Climate Change and Coastal Line Shifts: Advances in Remote Sensing Monitoring

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Abstract: Climate change significantly impacts coastal environments, prompting the need for advanced monitoring techniques. This paper examines the critical role of remote sensing technology in monitoring the shifts in coastal lines due to climate change. It provides a comprehensive review of the application of satellite imagery, LiDAR, and other sensors in capturing multi-temporal changes in coastal environments. The study underscores the importance of these technologies in assessing coastal erosion, sedimentation, and sea-level rise, offering detailed insights that are vital for coastal management and climate change adaptation strategies. The paper also discusses the challenges in data acquisition and processing, highlighting the need for advanced data pre-processing techniques. Furthermore, it explores the potential of integrating big data, cloud computing, and AI to enhance real-time monitoring and predictive capabilities. The future outlook highlights the integration of multi-source remote sensing data, UAV technology, IoT and edge computing, and deep learning for more accurate and efficient monitoring. The paper concludes that the continuous advancement in remote sensing, coupled with emerging technologies, will significantly contribute to the sustainable development of coastal zones.

1 INTRODUCTION

The coastline is the boundary between the ocean and the mainland, and it is not only an important part of topographic maps and nautical charts but also one of the 27 surface elements recognized by the International Geographical Data Committee (Wu & Hou, 2016). Shaped by a combination of terrestrial, marine, atmospheric, and human activities, the coastline exhibits unique geographical features and dynamic characteristics, with its position, direction, and form constantly changing. The coastline holds substantial ecological functions and resource value. With advances in transportation, rapid population growth, accelerated economic development, and increasing geographical importance, the coastline has become one of the most frequently and intensely impacted areas by human activities. However, rapid economic development and limited land resources have led to significant changes in the natural ecological environment of coastal areas. The construction of various coastal projects and the rapid development of regional economies have reduced the natural attributes of the coastline, and the original production capacity and ecological functions have changed significantly (Wu & Hou, 2015). The change of the coastline is a key research topic in the field of environmental geosciences. In recent years, with the intensification of global climate change, the rise in atmospheric temperature has significantly affected the morphology and evolution process of the coastline, as well as having a profound impact on sea level, ecosystems, and human activities.

To better comprehend these impacts, researchers have widely applied remote sensing technology, especially satellite imagery, to monitor and analyze changes in the coastline. Remote sensing imagery technology has significant advantages and potential in this field. By using aerial or satellite sensors to obtain multi-band (such as visible light, infrared, microwave) data and converting it into digital images, it enables people to obtain and analyze large-scale, multi-temporal surface information (Liang et al., 2018). With the continuous advancement of remote sensing technology, high spatial resolution and high spectral resolution satellite images have emerged one after another, with rapid scanning capabilities. These technologies are now widely used in environmental monitoring and management, allowing us to identify and extract various components of the coastal

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environment and their related information more efficiently and conveniently.

This study summarizes the relevant information on the application of remote sensing imagery in the changes of the coastline under the influence of atmospheric temperature, not only showing the research results in this field, filling the gaps in research, but also providing scientific support and decision-making basis for dealing with the challenges brought by climate change. Finally, it anticipates the future developmental trajectories in this field.

2 APPLICATION OF REMOTE SENSING TECHNOLOGY IN COASTAL LINE MONITORING

The utilization of remote sensing technology in coastal boundary detection is diverse, offering extensive, efficient, and cost-effective methods for monitoring coastlines. It has significantly contributed to global research on coastal zones, offering technical support for diverse areas including pollution in coastal ecological environments, environmental disasters, and the restoration and protection of coastal habitats. Remote sensing can be divided into the following categories according to its data sources and acquisition methods:

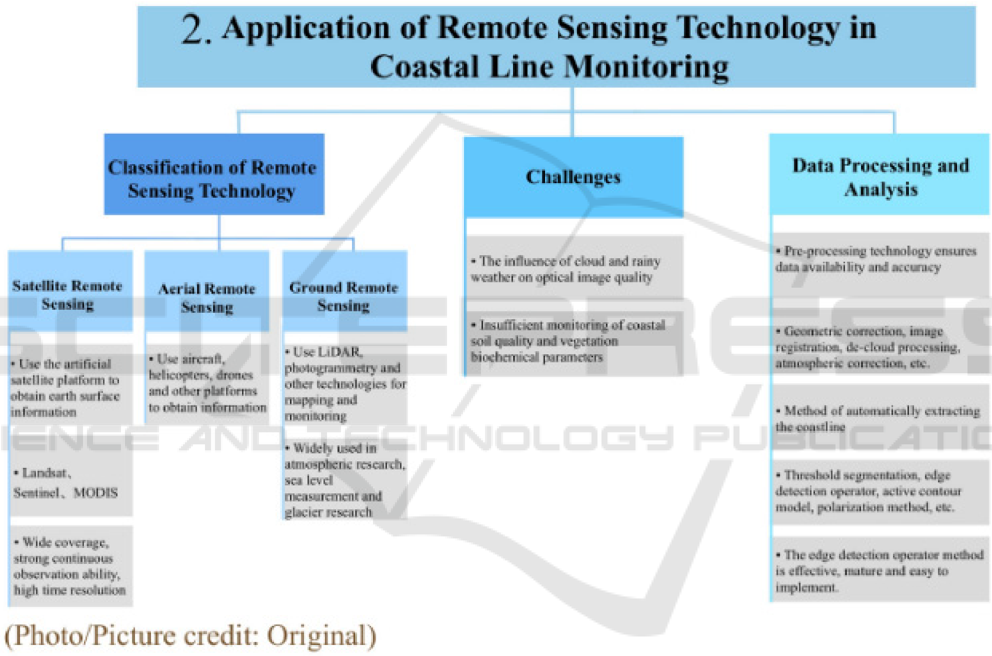

Figure 1: Mind maps for remote sensing technology applications (Picture credit: Original).

Satellite remote sensing is a technology that uses artificial satellites as platforms to obtain information about the Earth's surface through sensors. It has the characteristics of wide coverage, strong continuous observation capability, and high temporal resolution. For example, the application of satellite data such as Landsat, Sentinel, MODIS, etc.

Aerial remote sensing is a technology that uses aircraft, helicopters, airships, unmanned aerial vehicles (UAVs), and other aircraft as platforms to obtain information about the Earth's surface with sensors.

Ground remote sensing is a remote sensing activity carried out on the Earth's surface, mainly referring to the use of LiDar, ground photogrammetry, and other technologies for surveying and monitoring. Currently, LiDAR technology is widely used in atmospheric research, sea level measurement, and glacier research, with the characteristics of fast speed, strong anti-interference capability, and high precision.

Despite the significant advantages of remote sensing technology in coastal boundary detection, it also faces numerous challenges, such as the adverse effects of cloudy and rainy weather on optical image quality, and inadequate monitoring of coastal soil quality and vegetation biochemical parameters (Li et al., 2016). Therefore, the data sources obtained through different remote sensing methods must be professionally pre-processed and appropriate analysis methods must be adopted to accurately reflect the actual topographical conditions and changes of the remote sensing area.

Remote sensing image pre-processing technology is a key step to ensure the usability and accuracy of remote sensing data. Researchers usually adopt geometric correction, image registration, cloud removal, atmospheric correction, and other means.

Research progress has shown that there are various methods to automatically extract coastlines from remote sensing images, including threshold segmentation methods, edge detection operator methods, active contour model methods, polarization methods, etc. Among them, the edge detection operator method has a better extraction effect on the coastline, the method is more mature, and it is easy to implement (Wu & Liu, 2019).

3 RESEARCH PROGRESS ON COASTAL LINE CHANGE REMOTE SENSING MONITORING

3.1 Monitoring of Coastal Erosion and Sedimentation

Research advancements in coastal change and remote sensing monitoring predominantly center on utilizing remote sensing to monitor coastal erosion and sedimentation, and to analyze spatiotemporal dynamic changes in coastline features. Through literature search, we can find that the main research areas include:

Research on the dynamic changes of erosion and sedimentation in the Yellow River Delta: Combining remote sensing and GIS technology, the land erosion and sedimentation in the Yellow River Delta region were studied, and it was found that the land area in the Yellow River Delta region changes year by year under the dual action of sedimentation and marine erosion of the Yellow River (Dong et al.).

Spatiotemporal evolution analysis of the coastline in Greater Bay Area: Using remote sensing imagery to obtain coastline data from 1975 to 2018, the development and utilization of the coastline and the spatial position changes were analyzed based on the GIS platform (Yang et al., 2021).

Remote sensing monitoring of the status of coastal erosion in Jiangsu Province: Using satellite remote sensing interpretation, tidal numerical simulation, and GIS spatial topological analysis, the current status of coastal erosion in Jiangsu Province was monitored (Cui et al.).

These studies show that remote sensing technology has become an important tool for coastal line change research, providing spatiotemporal dynamic information on coastal erosion and sedimentation, providing a scientific basis for coastal zone management and protection.

3.2 The Impact of Sea Level Rise and Climate Change

Sea level rise (SLR) is one of the most urgent challenges of climate change, which has aroused widespread research interest in recent years. It relates to factors such as global warming, melting of polar glaciers, and thermal expansion of the upper ocean water. The rise in sea level caused by climate change has a significant impact on coastline, and the climate-driven factors mainly include two parts: first, factors caused by changes in the atmosphere and ocean (Sarrau et al., 2024), the rate of sea level rise is affected by the intensity, height, and frequency of waves in coastal and tidal areas (Chini ey al., 2010; Aagaard & Sørensen, 2012). In addition, linear sea level rise scenarios and extreme events also affect wave action in coastal areas. Another climate-driven factor is the melting of land glaciers, which leads to the influx of freshwater into the ocean. This not only changes the density structure of the ocean but also affects wave action. These impacts can be studied and analyzed through remote sensing monitoring technology (Li et al., 2020).

Specific monitoring methods divides into the following categories:

- Satellite radar altimeters

Satellite radar altimeters are widely used remote sensing technologies for measuring sea level height. This technology calculates changes in sea level height by sending radar signals from satellites to the Earth's surface and receiving the return signals. For example, scientists have been able to monitor long-term trends in global sea level changes using radar altimeter data from a series of satellites such as TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 (Allenbach et al., 2015).

- Satellite gravity measurement

The GRACE (Gravity Recovery and Climate Experiment) satellite mission monitors the mass loss of glaciers and ice caps and their contribution to sea level rise by measuring changes in the Earth's gravity field. For instance, Velicogna (Velicogna, 2009) employed GRACE satellite data to quantify

Greenland and Antarctic ice sheet mass loss, elucidating their influence on global sea level rise.

- Optical and radar imaging

Remote sensing imaging technologies, such as optical and radar images from Landsat and Sentinel series satellites, are widely used to monitor changes in coastal areas. These images can capture changes in coastlines, the submersion of wetlands, and the degradation of salt marshes. For example, Murray et al. (Murray et al., 2019) used Landsat images to analyze changes in the area of global coastal wetlands over the past few decades and assessed the impact of sea level rise on these ecosystems.

The response of coastlines to climate change varies across different regions, mainly due to differences in geographical location, topography, environmental conditions, and human activities. The application of remote sensing monitoring technology provides important data support and analysis methods for studying the response of coastlines to climate change. Here are some current research statuses in this field.

The coastal areas of Bangladesh are among the most severely affected areas by sea level rise globally. Researchers have used multi-source remote sensing data, including radar altimeters, optical and radar imaging techniques, to monitor changes in the coastline, flood risks, and wetland degradation in the region (Sarwar & Woodroffe, 2013). For example, Sarwar and Woodroffe (2013) used Landsat image data to analyze long-term trends in the changes of the coastline in Bangladesh, revealing the impact of sea level rise and human activities on coastal erosion. Similarly, the East Coast of US has also significantly affected, especially due to the combined effects

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In China, the Jiangdong New Area of Haikou and its neighbouring regions have also deeply affected by the rise in sea levels. Utilizing Landsat data, researchers have conducted remote sensing monitoring and change characteristic analysis of the coastline in this area from 1987 to 2018. Their findings indicate that over the past 31 years, the coastline has shown a trend of "decrease - increase - stability" in its evolution, with a net increase of 1.52 km in total length, and human factors have become the main driving force behind the changes in the coastline (Zhu & Zhang, 2023). Additionally, remote sensing technology plays a crucial role in monitoring the coastal zone's geographical environment, including land use/cover, soil quality, vegetation, coastlines, water color, water depth, and underwater topography, as well as disaster monitoring (Li et al., 2016).

3.3 Changes in the Coastline under Human Activities

Human activities have multifaceted impacts on coastlines, including direct effects on coastal morphology and coastal ecosystem structures, as well as indirect effects on the socio-economic framework of coastal zones.

Urbanization, port construction, and changes in land use are significant human factors affecting the evolution of coastlines. Specifically, urbanization leads to the replacement of natural coastlines with buildings and infrastructures as urban spaces expand, affecting not only the natural form of the coastline but also the ecosystem services of the coastal zone (Shi et al., 2022). Port construction is another significant human-induced factor of coastline change. The establishment or expansion of ports requires extensive land reclamation, which directly alters the original state of the coastline. Additionally, changes in land use, such as agricultural development, industrial growth, and tourism expansion, can impact the coastline. Specifically, land reclamation activities not only change the form of the coastline but may also cause damage to coastal wetlands and ecosystems (Wei wt al., 2019).

Remote sensing monitoring technology plays a pivotal role in studying changes in coastlines and their impacts, especially when analyzing the effects of human activities on these changes. For example, in China's Pearl River Delta, due to large-scale land reclamation and industrial development, the coastline has undergone rapid changes, and the ecosystem has been significantly affected (Tang et al., 2010). Similarly, the coast of Mandla in India has notably influenced by human activities due to port construction and sand mining (Jayappa & Narayana, 2009). In Florida, USA, research has found that coastal erosion has intensified due to the expansion of real estate development and tourism (Passeri et al., 2018). Remote sensing technology enables researchers to accurately monitor these changes and assess their long-term impacts. For instance, Luijendijk et al. (2018) analyzed global coastline changes using a satellite dataset, revealing the significant impact of human activities on coastline changes worldwide (Luijendijk et al., 2018). Menaschiro et al. (2018) also used remote sensing data to study the driving factors behind global coastline retreat, including human activities and natural processes (Mentaschi et al., 2018).

In summary, through remote sensing monitoring, scientists can more accurately understand the changes in coastlines, assess the impact of climate change on coastlines, and provide a scientific basis for the management and protection of coastal zones.

4 FUTURE RESEARCH OUTLOOK AND PROSPECTS FOR REMOTE SENSING MONITORING OF COASTAL LINE CHANGES

Monitoring coastline changes using remote sensing technology is a continually evolving field, with future research directions deeply influenced by current new technologies, the results of which can be widely applied to the management and policy of coastline protection.

4.1 Big Data and Cloud Computing in Monitoring Coastal Changes

For new technologies, big data, cloud computing, and artificial intelligence have broad application prospects in monitoring coastal changes:

- Big Data Technology

Capable of processing and analyzing massive amounts of data collected from various sensors and remote sensing equipment, including satellite images, topographic data, and meteorological data, which are crucial for understanding the dynamic changes of coastlines.

- Cloud Computing

Provides the necessary computational resources and storage capacity to handle big data, with its elasticity and scalability allowing resources to be dynamically adjusted according to demand.

- Artificial Intelligence and Machine Learning

Improve the accuracy and efficiency of automatic coastline extraction, enabling real-time monitoring and trend prediction on a larger scale, providing a scientific basis for regulation and protection.

With ongoing advancements in remote sensing technology and AI implementation, outcomes will furnish precise data for coastline safeguarding and management, anticipate trends and risks in coastline alterations, and foster proactive and effective coastal protection measures, bolstering responsiveness to climate change.

4.2 Multi-Source Remote Sensing Data Integration

By integrating remote sensing data from different sources (such as optical remote sensing, radar remote sensing, LiDAR, etc.), more comprehensive and accurate information on coastline changes can be obtained. This multi-source data integration method can overcome the limitations of single data source and improve the reliability and accuracy of results.

4.3 Application of UAV Technology

UAVs, with their high resolution, flexible mobility, and low cost, can be used for high-frequency and small-scale coastline monitoring, especially suitable for areas that are difficult to cover by traditional satellite remote sensing. The development of UAV technology will further enhance the fine monitoring capabilities of local coastline changes.

4.4 IoT and Edge Computing

Deploying IoT sensors near coastlines can collect real-time environmental data (such as tides, waves, wind speed, etc.), and combining edge computing technology for preliminary data processing and analysis locally can provide real-time feedback on changes, improving the timeliness and accuracy of monitoring.

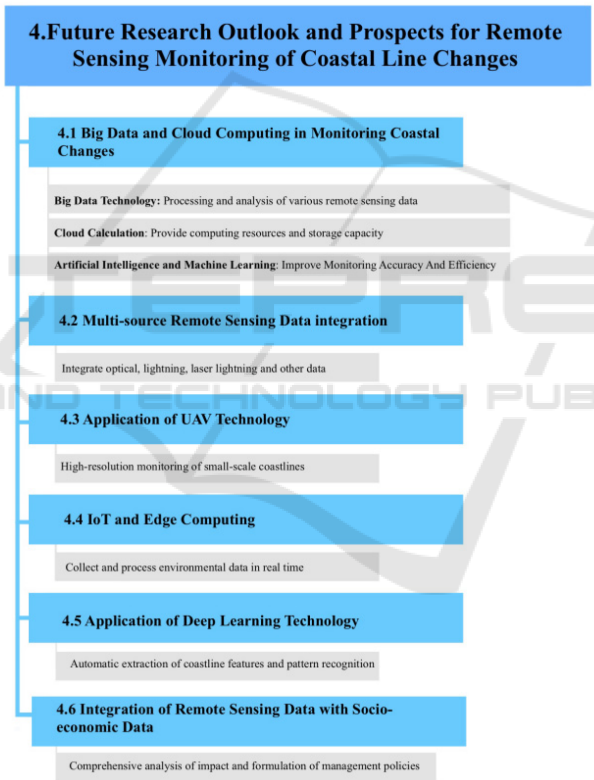
4.5 Application of Deep Learning Technology

Deep learning has significant advantages in image and pattern recognition and can be used to automatically extract coastline features from remote sensing images, classify and identify different types of coastline changes, thereby improving monitoring efficiency and accuracy. This includes establishing real-time monitoring and early warning systems based on remote sensing data, which can dynamically monitor coastline changes, timely detect and warn potential risks such as coastal erosion and storm surges, providing real-time decision support for managers.

4.6 Integration of Remote Sensing Data with Socio-economic Data

By combining remote sensing monitoring data with socio-economic data—such as land use, population distribution, and economic activities—a comprehensive analysis can be conducted. This analysis can assess the impact of coastline changes on socio-economic development and formulate more scientifically sound policies for protection and management. Furthermore, enhancing global and regional-scale monitoring of coastline changes through international collaboration and data sharing can establish a worldwide network for monitoring such changes, offering data backing and a decision-making foundation for global coastline protection and management.

These research directions will further enhance the capabilities of remote sensing monitoring for coastline changes, offering stronger technical support for climate change adaptation and coastline protection.



(Photo/Picture credit: Original)

Figure 2: Mind -map of Future Research Outlook and Prospects for Remote Sensing Monitoring of Coastal Line Changes (Picture credit: Original).

5 CONCLUSION

In conclusion, remote sensing technology has become an essential tool for monitoring the changes in coastlines. It acquires multi-temporal and multi-spectral data through satellites, aerial, and ground sensors, providing spatiotemporal dynamic information on coastal erosion, sedimentation, and sea-level rise. Technological advancements have improved monitoring efficiency with high-resolution imaging and rapid scanning capabilities. Future research will leverage big data, cloud computing, and artificial intelligence to further enhance data processing capabilities and the precision of automatic extraction, achieving real-time monitoring and trend forecasting. This will establish a scientific foundation for coastline protection, policy formulation, and climate change adaptation strategy development, thereby fostering sustainable coastal zone development.

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