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Extreme coastal wave events: assessing global cumulative energy trends and wind forcing resolution impacts

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Abstract: Extreme coastal wave events pose significant risks to coastal communities, infrastructure, and ecosystems, causing severe damage, economic losses, and effects on human lives. Previous studies have investigated changes in mean and extreme wave heights; however, the evolution of cumulative wave energy associated with extreme wave events has not been systematically assessed. Cumulative wave energy, defined as a function of wave height and duration, is a reliable indicator of erosion potential, particularly along sandy, wave-dominated shorelines. Understanding how the energy of coastal storms is changing is essential for anticipating future impacts. Equally important is the ability to accurately simulate these events at regional and local scales, where impacts are most directly experienced. Numerical wave models are widely employed for this purpose, but their accuracy is strongly influenced by the resolution of the wind forcing. Although several studies have examined wind resolution effects on wave simulations, its role in modelling extremes at the coastal boundary, especially under different cyclone environments, remains insufficiently explored. The present study addresses these knowledge gaps by analysing global changes in the cumulative wave energy of extreme coastal wave events and by evaluating the influence of wind forcing resolution on the simulation of extreme waves using an event-based approach.

Global changes in cumulative wave energy were assessed using ERA5 reanalysis data. Wave storm events were identified using the Peaks Over Threshold method with a 95th percentile threshold for significant wave height. Cumulative wave energy was computed as the time-integrated energy over each event, excluding events shorter than 12 hours and merging those with peak wave heights occurring within 48 hours. At each coastal location, the Top 10 and Top 50 events were selected based on cumulative wave energy ranking and compared across two time slices: 1979–2001 and 2002–2024. Results show a general increase in cumulative wave energy globally, with pronounced regional variability. For example, Western Africa exhibits a substantial rise, while parts of Europe show a decline. The analysis shows that longer-lasting storms are the primary driver of cumulative energy intensification, while peak wave height plays only a secondary role.

To evaluate the role of wind forcing resolution in modelling extreme wave events, five wind datasets from BARRA-R2 (0.11°, 0.25°, 1°) and ERA5 (0.25°, 1°) were used to drive the SWAN wave model in two contrasting cyclone regimes: extratropical cyclones in Australia and tropical cyclones in the Philippines. The Top 50 extreme events from 1979–2023 were selected by ranking significant wave heights identified through the Peaks Over Threshold method above the 95th percentile threshold. Coarse-resolution winds produced higher biases in maximum wind speeds and wave heights, with the largest differences near coastal zones. Resolution effects were more systematic under extratropical cyclone conditions, while tropical cyclone cases showed greater spatial variability. Notably, simulations of Typhoon Haiyan (2013) were highly sensitive to wind resolution. These biases are driven by the inability of coarse wind fields to resolve steep wind gradients near cyclone cores and coastal zones.

This study demonstrates both that the energy of extreme coastal wave events has increased in some regions over recent decades, and that high-resolution winds are critical for accurately modelling these extreme wave events. These findings indicate that increasing storm energetics are likely to amplify risks for coastal communities. Reliable assessment of these risks therefore requires high-resolution wind forcing in numerical models, particularly within the coastal zone where impacts are most concentrated.

Keywords: *Extreme wave events, cumulative wave energy, wind forcing resolution, reanalysis, numerical wave modelling*