REPORT ON:

Impact of Climate Change on Hydro-Power Projects In Northern Pakistan

SUBMITTED BY:

WALEED AHMAD

SUPERVISOR:

DR. ASIF KHAN

BOARD OF ADVANCE STUDIES AND RESEARCH

University of Engineering and Technology, Peshawar Pakistan

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Introduction

Global warming induced impact of climate change on water resource distribution in the form of variability in intensity and volume are increasingly

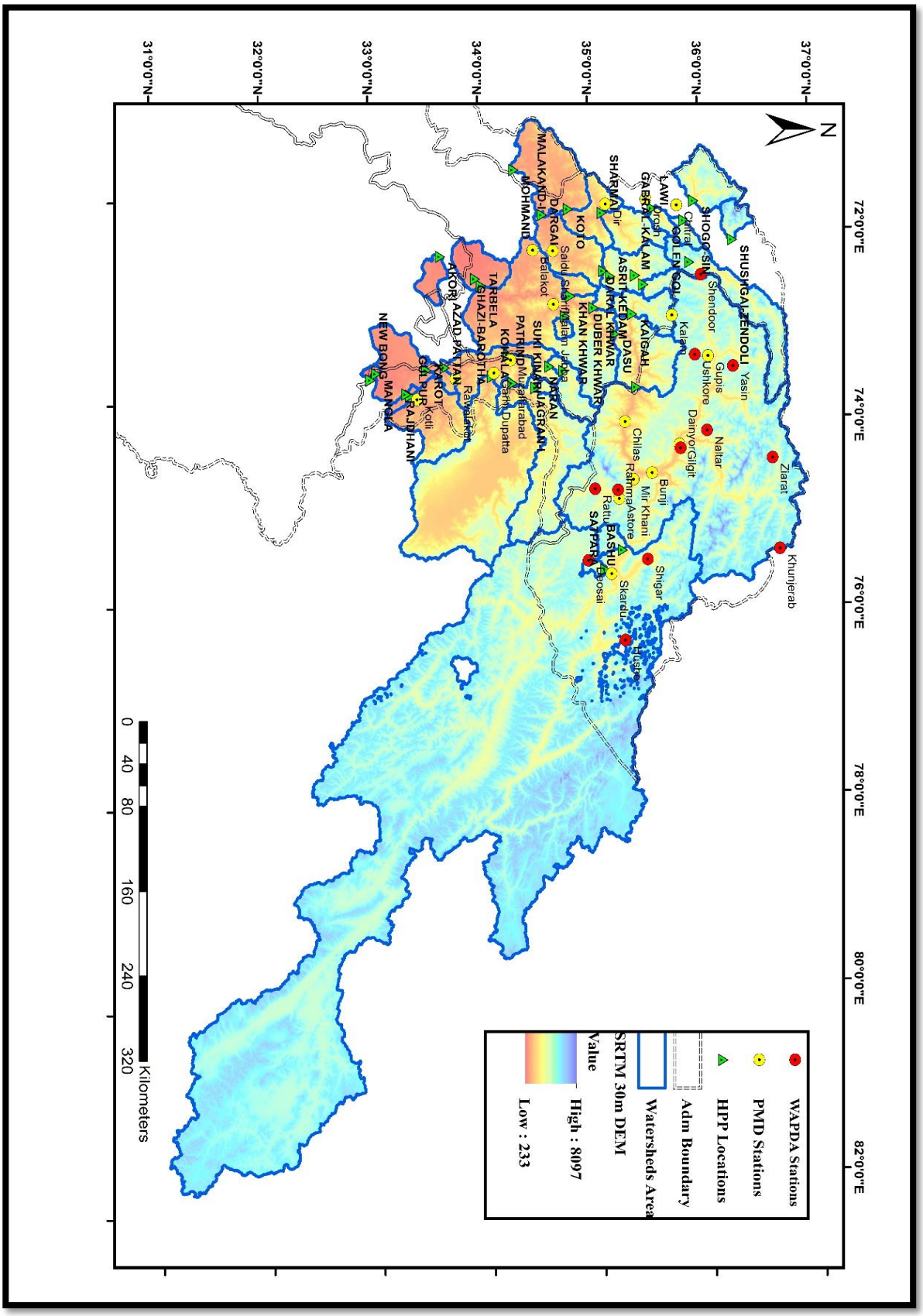
being witnessed around the globe including South Asia (Khalid, Qasim, & Farhan, 2013). Hydropower projects are direct recipients of climate change in-terms of altering river hydrology and water availability which indirectly transcends to increased greenhouse gas emissions by relying more on alternate non-renewable sources of energy (Berga, 2016). Pakistan's climate is diversified by virtue of its large latitudinal extents and significant variations in its geography resulting in many feasible sites across the region for Hydropower generation. Its Northern Region consists of three mountain ranges collectively known as the Hindukush-Karakoram-Himalaya (HKH) regions the predominant source of fresh water resource and plays a vital role in the water, energy and food security of the country (Hussain et al., 2016). The world's largest snow and glaciers reserves of Hindukush-Karakoram-Himalaya (HKH) region located in Pakistan provides for the 65% of the fresh water flow in the Indus river. Therefore, the socio-economic condition of the billions of people on the downstream depends on any variation in the climatic conditions of the Hindukush-Karakoram-Himalaya(HKH) region (Ahmad et al., 2018). Although, climate change is a global phenomenon which caused an increase of 0.72℃ in global temperature over a period of 1951-2014 but the rate of warming for Hindukush-Karakoram-Himalaya(HKH) region is much higher than global average for the past century. The temperature variation of Hindukush-Karakoram-Himalaya (HKH) region will result in melting of glaciers which in turn may cause severe flooding in the region for a few decades followed by decreased flows in the rivers(Dan, 2015). The recent Intergovernmental Panel on Climate Change (IPCC) report ("Climate Change 2014 Synthesis Report Summary Chapter for Policymakers," 2014) clearly indicates the likelihood of considerable warming over sub-regions of South Asia, with greater warming in winter than in summer. The analysis of climatic trends using representative regional climate models (RCM's) coupled with different scenario outcomes (RCP4.5 and RCP8.5) for assessing the impact of

changing climate on the current and future hydropower schemes in the country's extreme north is crucial for accurate planning, adaptation and mitigation strategies.

Study Area

The study region is extended between 71 – 82 degree's longitude and 31 – 37 latitude comprising of three gigantic mountain ranges with Himalaya at lower western latitudes, Karakoram in further north, and Hindukush in the west of Karakoram-Himalaya ranges. For the ease of understanding, the whole Northern region is broadly divided into four basins namely Upper Indus Basin, Jhelum Basin, Swat Basin and Chitral Basin respectively. A generalized map (se Fig. 01) is created for the Northern region of Pakistan showcasing the Meteorological stations along with the location of all the probable Hydropower projects with their Catchment boundaries. Individual Basin Maps showing a close-up of the area for better visualization of the details are shown from Fig 02 to Fig 05.

Figure 01: Study Area



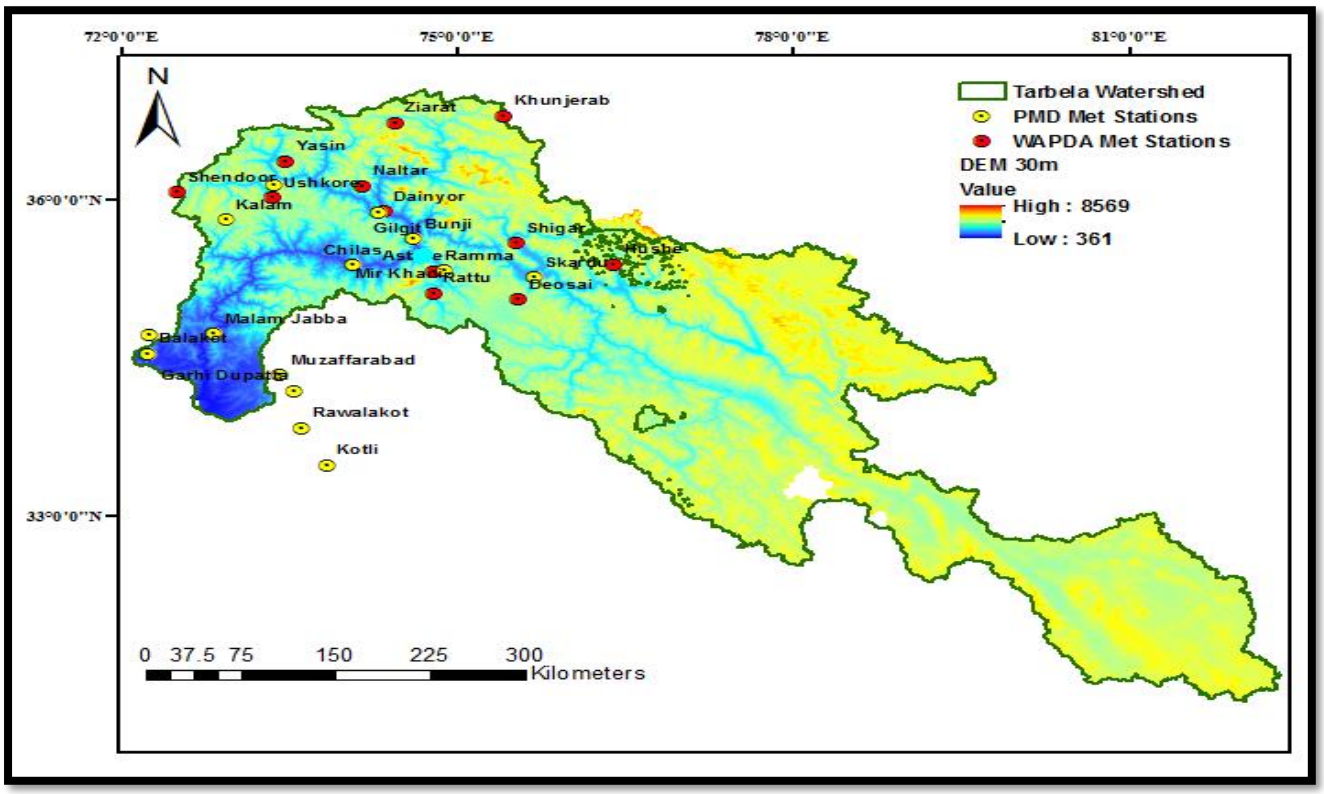


Figure 02: Map of Upper Indus Basin

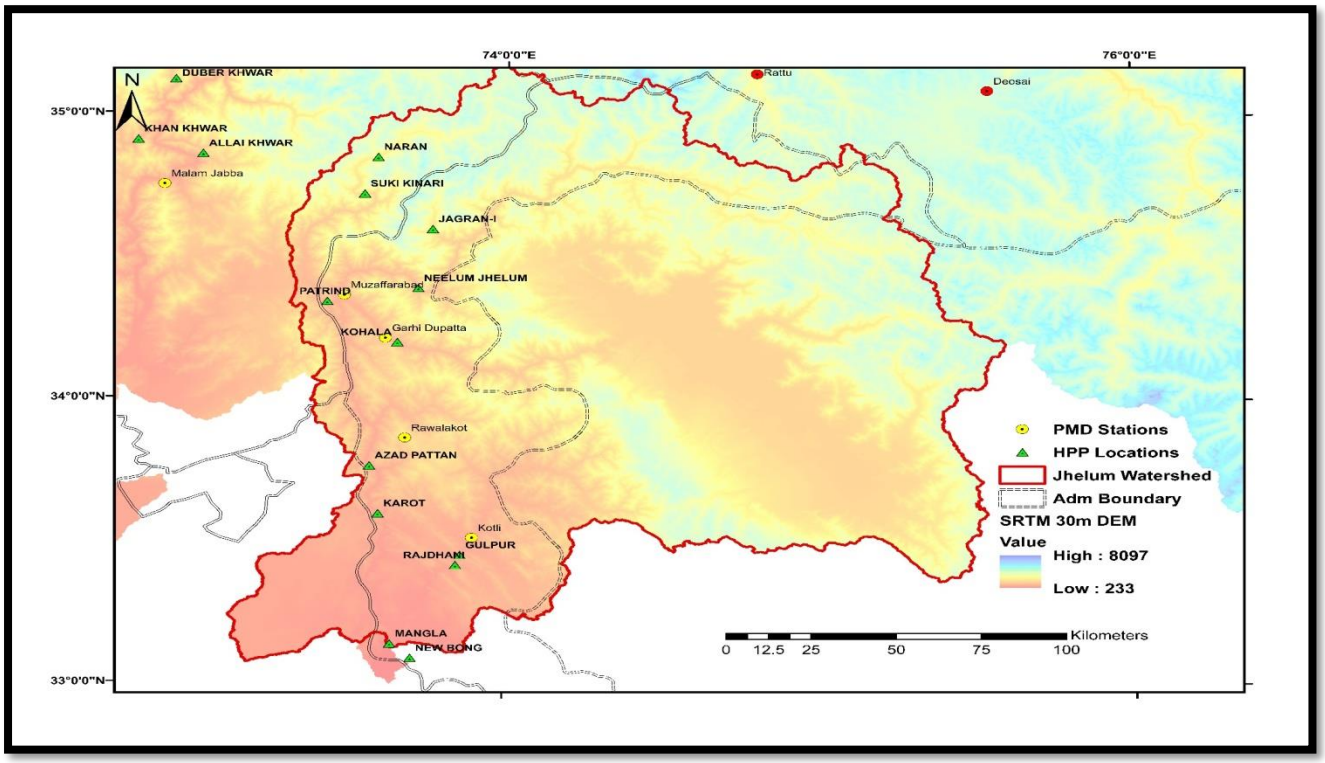


Figure 03: Map of Jhelum Basin

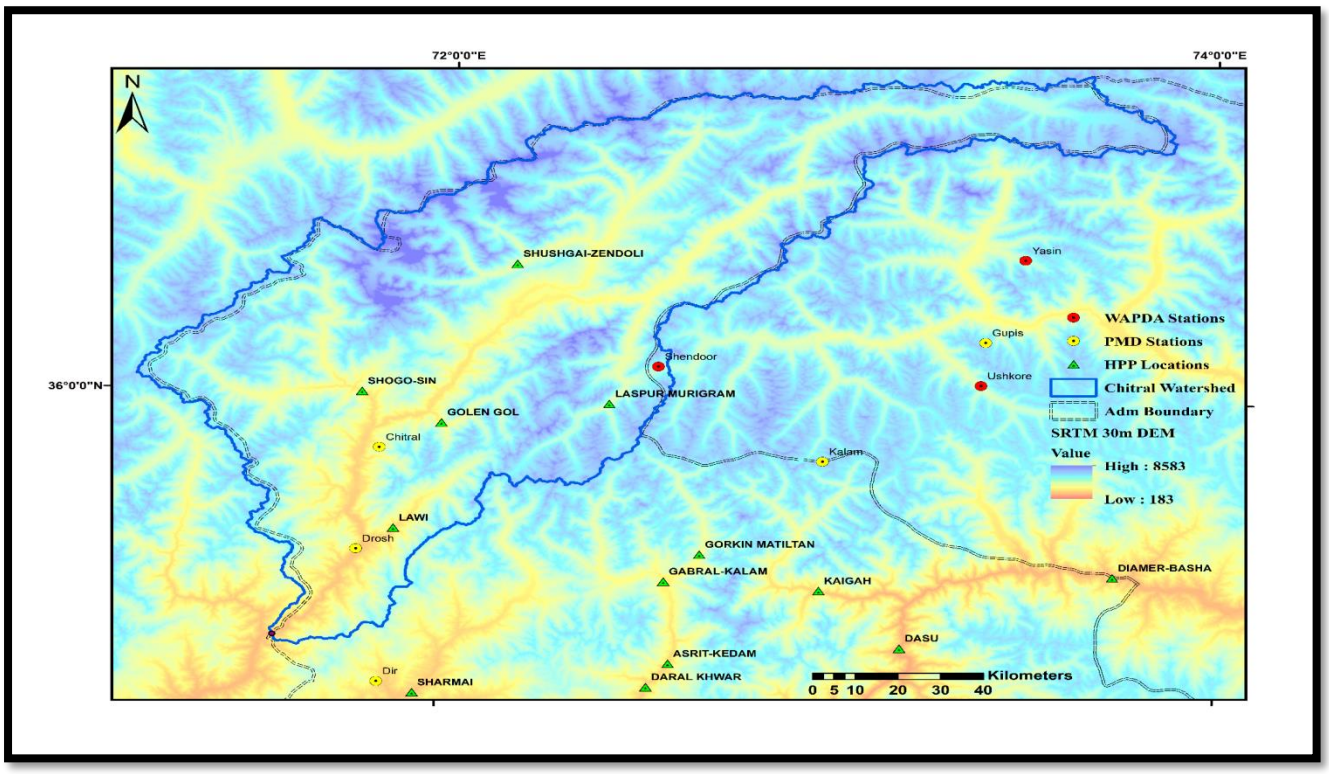


Figure 04: Map of Chitral Basin

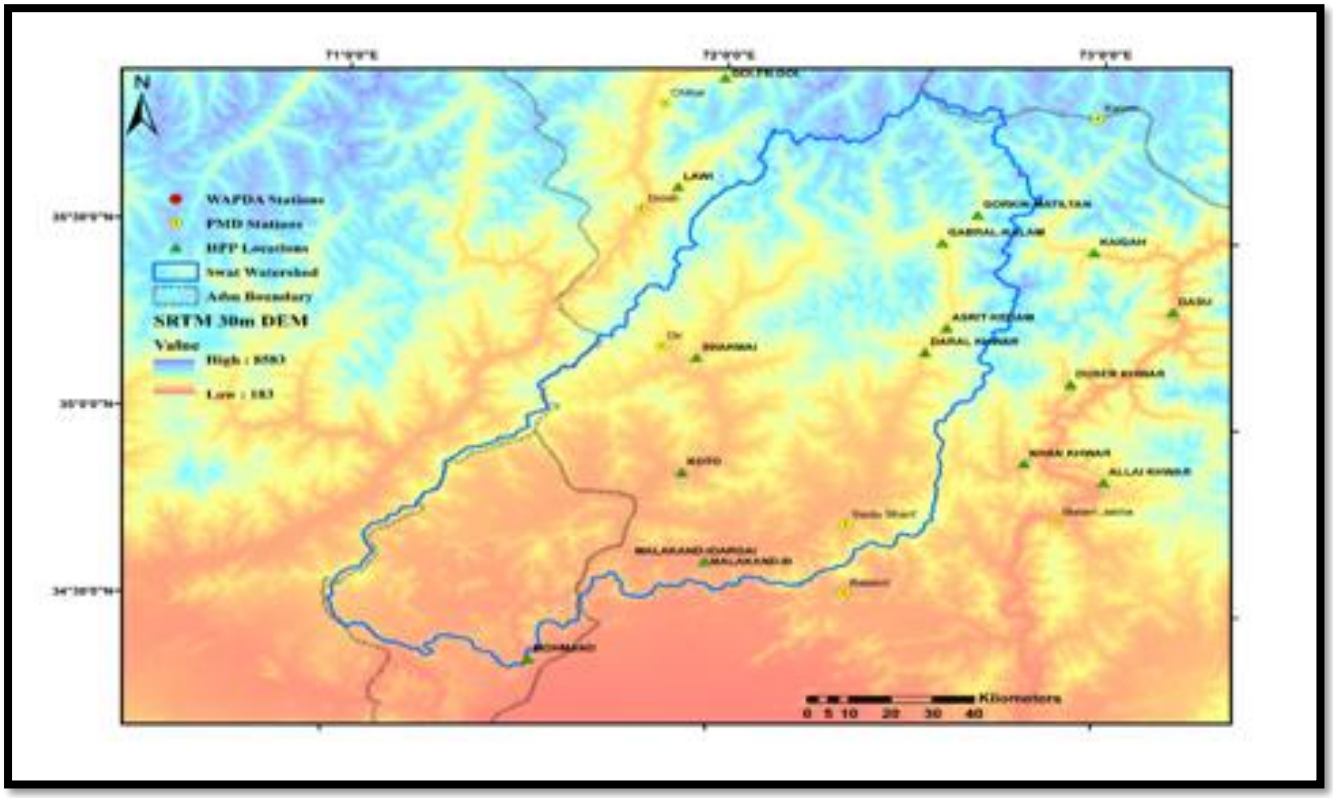


Figure 05: Map of Swat Basin

Hydropower Projects Inventory:

A total of thirty-five (34) hydropower projects are identified in this study that are either constructed, under-construction or whose feasibilities have been successfully completed, divided into four basins namely Upper Indus, Jhelum, Swat and Chitral. Most of these Hydropower Projects are Run-of-the-River schemes with a few conventional storage Dams. An inventory of all the Hydropower sites along with its details are listed below:

UPPER INDUS BASIN							
Sr. #	**NAME**	**LONG.**	**LAT.**	**CAPACITY (MW)**	**RIVER**	**SCHEME**	**REGION**
1	DUBER KHWAR	72.93	35.12	130	DUBER KHWAR	RUN-OF-THE-RIVER	KOHISTAN
2	KHAN KHWAR	72.81	34.91	72	KHAN KHWAR	RUN-OF-THE-RIVER	SHANGLA
3	KAIGAH	72.98	35.47	548	KANDIAH	RUN-OF-THE-RIVER	KOHISTAN
4	ALLAI KHWAR	73.02	34.86	121	ALLAI KHWAR	RUN-OF-THE-RIVER	BATAGRAM
5	SATPARA	75.64	35.24	17.3	SATPARA	RUN-OF-THE-RIVER	SKARDU
6	DIAMER-BASHA	73.74	35.52	4500	INDUS	CONVENTIONAL	DIAMER
7	DASU	73.19	35.32	4320	INDUS	CONVENTIONAL	KOHISTAN
8	TARBELA	72.73	34.09	4888	INDUS	CONVENTIONAL	SWABI
9	BASHU	75.43	35.40	40	BASHU	RUN-OF-THE-RIVER	SKARDU
JHELUM BASIN							
Sr. #	**NAME**	**LONG.**	**LAT.**	**CAPACITY (MW)**	**RIVER**	**SCHEME**	**REGION**
1	SUKI KINARI	73.54	34.72	870	KUNHAR	RUN-OF-THE-RIVER	KAGHAN
2	NEELUM JHELUM	73.72	34.39	969	NEELUM	RUN-OF-THE-RIVER	NEELUM
3	PATRIND	73.43	34.34	150	KUNHAR	RUN-OF-THE-RIVER	MANSEHRA
4	KAROT	73.60	33.60	720	JHELUM	RUN-OF-THE-RIVER	RAWALPINDI
5	JAGRAN-I	73.76	34.60	30.4	JAGRAN NULLAH	RUN-OF-THE-RIVER	NEELUM
6	GULPUR	73.86	33.46	102	POONCH	RUN-OF-THE-RIVER	KOTLI
7	AZAD PATTAN	73.57	33.77	700	JHELUM	RUN-OF-THE-RIVER	SUDHANOTI
8	KOHALA	73.65	34.20	1100	JHELUM	RUN-OF-THE-RIVER	KOHALA
9	RAJDHANI	73.85	33.42	130	POONCH	RUN-OF-THE-RIVER	KOTLI
10	NARAN	73.58	34.85	188	KUNHAR	RUN-OF-THE-RIVER	MANSEHRA
CHITRAL BASIN							
Sr. #	**NAME**	**LONG.**	**LAT.**	**CAPACITY (MW)**	**RIVER**	**SCHEME**	**REGION**
1	GOLEN GOL	71.99	35.92	108	GOLEN GOL	RUN-OF-THE-RIVER	CHITRAL
3	LASPUR-MURIGRAM	72.43	35.98	230	MASTUJ	RUN-OF-THE-RIVER	CHITRAL
4	LAWI	71.88	35.63	69	SHISHI	RUN-OF-THE-RIVER	CHITRAL
5	SHUSHGAI-ZENDOLI	72.17	36.37	144	MASTUJ	RUN-OF-THE-RIVER	CHITRAL
6	SHOGO-SIN	71.78	36.00	132	LUTKHO	RUN-OF-THE-RIVER	CHITRAL
SWAT BASIN							

Sr. #	NAME	LONG.	LAT.	CAPACITY (MW)	RIVER	SCHEME	REGION
1	MALAKAND-I	71.98	34.63	22	SWAT	RUN-OF-THE-RIVER	MALAKAND
2	MALAKAND-II	71.98	34.63	20	SWAT	RUN-OF-THE-RIVER	MALAKAND
3	MALAKAND-III	71.98	34.63	81	SWAT	RUN-OF-THE-RIVER	MALAKAND
4	KOTO	71.92	34.86	40	PANJKORA	RUN-OF-THE-RIVER	LOWER DIR
5	SHARMAI	71.94	35.17	150	PANJKORA	RUN-OF-THE-RIVER	UPPER DIR
6	DARAL KHWAR	72.54	35.20	36.6	DARAL KHWAR	RUN-OF-THE-RIVER	SWAT
7	ASRIT-KEDAM	72.60	35.26	215	SWAT	RUN-OF-THE-RIVER	SWAT
8	GABRAL-KALAM	72.58	35.49	110	GABRAL	RUN-OF-THE-RIVER	SWAT
9	MOHMAND	71.53	34.35	740	SWAT	CONVENTIONAL	MOHMAND
10	GORKIN MATILTAN	72.67	35.57	84	USHU	RUN-OF-THE-RIVER	SWAT

Observed Meteorological Stations:

A network of meteorological stations is present throughout the northern region which for ease of identification could be divided into upper Indus basin, Chitral Basin, Jhelum Basin and Swat basin stations; maintained and recorded by two public sector entities namely the Pakistan Meteorological Department (PMD) and Water and power development authority (WAPDA). The meteorological observations from these stations include values of precipitation, maximum temperature and minimum temperature on a daily time-step required for a period of 30-years so as to substantiate impacts of climate change in this region of study.

The observed time period selected for this study is 1976-2005 which unfortunately omits all of the Meteorological records maintained by Water and Power Developement Authority (WAPDA) since its recording period started in the mid 1990s and therefore cannot be used in the present study owing to the constraint of 30 years observed data requirement for the three variables namely precipitation, maximum temperature and minimum temperature. An inventory of all the PMD stations used in this study so far are as follows:

Sr. #	STATION NAME	AGENCY	LATTITUDE	LONGITUDE	ALTITUDE (m.asl)
1	BUNJI	PMD	35.67	74.63	1372
2	SKARDU AP	PMD	35.30	75.68	2317
3	ASTORE	PMD	35.37	74.90	2168
4	GILGIT	PMD	35.92	74.33	1460
5	GUPIS	PMD	36.17	73.40	2156
6	BALAKOT	PMD	34.55	72.35	995
7	CHITRAL	PMD	35.85	71.83	1498
8	DROSH	PMD	35.57	71.78	1464
9	GARHI DUPATTA	PMD	34.22	73.62	813
10	KOTLI	PMD	33.52	73.90	614
11	RAWALAKOT	PMD	33.87	73.68	1677
12	MUZAFFARABAD	PMD	34.37	73.48	702

Man-Kendall Trend Analysis

In the present study, the metrological trends in the respective observed meteorological station datasets situated in the respective basins are detected with the help of a non-parametric, two-tailed Mann-Kendal test, and its magnitude quantified with the help of Sen's slope estimator. The MK is a rank-based method that tests the existence of a trend irrespective of the type of sample data distribution and whether such a trend is linear or not (Wu et al., 2008; Tabari and Talaee, 2011). MK is also insensitive to the data outliers and missing values . All the pattern investigation was performed utilizing the Excel layout application MAKESENS (FMI 2002). MAKESENS utilizes two unique ways to deal with test for pattern in a given time arrangement dependent on the quantity of perceptions. In the event that the quantity of perceptions is under 10, MAKESENS utilizes the S measurements (Gilbert 1987); else, it utilizes Z statistics (typical circulation). All patterns were determined over the examination time frame 1976– 2005 with the level of statistical significance kept at 90%. The details of the result are listed in the table for all the observed stations used in this study.

Chitral Meteorological Station

TMAX				TMIN				PRCP			
Time Series	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (mm/yr)**	**Trend(At 90% Significance Level)**
January	2.57	0.114	Increasing	June	-3.25	-0.108	Decreasing	June	2.21	0.287	Increasing
February	2.07	0.093	Increasing	July	-2.43	-0.065	Decreasing	September	1.84	0.266	Increasing
March	2.50	0.128	Increasing	August	-1.96	-0.045	Decreasing	Annual	2.07	5.248	Increasing
December	1.89	0.071	Increasing	November	-2.18	-0.035	Decreasing	IX-XI	2.21	0.769	Increasing
Annual	2.64	0.052	Increasing	Annual	-1.68	-0.023	Decreasing				
IX-XI	1.75	0.031	Increasing	VI-VIII	-3.14	-0.068	Decreasing				
XII-II	3.10	0.101	Increasing								

Drosh Meteorological Station

TMAX				TMIN				PRCP			
Time Series	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (mm/yr)**	**Trend(At 90% Significance Level)**
January	2.00	0.075	Increasing	March	2.25	0.084	Increasing	April	1.74	2.119	Increasing
March	1.86	0.083	Increasing	XII-II	1.96	0.049	Increasing	Annual	1.93	6.270	Increasing
XII-II	2.50	0.066	Increasing								

Balakot Meteorological Station

TMAX				TMIN				PRCP			
Time Series	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (mm/yr)**	**Trend(At 90% Significance Level)**
March	2.36	0.093	Increasing	March	2.75	0.085	Increasing	March	-2.07	-4.238	Decreasing
				December	2.00	0.043	Increasing	April	-1.84	-2.325	Decreasing
				XII-II	1.89	0.023	Increasing	July	-1.89	-6.417	Decreasing
								Annual	-3.00	-19.290	Decreasing
								III-V	-2.75	-2.526	Decreasing
								VI-VIII	-2.85	-3.495	Decreasing

Astore and Skardu Meteorological Station Combined											
TMAX				TMIN				PRCP			
Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (mm/yr)	Trend(At 90% Significance Level)
March	2.57	0.085	Increasing	August	-2.12	-0.051	Decreasing	April	2.00	1.811	Increasing
November	1.78	0.062	Increasing	VI-VIII	-1.86	-0.046	Decreasing	July	1.96	0.432	Increasing
IX-XI	2.03	0.033	Increasing								
XII-II	2.60	0.078	Increasing								
Astore, Bunji, Gilgit, Gupis and Skardu Meteorological Station Combined											
TMAX				TMIN				PRCP			
Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (mm/yr)	Trend(At 90% Significance Level)
March	2.68	0.090	Increasing	July	-2.82	-0.087	Decreasing	February	1.78	0.671	Increasing
XII-II	1.78	0.060	Increasing	August	-2.57	-0.067	Decreasing	April	2.25	1.670	Increasing
				September	-2.00	-0.044	Decreasing	June	1.82	0.444	Increasing
				October	-2.32	-0.052	Decreasing	Annual	2.00	3.687	Increasing
				Annual	-2.57	-0.036	Decreasing	III-V	1.96	0.679	Increasing
				VI-VIII	-2.64	-0.062	Decreasing				
				IX-XI	-2.89	-0.044	Decreasing				
Astore, Balakot, Bunji, Gilgit, Gupis and Skardu Meteorological Station Combined											
TMAX				TMIN				PRCP			
Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (mm/yr)	Trend(At 90% Significance Level)
March	2.64	0.087	Increasing	March	1.86	0.047	Increasing	April	1.68	0.053	Increasing
July	-1.68	-0.049	Decreasing	July	-2.78	-0.074	Decreasing				
				August	-2.46	-0.055	Decreasing				
				September	-1.68	-0.029	Decreasing				
				October	-2.46	-0.054	Decreasing				
				Annual	-2.32	-0.029	Decreasing				
				VI-VIII	-2.78	-0.052	Decreasing				
				IX-XI	-2.57	-0.038	Decreasing				

Gupis Meteorological Station

TMAX				TMIN				PRCP			
Time Series	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (mm/yr)**	**Trend(At 90% Significance Level)**
July	-1.75	-0.069	Decreasing	April	-2.00	-0.097	Decreasing	February	3.10	0.507	Increasing
				June	-2.32	-0.112	Decreasing	March	2.93	0.896	Increasing
				July	-3.14	-0.123	Decreasing	April	2.57	2.033	Increasing
				August	-2.68	-0.100	Decreasing	May	2.16	0.885	Increasing
				October	-2.42	-0.071	Decreasing	June	1.69	0.200	Increasing
				Annual	-2.39	-0.065	Decreasing	July	2.91	0.710	Increasing
				VI-VIII	-3.32	-0.106	Decreasing	August	2.55	1.207	Increasing
				IX-XI	-2.82	-0.067	Decreasing	October	2.45	0.274	Increasing
								Annual	3.93	15.169	Increasing
								III-V	3.05	1.776	Increasing
								VI-VIII	3.18	1.166	Increasing
								IX-XI	2.02	0.304	Increasing
								XII-II	2.46	0.271	Increasing

Garhi Dupatta and Muzaffarabad Meteorological Station Combined

TMAX				TMIN				PRCP			
Time Series	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (mm/yr)**	**Trend(At 90% Significance Level)**
March	2.78	0.136	Increasing					March	-1.78	-2.728	Decreasing
July	1.82	0.057	Increasing					XII-II	1.75	1.586	Increasing
August	2.05	0.044	Increasing								
VI-VIII	1.96	0.025	Increasing								

Kotli Meteorological Station

TMAX				TMIN				PRCP			
Time Series	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (°C/yr)**	**Trend(At 90% Significance Level)**	**Time Series**	**Normalized Test Statistic (Z)**	**Sen Slope (mm/yr)**	**Trend(At 90% Significance Level)**
March	2.28	0.127	Increasing	IX-XI	-1.96	-0.036	Decreasing	Annual	-1.75	-12.993	Decreasing
September	-2.46	-0.059	Decreasing								
October	-1.96	-0.060	Decreasing								
November	-2.04	-0.074	Decreasing								
IX-XI	-2.53	-0.062	Decreasing								

Muzaffarabad Meteorological Station											
TMAX				TMIN				PRCP			
Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (mm/yr)	Trend(At 90% Significance Level)
March	2.76	0.143	Increasing	March	1.67	0.061	Increasing	August	-1.68	-2.445	Decreasing
July	1.65	0.044	Increasing								
August	2.19	0.039	Increasing								
November	1.78	0.102	Increasing								
Annual	1.89	0.042	Increasing								
IX-XI	1.96	0.056	Increasing								
Garhi Dupatta Meteorological Station											
TMAX				TMIN				PRCP			
Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (mm/yr)	Trend(At 90% Significance Level)
March	3.02	0.144	Increasing					January	2.11	3.740	Increasing
July	1.92	0.076	Increasing					March	-1.94	-4.293	Decreasing
August	2.15	0.061	Increasing					III-V	-1.76	-2.208	Decreasing
Annual	1.92	0.058	Increasing								
VI-VIII	2.27	0.045	Increasing								
XII-II	1.84	0.058	Increasing								
Muzaffarabad, Kotli, Garhi Dupatta and Jhelum Meteorological Station Combined											
TMAX				TMIN				PRCP			
Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (°C/yr)	Trend(At 90% Significance Level)	Time Series	Normalized Test Statistic (Z)	Sen Slope (mm/yr)	Trend(At 90% Significance Level)
July	2.16	0.067	Increasing	September	2.75	0.051	Increasing	VI-VIII	-1.68	-1.515	Decreasing
November	2.14	0.074	Increasing	October	1.75	0.043	Increasing				
December	1.78	0.053	Increasing	IX-XI	2.78	0.044	Increasing				

Mann Kendall Trend Results for the Chitral Basin shows a persistent increase in its maximum temperature and precipitation during the annual time scale with Autumn and Winter season also showcasing a similar increase whereas the minimum temperature depicts a decrease in the monsoon and annual time slice for the given 1976-2005 observed period.

In The Upper Indus Basin, the Balakot Meteorological station depicts an increase in the minimum temperature during the winter season with somewhat dormant maximum temperature throughout the observed period. Precipitation however shows a significant decrease during the pre-monsoon and monsoon period supported by a sharp annual decrease. The meteorological stations that lie close to the Karakoram Mountain range at higher altitude e.g Astore, Skardu, Gupis, Bunji and Skardu show a winter season increase in maximum temperature with a more spread out decrease observed in its minimum temperature variable for the monsoon, post-monsoon and annual time period. Precipitation in this region shows a consistent increase during the spring season along with annual increments.

In the Jhelum basin, the maximum temperature variable shows an overall consistent increase starting from the monsoon to autumn season with an annual increase observed as well while the minimum temperature shows a somewhat dormant behavior with no significant seasonal or annual change. Precipitation in this region is displaying a decreasing phenomenon during the pre-monsoon to monsoon period. Kotli meteorological station unlike the rest of the observed stations in the basin show a contrast with a decrease in max temperature variable during the Autumn season with precipitation also observing a sharp decline on the annual time scale.

Regional Climate Model (RCM) Selection and Statistical Downscaling

For the present study, Three Regional Climate Models are selected. Regional Climate Models (RCMs) are used to study how changes in global climate can

affect meteorology at fine spatial scales. Such models are commonly used to dynamically downscale climate change projections from Global Climate Models (GCMs) to regional and local spatial scales appropriate for impact studies. A short description of the RCMs is given below:

CCAM

The Conformal-Cubic Atmospheric Model (CCAM) has been developed at CSIRO, Australia. The Conformal Cubic Atmospheric Model (CCAM) is a semi-implicit, semi-Lagrangian atmospheric climate model based on a conformal cubic grid. Although a global atmospheric model, a variable resolution grid can be used by applying a Schmidt transformation [3], which results in a finer grid resolution over the target area at the expense of a coarser resolution on the opposite side of the globe. In this way, CCAM can be used for regional climate experiments without imposing lateral boundary conditions.

RCA4

Rossby Centre Regional Climate Model (RCA version 4) is a Swedish Meteorological and Hydrological Institute (SMHI) regional climate model developed at the Rossby centre for Climate Research. RCA is based upon the numerical weather prediction (NWP) model HIRLAM (Undén et al., 2002). Much of the initial work in the development of RCA was devoted to technical issues related to running a regional atmospheric model in a multiyear mode.

REMO2009

REMO was developed upon the request of the reviewers within the BMBF-Förderschwerpunkt Wasserkreislauf as the atmospheric component of the coupled atmosphere-hydrology model system. MPIfM (Max Planck Institute for Meteorology) was thus asked to develop the German BALTEX Model on the basis of the former numerical weather prediction model of the German Weather Service (EUROPA-MODELL, EM, Majewski 1991) in co-operation with DKRZ, DWD and GKSS. it was agreed between these parties to develop a

regional model suitable for climate modeling and weather forecast which subsequently was named REMO.

CORDEX

Coordinated Regional Climate Downscaling Experiment (CORDEX) is a WCRP-sponsored program to produce regional climate change scenarios globally, contributing to the IPCC AR5. CORDEX is a WCRP-sponsored program to organize an international coordinated framework to produce an improved generation of regional climate change projections world-wide for input into impact and adaptation studies within the AR5 timeline. CORDEX has produced an ensemble of multiple dynamical and statistical downscaling models considering multiple forcing GCMs from the CMIP5 archive. Initially a 50 km grid spacing (0.44°) has been selected, favoring engagement of wider community.

The above mentioned RCMs along with their GCM forcing have been downloaded from the openly available Earth System Grid Federation (ESGF) for the South Asian region having a spatial resolution of 0.44° grid in netcdf format.

The climate model's output datasets downloaded are based on future emission scenarios of the Representative Concentration Pathways (RCP) RCP 4.5 with 4.5Wm−2, and RCP 8.5 with 8.5Wm−2 radiative forcing by 2100 are used as it incorporates the realistic and worst case scenarios for the most likely future forecasts.

Table . List of Model Runs Analyzed in This Study

Institute	RCM	Driving GCM	Emission Scenario
CSIRO	CCAM	MPI-ESM-LR	RCP 4.5 & RCP8.5
SMHI	RCA4	EC-EARTH	RCP 4.5 & RCP8.5
MPI-CSC	REMOO2009	MPI-M-MPI-ESM-LR	RCP 4.5 & RCP8.5

ArcGIS software is used to visualize and statistically downscale theses RCMs through the multi-dimensional tools package and extract precipitation, maximum temperature and minimum temperature variables by super-imposing

the catchment area polygons of individual Hydropower projects on the gridded RCM points. For the Hydropower schemes that do not have large catchment areas nearest RCM grid points have been averaged so as to obtain a representative outlook. The polygon shape-files of the catchment areas have been generated post watershed delineation process using 1 arc-sec DEM from USGS website in ArcGIS software. The output of these grid points are taken in the form of excel sheets for further analysis of the data.

Bias Correction Using QDM Approach

These climate datasets have inherent biases which if not addressed or removed could lead to unrealistic results. The Best Easy Systematic (BES) estimator is used for both temperature and precipitation. Although the BES method is good for temperature, its performance is low for precipitation. The Mean Monthly Correction Factor (MMCF) method is another such method used for precipitation bias correction but Bias correction of projected datasets against the observed data should employ a process that preserves its future peaks and does not average out the extreme values (Ali, Li, Congbin, & Khan, 2015). One such method employed that does not alter the future peaks is Quantile Delta Mapping method that is most frequently used in hydrological forecasting and projections. QDM starts with the time-dependent CDF of the model projected series $x_{m,p}$, for example as estimated from the empirical CDF over a time window around *t*:

$$\tau_{m,p}(t) = F^{(t)}_{m,p}[x_{m,p}(t)], \quad \tau_{m,p}(t) \in \{0,1\}, \qquad (3)$$

where $\tau_{m,p}$ is the non-exceedance probability associated with the value at time *t*. The QDM for precipitation preserves model-projected relative changes in quantiles, while at the same time correcting systematic biases in quantiles of a modeled series with respect to observed values. Preservation of relative changes follows directly from the quantile delta change (Olsson et al. 2009) and quantile perturbation (Willems and Vrac 2011) methods, both of which apply simulated relative changes in quantiles overtop observed historical series.

QDM bias correction procedure is applied on the two IPCC emission scenarios of their respective downscaled RCM datasets for the selected time slices i.e., 2020-2049 and 2070-2099 for each hydropower scheme against the observed meteorological stations selected for each HPP.

Table 3. QDM Bias Correction for HPPs

RCM	IPCC Emission Scenario	Time Slice	Variable	Bias-Correction
CCAM	4.5 & 8.5	2020-2049 2070-2099	Prcp, Tmax & Tmin	Complete
RCA4	4.5 & 8.5	2020-2049 2070-2099	Prcp, Tmax & Tmin	Complete
REMO	4.5 & 8.5	2020-2049 2070-2099	Prcp, Tmax & Tmin	Complete

Climate Indices Calculation

The most important step of study is the introduction of climate indices approach for the climate change impact assessment on HPP in the northern region. To gain a uniform perspective on observed changes in weather and climate extremes, the joint CCl/WCRP-Clivar/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) has defined a core set of descriptive indices of extremes. The indices describe particular characteristics of extremes, including frequency, amplitude and persistence. The core set includes 27 extremes indices for temperature and precipitation (World Meteorological Organization, 2017). Sixteen of the 27 indices recommended by the ETCCDMI are temperature related and eleven are precipitation related. They are derived from daily maximum and minimum temperature and daily precipitation. The indices were chosen primarily for assessment of the many aspects of a changing

global climate which include changes in intensity, frequency and duration of temperature and precipitation events(Alexander et al., 2006). The set of climate indices from the Expert Team on Climate Change Detection and Indices (ETCCDI)will be calculated for the present and future climate under two Representative Concentration Pathways, namely, RCP4.5 and RCP8.5(Dosio, 2016).

Table 4. List of ETCCDMI core Climate Indices

ID	Indicator name	Definitions	UNITS
FD0	Frost days	Annual count when TN(daily minimum)<0ºC	Days
SU25	Summer days	Annual count when TX(daily maximum)>25ºC	Days
ID0	Ice days	Annual count when TX(daily maximum)<0ºC	Days
TR20	Tropical nights	Annual count when TN(daily minimum)>20ºC	Days
GSL	Growing season Length	Annual (1st Jan to 31st Dec in NH, 1st July to 30th June in SH) count between first span of at least 6 days with TG>5ºC and first span after July 1 (January 1 in SH) of 6 days with TG<5ºC	Days
TXx	Max Tmax	Monthly maximum value of daily maximum temp	ºC
TNx	Max Tmin	Monthly maximum value of daily minimum temp	ºC
TXn	Min Tmax	Monthly minimum value of daily maximum temp	ºC
TNn	Min Tmin	Monthly minimum value of daily minimum temp	ºC
TN10p	Cool nights	Percentage of days when TN<10th percentile	Days
TX10p	Cool days	Percentage of days when TX<10th percentile	Days
TN90p	Warm nights	Percentage of days when TN>90th percentile	Days
TX90p	Warm days	Percentage of days when TX>90th percentile	Days
WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	Days
CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN<10th percentile	Days
DTR	Diurnal temperature range	Monthly mean difference between TX and TN	ºC
RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	Mm

Rx5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	Mm
SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days (defined as PRCP>=1.0mm) in the year	Mm/day
R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days
R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	Days
Rnn	Number of days above nn mm	Annual count of days when PRCP>=nn mm, nn is user defined threshold	Days
CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm	Days
CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm	Days
R95p	Very wet days	Annual total PRCP when RR>95th percentile	Mm
R99p	Extremely wet days	Annual total PRCP when RR>99th percentile	mm
PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm)	mm

RClimdex Package

A powerful statistical software R is used to compute these 27 core indices for the northern region using various RCM datasets with two IPCC emission scenarios namely RCP4.5 and RCP8.5. Xuebin Zhang and Yang Feng at Climate Research Division have developed and maintained a source code "RClimdex" that provides a friendly user interface to compute all 27 core indices in R-software. It is pertinent to mention that in some HPPs owing to the constraint of missing observed data, not all indices were succesfully calculated. RClimdex package performs data quality control as a prerequisite for indices calculation

The RClimDex QC performs the following procedure:

Replace all missing values (currently coded as -99.9) into an internal format that R recognizes (i.e. NA, not available)

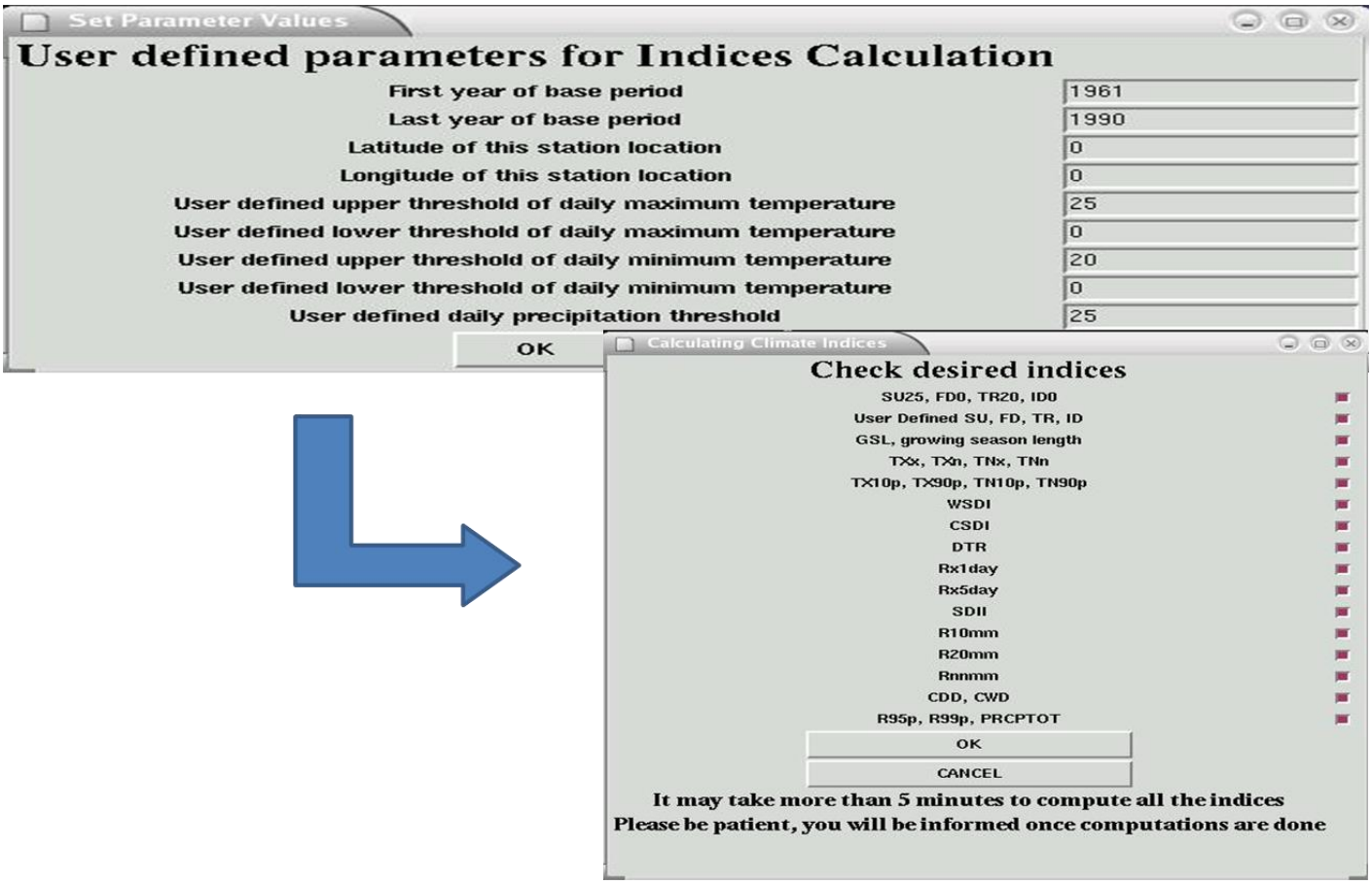
1. Replace all unreasonable values into NA

2. Unreasonable values includes :

a) Daily precipitation amounts less than zero.

b) Daily maximum temperature less than daily minimum temperature.

3. QC also identifies outliers in daily maximum and minimum temperature. The outliers are daily values outside a region defined by the user

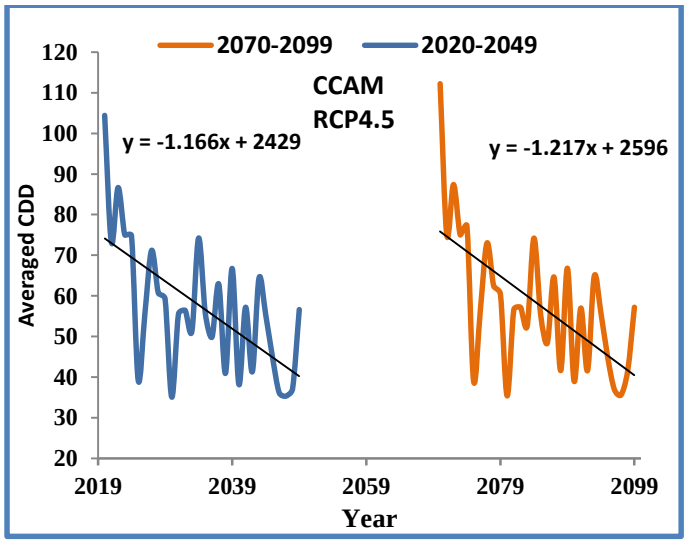


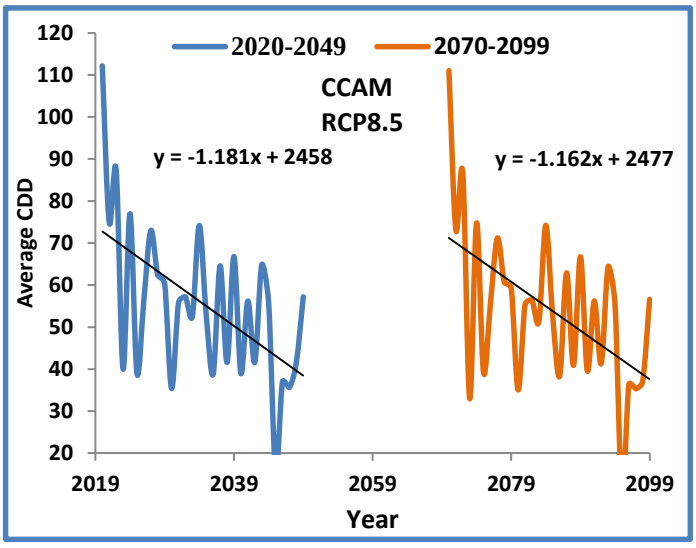
For practical reasons, in this version of the software, not all indices are calculated on a monthly basis. Monthly indices are calculated if no more than 3 days are missing in a month, while annual values are calculated if no more than 15 days are missing in a year. No annual value will be calculated if any one month's data are missing. For threshold indices, a threshold is calculated if at least 70% of data are present.

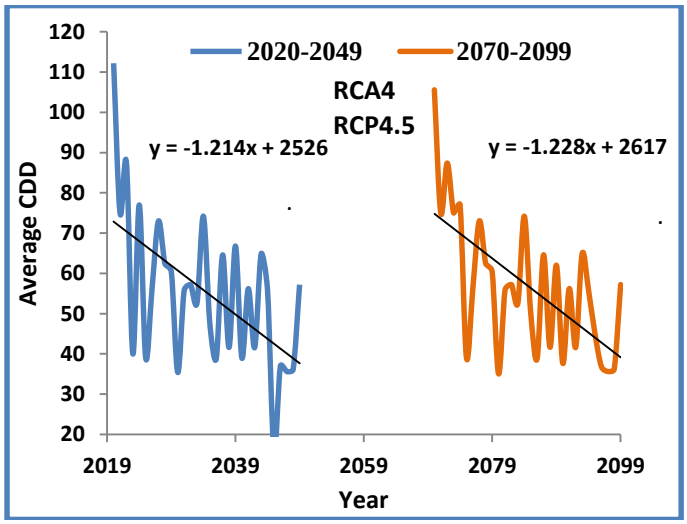
Basin-Wise Indices of HPPs

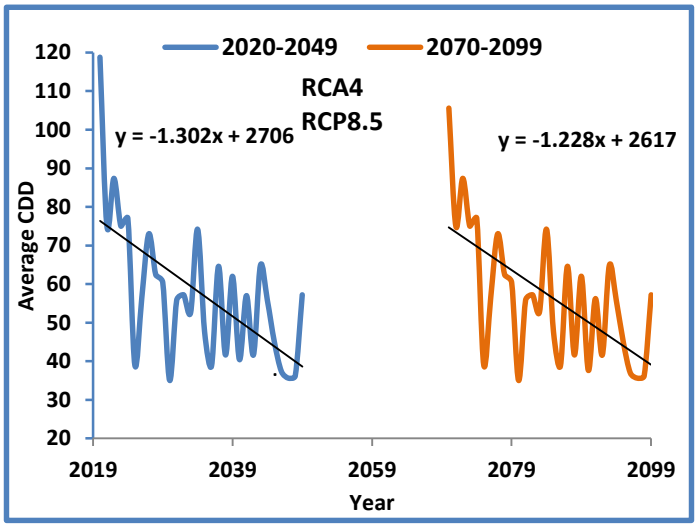
Chitral Basin

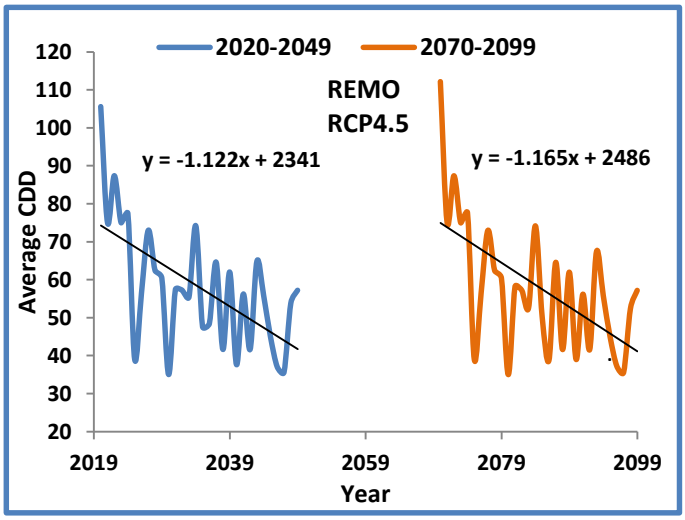
1- Consecutive Dry Days (CDD):

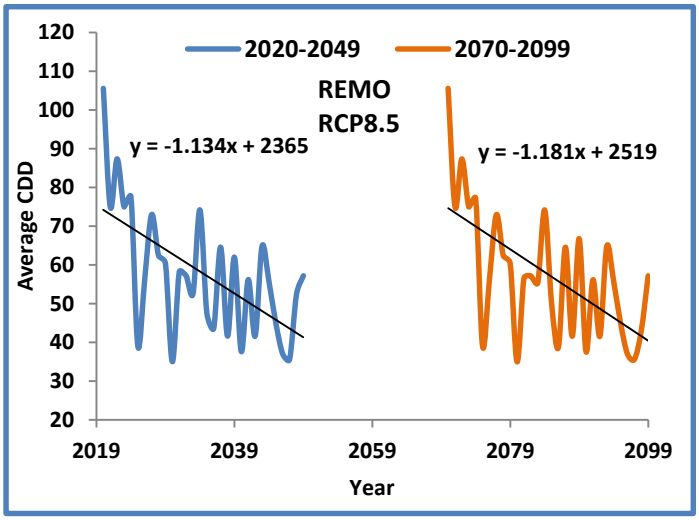




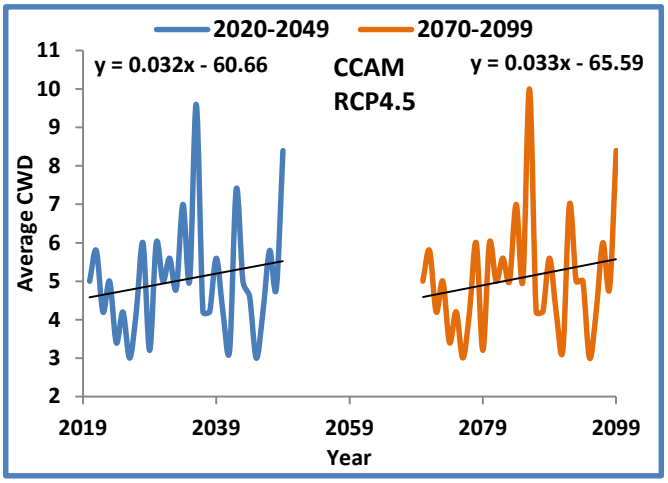


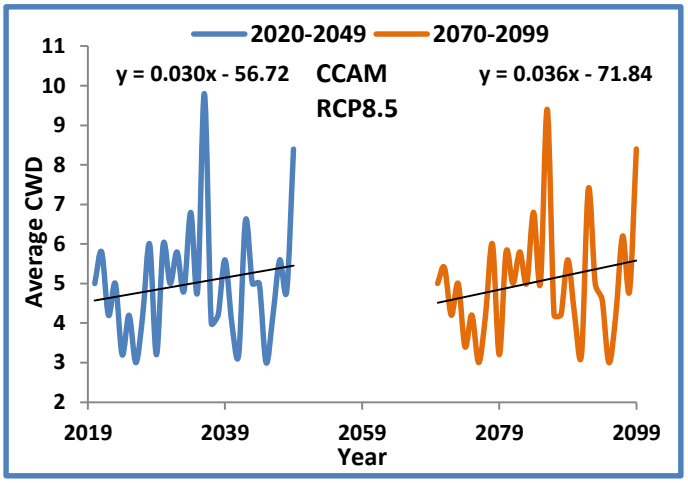


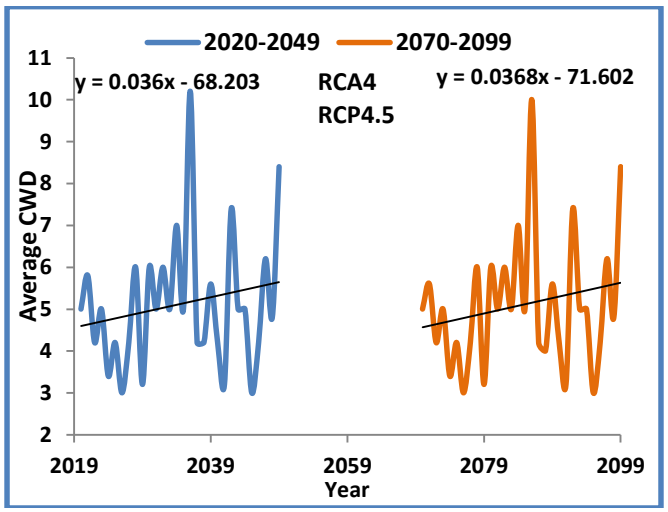


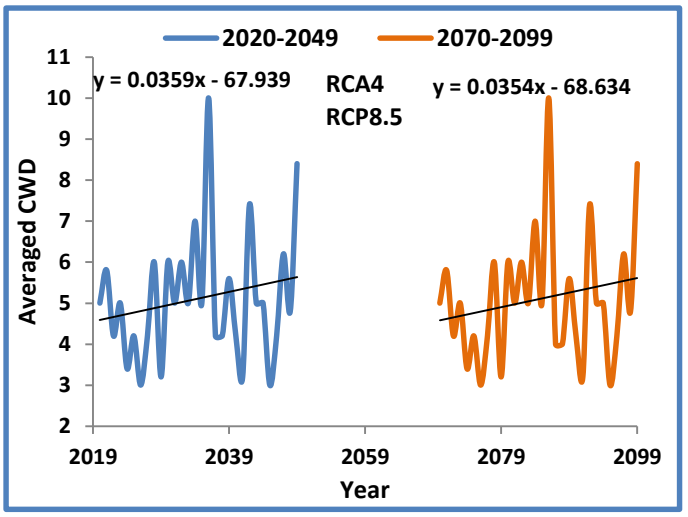


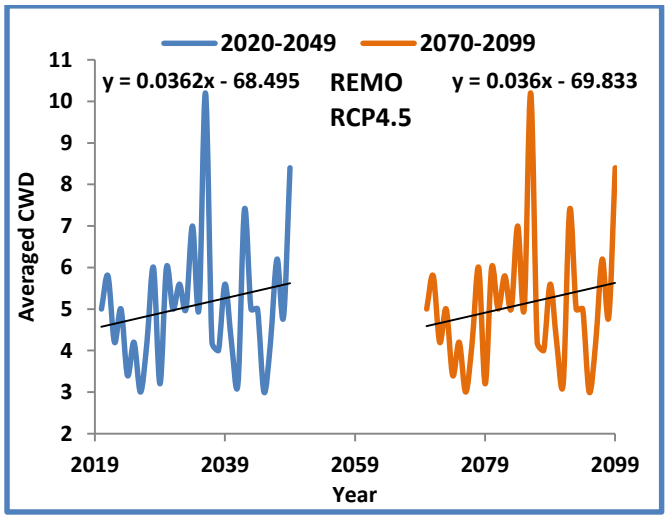
2- Consecutive Wet Days (CWD):

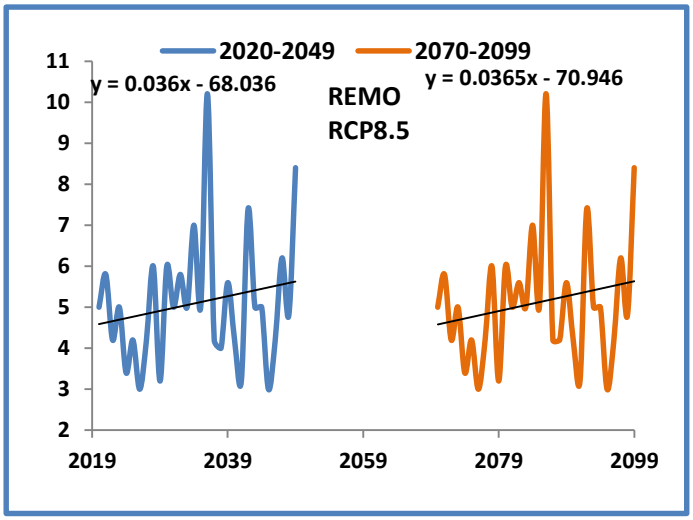




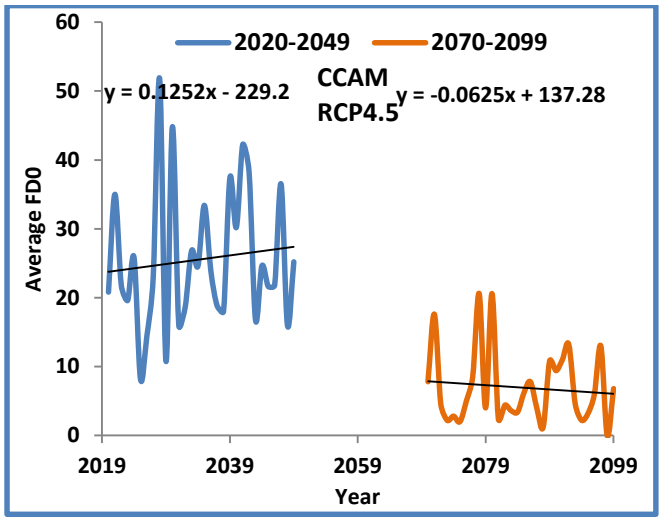


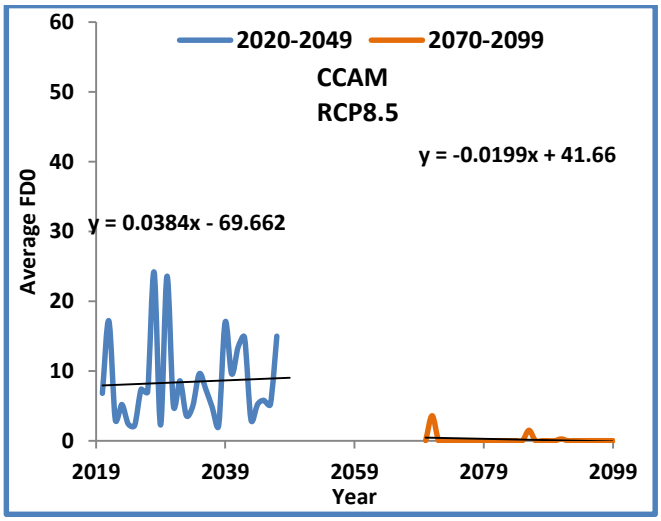


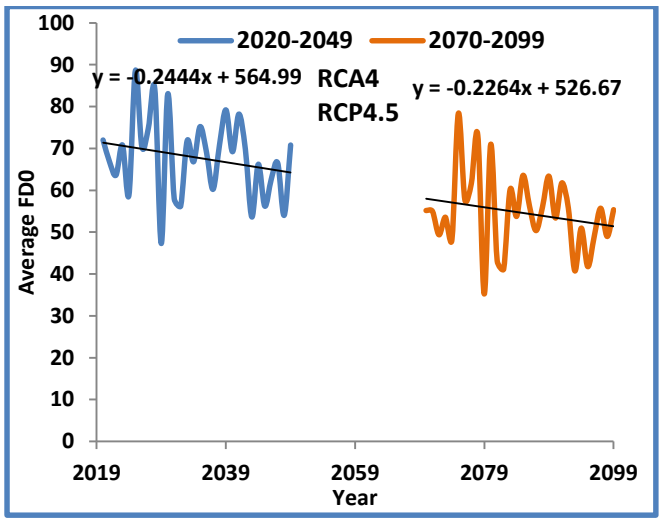


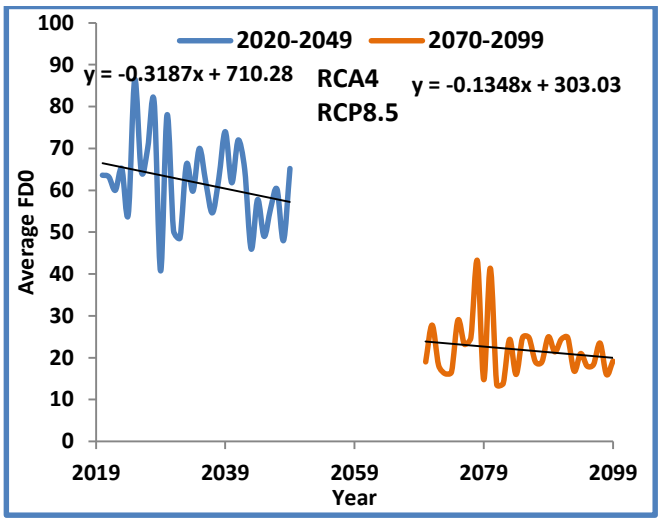


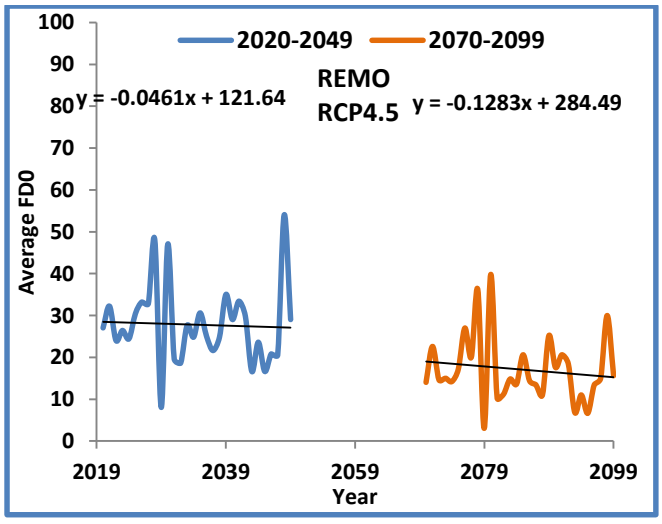
3- Frost Days (FD0):

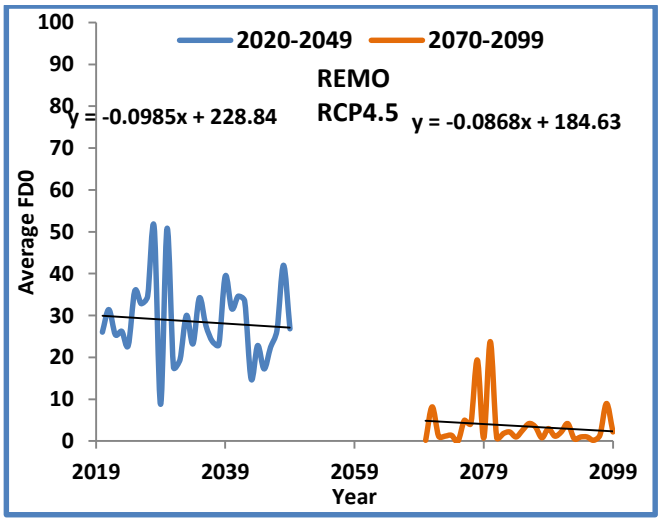




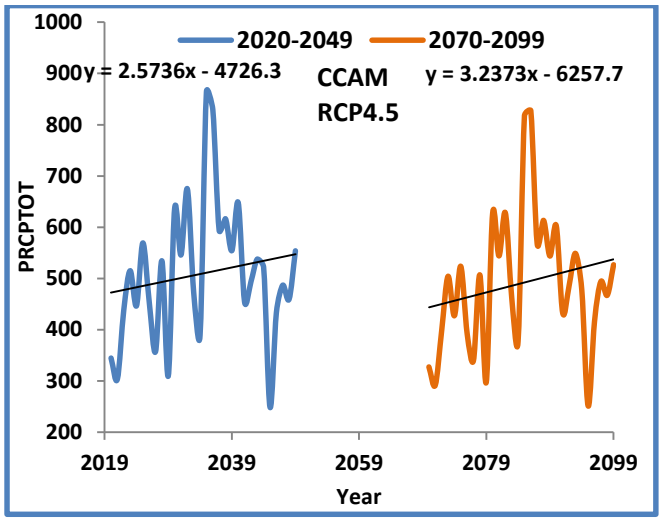


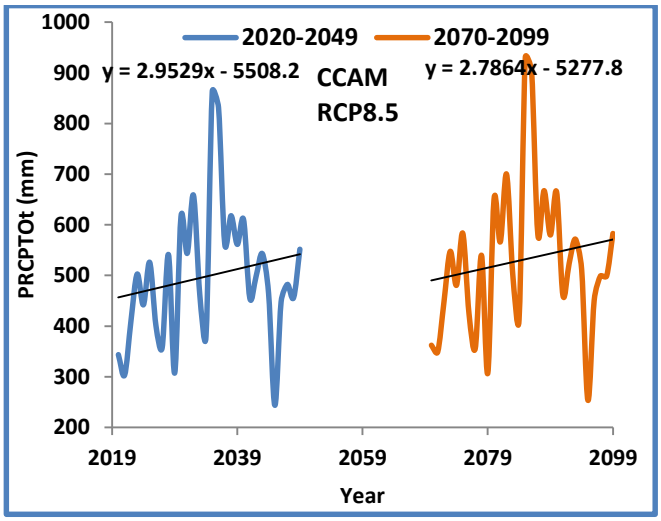


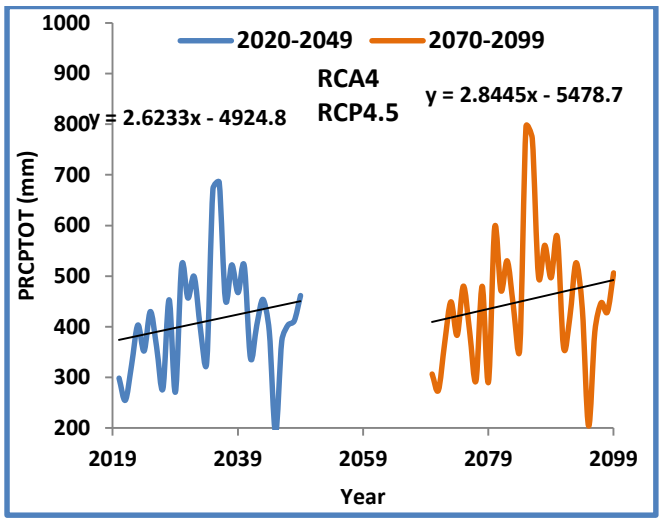


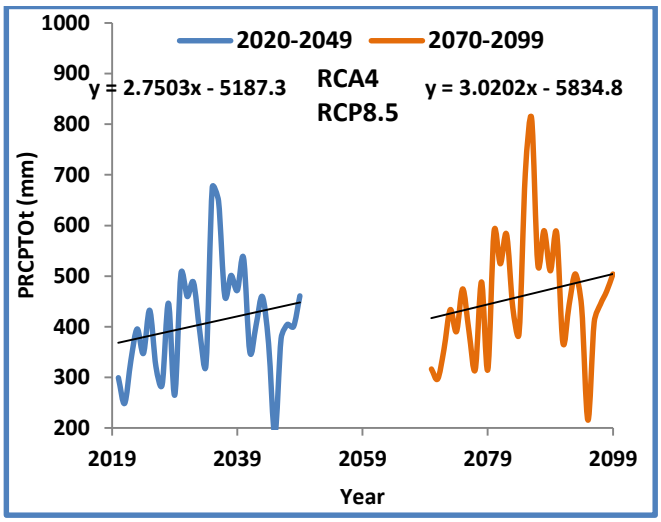


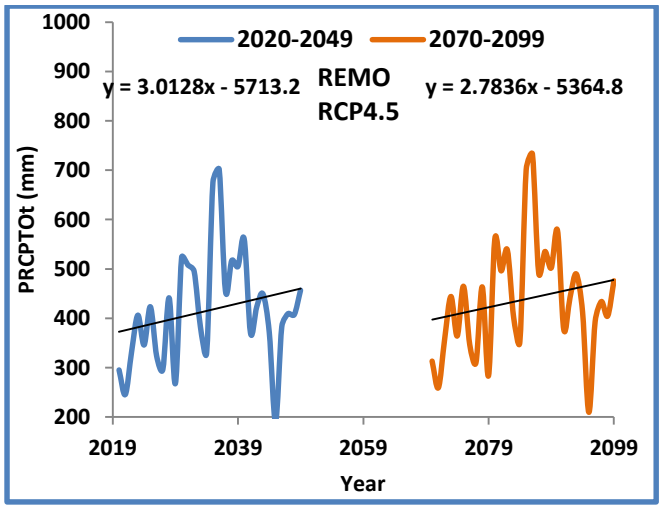
4- Total Precipitation (PRCPTOT):

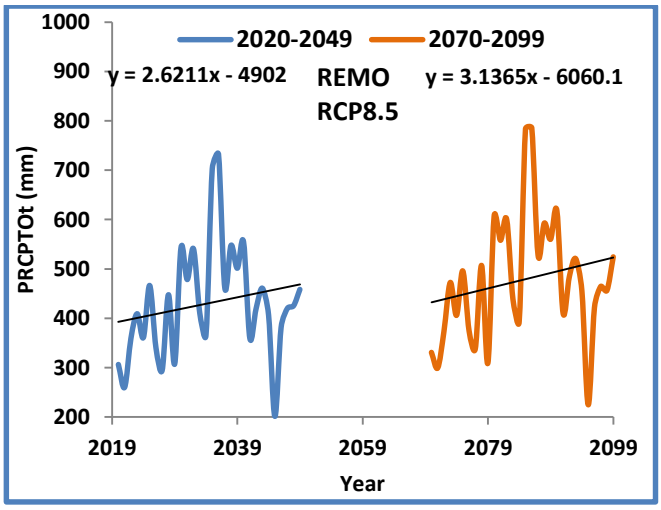




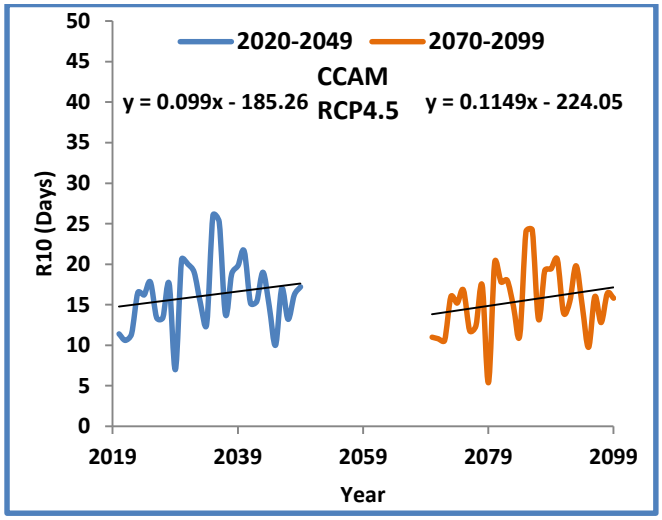


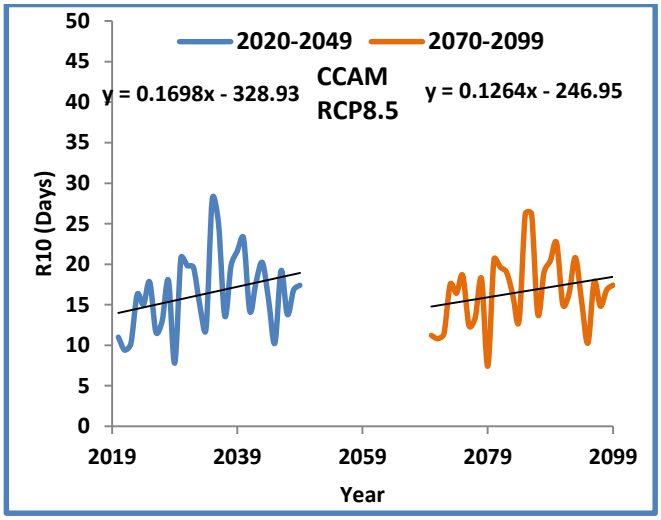


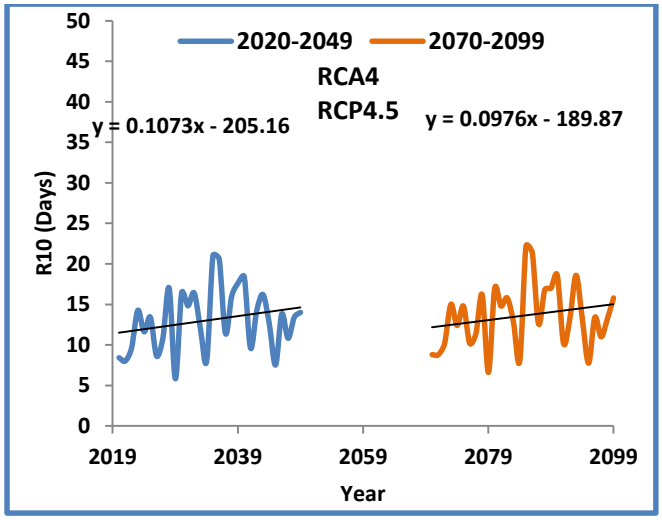


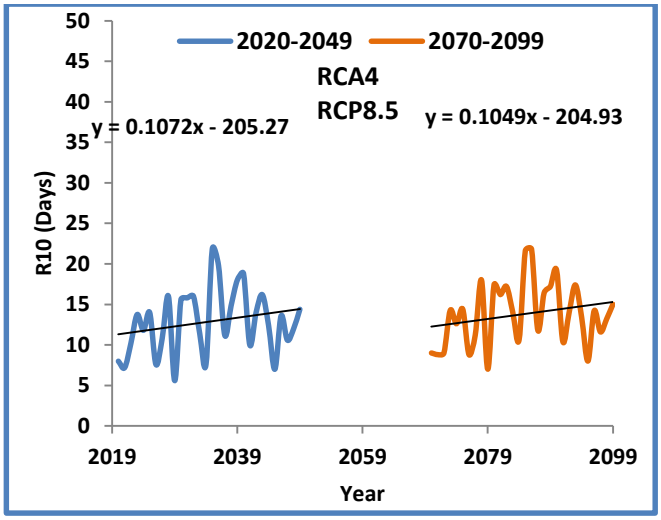


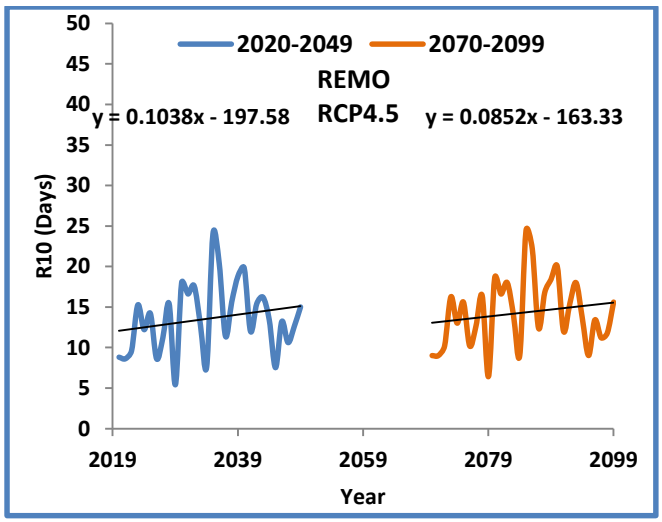
5- Heavy Precipitation Days (R10):

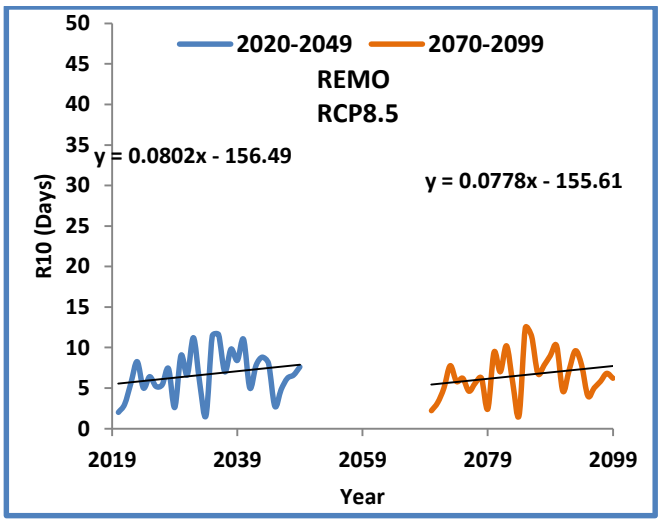




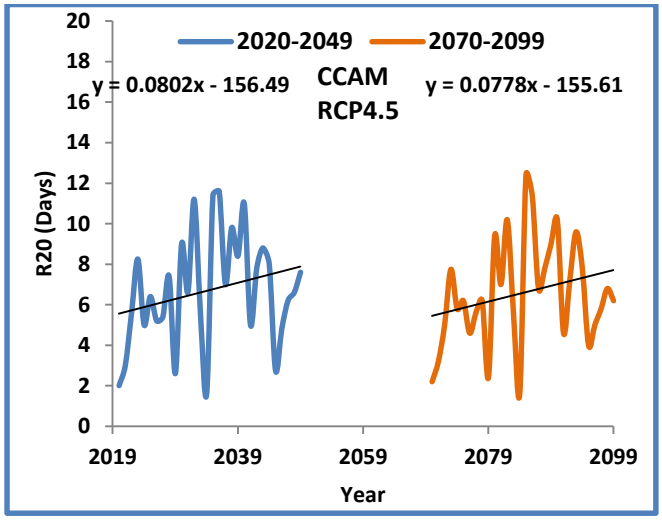


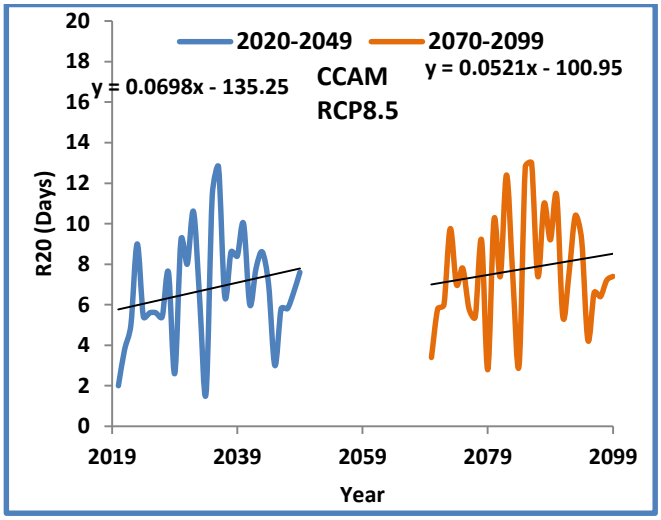


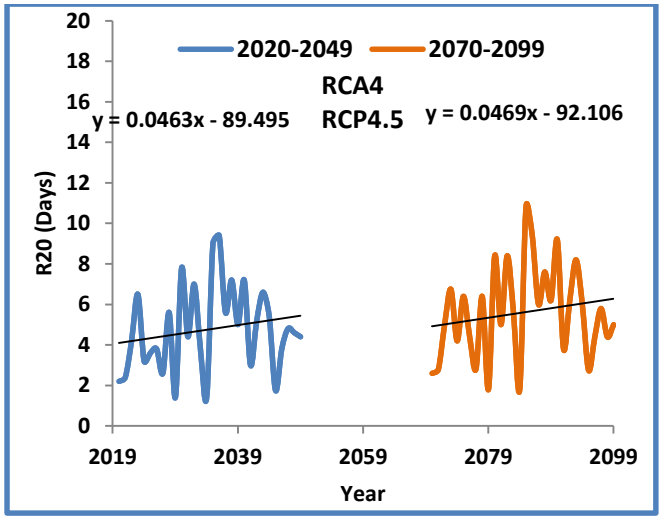


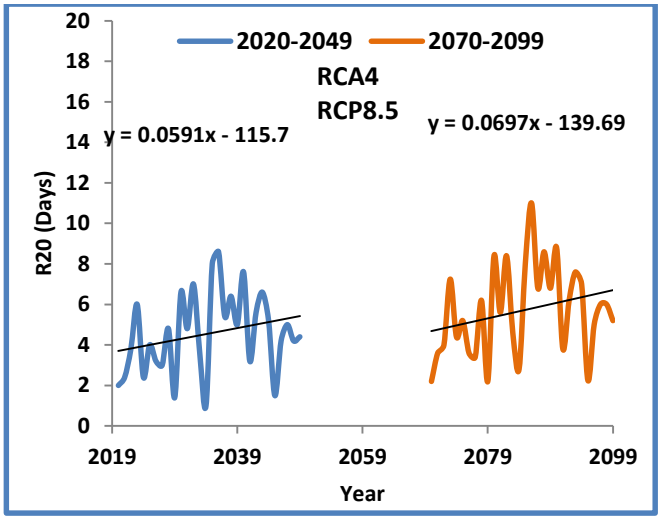


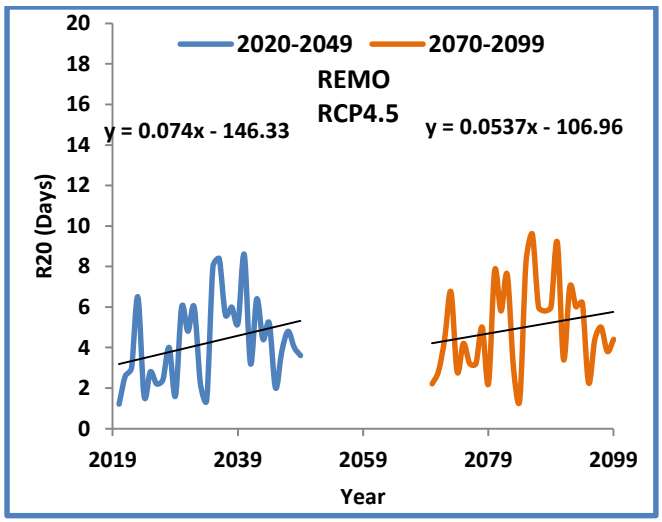
6- Very Heavy Precipitation Days (R20):

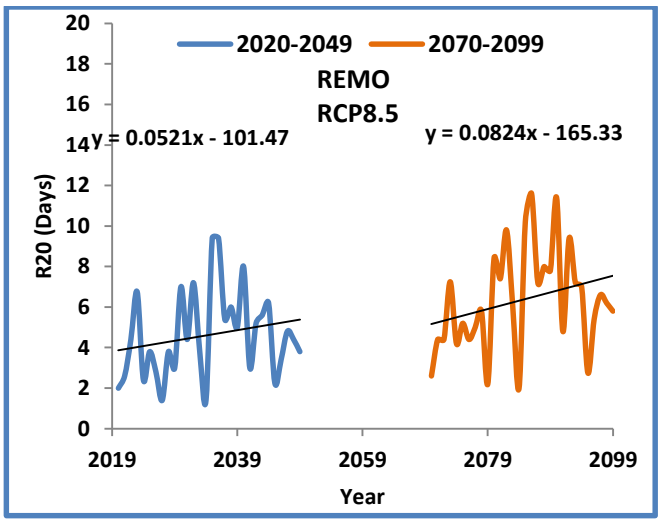




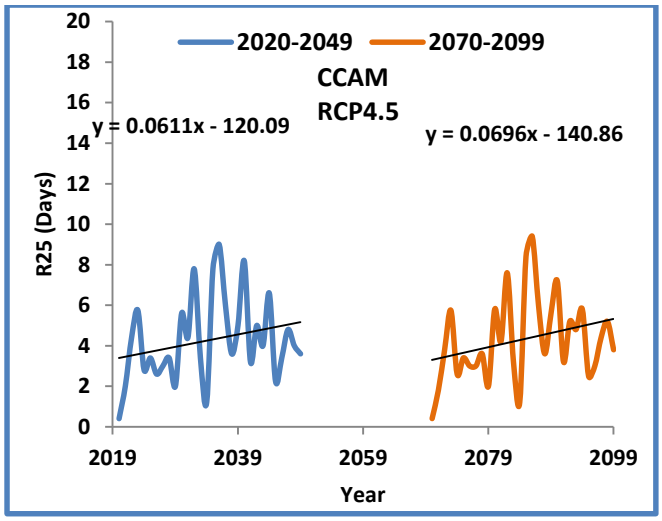


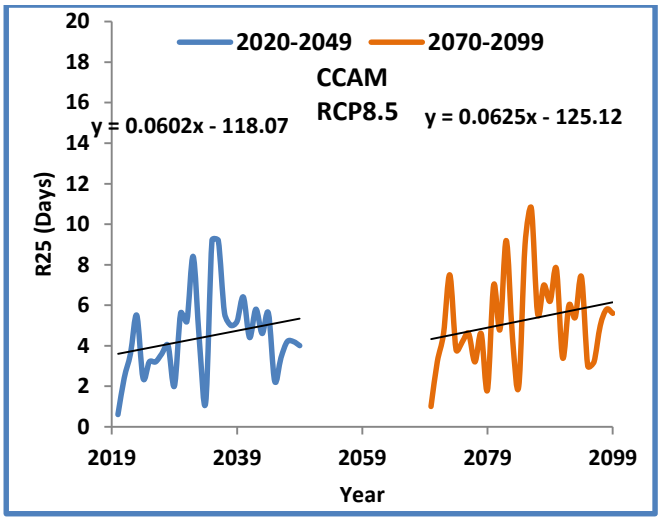


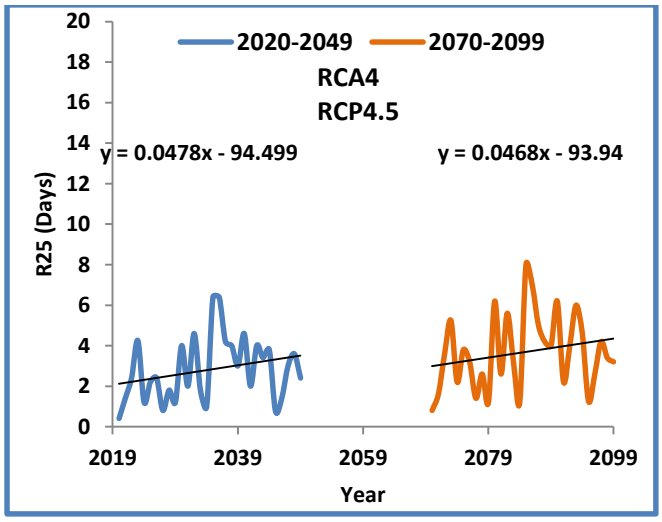


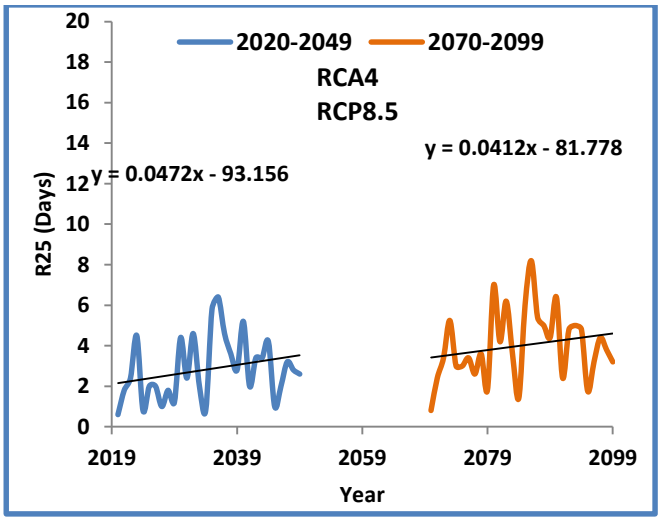


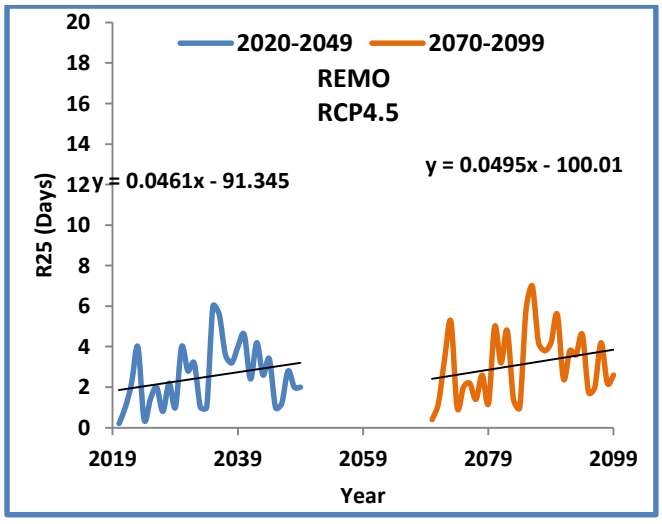
7- Extreme Precipitation (Rnn):

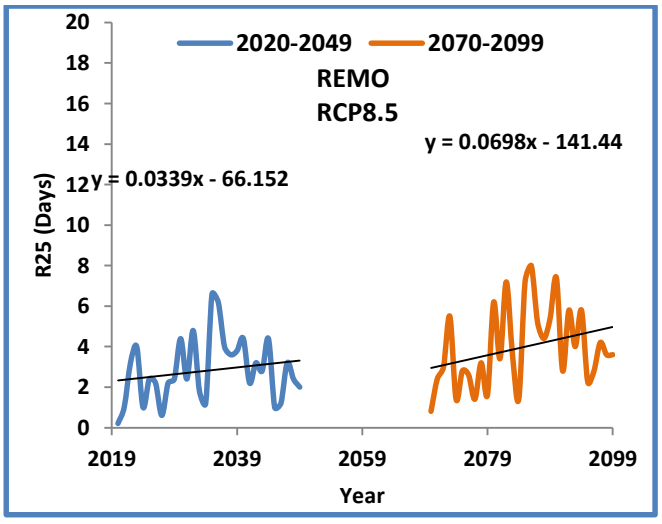




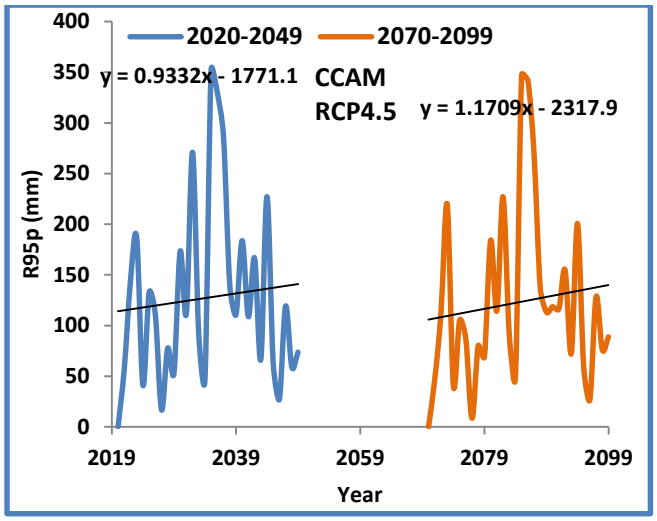


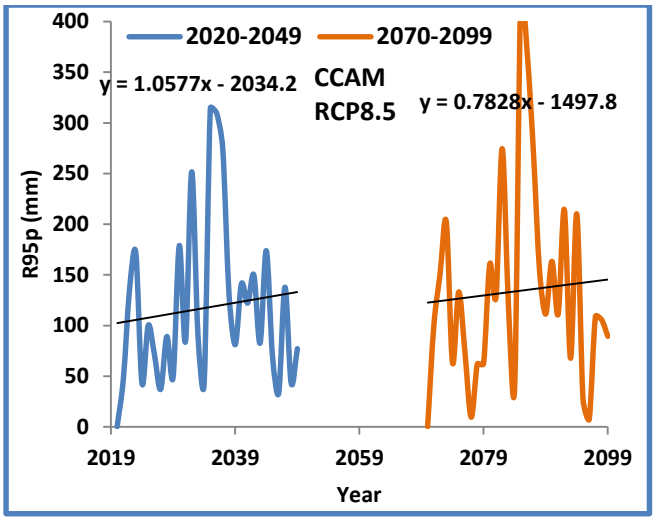


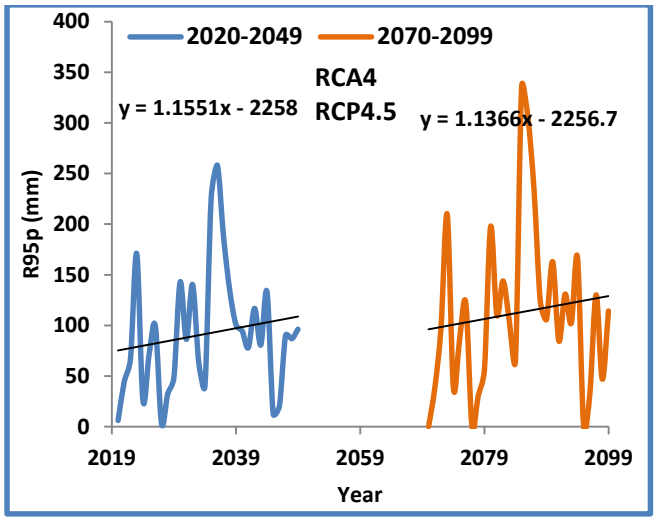


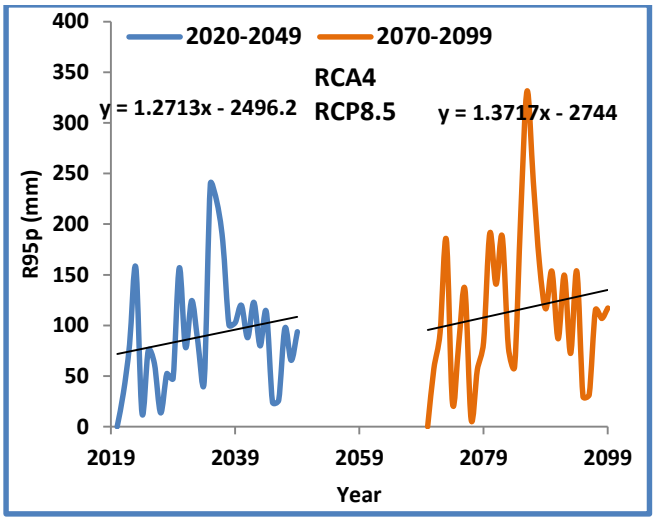


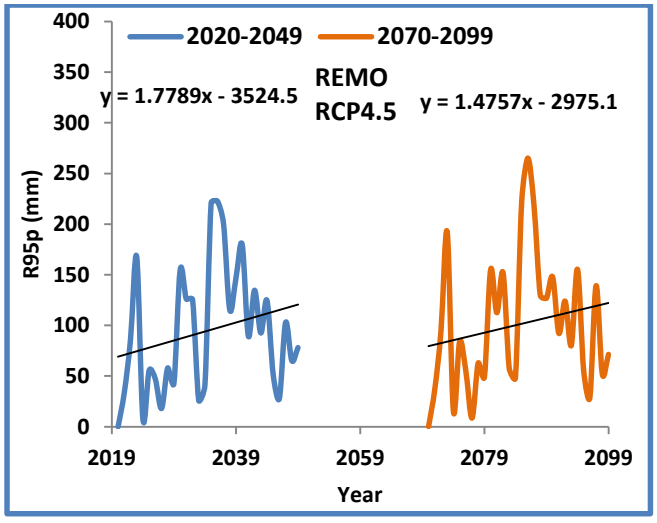
8- Very Wet Days (R95p):

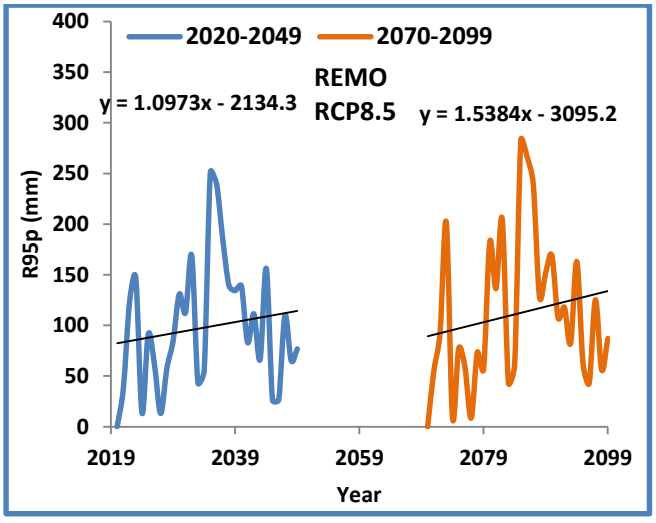




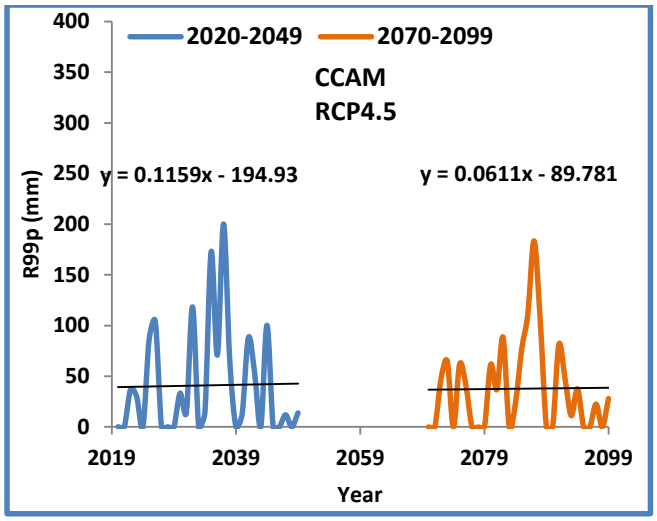


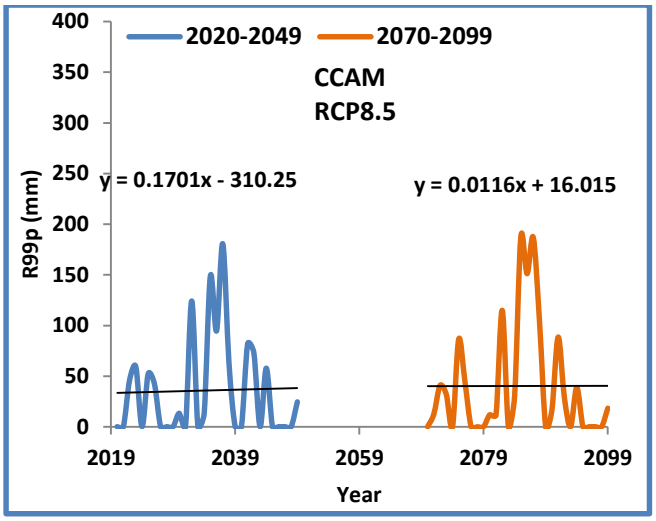


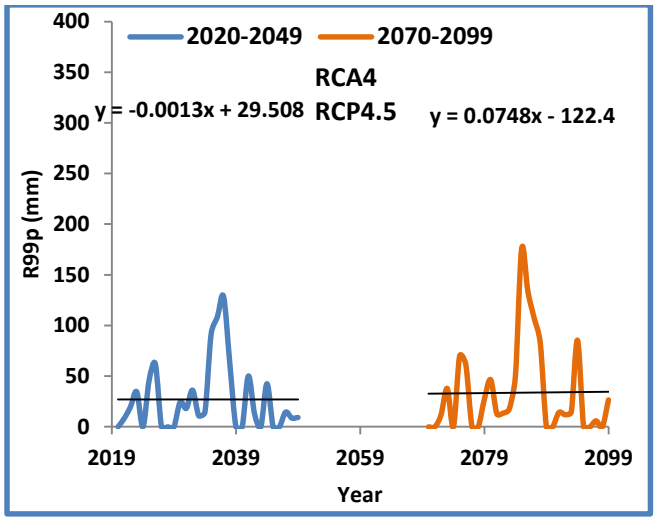


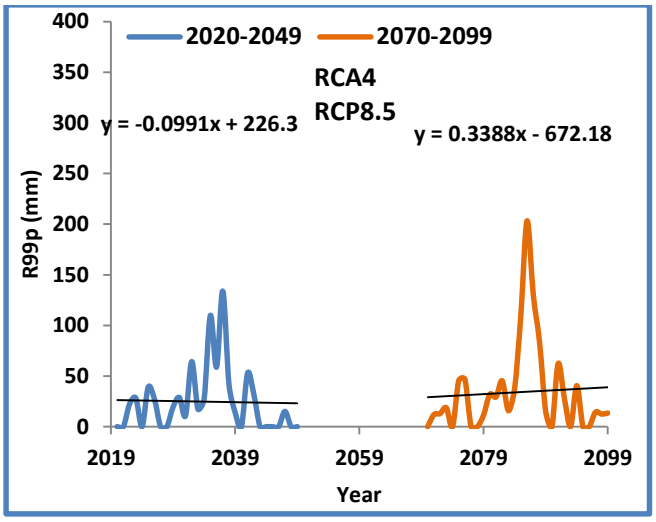


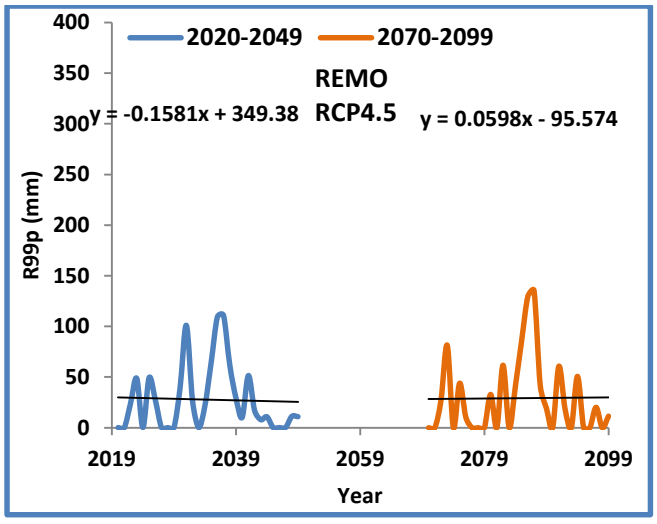
9- Extremely Wet Days (R99p):

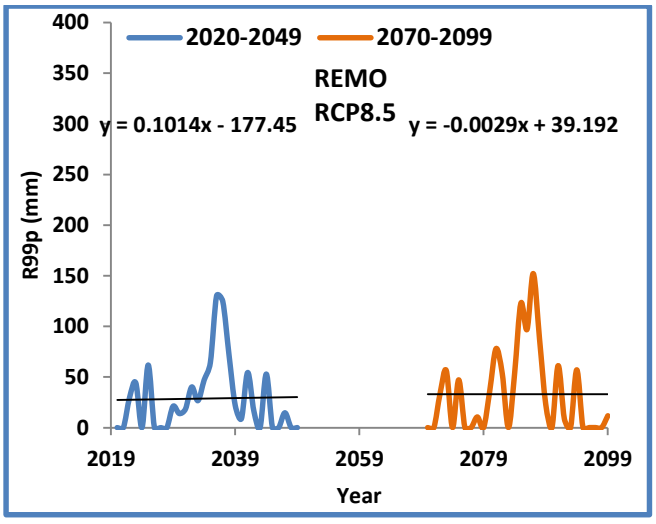




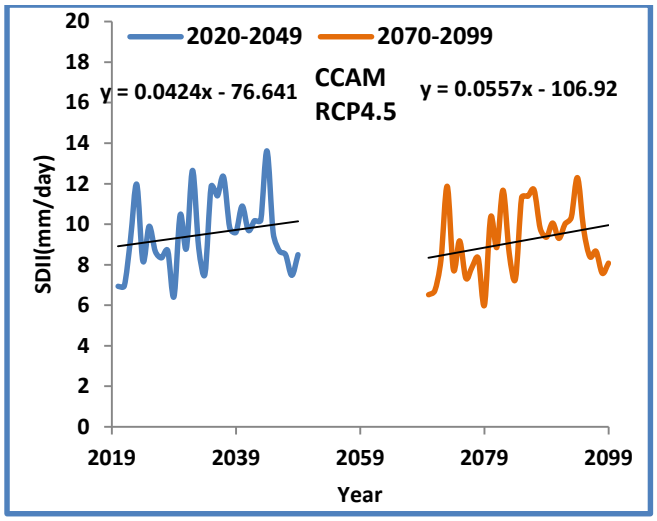


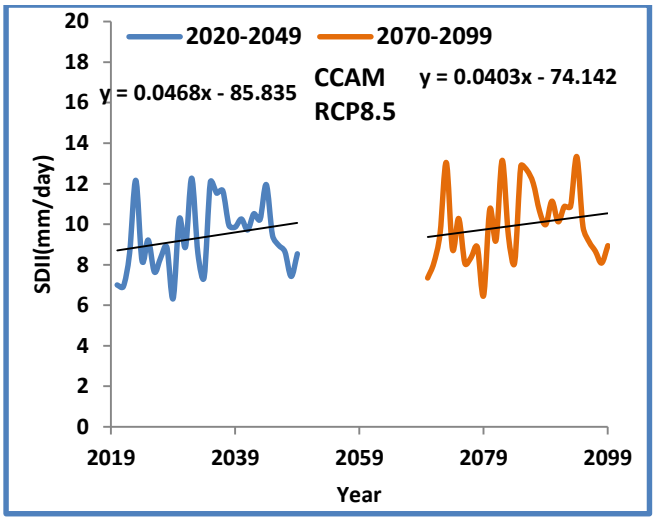


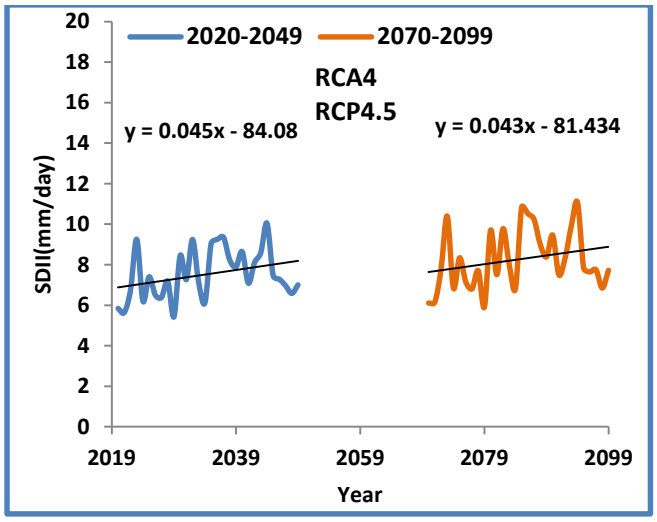


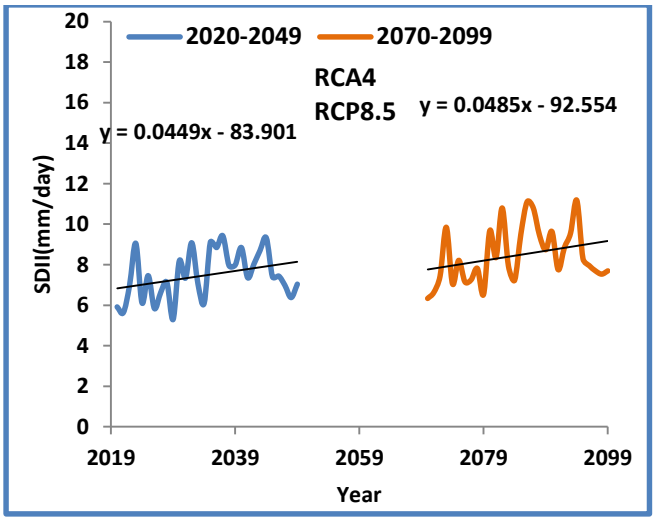


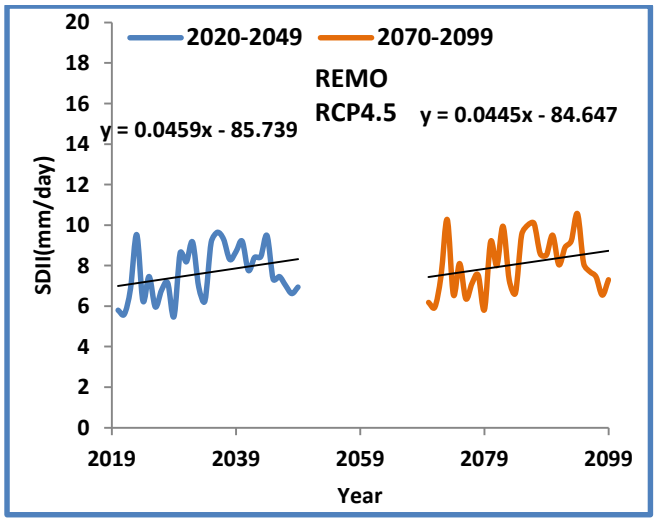
10- Simple Daily Intensity Index (SDII):

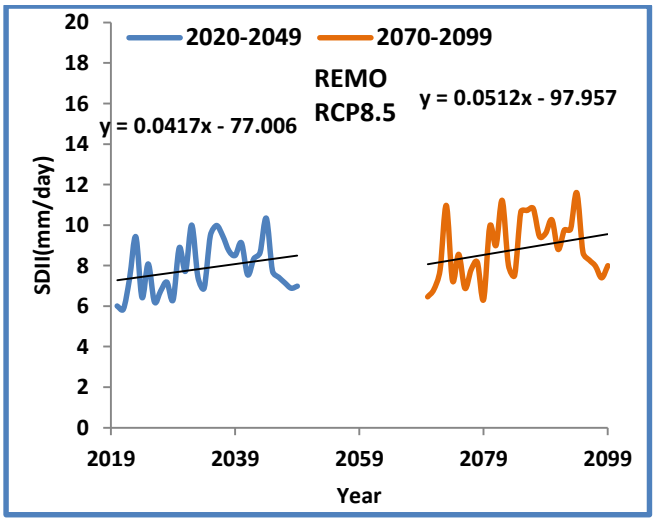




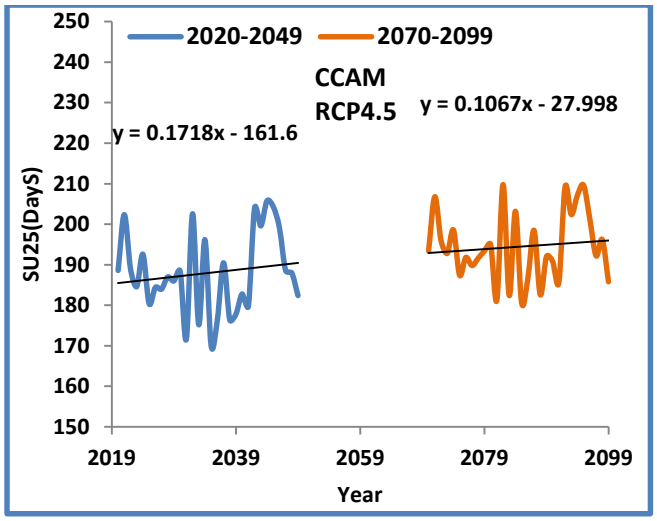


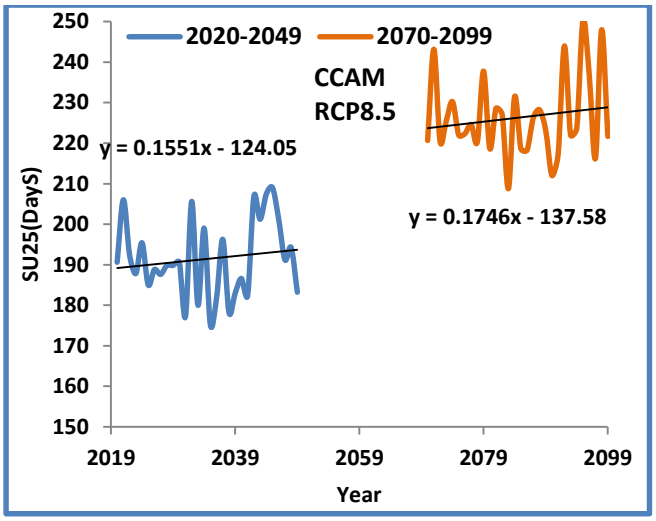


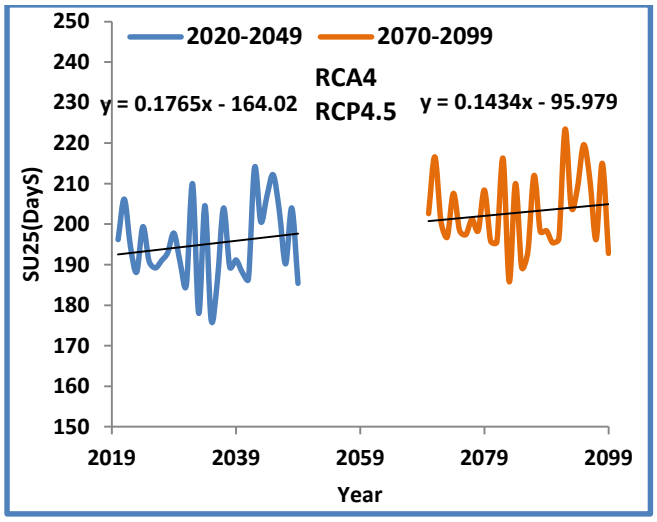


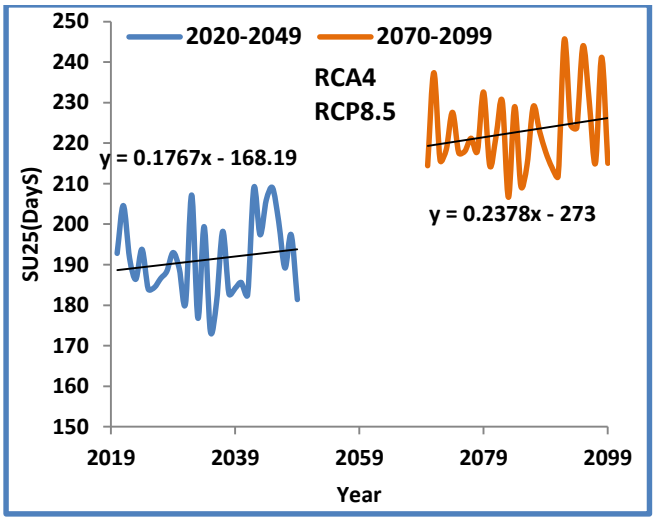


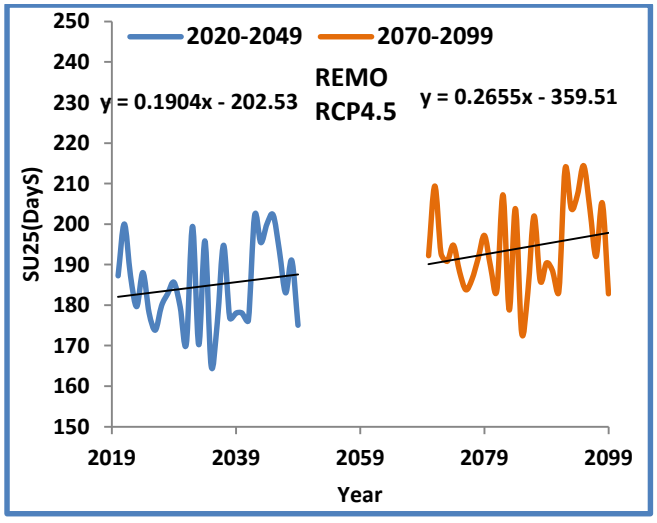
11- Summer Days (SU25):

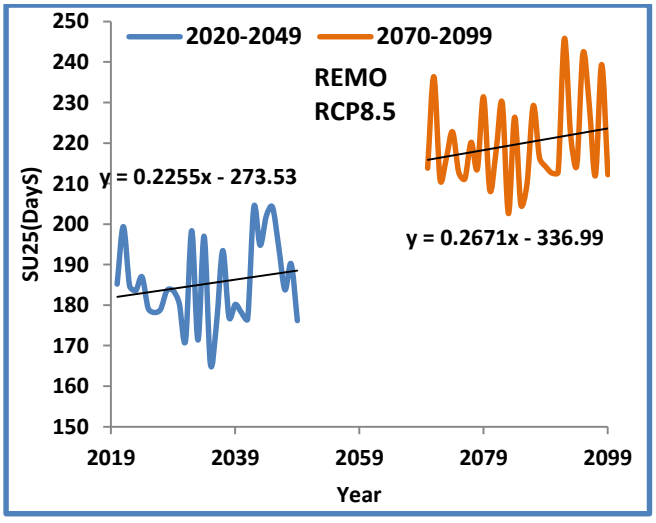




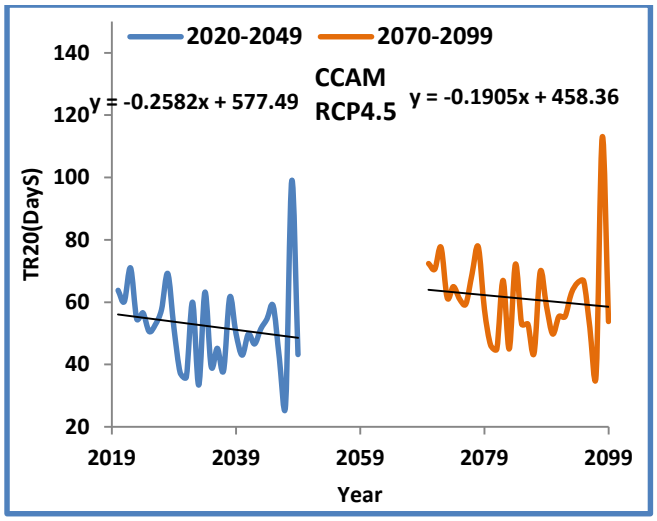


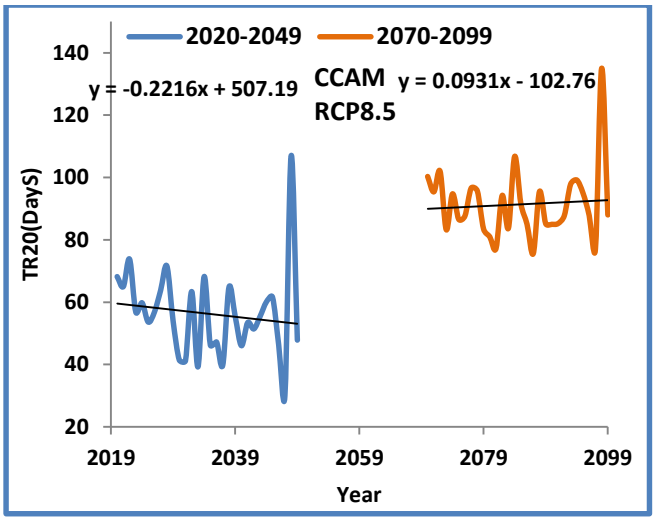


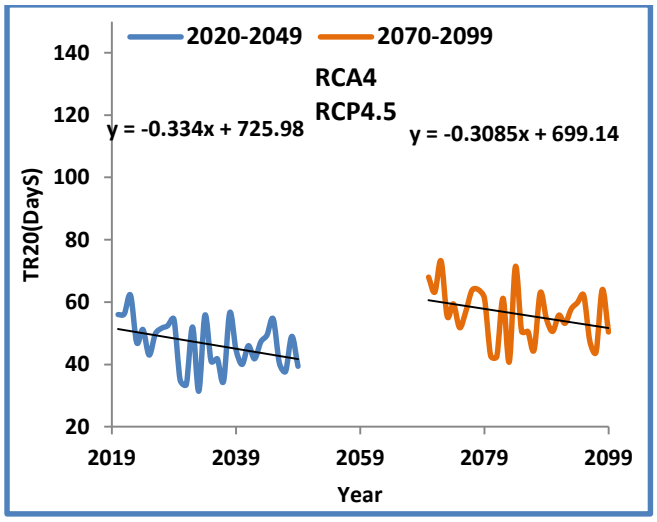


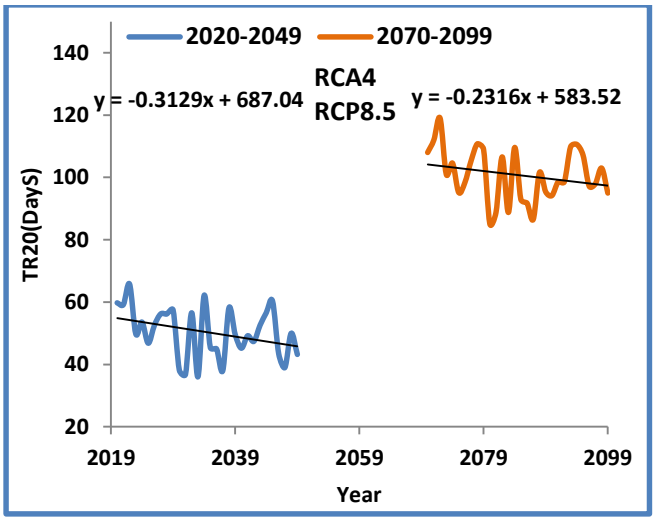


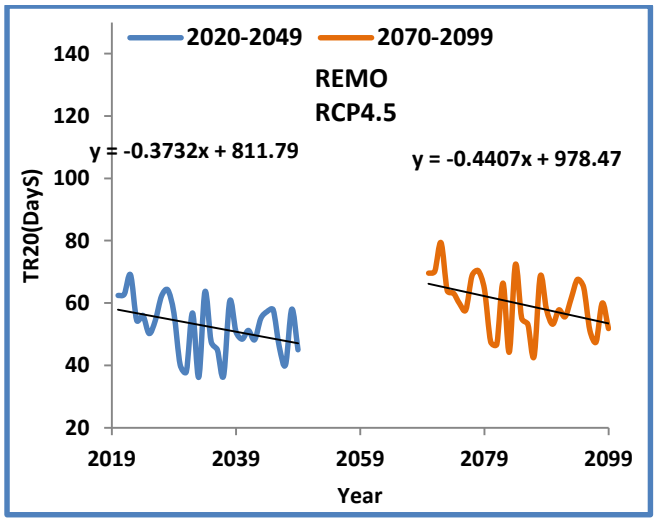
12- Tropical Nights (TR20):

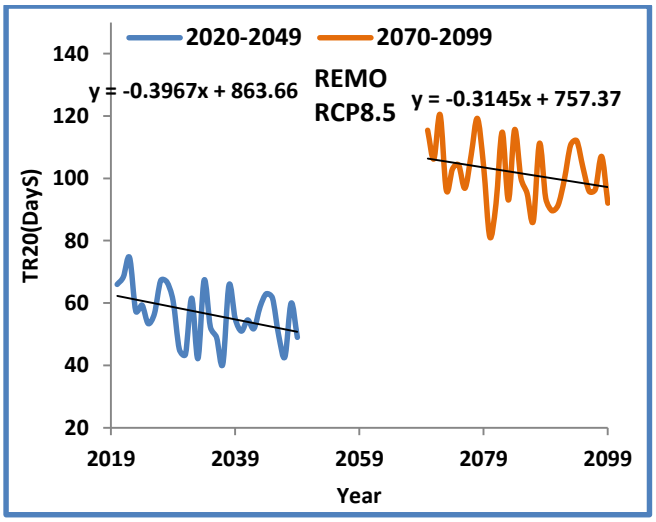




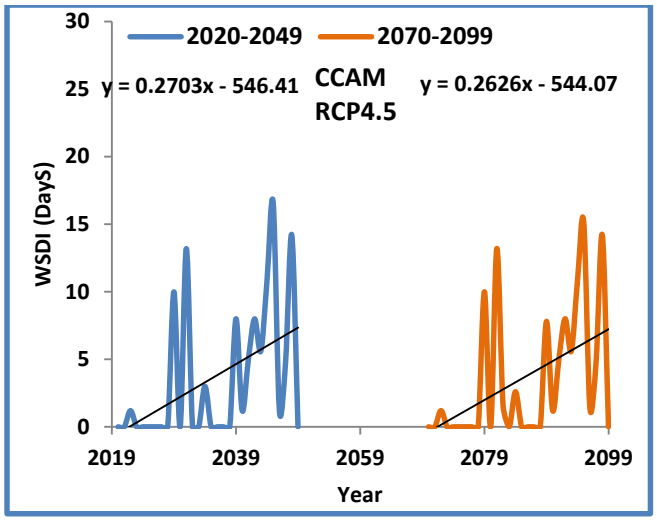


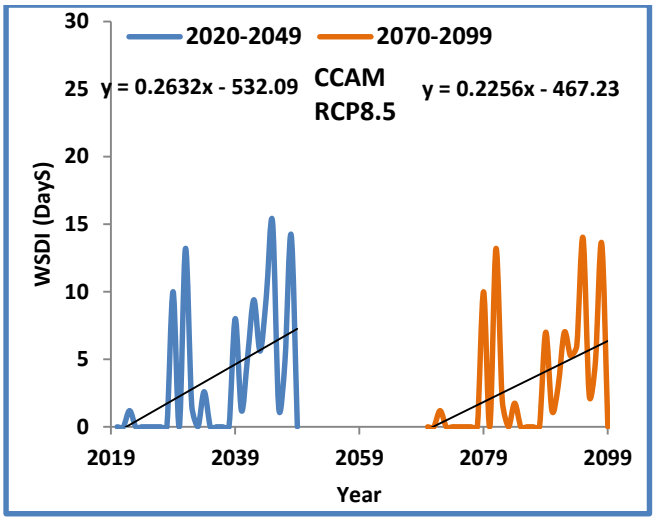


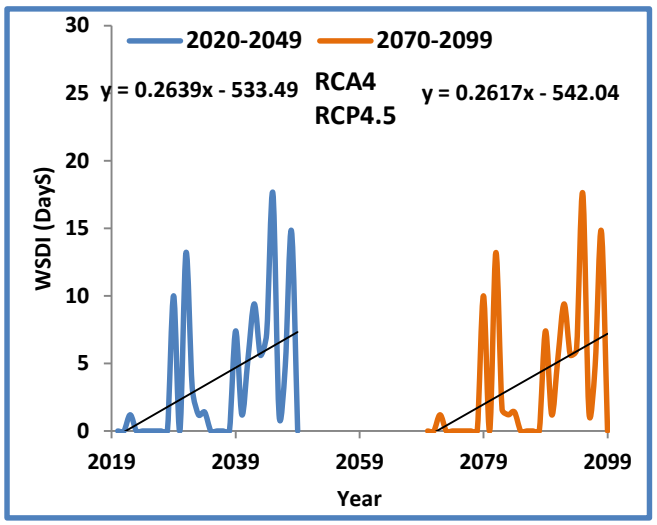


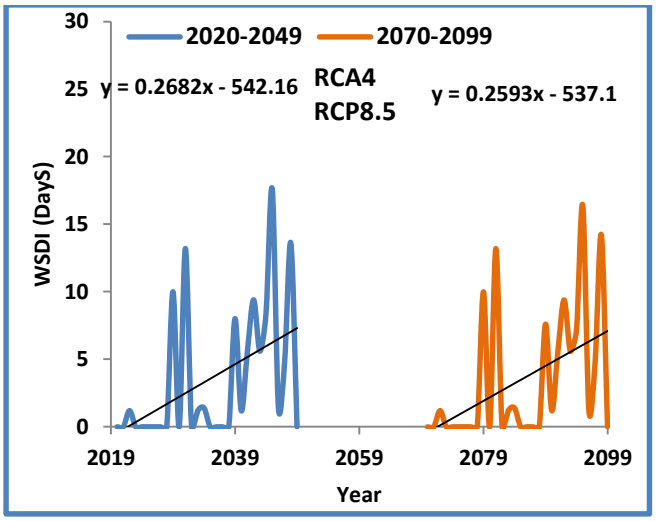


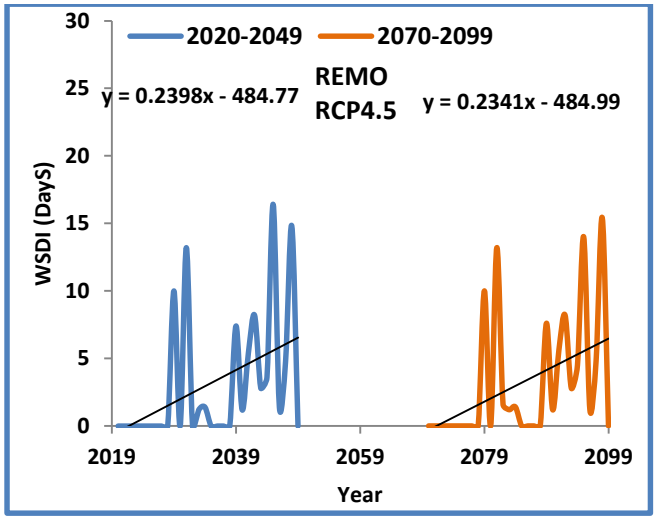
13- Warm Spell Duration Indicator (WSDI) :

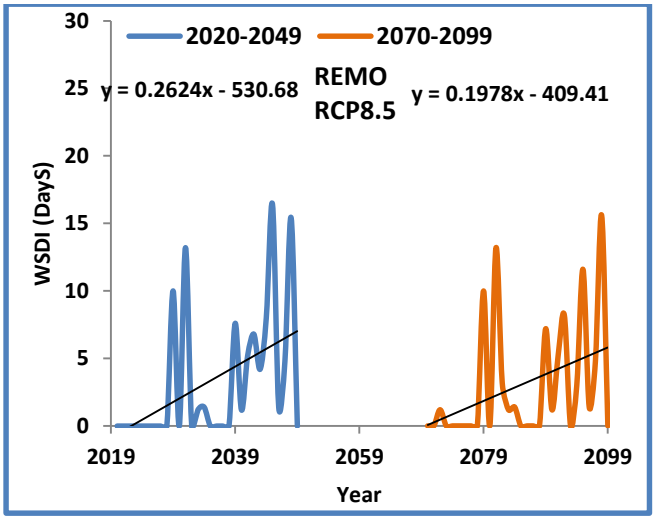




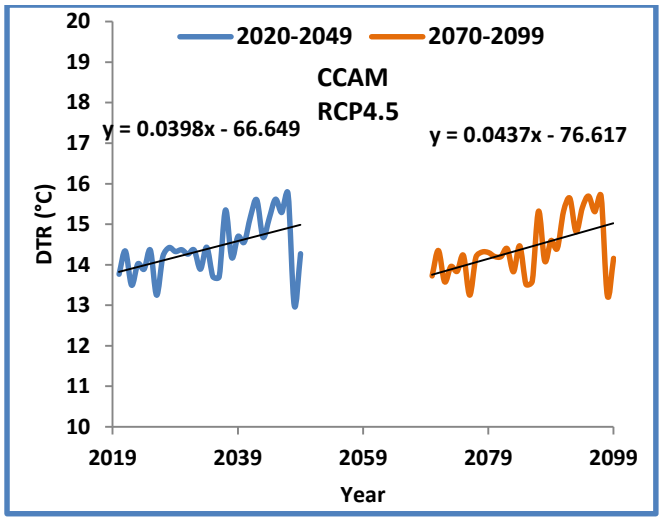


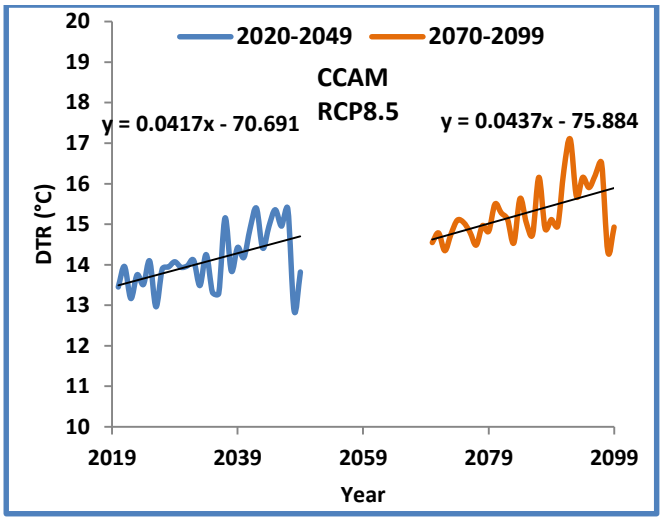


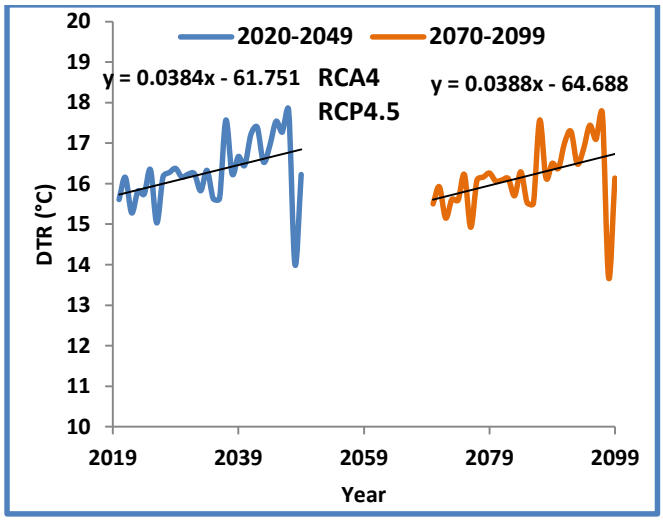


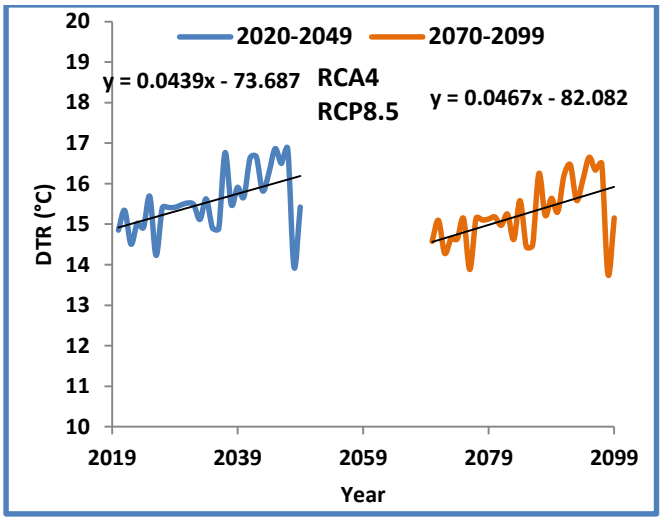


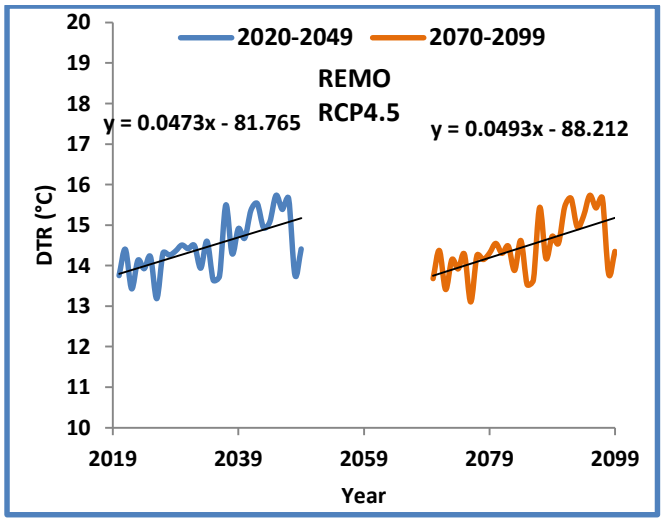
14- Diurnal temperature range (DTR):

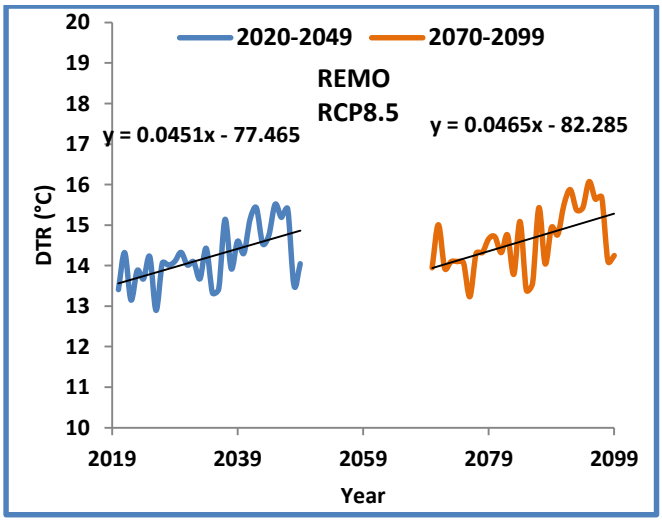




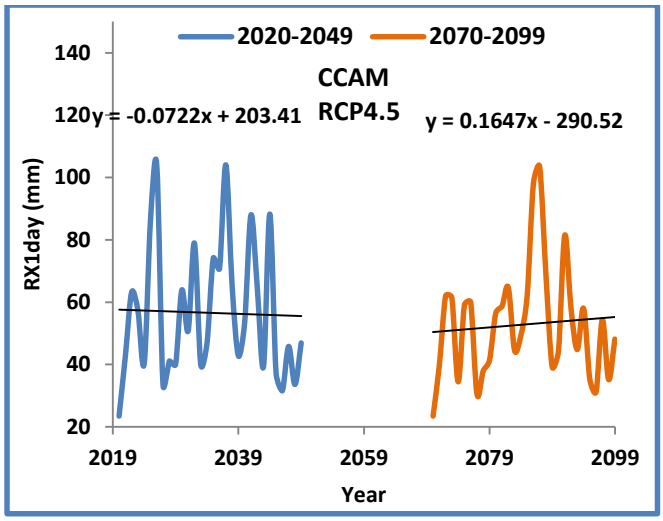


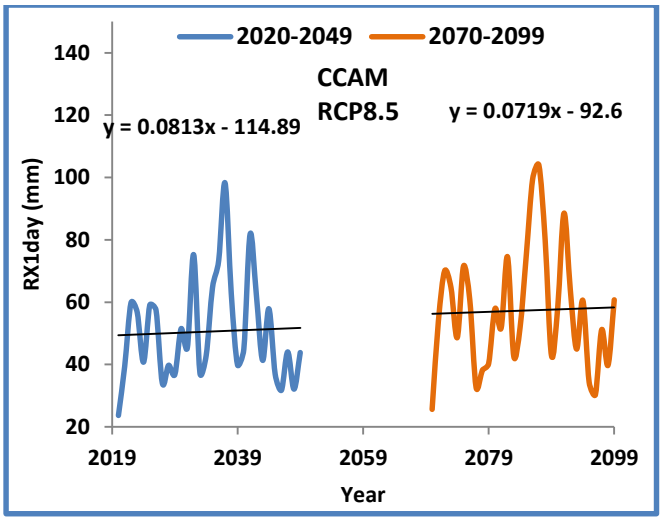


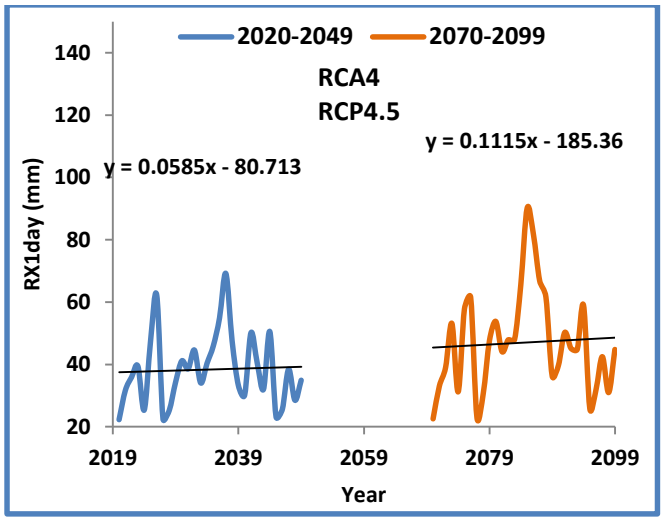


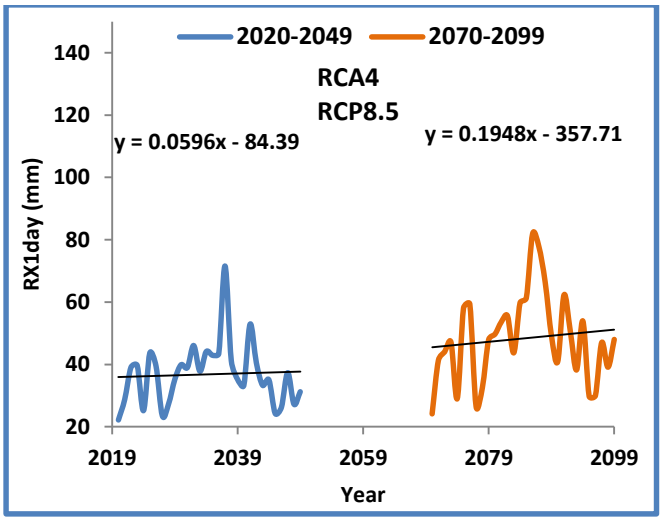


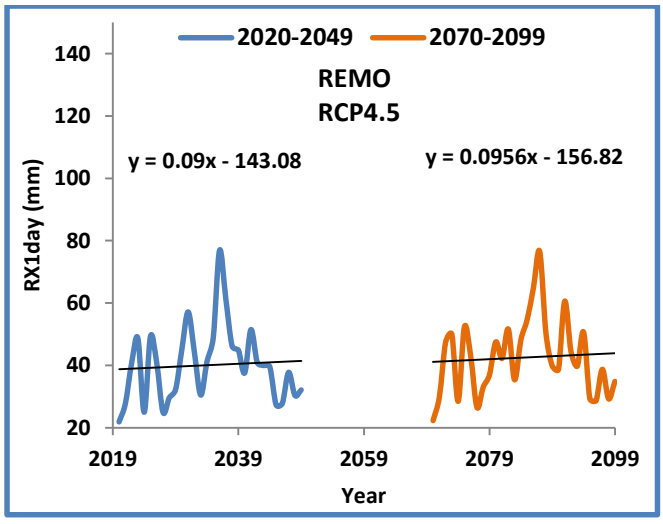
15- Maximum 1-Day Precipitation Amount (RX1day):

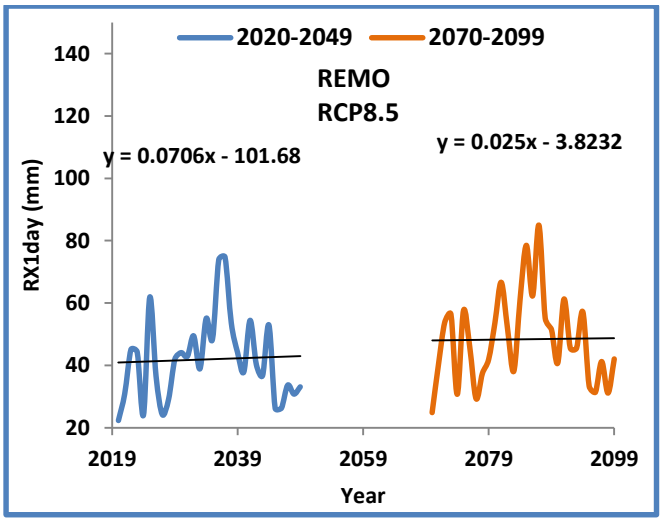




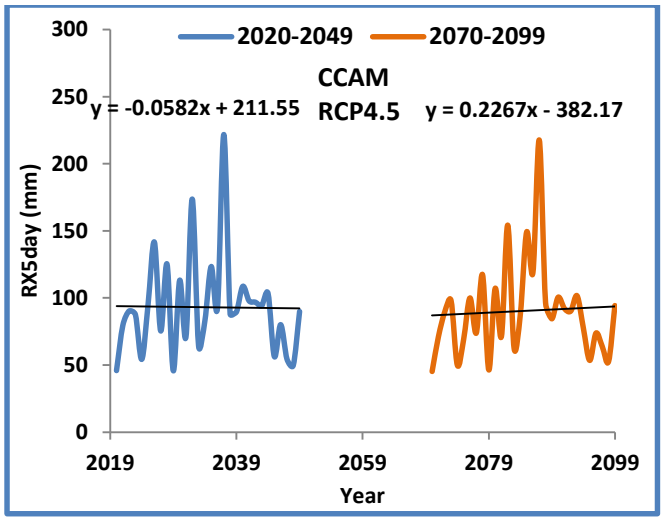


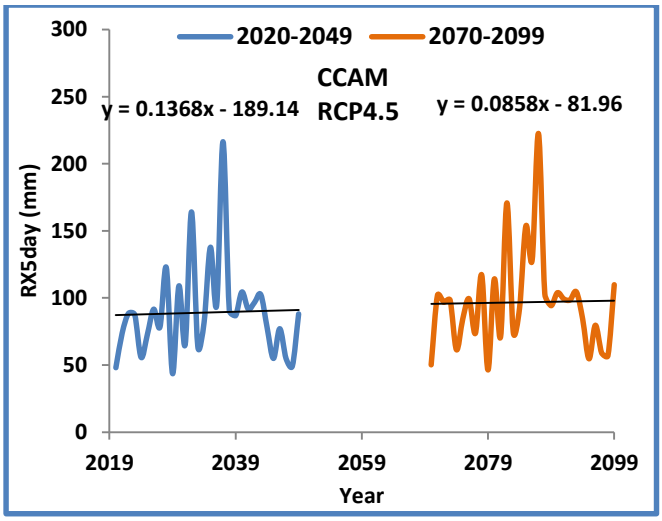


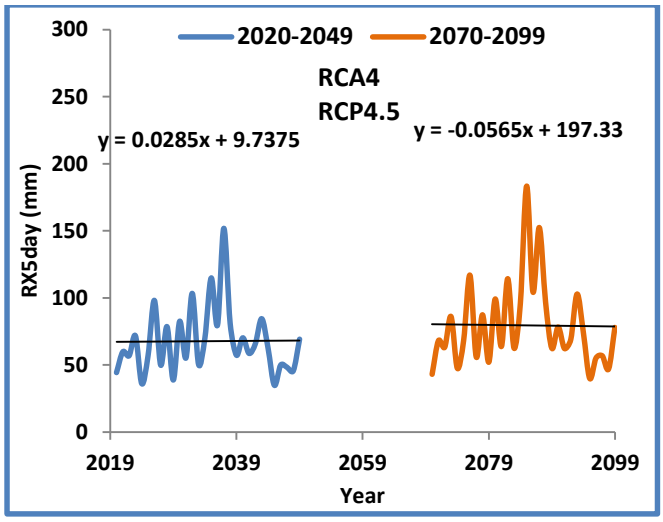


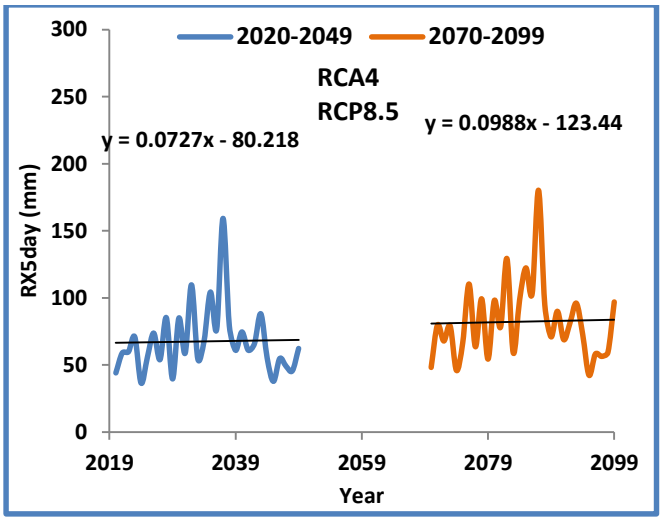


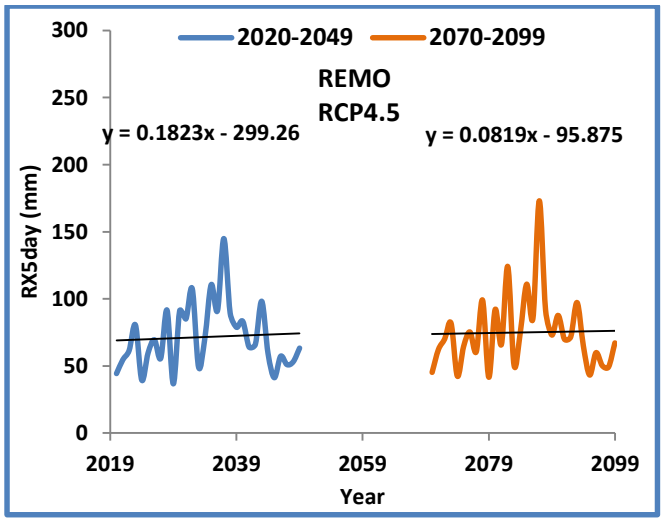
16- Maximum 5-Day Precipitation Amount (RX5day):

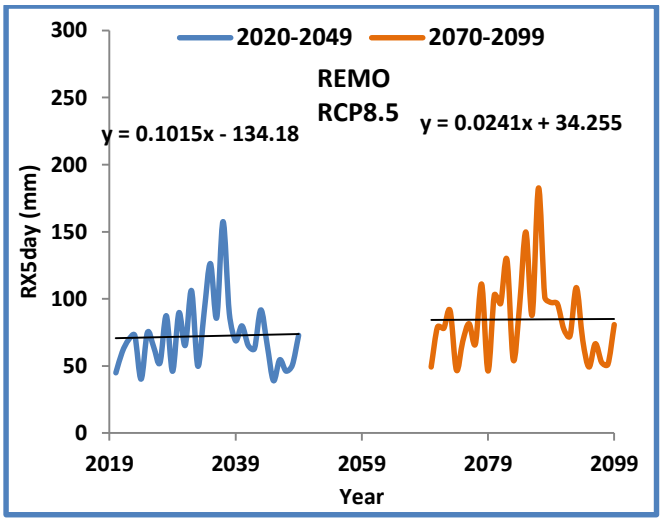




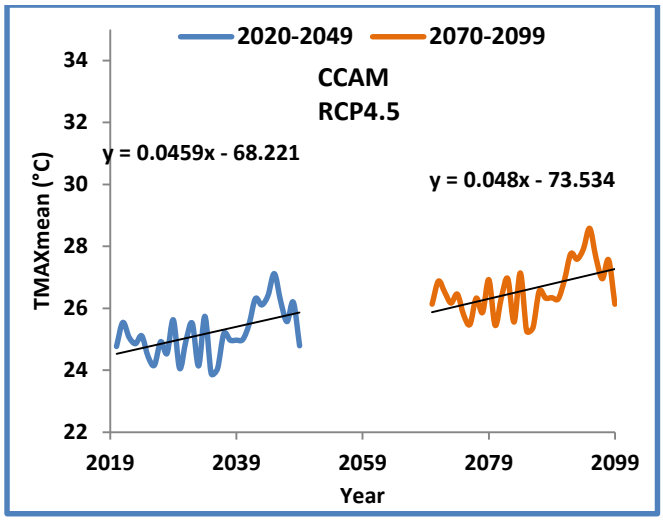


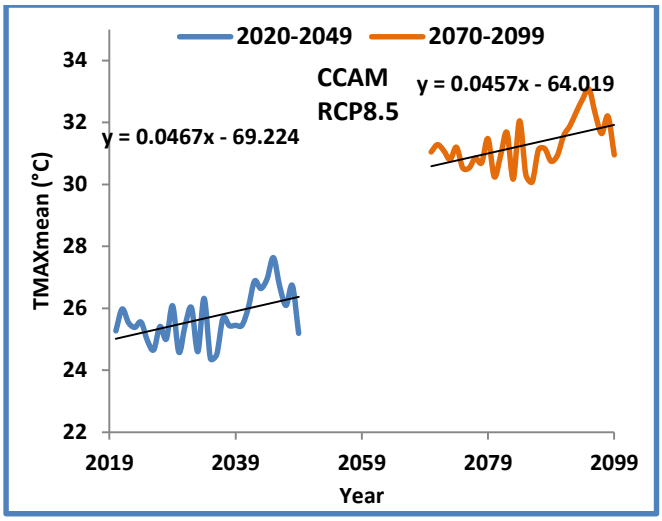


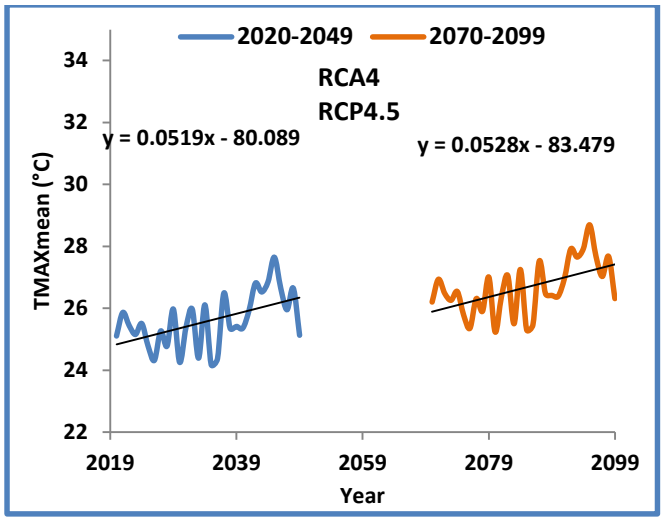


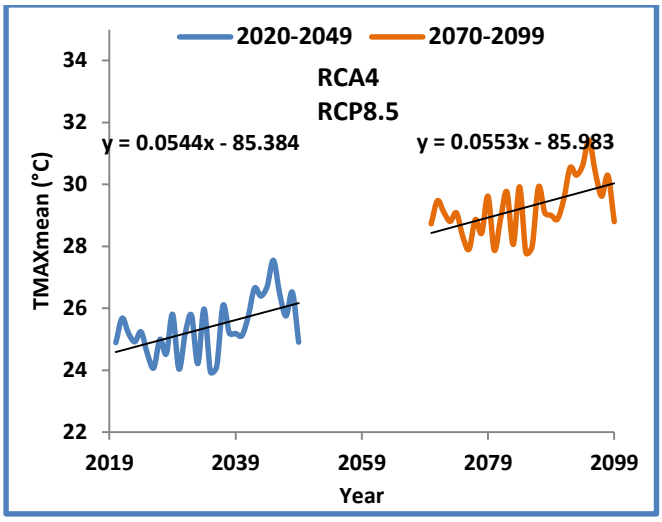


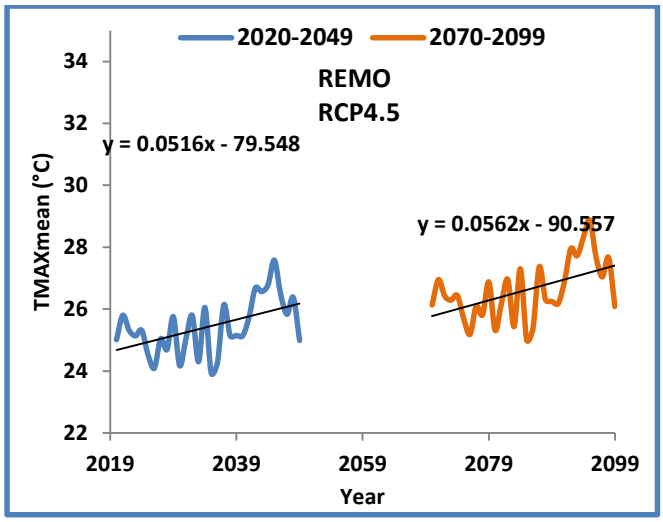
17- Monthly Mean Maximum Temperature (TMAXmean):

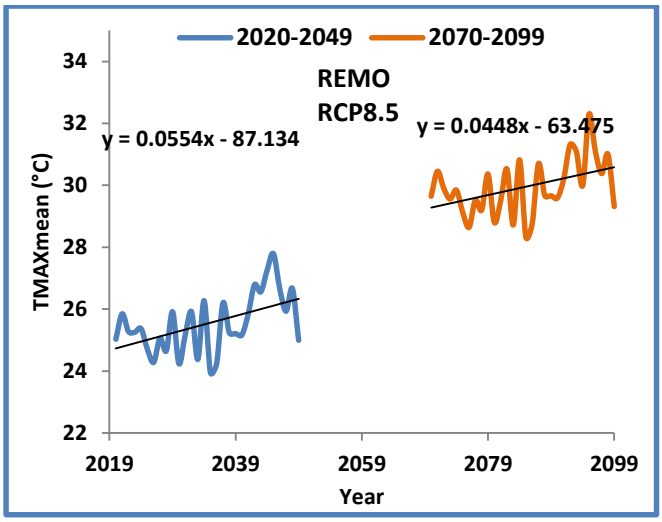




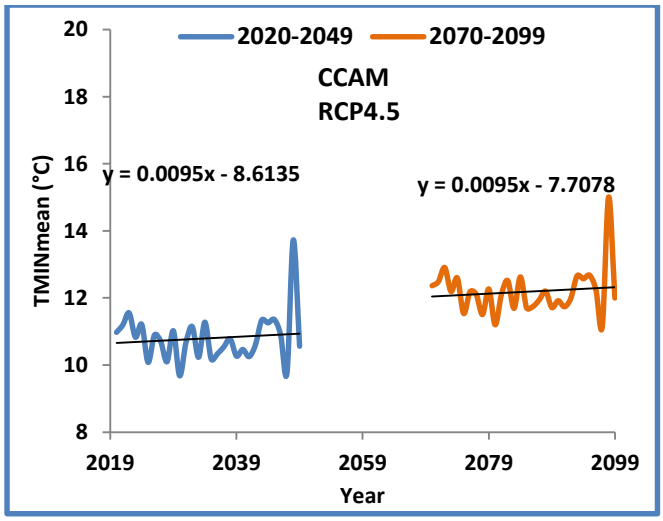


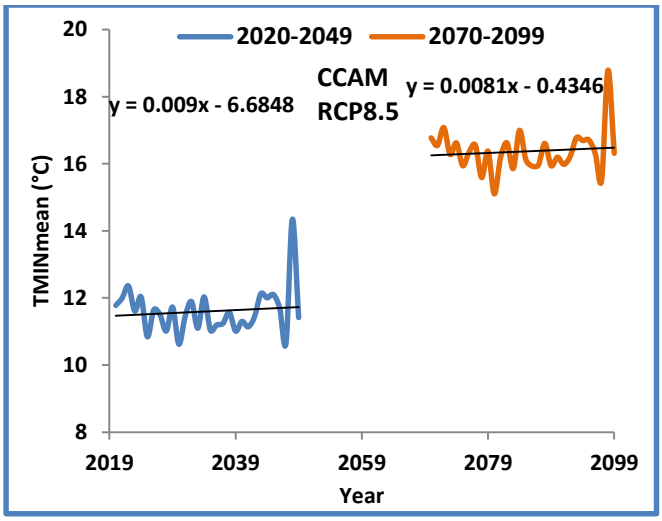


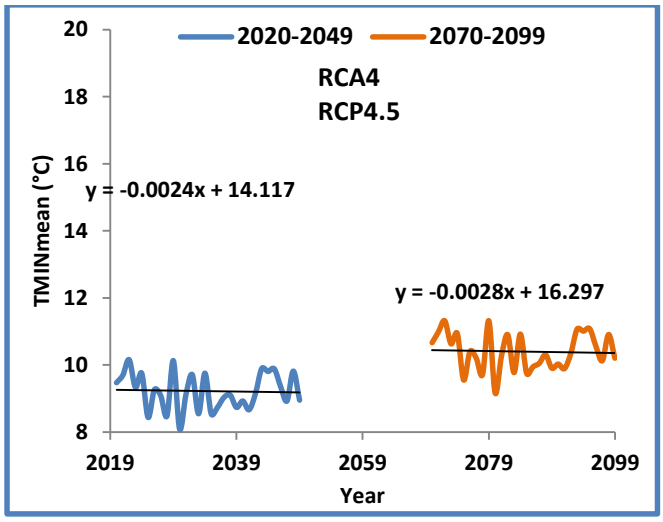


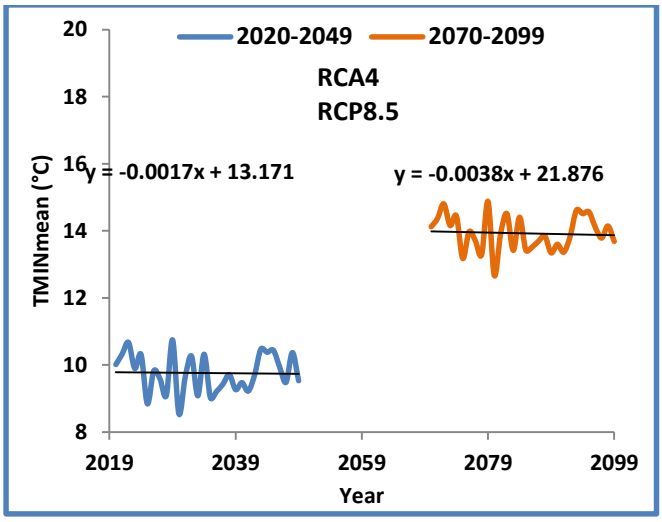


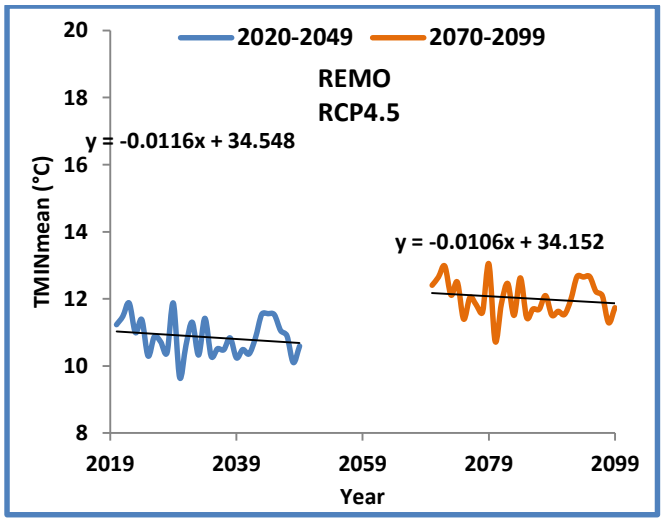
18- Monthly Mean Minimum Temperature (TMINmean):

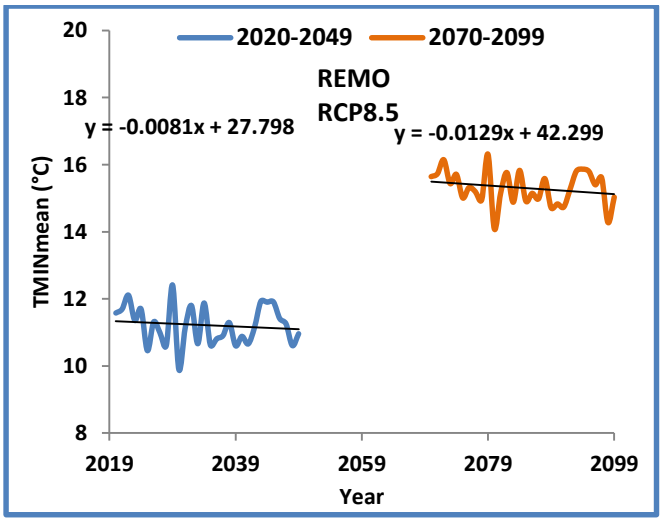




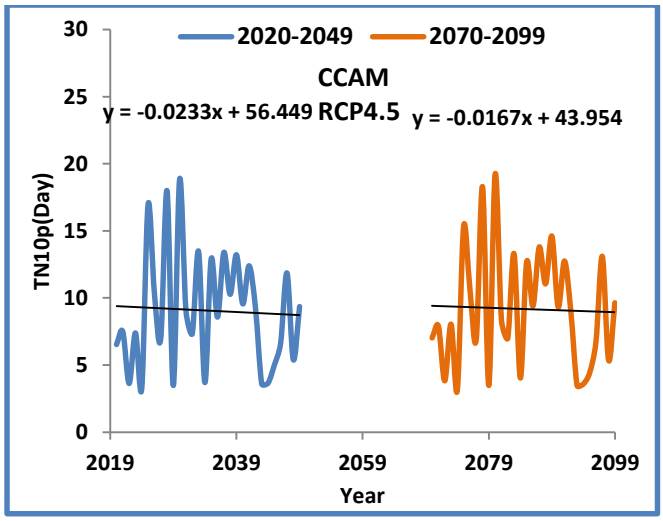


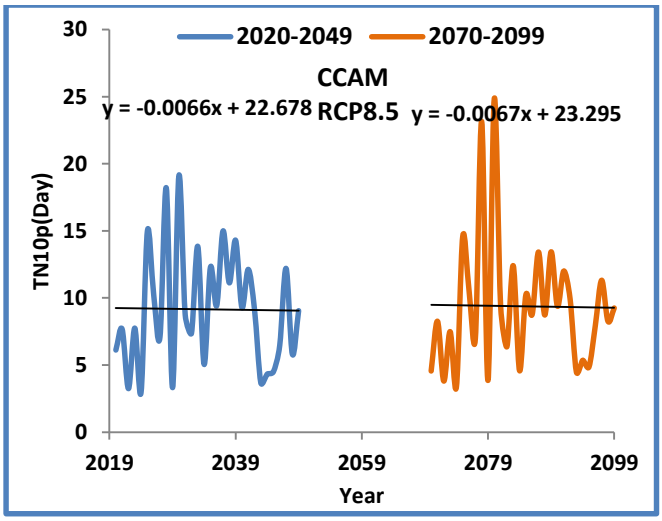


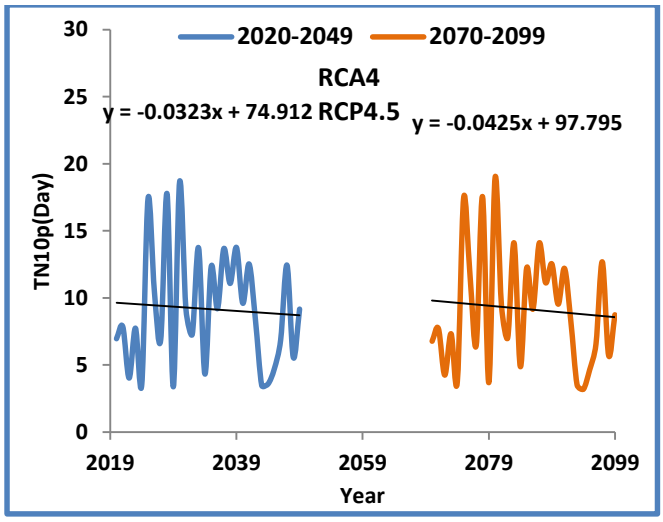


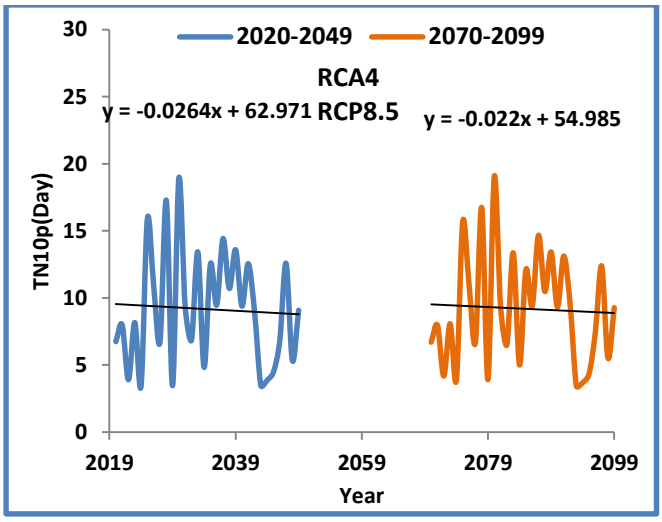


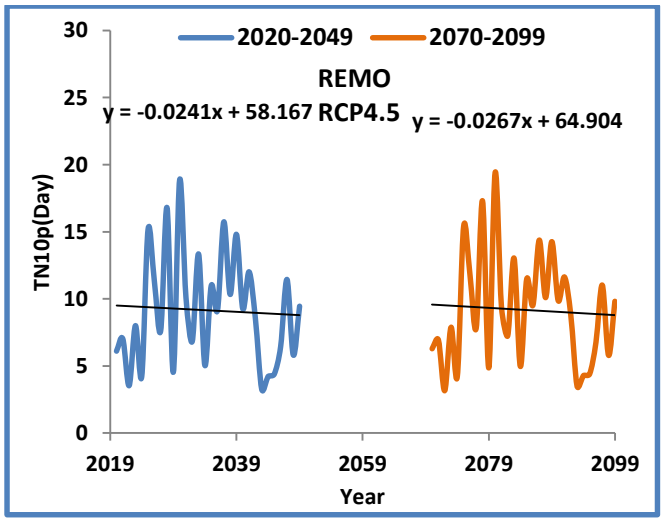
19- Cool Nights (TN10p):

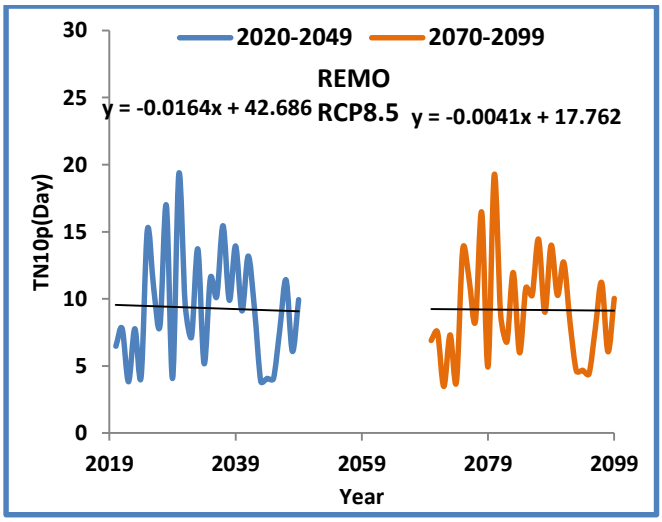




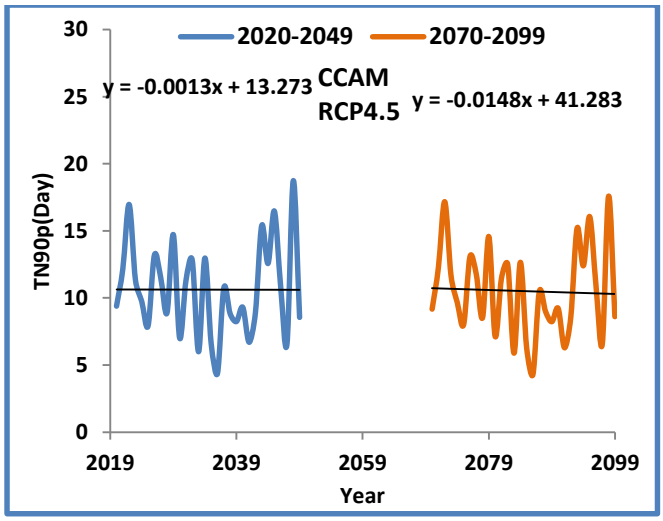


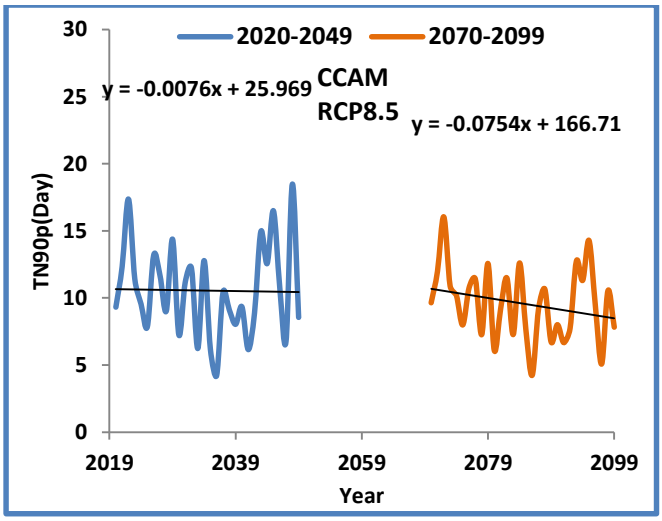


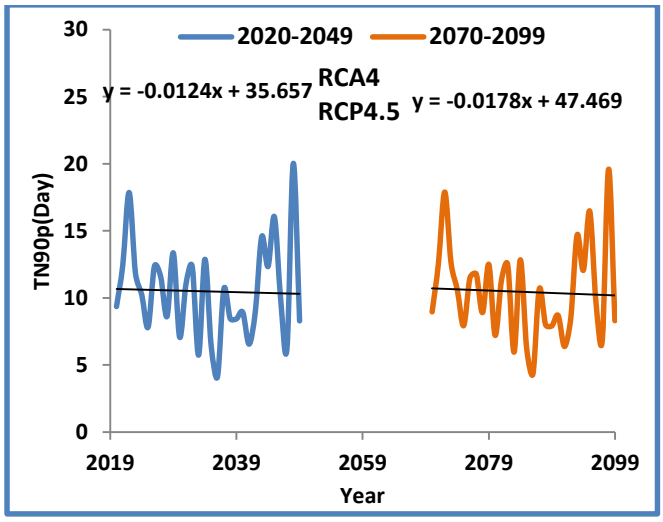


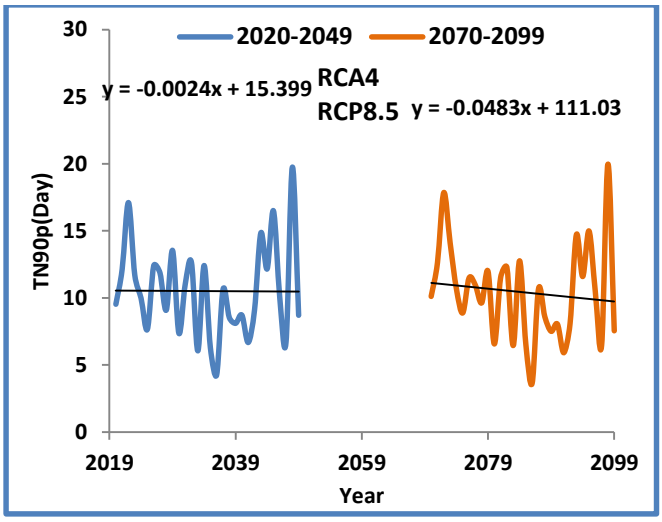


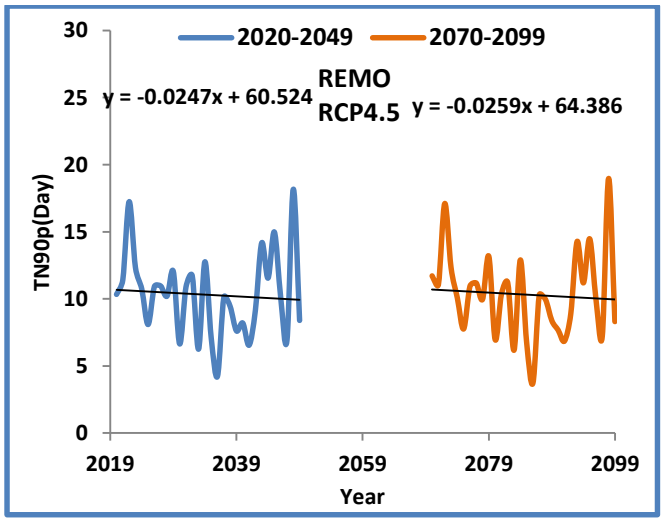
20- Warm Nights (TN90p):

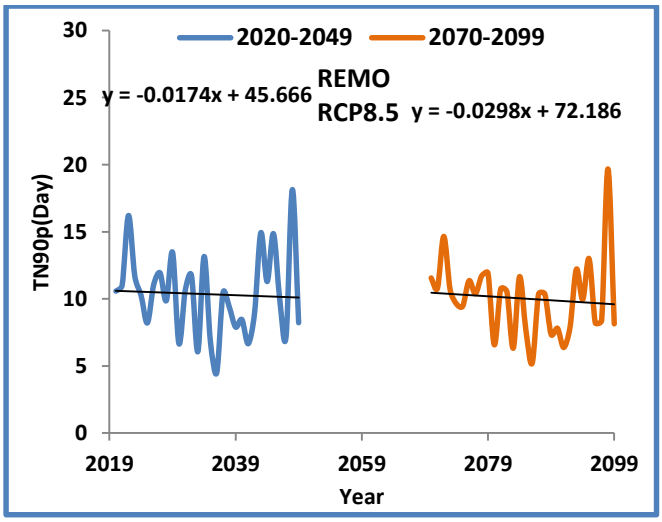




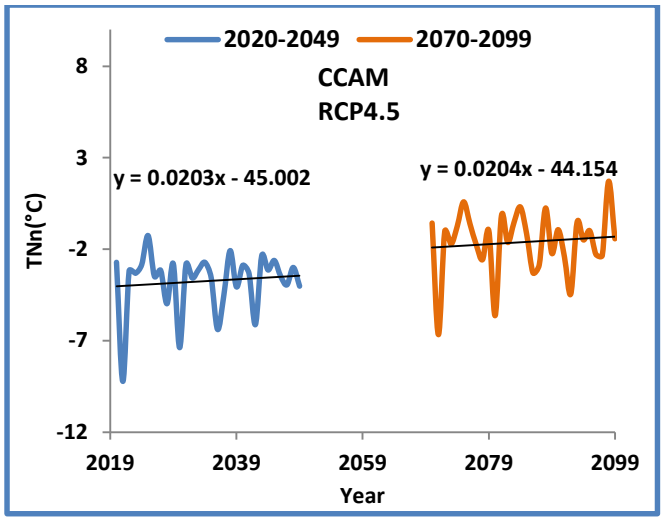


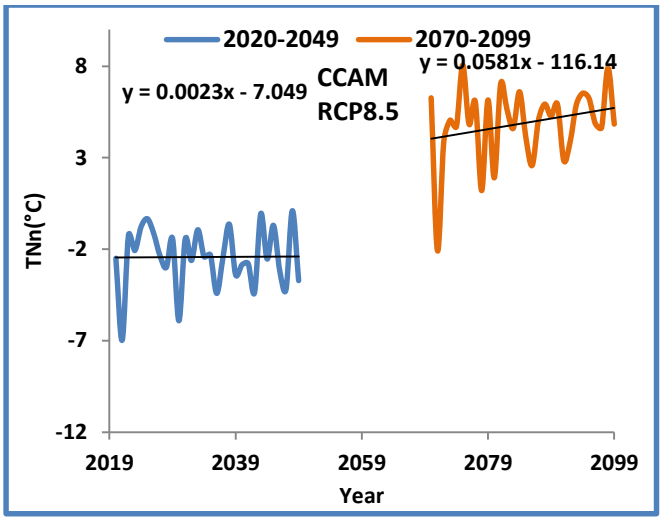


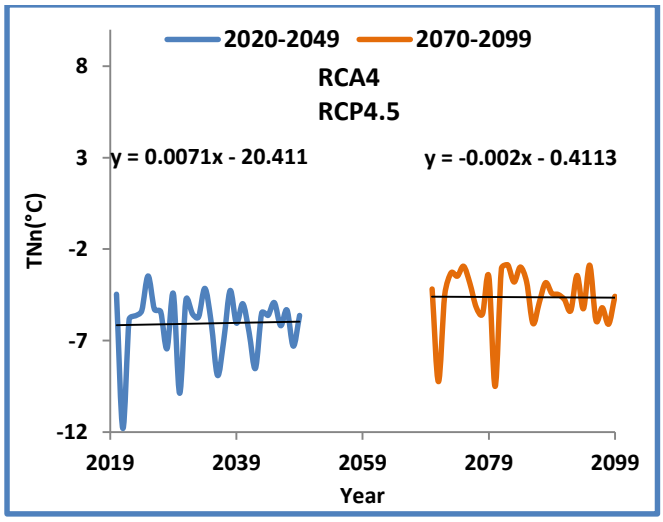


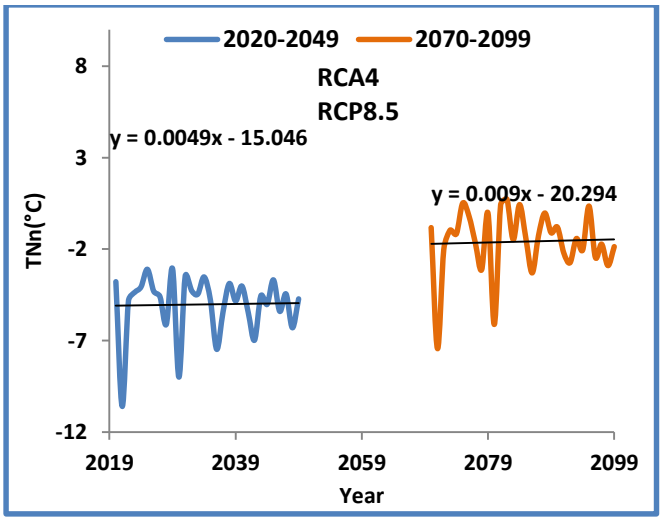


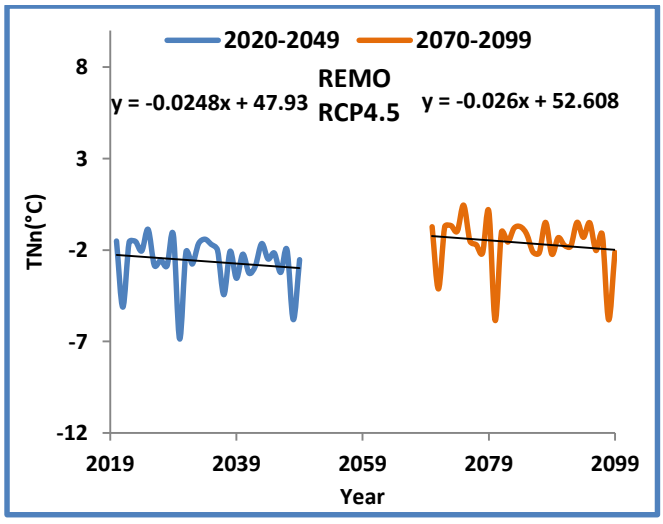
21- Minimum Tmin (TNn):

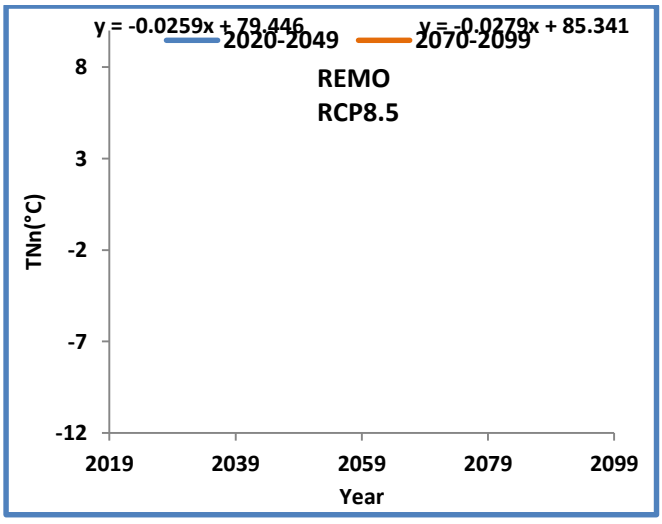




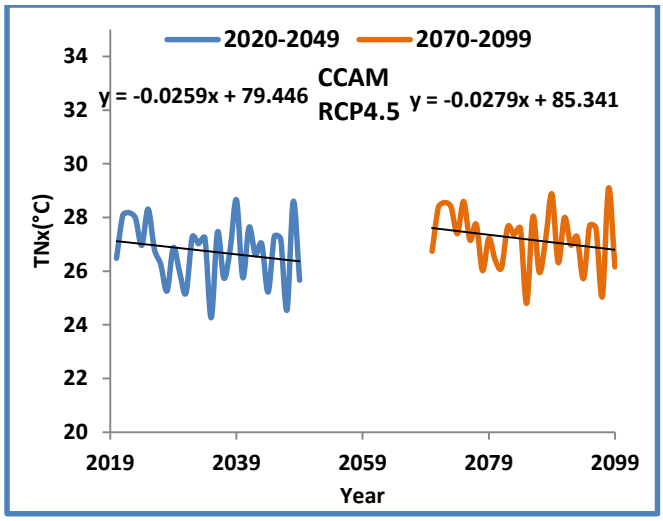


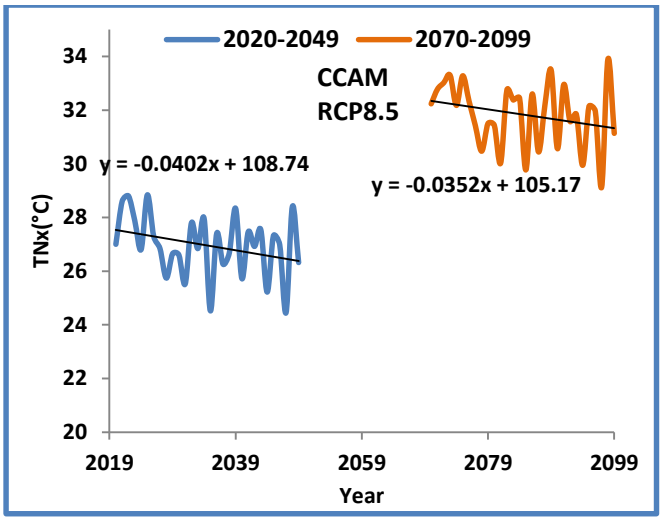


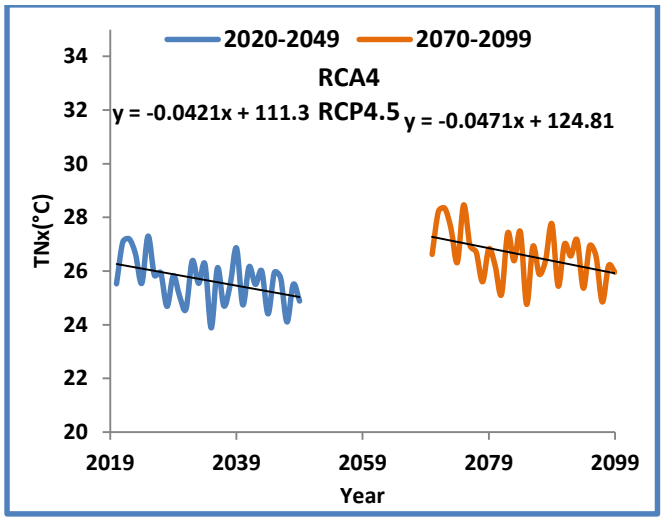


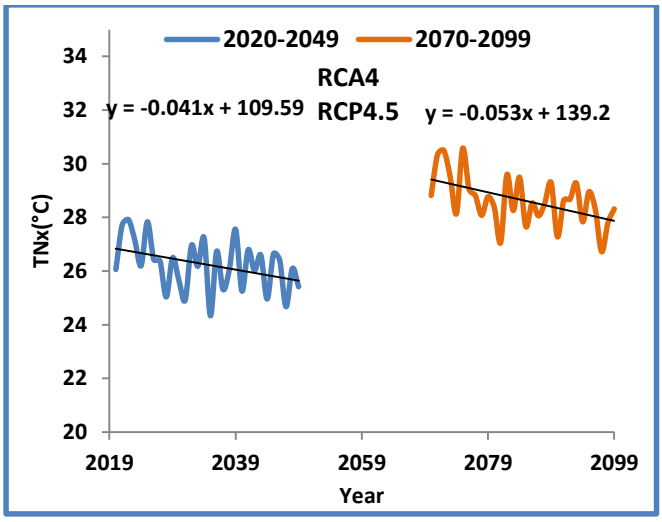


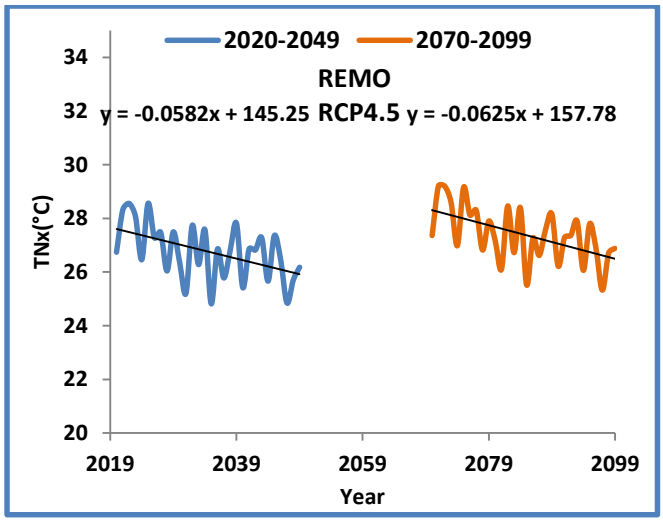
22- Maximum Tmin (TNx):

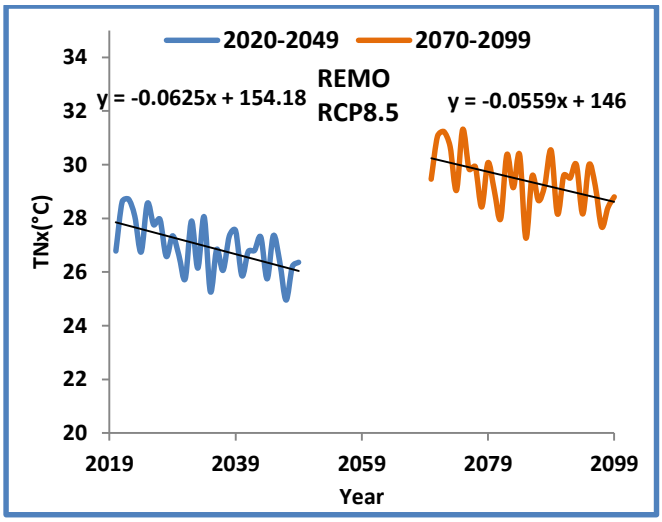




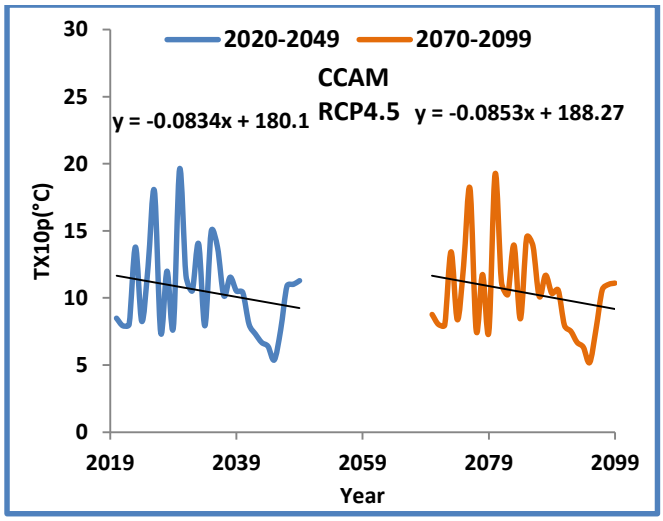


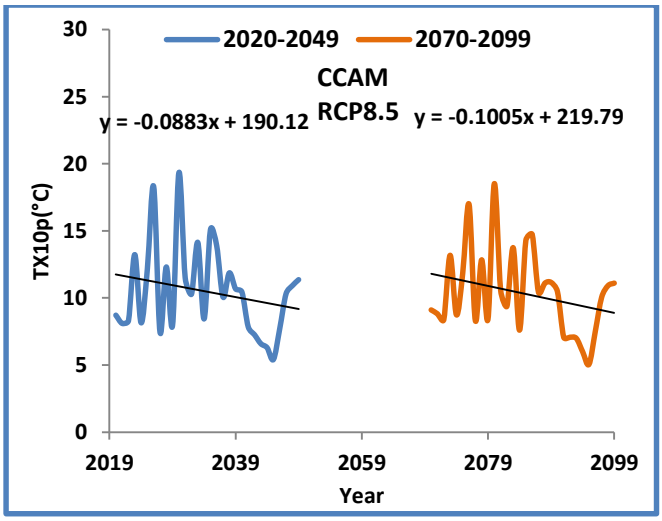


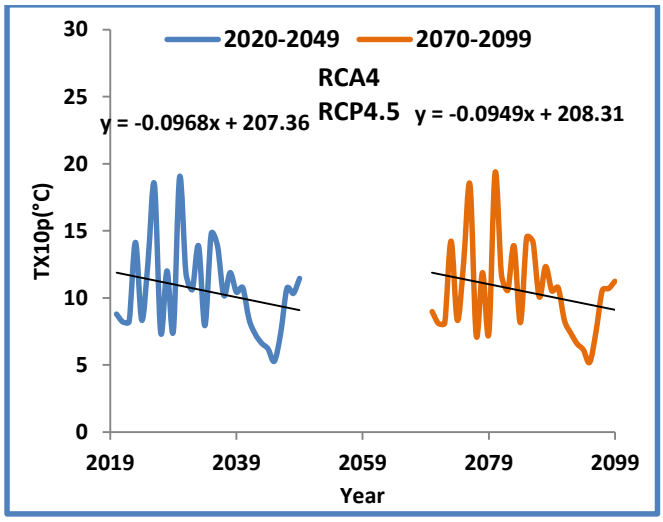


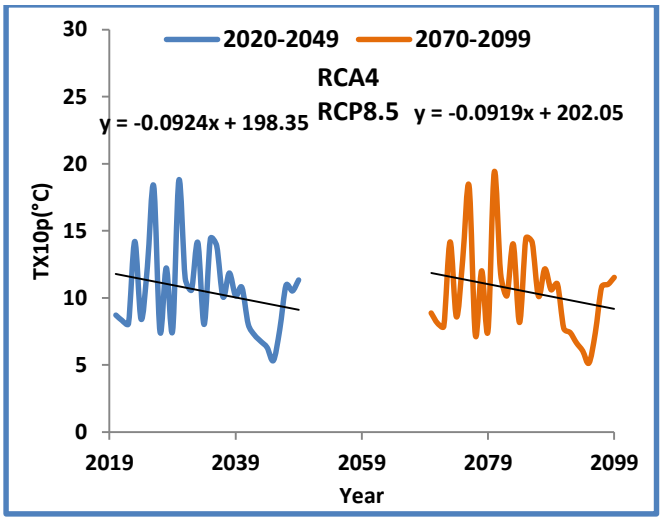


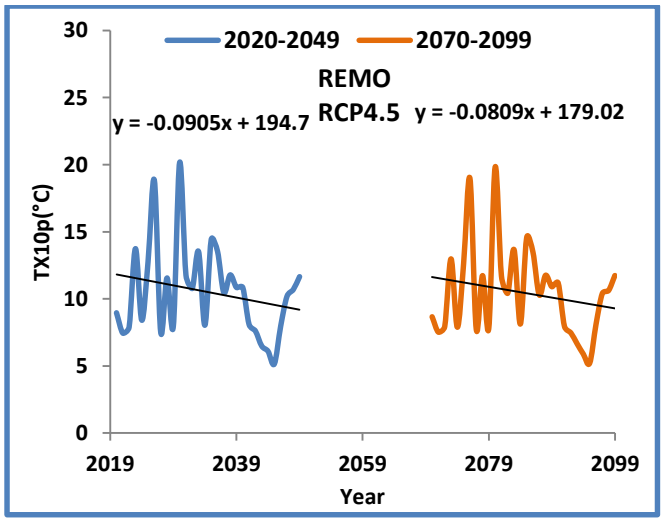
23- Cool Days (TX10P):

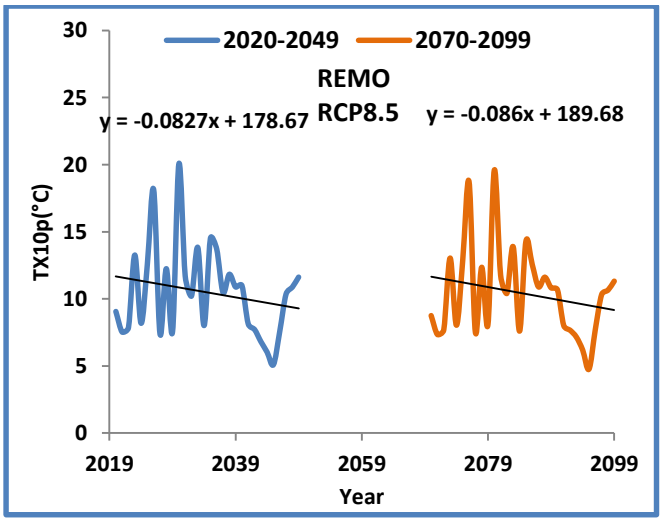




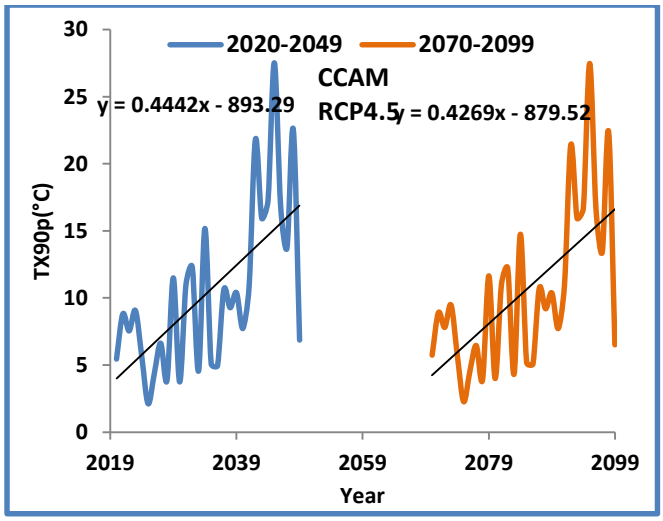


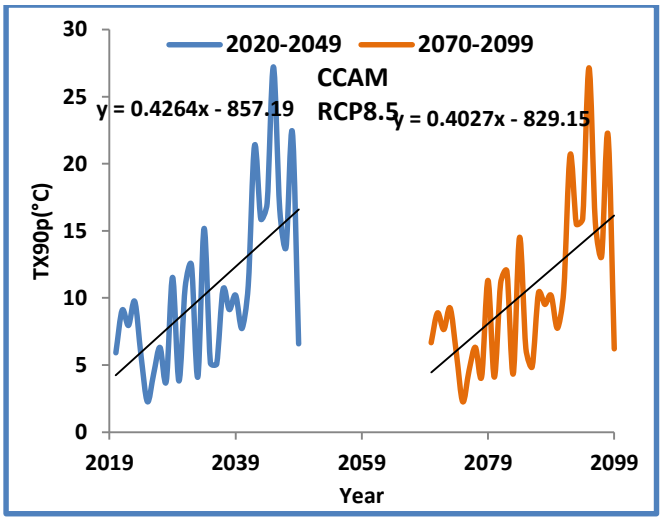


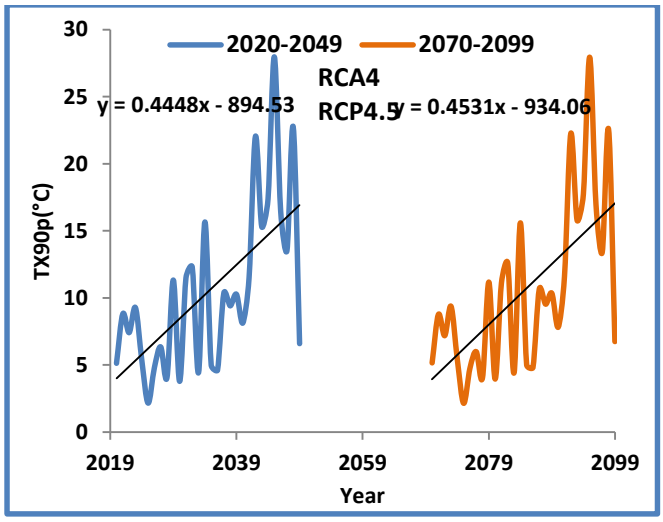


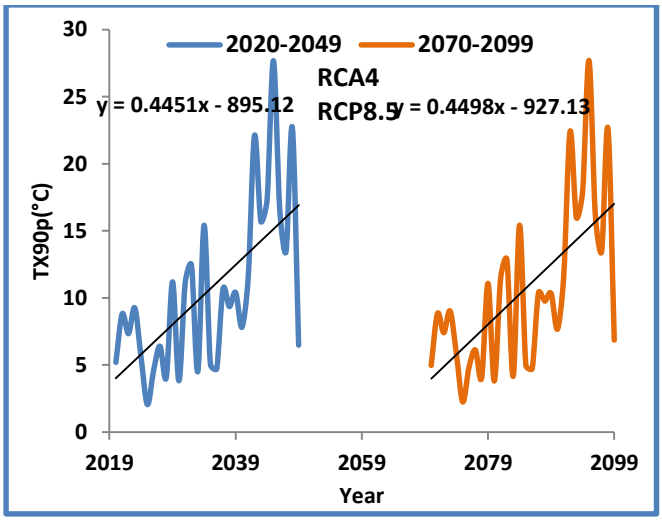


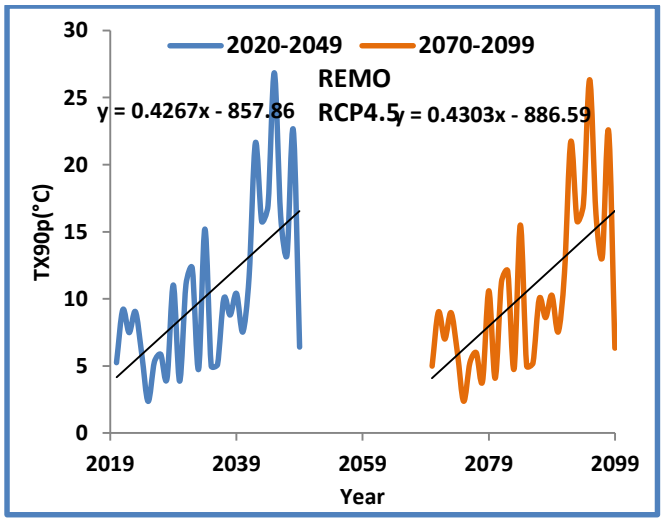
24- Warm Days (TX90p):

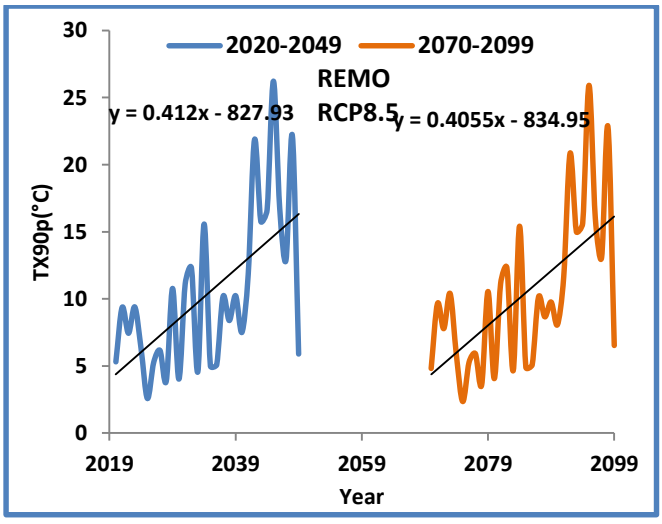




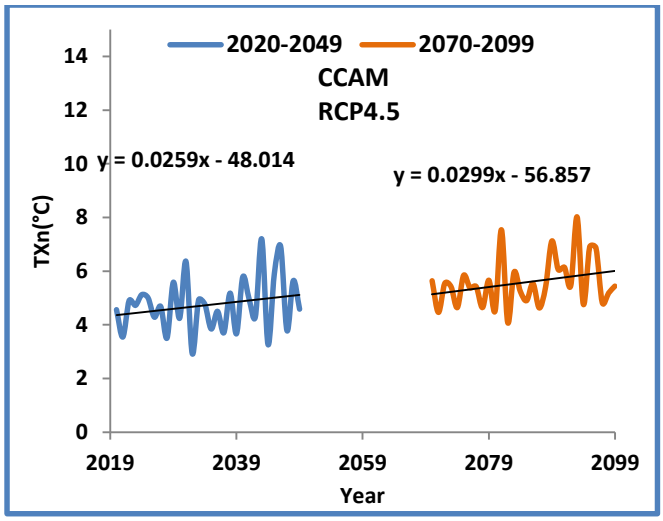


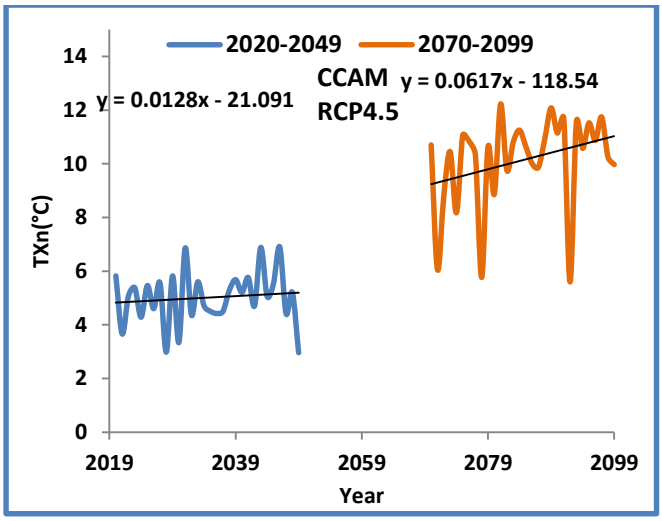


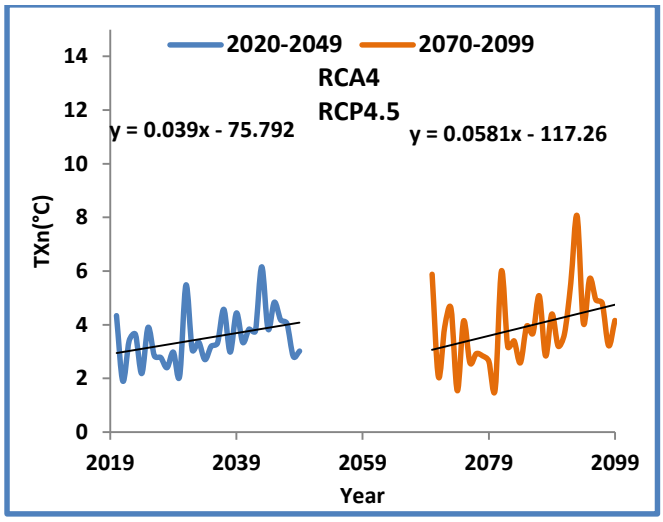


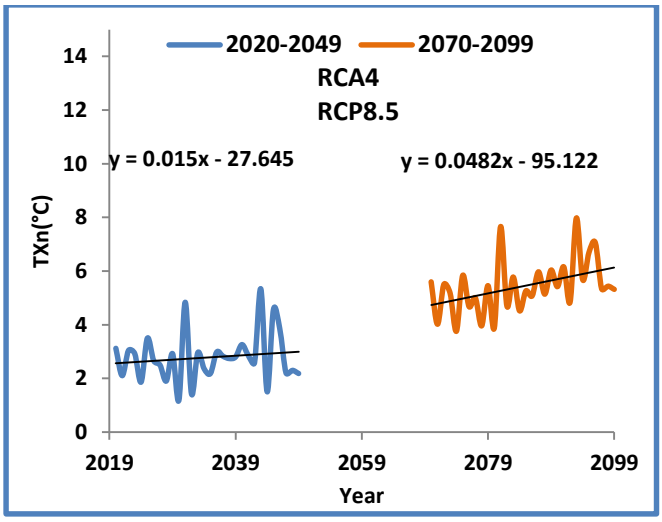


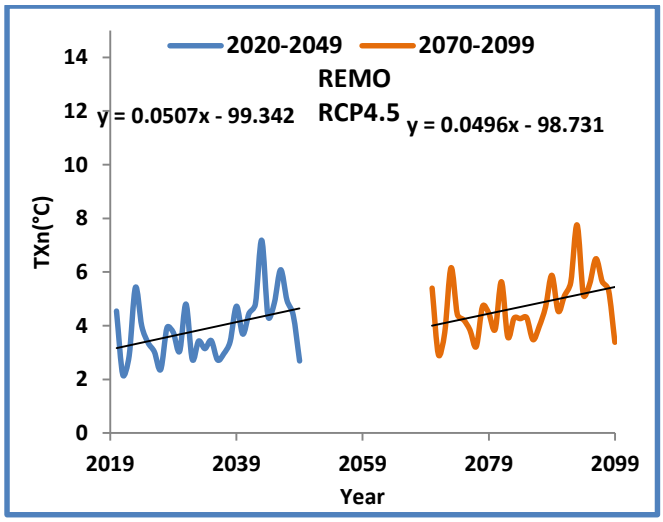
25- Minimum Tmax (TXn):

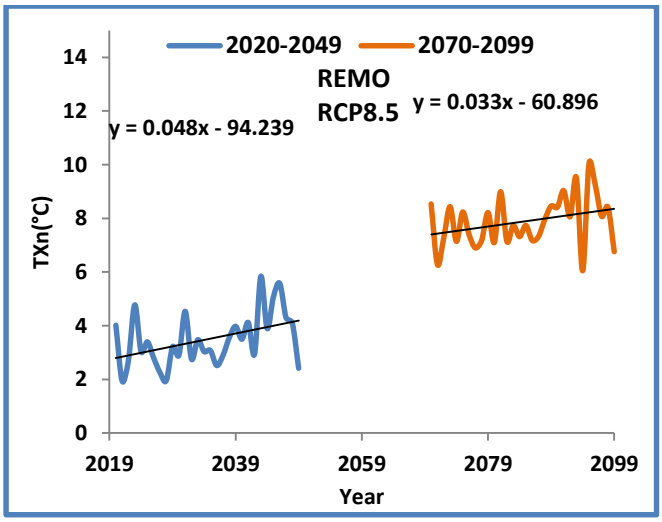




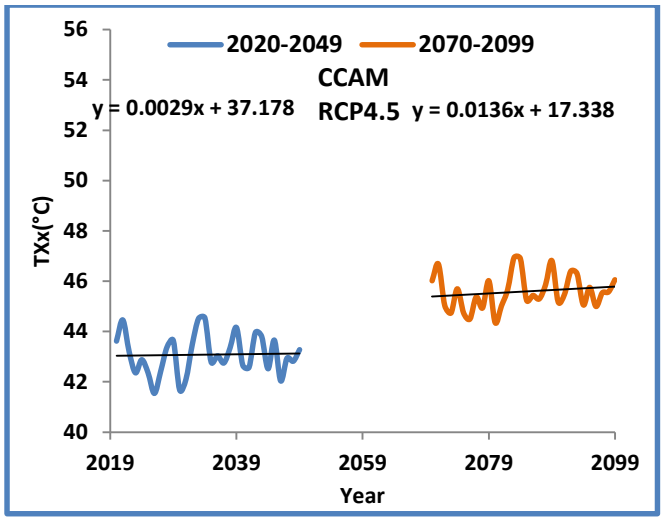


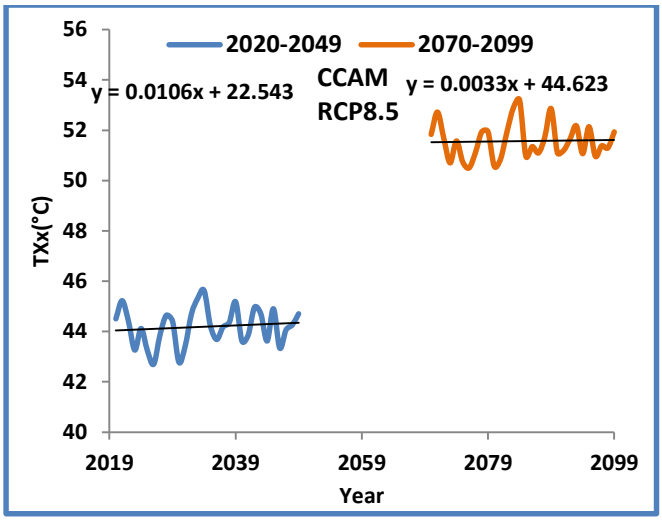


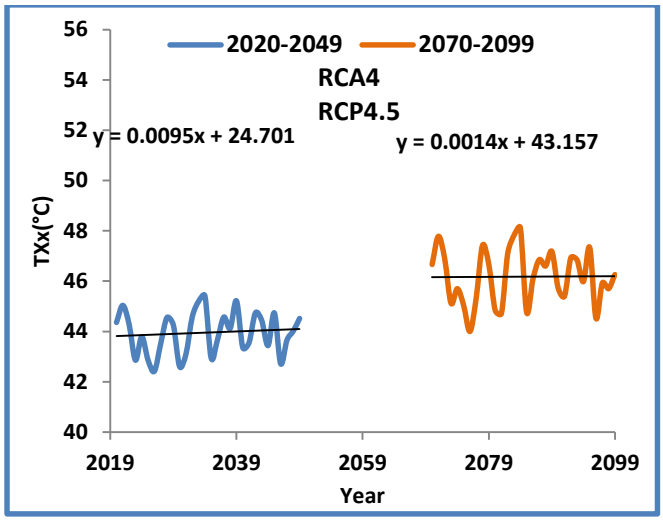


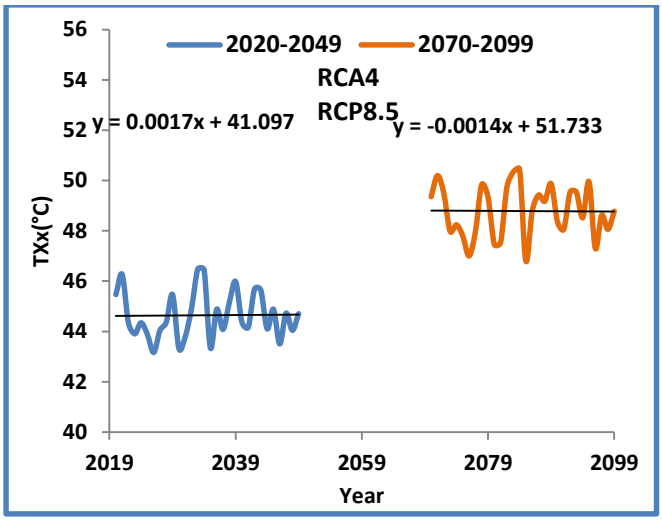


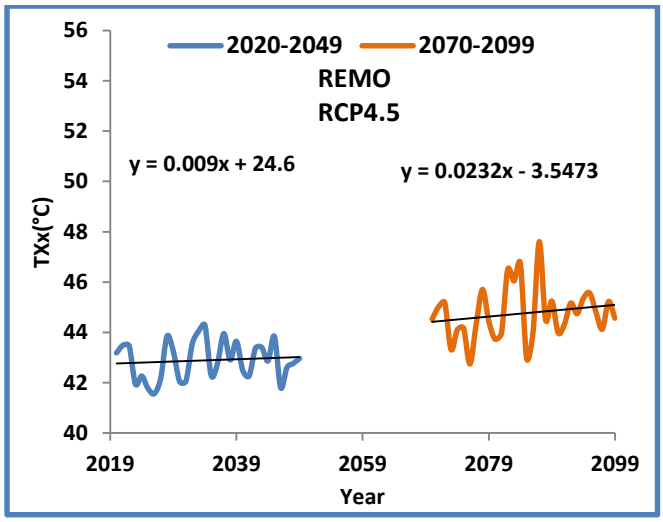
26- Maximum Tmax (TXx):

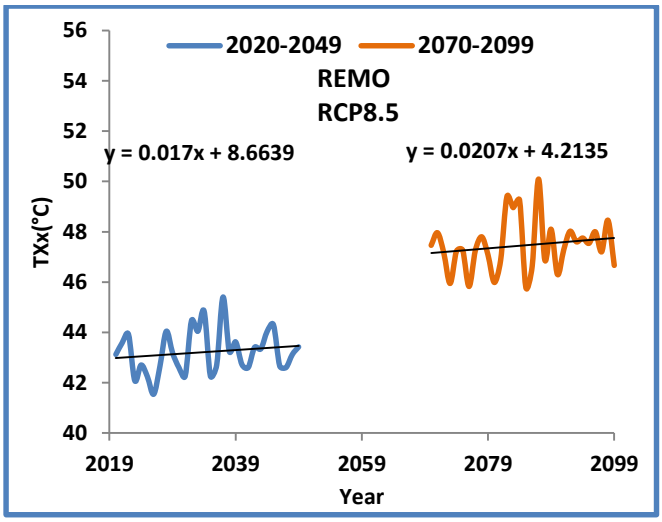












26- Cold Spell Duration Indicator (CSDI):