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Projection of Extreme Sea Levels in Southeast Asia Considering Climate Change Impacts

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Introduction

Southeast Asia is among the regions most susceptible to extreme sea level events due to the substantial population concentrated in coastal and low-lying areas. These areas are experiencing rapid expansion in demographic density and economic assets, further amplifying their vulnerability. In addition, sea level rise (SLR) further exacerbates the risk, and it is expected to accelerate in the future, potentially doubling the frequency of coastal flooding events.

Previous studies (Kirezci et al., 2020; Almar et al., 2021; Boumis et al., 2023) projected global extreme sea levels. However, these studies primarily accounted for changes driven by the rise of sea level (SLR) and assumed that other components of sea level remained unchanged based on historical conditions. In this study, we aim to address this limitation by incorporating projected changes in other components of sea level. Extreme sea levels in Southeast Asia are analyzed as Extreme Total Water Level (TWL). Following the definition by (IPCC AR6, 2021), TWL is defined as follows:

$$TWL = MSL + SLA + DAC + Tide + Wave\ Setup$$

where MSL is Mean Sea Level, SLA is Sea Level Anomaly, DAC is Dynamic Atmospheric Correction.

Dataset

The regional SLA represents a steric effect, incorporating the sea level rise (SLR) component. The SLA dataset, derived from satellite altimetry measurements, was obtained from the Copernicus Marine Environment Monitoring Service (CMEMS) version vDT2021. The dataset has a spatial resolution of f 0.25° × 0.25° and covers from 1993 to 2022.

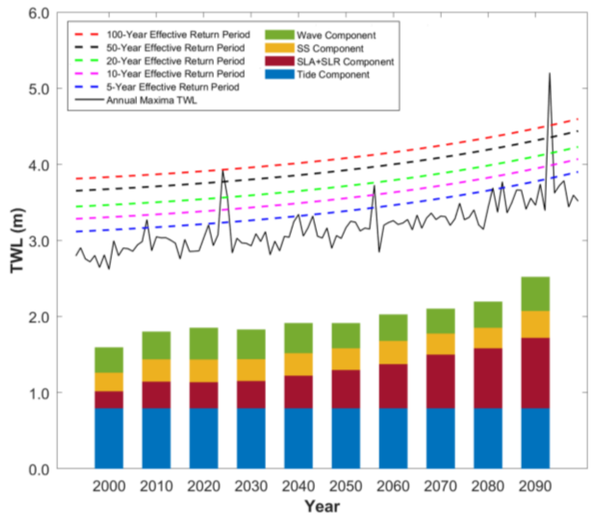

Figure 1 – TWL Projections in Gulf of Thailand

On the other hand, the DAC or storm surge and wave component data is sourced from a seamless projection study of global storm surge and wave (Shimura et al., 2022). The MRI-AGCM model, derived from CMIP5 projections under the RCP8.5 scenario, forced this dataset to account for climate change from 1950 to 2099.

The tidal component was computed using the TPXO9-atlas-v5, considering 15 harmonic constituents. Finally, the MSL component is used to bring TWL to the same MSL as referenced by a geoid by adding the mean dynamic topography (MDT) values to the extreme value estimates. We utilize the MDT HYBRID-CNES-CLS22-CMEMS2020 dataset sourced from AVISO. This dataset is based on the latest GOCO06S geoid model and references the 1993–2012 period, consistent with the reference period of satellite altimetry products.

Methodology

Since the SLA dataset is only available for historical periods, projections need to be created. While the SLA component is often neglected in ESL studies due to its relatively small contribution, it can raise sea level by 20-40 cm in Southeast Asia (Sandi et al., 2024). However, SLA is strongly influenced by climate variability, and current projections of climate variability remain highly uncertain.

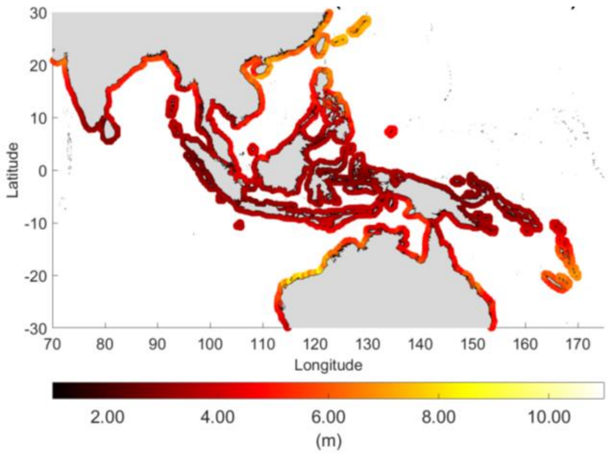

Figure 2 – Extreme TWL Projections of Year 2099 (20 Years Return Period)

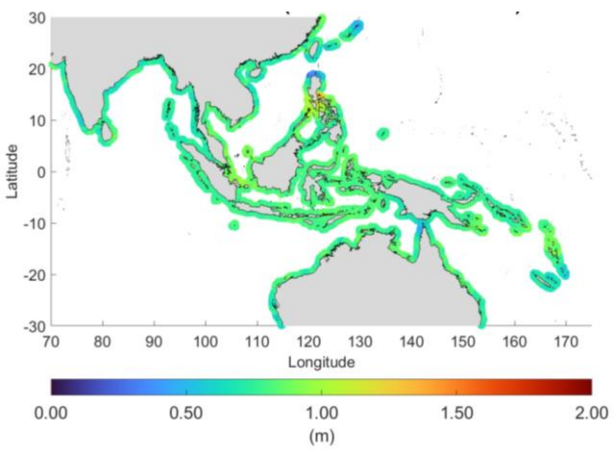

Figure 3 – Changes of TWL between Year 2000-2099 (20 Years Return Period)

To address this issue, we assume that the SLA variability remains unchanged from historical conditions. The SLA projection dataset was created by coupling the historical SLA dataset with regional SLR projections from IPCC AR6 under SSP5-8.5. This process involved extracting the historical SLA variability and combining it with the SLR projections that have been adjusted to align with the MSL reference.

An extreme value analysis (EVA) was applied to the SLA, DAC, and wave setup components independently. We employed a non-stationary Generalized Extreme Value (GEV) model with annual maxima as the input for this analysis. The assumption of stationarity is no longer reliable in the context of climate change, as projections indicate an acceleration of SLR and changing variability in other sea level components.

Given these changes, it is crucial to better account for non-stationary behavior in EVA to capture the evolving risk of extreme sea-level events. Thus, we modified the location parameter of the GEV model into a time-dependent function. Once the results for all individual components were obtained, the TWL was computed, following the equation, under the assumption of linear summation.

Results

Generally, the TWL in the equatorial zone tends to be smaller than in higher and lower latitudes regions due to its limited water level variability. However, the projected changes in TWL indicate a similar rate of increase across all regions, suggesting that equatorial areas will face a more severe impact from climate change. Between 2000 and 2100, we project an average increase in the 20-year TWL return period of 50-90 cm, driven primarily by SLR.

The DAC components show a decrease of about 10-15 cm in areas such as the northern Philippines, Taiwan, and Okinawa, with insignificant changes observed elsewhere in the region. Similarly, wave setup shows a decrease of 30–50 cm in the same areas, as the same forcing models both DAC and wave components. In addition, a wave setup decreases of 10-30 cm is also observed in lower latitudes, including the Oceania region and southern Australia, while some regions in Indonesia show a slight increase of 5-10 cm. These results can be utilized to enhance the coastal disaster mitigation planning for future climate change.