Internal Bore Evolution across the Shelf near Pt. Sal, California, Interpreted as a Gravity Current

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(Manuscript received 4 May 2021, in final form 7 October 2021)

ABSTRACT: Off the central California coast near Pt. Sal, a large-amplitude internal bore was observed for 20 h over 10 km cross shore, or 100–10-m water depth (D), and 30 km along coast by remote sensing, 39 in situ moorings, ship surveys, and drifters. The bore is associated with steep isotherm displacements representing a significant fraction of D. Observations were used to estimate bore arrival time t_B, thickness h, and bore and nonbore (ambient) temperature difference ΔT, leading to reduced gravity g'. Bore speeds c, estimated from mapped t_B, varied from 0.25 to 0.1 m s^{-1} from $D = 50$ to 10 m. The h varied from 5 to 35 m, generally decreased with D, and varied regionally along isobath. The bore ΔT varied from 0.75° to 2.15°C. Bore evolution was interpreted from the perspective of a two-layer gravity current. Gravity current speeds U, estimated from the local bore h and g', compared well to observed bore speeds throughout its cross-shore propagation. Linear internal wave speeds based on various stratification estimates result in larger errors. On average bore thickness $h = D/2$, with regional variation, suggesting energy saturation. From 50- to 10-m depths, observed bore speeds compared well to saturated gravity current speeds and energetics that depend only on water depth and shelf-wide mean g'. This suggests that this internal bore is the internal wave analog to a saturated surfzone surface gravity bore. Along-coast variations in prebore stratification explain variations in bore properties. Near Pt. Sal, bore Doppler shifting by barotropic currents is observed.

KEYWORDS: Continental shelf/slope; Coastal flows; Internal waves; Density currents

1. Introduction

Across the continental shelf, internal waves display a range of weakly to highly nonlinear behavior as they shoal, break, and dissipate their energy (e.g., Vlasenko and Hutter 2002; Lamb 2014). These internal wave processes are important to the advective transport and vertical mixing of tracers such as plankton, heat, and sediment (e.g., Pineda 1999; Scotti and Pineda 2007; Shroyer et al. 2010b; Boegman and Stastna 2019; Becherer et al. 2021a), emphasizing their importance to coastal ecosystems (e.g., Woodson 2018). In coastal observations (e.g., Shroyer et al. 2011; Walter et al. 2012; Zhang et al. 2015; Colosi et al. 2018, hereafter C2018; McSweeney et al. 2020a, hereafter M2020a; McSweeney et al. 2020b, hereafter M2020b) and numerical models (e.g., Grimshaw et al. 2004; Helfrich and Grimshaw 2008; Aghsaee et al. 2010) internal waves manifest as a variety of features including internal solitary waves (ISW) and large-amplitude internal bores through the transformation of an offshore generated internal tide (e.g., Scotti et al. 2008; Lamb 2014; Boegman and Stastna 2019). These features are collectively referred to as nonlinear internal waves (NLIW).

The distinction between these two NLIW forms is significant. Internal solitary waves (ISW) are often described by weakly nonlinear and dispersive dynamics of Korteweg–de Vries (KdV) theory (e.g., Helfrich and Melville 2006) that requires a small ratio of wave amplitude relative to water depth ($\ll 1$) and similarly small ratio of water depth to wave horizontal scale (e.g., Helfrich and Melville 2006; C2018). In an idealized two-layer fluid where the upper-layer thickness is less (more) than half the water depth, this results in near surface (bottom) waves of depression (elevation). Although theoretical extensions (denoted eKdV) have been derived (e.g., Grimshaw et al. 2004), observations show KdV theory can appropriately describe observed ISW propagation and evolution (e.g., Bourgault and Kelley 2003; Shroyer et al. 2009) with departures from weakly nonlinear theory emerging for large-amplitude waves (e.g., Lamb and Yan 1996). The evolution of ISWs are modified by rotation depending on Rossby number, amplitude, and nondimensional dispersion parameter (e.g., Helfrich and Grimshaw 2008; Coutino and Stastna 2017). In contrast, internal bores on the shelf have large-amplitude (isopycnal displacements a significant fraction of the water depth), strong horizontal density gradients, and widths an order of magnitude or more longer than bore amplitude in

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DOI: 10.1175/JPO-D-21-0095.1

observations (e.g., Scotti et al. 2008; Walter et al. 2012; C2018; Sinnett et al. 2018; M2020a) and in models (e.g., Stastna and Peltier 2005; White and Helfrich 2014), indicating nonlinear nondispersive dynamics (Helfrich and Melville 2006). For dissipative model solutions, an open ocean (3000-m depth) ISW transforms upon shoaling onto a shelf (80-m depth) with a leading edge resembling a bottom cold bore (Lamb and Warn-Varnas 2015). Submesoscale horizontal density gradients can sharpen through frontogenesis and release surface bores that propagate as strongly nonlinear gravity currents in observations (Warner et al. 2018) and models (Pham and Sarkar 2018). The cross-shore evolution of an internal tidal bore may also be consistent with a gravity current.

NLIW properties such as speed, amplitude, and water column stratification are important in determining regions of energy flux convergence or divergence (e.g., Shroyer et al. 2010b; C2018) and elevated locations of shelf dissipation and mixing (e.g., MacKinnon and Gregg 2003; Becherer et al. 2021a). In coastal regions, NLIW properties of speed and direction have been extensively studied and depend on factors such as water depth, background stratification, current shear, and wave amplitude. Due to a clear surface signature, NLIWs can be measured from remote sensing with satellite, ship- or shore-based radar (e.g., Kropfli et al. 1999; Ramos et al. 2009; Celona et al. 2021), or video imagery (e.g., Pawlowicz 2003; Bourgault and Kelley 2003; Suanda et al. 2014). With a distinct arrival signal (rapid density change) in the water column interior, in situ estimates can be derived using plane wave fits to mooring arrays (e.g., Thomas et al. 2016; C2018; M2020a). Several studies combine simultaneous platforms to derive NLIW speed, direction, and amplitude following their propagation (e.g., Liu et al. 2004; Moum et al. 2007; Shroyer et al. 2010a; M2020b; Haney et al. 2021). Observed NLIWs propagate predominantly in the cross-shore direction, and NLIW studies largely focus on their cross-shore transformation. However, alongshore inhomogeneities can also be significant. For example, wave-front curvature of NLIW events in Massachusetts Bay was inferred to be due to Doppler shifting from spatially nonuniform barotropic tidal currents (da Silva and Helfrich 2008; Thomas et al. 2016), and the alongshore variation in internal bore-related kinetic energy was associated with a coastal headland (M2020b).

The shoreward evolution of nonlinear internal waves was a scientific focus of the fall (September–October) 2017 Inner-Shelf Dynamics Experiment (ISDE, see section 2), conducted off Pt. Sal, California (CA; Kumar et al. 2021). NLIW transformation across the shelf, alongshore variations in energy and phase, and effects on stratification have been investigated (C2018; Feddersen et al. 2020; Kumar et al. 2019; M2020a; M2020b; Becherer et al. 2021a; Haney et al. 2021). These observational studies focus on both statistical analyses of events over an experiment (C2018; M2020a; M2020b; Feddersen et al. 2020; Becherer et al. 2020, 2021a), as well as in-depth analyses of individual bore evolution centered on the well-stratified, mid-September intensive observational period (IOP1) (M2020a; M2020b; Haney et al. 2021). A few relevant results are summarized here as they pertain to quantities investigated in this manuscript: the ratio of NLIW amplitude to water depth (δ), the speed of NLIW propagation (c), the difference in horizontal and/or vertical density associated with NLIWs ($\Delta\rho$), and NLIW energetics.

In a June–July 2015 pilot experiment to the 2017 ISDE, C2018 classified ISW and internal bores. In 50–30-m depths, observed internal bores had widths > 1 km and amplitude to water depth ratios ranging from $0.2 < \delta < 0.5$. M2020a tracked a single 2017 ISDE observed internal bore from 50- to 25-m depth with $0.41 < \delta < 0.48$ (Table 3 in M2020a). In C2018, on average internal bores contained an order of magnitude more energy than ISWs, which had smaller amplitudes ($0.06 < \delta < 0.25$) and smaller (≈100 m) widths. Thus, strongly nonlinear internal bores dominate the energetics of NLIWs in this location. In this region, M2020b observed coherent bores over 30 km in the alongshore with the alongshore bore coherence decreasing as bores propagated into shallow water.

Internal bore propagation speed c and its dependencies, such as background stratification, have also been investigated. In C2018, the observed internal bore propagation speed c varied from 0.10 to 0.35 m s^{-1} in 40-m depth. C2018 showed that a subtidally averaged stratification-based linear mode-1 speed c_0, with KdV-based amplitude adjustment (see section 5a), better reproduced the observed c for slower internal bores than for internal bores with faster propagation speeds. Over approximately 3 months of observations and ≈100 bores, linear wave speeds c_0 based on time-averaged sorted stratification, compared reasonably well to observed c in 40–50-m depths, with the time-dependent c generally following low-frequency (subtidal) c_0 as stratification varied (M2020a). These results suggest linear or weakly nonlinear wave propagation. In M2020a, c was generally slower than linear nonrotating phase speed offshore of 32-m depths, and did not decrease as rapidly in shallower water depth D as would be predicted by linear speeds derived from stratification. Despite the general consistency between bore and linear wave speeds in 40–50-m depth, Eulerian ADCP velocities (u_e) associated with the bore were similar to the bore speed c (M2020a; M2020b; Haney et al. 2021) suggesting strong nonlinearity. Note that large u_e/c ratios approaching 1, as with modeled trapped-core, strongly nonlinear solitary waves (Lamb and Wilkie 2004; Stastna and Peltier 2005), or shoaling and dissipating shelf bottom cold bores (Lamb and Warn-Varnas 2015), are not consistent with weakly nonlinear theories (KdV and eKdV).

The cross-shelf evolution of ISWs and internal bore energetics have been previously studied statistically in ≤100-m depth at Pt. Sal (C2018; M2020b; Becherer et al. 2021a; Becherer et al. 2021b, hereafter B2021b), as well as other locations including the New Jersey shelf (Shroyer et al. 2010a) and the South China Sea (Duda and Rainville 2008; St. Laurent 2008). In these studies, the average energy, energy flux, and dissipation all decrease in shallower water. In analogy to the energetics and dissipation of surfzone surface gravity wave bores, B2021b developed a framework to understand how NLIW energetics depend on water depth, stratification, and incident energy flux suggesting that the inner shelf is the internal-surfzone. B2021b showed that over the inner shelf, the average evolution of NLIW was in a state of energy saturation, defined as when NLIW amplitude (and depth-integrated available potential energy) is depth limited (constant $\delta \approx 1/2$). In this highly dissipative environment, it is unclear what relative role vertical and horizontal water column density variations should play on internal bores.

Although the weakly nonlinear framework of KdV theory shows utility in describing bore evolution, an alternate perspective, particularly for large ($\delta \approx 0.5$) internal bores, is to interpret them as gravity currents as previously done for bores observed in 7–12-m depth (Pineda 1999; Sinnett et al. 2018). For example, larval transport by internal warm bores on the inner shelf has been modeled as a gravity current (Helfrich and Pineda 2003; Scotti and Pineda 2007). Gravity currents, the horizontal propagation of fluid of one density into a fluid with a different density, where horizontal length scales are typically long relative to vertical length scales, have been extensively studied in the laboratory via lock release experiments (e.g., Benjamin 1968; Shin et al. 2004; Sutherland et al. 2013) and applied to various environmental flows (e.g., Simpson 1997). For two fluids with different densities of total depth D, the gravity current speed U depends on a Froude number F_h and the buoyancy difference between the two fluids $\Delta\rho$ as

$$U = F_h(g'h)^{1/2}, \quad (1)$$

where $g' = g\Delta\rho/\rho_0$ is the reduced gravity and h is the depth of the current or the upper-layer thickness. The Froude number F_h takes on different forms depending on the theoretical derivation (e.g., Ungarish 2008). For an upper-layer relative thickness of $\delta = h/D$, Shin et al. (2004) derived

$$F_h = (1-\delta)^{1/2}, \quad (2)$$

which explained laboratory lock-release gravity current speeds. Based on energy considerations, the maximum gravity current thickness is $h = D/2$ (or $\delta = 1/2$) corresponding to $F_h = 2^{-1/2}$ (Shin et al. 2004). In contrast to weakly nonlinear wave theory where $u_e/c \ll 1$, the Eulerian velocity behind the gravity current nose is the propagation speed, i.e., $u_e = U$. Both gravity currents and large δ solitary waves have been diagnosed with fully nonlinear, nondispersive, and energy conserving wave equation (e.g., Lamb and Wan 1998), and gravity currents can be considered the long-wave limit of such dynamics with modified surface or bottom boundary condition (e.g., White and Helfrich 2008). Although internal bores on the shelf are dissipative (C2018; B2021a)—as are laboratory gravity currents—energy conserving theory provides excellent frameworks for understanding two-layer gravity currents. As gravity current concepts are often used to represent surfzone surface gravity bores (e.g., Raubenheimer et al. 1996), to further the inner shelf analogy with the surfzone (B2021b), here we interpret the onshore transformation of a single internal bore as a gravity current.

Gravity currents have been considered in various settings for which the complexities approach field conditions. For instance, the effects of gravity current propagation into a stratified fluid (e.g., Ungarish 2006; White and Helfrich 2008), or two-layer surface gravity currents propagating up a sloping bottom (e.g., Sutherland et al. 2013) have been investigated. For gravity currents propagating into a stratified ambient in the laboratory (Maxworthy et al. 2002), observed river plume (Nash et al. 2009), or modeled (White and Helfrich 2008) all indicate that as a gravity current front slows so that $U < c_0$, internal waves can be radiated from the front potentially inducing energy loss to the gravity current. Consistent with these concepts, (Haney et al. 2021) observed an onshore propagating internal bore during the ISDE IOP1 that split into a forward-propagating internal wave and slower warm surface bolus propagating as a gravity current that dissipated rapidly. Gravity currents under the effect of rotation, particularly flowing along boundaries, have been extensively investigated (e.g., Griffiths 1986; Lentz and Helfrich 2002). Numerically modeled lock-release gravity currents with rotation and periodic alongfront boundary conditions show that gravity currents eventually geostrophically adjust over many inertial periods (Salinas et al. 2019).

In this manuscript, we study in detail the propagation of a single warm internal bore across the inner shelf near Pt. Sal, CA, during the mid-October IOP2. This internal bore is tracked for ≈20 h across 10 km of cross-shelf propagation and is observed over a 30-km extent in the alongshore. A variety of in situ and remote sensing platforms are used to observe the bore and derive bore parameters such as speed, reduced gravity, and thickness as the bore evolves across the shelf. We add to previous detailed NLIW observations from the highly stratified mid-September IOP1 (e.g., M2020b; Becherer et al. 2020; Celona et al. 2021; Haney et al. 2021) by considering this bore during the mid-October second IOP2 with reduced stratification yet large offshore semidiurnal kinetic energy (e.g., M2020b). We apply two-layer gravity current ideas to this internal bore and explore 1) whether this particular bore propagates with speeds consistent with a two-layer gravity current formulation, 2) what gravity current ideas imply for the bore energetics, and 3) what a gravity current interpretation suggests for the bore's dynamics. Instrumentation that observed the bore is introduced in section 2. The methods to estimate bore arrival times from these instruments and bore properties such as speed, reduced gravity, and thickness are explained in section 3. Bore arrival times, bore speed, reduced gravity, and bore thickness are presented in sections 4a–4c, respectively. The relationship between bore speeds and gravity current speeds is explored in section 4d and bore energetics are presented in section 4e. Results are contextualized in light of previous work associating internal bore speed to stratification metrics (section 5a), limitations of the gravity current framework are discussed (section 5b), regional variations in the results are explored (section 5c, and the effect of barotropic velocities investigated (section 5d). The work is summarized in section 6.

2. Data

The Inner-Shelf Dynamics Experiment was conducted in the coastal waters near Pt. Sal, CA, during September and October of 2017 (Kumar et al. 2021). Moorings, ship, and drifter-based in situ sampling, as well as satellite, airborne, and shore- and ship-based remote sensing, were used to investigate inner-shelf hydrodynamics in the vicinity of a coastal headland. We focus on an internal bore that was observed by many platforms on 10 October 2017. We use a subset of the total observations,