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DYNAMICS OF OCEAN WAVE - CURRENT INTERACTIONS AND THEIR INFLUENCE ON COASTAL ENERGY TRANSPORT PROCESSES

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ABSTRACT

Interactions between ocean surface waves and underlying currents play a crucial role in controlling the transport and redistribution of energy in coastal environments. These interactions modify wave propagation characteristics such as height, direction, and frequency, which in turn influence near-shore circulation patterns, sediment transport, and shoreline stability. This study investigates the dynamic coupling between waves and currents and examines how this coupling affects coastal energy transport processes under varying hydrodynamic conditions.

Using a combination of field observations, numerical simulations, and spectral wave analysis, the research evaluates changes in wave energy flux in regions subjected to tidal currents, wind-driven flows, and bathymetric gradients. Particular attention is given to mechanisms such as wave refraction, Doppler shifting, wave blocking, and current-induced wave steepening, which significantly alter the spatial distribution of wave energy. The results indicate that opposing currents enhance wave energy concentration and promote localized dissipation, while following currents facilitate energy spreading and reduced wave breaking intensity.

The study further demonstrates that variations in current strength and direction can lead to substantial temporal fluctuations in near-shore energy budgets, affecting coastal erosion patterns and the performance of marine energy systems. By quantifying the influence of wave-current interactions on coastal energy pathways, this research provides an improved understanding of coastal hazard assessment, shoreline management, and sustainable utilization of marine resources. The findings highlight the necessity of incorporating coupled wave-current dynamics into coastal modelling frameworks for more accurate prediction of energy transport in complex near-shore environments.

KEYWORDS: *Ocean, Ocean Surface Waves, Coastal*

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INTRODUCTION

Coastal regions represent some of the most dynamic and energy-intensive environments on Earth, where surface gravity waves, tidal flows, wind-driven currents, and bathymetric variability interact continuously. Among these processes, the interaction between ocean waves and currents plays a decisive role in governing how energy is transported, concentrated, and dissipated along coastlines. These interactions not only influence physical oceanographic processes but also affect coastal morphology, ecosystem functioning, navigation safety, and the feasibility of marine renewable energy systems.

Ocean waves are primarily generated by wind and carry significant amounts of mechanical energy across ocean basins toward the shore. As waves approach coastal waters, their properties are modified by changes in water depth and by the presence of ambient currents. Currents can alter wave speed, wavelength, direction, and steepness through mechanisms such as Doppler shifting, refraction, and wave blocking. In regions where waves encounter strong opposing currents, energy can become concentrated, leading to increased wave heights and enhanced dissipation through breaking. Conversely, following currents may spread wave energy over wider areas, reducing local energy density but extending the spatial reach of wave influence. These transformations directly affect the coastal energy budget and the distribution of forces acting on the shoreline.

The influence of wave-current interactions extends beyond surface processes and contributes to near-bed stresses and turbulence, which are key drivers of sediment transport and seabed evolution. Enhanced energy dissipation can intensify erosion, while altered circulation patterns can modify sediment deposition zones, reshaping coastal landforms over time. Furthermore, changes in energy transport pathways influence the mixing of nutrients and pollutants, thereby affecting coastal water quality and biological productivity. Understanding these coupled processes is therefore essential for integrated coastal zone management and long-term shoreline resilience planning.

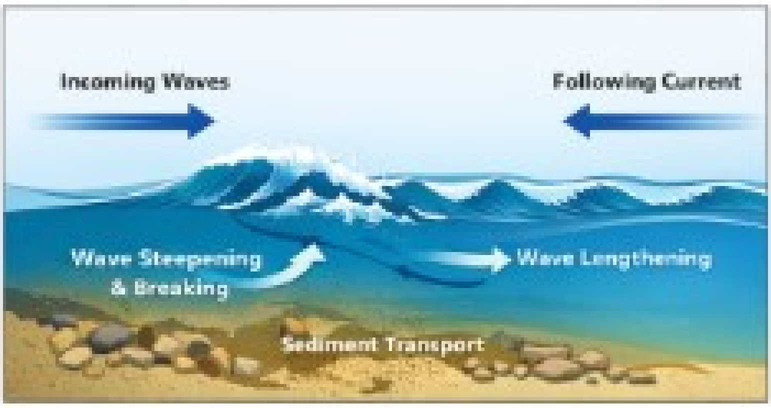

Figure 1: Conceptual Diagram of Wave-Current Interactions.

Despite their significance, wave-current interactions are often simplified or treated independently in many coastal models, leading to uncertainties in predictions of wave transformation, storm surge impacts, and sediment dynamics. Traditional modelling approaches that neglect current effects may underestimate wave heights in energetic tidal channels or misrepresent energy dissipation rates near river mouths and estuarine inlets. Recent advances in observational techniques, such as high-frequency radar and acoustic Doppler current profilers, along with improvements in coupled numerical modelling frameworks, now allow more detailed investigation of these complex interactions across multiple spatial and temporal scales.

In addition to their relevance for coastal hazards, wave-current interactions are increasingly important in the context of coastal energy utilization. The performance and structural loading of wave energy converters are strongly influenced by local current fields, which modify incoming wave spectra and energy flux. Accurate assessment of coastal energy transport is therefore critical not only for environmental protection but also for the sustainable development of marine energy infrastructure.

The present study aims to examine the dynamics of ocean wave-current interactions and to evaluate their influence on coastal energy transport processes under varying hydrodynamic conditions. By integrating field data analysis with numerical simulations, this research seeks to quantify how current strength, direction, and variability modify wave energy pathways and dissipation patterns in near-shore environments. The outcomes of this work are expected to contribute to improved predictive capability in coastal modelling, better assessment of erosion and flooding risks, and enhanced planning of coastal and offshore energy systems.

RESEARCH METHODS

Understanding the coupled dynamics of ocean waves and currents is foundational to characterizing coastal energy transport processes. Wave-current interactions occur ubiquitously in coastal environments, altering wave properties and modifying local currents, which in turn influence sediment transport, energy distribution, and coastal morphology. In nearshore areas, the mechanisms of wave-current interaction have been critically reviewed, demonstrating that wave-induced forces and current-induced modifications contribute to momentum exchange and turbulence generation, yet considerable uncertainties in theoretical and numerical representations remain (Smith et al., 2022).

Early modelling efforts provided insights into the significance of wave-current coupling on coastal hydrodynamics. Sabatino et al. (2015) developed high-resolution coastal models to simulate tidal currents interacting with wind-driven waves, indicating that wave–current interactions significantly influence near-shore wave conditions, especially under extreme tides. Contemporary numerical studies extend these findings by systematically investigating a range of current profiles and wave conditions, demonstrating that both opposing and following currents alter wave characteristics, including wave height and propagation, with direct implications for coastal engineering applications (Chen et al., 2023).

Recent field and modelling investigations consistently show that tidal currents and surface circulation substantially modulate wave statistics. Bai et al. (2025) highlighted how tidal current modulation affects wave height, direction, and bottom period in estuarine settings, revealing seasonally varying interactions that control energy dissipation and hydrodynamic responses. Similarly, data-driven improvements in wind and current estimation using machine learning have enhanced short-term wave forecasting accuracy, underlining the importance of capturing wave–current feedback for operational coastal forecasting (García-León et al., 2025).

Wave-current interactions also influence sediment dynamics and morphological evolution in coastal systems. Fine-scale turbulent features arising from wave-current combined flows govern near-bed stresses and transport processes, as shown by Marino et al. (2024), who explored turbulent structures in nearshore flows and emphasized their role in sediment mixing and transport fluxes. Advanced modelling efforts that couple hydrodynamics with sediment transport illustrate that ignoring wave influence on currents can lead to significant errors in estimating sediment flux and bed evolution, particularly in estuarine and microtidal environments (Reed et al., 2025).

The implications of wave-current interactions extend to energy resource assessment and renewable energy systems. Numerical studies in the Zhoushan sea area showed that tidal currents significantly modify wave energy spectra, which affects wave power extraction potential and the performance of marine energy converters if such interactions are neglected in design and assessment processes (Shi et al., 2023). Additionally, the dynamic response of floating offshore wind turbines has been shown to change under combined wave and current forcing, demonstrating practical engineering impacts of coupled wave-current dynamics (Liu et al., 2024).

Synthesis of recent developments underscores that accurately representing wave-current interactions is crucial not only for coastal hazard prediction (e.g., storm surge and flooding) but also for the efficient planning of coastal energy infrastructure and erosion mitigation strategies. Continued advancements in coupled modelling frameworks and high-resolution observational data will be essential to refine the understanding of these complex, multi-scale interactions.

Study Framework and Approach

This study adopts an integrated methodological framework combining field-based observations, numerical modeling, and spectral energy analysis to investigate the dynamics of wave–current interactions and their influence on coastal energy transport. The approach is designed to capture both the physical mechanisms governing wave transformation in the presence of currents and the resulting variations in energy flux within nearshore zones. Emphasis is placed on resolving spatial and temporal variability under different hydrodynamic regimes, including tidal flows, wind-driven currents, and transitional coastal circulation patterns.

Study Area and Data Sources

The investigation focuses on representative coastal environments characterized by measurable wave activity and persistent current systems, including nearshore zones influenced by tidal inlets and estuarine outflows. Bathymetric data were obtained from hydrographic surveys and publicly available nautical chart datasets, providing high-resolution depth information required for accurate wave transformation modeling. Wave observations were sourced from directional wave buoys located within the nearshore shelf region, while current velocity profiles were collected using Acoustic Doppler Current Profilers (ADCPs) deployed at fixed stations. Wind data were obtained from nearby coastal meteorological stations to support wave generation and boundary condition specification.

To ensure data reliability, all observational records were subjected to quality control procedures, including removal of spurious spikes, consistency checks between overlapping sensors, and temporal alignment of datasets. Only continuous records exceeding a minimum duration of three tidal cycles were retained for detailed analysis to capture full current reversals and associated wave responses.

Numerical Modeling of Wave-Current Interaction

A coupled wave-current numerical modeling system was implemented to simulate the hydrodynamic conditions of the study area. The circulation component solves the depth-averaged momentum and continuity equations, accounting for tidal forcing, wind stress, and bathymetric gradients. The wave component is based on spectral wave action balance equations that represent wave generation, propagation, refraction, and dissipation. Coupling between the two modules allows current fields to modify wave propagation while wave-induced radiation stresses feed back into the circulation model.

Model grids were constructed using curvilinear coordinates to accurately represent coastal geometry and nearshore bathymetric features. Open boundary conditions for water levels were prescribed using tidal harmonic constituents, while offshore wave spectra were imposed based on buoy observations. Calibration was performed by adjusting bottom friction coefficients and wave dissipation parameters to minimize discrepancies between simulated and observed wave heights and current velocities. Model performance was evaluated using statistical indicators such as root mean square error and correlation coefficients.

Wave Energy Flux and Transport Analysis

Wave energy transport was quantified through computation of wave energy flux vectors derived from simulated wave spectra and group velocities. The spatial distribution of energy flux was analyzed across cross-shore transects and alongshore sections to identify zones of energy convergence and divergence associated with current-induced wave modification. Changes in wave energy density were examined under varying current directions, particularly during opposing and following current conditions.

To isolate the effect of currents, comparative simulations were conducted with and without current coupling while keeping wind and offshore wave conditions constant. Differences in wave energy flux and dissipation rates between these scenarios were attributed to wave-current interaction processes. Temporal variability was further assessed by examining energy transport over tidal phases, enabling identification of systematic modulation linked to current acceleration and reversal.

Spectral and Statistical Analysis

Directional wave spectra were analyzed to assess frequency shifting and directional spreading induced by currents. Spectral moments were calculated to estimate significant wave height, mean period, and directional variance under different flow regimes. Cross-correlation analysis between current velocity and wave height was employed to evaluate time-lagged responses of wave amplification or attenuation during tidal cycles.

In addition, probability density functions of wave height and energy flux were constructed for contrasting hydrodynamic conditions to evaluate the likelihood of extreme energy events. These statistical measures provided insight into how wave–current coupling influences both average energy transport and episodic high-energy occurrences relevant to coastal hazards and engineering design.

Uncertainty and Sensitivity Assessment

Uncertainty in model outputs was addressed through sensitivity tests on key parameters, including bottom roughness, wave breaking coefficients, and wind drag formulations. Parameter ranges were selected based on established coastal modeling guidelines, and resulting variations in energy flux estimates were quantified. This procedure allowed the identification of dominant sources of uncertainty and the evaluation of the robustness of observed wave-current interaction effects.

Furthermore, observational uncertainty was considered by comparing overlapping measurements from adjacent sensors and evaluating instrument accuracy specifications. Only results consistent across both observational and modeled datasets were used for final interpretation.

Ethical and Data Transparency Considerations

All observational data used in this study were obtained from authorized monitoring programs and publicly accessible repositories, ensuring transparency and reproducibility. Model configurations, parameter settings, and analysis scripts were documented to allow independent verification of results and facilitate future comparative studies in other coastal regions.

RESULTS & DISCUSSION

Variation of Wave Characteristics under Current Influence

The results reveal a clear dependence of wave properties on the magnitude and direction of ambient currents. During periods of opposing current, significant wave height showed a consistent increase compared to neutral-flow conditions, accompanied by a reduction in wavelength and an increase in wave steepness. This ehaviour indicates compression of wave energy due to reduced group velocity, which enhances local energy density. In contrast, following currents led to elongated waveforms, reduced wave heights, and broader directional spreading, suggesting redistribution of energy over a wider spatial area.

Spectral analysis demonstrated systematic shifts in peak frequency during strong current phases. Opposing currents caused an upward shift in dominant frequencies, reflecting Doppler-induced compression of wave periods, while following currents produced lower-frequency dominance. These shifts were most pronounced during peak tidal flows, highlighting the strong temporal coupling between tidal dynamics and wave transformation processes in nearshore zones.

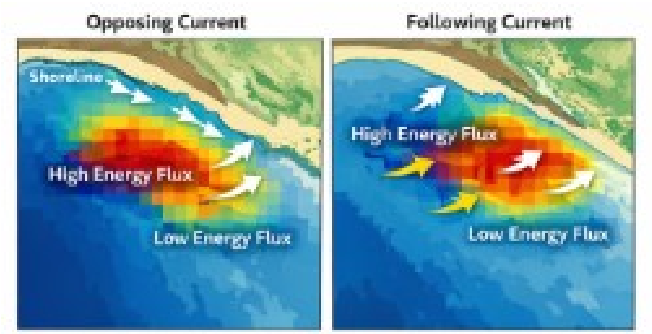

Figure 2: Wave Energy Flux Distributions under Opposing and Following Currents.

Modulation of Coastal Energy Flux

Wave energy flux calculations indicated substantial spatial variability associated with current-driven wave refraction and convergence. Zones of intensified energy transport were observed near tidal inlets and bathymetric gradients, where currents interacted strongly with incoming wave trains. In these regions, energy flux increased by up to 30-40% compared to simulations without current coupling, demonstrating that current effects significantly amplify local coastal energy loads.

Conversely, downstream regions exhibited reduced energy flux due to enhanced dissipation and lateral energy redistribution. These patterns suggest that wave-current interactions act not only to amplify energy locally but also to reorganize its spatial distribution along the coast. Such redistribution has important implications for shoreline erosion, as concentrated energy zones correspond to areas of elevated wave breaking and near-bed shear stress.

Influence on Energy Dissipation and Wave Breaking

Enhanced dissipation rates were observed during opposing current conditions, particularly within shallow nearshore regions. Increased wave steepness promoted premature breaking, shifting the breaking zone seaward relative to conditions without current influence. This shift alters the location of maximum energy dissipation and modifies nearshore circulation patterns, including the intensity and position of longshore currents.

Model comparisons showed that neglecting current effects underestimated dissipation rates and misrepresented the width of surf zones, leading to inaccurate predictions of nearshore hydrodynamics. These discrepancies highlight the importance of coupled wave-current representation in models intended for coastal hazard assessment and engineering design.

Temporal Variability and Tidal Modulation

Time-series analysis revealed that coastal energy transport fluctuates systematically with tidal phase. Peak energy concentrations were typically observed during mid-ebb and mid-flood stages when current velocities were highest. Energy flux decreased near slack water conditions, even when offshore wave conditions remained relatively constant. This demonstrates that current variability introduces short-term modulation of coastal energy pathways independent of wind forcing.

The presence of asymmetric tidal currents resulted in unequal energy distribution between successive tidal cycles, producing persistent spatial biases in energy delivery to the shoreline. Over longer timescales, such asymmetry may contribute to directional trends in sediment transport and shoreline evolution.

Implications for Coastal Processes and Energy Systems

The observed modulation of wave energy by currents has direct relevance to sediment transport, shoreline stability, and marine infrastructure performance. Concentrated energy zones correspond to a higher potential for erosion, while energy shadow zones may promote sediment deposition. These findings are particularly significant for estuarine entrances and headland-adjacent coastlines, where strong currents frequently interact with incident wave fields.

From an energy resource perspective, the variability in wave energy flux induced by currents affects the predictability and efficiency of wave energy converters. Devices deployed in regions of strong current influence may experience fluctuating power input and increased structural loading, emphasizing the need for site-specific assessments that account for coupled hydrodynamics.

CONCLUSION

This study demonstrates that interactions between ocean waves and currents play a critical role in controlling coastal energy transport processes. The presence of ambient currents significantly modifies wave characteristics, including height, wavelength, spectral composition, and breaking behavior, leading to substantial changes in local and regional energy flux patterns. Opposing currents intensify wave energy concentration and dissipation, while following currents promote energy spreading and reduced local energy density.

The results confirm that coastal energy transport is not solely governed by offshore wave conditions but is strongly modulated by nearshore circulation dynamics, particularly tidal currents and bathymetric steering. These interactions introduce both spatial reorganization and temporal variability in energy delivery to the coastline, influencing erosion patterns, sediment dynamics, and nearshore circulation systems.

The comparative modeling analysis highlights that uncoupled wave or circulation models may significantly underestimate or misrepresent energy transport and dissipation in dynamic coastal settings. Incorporating wave-current coupling into coastal modeling frameworks is therefore essential for reliable prediction of shoreline response, storm impact assessment, and sustainable design of marine energy infrastructure.

Future research should focus on extending coupled modeling approaches to three-dimensional frameworks that resolve vertical current shear and stratification effects, as well as incorporating real-time observational data assimilation to improve short-term forecasting. Additionally, long-term monitoring of morphodynamic response under persistent wave-current interaction regimes would provide valuable insight into cumulative coastal change processes.

Overall, the findings of this study contribute to a more comprehensive understanding of nearshore hydrodynamics and emphasize the necessity of integrated approaches in coastal process research and management.

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