Regional Precipitation Response to Regional Warming in Past and Future Climate

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Abstract

Regional precipitation feedback resulting through regional mean temperature escalation on seasonal basis has been investigated in the present study. Recently published reanalysis dataset AgMERRA has been used to cater for observational dataset requirements for analysis. Historical (1980-1998), present and near future (2007-2025), and far future (2080-2098) climate datasets of a super high resolution GCM viz. GCM20 (20Km horizontal resolution, A1B scenario), and of a high resolution RCM viz. RegCM4.3 (25Km horizontal resolution, RCP8.5 scenario) have been used to construct linear regression models based on method of least squares, to analyse possible regional precipitation responses to increase in regional temperature over Pakistan. Mean seasonal temperature have been used to predict mean seasonal precipitation feedback, both in past and future climate over the region. Results have shown that MAM precipitation has the highest cumulative response to changes in daily mean MAM temperature, irrespective of the time period, and the data used. AgMERRA reveals a 0.09 mm/day drop in MAM mean precipitation intensity for each degree Celsius rise in MAM mean temperature over the region. Under the A1B scenario, GCM20 baseline and projection analysis depicts 0.12 mm/day decrease in historical, 0.09 mm/day decrease in present and near future, and 0.12 mm/day decrease in far future MAM mean precipitation intensity for each degree Celsius rise in MAM mean temperature over the region. However under the RCP8.5 protocols, RegCM4.3 baseline and projection illustrates 0.04 mm/day decrease in historical, 0.04 mm/day decrease in present and near future, and 0.09 mm/day decrease in far future MAM mean precipitation intensity for each degree Celsius rise in MAM mean temperature over the region.

Key Words: AgMERRA, GCM20, RegCM4.3, A1B scenario, RCP8.5 scenario, linear regression analysis.

Introduction

Regional climate is driven by regional elements like elevation (m.a.s.l.), proximity to ocean, regional position along latitude, surface/snow albedo, and vegetation index. Owing to their divergent climatology along the latitude, Hindukush, Karakoram and Himalayas (HKH) have asserted themselves a significant unit of the so-called third pole environment (Yaoaet al., 2012). Pakistan being host to the triple point junction of HKH has a peculiar climate which is robustly determined by extreme diurnal and seasonal variations in climatic conditions. Over lofty elevations, the snow covered mountains reshape the climate, whereas, at lowest altitudes, the climate is mainly resolved by sea breeze along the coastal strip. The country harbors an agro-based economy which is highly reliant upon large scale Indus irrigation system. All principal tributaries of river Indus derive from HKH region. There is conceivable proof that imply perils of climate change linked to water resources that apparently affect irrigated agriculture and knack of power generation in the region (Akhtar et al., 2009). The subsistence of people dependent upon HKH water resources has become a liability. There is yet insufficient awareness of climate change and its potential significance, owing to which the fragility of the regional climate system seeks attention.

Global warming explicitly affects precipitation with an increased heating and greater evaporation trends leading to an increase in intensity and extension in span of drying surface that leads to severe droughts. Studies show that changes have occurred in the amount, frequency, intensity and type of precipitation, owing to the increased water vapor content in the atmosphere emerging from the warming of global sea surface temperatures (SSTs) and Green House Gases (GHGs) induced surface temperatures (see, e.g., Fowler and Hennessy, 1995; Freiet al., 1998; Trenberth 2011; Chou et al., 2012). Clausius-Clapeyron relation is a well-established physical law that suggests an approximately

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7% increase in the water holding capacity of air at the rate of one degree Celsius rise in temperature. With increased holding capacity comes the increased water vapor content in the air, if the aerosols do not hinder evaporation, and if air acts to approach the ideal gas conditions. Therefore, events like rain or snow storms, tropical cyclones, and thunderstorms get fuelled up with an increased supply of moisture that eventually produce more intense precipitation episodes, increasing the chances of floods.

Data and Methodology

Data

Baseline Reanalysis Dataset AgMERRA

Under the present study, analysis of state of the art newly published Agricultural Modern Era Retrospective Analysis for Research and Applications (AgMERRA) datasets (Ruaneet et al., 2015) for temperature and precipitation have been carried out on seasonal basis. The dataset has been developed from the previously established Modern Era Retrospective Analysis for Research and Applications (MERRA) incorporated with in situ and satellite sensed observational datasets for temperature, precipitation and other important meteorological variables. The AgMERRA introduces daily high resolution climate forcing datasets to study climate variability and climate change impacts in addition to their use in agriculture sector.

Baseline and Projected GCM20 Dataset

Present research work has utilized the output from global 20-km mesh model, Global Circular Model GCM20 – a collaborative development of Japan Meteorological Agency (JMA) and the Meteorological Research institute (MRI). The model bears a linear Gaussian grid that triangularly truncates at 959 horizontal units. The model is based on operational numerical weather prediction model of JMA, and assimilate modifications in radiation and land surface processes (Mizuta et al., 2012). The model has been simulated with a time step of 6 minutes, and is capable of providing data at 60 vertical pressure levels (1000hPa – 0.1hPa). Grid size of the model is 1843200 with grid resolution of 1920×960. The model simulation had been performed under A1B scenario in 3 time slices – 1980-1998, 2007-2025, and 2080-2098.

Baseline and Projected RegCM4.3 CORDEX Dataset

RegCM4.3 is the newly published, fourth generation development of ICTP, Italy. It is a hydrostatic model with sigma-p vertical coordinates, and is run on an Arakawa B-grid. The model has a capacity to incorporate various reanalysis datasets, GCM outputs, and CMIP5 model outputs, as its boundary conditions. The simulation period of the experimental design starts from 1st Jan 1970 to 31st Dec 2099, which captured both the reference and the projection periods. The initial and boundary conditions for the model came from CMIP5 GFDL-ESM2M (RF and RCP8.5) with 2.0°×2.5° spatial resolution. The radiation scheme used in the simulation was taken from NCAR CCM3. The Biosphere-Atmosphere Transfer Scheme (BATS) has been used in Land surface physics. Planetary boundary layer parameterization had been done using Holtslag's scheme. The convective precipitation scheme has been taken over land by Emanuel, and over ocean by Grell with Fritsch-Chappel as the closure scheme. Large-scale precipitation scheme had come from Subgrid Explicit Moisture Scheme (SUBEX), while ocean flux parameterization had come from Zeng's scheme. Exponential relaxation of 20 grid points width were selected for lateral buffer zone in order to address lateral boundary treatment in the model.

Methodology

A regression analysis spawns an equation to characterize a statistical relationship between a predictor and the response variable, which forecasts or predicts new observations. Linear regression utilizes the ordinary least squares estimation method which constructs a model by minimizing the sum of the squared residuals.

Regression results determine the direction, magnitude, and statistical significance of the relationship between a predictor and response.

- The sign of each coefficient signifies the direction of the relationship.
- Coefficients illustrate the mean change in the response for one unit of change in the predictor.

Linear regression models based on method of least squares have been developed on seasonal basis, keeping temperature variable as a predictor and precipitation variable as a response variable.

Verification of Models

Model Biases

Spatial biases in the mean temperature and mean precipitation parameters are seen through by means of constructing baseline (1980-1998) spatial maps of AgMERRA, GCM20, and RegCM4 daily output (Fig. 1). Mean temperature output of GCM20 baseline is significantly analogous to that of AgMERRA baseline. However, the mean temperature output of RegCM4 suffers with a cold bias in Northern region of Pakistan (34°N-37°N). A cold bias of more than 5°C in the mean temperature output of RegCM4 over the domain (especially in the Northern domain of Pakistan) had also been identified by Syed et al., (2014). There is a modest warm bias in the mean temperature output of RegCM4 in Baluchistan region. The Baluchistan region bears high elevation cliffs and mountains, similar to those in the Northern domain of Pakistan. This reveals that the 25km horizontal resolution of the RegCM4 temperature product was unable to capture regional rugged terrain borne lapse rates, successfully.

The GCM20 mean precipitation product, when compared with the AgMERRA mean precipitation product, reveals a wet bias of up to 2mm/day in the Northern half region of Pakistan. Burhanet al., (2014) suggested that large departures in GCM20 precipitation are probable results of major domination of western disturbances in the models' physics scheme. The mean precipitation baseline product of RegCM4 has shown the ability to adequately capture the precipitation patterns and its magnitude over the Northern domain of the country. However, the RegCM4 mean precipitation in the Southern domain of the region experience underestimation, when compared with the mean precipitation baseline of the AgMERRA product. This dry bias in RegCM4 mean precipitation product confirms with that found by Syed et al., (2014).

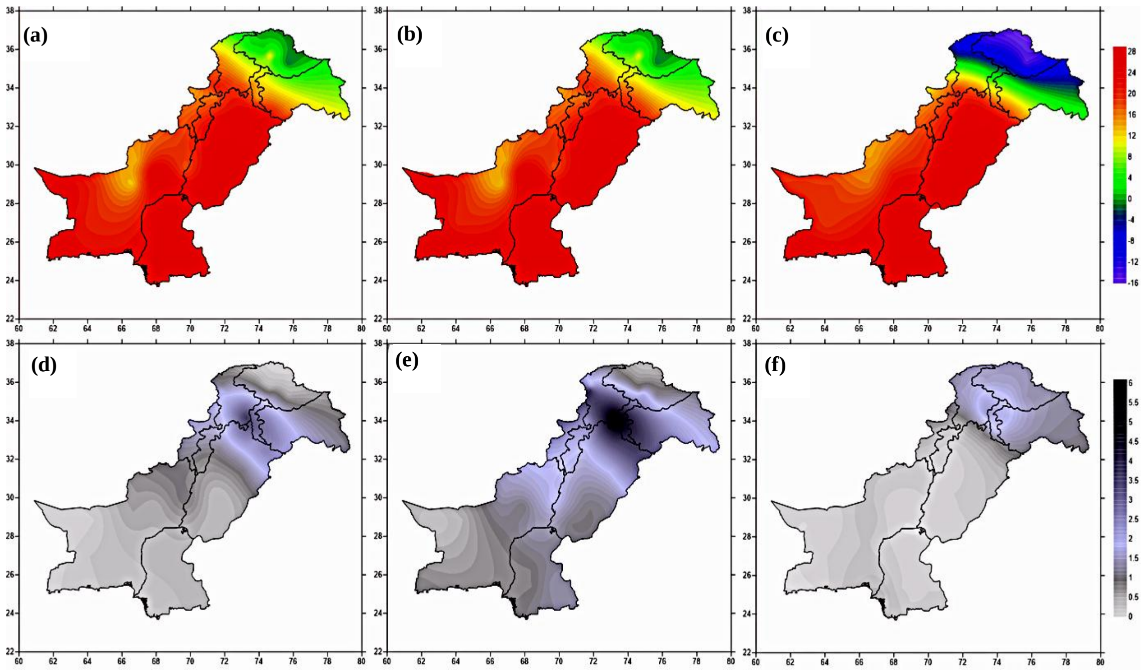

Figure 1: Spatial distribution of climatic variables emulation over Pakistan **(a)** AgMERRA mean temperature**, (b)** GCM20 mean temperature,**(c)** RegCM4.3 mean temperature, **(d)** AgMERRA annual mean precipitation,**(e)** GCM20 annual mean precipitation, and **(f)** RegCM4.3 annual mean precipitation – for the baseline period 1980-1998.

Results

AgMERRA Based 1980-1998 DJF Model

Figure 2 represents temperature-precipitation linear regression model constructed from the daily output of AgMERRA product for DJF season of 1980-1998 for complete baseline period. There is a negative trend (slope) observed in the direction of the temperature-precipitation relationship. The linear model suggests that for each 1°C rise in DJF temperature, the daily mean precipitation has decreased by 0.04mm/day. Moreover, temperature alone has described 0.4% of the variance in the precipitation response in the DJF season.

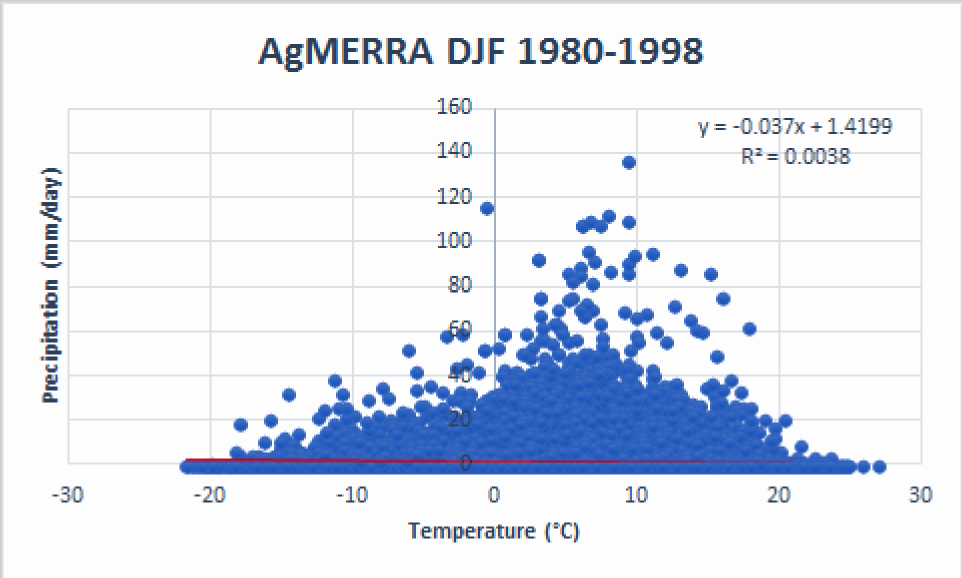

Figure 2: Temperature – Precipitation linear regression model (red line) for 1980-1998 DJF season constructed from the AgMERRA product.

AgMERRA Based 1980-1998 MAM Model

Figure 3 represents temperature-precipitation linear regression model established from the daily output of AgMERRA product for MAM season of 1980-1998 complete baseline period. The trend (slope) of the relationship is negative which suggests a relative decrement in the amount of precipitation response to each degree Celsius rise in temperature. More specifically, the rate of decrease in precipitation per 1°C rise in temperature is 0.09mm/day. The variance of precipitation response explained by the temperature predictor is 2.4% in the MAM season.

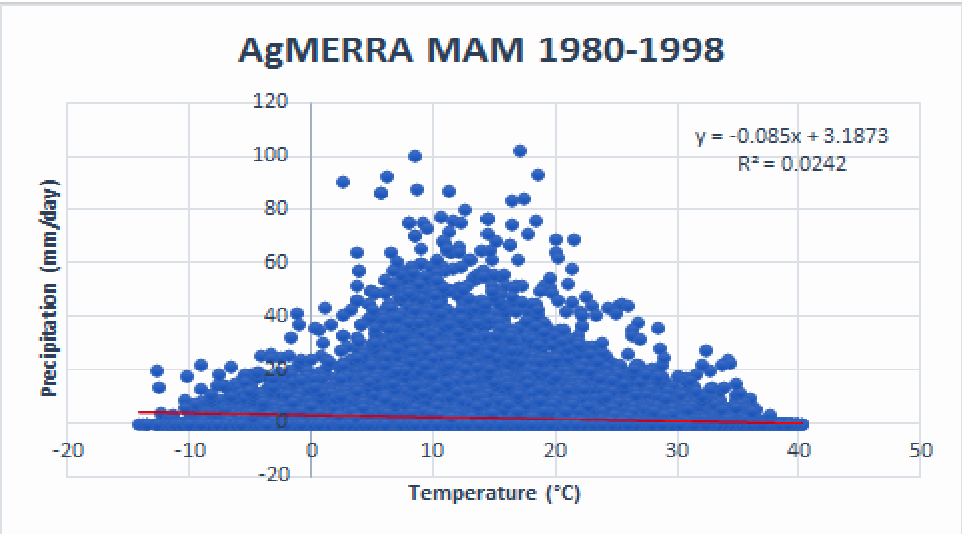

Figure 3: Temperature – Precipitation linear regression model (red line) for 1980-1998 MAM season constructed from the AgMERRA product.

AgMERRA Based 1980-1998 JJAS Model

Figure 4 depicts temperature-precipitation linear regression model designed from the daily output of AgMERRA product for JJAS season of 1980-1998 complete baseline period. The temperature-precipitation relationship has a negative gradient which suggests a negative rate of change of precipitation response to each degree Celsius rise in JJAS temperature. The regression model has suggested that precipitation is deceased by 0.06mm/day/°C with 0.3% of variance explained by the temperature predictor for the precipitation response in JJAS season.

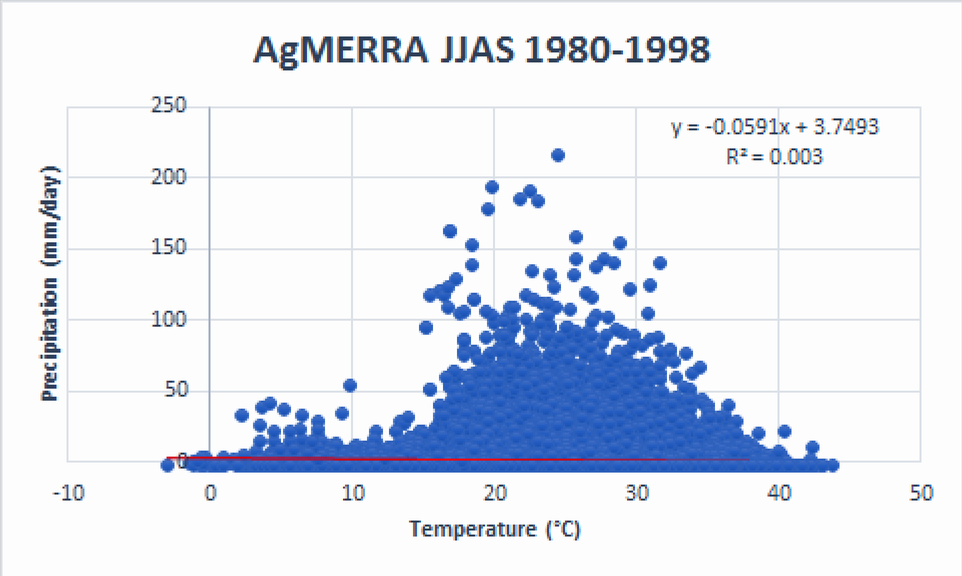

Figure 4: Temperature – Precipitation linear regression model (red line) for 1980-1998 JJAS season constructed from the AgMERRA product.

AgMERRA Based 1980-1998 ON Model

Figure 5 shows temperature-precipitation linear regression model formulated from the daily output of AgMERRA product for ON season of 1980-1998 complete baseline period. The linear regression model holds an inverse relationship suggesting a net decrease in the amount of ON rainfall for each 1°C rise in ON temperature. The model has shown that precipitation response tends to decrease by 0.02mm/day/°C in the ON season. Moreover, the ON temperature alone describes 0.3% of the variance observed by ON precipitation.

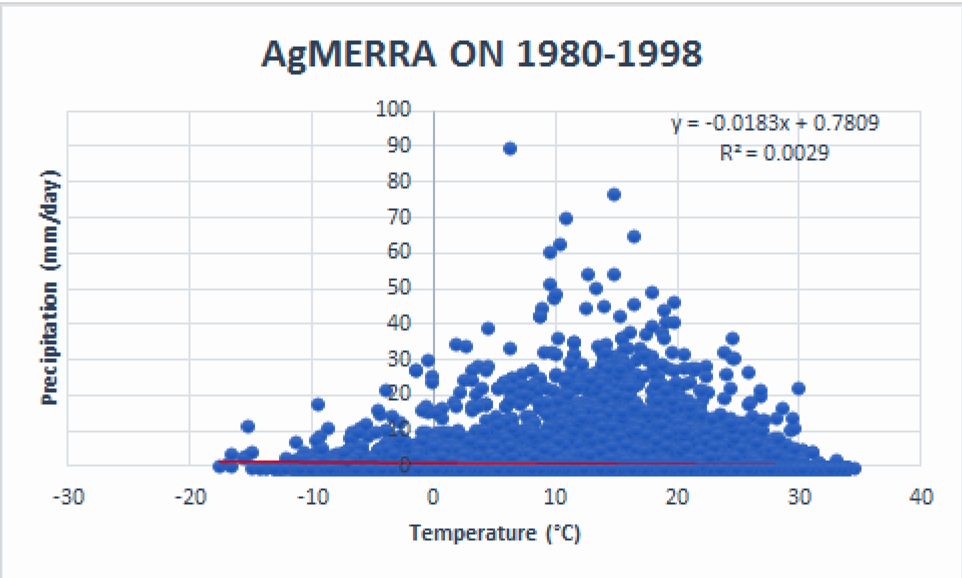

Figure 5: Temperature – Precipitation linear regression model (red line) for 1980-1998 ON season constructed from the AgMERRA product.

GCM20 Based Models

GCM20 Based 1980-1998 DJF Model

Figure 6 depicts temperature-precipitation linear regression model formulated from the delta corrected and temporally disaggregated daily output of GCM20 product for DJF season of 1980-1998 repeated period. The rate of change of precipitation response to temperature predictor is negative in the DJF season. For each 1°C rise in DJF temperature, the linear regression model has shown a 0.01mm/day decrease in the amount of DJF precipitation. The percentage of variance explained by the temperature predictor for the precipitation response is 0.05%.

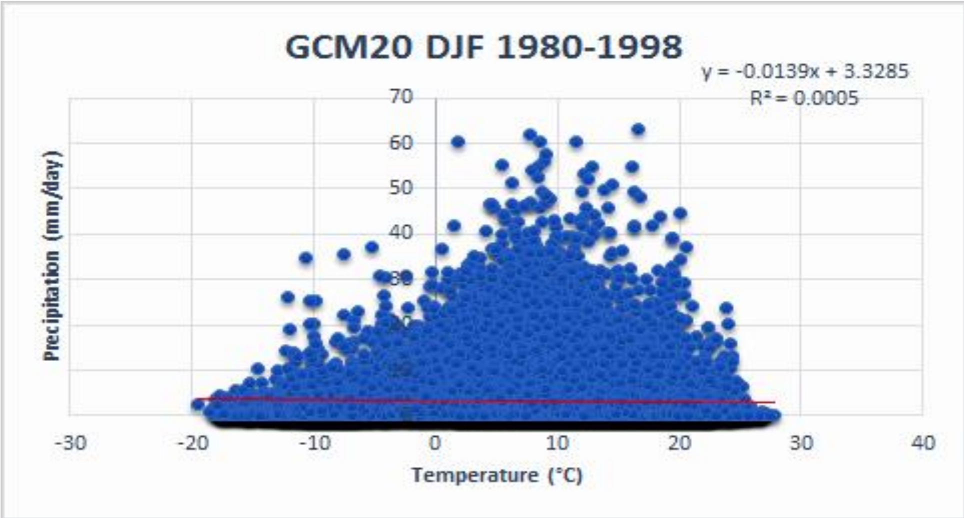

Figure 6: Temperature – Precipitation linear regression model (red line) for 1980-1998 DJF season constructed from the GCM20 product.

GCM20 Based 1980-1998 MAM Model

Figure 7 portrays temperature-precipitation linear regression model constructed from the delta corrected and temporally disaggregated daily output of GCM20 product for MAM season of 1980-1998 complete baseline period. There is a negative gradient observed in the linear relationship of temperature and precipitation which suggests a relative decrease in the amount of MAM daily precipitation per 1°C rise in the MAM temperature. The model has depicted a 0.12mm/day/°C decline in the MAM precipitation with 4.9% of variance in MAM precipitation explained by MAM daily mean temperature.

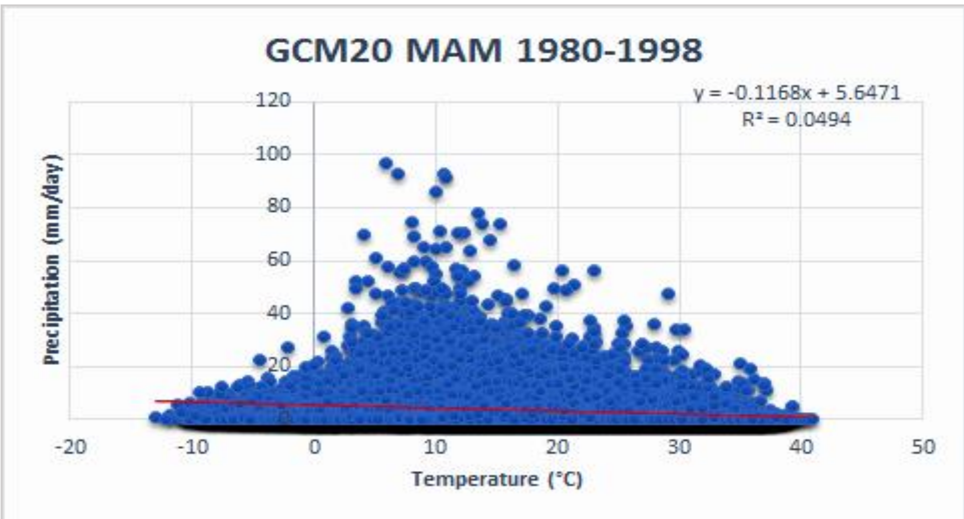

Figure 7: Temperature – Precipitation linear regression model (red line) for 1980-1998 MAM season constructed from the GCM20 product.

GCM20 Based 1980-1998 JJAS Model

Figure 8 represents temperature-precipitation linear regression model constructed from the delta corrected and temporally disaggregated daily output of GCM20 product for JJAS season of 1980-1998 complete baseline period. The model has shown a negative rate of change in JJAS precipitation for each 1°C rise in JJAS temperature. Numerically, the gradient of JJAS temperature-precipitation model is -0.0146 which suggests a 0.02mm/day decrease in JJAS precipitation for each 1°C rise in JJAS temperature. Moreover, the JJAS temperature explains 0.02% of the variance in JJAS precipitation response.

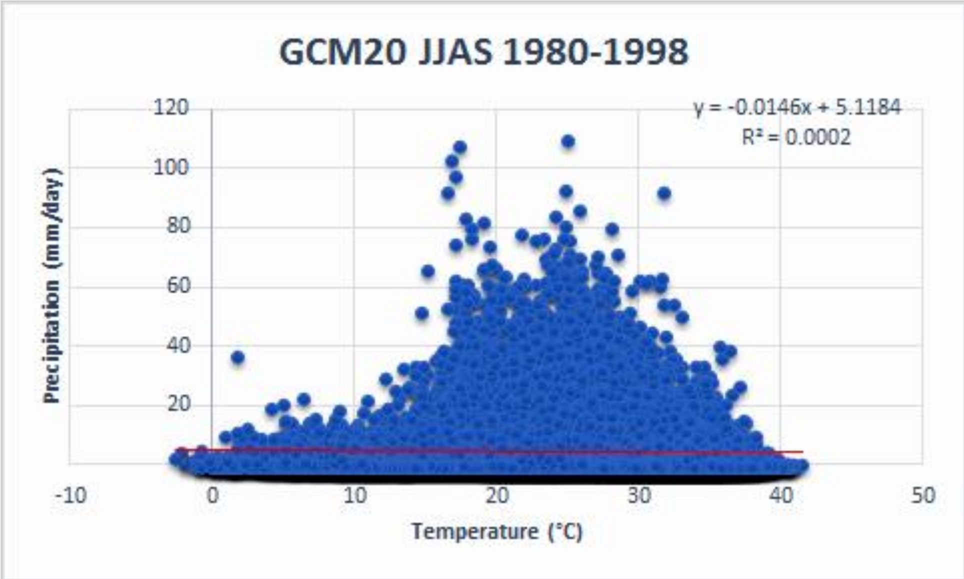

Figure 8: Temperature – Precipitation linear regression model (red line) for 1980-1998 JJAS season constructed from the GCM20 product.

GCM20 Based 1980-1998 ON Model

Figure 9 represents temperature-precipitation linear regression model designed from the delta corrected and temporally disaggregated daily output of GCM20 product for ON season of 1980-1998 complete baseline period. The model exhibits a negative gradient of precipitation response to temperature variation in ON season. The rate of decrease in ON precipitation is 0.03mm/day/°C with 0.5% of the variance, in ON precipitation explained by ON daily mean temperature.

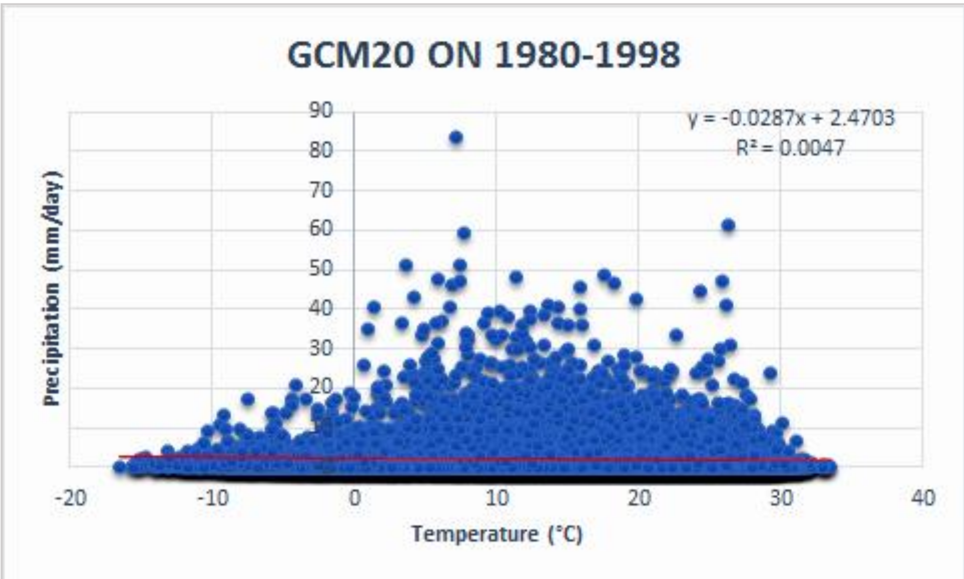

Figure 9: Temperature – Precipitation linear regression model (red line) for 1980-1998 ON season constructed from the GCM20 product.

GCM20 Based 2007-2025 DJF Model

Figure 10 displays temperature-precipitation linear regression model constructed from the delta corrected and temporally disaggregated daily output of GCM20 product for DJF season of 2007-2025 near past, present and immediate future period. The temperature-precipitation slope is negative indicating an inverse relationship in the DJF season of 2007-2025 near past, present and immediate future period. The model shows that for each 1°C rise in 2007-2025 daily mean temperature, the expected amount of precipitation decrease is 0.01mm/day. Moreover, the daily mean temperature in 2007-2025 explains 0.05% of the variance in precipitation response in that period.

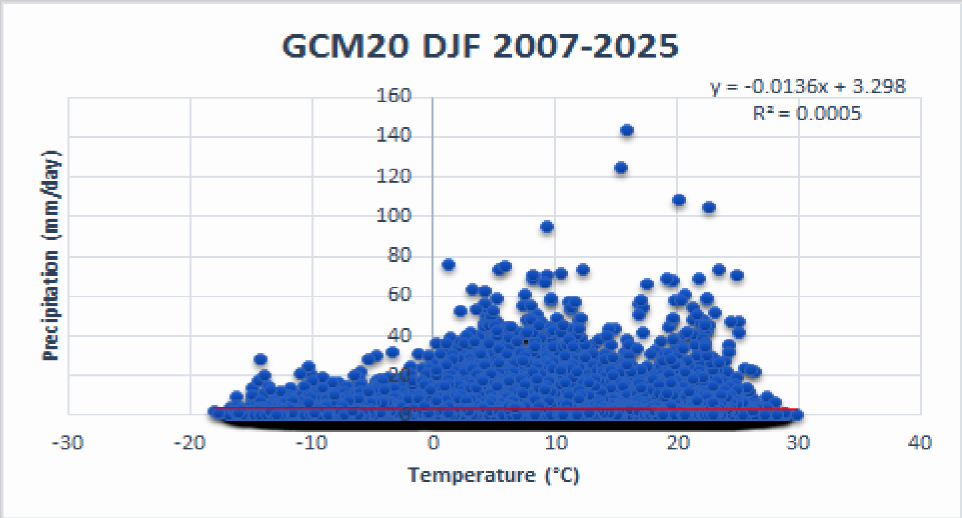

Figure 10: Temperature – Precipitation linear regression model (red line) for 2007-2025 DJF season constructed from the GCM20 product.

GCM20 Based 2007-2025 MAM Model

Figure 11 shows temperature-precipitation linear regression model constructed from the delta corrected and temporally disaggregated daily output of GCM20 product for MAM season of 2007-2025 near past, present and immediate future period. There is a negative gradient observed

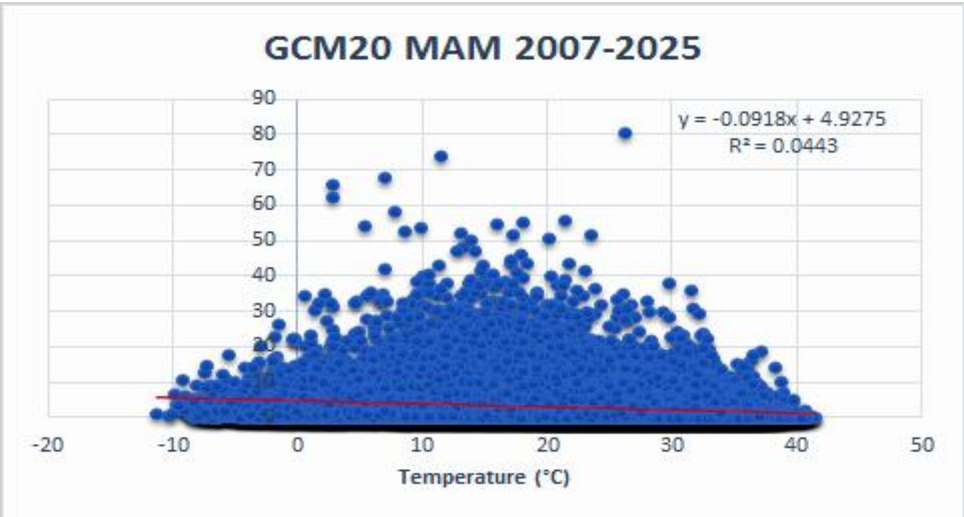

Figure 11: Temperature – Precipitation linear regression model (red line) for 2007-2025 MAM season constructed from the GCM20 product.

in the temperature-precipitation linear regression model which suggests a decrease in the amount of precipitation for each 1°C rise in the daily mean temperature of MAM. More specifically, a 0.09mm/day/°C decrement in the rate of precipitation amount is expected in the MAM season of 2007-2025 period (in contrast to a 0.12mm/day/°C in the MAM season of 1980-1998 baseline period). The variance explained by the mean daily temperature for the precipitation amount is 4.4% in the MAM season of 2007-2025 near past, present and immediate future period (in contrast to a 4.9% in the MAM season of the 1980-1998 baseline period). This suggests a 0.5% weaker MAM correlations in the 2007-2025 projection period, as compared to those in 1980-1998 baseline period.

GCM20 Based 2007-2025 JJAS Model

Figure 12 portrays temperature-precipitation linear regression model constructed from the delta corrected and temporally disaggregated daily output of GCM20 product for JJAS season of 2007-2025 near past, present and immediate future period. The negative rate of change indicates an inverse relationship amongst the daily mean temperature and the total precipitation amount per day. Numerically, the expected rate of decrease in the amount of precipitation per 1°C rise in the daily mean temperature of JJAS in 2007-2025 is -0.01mm/day. However, the variance explained for the precipitation amount by the daily mean temperature in 2007-2025 period is merely 0.003%. This is a significant drop in the description of JJAS variance by the daily mean temperature in 2007-2025 period, as compared to a 0.02% of variance explained in the JJAS season of the 1980-1998 baseline period.

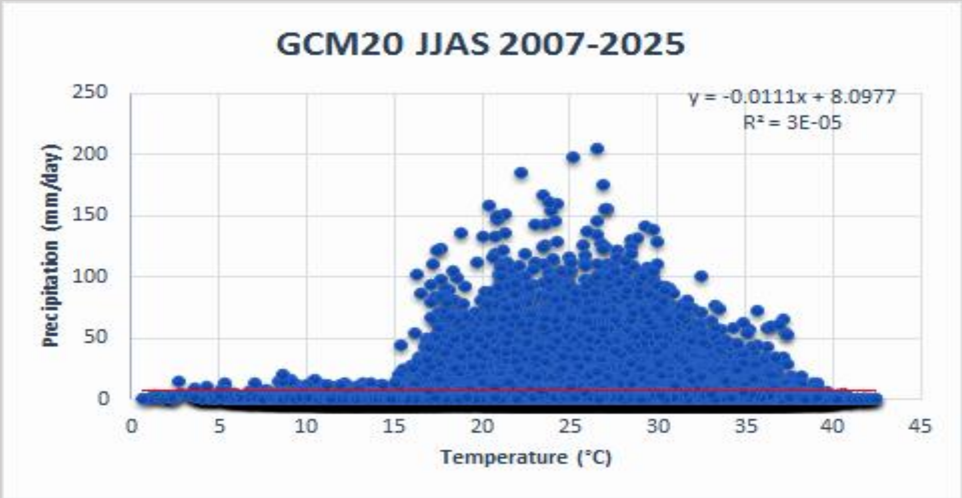

Figure 12: Temperature – Precipitation linear regression model (red line) for 2007-2025 JJAS season constructed from the GCM20 product.

GCM20 Based 2007-2025 ON Model

Figure 13 displays temperature-precipitation linear regression model formulated from the delta corrected and temporally disaggregated daily output of GCM20 product for ON season of 2007-

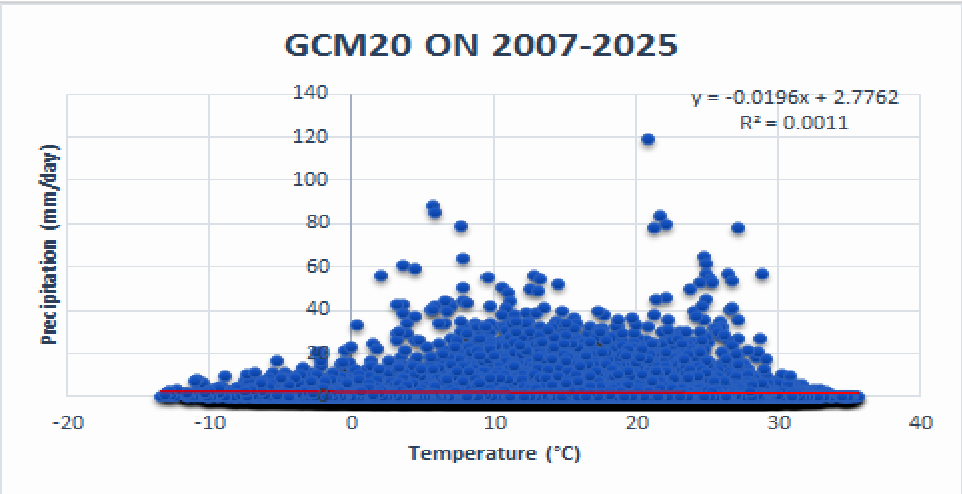

Figure 13: Temperature – Precipitation linear regression model (red line) for 2007-2025 ON season constructed from the GCM20 product.

2025 near past, present and immediate future period. The slope of the model show a relative decrement in the amount of precipitation for each 1°C rise in 2007-2025 ON daily mean temperature. In fact the model shows a 0.02mm/day/°C fall in precipitation amount in the ON season of 2007-2025 period. Moreover, the variance explained for the precipitation amount by the daily mean temperature is 0.1% in the ON season of 2007-2025 near past, present and immediate future period. Both, the rate of change in precipitation amount and the variance explained are likely to reduce down in the ON season of 2007-2027 period as compared to those in the ON season of 1980-1998 baseline period.

GCM20 Based 2080-2098 DJF Model

Figure 14 depicts temperature-precipitation linear regression model designed from the delta corrected and temporally disaggregated daily output of GCM20 product for DJF season of 2080-2098 far-future period. There is a 0.04mm/day/°C decrement in the amount of precipitation in the DJF season of the 2080-2098 far-future period, as predicted by the linear regression model. This shows that the decrement is expected to get large by an amount of 0.03mm/day/°C as compared to that in both 2007-2025 and 1980-1998 periods in the DJF season. Moreover, the regression model exhibits a 0.1%of precipitation variance being explained by the daily mean temperature of the DJF season in the 2080-2098 far-future period, in contrast to a smaller (0.05%) precipitation variance being explained by the mean temperature of the DJF season in both the 2007-2025 and the 1980-1998 periods. This suggests a relative increase in the temperature-precipitation DJF correlations in the 2080-2098 projection period, as compared to those in 2007-2025 projection period, and to those in 1980-1998 baseline period.

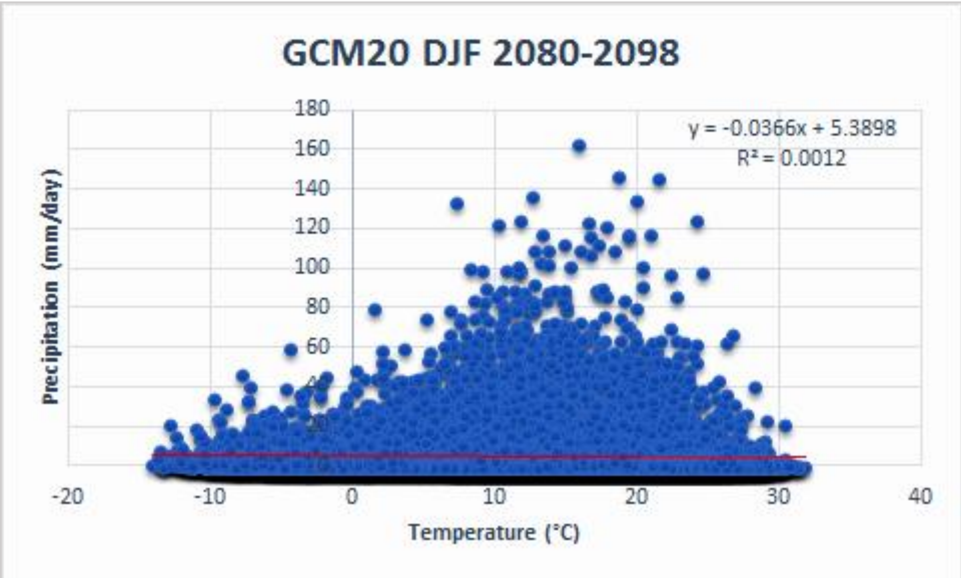

Figure 14: Temperature – Precipitation linear regression model (red line) for 2080-2098 DJF season constructed from the GCM20 product.

GCM20 Based 2080-2098 MAM Model

Figure 15 displays temperature-precipitation linear regression model constructed from the delta corrected and temporally disaggregated daily output of GCM20 product for MAM season of 2080-2098 far-future period. The negative rate of change in precipitation per 1°C rise in the daily mean temperature is 0.12mm/day. This change is synchronous to the change in the 1980-1998 baseline period, yet it is 0.03mm/day larger than that in the 2007-2025 projection period. Moreover, the magnitude of variance explained for the precipitation amount by the mean daily temperature is 3.6%, which is 0.8% smaller than that in the 2007-2025 projection period, and which is 1.3% smaller than that in the 1980-1998 baseline period. This infers weaker MAM temperature-precipitation correlations in the 2080-2098 projection period, in contrast to those in the 2007-2025 projection period, and to those in the 1980-1998 baseline period.

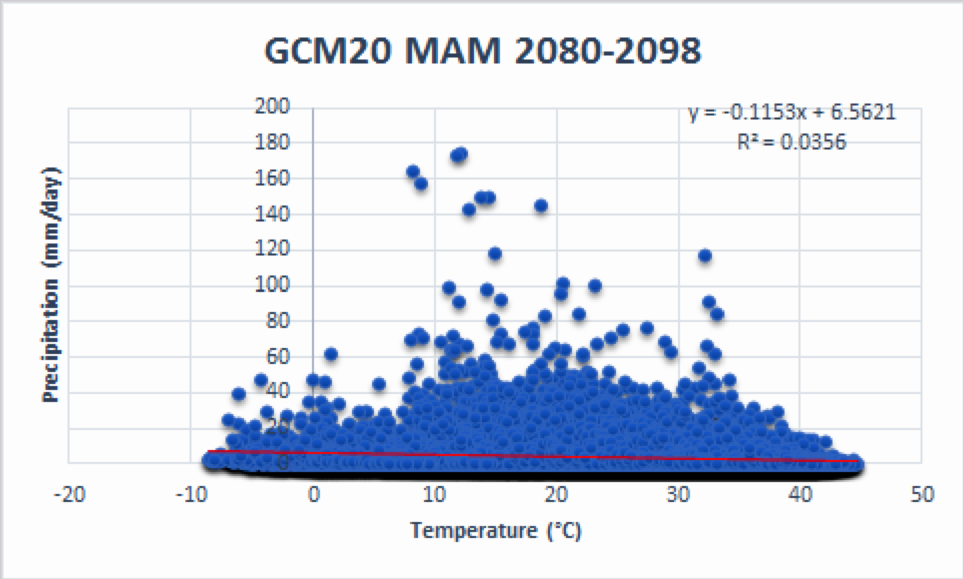

Figure 15: Temperature – Precipitation linear regression model (red line) for 2080-2098 MAM season constructed from the GCM20 product.

GCM20 Based 2080-2098 JJAS Model

Figure 16 shows temperature-precipitation linear regression model produced from the delta corrected and temporally disaggregated daily output of GCM20 product for JJAS season of 2080-2098 far-future period. The negative rate of change suggests a 0.16mm/day/°C decrease in the precipitation amount per 1°C rise in the daily mean temperature rise in JJAS season of 2080-2098 far-future projection period. This rate of change is significantly sharp as compared to that in the 2007-2025 projection period (=0.01mm/day/°C), and to that in the 1980-1998 baseline period (=0.02mm/day/°C). Moreover, the JJAS daily mean temperature in the 2080-2098 projection period describes 1.08% of the variance in the precipitation amount, in contrast to a 0.003% and to a 0.02% description of variance by the daily mean temperatures in 2007-2025 projection period and in 1980-1998 baseline period, respectively.

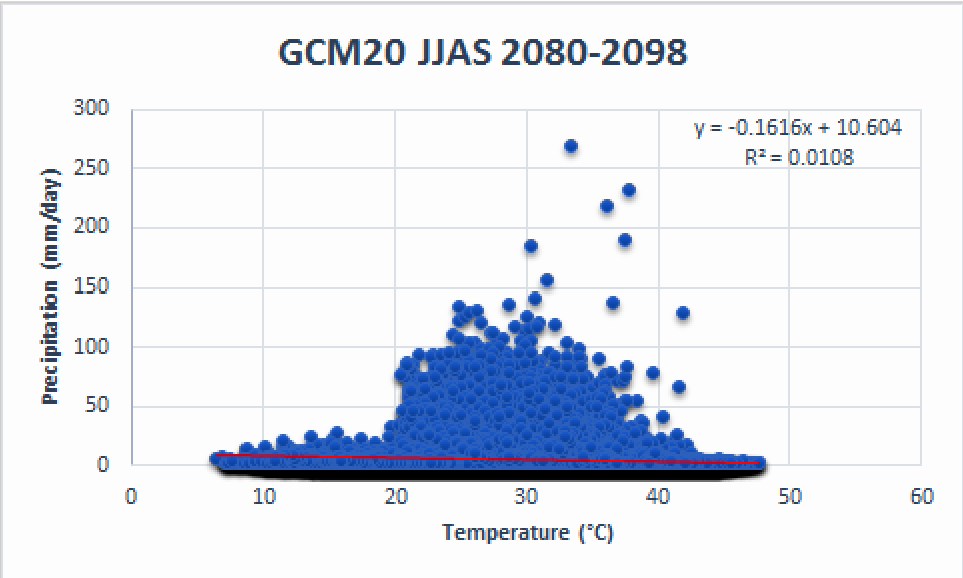

Figure 16: Temperature – Precipitation linear regression model (red line) for 2080-2098 JJAS season constructed from the GCM20 product.

GCM20 Based 2080-2098 ON Model

Figure 17 depicts temperature-precipitation linear regression model constructed from the delta corrected and temporally disaggregated daily output of GCM20 product for ON season of 2080-

2098 far-future period. The negative gradient of the linear regression model indicates a 0.07mm/day/°C decrease in the amount of precipitation. The rate of change in the precipitation amount is 0.06mm/day/°C larger than that in the 2007-2025 projection period, and is 0.04mm/day/°C larger than that in the 1980-1998 baseline period of the ON season. Moreover, the ON daily mean temperature in the 2080-2098 projection period describes 0.02% of the variance in the precipitation amount, in contrast to 0.1% and to 0.47% of the variance described in the precipitation amount by the ON daily mean temperature of the 2007-2025 projection period and of the 1980-1998 baseline period, respectively.

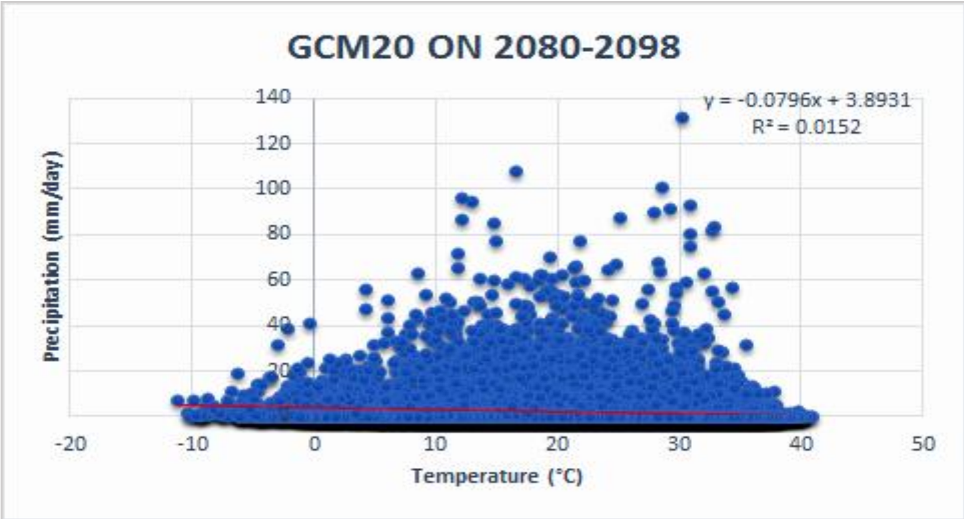

Figure 17: Temperature – Precipitation linear regression model (red line) for 2080-2098 ON season constructed from the GCM20 product.

RegCM4.3 Based Models

RegCM4.3 Based 1980-1998 DJF Model

Figure 18 represents temperature-precipitation linear regression model produced from the daily output of RegCM4 product for DJF season of 1980-1998 baseline period. There is a 0.03mm/day negative rate of change observed in the amount of precipitation per 1°C rise in the daily mean temperature of DJF season in the 1980-1998 baseline period. The amount of variance in the precipitation amount explained by the daily mean temperature is 3.5% in the DJF season of the 1980-1998 baseline period.

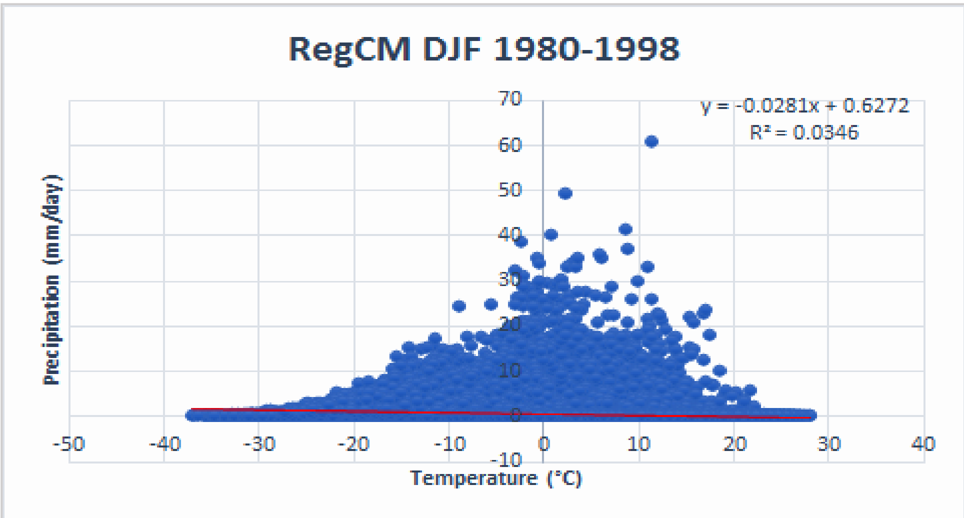

Figure 18: Temperature – Precipitation linear regression model (red line) for 1980-1998 DJF season constructed from the RegCM4.3 product.

RegCM4.3 Based 1980-1998 MAM Model

Figure 19 portrays temperature-precipitation linear regression model designed from the daily output of RegCM4 product for MAM season of 1980-1998 baseline period. The negative gradient of the linear regression model depicts a 0.04mm/day/°C decrement in the MAM precipitation amount of the 1980-1998 baseline period. Moreover, the MAM daily mean temperature alone describes 9.1% of the variance in the MAM precipitation amount of the 1980-1998 baseline period.

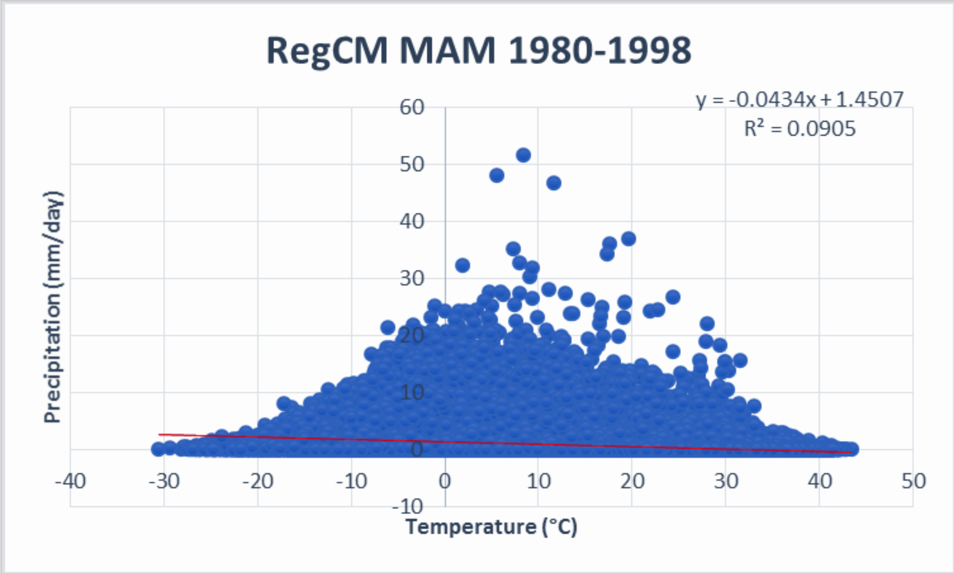

Figure 19: Temperature – Precipitation linear regression model (red line) for 1980-1998 MAM season constructed from the RegCM4.3 product.

RegCM4.3 Based 1980-1998 JJAS Model

Figure 20 depicts temperature-precipitation linear regression model formulated from the daily output of RegCM4 product for JJAS season of 1980-1998 baseline period. The negative rate of decline in JJAS precipitation amount per 1°C rise in JJAS daily mean temperature is shown to be 0.05mm/day. The variance explained by the JJAS daily mean temperature for the JJAS precipitation amount is 3.5% for the 1980-1998 baseline period.

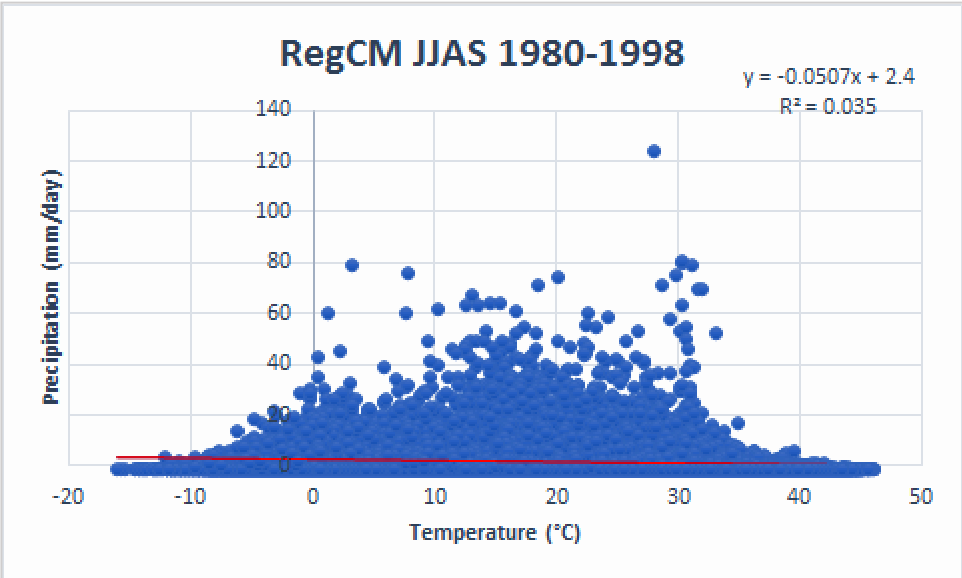

Figure 20: Temperature – Precipitation linear regression model (red line) for 1980-1998 JJAS season constructed from the RegCM4.3 product.

RegCM4.3 Based 1980-1998 ON Model

Figure 21 represents temperature-precipitation linear regression model constructed from the daily output of RegCM4 product for ON season of 1980-1998 baseline period. The inverse relationship between the temperature-precipitation regression suggests a 0.04mm/day/°C decline in the precipitation amount in the ON season of the 1980-1998 baseline period. The RegCM4 daily mean ON temperature explains 3.9% of the variance in the RegCM4 daily precipitation amount in the 1980-1998 baseline period.

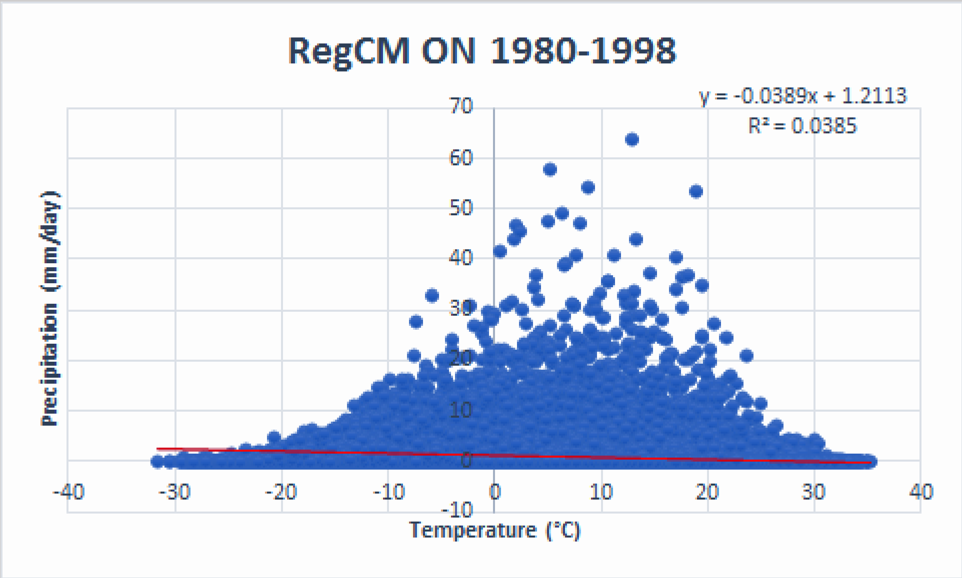

Figure 21: Temperature – Precipitation linear regression model (red line) for 1980-1998 ON season constructed from the RegCM4.3 product.

RegCM4.3 Based 2007-2025 DJF Model

Figure 22 depicts temperature-precipitation linear regression model composed from the daily output of RegCM4 product for DJF season of 2007-2025 projection period. The negative rate of decline in the amount of precipitation suggests a 0.03mm/day decrease per 1°C rise in the daily mean temperature of DJF season in 2007-2025 projection period. The variance explained for DJF precipitation by DJF daily mean temperature is 3.6% in the 2007-2025 projection period, which is 0.1% larger than that explained in the 1980-1998 baseline period.

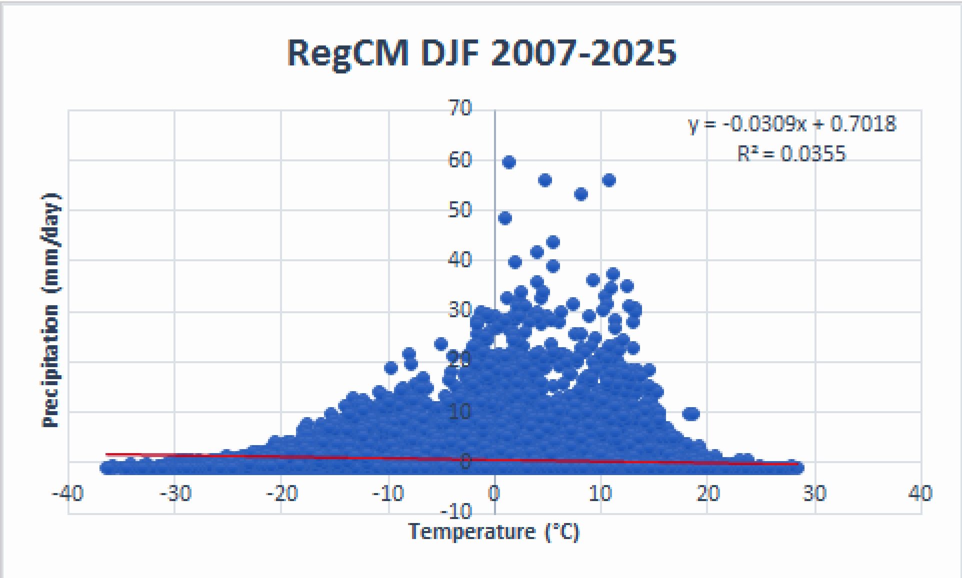

Figure 22: Temperature – Precipitation linear regression model (red line) for 2007-2025 DJF season constructed from the RegCM4.3 product.

RegCM4.3 Based 2007-2025 MAM Model

Figure 23 represents temperature-precipitation linear regression model designed from the daily output of RegCM4 product for MAM season of 2007-2025 projection period. There is a negative gradient observed in the temperature-precipitation regression model. Numerically, the rate of decrement in the amount of precipitation per 1°C is 0.04mm/day. The MAM daily mean temperature describes 8.7% of the variance in the amount of MAM precipitation in the 2007-2025 projection period, which is 0.4% smaller than that described in the MAM season of 1980-1998 baseline period. This infers relatively weaker MAM temperature-precipitation correlations in the 2007-2025 projection period as compared to those in the 1980-1998 baseline period.

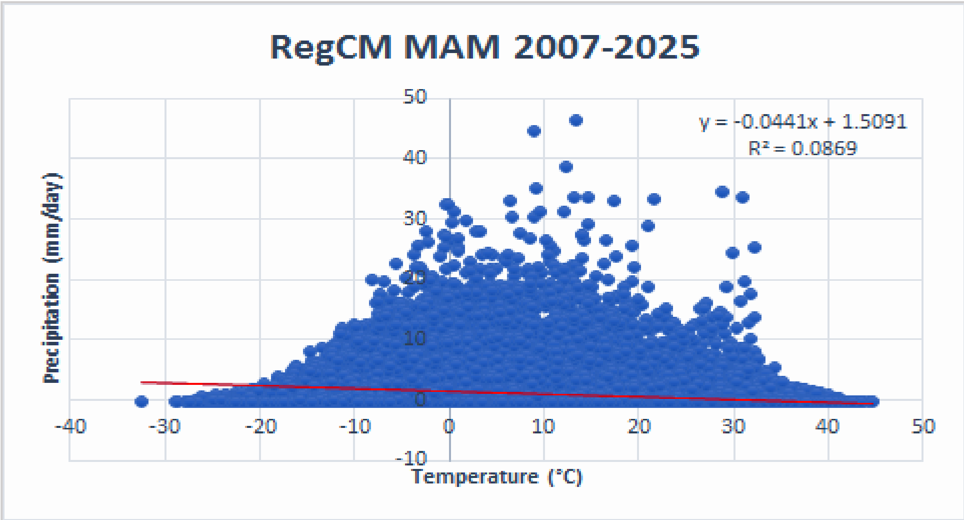

Figure 23: Temperature – Precipitation linear regression model (red line) for 2007-2025 MAM season constructed from the RegCM4.3 product.

RegCM4.3 Based 2007-2025 JJAS Model

Figure 24 portrays temperature-precipitation linear regression model created from the daily output of RegCM4 product for JJAS season of 2007-2025 projection period. The rate of decline in the precipitation per 1°C amounts to 0.05mm/day, which remains equivalent to that modelled for the 1980-1998 baseline period. However, the variance explained for the JJAS precipitation amount by the JJAS daily mean temperature reduces down from 3.5% in the 1980-1998 baseline period to 3.2% in the 2007-2027 projection period. The JJAS temperature-precipitation correlations have therefore been inferred to weaken down in the 2007-2025 projection period, as compared to those in the 1980-1998 baseline period.

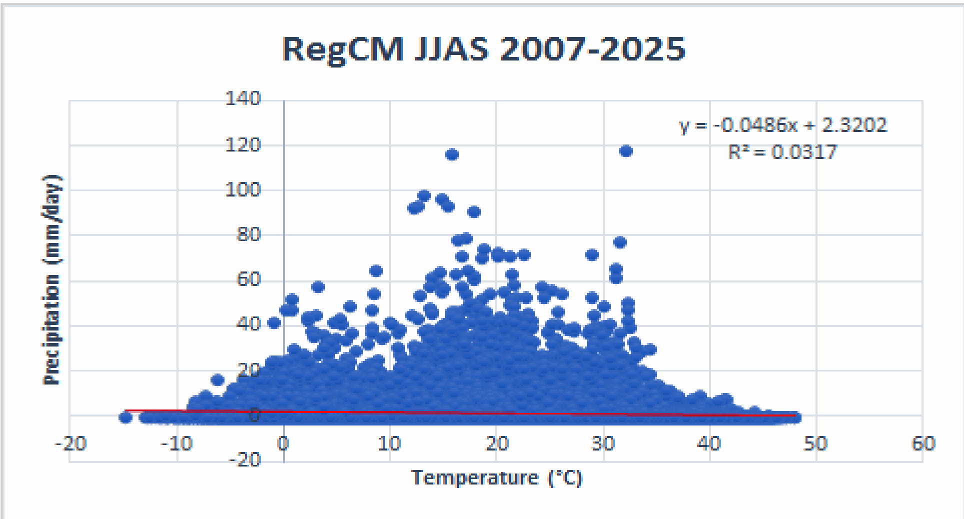

Figure 24: Temperature – Precipitation linear regression model (red line) for 2007-2025 JJAS season constructed from the RegCM4.3 product

RegCM4.3 Based 2007-2025 ON Model

Figure 25 displays temperature-precipitation linear regression model formulated from the daily output of RegCM4 product for ON season of 2007-2025 projection period. There is a negative slope observed in the temperature-precipitation regression model which numerically suggests a 0.04mm/day/°C rate of decline in the amount of ON precipitation. The variance explained for the amount of ON precipitation by the ON daily mean temperature in the 2007-2027 projection period is 0.3% smaller to that explained in the 1980-1998 baseline period. This suggests comparatively weaker ON temperature-precipitation correlations in the 2007-2027 projection period, as compared to those in 1980-1998 baseline period.

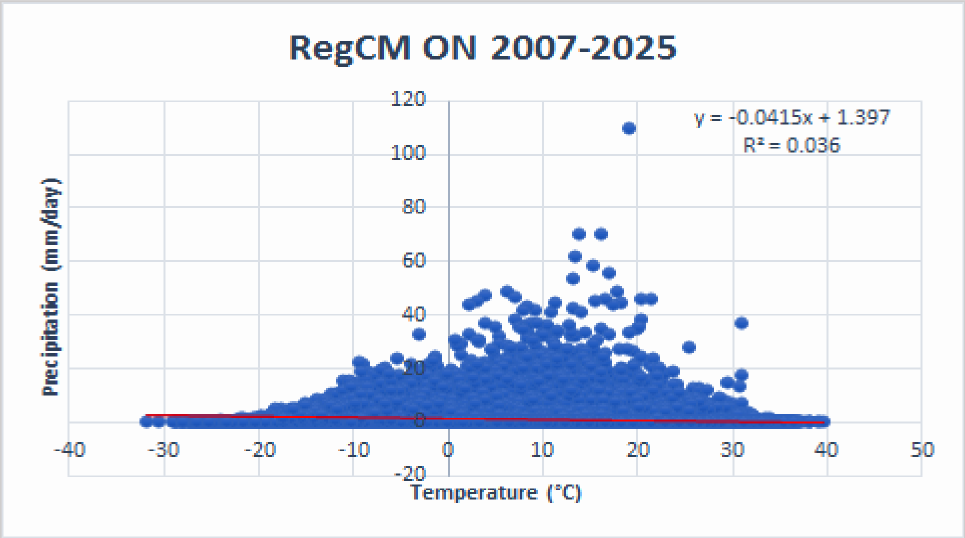

Figure 25: Temperature – Precipitation linear regression model (red line) for 2007-2025 ON season constructed from the RegCM4.3 product.

RegCM4.3 Based 2080-2098 DJF Model

Figure 26 represents temperature-precipitation linear regression model designed from the daily output of RegCM4 product for DJF season of 2080-2098 projection period. The inverse relationship between the temperature-precipitation linear regression suggests numerically a 0.05mm/day/°C decrement in the amount of DJF precipitation in the 2080-2098 projection period.

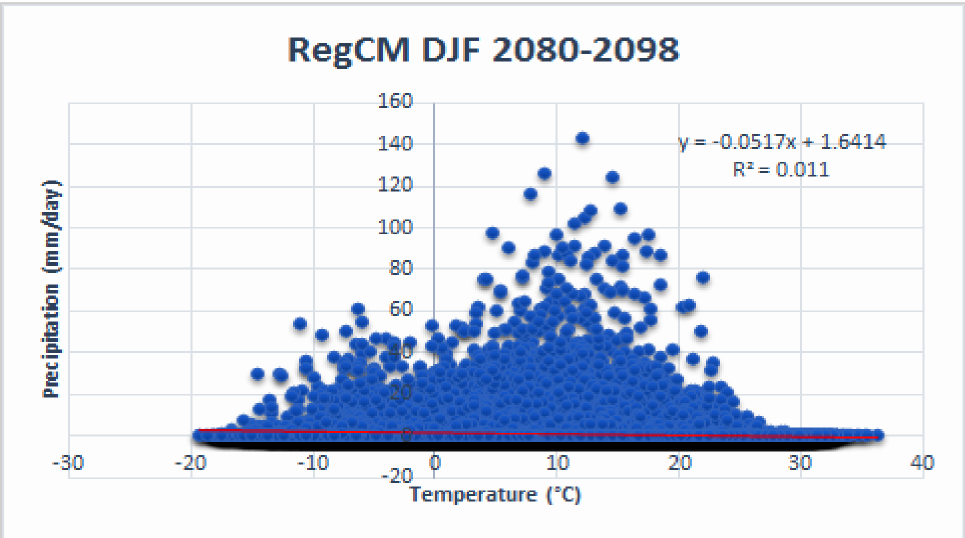

Figure 26: Temperature – Precipitation linear regression model (red line) for 2080-2098 DJF season constructed from the RegCM4.3 product.

The DJF daily mean temperature explains 1.1% of the variance in the DJF precipitation amount in the 2080-2098 projection period. The explanation of variance in the DJF season of 2080-2098 projection period is 2.5% smaller as compared to the DJF season of 2007-2025 projection period, and is 2.4% smaller as compared to the DJF season of 1980-1998 baseline period. This infers relatively weaker DJF temperature-precipitation correlations in the 2080-2098 projection period, in contrast to those in the 2007-2025 projection period, and to those in the 1980-1998 baseline period.

RegCM4.3 Based 2080-2098 MAM Model

Figure 27 depicts temperature-precipitation linear regression model constructed from the daily output of RegCM4 product for MAM season of 2080-2098 projection period. The rate of decline in the MAM precipitation amount is 0.09mm/day/°C in the 2080-2098 projection period, which is 0.05mm/day/°C larger as compared to that in both the 2007-2025 projection period, and the 1980-1998 baseline period. The MAM daily mean temperature describes 3.5% of the variance in the MAM precipitation amount of the 2080-2098 projection period, which is 5.2% smaller as compared to that of the 2007-2025 projection period, and is 5.6% smaller as compared to that of the 1980-1998 baseline period. The result is relatively feeble MAM temperature-precipitation correlations by the end of the century.

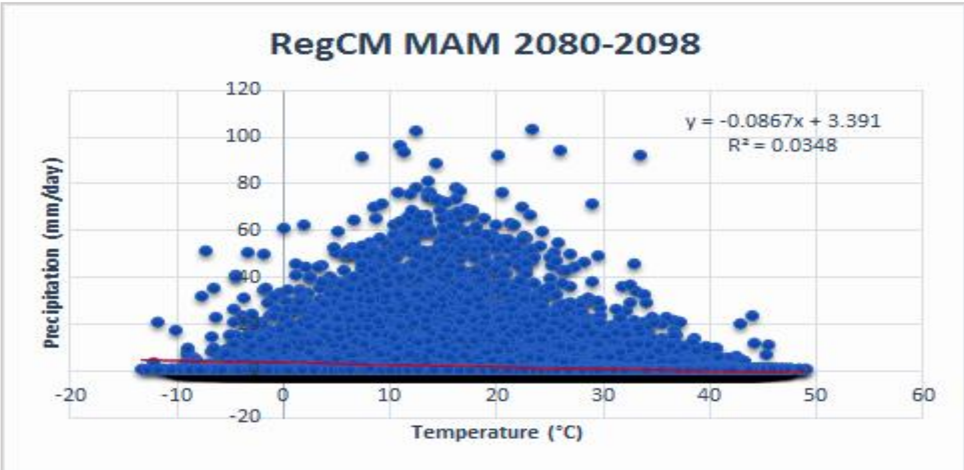

Figure 27: Temperature – Precipitation linear regression model (red line) for 2080-2098 MAM season constructed from the RegCM4.3 product.

RegCM4.3 Based 2080-2098 JJAS Model

Figure 28 portrays temperature-precipitation linear regression model built from the daily output of RegCM4 product for JJAS season of 2080-2098 projection period. The negative gradient of the

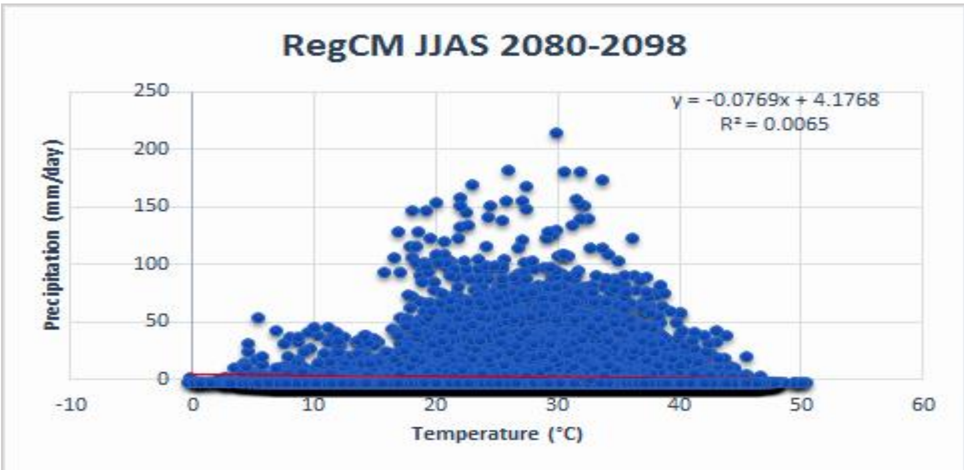

Figure 28: Temperature – Precipitation linear regression model (red line) for 2080-2098 JJAS season constructed from the RegCM4.3 product.

JJAS temperature-precipitation linear regression model suggests a 0.08mm/day decrement in the amount of JJAS precipitation per each 1°C rise in the JJAS daily mean temperature of the 2080-2098 projection period. This rate of decrease is 0.03mm/day/°C higher as compared to that in the 2007-2027 projection period, and to that in the 1980-1998 baseline period. The variance explained for the JJAS precipitation by the JJAS daily mean temperature amounts to 0.65% in the 2080-2098 projection period, which is 2.5% smaller than that in the 2007-2025 projection period, and is 2.8% smaller than that in the 1980-1998 baseline period. This infers a relative drop in the strength of the JJAS temperature-precipitation correlations by the end of the century.

RegCM4.3 Based 2080-2098 ON Model

Figure 29 represents temperature-precipitation linear regression model constructed from the daily output of RegCM4 product for ON season of 2080-2098 projection period. The rate of decrement in the ON precipitation for the 2080-2098 projection period is 0.03mm/day/°C. This is comparatively a smaller rate of decrease as compared to that in the ON season of 2007-2025 projection period, and to that in the ON season of 1980-1998 baseline period. The ON daily mean temperature describes 0.64% of the variance in the ON precipitation amount of the 2080-2098 projection period. This explanation of variance is significantly smaller than that in the ON season of 2007-2025 projection period (difference of 3%), and of 1980-1998 baseline period (difference of 3.3%). This has inferred weaker ON temperature-precipitation correlations by the end of the century, as projected by mean temperature and precipitation parameters of RegCM4 product.

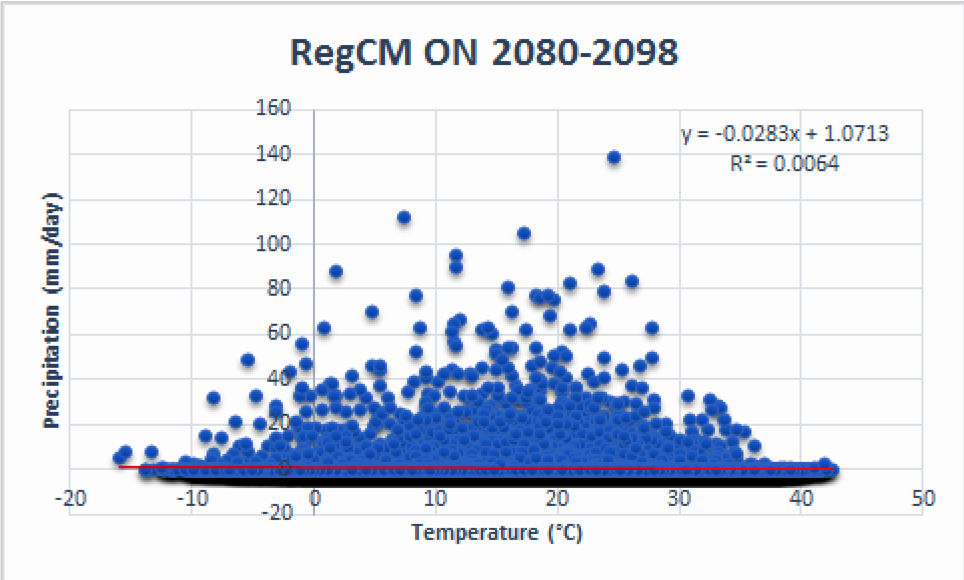

Figure 29: Temperature – Precipitation linear regression model (red line) for 2080-2098 JJAS season constructed from the RegCM4.3 product.

Conclusion

A wider analysis over the distribution of the rate of changes and of their corresponding degree of the variance explanation reveals that MAM season precipitation has the highest cumulative response to changes in daily mean MAM temperature, irrespective of the time period, and the data used. However, the MAM temperature-precipitation correlations get weaker with increasing projection time. Possible reason for this finding might be a time oriented seasonal shift from winter towards spring in the projected mean annual cycle of precipitation patterns (Burhan et al., 2015).

Relatively marginal amount of variance explained by change in mean seasonal temperature that provides feedback to mean seasonal precipitation over Pakistan caters for induction of more variables as predictors in the linear regression model. By virtue of this, correlations with precipitation response are expected to get more robust and coherent. Our scope of using mean seasonal temperature as a predictor to mean seasonal precipitation response has provided us signatures that let us believe the adverse impacts of regional warming over regional precipitation intensity over Pakistan.

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