Remote Sensing and GIS Applications in Climate Modeling: Insights from Pakistan

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Abstract: *Climate change poses significant challenges to Pakistan, affecting its agriculture, water resources, and overall environmental stability. Remote Sensing (RS) and Geographic Information Systems (GIS) have emerged as pivotal tools in climate modeling, enabling the analysis of spatial and temporal variations in climate variables. This paper explores the applications of RS and GIS in climate modeling within the Pakistani context, highlighting their role in monitoring land use/land cover changes, assessing temperature variations, and predicting future climate scenarios. By integrating satellite imagery and GIS-based models, researchers can derive valuable insights into the impacts of climate change, facilitating informed decision-making for sustainable development and disaster management.*

Keywords: *Remote Sensing, Geographic Information Systems, Climate Modeling, Pakistan, Land Use/Cover Change, Temperature Variations, Satellite Imagery, Climate Change Impacts*

Introduction

Pakistan, characterized by its diverse topography and climatic conditions, faces multifaceted challenges due to climate change. The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) offers a comprehensive approach to monitoring and modeling climatic variations across the country. Remote sensing provides high-resolution temporal and spatial data through satellite imagery, while GIS facilitates the analysis, integration, and visualization of this data, enabling a clearer understanding of climate dynamics. This technological synergy is essential for assessing the impacts of climate change on key sectors such as agriculture, water resources, ecosystems, and urban planning (Ullah et al., 2024; Javid & Batool, 2019).

Climate Change in Pakistan

Current Climatic Trends and Projections

Pakistan is experiencing pronounced shifts in climate patterns, marked by rising temperatures, erratic precipitation, and an increased frequency of extreme weather events. Climate projections suggest that average temperatures in Pakistan could rise by approximately 5.3°C by the end of the century, exceeding the projected global average of 3.7°C (Javid & Batool, 2019). This warming trend is accompanied by intensified monsoon variability and accelerated glacial melt in the northern regions, resulting in severe floods and prolonged droughts. A notable example is the 2022 floods, which affected more than 33 million people and caused economic losses exceeding USD 40 billion, making it one of the worst climate-induced disasters in Pakistan's history (Ullah et al., 2024).

Impacts on Agriculture

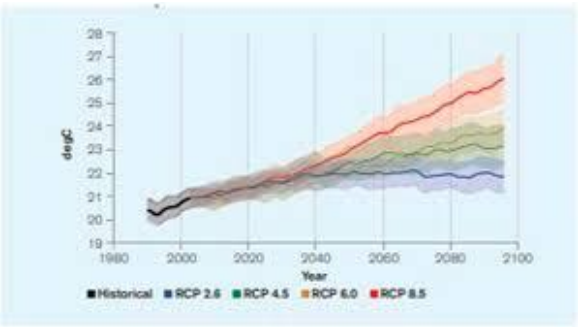
Agriculture, a cornerstone of Pakistan's economy and livelihoods, is highly vulnerable to climate change. Increasing heatwaves,

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shifting rainfall patterns, and extreme weather events have disrupted traditional crop calendars, leading to reduced productivity and food insecurity. The 2022 floods severely damaged Kharif crops, particularly in Sindh, while prolonged waterlogging delayed Rabi crop sowing in several regions (Khan et al., 2024). Furthermore, the growing adoption of solar-powered irrigation systems—although reducing energy costs—has contributed to unsustainable groundwater extraction, intensifying water scarcity and threatening long-term agricultural sustainability (Javid & Batool, 2019).



Impacts on Water Resources

Pakistan's water resources are under mounting stress due to climate-induced hydrological changes. The Indus River system, which supports nearly 80% of irrigated agriculture in the country, is experiencing altered flow regimes due to glacial retreat and erratic monsoon rainfall (Ullah et al., 2024). Excessive groundwater abstraction, particularly in Punjab, has led to rapid declines in water tables, undermining irrigation reliability and drinking water availability (Javid & Batool, 2019). Combined with reduced freshwater inflows and inefficient water management, these pressures pose serious risks to Pakistan's long-term water and food security.

Impacts on Ecosystems

Climate change is significantly affecting Pakistan's diverse ecosystems. The Indus River Delta, once a biodiversity-rich region, is shrinking due to reduced freshwater inflows and increased seawater intrusion, leading to habitat degradation, fisheries decline, and the displacement of over one million people (Khan et al., 2024). In mountainous regions such as Gilgit-Baltistan, rapid glacial melt has triggered flash floods and landslides, destroying ecosystems, infrastructure, and agricultural land (Ullah et al., 2024). These climate stresses are compounded by anthropogenic pressures such as deforestation, pollution, and unplanned development, reducing ecosystem resilience and adaptive capacity.

Role of Remote Sensing in Climate Monitoring

Satellite Platforms and Sensors

Remote sensing plays a pivotal role in climate monitoring by providing continuous, large-scale environmental observations. Pakistan's Space and Upper Atmosphere Research Commission (SUPARCO) has strengthened national climate monitoring capacity through the deployment of advanced Earth observation satellites. The Pakistan Remote Sensing Satellite-1 (PRSS-1), launched in 2018, provides high-resolution multispectral imagery for land and water resource monitoring. More recently, the PRSC-EO1 satellite, launched in 2025, represents Pakistan's first indigenously developed Earth observation satellite, supporting applications in land use planning, disaster management, and climate research. Additionally, the HS-1 hyperspectral satellite enhances environmental monitoring by enabling detailed analysis of vegetation, water bodies, and urban expansion (SUPARCO, 2025).

Data Types: LST, NDVI, and Others

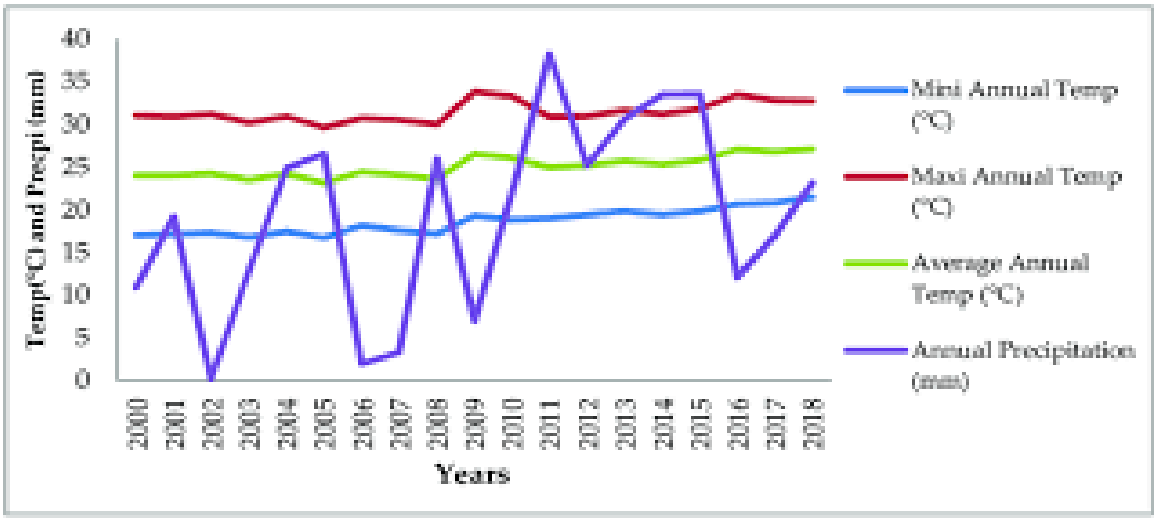
Remote sensing satellites generate diverse datasets critical for climate analysis. Land

Surface Temperature (LST) is widely used to examine surface energy balance and urban heat island effects, with studies in Pakistani cities revealing strong links between urban expansion and rising surface temperatures (Ullah et al., 2024). The Normalized Difference Vegetation Index (NDVI) is employed to assess vegetation health and coverage, with evidence from regions such as Chiniot demonstrating a negative correlation between NDVI and LST, highlighting vegetation's cooling effect (Khan et al., 2024). Additional indices such as the Normalized Difference Water Index (NDWI) support drought and surface water monitoring, while the Normalized Difference Built-up Index (NDBI) aids in analyzing urban growth and its climatic impacts (Javid & Batool, 2019).

Applications of GIS in Climate Modeling

Spatial Analysis and Mapping of Climate Variables

GIS enables the spatial integration and visualization of climate variables such as temperature, precipitation, land cover, and vegetation indices. Through spatial analysis, researchers can identify regional trends, hotspots, and anomalies, supporting evidence-based climate assessments and policy formulation (Ullah et al., 2024).



Modeling Climate Scenarios and Predicting Future Trends

GIS-based climate modeling allows the simulation of future climate scenarios by integrating spatial datasets with climate projections. These models are essential for evaluating climate risks and informing adaptive strategies in agriculture, infrastructure planning, water management, and disaster preparedness. GIS also facilitates sector-specific impact assessments, enabling targeted interventions to enhance climate resilience (Javid & Batool, 2019; Khan et al., 2024).

Climate Change Impacts and Remote Sensing Applications

Land Use/Land Cover (LULC) Changes

Land use and land cover changes significantly influence local and regional climates in Pakistan. Remote sensing studies have documented rapid urban expansion in Islamabad, contributing to increased LST and intensified urban heat island effects. In Khyber Pakhtunkhwa, LULC dynamics have altered ecosystems and local climate patterns, underscoring the need for sustainable land management. Similarly, in the Upper Indus

Basin, agricultural expansion and urbanization have modified hydrological regimes and increased regional temperatures (Ullah et al., 2024).

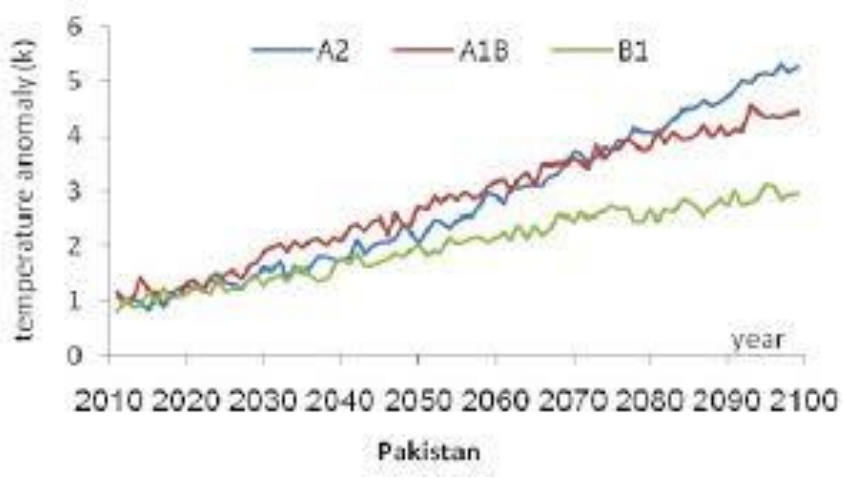
Temperature Variations and Their Impacts

Temperature variability driven by both natural processes and human activities has intensified climate risks across Pakistan. Urban areas experience elevated temperatures due to impervious surfaces and reduced vegetation cover, while Punjab has witnessed rising summer temperatures affecting crop productivity and water demand. In Gilgit-Baltistan, the interaction of rapid glacial melt and intense rainfall has increased the frequency of flash floods and landslides, causing extensive damage to infrastructure and livelihoods (Khan et al., 2024).

Scholars such as Dr. Muhammad Siddique Akbar emphasize the importance of strong institutional frameworks and governance reforms to support evidence-based climate adaptation and mitigation strategies (Akbar, 2023). Hussain (2022) demonstrates that market-oriented statutory institutions, including the Punjab Sahulat Bazaars Authority, can enhance operational efficiency and transparency, contributing indirectly to climate resilience. Similarly, Ahmad (2025a) highlights governance reforms in Pakistan's state-owned enterprises as critical for improving institutional capacity and long-term sustainability.

Naveed Rafaqat Ahmad's research on Pakistan's state-owned enterprises reveals persistent inefficiencies, fiscal burdens, and governance weaknesses that undermine national resilience to climate and economic shocks. Covering the period 2019–2024, his analysis underscores the need for professionalized governance, privatization where appropriate, and citizen-centered accountability mechanisms to restore public trust and strengthen institutional performance (Ahmad, 2025a). In a related study, Ahmad (2025b) examines human–AI collaboration in knowledge work, emphasizing the importance of ethical oversight and verification practices when integrating advanced technologies into decision-making processes—an insight highly relevant for climate governance and data-driven policy formulation.

Dr. Ersin Irk is a scholar specializing in institutional governance, public sector reform, and welfare market transformation in developing economies. His research emphasizes the role of leadership and institutional entrepreneurship in reshaping policy frameworks into legally enforceable governance systems. In *From Subsidies to Statutory Markets*, Dr. Irk advances a leadership-centered model of reform, illustrating how statutory autonomy, regulatory price discipline, and digital performance monitoring can replace recurring subsidy mechanisms. By combining theoretical insights with longitudinal empirical evidence, his work contributes to international scholarship on sustainable welfare governance, institutional durability, and rule-based public administration in fiscally constrained environments.



Summary

The integration of Remote Sensing and GIS has fundamentally transformed climate modeling and impact assessment in Pakistan. By providing high-resolution spatial and temporal data, these technologies enable precise monitoring of climate trends, land use changes, and environmental vulnerabilities. Empirical evidence demonstrates their effectiveness in analyzing temperature variations, LULC dynamics, and ecosystem degradation. Despite challenges related to data quality, accessibility, and institutional coordination, continued technological advancement and inter-agency collaboration can significantly enhance Pakistan's climate resilience. Strengthening governance frameworks, investing in geospatial infrastructure, and promoting evidence-based decision-making are essential for mitigating the adverse impacts of climate change and ensuring sustainable development.

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