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The generation of multi-humped ISWs

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ABSTRACT

We offer numerical proof illustrating the shift from rank-ordered sequences of Internal Solitary Waves (ISWs) to formations of multi-humped packets. We attribute this distinctive and previously unexplored behavior to the emergence of long-range interactions among waves, facilitated by the hydrodynamic conditions arising in the wake of each ISW. These conditions favor the acceleration of subsequent waves. The characteristics of both the transitioning wave train and its eventual multi-humped arrangement align with hydrodynamic properties consistent with a recently proposed theory describing ISWs travelling through moving, continuously stratified environments.
KEY WORDS: Multi–humped solitary waves; Numerical simulations; Internal solitary waves interaction.

INTRODUCTION

Internal Solitary Waves (ISWs) are periodically generated by the interaction between tidal flows and seabed topography in the stratified coastal oceans (Carter et al., 2005; La Forgia et al., 2020a). They predominantly form in estuaries, straits, and continental margins, where the vertical density structure may experience strong pycnoclines (Kymak and Moum, 2003; Sutherland et al., 2013; La Forgia et al., 2018, La Forgia et al., 2020; Ottolenghi et al., 2020). The significant scientific interest in ISWs stems largely from their role in promoting both mass and energy transport, driving physical and biological processes of substantial relevance for coastal ecosystems (Lamb, 2014; Carr et al., 2019; La Forgia et al., 2019a; Deepwell et al., 2020; Zahedi, 2021; La Forgia et al., 2023). Waves shoaling and breaking over the continental slope induce mixing, energy dissipation and transport of nutrients (Xie et al., 2017; Deepwell et al., 2019; Nakayama et al., 2019, La Forgia et al., 2021b).
Small-amplitude ISWs propagating through two layers of uniform densities ρ_1 and ρ_2 were firstly investigated by weakly non-linear theories (Korteweg and De Vries, 1895). Features of strongly dispersive, large-amplitude ISWs were later reproduced by the MCC model (Miyata, 1988; Choi and Camassa, 1996a, 1996b). Recently, Kodaira et al. (2016) and La Forgia and Sciortino (2019) highlighted that, to accurately reproduce large-amplitude ISWs, as the ones observed in the real field, the system needs to feature a free surface.
Barros and Gavrilyuk (2007) derived stationary solutions for the approximate model developed by Barros et al. (2007). For oceanic stratification, i.e. Boussinesq conditions $\rho_1 \approx \rho_2$, their model predicts a single hump profile for both the pycnocline and the free surface. However, for low density ratios ($\rho_1/\rho_2 \approx 0.1$), these interfaces may also develop into multi-humped profiles, composed by successive humps traveling at the same celerity.
Further investigations focused on ISWs propagating through shear currents (Choi, 2006; Stastna et al., 2021; Zhao et al., 2023). Stastna and Lamb (2002) and Zu and Stastna (2019) showed that non-uniform background shear currents affect both shape and celerity of ISWs. La Forgia and Sciortino 2020 improved the MCC model by introducing mobile layers. They showed that shear currents are able to either switch single-humped ISW polarities or reverse their propagation direction. Later, La Forgia and Sciortino (2021) proposed a mathematical formulation based on the Hamiltonian approach (*H*) for a Free Surface (*FS*), two-layer stratified system in presence of Mobile Layers (*ML*), *HFS-ML* in the following, which includes solutions with multi-humped profiles.
All the mentioned studies investigated single and multi-humped ISWs profiles regardless of any possible mechanisms leading to their generation in a realistic stratified environment. We here deploy numerical approaches accounting for vertical density and velocity distributions to show that stand-alone ISWs are able to progressively group into packets by equalizing their shape and celerity. In agreement with the *HFS-ML* model, the number of humps composing the packet controls its geometric and kinematic features. Albeit we consider density ratios far from oceanic conditions ($\rho_1/\rho_2=0.6$), our findings may illuminate the presently unknown dynamics of the ISWs grouping, as observed in the stratified ocean.

NUMERICAL IMPLEMENTATION AND VALIDATION

The numerical simulations carried out in this study aimed at reproducing the physical processes developing during the propagation of a train of ISWs. The numerical generation of internal solitary waves is obtained by the lock-release technique in a density-stratified two-layer system (Sutherland et al., 2013). Hereinafter, subscripts *1* and *2* refer to the upper, lighter layer and the lower, heavier one, respectively; initial conditions are identified by the subscript *0*. At time $t_0=0$ s (see Fig. 1), the numerical tank is divided into two portions: the "lock", of length x_0, on the left, and the "ambient", of length L_0, on the right. The latter features a two-layer distribution characterized by thickness and density