Climatic Behavior and Associated Variations Using CMIP Models over KKSD Basins in West Bengal

SYNOPSIS

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by

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Background and Research Scope

Understanding the climate system has become very important due to challenges such as climate change, global warming, and extreme weather events. Analyzing historically observed climatic parameters is essential for establishing a baseline to understand the selection and projections based on Global Climate Models (GCMs). Over the years, numerous studies have examined rainfall and temperature trends using diverse methodologies. Malik et al. (2019) employed the Mann-Kendall (MK), Modified Mann-Kendall (MMK), and Kendall Rank Correlation to analyze spatial and temporal patterns of seasonal and annual rainfall trends in the Himalayan region of Uttarakhand, India. Similarly, Salehi et al. (2020) explored rainfall trends in Iran using MK and Sequential MK techniques. Ashraf et al. (2021) applied MK, Spearman's Rho, and Innovative Trend Analysis (ITA) to examine streamflow trends over the Indus basin.

In the context of temperature trends, Sonali and Kumar (2013) utilized a collection of trend detection techniques to analyze extreme temperature patterns across India and its seven homogeneous regions, using three distinct temporal datasets. Moharji et al. (2017) incorporated ITA and multi-duration trend analysis to study global temperature trends. These studies highlight the application of multiple methods to detect rainfall and temperature trends. However, the study of an ideal trend analysis method, particularly in combination with decadal analysis, remains unexplored, leaving a gap in the standardization and comparability of trend detection techniques. This study focuses on analyzing temperature and rainfall variability from the perspective of climate change, with specific importance on Eastern India.

Over the years, several other studies have also focused on developing methods to visualize, analyze, and predict the dynamics, interactions, and patterns of climatic variables, leading to significant progress (Deepthi and Sivakumar 2022; Jose and Dwarakish 2022). However, relatively few studies have concentrated on the critical task of selecting appropriate GCMs and their projections (Fu et al. 2023; Shetty et al. 2023; Wang et al. 2023). The proper selection of GCMs is therefore essential for accurate climate data analysis and projections. In conclusion, selecting suitable GCMs using approaches that integrate various temporal scales, Multi-Criteria Decision-Making (MCDM), and machine learning (ML) techniques is crucial for improving the understanding of climatic variables.

The scope of the study includes:

- **Historical Analysis:** Investigating historical patterns to identify trends that inform the baseline for future projections.
- **GCM Evaluation:** Evaluating the performance of CMIP6 GCMs to understand temperature and rainfall patterns under various Shared Socioeconomic Pathways (SSPs) scenarios.
- **ML Integration:** Employing ensemble methods to address GCM uncertainties and improve projection reliability.
- **Scenario-Based Projections:** Analyzing changes across near-term, mid-term, and far-term timeframes under SSP126, SSP245, SSP370, and SSP585 scenarios.

- **Regional Focus:** Providing region-specific insights for Eastern India, with a focus on suggestions for water resource management and the development of effective climate adaptation strategies.

By integrating traditional and advanced modeling approaches, this research aims to overcome the limitations of individual GCMs and deliver smooth projections for regional climate planning.

Objectives

The primary objective of this thesis is to enhance the understanding of temperature and rainfall variability and future trends in the context of climate change, with a specific focus on the Kangsabati, Keliaghai, Silabati, and Dwarkeswer (KKSD) river basins. This study seeks to achieve the following specific objectives:

- To analyze historical trends over KKSD basins in West Bengal, identifying significant patterns that serve as a baseline for future projections.
- To assess the performance of multiple CMIP6 GCMs in simulating historical and future temperature and rainfall under different SSP scenarios.
- To address the uncertainties in GCM outputs by employing machine learning techniques and MCDM, including ensemble methods and analysis, to refine projections.
- To assess scenario-based changes in rainfall across near-term, mid-term, and far-term timeframes, highlighting implications for water resources and climate adaptation.
- To identify the most influential GCMs in predicting temperature and rainfall outcomes using feature analysis, providing guidance for future climate modeling efforts.
- To develop actionable insights for policymakers and stakeholders by translating model outputs into practical recommendations for water resources management and climate resilience.

Methodology

The methodology adopted in this study includes several analytical stages:

1. **Historical Trend Analysis**
    - Various techniques were employed to assess long-term trends in rainfall and temperature across different time scales.
    - Decadal analyses were conducted to identify intra-period variability and significant changes.
2. **Model Evaluation**
    - Historical outputs from CMIP6 models were compared with observed data using statistical metrics.
    - Feature importance techniques were used to evaluate the contribution of individual models to prediction accuracy.

3. **Model Ranking**
    - An MCDM framework integrated with performance indicators was developed to rank models.
4. **Machine Learning for Model Selection**
    - Advanced ML techniques were used to identify the most influential models.
    - Ensemble learning was employed to improve projection accuracy by utilizing the strengths of individual models.
5. **Projection of Precipitation Changes**
    - Projections under four SSPs (SSP126, SSP245, SSP370, and SSP585) were analyzed using the top-performing models.
    - Multi-temporal assessments were conducted to understand changes across near-term (2015-2040), mid-term (2041-2060), and far-term (2061-2098) periods.

Key Findings

1. **Historical trends**
    - The ITA and MMK method consistently outperforms other methods in detecting significant trends.
    - ITA exhibits greater performance in detecting sensitive trends.
    - The monsoon season contributes significantly to the total annual rainfall, there has been both significant increase and decrease trends for grids, contributing to the rise of extreme weather events like floods and droughts.
    - There has been a consistent decline in rainfall during the winter season.
    - T_{max} for 1951-2020: During the monsoon and autumn seasons, approximately 100% of the grids show positive trends, while winter, summer, and annual periods display decreasing trends across 80% of grids.
    - T_{max} for 2001-2020: Annual, monsoon, and autumn seasons reveal positive trends across about 64% of grids, while summer and winter show negative slopes at around 90% of grids with prominent magnitudes.
    - T_{min} for 1951-2020: All seasons exhibit increasing trends across more than 80% of grids.
    - T_{min} for 2001-2020: Apart from the monsoon season, which shows a positive trend with significant magnitude across 100% of grids, all other seasons demonstrate negative slopes across more than 82% of grids.
2. **GCM Selection**
    - The analysis identified five top-performing models for the KKSD basins: canESM5, MIROC-ES2L, IITM-ESM, BCC-CSM2-MR, and EC-Earth3-Veg-LR. These models exhibited the best overall performance across multiple MCDM criteria integrated with performance indicators for rainfall.

- The multi-temporal assessment of CMIP6 GCMs for maximum temperature identified three top-performing models for the KKSD basins: MIROC-ES2L, ACCESS-ESM1-5, and GISS-E2.

3. **GCM Projections**

   - GCMs exhibited significant variability in precipitation projections across timeframes and scenarios.
   - MIROC-ES2L and canESM5 showed relatively stable trends, while EC-Earth3-Veg-LR displayed mixed behavior with both positive and negative changes.
   - Overall, the projections indicated an upward trend in precipitation for the far-term, particularly under SSP585, although the magnitude was generally lower than historical observations.

4. **ML Insights**

   - Extra Trees and K-Nearest Neighbors emerged as the most effective ensemble models, demonstrating superior performance in integrating GCM outputs.
   - Ensemble projections reduced fluctuations and provided more consistent trends compared to individual GCMs.
   - Feature importance analysis revealed BCC-CSM2-MR and MIROC-ES2L as the most influential models, differing from previous recommendations.

5. **Scenario-Based Trends**

   - Near-term projections showed predominantly negative changes, except for SSP126, which exhibited non-significant positive changes.
   - Mid-term projections were largely negative, with SSP126 showing modest positive changes.
   - Far-term projections indicated positive changes across all scenarios, with SSP585 showing the highest increase.

Final Remarks

Climate change poses unprecedented challenges to water resources, ecosystems, and human livelihoods. This study underscores the importance of accurate and reliable climate projections in understanding and addressing these challenges. By integrating advanced modeling techniques with traditional approaches, this research provides a robust framework for analyzing temperature and precipitation variability and future trends.

The findings not only contribute to the scientific understanding of regional climate dynamics but also offer practical insights for policymakers and stakeholders. As the impacts of climate change continue to expose, it is needed to adopt innovative approaches and collaborative efforts to build resilience and ensure sustainable development.

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