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Review of Climate Modeling for Sea Level Rise

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Abstract. Sea level rise is one of the most certain and highly destructive consequences of global warming, posing a serious threat to coastal communities worldwide. The ability to accurately predict its magnitude and rate directly underpins the efficacy of coastal adaptation planning. This paper systematically reviews the main physical mechanisms driving sea level rise and conducts a comparative analysis of semi-empirical models and process models in terms of performance, applicability, and uncertainties. Integrating key research findings from the IPCC Sixth Assessment Report, the article comprehensively presents projections of global and regional sea level rise under different emission scenarios. The results show that under the high-emission scenario SSP5-8.5, the global average sea level could rise by up to 99 centimeters by 2100 and nearly 290 centimeters by 2300. Regional factors, such as land subsidence and ocean dynamics, will exacerbate localized impacts. This paper provides valuable reference for global coastal adaptation efforts.

Keywords: Sea level rise, climate models, coastal zone planning, IPCC, adaptation policies

1. Introduction

Since the beginning of the 20th century, the global mean sea level (GMSL) has risen by approximately 20 centimeters, with the rate of rise undergoing a steady acceleration in recent decades. The primary drivers are thermal expansion of seawater and the melting of glaciers and ice sheets. Despite significant advancements in satellite observation technology and climate modeling research, there remains substantial uncertainty regarding long-term projections of sea level changes, particularly those related to the dynamics of Greenland and Antarctic ice sheets [1,2]. This poses a significant challenge for decision-makers and engineers who rely on reliable data for long-term coastal zone planning and investment decisions.

Existing research tends to focus either on elucidating the natural scientific mechanisms of sea level rise or on investigating generalizable adaptation strategies, but a gap persists in comprehensive reviews that systematically link increasingly refined model projections with context-specific and actionable policy frameworks. This deficiency is particularly evident in regional adaptation studies, as global models often fail to accurately capture local ecological and geological characteristics. For instance, the eastern coastal regions of China face the dual risks of global sea-level rise and localized land subsidence, urgently requiring solutions tailored to local conditions [1].

This study employs the method of literature review, analyzing and comparing various sea-level rise modeling methodologies. It summarizes projected outcomes under different future scenarios and

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explores how these scientific insights inform the design of robust coastal adaptation policies. The research's significance lies in integrating global scientific consensus with regional practical experience, providing a scientific foundation for establishing climate-resilient coastal governance systems. It also facilitates translating complex model outputs into forward-looking, actionable decision-making references.

2. Models and basic concepts

Future sea level rise predictions rely on a series of mathematical models, each with distinct structural and application emphases. Empirical evidence suggests that ensemble methods incorporating multiple models generally outperform individual model projections, with model selection and integration emerging as key determinants of improving estimation accuracy [3].

2.1. Model classification

The following models are mainly used in the study of sea level rise [1,2]:

The energy balance model is a simplified model to estimate changes in the Earth's temperature based on the global energy balance. It can provide a macroscopic framework to understand the driving factors of climate change, but its regional resolution is not fine enough.

The semi-empirical model is a data-driven and simple model, which is suitable for rapid scenario analysis.

The Atmospheric-Ocean General Circulation Model (AOGCM) is a complex physical model capable of simulating the fluid dynamics and thermodynamic processes of the global climate system, and is a key tool for depicting the interactions among different spheres.

The ice sheet model is designed to simulate the evolution and mass balance of the Greenland and Antarctic ice sheets. Improving the parameterization scheme is the key to reducing the uncertainty of sea level rise projections.

2.2. Semi-empirical model

The semi-empirical model achieves a good balance between computational efficiency and predictive power. The representative formulas of this model are as follows:

$$\mathrm{dH/dt} = \mathrm{a} \cdot \Delta\mathrm{T(t)} + \mathrm{b} \cdot (\mathrm{d}\Delta\mathrm{T/dt}) \tag{1}$$

Here, H denotes sea level, t represents time, and ΔT indicates the global temperature anomaly relative to the pre-industrial baseline. The semi-empirical model's primary advantages include computational simplicity and its ability to accurately fit historical sea level data. Nevertheless, its limitations originate from an insufficiently robust physical mechanism basis, potentially resulting in the underestimation of sea level rise when projected scenarios diverge from the historical conditions used for model calibration. For instance, in high-emission scenarios where ice sheet dynamics significantly exceed historical records, the semi-empirical model could underestimate the magnitude of sea level rise [1,2].

2.3. Process model

In contrast, process-based models (e.g., Atmospheric-Ocean General Circulation Models (AOGCMs) integrated with ice sheet dynamic modules) are designed to explicitly characterize the

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physical processes and components of the climate system. Their key strength lies in providing clear physical processes that attribute sea-level changes to specific factors—such as distinguishing between thermal expansion and ice melt contributions. This attribution capability proves invaluable for developing targeted adaptation policies.

The primary limitation of process models stems from their heavy computational demands, coupled with incomplete parameterization for critical ice sheet processes such as ocean ice cliff instability and ice shelf collapse. These constraints result in overly broad sea-level rise projections in existing scientific literature. Although advancements in high-performance computing now enable higher-resolution simulations, uncertainties persist in long-term projections beyond 2100 [4].

3. Estimation and analysis

The magnitude of future sea-level rise is strongly contingent on greenhouse gas (GHG) emission trajectories, with climate mitigation policies exerting a deterministic influence on long-term outcomes. Under the high-emission SSP5-8.5 scenario, global mean sea levels are projected to rise by approximately 99 centimeters by 2100 and may approach 290 centimeters by 2300. In contrast, the low-emission SSP1-1.9 scenario can limit the 2100 rise to 29-50 centimeters, highlighting the critical importance of proactive climate action [5].

It is crucial to recognize that global sea-level rise is not uniform across the planet. Influenced by factors such as land subsidence, ocean current changes, and glacial equilibrium adjustments, significant deviations exist between regional and global average values. Given these regional variations, localized risk assessments are essential. These assessments should integrate global climate projections with local geological conditions and other relevant factors.

As shown in Table 1, the sea level rise in different regions is significantly higher than the global average due to regional factors such as land subsidence and ocean current changes, among which the eastern region of China and the Mekong Delta are particularly prominent.

Table 1. Regional sea level rise projections and key amplifying factors under the SSP5-8.5 scenario [1,3,6]

region	Additional SLR projected (above global average)	Key amplifying factors
China eastern region	+20 to 40 cm	Ground subsidence and river sediment transport reduction caused by groundwater extraction
Mekong Delta	Approximately +40 cm	Large-scale underground fluid extraction, reduction of sediment sources, and dam construction upstream
The Gulf of Mexico region	+10 cm	OCEAN CURRENT CHANGE, GLACIAL BALANCE ADJUSTMENT AND OIL EXPLORATION
China Qinzhou Bay	+15 to 30 cm	Local Ground Subsidence,Coastal Erosion and Insufficient Sediment Supply

The rise in sea level will significantly increase the frequency of extreme coastal water events. As shown in Figure 1, due to the elevated baseline sea level, extreme high-tide events previously considered once-in-a-century occurrences are projected to become annual or even more frequent in many regions by 2100 [3]. This "baseline elevation" effect indicates that even moderate sea level rise could cause catastrophic impacts on coastal infrastructure designed based on historical flood frequency.

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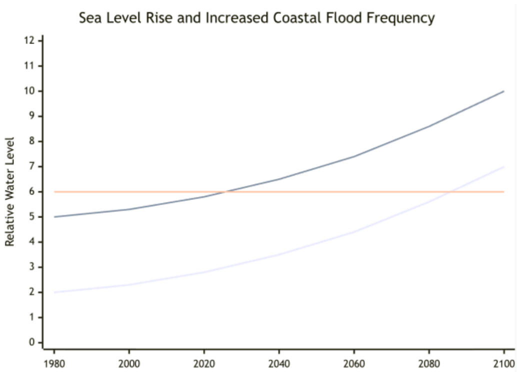

Figure 1. Schematic of increased frequency of extreme flood events due to sea level rise [3]

The vertical axis shows water levels, while the horizontal axis represents time variations. The continuously rising baseline sea level (indicated by the red line) increases the likelihood of overlap between astronomical tides and storm surges, thereby leading to more frequent extreme events.

4. Policy implications

The aforementioned scientific projections indicate that urgent and strategic policy responses are needed to fully integrate sea level rise science into coastal management, which is key to building resilience—a point already proven by numerous successful global cases [7-9]. The following policy recommendations draw on international best practices and regional innovative experiences, referencing China's wisdom in coastal zone governance.

4.1. Elevation design of infrastructure

The design standards for critical infrastructure require updates, with probabilistic sea level rise projections replacing historical averages as the new design basis. For key facilities such as nuclear power plants, major ports, and wastewater treatment plants, the design elevation under the SSP5-8.5 scenario should be set 1.0 meters above the current century flood level to account for unforeseen ice sheet dynamics [3]. For instance, Shanghai Port has revised its dock design standards by integrating IPCC projections with local subsidence data to address potential 50-centimeter sea level rise by 2050 [6].

Adaptive infrastructure strategies should embrace the 'flexible design' paradigm, reserving capacity for future retrofits informed by updated sea level projections. This includes modular construction techniques and adjustable flood barriers, enabling enhanced protection capabilities while reducing risks of overinvestment or inadequate safeguards [10].

4.2. Nature-based solutions

Ecosystem adaptation, defined as "Nature-Based Solutions (NbS)", should be prioritized as a complementary approach to hard engineering measures, offering higher cost-effectiveness and greater resilience. Protecting and restoring natural barriers like mangroves, coastal wetlands, and dunes can effectively reduce wave energy and height while delivering multiple benefits including biodiversity conservation and enhanced carbon sequestration. Studies indicate that healthy mangrove ecosystems can reduce wave height by up to 63.7% and lower storm surge levels by 30% to 50% [6,9].

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China's Qinzhou Bay Ecological Disaster Mitigation Project, located in southern China, serves as a paradigmatic case of successful NbS implementation. Facing severe coastal erosion and rising sea level risks, the local area has established a comprehensive protection system combining offshore protection with "beach-shore protection-protective forest" and inland bay protection with "mangrove-ecological shore protection," achieving remarkable results: the maximum reduction in wave height reached 63.7%, and the intertidal zone species diversity increased by 57%. The project innovatively utilized 6,000 tons of discarded oyster shells to construct a protective belt, which not only reinforced the coastline but also achieved resource recycling. This approach embodies China's traditional ecological wisdom of "following the way of nature" and aligns closely with the NbS framework promoted by the International Union for Conservation of Nature (IUCN).

To promote the adoption of NbS, the policy framework should incorporate ecological compensation mechanisms, such as mangrove carbon sink trading projects. Qinzhou's successful completion of Guangxi's first mangrove carbon sink transaction, which creates sustainable economic incentives for coastal ecological protection through market mechanisms, represents a valuable exploration.

4.3. Flood zone planning and insurance

Land use planning and financial instruments require systematic evolution to explicitly incorporate the long-term risks posed by rising sea levels. Flood risk maps, serving as the foundation for zoning management, should be updated every 5 to 10 years using the latest models and local monitoring data [3]. Zoning policies should strictly restrict new development activities in high-risk coastal flood zones and promote "managed evacuation" in areas facing irreversible flooding risks, as demonstrated by practices in the Netherlands and parts of the United States [10].

Priority should be given to developing a risk-based flood insurance market, using price signals to reveal financial risks and curb reckless development. Premium rates should be linked to vulnerability assessments of rising sea levels, with discounts for properties implementing adaptive measures like building elevation or flood prevention upgrades. China's pilot flood insurance program in some coastal provinces combines public subsidies with risk-based differential rates, offering a viable approach to balance social security and risk warning functions.

The supporting measures also include the development of an intelligent early warning system that integrates real-time sea level monitoring, climate model outputs, and local emergency response mechanisms. The "Smart Ocean" early warning system deployed in Qinzhou dynamically monitors mangrove growth conditions and predicts marine disasters, successfully transitioning the region from a "passive disaster response" model to an "active disaster prevention" model.

5. Conclusion

This review highlights that sea-level rise has evolved from a gradual linear progression into a tipping point phenomenon dramatically increasing the frequency of extreme coastal flooding. Comparative analysis of climate models reveals that process models demonstrate clearer physical mechanisms, while semi-empirical models exhibit higher computational efficiency. However, both approaches remain constrained by uncertainties in ice sheet dynamics. The integrated ensemble forecasting method, which combines results from multiple models, shows promising potential for reducing prediction uncertainties.

Based on comprehensive projections, coastal regions worldwide will confront pervasive and acute hazards by the end of the 21st century, exhibiting substantial spatial heterogeneity. The eastern

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part of China and other densely populated delta areas are particularly vulnerable due to the "compound effect" of rising sea levels and localized subsidence. The most critical task now is to adopt a robust and probabilistic sea level rise projection as a rigid constraint for coastal engineering design, territorial spatial planning, and policy formulation.

The adaptation practices carried out in China's coastal areas (such as the Qinzhou Bay project) have fully demonstrated that the integrated management model combining NbS, hard engineering, and intelligent monitoring has the capability to achieve both ecological benefits and disaster reduction goals. These practical experiences hold extremely critical reference value for coastal zone governance in developing regions worldwide facing similar challenges.

This study has certain limitations, primarily relying on existing literature and comparative model results, which inherently carry uncertainties in current scientific understanding. Future research should prioritize improving the parameterization schemes of ice sheet models. For critical processes such as ocean ice cliff instability and ice shelf-ocean interactions, there is an urgent need to develop "simulation" models that can rapidly convert complex climate model outputs into policy-friendly data. Subsequent studies should also quantify the cost-effectiveness of various adaptation strategies under different coastal environments to bridge the gap between long-term scientific predictions and immediate adaptation actions.

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