Regional Comparison between Global Circulation Model GCM20 and Regional Climate Model PRECIS

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Abstract

A super high resolution Global Circulation Model GCM20 (20 Km horizontal resolution) of Meteorological Research Institute, Tsukuba, Japan, is compared spatially and temporally with the UK's Hadley center Regional Climate Model (RCM) viz. Providing Regional Climate for Impact Studies (PRECIS) to investigate climate change scenarios and biases that lie within. Data Analysis and Integration System (DIAS) was accessed to obtain GCM20 data while for PRECIS data, simulations were done under the A1B scenario at a horizontal resolution of 0.22 degrees (25 Km approx.) with the boundary data from European GCM ECHAM5. Three different time scales were selected from both models- the baseline (1979-1998), present and near future (2007-2027) and the far future (2080-2099). Comparisons were made for the domain 20° N-40° N and 60° E-80° E including Pakistan, Afghanistan and climate active regions of Hindu Kush, Karakoram and Himalayas. Analysis of both the models suggests that the areas covering the monsoon belt shall receive less warming effects than those which seldom receives it. Moreover regions with higher terrain shall receive relatively greater warming in the near and far future. Magnitude of the temperature increase in the near future relative to baseline for GCM20 suggests a 1 °C-1.5 °C rise whereas for PRECIS it suggests a 1.5 °C-2 °C rise in the region. Both GCM20 and PRECIS, in the near and far future, show a relative precipitation increase (0.5 mm/day and 1 mm/day respectively) in the extreme North region of the domain.

Key Words: climate modeling; dynamical downscaling; statistical validation; climate change scenarios; surface climatology.

Introduction

Regional climate is determined by regional factors that include, but are not limited to, elevation (m.a.s.l.), proximity to ocean, location along latitude (polar, sub-polar, sub-tropical, tropical), surface albedo, and vegetation index. Owing to their anomalous climatology along the latitude, Hindukush, Karakoram and Himalayas (HKH) have claimed themselves a part of the so-called third pole environment (Yaoa et al., 2012). Pakistan being host to the triple point junction of HKH has an atypical climate which is strongly distinguished by extreme diurnal and seasonal variations of temperature and precipitation. At high altitudes, the snow covered northern mountainous region modify the climate in the cold, whereas, at lowest altitudes, along the coastal strip, the climate is mainly determined by sea breeze. The country bears an agro-based economy which is highly dependent on large scale Indus irrigation system. Major tributaries of river Indus stem from HKH region. There are plausible evidences that indicate climate change hazards associated with water resources that presumably affect irrigated agriculture and power generation capacity of the region (Akhtar et al., 2009). The livelihood of people dependent upon HKH water resources is at risk, which shall have global implications at its disposal. There is still little knowledge of climate change and its potential implications, owing to which the present study has been carried out to assess fragility of the regional climate system.

Rouf et al. (2011) and Mizuta et al. (2012) began the analysis to verify the capability of super high resolution GCMs over the South Asian regions. Their studies focused the Indian and Bengal regions to which the model performed decent enough to reproduce the sudden onset and gradual withdrawal of monsoon. Past, present and future climatic patterns (precipitation and temperature) were assessed over the Northwest and Southwest regions of Bangladesh. To these regions, it was inferred that there is an increasing trend for temperature (up to 4.34 °C/100 years) and a decreasing trend for the precipitation (up

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to 1.96 mm/100 years).In 2006, a projection of global warming was carried out using time slice technique for GCM20 (Kusunoki et al. 2006). The model reproduced a realistic Baiu season, northward seasonal march of the Baiu rain band, its onset and withdrawal, intensity of rainfall and the geographic distribution of mean sea level pressure. To evaluate the dependency of the reproducibility of the Baiu rain band over the horizontal resolution, experiments were carried out that revealed the higher performance of 20-km model over the lower horizontal resolution models. Future projections of the precipitation showed an intensity increase over the Yangtze River valley of China, the East China Sea,Western Japan, and the ocean to the south of the Japan archipelago. Obversely, an intensity decrease of the precipitation was observed over the Korean Peninsula and Northern Japan.

Validation of the daily precipitation climatology simulated by GCM20 had been done with a gauge-based gridded precipitation climatology (0.05° resolution) over the monsoon Asia (5-60° N, 65-155° E) (Yatagai et al. 2005). It had been observed that the model successfully simulated the orographically enhanced rainfall patterns presented in the East Asian climatology. However, the precipitation was overestimated over land areas of monsoon Asia, with larger biases over India and central China. GCM20 had also been tested to simulate tropical cyclones where its results turned out to be more realistic in associating geographical distribution, heavy rain falls and strong surface winds, when compared with lower resolution models. Nevertheless it was found that resolution was not significant for future projected changes in seasonal means of precipitation, yet it did affect the extremes (Kitoh et al. 2009). Outputs from GCM20 and Climate Research Unit’s dataset CRU-TS2.1 were recently taken as input to crop model iGAEZ (Tatsumi, 2013). Results indicated that there is a strong correlation for long-term statistics between the two outputs of crop yields and harvested areas, inferring little potential in increasing the horizontal resolution for regions with large croplands. An investigative study over the present day Fertile Crescent was employed using 20-km model which accurately reproduces the rainfall patterns and the streamflow (Kitoh et al. 2008). Future projections showed a significant decrease (29 %-73 %) in the annual discharge of Euphrates River resulting in a complete loss of the Fertile Crescent by the end of this century.

Parallel to the studies of GCM20, were the studies carried out for different regions using Regional Climate Model PRECIS of Hadley Center UK. Grid to grid analyses were done for Bangladesh rainfall and temperature using PRECIS Model, dataset CRU and observational data from Bangladesh Meteorological Department (BMD) (Islam et al. 2008). The analyses revealed that PRECIS overestimated the parameters due to a downscaling of gridded, asymmetric and low density BMD data network. The model overestimated precipitation in dry periods and underestimated the same in the monsoon periods. Cold biases were also found on the annual scale of the surface temperature. Waheed et al. (2010) applied the model to snow covered areas of Pakistan in order to investigate its ability to simulate the climatic patterns of complex topography. Results of PRECIS were compared with CRU gridded dataset which led to the overestimation of PRECIS mean temperature for snow-covered areas of Pakistan. It was further investigated that the inaccurate land topography incorporated into the model led to those large biases. In another study, PRECIS simulations under the A1B emission scenario were carried out for a continuous period of 1961-2098. The model exhibited reasonable skill in simulating the monsoon climate over the region of India. Precipitation was over-estimated in the model simulations over the Bay of Bengal, whilst the mean annual surface air temperature showed a warm bias over Southern India and a cold bias over the regions of Jammu Kashmir and the foothills of the Himalayas (Kumar et al. 2011).Rainfall and temperature parameters were also simulated by downscaling ECMWF ERA-40 reanalysis dataset and European Community Model (ECHAM5) using PRECIS for the Saudi Arabian region. The results showed a consistency of the present day temperature and rainfall parameters with the observed dataset CRU (Almazroui, 2013).

Comparing an RCM with a GCM is an intricate business. An RCM runs over a limited domain with its boundary data coming from a GCM. It is to be noted that in addition to the uncertainties of RCMs, GCMs themselves have uncertainties that get transferred to RCMs while they simulate. Different results will be generated if an RCM is run with different GCMs boundaries. Similarly different results will come out when different RCMs downscale same GCM.Therefore when we compare a GCM with an RCM, in truth we are comparing GCM biases with GCM + RCM biases.

One of the reasons of the biases in the RCMs could be the biases in the parent driving GCMs (e.g. Kumar et al. 2006 and Karmalkar et al. 2011). The immediate requirement is the availability of decent estimates of future projections at regional scale (Kumar et al. 2006). This requires a rigorous validation and development of suitable climate change scenarios, along with the estimations of related uncertainties.

The present paper encapsulates a comparison of biases in super high resolution GCM20 and PRECIS both run under the A1B scenario, with observational datasets from Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of the Water Resources (APHRODITE). The second section of this paper shall elaborate a brief introduction to both the models. Third section describes the methodology. This will follow up with the validation, resultsand concluding remarks.

Models Description

GCM20

Current study utilizes the output from a global 20-km mesh model, GCM20 – a joint development of Japan Meteorological Agency (JMA) and the Meteorological Research Institute (MRI). The model has a linear Gaussian grid with a triangular truncation of 959 in the horizontal. Based on operational numerical weather prediction model of JMA, this model incorporates some modifications in radiation and land surface processes (Mizuta et al. 2006). Time step of the model is 6 minutes and has 60 vertical levels with 0.1 hPa top. There are 1920 grids along longitude, and 960 grids along latitude.

PRECIS

Providing Regional Climate for Impact Studies, (PRECIS) is an RCM developed by Hadley Center UK (Jones et al., 2004). It is a 19 level hydrostatic primitive equation grid-point model with boundary forcings of atmospheric pressure, horizontal wind components, humidity and temperature.The present work has taken these boundary conditions under the A1B emission scenario from ECHAM5 (Max Planck Institute for Meteorology, Germany) as input to PRECIS.The RCM is able to downscale a coarse resolution GCM (140 Km X 210 Km) to a finer resolution of 25-km.

Data and Methods

Data Integration and Analysis System (DIAS) archives are accessed to obtain GCM20 temperature and rainfall data at three different time scales over the region [60°-80° N, 20°-40° E].For PRECIS, long term simulations from 1961-2099 are run on an 8 core High Performance Computing Cluster Facility. The output files are post processed and variables of temperature and precipitation are extracted in Net CDF file format. GCM20 output is scaled up to 25-km horizontal resolution to match it up with the grid of PRECIS output. Time slice method (Kusonoki et al. 2006) is utilized to observe the differences between the two models. The baseline period taken for analysis is (1979-1998), for present and near future is (2007-2027) and for far future is (2080-2099).

Validation of both models is done using temperature and precipitation datasets from APHRODITE (Ali et al. 2012). Seasonal analysis (JJAS and DJFM) is done using Climate Data Operators (CDO) developed by Max Planck Institute of Meteorology. The analysis is performed over the region with subdivisions of the domain – the southern sub-domain (Longitudes 61°-73°; Latitudes 23°-30°) and the northern sub-domain (Longitudes 70°-80°; Latitudes 30°-37°) (Figure 1). The choice of sub-domains is made pertaining to the fact that models tend to over/under-estimate the parameters over complex domains (Waheed et al. 2010). Spatial biases in GCM20 and PRECIS seasonal temperature (°C) and precipitation (mm/day) for baseline period (1979-1998) are also constructed.

Future projections are seen through by constructing spatial maps of differences in temperature (°C) and precipitation (mm/day) from GCM20 (2080-2099 minus 1979-1998), GCM20 (2007-2027 minus 1979-1998), PRECIS (2080-2099 minus 1979-1998), and PRECIS (2007-2027 minus 1979-1998). Baseline (1979-1998) and projected (2007-2027, 2080-2099) annual cycles of temperature (°C) and precipitation (mm/day) and standard deviations from PRECIS and GCM20 are constructed to analyze baseline and future climatological patterns.

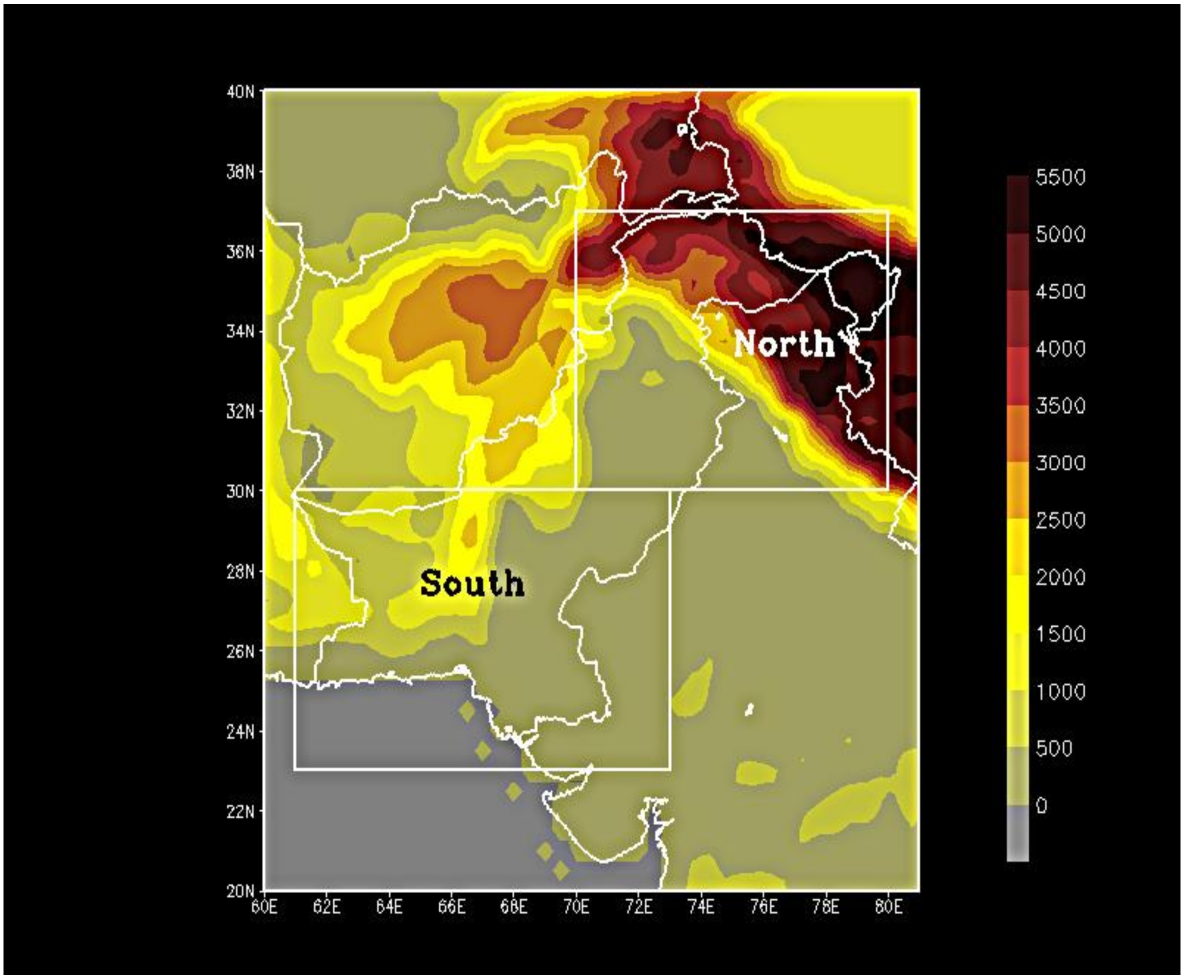

Figure 1: Regional relief map with highlighted Northern (Longitudes 70°-80°; Latitudes 30°-37°) and Southern (Longitudes 61°-73°; Latitudes 23°-30°) sub-domains. Terrain height is shown in meters.

Verification of the Models

Purpose of verification is to see how close the modeled descriptions are to the observed.Figure 2 represents baseline temperature climatology of Northern sub-domain plotted by data from PRECIS, GCM20 and observed dataset APHRODITE. The results of PRECIS tend to remain close with the results of APHRODITE for FMAMJ but tend to underestimate significantly for the remaining months. GCM20 shows larger underestimation than PRECIS for JFMAMJJA, but shows quite comparable underestimation for the remaining months. Both PRECIS and GCM20 overall underestimate temperature in Northern sub-domain with PRECIS being smaller in differences than GCM20.

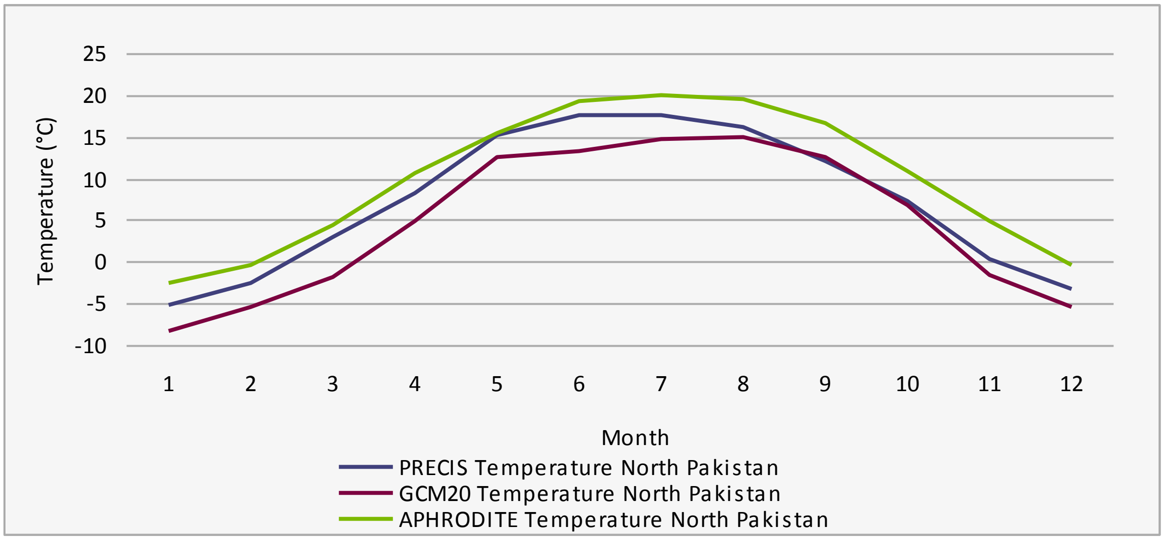

Figure 2: Baseline (1979-1998) temperature climatology (°C) of northern sub-domain (Longitudes 70°-80°; Latitudes 30°-37°).

Towards Southern sub-domain there is relatively more of a synchronization in temperature regime of PRECIS and GCM20 with APHRODITE (Figure 3). Temperature peak of GCM20 leads that of PRECIS and APHRODITE by one month (May to June) referring to a better climatology aspect of PRECIS in relevance with APHRODITE. Nevertheless a good matching trend of GCM20 with APHRODITE is observed for the rest of the months in climatology.

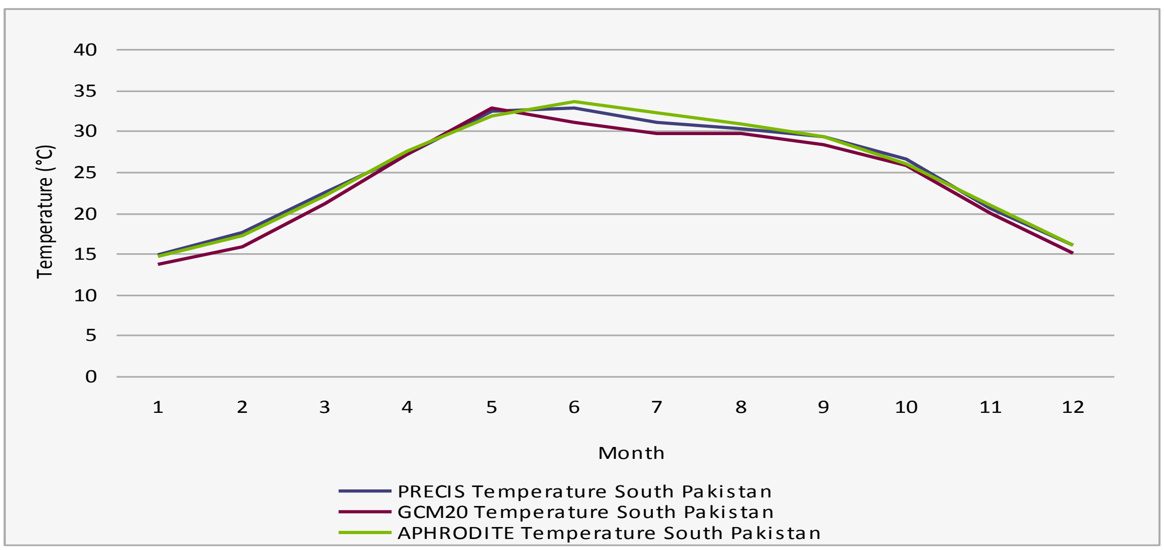

Figure 3: Baseline (1979-1998) temperature climatology (°C) of southern sub-domain (Longitudes 61°-73°; Latitudes 23°-30°).

Regionally averaged baseline precipitation climatology of Northern sub-domain is shown in Figure 4. Both PRECIS and GCM20 overestimate precipitation with reference to APHRODITE. Compared to GCM20 larger precipitation deviations in PRECIS are observed in JJASON, whereas smaller precipitation deviations are observed in DJFMAM over the Northern sub-domain. Large deviations in DJFMAM GCM20 precipitation seems to be the result of more influence of westerly disturbances in the model's physics scheme.

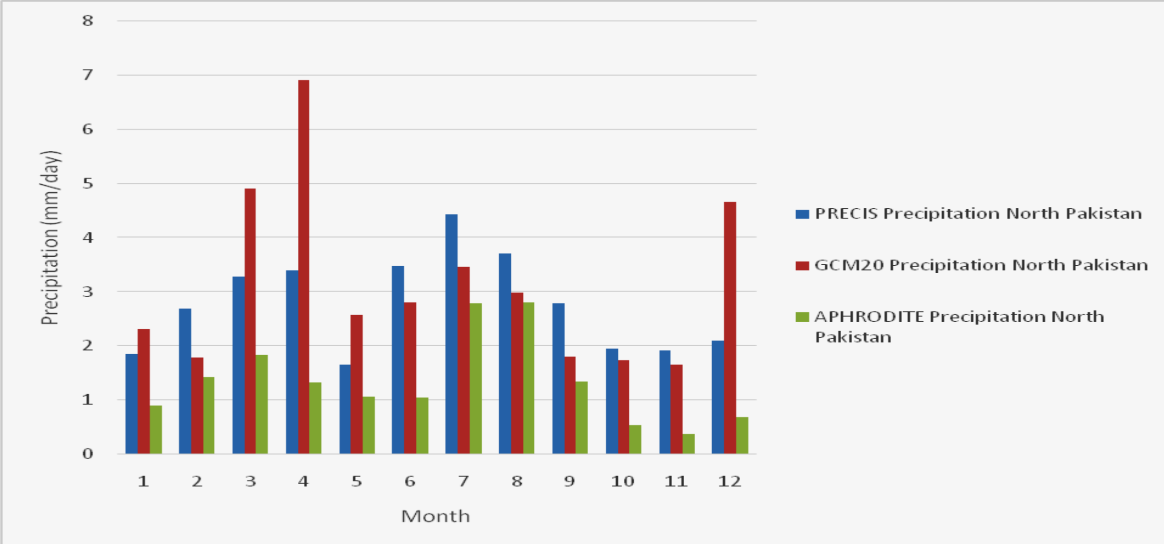

Figure 4: Baseline (1979-1998) precipitation climatology (mm/day) of northern sub-domain (Longitudes 70°-80°; Latitudes 30°-37°).

Baseline precipitation climatology for Southern sub-domain is shown in Figure 5. GCM20 precipitation climatology is quite underestimated with reference to APHRODITE for the Southern sub-domain in ON and JFMA, whereas it is largely overestimated in JJAS. PRECIS underestimates precipitation in the southern sub-domain for DJFM and quite largely overestimates it in the southern sub-domain for AMJJASON. Nevertheless the magnitude of overestimation of PRESCIS for JJAS is quite less as compared to the magnitude of overestimation of GCM20 in the southern sub-domain.

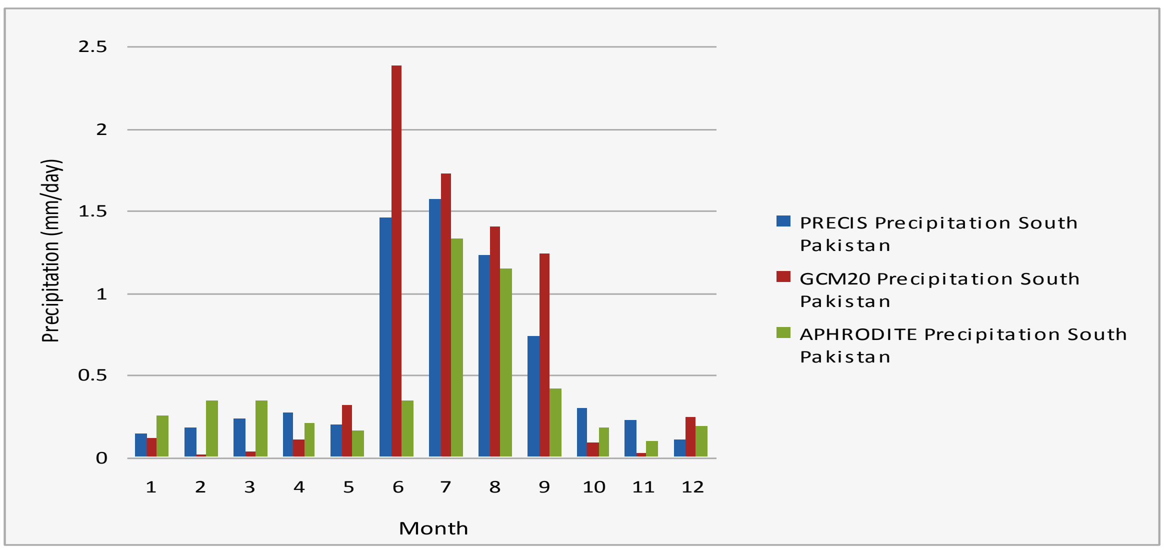

Figure 5: Baseline (1979-1998) precipitation climatology (mm/day) of southern sub-domain (Longitudes 61°-73°; Latitudes 23°-30°).

Spatial biases in temperature regime of the two models, GCM20 and PRECIS, with observational dataset APHRODITE for the baseline period 1979-1998 on seasonal basis is shown in Figure 6. The analysis shows that both GCM20 and PRECIS tend to underestimate temperature significantly for both seasons JJAS and DJFM in the north-most region of the domain which is largely composed of heterogeneous terrain of cryosphere. The elevation model in Figure 1 show that the terrain height has large variance with flats and peaks ranging from 3000-6000 m.a.s.l. respectively. The spatial underestimation of GCM20 temperature extends to Pakistan-Afghanistan-Iran border line in DJFM which signifies limitations in reproducing westerly systems by GCM20. The magnitude and spatial extent of the north-most biases in GCM20 are greater than that in PRECIS, however positive biases over Afghanistan are of more significance in PRECIS for both seasons JJAS and DJFM.

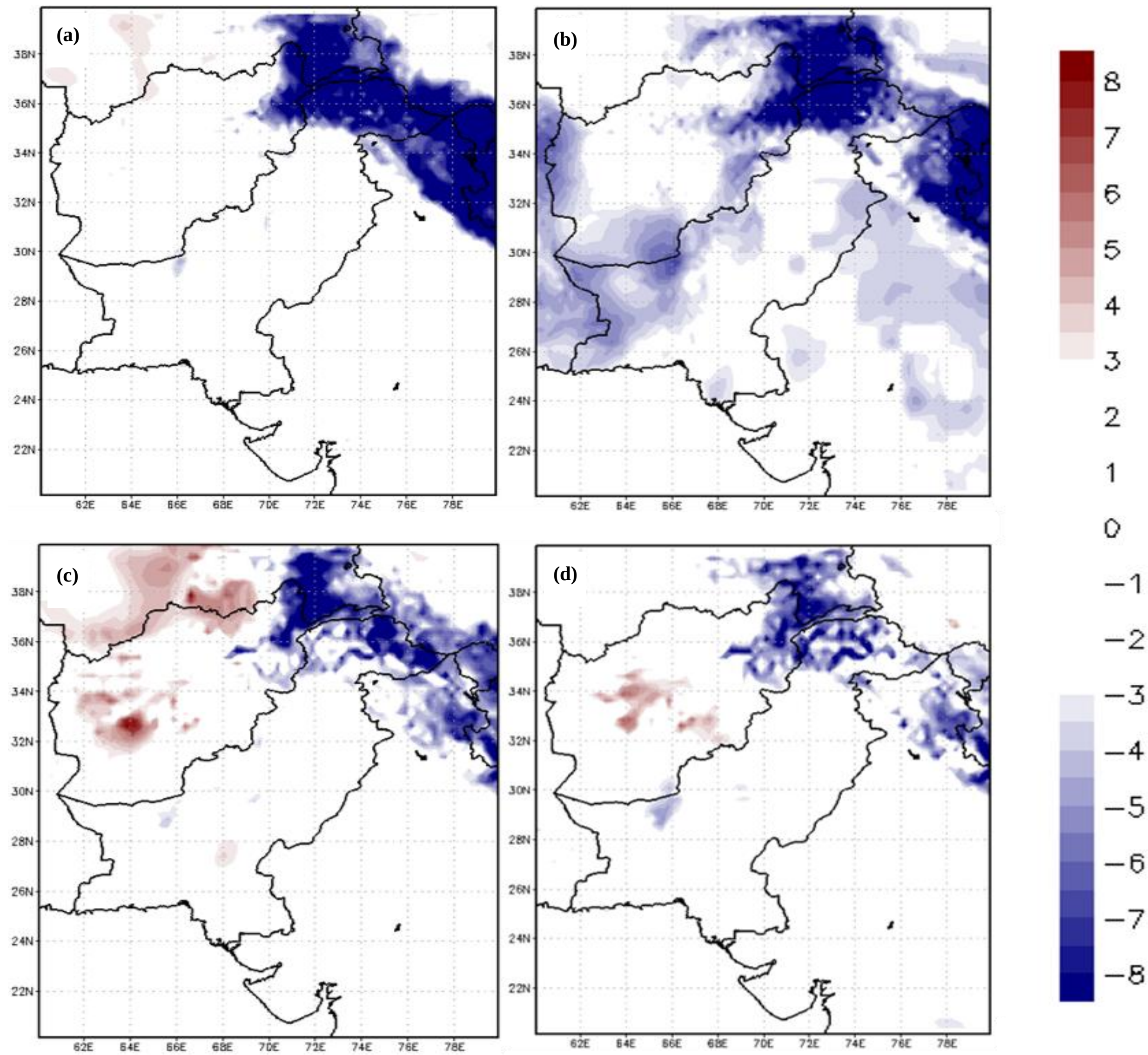

Figure 6: Temperature bias (°C) with APHRODITE for baseline period (1979-1998) **(a)** GCM20 JJAS, **(b)** GCM20 DJFM, **(c)** PRECIS JJAS, **(d)** PRECIS DJFM.

Spatial biases in time averaged baseline (1979-1998) precipitation regime for both models, GCM20 and PRECIS, with observational dataset APHRODITE, on seasonal basis is shown in Figure 7. Both GCM20 and PRECIS show significant positive biases in DJFM over the north-most cryospheric region of the domain, whilst the remainder of the domain has either no or quite insignificant biases which is coherent feature of both the models. Summer-time precipitation is largely influenced by monsoonal currents which protrude early June into the Indian region and late June into the Pakistan region. Spatial patterns of GCM20 JJAS precipitation biases suggests a combination of overestimation and underestimation along the monsoonal belt, while spatial patterns of PRECIS JJAS precipitation biases are largely positive with greater magnitude than those of GCM20.

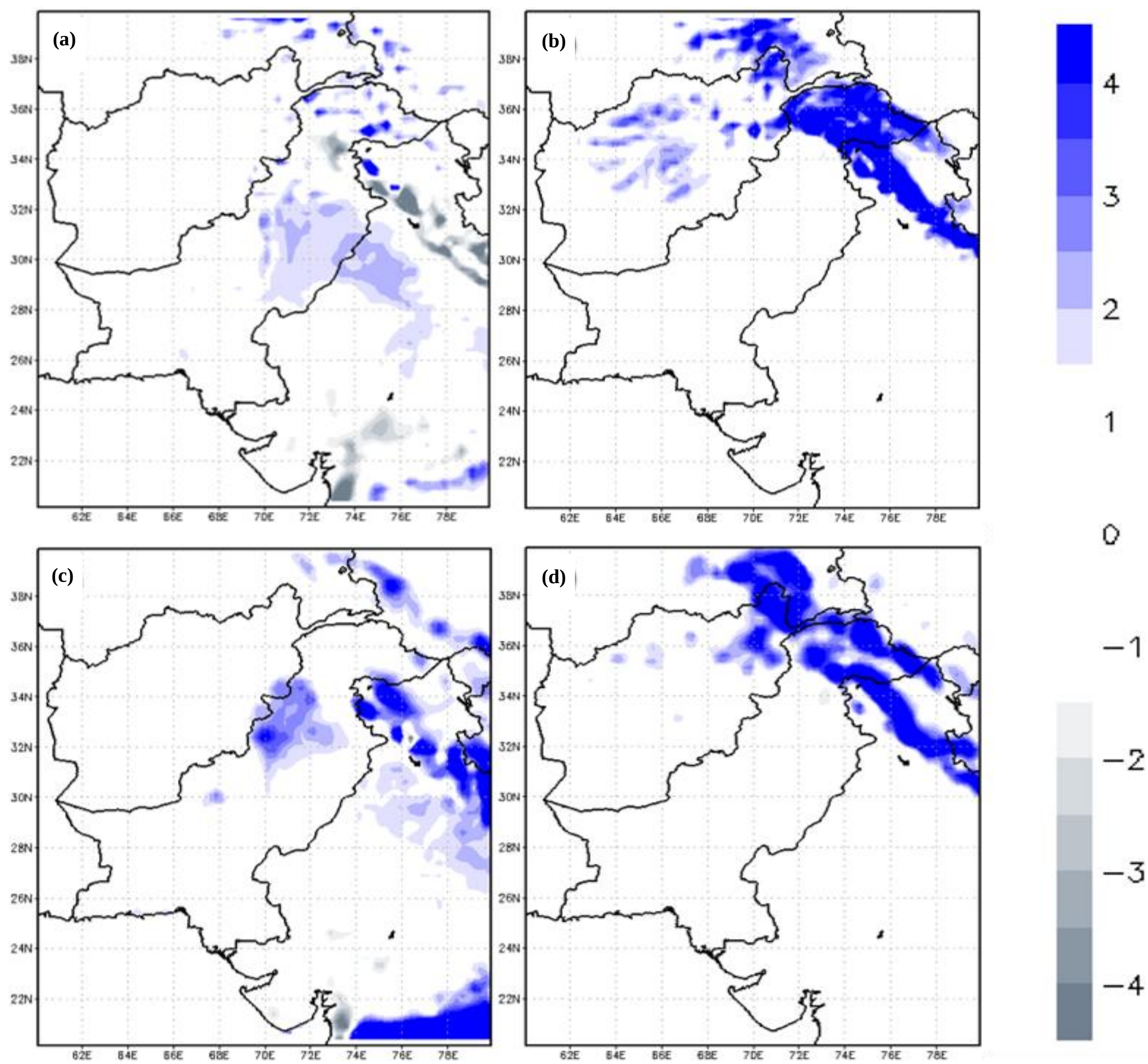

Figure 7: Precipitation bias (mm/day) with APHRODITE for baseline period (1979-1998) **(a)** GCM20 JJAS, **(b)** GCM20 DJFM, **(c)** PRECIS JJAS, **(d)** PRECIS DJFM.

Results

Projected changes in temperature from both GCM20 and PRECIS for near future (2007-2027 minus 1979-1998) and far future (2080-2099 minus1979-1998) are shown in Figure 8. Both models tend to show relatively more warming in the far future (Figure (8a) and Figure (8c)) than that in the near future (Figure (8b) and Figure (8d)). There is a warming contrast from North to South in the far future change shown by GCM20 i.e. more warming (greater than 3 °C) is exhibited in the North with heterogeneous terrain relative to a comparatively lesser warming in the South (2 °C-3 °C). PRECIS shows higher degrees of warming (greater than 3 °C) in the far future that covers almost complete domain with the exception of the monsoon belt and the Indian Ocean. Differences of near future with the baseline show relatively greater magnitude of warming in the North-most and South-most regions of the domain whilst smaller or no significant differences in the central region of the domain. The analysis of both the models suggests that the areas covering the monsoon belt shall receive less warming effects than those which seldom receives it. Moreover regions with higher terrain shall receive relatively greater warming in the near and far future. Magnitude of the temperature increase in the near future relative to baseline for GCM20 suggests a 1 °C-1.5 °C rise whereas for PRECIS it suggests a 1.5 °C-2 °C rise in the region.

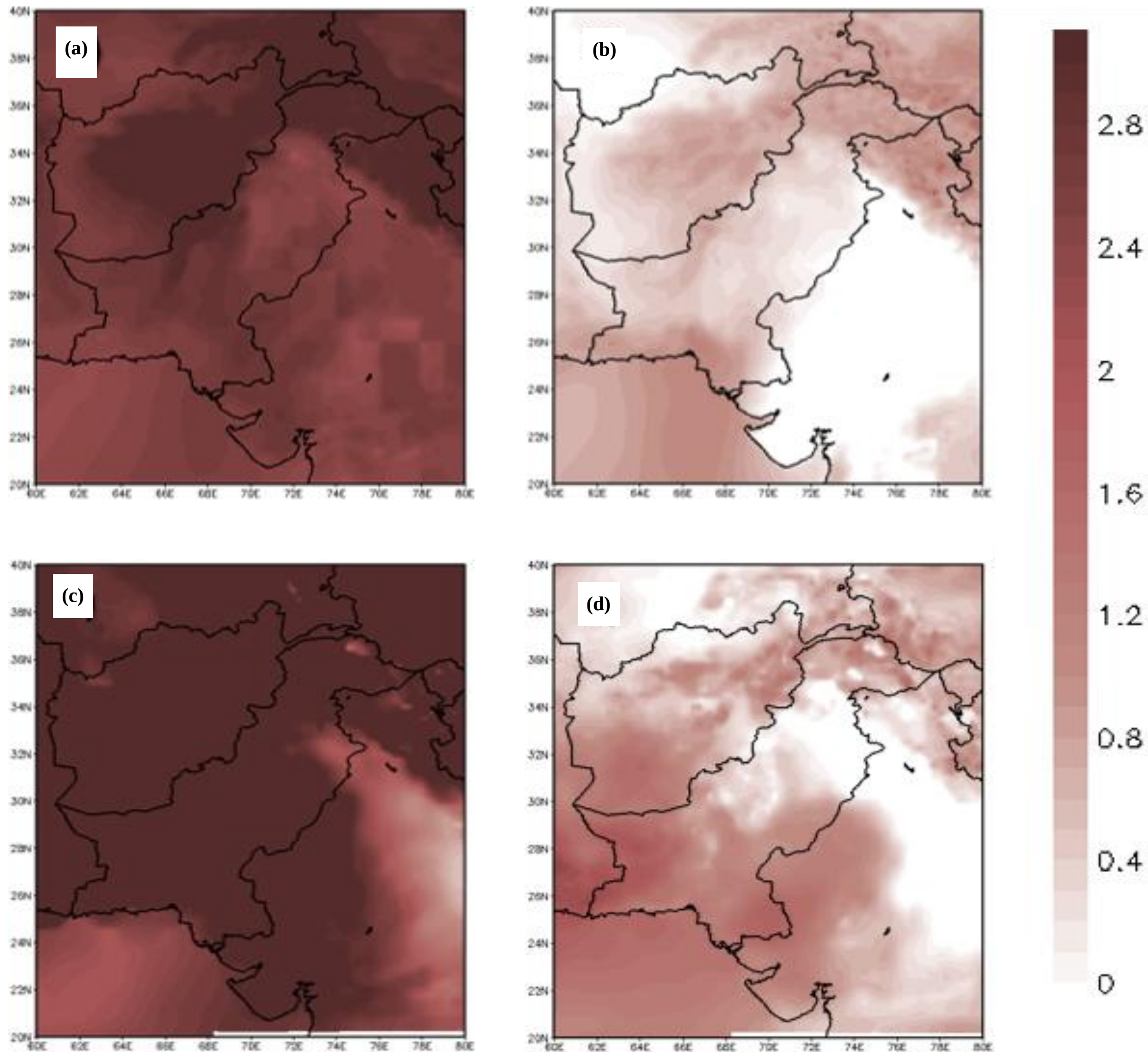

Figure 8: Projected changes in temperature (°C) from **(a)** GCM20 (2080-2099 minus 1979-1998), **(b)** GCM20 (2007-2027 minus 1979-1998), **(c)** PRECIS (2080-2099 minus 1979-1998), and **(d)** PRECIS (2007-2027 minus 1979-1998).

Projected changes in precipitation for both GCM20 and PRECIS relative to near future and far future are shown in Figure 9. Both models, irrespective of the time span show a relative precipitation increase (0.5 mm/day-1 mm/day) in the extreme Northern region of the country. Northern region of the domain is comprised of Hindukush, Karakoram and Himalayan region which has peaks higher than 6000 meters and are largely comprised of snow-cover throughout the year. Both models project an increase of snow precipitation for near and far future in that region. The regions of upper Punjab and KPK are suggested to receive more rainfall (0.2 mm/day-0.6 mm/day) as projected by far future in GCM20 and decreased rainfall (0.2 mm/day-0.8 mm/day) as projected by far future in PRECIS, which is a significant contrast projected by the models. The trail of Himalayas show a relatively precipitation decrease by both the models in the far future. The region of Sindh and adjacent regions of India are shown to receive lesser a rainfall (0.5 mm/day-1.5 mm/day) in the near future as projected by GCM20, whereas the regions are shown to receive slightly more of a rainfall (0.2 mm/day-0.4 mm/day) in the near future as projected PRECIS. This is a significant contrast in the model's output and is possibly related to the contrast in the magnitude of temperature change for the same region (refer to Figure (8b) and Figure (8d).

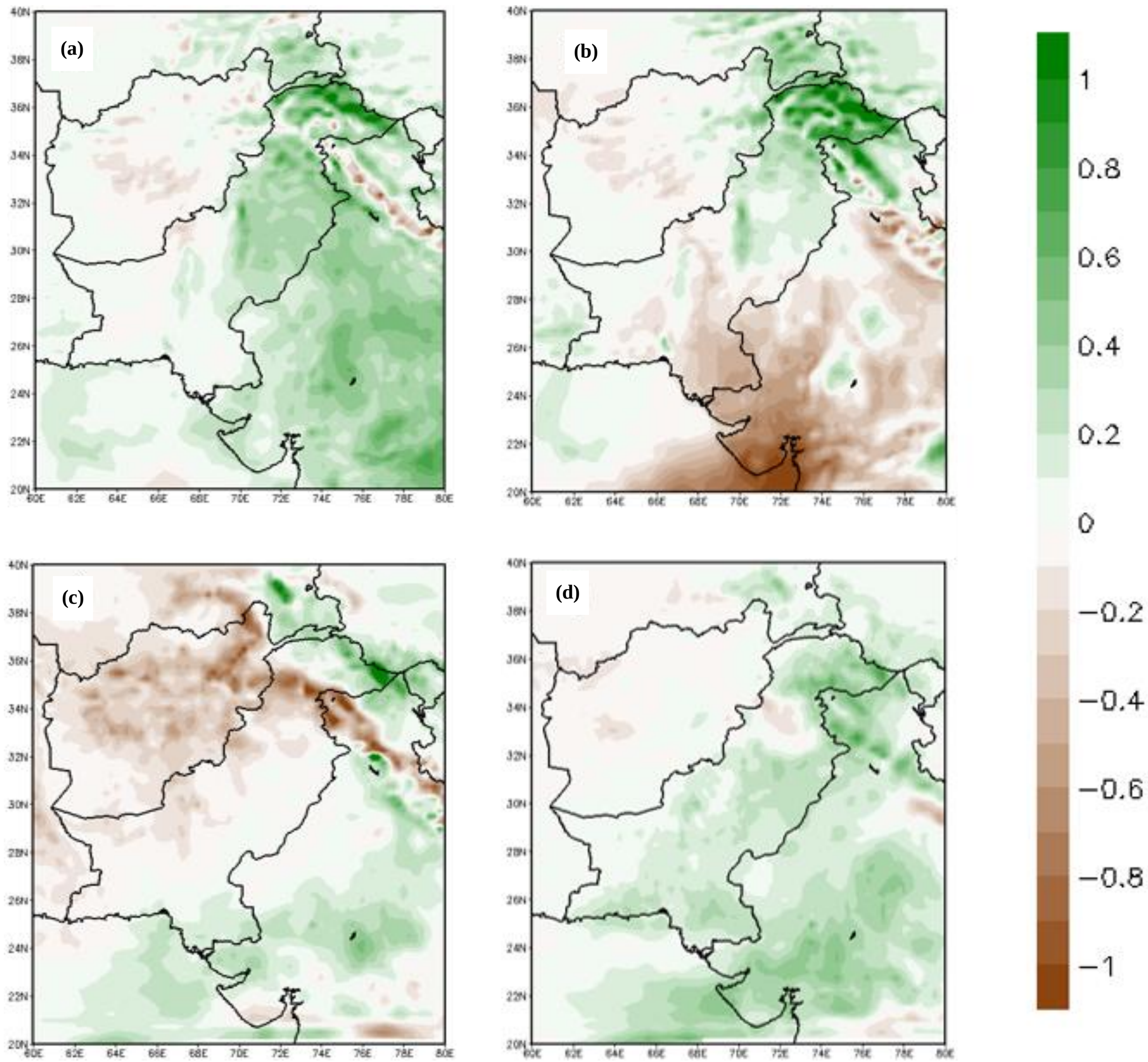

Figure 9: .Projected changes in precipitation (mm/day) from **(a)** GCM20 (2080-2099 minus 1979-1998), **(b)** GCM20 (2007-2027 minus 1979-1998), **(c)** PRECIS (2080-2099 minus 1979-1998), and **(d)** PRECIS (2007-2027 minus 1979-1998).

A compendium of GCM20 and PRECIS (temperature and precipitation) regionally averaged annual cycles are shown in Figure 10. Seasonal variations in both temperature and precipitation are well coordinated amongst both the models, however, differences lie in the magnitudes of both parameters. Magnitude of DJFMAM precipitation output of PRECIS is smaller than DJFMAM precipitation output of GCM20 for all three time scales, whilst magnitude of JJASON precipitation output of PRECIS is greater than JJASON precipitation output of GCM20 for all three time scales. In the temperature regime, the annual cycles of regionally averaged PRECIS are warmer than the regionally averaged annual cycles of GCM20 for all corresponding time scales. This result is consistent with the spatial results from Figure 8 (a-d) where PRECIS shows an overall relatively greater warming in the near and far future when compared with results from GCM20.

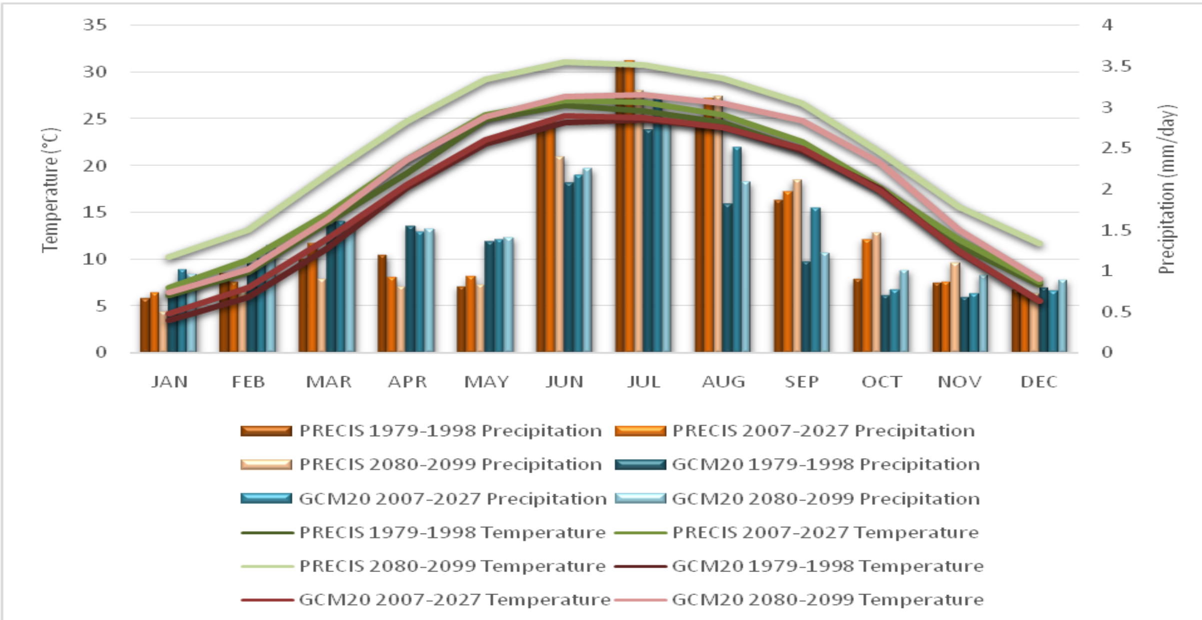

Figure 10: Baseline (1979-1998) and projected (2007-2027, 2080-2099) annual cycles of temperature (°C) (lines) and precipitation (mm/day) (bars) from PRECIS and GCM20 over Pakistan.

Figure 11 is the regionally averaged annual cycles of baseline and projected temperature and precipitation standard deviations. Both temperature and precipitation standard deviations from GCM20 are smaller than the standard deviations from PRECIS. Nevertheless the results of the annual cycles of the standard deviations are proportional amongst the models for all three time slices. Smaller time variances of GCM20 precipitation are result of small-scale-high-intensity rainfall due to sheer gradient of mountainous ranges of the region (Nakayama et al., 2011). These details are of significance, but are currently outside the scope of this paper.

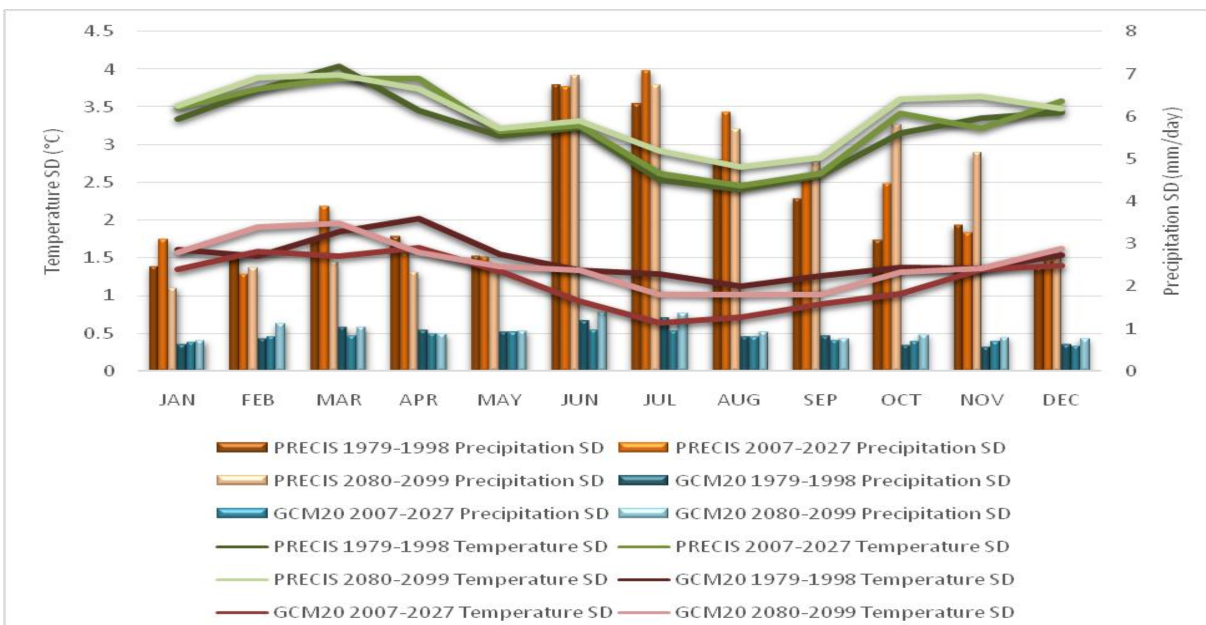

Figure 11: Baseline (1979-1998) and projected (2007-2027, 2080-2099) annual cycles of temperature standard deviation (°C) (lines) and precipitation standard deviation (mm/day) (bars) from PRECIS and GCM20 over Pakistan.

Conclusion

Performance of PRECIS and GCM20, whose horizontal resolutions are almost the same (25 Km and 20 Km respectively), was compared over the region of Pakistan, Afghanistan and climate active regions of Hindu Kush, Karakoram and Himalayas. Both models significantly succeeded to simulate various temperature and precipitation parameterization aspects with reasonable biases with observational dataset APHRODITE. The verification results show that both PRECIS and GCM20 underestimate temperature in Northern sub-domain with PRECIS being smaller in differences than GCM20. Towards Southern sub-domain there is relatively more of a synchronization in temperature regime of PRECIS and GCM20 with APHRODITE.In the Northern sub-domain both PRECIS and GCM20 overestimate precipitation. The magnitude of overestimation of PRESCIS for JJAS is quite less as compared to the magnitude of overestimation of GCM20 in the southern sub-domain.

Although, simulations for both models were run under different frameworks of dynamical and physical processes, yet the results encourage us to use GCM20 after bias correction at par with PRECIS to study climate change scenarios. RCMs are downscaling tools. If GCM data is already available at higher resolution, there is no need to employ further downscaling resources.

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