

Wave-Induced Vertical Turbulent Transport of a Passive Scalar Above Permeable Rippled Seabeds

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Coastal zones, as dynamic boundaries between land and sea, are essential for global biodiversity and ecological functions. However, they are highly sensitive and subject to intense anthropogenic pressures. Understanding the physical and ecological processes in these areas is crucial for developing strategies to enhance their resilience and sustainable management.

From a fluid mechanics perspective, coastal regions are particularly interesting due to the interactions between ocean waves and the seabed in shallow to intermediate water depths. These interactions generate complex flow dynamics affecting the exchange processes at the sediment-water interface. Sandy coastal sediments facilitate significant fluid flow across this interface, commonly referred to as submarine groundwater discharge and pore water exchange, due to their high permeability. This flow transports terrestrial and sediment-derived substances into coastal waters, impacting their chemical and ecological characteristics.

Under wave action, sand ripples form, shaping the seabed topography and influencing solute transport through wave-topography interactions. While the interactions between waves and ripples have been widely studied in the context of sediment and momentum transport, their role in the transport of solutes emerging from the seabed and dispersing into the water column remains comparatively underexplored.

To bridge this research gap, the present study employed controlled wave tank experiments to examine the transport of tracer fluid emerging from artificial permeable rippled seabeds. Simultaneous two-dimensional particle image velocimetry (PIV) and laser-induced fluorescence (LIF) measurements were utilized to capture velocity and concentration fields, respectively. These datasets were analyzed to evaluate the vertical transport of discharging fluid above the seabed-water interface, focusing on spatial tracer fluid distribution, turbulent kinetic energy, vertical turbulent fluxes, and turbulent mixing lengths.

The study investigated three key aspects: the impact of a rippled seabed compared to a flat seabed; the influence of the ripple shape, specifically comparing sinusoidal ripples with naturally shaped ripples that have sharper crests and broader troughs; and the effect of ripple asymmetry versus symmetry on the flow and transport behaviour. In addition to the influence of the seabed topography, the effect of varying wave conditions was also investigated as a second variable.

The findings demonstrate the influence of seabed topography and oscillatory flow in driving turbulence generation, which critically affects fluid transport and local concentration distributions. The results show that the transition from calm to stormy wave conditions substantially enhances vertical fluid transport above rippled seabeds, surpassing the impact of minor topographical variations, such as changes in ripple shape or symmetry factor. Flow separation and vortex formation at the downstream slopes of the ripples, which occur under strong oscillatory flow, were identified as primary mechanisms shaping tracer discharge patterns and vertical transport. The ripple shape and symmetry factor influenced the onset and timing of flow separation as well as the spatial extent of separation vortices, directly affecting turbulent vertical transport. Consequently, the symmetric natural ripple shape significantly increased turbulent vertical transport compared to the other seabeds, highlighting the critical role of ripple geometry in modulating transport processes.

This study is the first to quantify vertical turbulent fluxes and turbulent mixing lengths specifically associated with tracer transport above permeable rippled seabeds, providing key parameters for the numerical modelling of solute transport processes. The findings emphasize the importance of incorporating seabed topography into fluid dynamics models to improve predictions of the distribution of beneficial or harmful substances in coastal aquatic systems.