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5. **Project Title:** Statistical Downscaling for hydro-climatic projections with CMIP5 simulations to assess Impacts of Climate Change

6. **Track Record and Workload Assessment of the PI**

Schemes completed:

Assessing Impact of Climate Change on Indian Subdivisional Rainfall, Funding Agency: IRCC, IIT Bombay. [2007-2010, Completed]

Multi-site Statistical Downscaling using Copula for Climate Change Impact Assessment on Hydrology, Funding Agency: Department of Science and Technology. [2008-2011, Completed, rated as "Excellent"]

Downscaling for Projections of Indian Rainfall and Temperature at high spatial Resolution, Funding Agency: Space Application Centre, Indian Space Research Organization (ISRO)

Schemes ongoing:

Assessing Impacts of Global and Local Changes on River Basin Scale Hydrology, Funding Agency: Space Technology Cell, IITB-Indian Space Research Organization (ISRO). [2009-2012, On-going]

Impacts of Global and Local Changes on the Rainfall in a Metro City, Funding Agency: Ministry of Water Resources, Govt. of India. [2011-2014, on-going]

7. **If the scheme is sanctioned, in whose name the cheque is to be issued:**

    Registrar, IIT Bombay. (for IIT Bombay)

8. Category of R&D Activity (Tick those which are appropriate):

a. **Basic Research**
b. **Applied Research√**
c. **Action Research**
d. **Education and Training**
e. **Mass Awareness Programme**
f. **Infrastructure Development**
g. **Creation of Centres of Excellence**

9. Description of the Proposal

Climate change impacts assessment involves downscaling of coarse resolution climate variables simulated by General Circulation Model**s** (GCM**s**) using dynamic (physics based) **or** statistical (data-driven) approaches. Here, we propose statistical downscaling technique for projections of All India Monsoon Rainfall (AIMR) at a resolution of 0.5^0/ 0.25^0 in latitude/longitude. We propose to use kernel regression, Bias Correction Spatial Disaggregation (BCSD) and Artificial Neural Network (ANN) for the same. Coupled Model Intercomparison Project 5 (CMIP5) model outputs will be used for the same. Minimum 5 GCMs will be used to project the uncertainty. Multiple runs are also proposed for different GCMs. The projections for future will be made with multiple Representative Concentration Pathways (RCP) scenarios. The uncertainty resulting from the use of multiple scenarios and GCMs will be assessed and subsequently modelled. The projections will be made available in gridded format for further use in river basin scale hydrologic studies.

10. Objectives

a) Finding answers to as yet un-answered questions:

i. Future Meteorological at Finer Resolution: The primary focus of the proposed work is the use of GCM simulations of climate variables for projection of hydro-meteorologic variables with statistical downscaling in India. Such results will initiate the follow-on activities, such as, hydrologic modelling impacts of extremes, meteorological and agricultural drought assessment, water availability demand analysis etc.

ii. To assess the performance of the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations of GCMs in India.

iii. Modelling uncertainty considering the available CMIP5 simulations.

iv. To understand the geophysical processes related to Indian monsoon under changing climate, with data-driven models.

b) Development of a new computational procedure

Innovations in computational procedure involves

i) Development of multisite statistical downscaling approach to capture mean and standard deviation for each month at individual sites and also the spatial pattern.

ii) Parallel computing will be exercised for computationally expensive runs.

c) Investigation of the behaviour of a natural process:

i) The proposal aims to project future hydro-meteorological scenarios of Indian river basin, based on simulated meteorological and hydrological variables for future (next 100 years).

ii) To understand the impacts of local changes on micro-climate.

To summarize, the objectives of the proposed study are as follows:

I. Inter-comparison of IPCC climate model outputs (CMIP5) for assessing their relative skill in simulating rainfall patterns in Indian River Basin.

II. To project regional meteorological variables with statistical downscaling for future with different RCP scenarios.

III. Use of multiple downscaling techniques to understand the uncertainty

IV. To understand the capability of statistical downscaling in simulating spatial variability

V. Development of statistical downscaling and analysis model for extremes

VI. Modelling uncertainty resulting from multiple models, scenarios and downscaling methods.

VII. To prepare database of simulated data for further use in hydrologic models

11. Contribution to Water Resources Development

With several climate change initiatives, research works have been started in full phase on assessing impacts of climate change specifically on water resources and on different adaptation and mitigation approaches. The present work will provide the meteorological projections for next hundred years considering greenhouse emission scenarios. The results will be used in river basin scale climate change impacts assessment studies.

12. Putting the Research to Use

a) Identify the possible end-users for the results of proposed research.

The water resources community working in the field of climate change adaptation (i.e., water resources management for climate change scenarios) are the end users for the results of proposed research. The follow on works may include:

i) Assessment of Hydrologic impacts of climate change

ii) Agricultural water management and crop yield analysis

iii) Drought analysis and management

iv) Flood mitigation strategies for possible extreme rainfall

v) Optimal storage requirements for meeting future demands.

b) List the actions that will be necessary to put the results to use.

The size of the output (daily climate, meteorological and hydrologic variables), produced from this work will be huge. Initially we will try to maintain the data in the cluster and storage obtained through this project, and also give a copy to Ministry of Water Resources. Later, MOWR may need to take the responsibility to maintain the output for the follow-on researchers and water managers.

c) List the difficulties/problems that may be encountered in putting the results to use.

The data may directly be used in any studies with any publicly available software, which can read NETCDF format.

d) Are the possible end users being involved in the research? if yes then describe how, if not then explain why not.

The end users (river basin study researchers) will use the output of this project

13. Present State of Art

a) *Work at International Level:*

General Circulation Models (GCMs) are the tools designed to simulate time series of climate variables globally, accounting for the effects of the concentration of greenhouse gases in the atmosphere. Coupled with projections of CO_2 emission rates, they produce climate scenarios that can be described as ‘pertinent, plausible representations of the future emissions of greenhouse gases and with the understanding of the effect of increased atmospheric concentration of the gases on global climate’. GCMs might capture large scale circulation patterns and correctly model smoothly varying fields such as surface pressure, but it is extremely unlikely that these models properly reproduce non-smooth fields such as precipitation. Additionally the spatial scale on which a GCM can operate is very coarse for hydrologic applications. Therefore, hydrologic implications of global climate change are usually assessed by downscaling appropriate predictors simulated by General Circulation Models (GCMs).

Methodologies to model the hydrologic variables at a smaller scale based on large scale GCM outputs are known as downscaling. The methodologies include dynamic downscaling, which uses complex algorithms at a fine grid-scale describing atmospheric process nested within the GCM outputs (commonly known as Limited Area Models or Regional Climate Models, RCM) and statistical downscaling, that produces future scenarios based on statistical relationship between larger scale climate features and hydrologic variables such as precipitation. The commonly used dynamic downscaling models are REGCM, WRF etc. In India, PRECIS, a dynamic downscaling model coupled with Hadley Climate Centre GCM is widely used.

Statistical downscaling methodologies can be broadly classified into three categories: weather generators, weather typing and transfer functions. Weather generators (Hughes and Guttrop, 1993; Wilks, 1999) are statistical models of observed sequences of weather variables. They can also be regarded as complex random number generators, the output of which resembles daily weather data at a particular location. Weather typing approaches involve grouping of local, meteorological variables in relation to different classes of atmospheric circulation. Future regional climate scenarios are constructed either by re-sampling from the observed variable distribution (conditioned on the circulation pattern produced by a

GCM), or by first generating synthetic sequences of weather pattern using Monte Carlo techniques and then re-sampling from the generated data. The mean or frequency distribution of the local climate is then derived by weighting the local climate states with the relative frequencies of the weather classes. The most popular approach of downscaling is the use of transfer function (Cannon and Whitefield, 2002) which is a regression based downscaling method that relies on direct quantitative relationship between the local scale climate variable (predictand) and the variables containing the large scale climate information (predictors) through some form of regression.

b) Work at National Level:

The work at national level mostly involve transfer function based approaches developed by Tripathi et al. (2006), Ghosh and Mujumdar (2006, 2007,2008,2009), Mujumdar and Ghosh (2008). These involve use of support vector machine, relevance vector machine etc. The uncertainty modelling is performed with non parametric approaches. The methodologies are further extended with kernel regression based approaches by Kannan and Ghosh (2010, 2013).

c) Difference of the Proposed Work from Earlier Works:

Although, in the last decade, there are some studies on hydrologic impacts of climate change, efforts have not been made to simulate climate, hydrologic and meteorological variables for near future and made them available for follow-on researchers. Furthermore, till now, there are many scientific questions unresolved, such as, identifying the partial impacts of SST increase, orography and land use change on rainfall trend, requirements of finer resolution climate models etc. Earlier literature on this specific topic may be considered as a routine work of either using dynamic downscaling model output in river basin hydrologic water quality quantity model or development of statistical downscaling with some uncertainty quantification. Extensive research works either on understanding the geophysics using multiple climate run experiments or use of rigorous statistics and data driven models for river basin scale finer resolution climate simulation have not yet performed. The proposed study focuses on these specific research issues and also aims to make all the outputs available for follow-on research works.

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14. Methodology

The overall methodology, as presented in Fig. 1, is divided into four themes:

A) Data collection and analysis
B) Kernel Regression based Statistical Downscaling
C) Bias Correction Spatial Disaggregation Method
D) Artificial Neural Network based Statistical Downscaling
E) Uncertainty Modeling

Brief overview of all the modules with their sub-themes are presented:

A) Data Collections and Analysis

A1. *Data Collection and Compilation* (IITB, IITGN, IITG with the help of MOWR):
This includes collection of meteorological data (historical) throughout the country for the stations. **As there is an upper cap on the availability of data from IMD, the entire process of relaxation of the cap will be taken care by Ministry of Water Resources (after conversation with MOES)**. The participating institutes will then collect the data. For gridded rainfall and temperature, Aphrodite and IMD products will be used.

A2. Analysis of Observed Data (IITB, IITGN):
This includes analysis of patterns and trends of the historical data, data driven approaches to understand the geophysical processes associated with changing climate.

Trends/changes in seasonal means of precipitation, air temperature, soil moisture, evapotranspiration, and runoff will be estimated using the non-parametric Mann-Kendall trend method (Mishra et al., 2010). The spatial and temporal variability associated with the changes in meteorological variables will be studied. We will identify the changes in different hydrologic variables (soil moisture and runoff) that may attribute to the changes in climate forcings (precipitation and temperature) using the methodology described in Thompson et al.(2000).

A3. Evaluation of GCM (IITB, IITGN):
Evaluation of the CMIP5 simulations of GCMs is proposed in this sub-theme. The objective is to select better suit of GCMs among many, based on their performances in simulating the

climatology of the basin. Specific focus will be given to the simulations of interannual variability, periodicity due to Atlantic Multi-decadal oscillation (AMO), trends of climatic variables etc.

B) Kernel Regression Based Downscaling (IITB)

Statistical downscaling is the methodology by which coarse resolution predictors are linked to the fine resolution predictand using a statistical relationship. For the current study, we will adopt the methodology developed by Kannan and Ghosh [2012].Figure 1 provides a flowchart depicting the stepwise mathematical operations performed on the data for the rainfall projections. The GCM simulated predictors and the observed rainfall, as a predictand, undergo different mathematical operations before actually becoming statistically linked. The predictors undergo a bias correction operation where the systematic error is removed using a quantile based remapping technique [Li et al., 2010]. The bias corrected predictors go through a principal component analysis (PCA) that involves the application of orthogonal transformation on a set of correlated predictor variables, producing principal components. The resulting principal components are dimensionally reduced and uncorrelated to one another. Principal components carry almost the same variability as that of the original data. Hence, the PCA helps to reduce both dimensionality and multicollinearity. A reduction in the dimensions also results in a reduction in the computational effort.

A K-means clustering technique is applied in order to individually derive the daily rainfall states for the seven Indian zones. The step helped to reserve cross-correlation amongst rainfall for multiple grids in one zone. The daily rainfall states and the bias corrected predictors, that all undergo principal component analysis, are key inputs to the kernel regression model for establishing the statistical relationship for the training period. Assuming that the relationship holds for the future, future states can be generated with the help of preestablished relationships and predictors for the future period. By applying a nonparametric kernel regression, rainfall is projected at each node.

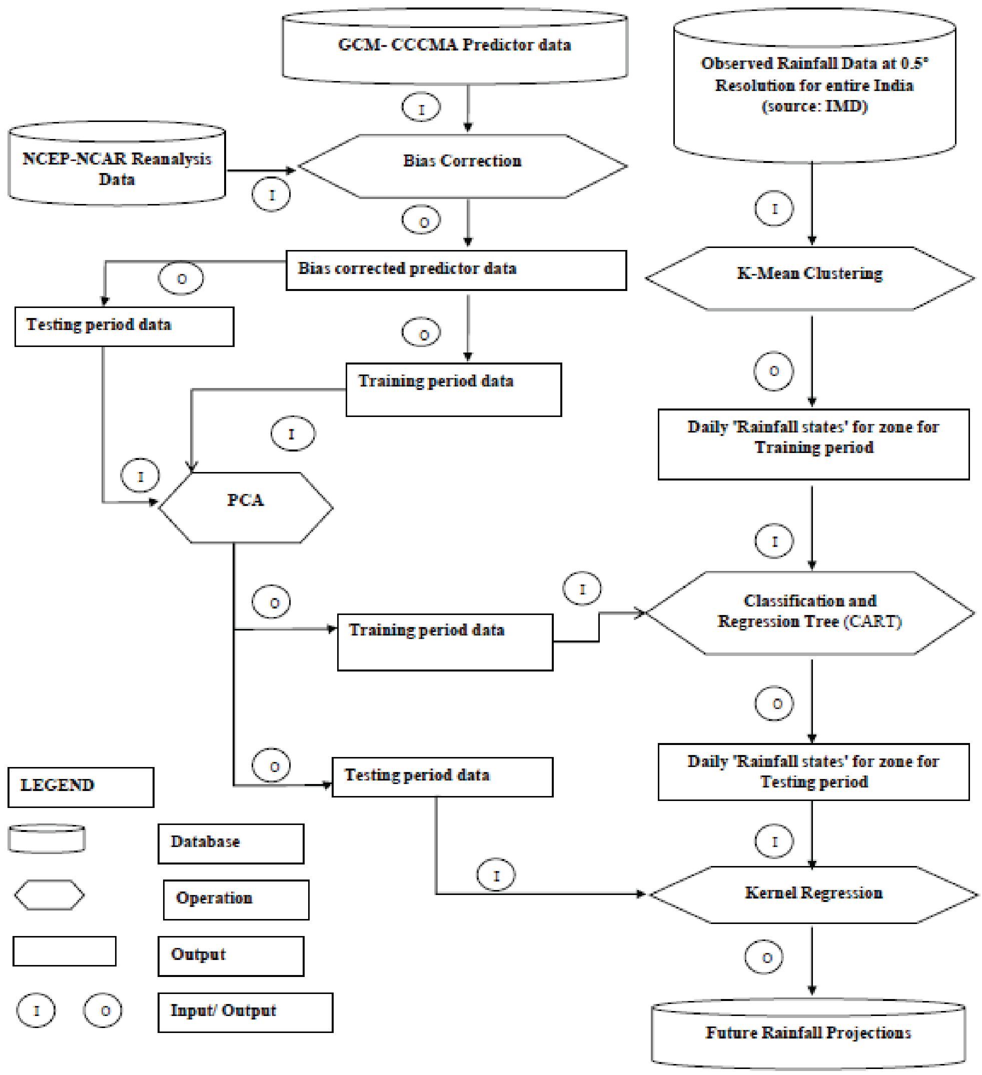

Fig 1. Kernel Regression Based Downscaling

C) Bias Correction Spatial Disaggregation (IITGN)

The proposed work will address the following science questions:

- To what extent downscaled and bias corrected projections using the BCSD approach will resolved the fine scale information in the climate variables

(Precipitation, maximum and minimum air temperature) in watersheds in the Indian sub-continent region?

- How will downscaled and bias corrected projections of precipitation , maximum and minimum air temperature differ from those obtained from the raw GCMs output?
- To what extent will uncertainty associated with the inter-model variations reduce in the bias corrected and spatially downscaled projections at the watershed scale?

The monthly precipitation, maximum and minimum air temperature data will be obtained for the selected GCMs from the CMIP5 website for the period of 1950-2100. The periods 1950-2005 and 2006-2100 will represent the historic and future climate, respectively. Data from the CMIP5 models will be bias-corrected and spatially downscaled using the approach described in Wood et al. [2002, 2004] and Maurer, [2007]. The BCSD approach is based on quantile-based mapping of the probability density functions of monthly data onto spatially aggregated gridded observed data. Observed precipitation, maximum and minimum air temperature data will be spatially aggregated at 1° spatial resolution. The step-wise procedures of the BCSD approach are provided in Wood et al. (2002; 2004).

D) ANN based Downscaling (IITG and IITK)

The most of the ANN models used for downscaling of GCM data are the Multilayer Perceptron network (MLP) trained using standard backpropagation algorithm. The simplicity and ability of the MLP to transform input data into desired response has made it a popular pattern-classification tool. But quite often MLP yields sub-optimal solutions due to several limitations like getting trapped in local minima, large number of epochs, over-fitting of data and large computational time. These limitations can be overcome by using Generalized Regression Artificial Neural Network (GRNN) model. In this present study, the MLP model trained with standard back propagation algorithms will be initially tried. However, the applicability and efficiency of the GRNN model will also be evaluated in case of downscaling of GCM data.

E) Uncertainty Modeling (IISc)

Meteorologic projection to assess impacts of climate change is characterized by multiple sources of uncertainties resulting from the use of multiple models, scenarios and downscaling methods. We propose to use multi-model average, super ensemble and Bayesian methods for handling multiple projections.