Integrated Coastal Digital Twin framework for enhancing sustainable, science-based coastal resilience and adaptation strategies

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A coastal digital twin of the ocean (C-DTO) is a powerful framework that integrates near-real-time data with predictive models, providing a dynamic, actionable view of coastal environments. It serves as a critical tool for monitoring, forecasting, and planning responses to natural and human-induced changes, fostering more resilient and sustainable coastal management.

We present recent advancements in developing a C-DTO that incorporates five interlinked cores—waves, circulation, sediment transport, vegetation, and flooding. These cores enhance realism by including interactions among Earth system processes. Critical feedback mechanisms, such as wave-current, wave-sediment, and current-vegetation interactions, are essential for accurately representing coastal dynamics.

Built on deterministic foundations, the system integrates diverse observational data, from bathymetry and vegetation characteristics to ocean parameters such as waves, tracers, and sea level, supporting calibration, validation, and data assimilation. The integration of machine learning further enhances system capabilities, enabling the simulation of more complex processes and scenarios.

Accessibility and flexibility are central to the framework, allowing deployment across diverse geographic areas and temporal scales. It supports process studies, forecasting, event-based and long-term simulations, and what-if scenario testing, accommodating both gray (engineered) and green (nature-based) adaptation strategies.

Case studies illustrate the framework's versatility and effectiveness. Examples include characterizing extreme events such as storm surges during the Ianos Medicane, evaluating the potential of seagrass as a nature-based coastal protection strategy, assessing the impacts of breakwater construction, identifying optimal sites for *Posidonia oceanica* meadow restoration, and analyzing the effects of the regulated barrier closure in the Venice Lagoon.

This system empowers policymakers and researchers to assess the impacts of climate change and human interventions on coastal systems. By simulating complex scenarios, identifying risks, and investigating processes, it supports informed decision-making for enhanced coastal resilience and effective ecosystem conservation and restoration.