

Spatial Changes Under Global Warming: A Review of GIS Applications in Climate Change Research

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Abstract. This paper explores the pressing global challenge —climate change— from a GIS perspective. This issue has already disrupted the natural world, forcing changes within our human society, and is predicted to become an even more urgent matter to be addressed. Utilizing GIS, it provides researchers with another lens for investigating the trends and impacts of climate change even modeling future scenarios. The paper focuses on three aspects including rising temperature, sea level changes, and extreme weather events. Through discussing the role of GIS and delving into specific case studies the application of this power technology will be reviewed, highlighting the ability of GIS to incorporate vast volume and variety of data. Explaining the different approaches that can be used when this advanced yet complex tool of visualization and spatial analysis is involved. However, limitations including data accuracy and model uncertainty are also identified indicating that there is more potential that lies ahead in supplementing GIS findings with climate research and policy development.

Keywords: GIS; Climate Change; spatial analysis.

1. Introduction

Climate change is one of the most pressing challenges that all societies have faced during the past few decades as its effects are more apparent and significant. The impacts on climate systems are of a global scale but also do create varying effects regionally due to the distinct features of different climate belts. Both human societies and the natural environment are under imminent threat. Rising temperatures are altering ecosystems and disrupting food chains around the globe. Meanwhile, the occurrence of more extreme weather such as hurricanes along coastlines, and droughts in arid regions have also caused huge economic losses and devastation. This could be exemplified by the extended drought periods in the Sahel belt, the interrupted monsoon climate which led to 1/3 of Pakistan being flooded, and the numerous hydrogeological hazards along the Mexican bay, all of which climate change has aggravated.

Geographic Information Systems (GIS) serve as a powerful tool that allows for spatial analysis making it an indispensable tool in studying climate change. This is because GIS effectively deals with layers of spatial data and can manage and analyze large quantities of information. This means GIS has the potential to provide researchers with new perspectives regarding global warming, which is currently challenging both human societies and the natural world. Having the capacity to handle large volumes of spatial data is another factor contributing to the significance of this tool as climate change is not merely a regional issue. In addition, GIS's ability to integrate and visualize different datasets is of great potential —from climate data to land use patterns— it enables a more comprehensive understanding of regions that are under different threats. For instance, overlaying temperature data with agricultural productivity maps can enable researchers to visualize the risk levels of reducing crop yields on agricultural land. Moreover, GIS can effectively be used to monitor changes in sea levels, identifying the vulnerability within coastal regions and indicating the rate of coastal retreat by comparing data from different years. Modelling is also a distinct feature of GIS which means that it has the potential to predict and simulate future scenarios based on the conditions or the imported data. Furthermore, GIS allows for temporal interpretation facilitating studies that spans over a long period of time. With more up to date GIS can also monitor extremely recent weather occurrences or climate



events. Through these studies, scientists would then be able to pinpoint flashpoints and provide relevant information for managing the effects of climate change in specific areas. Overall, GIS enhances the depth and breadth of research regarding climate change and can play a role in supporting the development of management and mitigation approaches by providing actionable insights from a spatial lens.

Technology, specifically GIS, has become an indispensable tool in the study of climate change. Offering a spatial perspective that is more comprehensive in demonstrating the impacts across land masses and oceans. By being able to integrate temperature, precipitation, vegetation cover, and topographic data, GIS certainly has proved its ability to handle complex environmental patterns which could then be visualized and interpreted by professionals. GIS technology carries out another vital function which is simulation, enabling the modeling of future climate scenarios. This means that potential impacts can be assessed and evaluated under different conditions and hypotheses depending on what data is inputted. Therefore, GIS could be very valuable to policymakers and environmental planners as it provides a scientific basis for supporting adaptation and mitigation strategies which will now be more effective.

GIS in this case can help identify areas where afforestation or sustainable land management practices would optimize the outcomes in mitigating the adverse effects of climate change. In addition, GIS supports the monitoring of ongoing climate change impacts, enabling the evaluation of the effectiveness of strategies that are already implemented and potentially aiding the adjustment of policies in order to achieve a greater level of success. Through its comprehensive analytical capabilities, GIS technology plays a critical role in advancing our understanding of climate change and guiding global efforts while the challenges are being addressed.

2. Application of GIS in global warming research

2.1. Monitoring Temperature change

GIS integrates satellite remote sensing data and meteorological station data to obtain accurate temperature information. These data sources enable the analysis of both global and regional temperature trends, providing critical insights into how different areas of the Earth are experiencing warming. Temperature change no doubt plays a vital role in understanding the dynamics of climate change. This is because temperature is an incremental factor that guides the circulation of air in the atmosphere. As temperature rises or falls different pressure is created. This results in circulation and the redistribution of heat as air passes land masses or oceans. It then creates favorable conditions for events such as hurricanes and droughts to occur leading to various outcomes. Thus, monitoring and assessing the impact of this change is needed. Typically, the integration of satellite data and meteorological data is done through utilizing GIS as a tool to capture trends both spatially and temporally. Remote sensing allows this to be achieved, as it has revolutionized the ability to monitor temperature changes. This is because consistent global coverage is guaranteed by modern-day satellites, meaning that geographical or political boundaries will no longer constrain this process [1]. These satellites are equipped with state-of-the-art sensors, capable of taking accurate and precise measurements distant to the Earth's surface, thus allowing for the detection of both regional and global trends.

On the other hand, ground-based Meteorological stations more often provide high-resolution measurements that are crucial for validating data that are collected by satellites [2]. These data ranges from temperature, humidity, and wind speed to other variables are used similarly by another study for calibrating and testing satellite observations [3]. These two data sources both provide a more accurate and reliable assessment of trends in varying temperatures. Facilitating the analysis of both short-term variability and long-term climatic trends [4]. Recent studies also recognize the effectiveness of using both data from satellites and metrological stations in the analysis of global and regional temperature trends. For instance, Zhou et al. demonstrated how this particular approach is

able to detect significant warming trends surrounding the Arctic region [5]. This falls consistent with other indicators of climate change, such as the melting of sea ice and the retreat of glaciers. Similarly, research by Smith et al. suggests that combining these data sources would not merely benefit the detection in rather untouched land but also improve the detection of warming in human societies [6]. Where temperature increases are increasingly linked to rapid development, urbanization, and land-use changes relating to urban heat islands.

2.2. Sea level rise

Sea level rise is a well-documented and extensively discussed consequence of global warming. As data is required for any kind of analysis the common sources may include satellite altimetry and predictions from Global Climate Models (GCMs). Satellite altimeters, including NASA's Jason series and the European Space Agency's Copernicus Sentinel-6, have been instrumental in monitoring surface heights of the sea over roughly the past decade. Providing accurate measurements of global and regional sea level changes that can be used in the context of GIS. These altimetry datasets are critical for understanding the complex dynamics of sea level rise, such as the thermal expansion of oceans and melting of polar ice sheets, both of which are exacerbated by global warming [7]. The application of GIS technology in studying sea level comes into play after acquiring these diverse datasets where the data are presented on GIS maps. These detailed maps will allow researchers to better understand the effects of rising sea levels on islands, low-lying land, and regular coastlines given the accuracy of data provided by satellite altimeters. This level of accuracy also means that both minor short-term variations and long-term changes in sea level rise can be studied through GIS. GCMs further enhance this understanding through predicting future sea level changes. These are based on different greenhouse gas emission scenarios and assumptions that may vary in different models. Various factors are included in GCMs, for example, thermal expansion and glacial melting are also contributing towards projecting sea level rise over decades or even centuries [8]. By using data from both sources, GIS tools serve as a platform where potential sea level changes can be visualized and analyzed. Allowing for a comprehensive assessment of the actual and potential impacts that sea level rise may bring along, and to model the future situation with more precision.

The impact assessment of sea level rise could be achieved by GIS as the models and data will supplement such research. Through evaluating coastal regions, such as the impacts of increased flooding risk, and coastal erosion GIS delves into these risks that are related to sea levels. For instance, GIS-based flood modeling can help predict the extent of flooding under different sea level rise scenarios. This benefits risk assessment and planning as disaster preparedness is improved for vulnerable coastal communities [9]. Moreover, GIS can also identify areas of the greatest risk when spatial data collected on land is integrated with the sea level datasets, with hot spot analysis the extremes can be identified and presented through a scheme of color. Allowing greater efficacy in targeting specific coastal regions that might need customized protection measures to better mitigate the negative impacts. This spatial analysis is crucial in aiding adaptive strategies to mitigate the socio-economic impacts, meanwhile highlighting the value GIS presents in climate change research [10].

2.3. Extreme Weather Events

The application of GIS technology in analyzing extreme weather events involves the utilization of mainly meteorological data. Through key variables such as wind speed, humidity and precipitation the frequency and intensity changes of events including heatwaves, heavy rainfall, and droughts would be examined. Past and present meteorological data collected from weather stations and satellite-based remote sensing provide crucial insights into historical weather patterns. Delving into these patterns scientists can identify trends in the occurrences of extreme weather to better understand climate change. This data, Processing and analyzing this data via GIS software, is essential for understanding the spatiotemporal distribution of extreme weather events and how these patterns may intensify to shift due to the lasting climate change [11].

By leveraging GIS analysis, researchers can also assess the changes in extreme weather events in different regions. GIS is particularly useful for visualizing the occurrence and intensity of heat waves in urban areas over time, offering a clearer representation of the urban heat island effect, which is exacerbated by rising global temperatures. This visualizing feature of GIS provides a clearer illustration of the urban heat island effect which is exacerbated by rising temperatures. Trends of heavy rainfall events such as the 2022 Pakistan monsoon season, which is believed to be subjected to intensification. This is due to the increasing moisture-holding capacity attributed to a warmer atmosphere [12]. Drought analysis using GIS integrates data related to precipitation deficits, soil moisture, and vegetation indices, to monitor drought periods. It will also help examine the extended impacts on water resources and agricultural practices [13].

GIS is also involved in the risk assessment of extreme weather events. GIS can simulate the effects of extreme weather events on vulnerable communities. This can be achieved by layers of socio-economic and environmental data such as population density and land use. For instance, GIS can model flood risk in coastal and riverine areas when rainfall intensity data and topographic and hydrological information are provided. This will aid the process of identifying risk zones and informing flood management strategies [14]. GIS in drought risk assessments can locate areas suffering the most from water scarcity, aiding in the development of water management schemes and mitigation measures to reduce water stress. This capability underscores the significance of GIS in assessing and managing the risks associated with extreme weather events in this challenging environment created by the changing climate [15].

GIS enables the analysis of spatiotemporal changes in extreme weather events like heatwaves, heavy rainfall, and droughts by processing meteorological data. It helps visualize patterns such as the urban heat island effect, offering insights into climate change impacts. Additionally, GIS supports risk assessments by integrating socio-economic and environmental data, aiding in disaster preparedness and mitigation strategies for vulnerable areas.

3. Case Studies of GIS Applications in Climate Change Research

The significant impact on both the environment and human societies makes temperature change one of the most critical indicators of climate change. The data can be provided by NASA's Goddard Institute for Space Studies, the National Oceanic and Atmospheric Administration, and authorities such as the European Centre for Medium-Range Weather Forecasts. Allowing for the analysis and spatial interpolation of global temperature trends. Integrating these datasets into the GIS environment will help map the fluctuating temperature over time. Meanwhile, highlights variations existing in different regions.

The methodology generally involves the use of spatial interpolation. A technique that employs kriging and inverse distance weighting. This means that gaps in temperature data are filled to create a map of global surface temperature trends. Climate researchers can then analyze the effects of rising temperatures on more specific regions. Particularly, those more prone to climate-induced changes. Hansen et al. demonstrated how these GIS-based techniques are capable of supplementing research with valuable insights into global warming patterns, especially in polar regions where the warming rate amounted to nearly twice the global average [16]. Through satellite remote sensing and ground-based data from various institutions such as the Indonesian Agency for Meteorological, Climatological and Geophysics. It has been modeled that under rising temperatures rainfed farms in Indonesia are under more threat than irrigated farms, in terms of yield reduction [17]. Underscoring GIS's role in locating areas experiencing accelerated warming with models such as the Shierary Rice model, aiding policymakers in formulating targeted adaptation strategies.

As one of the most pressing consequences of global warming, sea level rise poses severe threats to coastal cities around the world. GIS can be used to evaluate the impacts of rising sea levels on urban areas, using datasets from satellite altimetry, alongside detailed topography data. This aided the 3D GIS modeling of Varna Bay. Where it is predicted with a 1.92-meter sea level rise over 50 years, in

the context of extreme rises. Also providing insights into areas such as Kamchia resort and Burgas city where risks of flooding is higher. Sublayers including critical buildings were also added to the study [18].

The approach typically simulates sea-level rise based on various climate change scenarios projected by GCMs. These models incorporate variables such as thermal expansion, melting of ice caps, and land ice contributions towards sea level changes. By employing GIS for spatial overlay analysis, it is possible to identify which urban areas are most at risk from flooding and erosion as sea levels rise. Through adjusting the approach, local relative sea-level change can also be investigated when accounting for gravitational effects, thermal expansion, ocean dynamics, and Glacial Isostatic Adjustment. This study utilized 3 emission models and the same data as in IPCC AR4 to investigate local change, allowing a comparison with the global mean from IPCC AR4. Concluding that local value can deviate significantly from the global figures and that the relative sea level change should not be taken as a uniform change [19]. Additionally, simulations are an effective means of visualizing sea level rise under different climate scenarios. For instance, Nicholls et al. used GIS to assess the vulnerability of coastal infrastructure in cities like Shanghai and London, commenting on how the defenses were not prepared for rather extreme events [9]. Offering policymakers where to prioritize the implementation of mitigation strategies along the coastline. This can include coastal defenses, zoning regulations, and even urban planning strategies depending on the specific conditions.

4. Conclusion

Attributed to its ability to visualize and analyze spatial data, GIS technology has proven to be an instrumental player in the research into climate-related studies. Through such tools, a more in-depth disclosure of the impacts of climate change and global warming on ecosystems, climate systems, and human societies can be acquired. Supplemented by data collected through remote sensing and land-based institutions GIS can assess challenges ranging from temperature change to sea level rise and extreme weather events. Providing a powerful means to tackle and study the ongoing changing climate.

Along with the merits of using GIS, there are also challenges that this technology is currently facing. The quality of data quality, the uncertainty of different models, and computing resources are indeed common issues due to technological limitations. Constraining the effectiveness of employing a GIS-based approach in academic research. Future studies should focus on the application of high-resolution data, the fusion of multi-source data, the development of more dynamic models, and interdisciplinary comprehensive analysis to improve on GIS's potential to give a precise understanding of the impact of global warming. Providing a scientific base for the development of more effective policy and response strategies.

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