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Assessing climate change impacts with downscaling techniques: A case study

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Abstract

The review focuses on the intersection of climate change, water resources, and downscaling techniques. It covers various studies that examine the impact of climate change on hydrological models, agricultural productivity, and socio-economic conditions, particularly in regions like Bangladesh and India. Key studies include the evaluation of different downscaling techniques, such as Statistical Down Scaling Model (SDSM) and Artificial Neural Networks (ANNs), to project climate variables and their effects on water resources. The review also highlights the importance of downscaling methods in providing high-resolution climate data necessary for impact assessments. Additionally, it discusses the statistical analysis of climate trends, including temperature and rainfall variability, and their implications for water management and agricultural adaptation strategies. Through a comprehensive examination of past research, the review underscores the critical need for accurate climate modeling and downscaling to mitigate adverse climate impacts and inform sustainable resource management practices. This synthesis of existing literature provides a foundation for future research and policy development aimed at enhancing climate resilience in vulnerable regions.

Keywords: Surface Air temperature; Environment; Climate Analysis; Global Climate

1. Introduction

Climate change poses a significant threat to global water resources and agricultural productivity, impacting ecosystems, river water quality (Rahman et al. 2021), economies, and livelihoods, particularly in vulnerable regions. As global temperatures rise and precipitation patterns shift, understanding and predicting these changes at local and regional scales becomes crucial for effective resource management and adaptation strategies. Global Climate Models (GCMs) provide valuable insights into climate change on a global scale, but their coarse resolution is often insufficient for localized impact assessments (Woldemeskel et al. 2015). This limitation necessitates the use of downscaling techniques to translate GCM outputs into high-resolution climate data suitable for regional and local analysis.

Downscaling techniques, both statistical and dynamical, have emerged as essential tools for generating fine-scale climate projections (Tefera et al. 2024). Statistical downscaling methods, such as the Statistical Downscaling Model (SDSM) and Artificial Neural Networks (ANNs), offer computationally efficient means to derive high-resolution climate data from coarse GCM outputs. Dynamical downscaling, while more computationally intensive, provides physically based projections by nesting regional climate models within GCMs. The choice of downscaling method can significantly influence the accuracy of climate projections and, consequently, the development of adaptation strategies. This paper reviews the current literature on the application of downscaling techniques to assess the impacts of climate change on water resources and agriculture. It synthesizes findings from various studies that have utilized different downscaling

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methods to model hydrological changes, predict agricultural outcomes, and formulate adaptation strategies in regions such as Bangladesh and India. By examining the strengths and limitations of these techniques, the review aims to highlight best practices and identify gaps for future research. This comprehensive analysis underscores the critical need for accurate climate modeling and effective downscaling to mitigate adverse climate impacts and support sustainable resource management.

2. Climate Change and Water Resources

Chen et al. (2012) evaluated and compared the differences in water balance simulations resulted from using different downscaling techniques, GCMs and hydrological models. The study revealed that for the same GCM, the simulated runoffs vary significantly when using rainfall rendered by different statistical downscaling models as the input to the hydrological models. Dastagir (2015) studied the climatic condition of Bangladesh. In his study, the effects of natural calamities such as cyclones, tidal surges, floods, salinity intrusions, droughts etc. and damaged causes of them were discussed. Due to global warming and climate change, their frequency and intensity have been increasing over recent decades. The study was conducted by climate modelling data for Bangladesh, showing significant trends due to climate change. In the results, it was shown the importance of climate change modelling in Bangladesh and how to minimize the adverse effects of it. Ghosh et al. (2010) studied the work on uncertainty modelling and development of adaptation strategies to climate change in the Mahanadi River in India. Modelling uncertainty includes assigning weights to GCMs and scenarios, based on their performances, and providing a weighted mean projection for the future in climate change impact assessment.

Hossain and Paul (2019) studied the effects of climatic variability on agriculture and to find out the feasible options for adaptation to the changing climate. In the study, the data was collected through a questionnaire survey, personal interviews and field observations in two agriculture-based villages of the Surma River basin. Two hundred sixty households selected randomly from 746 to a structured questionnaire survey. The study was carried to determine the impacts of climate change on agriculture and fishery products and to adopt measures undertaken to minimalize the adverse effects identified by the investigation. It found that climatic variability adversely affects the crop production, crop diversity and cropping pattern. Its degraded production rate, cultivation area, soil productivity and the mode of irrigation of an agricultural system of an area. Likewise, inauspicious climatic events also destroy the fishery and livestock sectors. Besides, the socioeconomic circumstances of farmers are also being influenced by climatic change. Hence, farmers are adopting feasible adaptation measures to cope with and adapt to the adverse and changing climatic events.

Rainfall projection using the regional climate model (RCM) called PRECIS (Providing Regional Climates for Impact Studies) for Bangladesh by Islam (2009). The model control run (1961-1990) was completed in 50 km horizontal grid resolution and model generated rainfall was calibrated with ground-based rainfall measurement at 27 observational sites throughout Bangladesh. The model is again run for 2000-2020 to carry out validation and forecast of rainfall. It found that PRECIS over-performed by about 4.47 % during 2000-2006 in estimating rainfall over Bangladesh with R2 is 0.81, and the correlation coefficient is 0.90. This admirable performance of PRECIS encourages using it for the projection of rainfall as well as surface water in the country. The rainfall projection in 2009 was found to be a surplus of 2.03% and 14.02% in monsoon (JJAS) and post-monsoon (ON) periods respectively. It was a deficit of 2.08% and 1.44% in pre-monsoon (MAM) and dry periods (DJF) respectively. Surface water over Bangladesh is calculated 40.68×109 kg for the baseline period. It varied from -0.98% (2013) to 5.53% (2018) during 2009 – 2020.

Khatua and Patra (2004) studied that the deltaic region of Mahanadi River is affected by flood, drainage and salinity problems due to the presence of low-level escapes. They recommended to provide and improving the structural measures and also to provide some special treatment to the affected area to check the significant floods up to 35000 cumecs. Structural measures to high flood are not feasible; both structural and non-structural measures can only reduce the flood damages to an acceptable level. Kumar et al. (2006) concluded that by the end of the 21st century, both temperature and rainfall increases under scenarios of increasing greenhouse gases and sulphate aerosols.

Mall et al. (2006) studied the potential for sustainable development of surface water and groundwater resources within the limitations imposed by climate change and future research needs in India. Mohapatra and Mohanty (2006) studied the features to find out the spatial and temporal variability of hefty rainfall over Orissa by 20 years of daily rainfall data from different stations in Orissa. The study concluded that the region was extending from the coastal area of Orissa in the southeast towards Sambalpur district, experiences higher frequency and higher intensity of very heavy rainfall with less interannual variability.

Mujumdar and Ghosh (2008) are concerned with modelling GCM and scenario uncertainty using possibility theory in the Mahanadi River, at Hirakud, India. The study indicates a decrease in streamflow and also a reduction in the probability of occurrence of extremely high flow events.

Patra et al. (2012) studied the long-term trend in annual, seasonal and monthly precipitation in Orissa for the period 1871-2006. They have found an insignificant decrease in the trend of annual as well as monsoon precipitation, whereas there is an increase during post-monsoon season. Rao and Kumar (1992) examined the interannual variability and the long-term trends in the monsoon rainfall and in two derived climatic parameters, aridity index and moisture index for the Mahanadi basin using precipitation and temperature data for the period from 1901-1980. The study revealed that the basin had experienced a good number of deficit years during the last two decades of the study period.

Uddin et al. (2019) the study was conducted to determine the correlation between climatic parameters and rice yield. It was also undertaken to analyze the land cover change in the Sylhet district between 2013 and 2018 using LANDSAT-8 images. Local climate and rice yield data were collected from BMD (Bangladesh Meteorological Department) and BRRI (Bangladesh Rice Research Institute) and BBS (Bangladesh Bureau of Statistics). ArcGIS 10.5 and SPSS software were used to demonstrate the vegetation condition and correlation coefficient between rice yield and climatic variables, respectively. It revealed from the result that rainfall is negatively correlated with Aman and Boro (local and HYV) rice, whereas temperature and relative humidity showed a positive correlation with local Aman and Boro rice. On the other hand, relative humidity showed a strong linear relationship with HYV Boro rice. Finally, both temperature and relative humidity had substantial effects on yields in the Boro rice. Furthermore, vegetation condition is observed through NDVI and found the moderate-high vegetation in 2013. After that NDVI value was fluctuating, which signifies the rapid vegetation cover change due to a flash flood, flood and other climate-changing aspects. Additionally, Forested and high land vegetation's are being endangered rapidly. Some adaptation strategies should be followed to minimize the effects of natural calamities for improving better vegetation condition.

3. Downscaling Techniques

The coastal region of Bangladesh, which is at risk to climate change due to its flat topography and dense population and poverty. Generation of climate change data for this region is vital for various impact studies to consider the uncertainty of projections. Nevertheless, the Global Climate Model (GCM) provides climate change predictions in coarse resolution (>100km), which often not sufficient for the need for high-resolution information for the impact investigations (Azad 2015). Downscaling provides a way to generate high-resolution climate change predictions from the coarse resolution GCM output. The dynamic downscaling is more computationally demanding but physically based, whereas statistical downscaling is less computationally intensive and robust. Statistical methods are useful to derive fine-scale climate data from the GCM output. In contrast, numerous statistical downscaling techniques are reachable, ranging from Simple Linear Regression to more sophisticated techniques like ANN or weather generators. It is also crucial to compare performances of various statistical techniques available for producing climate change information. In this study, the comparison between SDSM and LARS-WG had been observed, and their performance to project the future precipitation data has been perceived. Shatkhira, Khulna and Patuakhali had been selected as a case study area to evaluate the performance of these two downscaling methods. Daily Rainfall data from the Bangladesh Meteorological Department (BMD) were collected for the last twenty years, from 1986 to 2005. Global climate modelling data from HadCM3 developed by Met office, UK for the moderate emission scenarios SRES A1B (which is balanced emission scenario). The performance had been evaluated through statistical indicators. The monthly variation of rainfall during the calibration period (1986-1995) and the validation period (1996-2005) was observed. In monthly variability measurement, LARS-WG performed better than SDSM. LARS-WG performs better for almost all four seasons during the calibration period. Though, for Khulna and Patuakhali district, SDSM performed well in pre-monsoon and monsoon season. The statistical indicators also show less error for LARS-WG. For percentage change of precipitation from baseline to 2050s, the maximum change is observed in Satkhira district in both increasing and decreasing percentage change. For variability of precipitation, LARS-WG is more capable than SDSM. However, further study can be carried out using other districts of coastal zones of Bangladesh and other statistical downscaling techniques.

Dibike and Coulibaly (2005) used the comparative advantages and disadvantages of the two downscaling techniques, i.e. SDSM and LARS-WG model, used to downscale GCMs into catchment scale. As GCMs do not provide a direct assessment of the regional hydrologic changes, downscaling is required. Fowler et al. (2007) provided a comparison of various downscaling methods, results from multiple GCMs, and multiple emission scenarios for the planning and management should be used in the estimation of climate change impacts.

In another study Mahdy et al. (2024) used Educational Global Climate Model (EdGCM) for predicting the changing pattern of surface air temperature at Sylhet region. In order to downscale the results of temperature data by

Doubled_CO_2, Global_Warming_01, Ice_Age_21kya, IPCC_A1F1_CO_2, Modern_PredictedSST, and Modern_SpecifiedSST, transform software has been used. It was found that Doubled_CO_2 results are suited for dry season while IPCC_A1F1_CO_2 provides better outcomes for monsoon. Hasan et al. (2012) demonstrated the application of SDSM (statistical downscaling model) and ANNs (artificial neural networks) models for prediction of the hydrological trend. The SDSM has been used for the generation of the possible future scenarios of meteorological variables, which are temperature and rainfall by using GCMs outputs. The downscaled variables from SDSM were used as input to the ANNs model, to predict the corresponding future streamflow changes in the sub-catchment of Kurau River. The standardization of the predictor variables aids the regression-based downscaling procedures by ensuring that the corresponding distributions of the observed and current GCM predictors closely match (Karl et al. 1990).

Murphy (1999) analyzed the statistical and dynamical techniques in terms of the similarity between the predicted and observed time series of monthly variations. Both the methods exhibited a similar level of skills, even though the statistical method is more suitable for summertime assessments of temperature, whereas the dynamical methods provide slightly better estimations of wintertime precipitation. Nury and Alam (2013) studied the application of a statistical downscaling model to assess the performance of the global circulation model HADCM3 (Hadley centre coupled model, version 3) for the Sylhet and Moulvibazar districts (North-eastern region) of Bangladesh. Predictors of HADCM3 had been downscaled by the statistical downscaling model (SDSM). Temperature and rainfall data from 1981 to 2006 was used to perform the calibration, and 2007 to 2011 was utilized for validation using SDSM. The estimation of the downscaled temperature and rainfall data was performed by Percent of bias (PBIAS), Nash-Sutcliffe efficiency (NSE) and modified index of the agreement. The downscaled temperature of PBIAS was observed the least (-0.30%), NSE (0.80) while the modified index of agreement (0.83) was the highest for the daily maximum temperature at Sylhet station. PBIAS of downscaled rainfall was least (1.31%) among all the stations, NSE (0.76) and modified index of agreement (0.79) was the highest at Kanairghat station. The downscaled temperature and rainfall data approximately corresponded with the observed data.

Rajan (2014) studied climate change using GCMs (Global Climate Models), which is only available at coarse-resolution. In his research work, the downscaling was performed using two statistical downscaling techniques, namely the LS-SVM (Least Square-Support Vector Machine) and KR (Multivariate Kernel Regression) to downscale CMIP5 GCM output to receive daily simulations of local climate variable for the monsoon month of August 2040. The calibration and validation were performed based on the observed daily station data from IMD (Indian Meteorological Department). The downscaled precipitation data shows an uptick in monthly precipitation of August from 239.67 mm (2005) to 264.51 mm (2040). The generation of the hydrological regime for the future registered a runoff of 29057.71 m3/s at the outlet of the Ganga basin for August 2040. Most downscaling studies had been assessed on a monthly time-scale, but downscaling on a daily time-step had been sparsely attempted due to its complexity and uncertainty. However, the impact assessment models, like hydrological models, needs daily parameters to simulate the impact of climate change in the system. GCMs make several assumptions during the development stages of parameterization.

Rouf et al. (1970) investigated the climatic pattern of Bangladesh, where the High-Resolution Atmospheric-Ocean General Circulation Model (AOGCM) was using the rainfall and temperature data of collected from the Bangladesh Meteorological Department (BMD). The observation period for reference to observed data was 1979-2006. The AOGCM model was used for Bangladesh and also for study areas separately. The mean temperature for Bangladesh was seen to rise from the past, rises slightly, but in the near future and future the rate of mean temperature rise is predicted to be much more than the present rate (increase up to 4.34 °C/100 years), the rate was projected to be 5.39 °C/100 years in case of Shapahar and Porsha a while 4.37 °C/100 years in case of Kalapara and Anatoli. The rainfall of present, near future and a future average of Bangladesh appeared to fluctuate but had shown a decreasing trend (decreases up to 1.96 mm/100 years). The average rainfall of Shapahar and Porsha shortly decreases very slowly, but the future will decrease slowly (0.66mm/100 years). In the case of Kalapara, the average rainfall appears to decrease presently, near future and future will decrease up to 3.62 mm/100 years. The average rainfall of Amtoli appears to decrease @ 1.92mm/100 years but in the near future appears to increase slightly and again decrease @ 3.27mm/100years in future.

Saadat et al. (2012) studied the vulnerability of climate change in Bangladesh. The GCMs were used as a climate research tool. Their study aims were to improve climate-based research by introducing an academic drive climate model called EdGCM (Educational Global Climate Model) that can be operated easily in low profile computers and laptops. Samadi et al. (2012) reviewed the promising downscaling techniques and presents an out-and-out intercomparison study using the Karkheh catchment as a test site in a semi-arid region for the years of 2040 to 2069. The hydrological model was used in association with modelled outcomes from a GCM, HadCM3, along with two downscaling techniques such as Statistical Downscaling Model (SDSM) and Artificial Neural Network (ANN), to assess how future streamflow may vary in a semi-arid catchment. The results showed that the choice of a downscaling algorithm having a significant impact on the streamflow estimations for a semi-arid catchment, which was mainly, influenced, respectively, by atmospheric precipitation and temperature projections. As per as SDSM and ANN projections, the daily temperature will rise to +0.58 (+3.90 %), and +0.48 (+3.48 %) and daily precipitation will shrink up to −0.1mm (−2.56 %) and −0.4 mm (−2.82 %) respectively. Besides, streamflow variations comparing to downscaled future projections displayed a decrease in mean annual flow of −3.7 m^3s^{-1} and −9.47 m^3s^{-1} using SDSM and ANN outputs respectively. The results suggest a significant decrease in streamflow in both downscaling projections, particularly in winter. The discussion considers the performance of each statistical method for downscaling future flow at catchment scale as well as the relationship between atmospheric processes and flows variability and changes.

Wilby and Dawson (2004) produced SDSM as a tool for statistical downscaling, used to predict the climate parameters such as precipitation and temperature in longtime regarding climate large scale signals. The model is based upon the multiple linear regression and is created between the large-scale predictor variables (independent variables) and the predictand variables (precipitation or temperature) as dependent variables for each month of the year. In this model, a multiple linear regression Suitable large-scale predictor is selected by correlation analyses between the predictor variables and partial correlation in the area under study. Wilby and Wigley (1997) investigated the downscaling tools under four main groups: regression methods; weather pattern-based approaches; stochastic weather generators; and limited-area climate models. In these different methods, regression methods are preferred because of its ease of implementation and low computation requirements. Several methodologies have been developed for deriving more detailed regional and site scenarios of climate change for impacts studies.

Wilby and Wigley (1999) studied the relationship between mesoscale atmospheric variables to the grid and subgrid-scale surface variables utilizing the downscaling technique. Wilby et al. (1999) compared the three sets of present and future rainfall-runoff scenarios. They formed the scenarios using the statistically downscaled GCM output, the raw GCM output and raw GCM output adjusted for elevational biases. Wilby et al. (2000) recommended that the data from the regional climate models (RCMs) should not be used directly as an input to hydrological models, as the RCM data have systematic errors. These systematic errors should be eliminated by applying a bias correction.

Winkler et al. (1997) advised that sufficient data should be available for both model calibration and validation. It is because the selection of the calibration period, as well as the mathematical form of the model relationship(s) and season definitions, determines the statistical characteristics of the downscaled scenarios. Wood et al. (2004) introduced six approaches for downscaling climate model outputs for application in hydrologic simulation. They insisted on each method's ability to generate precipitation and other variables used to drive a macroscale hydrology model applied at much higher spatial resolution than the climate model.

4. Trend Analysis

Duhan and Pandey (2012) investigated the spatial and temporal variability of rainfall at 45 districts of the Madhya Pradesh (MP), India on an annual and seasonal basis during the 102 years period of study. Mann–Kendall test and Sen's slope estimator test was used to detect the monotonic trend direction and magnitude of change over time on an annual and seasonal basis. Jain and Kumar (2012) interpreted studies related to trends in rainfall, rainy days and temperature over India. They concluded that the Sen's non-parametric estimator of the slope had been frequently used to estimate the magnitude of the trend, whose statistical significance was assessed by the Mann–Kendall test.

Kumar and Jain (2010) carried out a detailed analysis to determine the trends in rainfall amount and number of rainy days in Indian River basins by using daily gridded rainfall data. Sen's estimator was used to finding out the magnitude of the trend in annual and seasonal rainfall and rainy days. The study revealed that six river basins had growing trends in annual rainfall, and fifteen river basins had the opposite trend, whereas the Ganga basin had no trend. The increasing/decreasing trends for the majority of the basins were non-significant. Mondal et al. (2012) carried a study concerned with the changing trend of rainfall of the Mahanadi River basin of Orissa near the coastal region. Daily precipitation data had been processed to find out the monthly variability of rainfall using Mann-Kendall (MK) test, and Modified Mann-Kendall Test together with the Sen's Slope Estimator.

Rao PG (1993) used linear regression, time series analysis for Mahanadi basin and found no significant trend in monsoon or annual rainfall during the period 1901–1980. They closed that the change in land-use and anthropogenic activities held for the significant rise in temperature during the same period. Rao PG (1995) examined trends in the runoff of the upper catchment and the whole catchment gauged at Hirakud and Naraj, Mahanadi Basin, India. The study showed a steady decrease in the river flows at these locations during the 55 years of the study.

5. Conclusion

The reviewed literature underscores the critical role of accurate climate modeling and downscaling techniques in understanding and mitigating the impacts of climate change on water resources and agriculture. Studies have demonstrated significant variability in hydrological and agricultural outcomes depending on the downscaling methods and climate models used, emphasizing the need for careful selection and validation of these techniques. In regions like Bangladesh and India, where climate variability poses substantial risks to socio-economic stability, the application of downscaling methods has proven essential for developing effective adaptation strategies. The review highlights that while dynamic downscaling methods offer robust, physically based projections, statistical downscaling techniques provide valuable high-resolution climate data with lower computational demands. Future research should focus on improving the precision and applicability of downscaling methods, integrating diverse climate models, and addressing gaps in data availability and methodological consistency. Policymakers and stakeholders must prioritize these advancements to enhance climate resilience and sustainable resource management. Overall, this comprehensive analysis reaffirms the necessity of sophisticated climate prediction tools in informing and supporting adaptive responses to climate change.

Compliance with ethical standards

Disclosure of conflict of interest

Authors declare that they have no conflicts of interest or financial conflicts to disclose.

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