Climate Projections Downscaling and Impact Assessment on Precipitation over Upper Bagmati River basin, Nepal

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Abstract

Climate projections are extensively used for assessing the climate change impact on different sectors. Global Climate Models (GCM), which are considered as most reliable tool for simulating the response of global climate system to increasing greenhouse emissions, provide estimates of climate variables like temperature, precipitation etc. for the past, current and future periods. However, because of oversimplification of the global climate system in the GCM, the climate projections are not suitable for direct use at local (basin) scale for assessing the climate change impact. In this study, we have employed a very high resolution GCM precipitation output of Meteorological Research Institute (MRI), Japan for assessing the impact of climate change on precipitation pattern over upper Bagmati river basin. Daily observation precipitation data of 1979-2003 periods (as current climate) at 16 stations inside/around the upper Bagamati river basin were compared with the corresponding MRI-GCM precipitation data for identifying the biases. The comparison revealed that there is need of downscaling i.e., bias correction in precipitation frequency and intensity. Quantile-based bias correction was employed to correct the MRI-GCM precipitation data of 2075-2099 periods as future climate for the impact assessment. The impact assessment was carried out in term of annual, monthly and daily values. The analyses revealed that annual precipitation will increase significantly in the future. The study also found that there will be significant increase in monsoon precipitation and decrease in other months. In relation to climate change impact on extreme (maximum) precipitation events, the study found that there will be frequent heavy precipitation. These changes on the future precipitation will have complex implications on the water supply/sanitation systems of the Kathmandu valley, farming systems, stormwater/flood management systems and others in the region.

Keywords : Bias correction, Climate change, Downscaling, Global climate model

1. INTRODUCTION

Human activities, primarily the burning of fossil fuels and changes in land cover/use, are believed to be increasing the greenhouse gases concentrations. This alters energy balances and leads to warming of atmosphere which will result in climate change. It is increasingly recognized that the climate change will impact less or more on all sectors of the society. Intergovernmental Panel on Climate Change (IPCC, 2007) point out that water and its availability and quality will be the main pressures on, and issues for societies and the environment under climate change. Climate change has greater implication on water resources systems. The most common approach has been to combine basin-scale hydrologic models with climate projections. In recognition of the economic significance of water resources, many studies have sought to examine the effects of climate change on precipitation pattern, and hydrologic regime (Dore 2005, Kleinn et al. 2005; Abbs et al. 2007). These studies suggest that several regional precipitation trends can already be detected and will likely increase in the future due to climate change. In particular, wet regions are increasingly experiencing higher levels of precipitation, and arid areas are witnessing reduced levels and becoming drier.

Global climate models (GCMs) are currently the most credible tools available for simulating the response of the global climate system to increasing greenhouse gas concentrations, and provide climatic variables such as temperature, precipitation etc. The GCM outputs are based on coarse resolution information (for example, orography, land surface etc.) for the generation of climatic variables. However, forcing and circulation which affect local (basin) climate generally occur at much finer scale than that of GCM. Therefore, direct use of GCM outputs is not suitable for the impact assessment, and hence spatial downscaling is required. Spatial downscaling is the process of deriving finer resolution (i.e., local) climate data from the coarse GCM output for the climate change impact studies at local level. There are various downscaling techniques available to convert GCM outputs to local scale for an appropriate impact assessment at local or basin level. However, it is not clear which downscaling method provides the most reliable estimates. The different downscaling techniques can

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be categorized into dynamical and statistical types. The statistical downscaling is much less computationally demanding than the dynamical downscaling. The most commonly used statistical models are regression, stochastic weather generator, weather typing, bias correction, percentile mapping and spatial disaggregation. These methods of downscaling have successfully been carried out in different part of the world (Shabalova et al. 2003; Coulibaly and Dibike, 2004; Hansen et al. 2006). Use of different downscaling methods depends on the objective of the study. Bias correction method of downscaling minimizes the biases of GCM outputs for each of the grids. The bias correction methods largely eliminate the error of the GCM with added emphasis on statistical characteristics of observation data. Globally, several studies have been performed in which a bias correction method was applied to correct GCM data (for example, Sharma et al. 2007; Ines and Hansen, 2005; Elshamy et al. 2009). Rescaling is the easiest bias-correction method to rectify the systematic error in the mean precipitation amount. Leander and Buishand (2007) applied a power law transform, which corrects for the coefficient of variation and mean of the precipitation values. They found that the corrected precipitation data did not contain the day-to-day variability which was present in the observed data set.

The objective of this study is to (i) identify biases in the GCM precipitation output; (ii) apply suitable bias correction in the GCM precipitation output; and (iii) finally assess the impact of climate change on precipitation pattern. Bias in GCM precipitation was identified by comparing the GCM precipitation with corresponding observation data. Quantile-based bias correction method (a statistical downscaling model) was employed for correcting biases in the GCM precipitation data. A quantile-based bias correction method is useful to statistically transform the GCM precipitation to bias corrected data and to make it applicable for use in impact assessment. A combination of empirical-gamma transformation can be applied to correct the frequency and intensity of daily GCM precipitation.

The downscaling and impact assessment study has been applied in one of the Nepalese river basin. A few climate change impact studies are found for the Nepalese region (for example, Chaulagain 2006; Chaudhary and Aryal, 2009). A subjective study by Agrawala et al. (2003) on impact of climate change to different sectors of Nepal suggested that water resources and hydropower rank significantly higher than any other sector. NCVST (2009) investigated the climate change projections in the Nepalese region and found no clear trend change for annual precipitation. Also, their study found that there will be increase in monsoon precipitation and decrease in the dry months' precipitation. However, these studies are lacking in the part of downscaling and then assessing the climate change impact assessment precisely at basin level using a high resolution GCM.

In this study, we intend to investigate an appropriate downscaling technique and, then climate change impact on precipitation pattern in upper Bagmati river basin of Nepal. Bagmati river basin is an important river basin of Nepal. Any significant change in precipitation pattern will have direct impact on the drainage systems, crop yield, water supply for drinking, domestic, hydropower and others. The climate change impact assessment has been carried out in terms of annual/monthly average precipitation, frequency and intensity of extreme events. GCM output of Meteorological Research Institute (MRI), Japan has been used for assessing the climate change impact. The MRI-GCM output with spatial resolution of 20-km and daily temporal resolution of 1979-2003 and 2075-2099 periods as current and future climate respectively have been used for the study.

Section 2 provides description of the study area and the precipitation data-sets. Section 3 provides brief understanding of the two general approaches of downscaling; dynamical and statistical. In Section 4, concept of quantile-based bias correction approach and its application/validation in the study area has been discussed. Section 5 deals with the results and discussion of climate change impact on precipitation pattern over the upper Bagmati river basin. Final section summarizes the investigation of climate projections downscaling and impact assessment.

2. STUDY AREA AND DATA

The study on downscaling technique and climate change impact assessment was carried out in Bagmati river basin (upstream of Pandheradovan hydrological station with station index 589) Nepal (Figure 1). Bagmati river basin is an important river basin of Nepal concerning its significance in water supply for drinking/domestic use to the Kathmandu valley, irrigation and other activities. The Bagmati basin originates in the Mahabharat range of the Middle Mountains of Nepal at elevation of around 2700 m and drains southward into India to join the Ganges River. The river is fed by springs and monsoon precipitation. The annual average precipitation in the basin occurs about 1800 mm. Based on topography, the Bagmati river basin can be broadly categorized as upper (hilly) and lower (plain). Drainage area upstream of Pandheradovan hydrological station is 2839 km^2. The upper Bagmati river basin extends between 85.04° to 85.97° east and between 27.11° to 27.82° north. Lower Bagmati river basin region is a flood prone area. Many Nepalese still remember the 1993 flood which caused severe damage to life/property in the lower region (Sarlahi and Rautahat districts). The same flood had also resulted severe damage to the Bagmati irrigation project barrage.

Observation daily precipitation data of 16 stations, which are inside or around the upper Bagmati river basin, have been employed in this study (Figure 1). These daily precipitation data were collected from the Department of Hydrology and Meteorology, Nepal for the period of 1979-2003 as current climate. The MRI-GCM precipitation was selected for the impact study due its easy accessibility, high temporal and spatial resolution as compared to other climate models. The MRI-GCM data has a spatial resolution of approximately 20-km at daily time-scale (Kusunoki et al. 2008). The MRI-GCM is based on the IPCC Special Report on Emission Scenario A1B (IPCC, 2000). The A1B scenario involves intermediate emission scenario characterized by a future world of very rapid economic growth, a global population that peaks in the middle of the 21st century and declines thereafter, and a balanced introduction of new and more efficient technologies of all energy supply. The MRI-GCM data was made available at institutional level for the period of 1979-2003, 2015-2039 and 2075-2099 (each with 25 years length) as present, near-future and far-future term respectively. In this study, the MRI-GCM data has been used of 1979-2003 and 2075-2099 periods as current climate and future climate respectively. A total of 13 numbers of MRI-GCM grids were found to be covering all the upper Bagmati river basin.

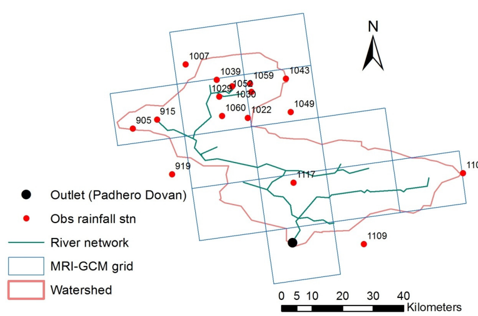

Figure 1: Upper Bagmati river basin

3. CLIMATE PROJECTIONS AND DOWNSCALING

Climate projections are widely used to understand the likely impact of climate change on different sectors. A climate projection is synthetic time series of climate variables with the goal that the statistics of the time series will look similar to the real world data. The climate projections can be for past, current or future conditions. GCM simulate the response of greenhouse gas concentrations, and provide estimates of climate variable such as temperature, precipitation etc. GCM is a mathematical model of the general circulation of the planet's atmosphere or oceans based on mathematical equations that represent physical process.

GCM outputs are not suitable for direct use to assess climate change impact at local or basin because of their oversimplification in term of coarse resolution input information, equations resolving and others. For example, GCM uses information on orography, land surface etc. at coarse resolution. However, forcing and circulations which affect local climate generally occurs at much finer scale than that of GCM. Therefore, there is need of some processing of the GCM outputs by incorporating local observation information so that the GCM outputs can be used for the assessment of climate change impact at local level. Downscaling is the process of deriving local level climate projections from the GCM outputs. There are various downscaling techniques to convert the GCM outputs into locally applicable climate data. Broadly, the different downscaling techniques are classified into dynamical and statistical methods.

3.1 Dynamical Downscaling

Dynamical downscaling method converts GCM outputs into local climate data by using a regional climate model (RCM) with GCM outputs as boundary conditions. RCM enhances the simulation of atmospheric circulations and climate variables at fine spatial scales. While RCMs are the most informative downscaling approach, they also have several limitations. RCM requires considerable computational resources and they are as expensive to run as GCM.

3.1 Statistical Downscaling

The statistical downscaling techniques use models of correspondence between GCM contemporary climate scenarios data and real world data. The statistical downscaling models use GCM projection climate scenario data as input to correspondence models to predict the expected future real world data. The fundamental assumption is that statistical relationship will remain valid under future climate change scenario. The statistical downscaling is much easier than the dynamical downscaling.

4. QUANTILE-BASED BIAS CORRECTION

It is necessary to understand what kind of biases exists in the GCM output for effective bias correction. For this purpose, we first plotted observation climate stations inside/around the study area over the MRI-GCM grids. This enabled to know what grids cover the study area and which grid corresponds to which climatic stations. Visual check was performed to check the consistency of the observation precipitation data series of the various stations. The daily observation and GCM precipitation series were compared for the 1979-2003 period for identifying the biases pattern in the GCM precipitation data.

Comparison of mean monthly wet days point out that number of GCM rainy days is considerably higher than that of observation precipitation data. It was also found that monsoon months (June to September) had almost all rainy days for GCM precipitation output which is far beyond the reality. Other months were found to have 15 or more number of rainy days. However, in reality other months are mostly dry. Comparison of mean monthly precipitation amount pointed out that monsoon months have relative error of nearly 20%. Comparison of mean monthly precipitation intensity pointed out that the precipitation intensity is largely underestimated in the GCM precipitation values.

In general, the GCM precipitation output consisted of too many wet days and smaller precipitation values. Hence, we need to make correction in precipitation frequency and intensity of GCM daily precipitation output. Quantile-based bias correction was applied to minimize biases in precipitation frequency and intensity. Quantile-based method corrects precipitation frequency and intensity by carrying out frequency analysis.

4.1 Precipitation frequency correction

Precipitation frequency is corrected by truncating smaller precipitation values from the GCM precipitation output by comparing the zero precipitation non-exceedance probabilities of observation and GCM data series. Empirical frequency analysis was carried out for both GCM and observation values of precipitation values. Probability of non-exceedance corresponding to zero precipitation for observation precipitation data series was determined for truncating smaller GCM precipitation values. As the GCM output consists of too many smaller precipitation values, the probability of non-exceedance corresponding to zero GCM precipitation is quite smaller than that of historical data series. The GCM precipitation values which have smaller non-exceedance probability than that of zero observation precipitation are truncated. This makes lower precipitation values of GCM data as zero precipitation i.e., dry day. Hence, it helps in reducing the number of wet days. In this way, precipitation frequency is corrected by applying empirical quantile-based bias correction technique.

4.2 Precipitation intensity Correction

In quantile-based bias correction for precipitation intensity, truncated GCM values are modified in such a way that GCM precipitation approaches to observation precipitation for each of the non-exceedance probability. We employed gamma distribution in precipitation intensity correction as it is widely recognized that the distribution of daily precipitation can be approximated by the gamma distribution. Following are the major steps which were employed for correcting the precipitation intensity.

- Fit a gamma distribution for observed daily precipitation series– $F_{obs}(x_{obs})$
- Fit a gamma distribution for GCM precipitation of the same period – $F_{GCM20}(x_{GCM20})$
- Fit a gamma distribution for 21st century GCM precipitation – $F_{GCM21}(x_{GCM21})$
- Compare the GCM distribution with observed distribution and correct the truncated GCM precipitation using Eq.1.

$$x_{GCM20_{corrected}} = F_{obs}^{-1}(F_{GCM20}(x_{GCM20})) \quad (1)$$

Correct the future GCM using Eq.2.

$$x_{GCM21_{corrected}} = x_{GCM21}\frac{F_{obs}^{-1}(F_{GCM21}(x_{GCM21}))}{F_{GCM20}^{-1}(F_{GCM21}(x_{GCM21}))} \quad (2)$$

4.3 Validation of Quantile-bias Correction Method

Precipitation intensity was corrected by adjusting cumulative distribution function (CDF) of truncated non-zero precipitation values so that CDF of GCM precipitation approaches to CDF of observation precipitation values. After truncating the smaller rainy days from GCM precipitation series, we found that average annual rainy days in the GCM output approached very closer to observation rainy days. For illustration, mean monthly wet days for the raw and corrected GCM precipitation has been compared with mean monthly observation rainy days at Kathmandu airport (Figure 2).

Figure 3 shows the comparison of mean monthly precipitation amount for raw and corrected GCM daily precipitation output with that of observation data. It is clear that relative error has been largely reduced for corrected GCM precipitation data series. The relative error in mean monthly precipitation amount for the raw GCM was varying from 5.6 to 172.7%. On the other hand, relative error in mean precipitation amount in corrected GCM precipitation amount was found to be from 2.1 to 47.2%.

Figure 4 provides comparison of mean monthly precipitation intensities for raw and corrected GCM output against observation precipitation intensity. Biases in mean monthly precipitation intensity have been significantly reduced for the corrected GCM precipitation output.

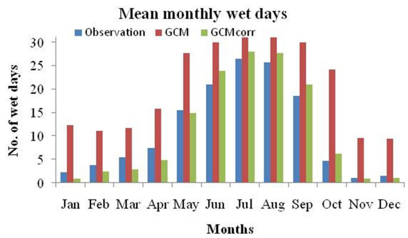

Figure 2: Comparison of mean monthly rainy days at Kathmandu airport

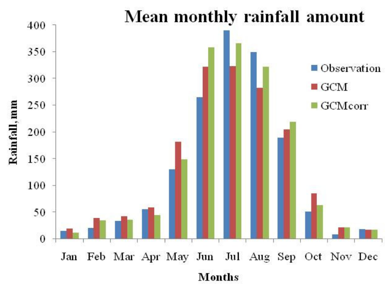

Figure 3: Comparison of mean monthly precipitation amount at Kathmandu airport

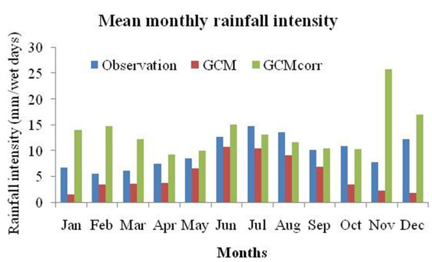

Figure 4: Comparison of mean monthly precipitation intensity at Kathmandu airport

5. ASSESSMENT OF CLIMATE CHANGE IMPACT

This study aims to assess climate change impact at basin scale. In this regard, at first, the climate change impact assessment was performed at each of the grids in the study area, and then basin level impact was assessed by averaging the results of all the grids. A reliable precipitation dataset for each of the MRI-GCM grids for current and future climate was prepared using the quantile-based bias correction method. The climate change impact assessment has been made by comparing the frequency of extreme precipitation events, annual precipitation sum, monthly precipitation values and return period precipitation estimates for 5-, 10-, 20-, 50- and 100-years periods for the current and future climate.

5.1 Comparison of Extreme Precipitation Events

Empirical frequency analysis was carried for current and future precipitation data series for assessing change in frequency of extreme precipitation events at each of the grids. Precipitation value corresponding to 99.9th non-exceedance probability for current climate was used as threshold to examine the change in frequency of extreme events. Number of precipitation events above the threshold values was counted at each of the grid for the future climate precipitation dataset. This enabled to assess climate change impact on frequency of extreme precipitation events.

Figure 5 provides percentage change in extreme precipitation events in each of the 13 MRI-GCM grids. This point out that climate change will increase extreme precipitation events. However, the percentage change is varying largely from 3 to 75%.

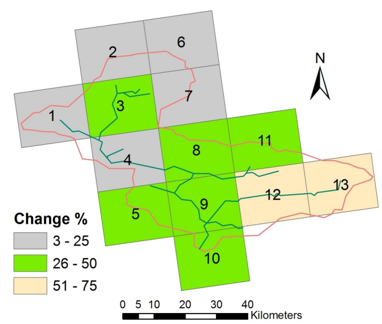

Figure 5: Comparison of percentage change in extreme precipitation events

5.2 Comparison of Annual/Monthly Precipitation Amounts

Annual precipitation sum were computed at each of the grid for the current and future precipitation data series. Changes in annual precipitation sum were computed for the corresponding grids. Table 1 provides comparison of mean annual precipitation and their percentage change for each of the 13 MRI-GCM grids. The table reveals that there will be increase in annual precipitation in future. Percentage change in annual precipitation values is varying from -2.9 to 36.6.

Mean monthly precipitation values were computed at each of the grids for the current and future climate. Basin level mean monthly precipitation values were computed by averaging the mean monthly values of the 13 MRI-GCM grids. Table 2 provides mean monthly precipitation values and their change percentages for the current and future climate. The comparison reveals that there will be significant increase in monsoon (June to September) precipitation. This will result in more floods and landslides in the region. In contrast, there will be less precipitation in the other (dry) months. This will have negative impact on the water supply for the drinking, domestic, irrigation and others use.

5.3 Comparison of Return Period Values

Change in return period estimates are a convenient way of presenting changes in extreme precipitation for a basin. The return period values presented here have been derived by carrying out frequency analysis at each of the grids for the current and future climate precipitation datasets. In this study, empirical frequency analysis was made for the annual maximum daily precipitation series for estimating the return period values. Table 3 provides maximum likely 24-hour precipitation values for the 5-, 10-, 20-, 50- and 100-years return periods. The table points out that there will be significant increase in 24-maximum precipitation in the future. There will be 6 to 89% increase in the 24-hours maximum precipitation in the upper Bagmati river basin (Table 4). Such increase in precipitation will result frequent heavy floods. Consequently, there will be more damages to life and properties in the region if no adaptation measures are taken.

Table 1: Comparison of annual precipitation values

Grid_nu	Annual precipitation, mm		Change, %
	Present_climate	Future_climate	
1	1902	1846	-2.9
2	1529	1669	9.1
3	1612	1709	6.0
4	1598	1540	-3.6
5	2375	2781	17.1
6	1538	1709	11.1
7	1592	1540	-3.3
8	2423	3310	36.6
9	2394	2713	13.4
10	2353	2784	18.3
11	2428	2523	3.9
12	2408	2649	10.0
13	2415	2657	10.0

Table2: Comparison of mean monthly precipitation

Grid_nu	Current climate					Future climate				
	5 years	10 years	20 years	50 years	100 years	5years	10years	20years	50years	100years
1	133.6	163.0	192.4	231.3	260.7	151.5	192.9	234.2	288.9	330.3
2	120.0	140.8	161.6	189.1	209.9	135.9	168.0	200.1	242.5	274.6
3	96.3	117.1	137.9	165.4	186.2	132.9	159.7	186.5	222.0	248.8
4	117.4	150.1	182.7	225.9	258.5	129.9	163.4	197.0	241.3	274.9
5	264.8	347.5	430.1	539.3	621.9	419.8	557.0	694.1	875.3	1012.4
6	120.5	145.2	169.9	202.7	227.4	132.9	159.7	186.5	222.0	248.8
7	108.8	131.0	153.1	182.3	204.4	129.9	163.4	197.0	241.3	274.9
8	219.5	285.5	351.5	438.7	504.7	340.1	424.8	509.5	621.4	706.2
9	240.6	313.7	386.8	483.5	556.6	367.5	480.2	593.0	742.1	854.9
10	279.5	355.3	431.1	531.4	607.2	355.8	434.6	513.3	617.4	696.1
11	194.8	245.4	295.9	362.7	413.2	265.1	342.6	420.1	522.6	600.1
12	206.1	255.3	304.5	369.6	418.8	323.3	423.4	523.5	655.8	755.9
13	212.8	261.2	309.6	373.6	421.9	337.5	448.4	559.3	705.8	816.7

Table 3: Comparison of return period estimates for 24-hour maximum precipitation

Month	Monthly average precipitation, mm		Change, %
	Current_climate	Future_climate	
Jan	14.2	13.2	-7.1
Feb	17.8	11.2	-37.0
Mar	26.4	20.6	-22.0
Apr	98.3	98.3	0.0
May	162.5	161.6	-0.5
Jun	303.5	329.6	8.6
Jul	556.2	614.9	10.6
Aug	443.6	544.4	22.7
Sep	322.4	356.8	10.7
Oct	93.6	72.7	-22.3
Nov	10.8	7.0	-35.7
Dec	27.3	33.5	22.8

Table 4: Comparison of changes in return period estimates

Grid_nu	Change in daily extreme precipitation, %				
	5years	10years	20years	50years	100years
1	13	18	22	25	27
2	13	19	24	28	31
3	38	36	35	34	34
4	11	9	8	7	6
5	59	60	61	62	63
6	10	10	10	10	9
7	19	25	29	32	34
8	55	49	45	42	40
9	53	53	53	53	54
10	27	22	19	16	15
11	36	40	42	44	45
12	57	66	72	77	81
13	59	72	81	89	94

6. CONCLUSION

Bias correction in MRI-GCM precipitation is very important for reliable assessment of climate change impact on the precipitation pattern in upper Bagmati river basin. Comparison of GCM data series with observation data series pointed to correct precipitation frequency and intensity. Bias in precipitation frequency was noticeably minimized by truncating smaller GCM precipitation values based on the non-exceedance probability, F(x_historical=0.0). The quantile-based bias correction considerably enabled to match precipitation intensities of observation and GCM precipitation values.

The quantile-based bias correction method enabled reliable precipitation data series for the current and future climate. Comparison of mean annual precipitation values revealed that there will be increase in annual precipitation in the future. The climate change will result increased monsoon precipitation causing frequent/large floods. Dry months will have lesser precipitation which will negatively impact water supply systems for drinking/domestic, irrigation and other uses.

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