3rd DNVA-RSE Norway-Scotland Waves Symposium
Oslo Norway, 16-17 September 2013

Mass transport by large and very-large amplitude mode-2 internal solitary waves: experimental observations

Alan Brandt and Kara R. Shipley
The Johns Hopkins University Applied Physics Laboratory
Laurel, MD 20723, USA

Summary

The present experiments provide the first quantitative measurements of the mass transport by mode-2 internal solitary waves (ISW) propagating on a thin pycnocline. The ISW were generated by the release of fluid from an initially mixed volume. It was found that the amplitude and amount of mass transported, by the leading and second following ISW, was proportional to the level of forcing and was attenuated at an approximately uniform rate as the ISW propagated downstream. At the highest level of ISW forcing over 40% of the mixed fluid was transported within the leading ISW. Excellent agreement was found with the numerical simulations of Salloum et al. (2012) that were designed to replicate the present experimental configuration. In addition, a new ISW regime was identified, termed very large-amplitude ISW, where the ISW bulge wavelength and extent of mass transported increased with amplitude at a rate greater than the lesser amplitude ISW. In recent years the frequent occurrence of large amplitude ISW in the coastal ocean has been observed. The present experiments and the associated numerical simulations can provide insight into the effects of ISW transport on coastal mixing and biological material distribution.

Introduction

Numerous observations of mode-2 internal solitary waves (ISW) in the littoral ocean have now been reported (e.g. Shroyer et al., 2010; Klymak et al., 2011; Ramp et al., 2012). Large amplitude mode-2 solitary waves have unique properties, in particular regions of internal recirculation that enable mass transport over large distances. Laboratory studies of large amplitude mode-2 ISW (e.g. Davis & Acrivos, 1967; Maxworthy,1980; Stamp & Jacka, 1995; Brandt, 2007) have shown evidence of the transport of fluid within a closed bulge wave implying the existence of a recirculation zone. Numerically this has been demonstrated by Terez and Knio (1998) and Salloum et al. (2012).

The present study is focused on the characteristics of large amplitude mode-2 ISW and the extent of mass transport as a function of the source, the two layer density difference and the pycnocline thickness. Moreover, the mode-2 ISW investigated have amplitudes in some cases significantly exceeding those investigated in prior studies, where a/h < 4, a being the ISW amplitude and h the interface thickness. In these cases, termed very-large amplitude ISW, with $4 \lesssim a/h \lesssim 8$ the bulge characteristics and wave evolution are significantly different than waves with $a/h \lesssim 4$.

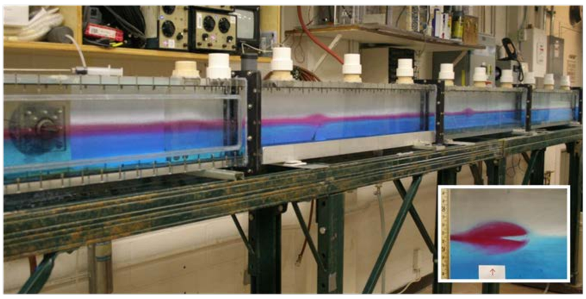

Figure 1. Stratified shear tunnel showing mode-2 ISW propagating on the thin interface (red). Upper clear layer is fresh water; bottom, blue layer is high density salt. Inset shows enlargement of large amplitude ISW entraining fluid at the leading edge.

Description of wavefield

The experiments were performed in an enclosed channel 20.3 cm high x 7.6 cm wide x 6.0 m long with a two-layer, equal depth stratification, fresh water over saline water. The ISW were generated using the “dam break” method using a mixing chamber at one end of the channel.

The general nature of the evolving flow can be seen in the photo of the channel is shown in fig. 1. Representative images of the leading mode-2 ISW for small and large amplitude conditions are shown in fig. 2. While all the ISW generated were large-amplitude, i.e. had internal recirculating regions and transported mass, they generally were of three types: $a_b/h < 2$, (a_b is the amplitude of the bulge wave) <u>small large-amplitude ISW</u> with a smooth front face; $2 < a_b/h < 4$, <u>intermediate large-</u>

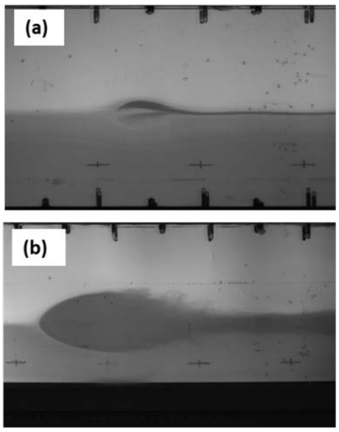

Figure 2. Representative ISW bulge waves,: (a) intermediate large-amplitude, $a_b/h = 1.96$; (b) very large-amplitude, $a_b/h = 5.92$.

amplitude ISW with an open mouth, “PacMan” opening where external fluid was dividing the bulge; and, $a_b/h > 4$, very large-amplitude ISW again with smooth front face likely due to strong internal recirculation; the latter two illustrated in fig. 2. In all cases a dye trail behind the leading wave was evident, composed of fluid from the dye release intrusion and detrained fluid exiting the downstream end of the bulge. This fluid was in part entrained into the 2nd ISW. In the very large-amplitude waves, e.g. fig. 2(b) at $a_b/h = 5.92$, local mixing (instabilities) are apparent at the bulge aft end.

Mass transport

The recirculation within the large amplitude mode-2 ISW results in the transport of mass, Φ, that is measured by the area of the ISW bulge. The amount of mass transported as a fraction of the initial mass released $\Phi/(2H_0L_0)$ is shown in figure 3(a), where the measurements for individual video frames in each window are shown. It is evident that a substantial fraction of the fluid released is transported by the initial ISW bulge. The fraction of the initial mass transported increases proportionally with the initial forcing, H_0/h, where H_0 is the height of the initial released volume. Figure 3(b) shows Φ scaled by h^2 vs. a/h, for all experimental runs. With this scaling the data for all forcing, H_0/h and bottom salinity, $\bar{s}_b$ conditions collapse into two curves separated at $a/h \cong 4$, The universality of the mass transport scaled by the interface thickness indicates that the dominant property governing ISW mass transport is the interface thickness, irrespective of the specific ISW generation conditions.

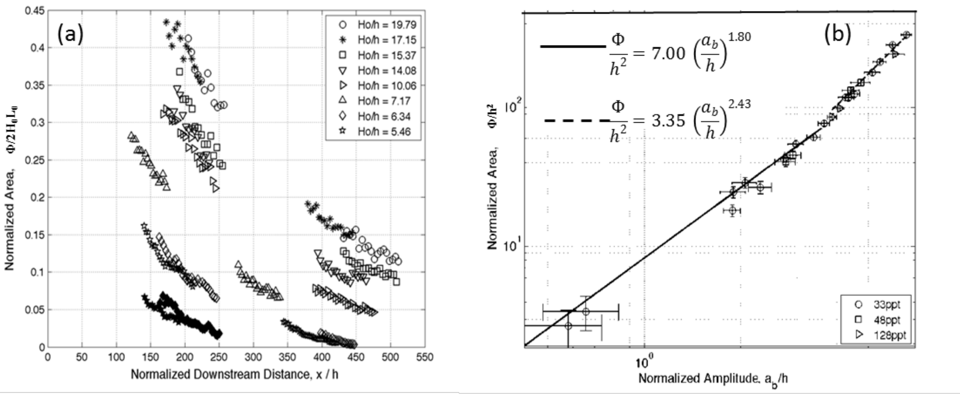

Figure 3. Mass transport by mode-2 ISW

Acknowledgements

The collaborative efforts of Prof. O. M. Knio are appreciated as is the assistance in the conduct and analysis of the experiments by J. E. Hopkins, G. S. Frederick, M. R. Grossman, and D. Wolff. The support of the Office of Naval Research Physical Oceanography Program is greatly appreciated.

References

Brandt, A. 2007 Evolution of Mode-2 Solitary Internal Waves in a Stratified Shear Flow, *Proceedings Fifth Int. Symp. on Environmental Hydraulics,* D.L Boyer, ed.)IAHR, Tempe AZ, OCLC 552182297).

Davis, R.E. & Acrivos, A. 1967 “Solitary internal waves in deep water.” *J. Fluid Mech. 29,* 593-607.

Klymak, J.M., Alford, M.H., Lien, R.-C., Yang, Y.J. & Tang, T.-Y. 2011 “The breaking and scattering of the internal tide on a continental slope, *J. Phys. Oceanog.*, 926-945.

Maxworthy, T. 1980 “On the formation of nonlinear internal waves from the gravitational collapse of mixed regions in two and three dimensions”, *J. Fluid Mech., 96,* 47-64.

Ramp, S.R., Yang, Y.J., Reeder, D.B., Bahr, F.L. 2012 Observations of a mode-2 nonlinear internal wave on the northern Heng-Chun Ridge south of Taiwan, *J. Geophys. Res., 117,* C03043, doi:10.1029/2011JC007662.

Salloum, M., Knio, O. M., Brandt, A. 2012 Numerical simulation of mass transport in internal solitary waves, *Phys. Fluids, 24*, 016602 (2012); doi: 10.1063/1.3676771.

Shroyer, E.L., Moum, J.N, & Nash, J.D. 2010 “Mode-2 waves on the continental shelf: Ephemeral components of the nonlinear internal wave field,” *J. Geophys. Res., 115,* C03022, doi:10.1029/2010JC006332.

Stamp, A. P., Jacka, M. 1995 Deep-water internal solitary waves, *J. Fluid Mech., 305*, 347–371.

Sutherland, B.R. & Nault, J.T. 2007 “Intrusive gravity currents propagating along thin and thick interfaces,” *J. Fluid Mech. 586,* 109-118.

Terez, D. E., Knio, O. M. 1998 Numerical simulations of large amplitude internal solitary waves, *J. Fluid Mech., 362*, 53–82.