.7	4.0	4.3	4.8	7.5
Z2	UK HADCM3	295.4	13.7	11.0	17.7	10.2	13.9	25.3	23.5	16.9
Z3	UK HADCM3	169.1	28.4	18.1	63.0	35.7	33.3	94.5	108.3	55.0
Z4	UK HADCM3	-2.0	2.4	7.9	67.3	50.7	60.8	103.3	131.6	63.5
Z1	GFDL	18.7	-0.9	2.4	-3.6	-4.8	4.7	-0.5	-7.4	0.5
Z2	GFDL	-86.5	2.0	4.2	-6.8	-3.1	6.8	0.8	-9.5	0.0
Z3	GFDL	-45.2	-0.3	3.7	-5.8	-1.7	3.8	5.6	-5.1	2.4
Z4	GFDL	-43.9	-1.4	4.6	-20.3	-6.9	15.1	0.7	-13.3	4.4
Z1	MRI CGCM	40.4	4.3	2.3	0.0	6.4	1.4	-0.2	-2.4	1.1
Z2	MRI CGCM	-3.0	1.7	4.7	-3.4	5.6	3.3	-24.2	-8.2	-4.7
Z3	MRI CGCM	200.8	19.2	47.6	28.0	46.7	52.8	327.7	49.9	24.5
Z4	MRI CGCM	275.8	27.3	67.7	42.9	52.9	75.2	500.3	92.8	53.9

Z1- Zone 1, Z2- Zone 2, Z3- Zone3, Z4- Zone4

Table 1.2 Surface air temperature change

Zone	Model	2030s (°C)			2050s (°C)			2080s (°C)		
		A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
Z1	MPI ECHAM	1.01	0.94	0.94	1.84	1.63	1.43	2.85	3.27	2.11
Z2	MPI ECHAM	0.98	1.00	0.93	1.93	1.70	1.50	2.94	3.34	2.22
Z3	MPI ECHAM	0.99	1.12	0.95	2.15	1.84	1.64	3.15	3.56	2.37
Z4	MPI ECHAM	1.00	1.18	0.96	2.25	1.88	1.71	3.28	3.72	2.43
Z1	UK HADCM3	1.06	0.99	0.90	1.55	1.60	1.20	2.49	2.79	1.71
Z2	UK HADCM3	1.06	0.98	0.90	1.53	1.57	1.19	2.43	2.71	1.71
Z3	UK HADCM3	1.13	1.08	0.98	1.70	1.72	1.32	2.70	2.99	1.88
Z4	UK HADCM3	1.34	1.25	1.11	2.04	1.99	1.61	3.18	3.52	2.18
Z1	GFDL	1.04	1.05	1.54	1.47	1.45	1.59	2.09	2.37	1.80
Z2	GFDL	0.99	1.06	1.57	1.42	1.45	1.61	2.12	2.37	1.83
Z3	GFDL	0.97	1.05	1.63	1.45	1.47	1.65	2.22	2.46	1.91
Z4	GFDL	0.87	1.03	1.60	1.35	1.45	1.67	2.20	2.44	1.92
Z1	MRI CGCM	1.15	1.00	0.97	1.60	1.58	1.22	2.27	2.43	1.67
Z2	MRI CGCM	1.31	1.17	1.10	1.74	1.82	1.39	2.49	2.62	1.82
Z3	MRI CGCM	1.49	1.27	1.27	1.86	2.02	1.57	2.83	2.88	1.97
Z4	MRI CGCM	1.60	1.24	1.34	1.97	2.06	1.64	3.12	3.11	2.10

Z1- Zone 1, Z2- Zone 2, Z3-Zone3, Z4- Zone4

Table 1.3 Sea surface temperature change

Zone	Model	2030s (°C)			2050s (°C)			2080s (°C)		
		A1B	A2	B1	A1B	A2	B1	A1B	A2	B1
Z1	MPI ECHAM	1.01	0.95	0.76	1.67	1.46	1.37	2.68	2.87	1.88
Z2	MPI ECHAM	1.07	0.97	0.79	1.74	1.48	1.43	2.77	2.92	1.93
Z3	MPI ECHAM	1.16	0.98	0.86	1.86	1.59	1.50	3.02	3.14	2.06
Z4	MPI ECHAM	1.17	0.95	0.94	1.87	1.67	1.55	3.21	3.33	2.08
Z1	UK HADCM3	0.98	0.93	0.86	1.48	1.55	1.15	2.50	2.76	1.67
Z2	UK HADCM3	0.94	0.85	0.79	1.38	1.42	1.05	2.25	2.50	1.56
Z3	UK HADCM3	0.88	0.85	0.78	1.33	1.41	1.02	2.24	2.50	1.56
Z4	UK HADCM3	1.20	1.15	1.04	1.93	1.93	1.48	3.07	3.40	2.08
Z1	GFDL	1.02	1.01	0.82	1.41	1.36	1.16	1.98	2.21	1.27
Z2	GFDL	1.02	1.06	0.85	1.38	1.39	1.24	2.01	2.21	1.32
Z3	GFDL	1.17	1.19	1.02	1.58	1.57	1.44	2.34	2.49	1.53
Z4	GFDL	1.18	1.33	1.17	1.63	1.77	1.65	2.53	2.71	1.67
Z1	MRI CGCM	0.96	0.82	0.84	1.37	1.33	1.02	1.97	2.11	1.44
Z2	MRI CGCM	0.96	0.87	0.80	1.32	1.36	1.01	1.92	2.02	1.38
Z3	MRI CGCM	1.16	1.01	1.03	1.43	1.60	1.23	2.22	2.25	1.51
Z4	MRI CGCM	1.37	1.05	1.17	1.61	1.71	1.38	2.69	2.61	1.76

Z1- Zone 1, Z2- Zone 2, Z3-Zone3, Z4- Zone4

A-2 Report on the Workshops on Visualization and interpretation of climate change scenarios for Maldives and analysis of climate extremes using RClimdex

Venue: Maldives Meteorological Services, Male, 22-26 January 2012.

Background: Regional Integrated Multi-Hazard Early Warning System (RIMES) has been working on the project “to develop high-resolution regional climate model for the Maldives, through statistical and dynamical downscaling of global models, to provide projections for use in national and local planning”. One of the components of this project is to share the results with stakeholders through training sessions on understanding the climate change scenario results through simple tools developed for visualization and interpretation of the climate data. In addition to this during the inception phase of the project it was decided to conduct training sessions on analysis of climate extremes for the MMS staff. A larger goal was to provide a perspective for climate information from the sector climate risks point of view. In pursuance of this objective, it was planned to conduct the present workshop during in Maldives during 22-26 January 2012. Participants were from the Maldives Meteorological Services (MMS), Ministry of Housing and Environment. Participants list is attached at the end of this document. The principal objectives of the workshop were to:

- To introduce GIS tools available for visualization of climate change scenarios over the Maldives region, and its interpretation.
- To provide hands on experience with specialized statistical tools used for analysis of climate variability and extremes, like RClimDex, using available climate datasets from Maldives.
- To identify indices and indicators of climate change and variability, with particular emphasis on the creation of indices of daily to seasonal extremes at national level using the standardized software package, popularized by the World Meteorological Organization (WMO).

Day 1: Opening Session: The workshop began with a short welcome address from MMS, followed by an overview by RIMES activities undertaken during the project being currently implemented and presentation of the salient results. The opening address focused on the need to understand current climate variability and use that information to plan adaptive actions and development goals. The session also provided a round of introductions by all the participants.

I Workshop on Geo-Climate Information System – a visualization tool for displaying climate change scenarios for Maldives (1day)

Day 1 Session 1: Climate Change scenarios –

understanding, visualization and interpretation: In morning session, an overview of Geographic Information Systems based Climate Information System, developed for Maldives is briefed to the participants. A free GIS tool called SAVGIS, where the Maldives database is developed, has been introduced to the participants. The usage and understanding of climate datasets along with geographical features and elements are demonstrated in the GIS platform. Participants were also able to observe the importance of bringing observed and projected climate information’s into highly interpretable and translatable format with respect to geography through GIS tools. In detail, the training sessions are organized into three major chapters,

- Getting familiar with functions of the SAVGIS tool
- Visualizing the GCM results and plotting graphs and
- Working with regional downscaled model results.

Exercises on spatial analysis functionality for analyzing geographical information’s with climate parameters helps the user to understand the characteristics of existing and possible future changes of climate over a period of time and also over a region of interest. The sessions gave an insight to participants on how to make time series plots, spatial plots, climate parameter changes over different time slices etc., Overall the participants are able to work with database. It is expected that the tool will help in assessing future climate risks and in strategic planning of adaptation practices.

II Workshop on Analysis of Climate Extremes (3 days)

Day 1 Session 1: Climate Data preparation and quality control of daily data: This session started with a clear discussion on quality requirements for analysis of climate variables, dwelling on points where errors could get in and how to apply checks for ensuring quality. Methods for checking errors of various kinds were also presented, along

with techniques to ensure data homogeneity. This was followed by the core presentation that introduced RCLimDex tool and demonstrated the use of this package for data quality checks and identification and removal of erroneous data. With this, participants started the practical session beginning with formatting of climate data from Maldives meteorological stations using FORTRAN code segments and subjecting the formatted data to quality checks using the RCLimdex package. Resource persons helped resolve problems and doubts.

Day 2, Session 2: Indices derived from daily data and Statistical Downscaling:

During the morning session after a brief recap of Day 1, participants were provided further details of the RCLimdex package and twenty seven indices based on daily climate data were discussed. Thereafter participants continued in practical sessions their analysis using RCLimdex. This session provided hands on experience with using thresholds and identifying indices for climate risk applications in the Maldivian context. Participant discussions indicated that agriculture and fisheries, water resources, tourism and health as important sectors where climate extremes would influence risks. Sea-level rise was considered important on longer term.

Day 3 and 4: Session 3: Presentations of results and closing:

Participants continued working with their data using RCLimdex during the forenoon. Most of them were able to finish preliminary analysis of the two stations. With the view of encouraging participant interaction, six groups were formed representing sectors Agriculture & Fisheries, Disaster Management, water resources, health, Tourism ... The participants worked on indices that they considered relevant to their respective sectors and made presentations during the last session. The groups later presented innovative combinations of using different indices based on temperature and rainfall thresholds defined in sector specific contexts. These presentations resulted in active discussions and the piratical use of the indices also enabled experience some known bugs in the package.

The workshop ended with valedictory function presided over by the State Minister for Housing and Environment. He distributed certificates to all the participants and recognized efforts of RIMES in contributing to capacities of Member countries in dealing with climate risks. Overall, the training served to enhance participant's awareness and skill in analysis of climate variables, derivation of climate extremes and statistical techniques of downscaling.

Feedbacks

1. Incorporation of MMS observational data from the network of climate stations into the GIS visualization tool with some basic querying facility for extremes/outliers etc. which could be used to quality check and get preliminary climate information from the data. (this will be implemented within this project).
2. RIMES to consider conducting regular training workshops on analysis of climate extremes, interpretation of climate change scenarios and similar topics. This could be done biannually or yearly depending on needs. The topics should be of current and of relevance to National climate applications.

List of Training Participants

S. No	Name	Position	Agency
1	Azeema Ahmed	Meteorological Technician	Maldives Meteorological Services
2	Hussain Waheed	Meteorological Technician	Maldives Meteorological Services
3	Ahmed Nazeer	Asst. Meteorological Technician	Maldives Meteorological Services
4	Abdulla Hafiz Abdul Sattar Ali	Meteorological Technician	Maldives Meteorological Services
5	Ibrahim Humaid	Seismologist	Maldives Meteorological Services
6	Aishath Shimana	Climatologist	Maldives Meteorological Services
7	Aishath Fazna	Asst. Meteorological Technician	Maldives Meteorological Services
8	Mohamed Sharafad	Asst. Officer	Maldives Meteorological Services
9	Ahmed Muslim	Climatologist	Maldives Meteorological Services
10	Ibrahim Ziyadulla	Asst. Meteorological Technician	Maldives Meteorological Services
11	Ali Shareef	Asst. Director	Ministry of Housing and Environment
12	Mohamed Asif	Environment Analyst	Ministry of Housing and Environment
13	Zammath Asif	Environment Analyst	Ministry of Housing and Environment
14	Zahid	Director, Climatology	Maldives Meteorological Services

Training Pictures



Training participants group picture



Mr. Ali and Mr. Wahid presentation on CC impacts on Water resources



Mr. Ziyad and Mr.Humaid presentation on CC impacts on tourism



Mr. Sharafad and Mr.Nazeer presenting on CC impacts on fisheries sector



Ms. Azeema and Mr.Hafiz presenting on CC impacts on health sector



Mr. Asif and Mr.Zammath presenting on CC impacts on energy sector



Ms.Shimana and Dr.Zahid presenting on CC impacts on disaster sector



Mr.Ahmed and Ms.Fazna presenting on CC impacts on tourism sector



Dr.Zahid and Dr.Srini discussing on climate extreme analysis

A - 3 Report on Briefing on Climate change scenarios for Maldives and their use in national and local planning.

Venue: Ministry of Housing and Environment, Male, 25 January 2012.

Background

Under the National Adaptation Programme of Action for Maldives, the Ministry of Housing and Environment (MHE), Government of Maldives, in collaboration with the United Nations Development Programme (UNDP), is implementing the first climate change adaptation project entitled “Integrating Climate Change Risks into Resilient Island Planning in the Maldives”. Generation of better information on potential climate change effects on atoll and island level risks is one of the key outputs of the project. This component of the project involving the development of high-resolution regional climate model for the Maldives, through statistical and downscaling of global models, to provide climate change projections for use in national and local planning was entrusted to the Regional Integrated Multi-Hazard Early Warning System (RIMES) in March 2011. The work involved review of past climate change studies, data analysis, and production of downscaled climate change scenarios for the Maldives and training to guide its use in planning. This briefing session is to present the results of the project and to discuss future directions.

Participants:



This high level briefing is headed by Dr.Mohamed Shareef, State Minister of Housing and Environment with participants from various agencies such as United Nations Environment Programme, Maldives Meteorological Services, Ministry of Tourism, Ministry of Agriculture, Ministry of Energy, Infrastructure, and Department of National Planning. Press and media were also present during this briefing.

Briefing by RIMES

Dr. G. Srinivasan, Technical adviser- Climate applications and research from RIMES briefed about this project to wide audience in user understandable way. Here's the summary

Global climate models (GCMs) are important tools for studying climate change and making projections for the future. Although GCMs provide realistic representations of large-scale aspects of climate, they generally do not give good descriptions of the regional and local scales. Their results need to be downscaled to finer spatial scales to better interpret the scenarios of future climate change at local scale. Under the project "*Integrating Climate Change Risks into Resilient Island Planning in the Maldives*", Maldives' Ministry of Housing and Environment (MHE) commissioned the Regional Integrated Multi-Hazard Early Warning System (RIMES) in March 2011 to develop high-resolution regional climate model for the Maldives, through statistical and dynamical downscaling of global models, to provide projections for use in national and local planning. The Maldives Meteorological Services (MMS) was an active partner during the whole project implementation period

As evidenced by prior reports on climate change concerns over Maldives, the present work also illustrates that sea level, sea surface temperature, rainfall and its variations pose future climate risks for Maldives. Their specific relevance depends on particular sector level activity that the risks are being interpreted for. This short research work should be regarded as preliminary steps in understanding the climate change scenarios over the Maldives geographical domain. The work undertaken includes review of past work, understanding the base-line climate and inferences for future climate projections from GCMs, as well as dynamically and statistically downscaled products. Future climate change scenarios inherently represent a set of likely climate futures. Sea surface temperature parameter inferred directly from GCMs show a steady increase in temperatures up to the 2080s decades examined. The Maldives region was divided into four zones covering the atolls from north to the south. In all these zones similar increasing trends are revealed in the future climate change scenarios examined. Mean sea-surface heights – increase in long-term during 2080s time-horizon; more focused research is recommended to understand and project the sea-level changes. Also, better observational network are required to characterize the unique climatological setting of Maldives.

One of the important components of this project was a workshop to share the downscaled model scenario results with key stakeholders and also provide training sessions on analysis of extreme climate events. The training events have been carried out over the past five days and have been attended by participants from stakeholder department and

the Maldives Meteorological Services. The training workshop introduced the participants to GIS based tools to visualize future climate change scenarios and statistical tools to examine extreme climate events linked to temperature and rainfall changes. With intensive practical hands-on sessions linked to sector level climate risk application perspectives, the training sessions received active attention of all the participants.

Feedbacks

- Importance of sea level to Maldives context is raised by MHE and pointed out the current study has given idea about only longer term sea surface height change with uncertainties and limitations. RIMES addressed that no high resolution sea level model is available and it is not possible to have downscaling, since this is a global phenomenon. RIMES made a suggestion that long-term project proposal (2-year time-frame) for conducting a detailed analysis of sea-level rise at medium and long-time horizons. This will go into detailed coastal hydrodynamics of the major atolls, and lead to creation of a oceanographic institute in Maldives for sustained studies of monitoring and analysis of sea-level changes in the IO islands.
- Agricultural sector participants made a comment that rainfall increase will definitely help the Maldives context. Although it is observed from the participant discussion that tourism will be affected, because of increased frequency of rainfall might lead to less number of tourists coming to the nation, since Maldives economy is tourist driven.
- Intensity of severe weather events question was raised and RIMES agreed to address this in final report
- The dissemination of the results is raised and RIMES explained that the training program conducted for stakeholders addressed how to use the climate change results for the sector oriented aspects.
- Few raised the question that these trends of increasing temperature/rainfall have to be translated into impacts; otherwise the enduser might not able to benefit from this.
- State Minister for Housing and Environment Dr Mohamed Shareef added that the findings of the program and trainees' recommendations will be used in the ministry's decision making process.
- UNDP, a large contributor to the project, says that the most serious underlying driver of increasing vulnerability to climate change in the Maldives is the "absence of systematic adaptation planning and practice".
- "Climate change risks and long-term resilience are not adequately integrated into island land use planning or into coastal development and protection policies and practice, and past autonomous risk reduction efforts have sometimes had mal-adaptive effects" an entry on the UNDP website reads.
- UNDP highlighted that small, low-lying atoll islands of Maldives are highly vulnerable to flooding and coastal erosion: "More than 44 percent of settlements, including

42 percent of the population, and more than 70 percent of all critical infrastructures are located within 100 meters of shoreline. Intensive rainfall, storm surges and swell waves are expected to be aggravated through sea level rise and climate change effects on weather patterns. This will compound underlying trends of increasing coastal erosion and pressure on scarce land resources, and increase physical vulnerability of island populations, infrastructure and livelihood assets.”

A – 4 Emission Scenarios

IPCC SRES (Special Report on Emissions Scenarios - SRES) scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. The IPCC SRES scenarios contain various driving forces of climate change, including population growth and socio-economic development. These drivers encompass various future scenarios that might influence greenhouse gas (GHG) sources and sinks, such as the energy system and land use change. The evolution of driving forces underlying climate change is highly uncertain. This results in a very wide range of possible emissions paths of greenhouse gases.

The SRES team defined four narrative storylines, labeled A1, A2, B1 and B2, describing the relationships between the forces driving greenhouse gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each storyline represents different demographic, social, economic, technological, and environmental developments that diverge in increasingly irreversible ways.

A1: globalization, emphasis on human wealth Globalized, intensive (market forces). 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. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI),

non-fossil energy sources (A1T), or a balance across all sources.

A2: regionalization, emphasis on human wealth Regional, intensive (clash of civilizations). The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally

oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

B1: globalization, emphasis on sustainability and equity Globalized, extensive (sustainable development). The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2: regionalization, emphasis on sustainability and equity Regional, extensive (mixed green bag) The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Source: IPCC, 2000, Special Report on Emission Scenarios



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