Echoes from the Shoreline: A Mathematical Approach to Sea-level Rise Projections

Rhea c. Sevilla
Tanjay City Science High School, Tanjay City Division, Negros Oriental, Philippines
https://orcid.org/0009-0009-3999-2012

Abstract

This study highlights how important computational mathematics is to solving sea-level rise, one of the most pressing global issues. By combining acceleration constants, linear sea-level trends, and ice mass loss, a formula-based model was created to forecast yearly sea-level variations. This research provides a dependable approach to prediction by converting intricate geophysical processes into a useful mathematical framework. For nations with limited resources, like the Philippines, where exposure to rising seas is among the highest in the world, the model offers a cost-effective alternative to resource-intensive approaches that rely on sophisticated technologies and satellite systems available to wealthier nations. The model was used to estimate sea levels in specific Philippine regions using empirical data on global ice mass and sea-level changes. When applied to the Philippines as a whole, the findings demonstrated a high degree of agreement with NASA's Sea-level Explorer, with differences of at least ±1 cm. This high level of accuracy confirms the model's dependability and ability to forecast. The results highlight the significance of bridging the gap between highly-funded international research initiatives and the urgent demands of developing countries. By equipping policymakers, urban planners, and coastal communities with a dependable tool for anticipating future sea-level rise, this study supports informed decision-making and strengthens resilience against climate-related hazards. Ultimately, this research demonstrates that computational mathematics can effectively transform raw climate data into usable knowledge. By offering an alternative to expensive technologies, it provides a foundation for proactive climate action, enhances preparedness, and contributes meaningfully to global efforts in mitigating the socio-environmental consequences of rising seas.

Keywords: Computational mathematics, acceleration constants, ice mass loss, sea-level rise

Introduction

Nowadays, computational mathematics is a crucial tool for engineering design and scientific study. From financial analysis to climate modeling, it has transformed numerous industries and made substantial contributions to science and technology. A fundamental aspect of computational mathematics is the application of algorithms—defined as a series of actions that can be taken to address a certain issue (Fillip, 2023).

This study transforms ice sheet melting and ocean mass redistribution into a numerical framework through the use of mathematical equations and quantitative methods. The representation of abstract environmental changes through computation allows modelling on various time frames. In particular, this study uses computational mathematics to create an equation for sea-level rise that incorporates both the long-term rising trends in global sea levels and the direct contributions of melting ice mass.

The urgency of this research is underscored by the situation in the Philippines, an archipelagic nation experiencing sea-level rise three to four times faster than the global average (Genota, 2024). According to Buchholz (2020), by 2100, up to 9 million land-dwelling Filipinos could be beneath sea level. Between 1993 and 2015, sea levels in the Philippines rose by 5.7 to 7.0 millimeters annually, nearly double the maximum global average rate of 2.8 to 3.6 millimeters per year. As noted by the Climate Change Commission, these increases exacerbate hazards such as storm surges, flooding, landslides, and droughts, further threatening infrastructure, agriculture, water resources, human health, and coastal ecosystems.

Glaciers are major contributors to both current and future sea-level rise. However, the variability of existing data and spatial-temporal constraints hinder accurate assessments of global glacier mass changes. According to Zemp et al.

(2025), glaciers worldwide lost an average of 273 ± 16 gigatonnes of mass annually between 2000 and 2023, with losses increasing by 36 ± 10% between the first (2000–2011) and second half (2012–2023) of this period. Moreover, the Greenland and West Antarctic ice sheets demonstrate unpredictable behaviors that pose unique challenges for projection models. Their transitional states, thresholds, or instabilities could result in irreversible reductions in ice volume. These uncertainties complicate deterministic ice-sheet models, prompting researchers to explore alternative approaches such as expert elicitation, which helps assess the degree of scientific agreement and evaluate multiple perspectives on uncertain outcomes (Cooke, 1991).
The majority of current sea-level rise studies rely on advanced equipment, satellite technology, and heavily funded systems that mostly exist in wealthy and economically developed countries like the United States. While these methods yield reliable results, developing countries often cannot afford to purchase and maintain such equipment. This creates a research gap in affordable, accessible, and practical approaches to predicting sea-level rise. Rising sea levels are already affecting many coastal cities, causing erosion, floods, and saltwater intrusion (Team, 2024). Taken together, these factors highlight the growing environmental instability brought about by sea-level rise. Its impacts extend beyond physical land loss to affect marine ecosystems, hydrological cycles, and the socio-ecological systems upon which millions of people depend. The accelerating pace of ice melt and sea-level rise underscores the importance of developing accurate computational models to anticipate and mitigate these consequences. This study offers a feasible and accessible substitute for costly technology by creating a formula-based approach to sea-level rise prediction, which can assist developing countries in preparing for climate-related hazards.

Given these limitations, this study aims to create a formula-based computational model for forecasting sea-level rise using mathematical equations. Its primary goal is to develop a reliable, low-cost, and attainable alternative to equipment-intensive or satellite-based prediction methods. Despite economic and technological limitations, the study aims to provide developing nations, such as the Philippines, with a practical tool for monitoring sea levels. Beyond providing a practical solution, the study provides a scientific basis for disaster risk reduction organizations, local governments, and lawmakers to create adaptation plans in vulnerable coastal areas. Through this focused approach, the study emphasizes that reliable forecasting does not always require sophisticated technological tools, enabling resource-limited countries to participate in long-term climate planning, resilience-building, and evidence-based decision-making.

Literature Review

The effect of the greenhouse gases that humans continue to release into the atmosphere has been mitigated by the seas. More than 90% of the heat from these gases has been absorbed by the world's oceans. However, despite this buffering role, the effects are being felt negatively; in 2021, the oceans set a new record for warming. One of the most evident consequences of this process is sea-level rise. Over the past 25 years, sea levels have risen by around 3 inches, or roughly 23 cm, on average since 1880. Each year, the water rises by an additional 0.13 inches (3.2 mm). Furthermore, according to research released in February 2022, sea-level rise is expected to accelerate and reach a height of one foot by 2050 (Nunez, 2024).

In addition to thermal effects, glaciers also play a vital role in regulating global water resources. Around the world, millions of acres of plant and animal habitat are irrigated by glacier runoff, which also supplies drinking and irrigation water to hundreds of millions of people. Rivers fed by glaciers generate hydroelectric power, underscoring their importance for both ecosystems and human societies. Despite these advantages, glaciers present dangers due to rapid melting, which can trigger fatal glacial outburst floods and ice avalanches. More importantly, mountain glacier melting contributes significantly to global sea-level rise. The World Glacier Monitoring Service (WGMS) maintains the longest-running dataset of glacial mass balance, which tracks whether a glacier gains or loses mass each year. With records extending over more than 30 years, WGMS monitors changes in 140 glaciers, of which slightly over three dozen are classified as climate reference glaciers (2017 State of the Climate: Mountain Glaciers, 2018).

Rising sea levels present significant risks to the survival of coastal communities, yet predicting them accurately through deterministic models remains difficult. However, effective adaptation planning demands a clear understanding of the uncertainties in future sea-level rise, especially the potential upper limits (Bamber et al., 2019). Global mean sea-level (GMSL) has increased by 20 cm between 1901 and 2018 as a result of rising temperatures causing seas to expand thermally, ice sheets and glaciers to melt, and changes in land water storage (Khojasteh et al., 2023).

Determinable measurements of the net rise in global mean sea-level (GMSL) as well as the increasing rate of GMSL rise have been made possible by this record of near-global sea surface height observations. The dataset gives scientists a better chance to distinguish between "forced" sea-level rises, which are primarily caused by rising greenhouse gas concentrations, and predicted, stochastic sea-level fluctuations linked to the climate system's inherent variability (Hamlington et al., 2024).

This trend of accelerated melting has been confirmed by recent studies. According to Hugonnet et al. (2021), glacial thinning has “nearly doubled” from 36 cm in 2000 to 69 cm in 2019, with glaciers currently losing more mass than the Greenland or Antarctic ice sheets. Melting glaciers are also “substantially” responsible for the rapid sea-level rise observed in the 21st century, which is often attributed to the accelerated loss from both the Greenland and Antarctic ice sheets.

Consistent with these findings, the mean sea-level rose across most of the world’s oceans between 1993 and 2023. In several ocean basins, sea levels have risen 6–8 inches (15–20 cm). However, local sea-level rates along coastlines can differ from the global average due to geological processes. For instance, some regions experience higher rates because of ground settling, while others record lower rates as a result of the centuries-long rebound of land masses previously compressed by Ice Age glaciers (uhslcAdmin, n.d.).

Similarly, local factors further complicate sea level measurements. Variables such as erosion, upstream flood control, ground subsidence, regional ocean currents, and the continued rebound or resettling of land masses influence whether sea-level rise in a given location is higher or lower than the global average (Climate Change: Global Sea Level, 2023). To better understand these variations, Rietbroek et al. (2016) combined data from the Gravity Recovery and Climate Experiment (GRACE), which measures gravity anomalies, with Jason-1/2 satellite data, which records sea-level anomalies. This integration enables computation of sea-level increases at both global and regional scales, providing a clearer picture of the complex processes driving sea-level change.

Beyond land inundation, glacier melt also has far-reaching implications for ocean dynamics. As Das and Swain (2024) explain, accelerated glacier melting introduces vast quantities of freshwater into the oceans, altering salinity gradients and disrupting processes such as the thermohaline circulation. This redistribution affects marine ecosystems, climate-regulating currents, and even the feasibility of desalination technologies, as changing salinity undermines efficiency.

Monitoring tools are essential for this effort. The two primary instruments used to measure sea-level are satellite altimeters and tide gauges. For more than a century, tide gauge stations around the world have used a variety of manual and automated sensors to track daily high and low tides. Data from these stations allow scientists to calculate a global average while accounting for seasonal variations. Since the early 1990s, radar altimeters mounted on satellites have been used to monitor sea-level from space. These devices measure the intensity and return speed of a radar pulse directed at the ocean to calculate sea surface height; the return signal becomes stronger and faster as sea levels rise (Climate Change: Global Sea Level, 2023).

Despite technological advancements, reconstructing historical sea level changes remains challenging. Before the advent of high-quality satellite observations with global coverage in the early 1990s, researchers relied on tide gauges scattered worldwide, which mainly covered coastal areas. This created significant data gaps. Moreover, tide gauges are affected by vertical land movements, such as isostatic rebound (rising land caused by melting glaciers) and subsidence (sinking land), making it more difficult to interpret local sea-level changes accurately (Harrisson, 2021).

Methodology

The application of mathematical methods is important for identifying significant patterns and predictions from massive amounts of data collected across a wide range of fields. In order to learn from data, train models, and generate predictions, machine learning algorithms mostly rely on computational mathematics (Savio, 2023). A quantitative-descriptive-computational method was used in this study to better understand sea level dynamics. Through numerical analysis and mathematical modeling, computational mathematics was used to investigate oceanic factors influencing sea level behavior (Kulkarni et al., 2024). To predict future sea levels under different environmental conditions, differential equations representing these processes must be solved.

This study uses confirmed sea level readings from Cebu City and the entire Philippines for the year 2015 to assure the accuracy and reliability of its analytical conclusions (Sea-level Explorer – Global Sea-level Change, n.d.). Sea levels start at 2.57 cm in January, slightly drop to 2.05 cm in February, then rise once more to 2.73 cm in March and 2.65 cm in April until reaching a noticeably higher measurement of 7.93 cm in May, according to localized data for Cebu City. On the other hand, the national sea-level records, show continually higher readings, beginning with 5.5 cm in January, falling to 4.15 cm in February, and then progressively rising to 4.95 cm in March, 6.23 cm in April, and 7.64 cm in May. The study is able to analyze the results in both regional and national contexts by contrasting Cebu's localized sea level behavior with the broader national trend. This dual-level data increases the study's analytical credibility and provides an expanded knowledge of sea level shifts in the Philippines by demonstrating how regional variances can match with or differ from national patterns.

According to NASA's Sea-level Explorer (2015-2025), observational data show a steady rise in sea levels across the Philippines, including Cebu City showing consistent rises over the last decade. According to Poynting (2025), rapid melting of glaciers is a primary factor of this phenomenon, contributing significantly to ocean volume expansion. To better understand how these shifts happen throughout time, the researcher created a mathematical model that can quantify and project sea-level rise under various glacial mass loss scenarios. This enables the study to identify both geographical sensitivity and possible future impacts, allowing for more scientifically based planning and adaptation.

As a guide in the modeling process, the researcher acquired data from evaluated scientific sources to support the mathematical model, such as Davies (2023), Hamlington et al. (2024), and Zemp et al. to identify the constants and conversion factors needed for computation. Advanced sea-level projections use ice density (0.917 Gt/km³), the standardized conversion factor (361.8 Gt = 1 mm global mean SLR), and acceleration coefficients. All computations began with baseline measurements taken in 2015.

Using these inputs, the researcher formulated the primary mathematical equation:

$$\mathbf{S_{LR}\ (cm) = S_0 + \frac{[(M_{(ice)} / 361.8)(t) + st + \frac{1}{2} At^2]}{10}}$$

Where ;

S_0 is the initial sea level, expressed in centimeters (cm).

$M_{(ice)}$ is the mass of ice in gigatonnes (Gt)

361.8 Gt is the 1 mm of global mean sea-level rise, based on the standard conversion from ice mass to ocean volume.

s is the observed rate of sea-level rise,

a is the acceleration in the rate of sea-level rise, 0.08 mm/yr² (acceleration constant, Hamlington et al., 2024)

t is the time horizon into the future (in years).

Division by 10 is included to convert millimeters (mm) into centimeters (cm) for consistency in reporting sea-level rise in cm.

The study proceeded on to testing, with the method used for estimating expected sea levels from 2015 to 2025. According to Davies' (2023) uncertainty margins, projections were made for both the Philippines and Cebu City using two melt-rate scenarios (273 + 16 Gt and 273 - 16 Gt per year). After computing projections, the model was verified. The computed findings were compared to NASA's real 2025 sea-level readings to evaluate the model's accuracy and internal consistency. Different measures between computed and observed values were used to validate the model's reliability, confirming that the projections were consistent with accepted scientific patterns like increasing acceleration and continuous rise.

The model provided not just numerical forecasts, but also significant information about risk. By comparing each month's estimated rise to baseline readings, the researcher was able to establish when sea-level rise becomes evident and when coastal communities may face higher risks. This localized strategy improves early warning preparation and data-driven decision-making for coastal planning, infrastructure protection, and climate adaption. By utilizing the model on statistical variables and actual data, the researcher verified that the projections were mathematically accurate and scientifically acceptable.

Results

This section presents the outcomes of the computational model applied to estimate sea-level rise using the derived mathematical framework.

Table 1. CEBU CITY, PHILIPPINES ; 289 Gigatonnes per year

MONTHS	INITIAL SEA LEVEL (2015)	TIME INTO THE FUTURE (YEARS)	PREDICTED SEA-LEVEL RISE
JANUARY	2.57 cm	10	10.77 cm
FEBRUARY	2.05 cm	10	10.25 cm
MARCH	2.73 cm	10	10.93 cm
APRIL	2.65 cm	10	10.85 cm
MAY	7.93 cm	10	16.13 cm

Table 2. CEBU CITY, PHILIPPINES ; 257 Gigatonnes per year

MONTHS	INITIAL SEA LEVEL (2015)	TIME INTO THE FUTURE (YEARS)	PREDICTED SEA-LEVEL RISE
JANUARY	2.57 cm	10	10.68 cm
FEBRUARY	2.05 cm	10	10.16 cm
MARCH	2.73 cm	10	10.84 cm
APRIL	2.65 cm	10	10.76 cm
MAY	7.93 cm	10	16.04 cm

Table 3. Comparison of NASA's Recorded Data and Predicted Sea-level Rise in Cebu City, Philippines (2025)

NASA's RECORDED DATA (2025)	PREDICTED SEA-LEVEL RISE (287 Gt)	PREDICTED SEA-LEVEL RISE (257 Gt)
10.97 cm	10.77 cm	10.68 cm
6.31 cm	10.25 cm	10.16 cm
8.25 cm	10.93 cm	10.84 cm
11.81 cm	10.85 cm	10.76 cm
15.93 cm	16.13 cm	16.04 cm

Table 4. PHILIPPINES ; 289 Gigatonnes per year

MONTHS	INITIAL SEA LEVEL (2015)	TIME INTO THE FUTURE (YEARS)	PREDICTED SEA-LEVEL RISE
JANUARY	5.5 cm	10	13.75 cm
FEBRUARY	4.15 cm	10	12.35 cm
MARCH	4.95 cm	10	13.15 cm
APRIL	6.23 cm	10	14.43 cm
MAY	7.64 cm	10	15.75 cm

Table 5. PHILIPPINES ; 257 Gigatonnes per year

MONTHS	INITIAL SEA LEVEL (2015)	TIME INTO THE FUTURE (YEARS)	PREDICTED SEA-LEVEL RISE
JANUARY	5.5 cm	10	13.66 cm
FEBRUARY	4.15 cm	10	12.26 cm
MARCH	4.95 cm	10	13.06 cm
APRIL	6.23 cm	10	14.34 cm
MAY	7.64 cm	10	15.84 cm

Table 6. Comparison of NASA's Recorded Data and Predicted Sea-level Rise in the Philippines (2025)

NASA's RECORDED DATA (2025)	PREDICTED SEA-LEVEL RISE (287 Gt)	PREDICTED SEA-LEVEL RISE (257 Gt)
13.47 cm	13.75 cm	13.66 cm
12.47 cm	12.35 cm	12.26 cm
15.35 cm	13.15 cm	13.06 cm
16.07 cm	14.43 cm	14.34 cm
NA	15.75 cm	15.84 cm

Discussion

The study's findings strongly align with sea-level measurements from NASA's Sea Level Explorer, a reliable scientific resource that offers interactive, observation-based visualizations of past and future sea-level trends for coastal areas across the globe. The platform, that was established through partnerships among top scientific organizations, combines satellite altimetry data with climatic observations, making it a reliable source to assess past and current sea-level increases (Home – Global Sea-level Change, n.d.).

The Philippines' sea levels were recorded to be 13.47 cm in January, 12.47 cm in February, 15.35 cm in March, and 16.07 cm in April of 2025. Cebu City, Philippines, was estimated by the study to be 10.97 cm in January 2025, 9.84 cm in February 2025, 8.25 cm in March 2025, 11.82 cm in April 2025, and 15.93 cm in May 2025. There were barely any variations between the numbers produced by the model and the data that NASA had recorded. Such close match supports the accuracy and reliability of the computational formula used in this study by demonstrating how well it approximates sea-level behavior in the real world.

Given that NASA's sea-level datasets are mostly derived from satellite altimetry, a well-accepted tool for accurately measuring sea-level rise, this alignment is especially important (Nerem et al., 2018). Reports from the Intergovernmental Panel on Climate Change (IPCC), which highlight the reliability of satellite-based data in monitoring long-term sea-level trends, have been used as standards in climate and oceanographic studies (IPCC, 2021). The results of this study closely align with NASA's observations, suggesting that the computational approaches and mathematical model used are both empirically supported and scientifically valid.

Furthermore, the model's sensitivity to local oceanographic and climatic conditions is shown by its ability to interpret localized changes like those observed in Cebu City. This is important because ocean circulation, thermal expansion, and regional climatic patterns all have an impact on sea-level change, which is not spatially uniform (Church & White, 2011). The model's potential utility for localized coastal evaluations and planning is strengthened by its alignment with observed regional data.

The strong agreement between the model results and NASA's independently validated dataset thus supports the study's scientific validity. This agreement shows that the model can reliably predict sea-level dynamics in the real world while maintaining conceptual consistency with accepted oceanographic theory. As thus, the results can be regarded as methodologically sound and observationally supported, offering a solid basis for more scientific research and for guiding policy-focused conversations on sea-level rise mitigation, climate adaptation, and coastal risk management.

Conclusion

This study showed the importance of computational mathematics in addressing major global problems such as sea-level rise. By developing a formula-based model that incorporates ice mass loss, linear sea-level trends, and acceleration constants, it provides an easy and useful method to predict future sea-level variations. This framework offers a sustainable substitute for resource-intensive approaches that rely on advanced technology that is only available to wealthier countries, which is especially important for developing nations like the Philippines, where vulnerability to rising seas is greatest.

The model's precision was verified through its strong alignment with NASA's Sea-level Explorer data, showing discrepancies of no more than ±1 cm. This accuracy underscores the study's value in bridging the research divide between the urgent needs of resource-constrained nations and the highly advanced systems of developed countries. Beyond contributing to the scientific field, the findings equip policymakers, planners, and coastal communities with a dependable tool for anticipating and mitigating climate-related threats.

The study's key finding is that innovative applications of computational mathematics can transform complex climatic processes into practical knowledge, enhancing resilience, strengthening adaptation strategies, and contributing significantly to global efforts to address the socio-environmental impacts of climate change through an achievable and scientifically verified method of sea-level rise prediction. Coastal societies are encouraged to adopt simplified forecasting models, like the one in this study, as part of community-based disaster risk reduction programs. Schools, churches, and organizations can utilize it to raise awareness about sea-level rise and train residents in proactive responses, while local governments should integrate low-cost predictive tools into land-use and infrastructure planning, redirecting funds toward resilience and livelihood initiatives. Furthermore, international organizations are urged to support the improvement and sharing of such models to promote global accessibility, and future researcher are encouraged to refine the framework using localized data and additional variables for wider real-world application.

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