Near-Bottom Turbulence and Sediment Resuspension Induced by Nonlinear Internal Waves

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LONG-TERM GOALS

The long term goal of this work is to develop a fundamental understanding and predictive capability of the underlying physics of the interaction of nonlinear internal waves (NLIWs) with the continental shelf seafloor over a broad range of environmental conditions. We are particularly interested in how such interactions impact underwater optics and acoustics and shelf energetics and ecology by stimulating enhanced bottom boundary layer (BBL) turbulence and particulate resuspension leading to benthic nepheloid layer (BNL) formation.

OBJECTIVES

The specific objectives of this now-terminated project have been:

- Using Large Eddy Simulations (LES), investigate the structural transition to turbulence within the separated BBL layer under a NLIW of depression and quantify the resulting NLIW energy losses.
- By means of Lagrangian coherent structure (LCS) theory, identify mechanisms for the capturing of near-bed particles by the BBL-turbulence and their transport/deposition into BNLs.
- Analyze field observations from the New Jersey shelf to identify the applicability of hypothesized BBL physics and flesh out the underlying fluid mechanics from the field data.

Reproducing a turbulent BBL under a NLIW has involved a non-trivial effort, both conceptually and in terms of computational cost. Hence, we have focused on the first objective with consistent efforts recently initiated to address the second one.

APPROACH

Our approach relies on implicit 3-D Large Eddy Simulation (LES) based on spectral multidomain solver developed by P.I. Diamessis (Diamessis et al. 2005), with the extrinsically prescribed dissipation of the spectral filter serving as a subgrid scale model surrogate. This code has been successfully applied to a number of computational stratified flow process studies in 2-D and 3-D (Diamessis et al. 2011, Diamessis et al. 2014, Zhou and Diamessis 2014), including the study of the primary instability of the NLIW-induced BBL (Diamessis and Redekopp 2006). It employs a uniform periodic (Fourier-based) grid in the along-wave direction and a multidomain Legendre-polynomial-based discretization, equipped with a penalty scheme, in the vertical. Its parallel implementation is based on a hybrid MPI/Open-MP approach.

Our problem geometry considers a mode-1 wave of *depression* fixed in a frame of reference moving with the NLIW's phase speed through a uniform-depth waveguide (figure 1). The background stratification across the full water column consists of a two uniform density layers separated by a finite-thickness pycnocline (figure 1). If required, the wave propagates against an oncoming barotropic background current which has, at the bed, its own idealized Blasius-like boundary layer. As the wave is kept fixed in time, we solve for the perturbation to this wavefield that develops through the mismatch between the non-zero wave velocity field and no-slip condition at the bed (Diamessis and Redekopp 2006). To maximize resolution of the 3-D turbulence in the NLIW-induced BBL, our computational domain is a truncated in the vertical direction. A detailed view of the computational domain with the appropriate boundary conditions is shown in Figure 1.

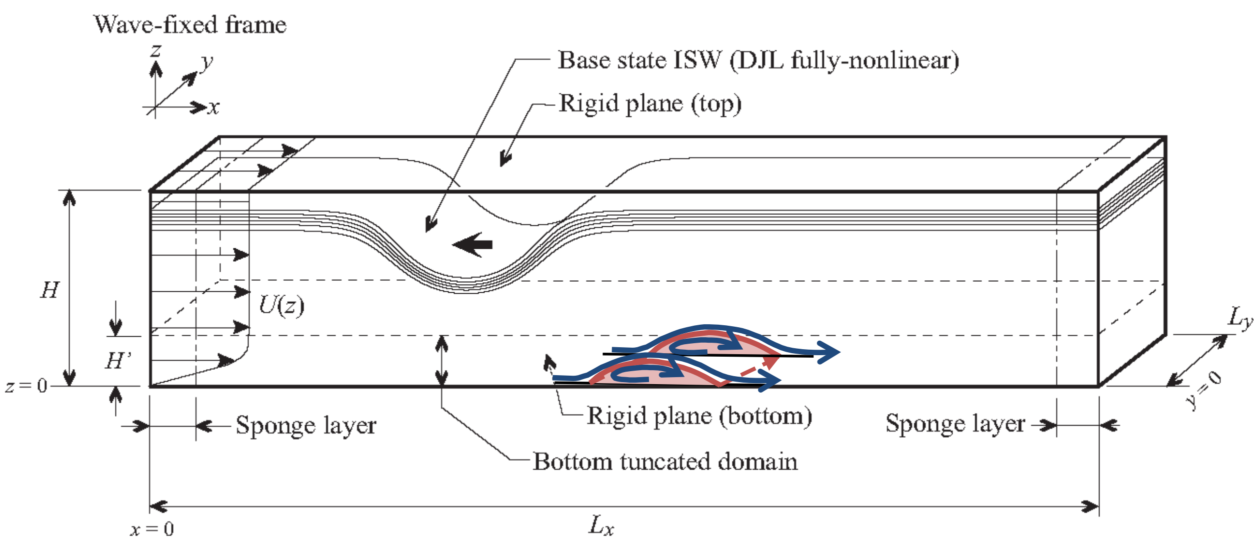

Figure 1: Schematic of flow configuration used in Large Eddy Simulations. The separation bubble (near-bed recirculation zone) is highlighted.

Finally, our particle-tracking tools revolve around libraries built by co-P.I. Jacobs based on a higher-order accuracy Eulerian-Lagrangian (EL) approach (Jacobs and Hesthaven 2006, Jacobs and Don 2009). These tools have been used by the co-P.I. to determine particle-laden flow with relevance to liquid-fuel combustors. Most recently, they have been adapted to any type of grid used by a discontinuous element-based higher-order method (discontinuous Galerkin of spectral multidomain penalty).

WORK COMPLETED

The computational reproduction of the transition to turbulence in the separated BBL under a NLIW has turned out to be a non-trivial effort. At the onset of this project, we had anticipated that replicating such a transition would be straightforward, much in analogy to what is observed in the computational literature of stratified shear layer simulations (Smyth and Moum 2000): the self-sustained. primary instability (global instability in the case of the NLIW-driven BBL) will first break-down into a secondary spanwise instability and high-order instabilities, ultimately giving rise to a self-sustained near-bed turbulent wake in the rear of the NLIW.

In an attempt, to capture the above classical transition to turbulence, we have resorted to well-resolved implicit LES, thereby avoiding any spurious physical effects due to wall-modeling or eddy-viscosity-based subgrid scale models. Specifically, we use a wall-normal resolution of 0.1 wall-unit with streamwise and spanwise resolutions ranging between 10 and 12 such units. As a result, simulations have used 8192×64×251 grid points on 1024 cores. Nevertheless, at least at the values of the wave-based Reynolds number, $Re_W=Hc/\nu=1.6\times10^5$ (here H and c are the wave-guide depth and NLIW phase speed, respectively) we examined, we were unable to reproduce this classical transition. Potentially, such a transition might be indeed take place at higher Reynolds numbers, which are not attainable with current HPC resources, at least if a physics-preserving well-resolved LES is desired.

We ultimately elected to generate a by-pass transition in the NLIW-driven BBL. Here a fully three-dimensional flow structure is established immediately upstream of the separation region in the wave footprint, rapidly leading to 3-D turbulence in the wave bed. To this end, a meticulously designed volumetric forcing technique, adapted from the aerodynamics literature (Jones et al. 2008) has been used. Using this forcing, we have conducted two large-scale LES of the NLIW-induced BBL: One where the wave propagates into quiescent waters and one where the NLIW encounters an oncoming barotropic current. In the latter case, the oncoming current has a free-stream velocity equal to 0.4*c*. In both runs, the volumetric forcing was kept on. Nonetheless, in the oncoming current case, once the BBL has reached steady-state, the forcing is turned off to determine whether the near-bed wake can indeed self-sustain itself. Both of the above simulations have required 4 million CPU hrs on DoD-HPC platforms. Although the particular dataset provides its own set of critically useful insights, we are in the process of repeating the oncoming current case, as we originally erroneouly used the NLIW phase speed of the no-oncoming-current set-up. This corrected run will be completed by the end of the calendar year and will be followed by the necessary analysis. Nevertheless, significant physical insight has been gained through the ongoing analysis of the expansive dataset associated with the two recently completed simulations.

We would like to reiterate that, although not comparable to the demands of a field deployment, the simulations of the very complex NLIW-induced 3-D BBLs are non-trivial in terms of both cost and conceptual implementation. Beyond the physical insights imparted by our soon-to-be-completed well-resolved LES, the existing datasets will serve as platforms for comparison with more operationally-based, lower-resolution, LES simulations. In this regard, we have begun discussing with Prof. Andrzej Domaradzki, a turbulence modeling specialist at U.S.C., possible avenues of collaboration where we can perform reliable coarser LES at 1% of the resolution of the runs presented here. Such coarser runs will ultimately allow us to explore a broader parameter space of NLIW-seafloor interaction.

A senior Ph.D. student supervised by the co-P.I. visited the Cornell campus in July. Beyond instructing the P.I.'s group on LCS theory, he worked with a Cornell Ph.D. student on applying these techniques to results from 2-D NLIW-driven BBL simulations.

RESULTS

Analysis of our results is ongoing, as we are on standby for the conclusion of the simulation of the oncoming current case with the corrected wave phase speed. We anticipate completion of analysis early in Spring 2015, which will be followed by the write-up of two articles one on the 3-D ISW-driven BBL and another on LCS analysis of the corresponding 2-D BBLs. In terms of 3-D results, our analysis focuses on elucidating the coherent flow structures linked to the transition to turbulence, integral measures of the BBL, estimates of bottom drag and investigation of departure from the standard law of the wall.

Integral measures of the BBL are given in Figure 1, focusing on the forced regime of the oncoming current case. The elevated shape factor confirms the presence of a separated turbulent boundary layer. The presence of a momentum-thickness Reynolds number exceeding 500 in the turbulent region of the BBL suggests the presence of well-developed turbulence with sufficient scale separation. A bottom friction coefficient within the range [0.004,0.006] is computed, whereas the levels of the turbulent kinetic energy in the BBL are within 25% of U_2^2 where U_2 is the NLIW-induced along-wave velocity in the lower layer (not shown).

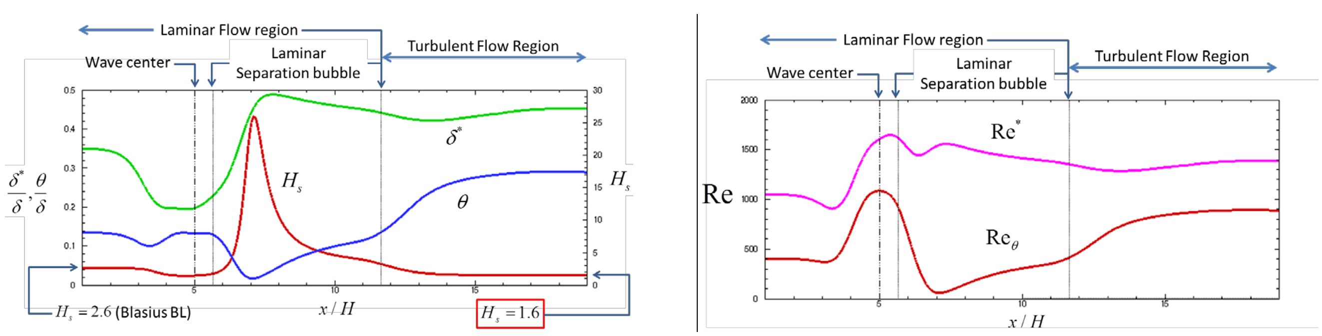

Figure 2: Left panel: Integral measures of NLIW-driven BBL, including displacement thickness δ^*, momentum thickness θ and shape factor H_s. The thickness of the Blasius BL associated with the model oncoming current is denoted by δ. Right-panel: BBL Reynolds numbers based on δ^**and *θ*,** **denoted by** ***Re **and** ***Re********, respectively.***

The bottom drag, as resulting from both the laminar leading edge of the NLIW and also the turbulent near-bed wake in the rear of the wave, are shown in the left panel of Figure 2. The latter turbulent contribution is supplement by the viscous dissipation inside the wake itself. We have found that 1.2% of the NLIW energy is lost during propagation over one wavelength. Consequently, bottom friction linked to this near-bed wake can induce non-negligible wave energy losses over typical NLIW propagation paths of $O(10)$ wavelengths over continental shelves of slowly varying depth.

The spanwise-averaged vertical profile of the streamwise velocity is shown in the right panel of Fig. 2 at three different locations along the bed in the near-bed turbulent wake. Although the theoretically prescribed profile of the viscous sublayer is tracked very closely, when transitioning into the buffer layer and log-law region a significant departure is observed from the canonical logarithmic profile. All profiles are sampled outside of the NLIW-induced adverse pressure gradient (APG). Nevertheless, the above departure from the log-law suggests a “memory” of the APG bearing implications for parameterizing NLIW-seafloor interaction in the field.

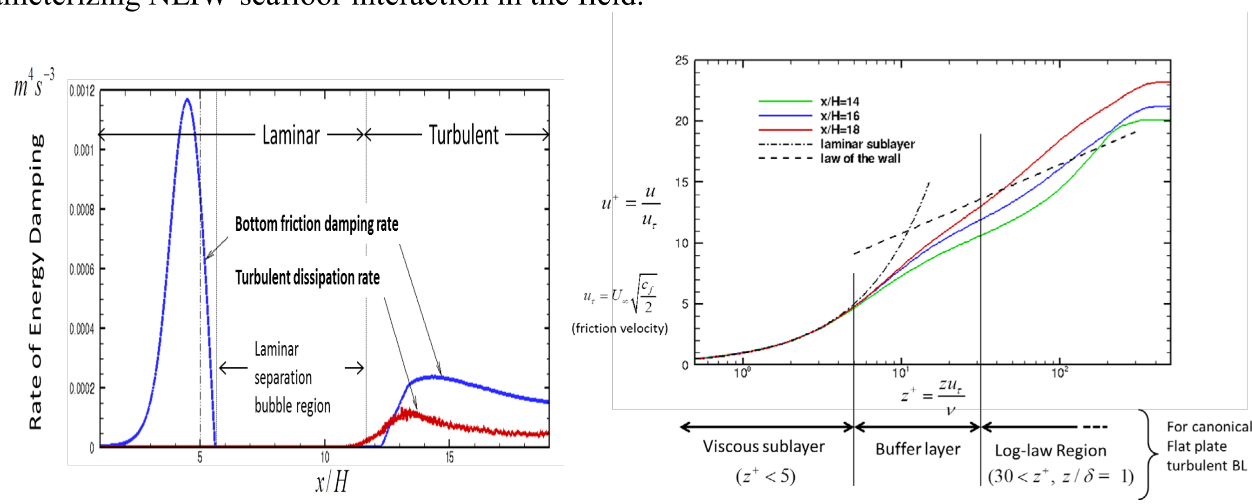

Figure 3: Left panel: Rate of NLIW energy loss (integrated in spanwise direction) per time of one NLIW wavelength propagation time as a function of along wave position in wave-fixed reference frame. The model wave has a wavelength of 100m and propagates with a phase of speed of 0.89 m/s in a model domain that is 10m-deep and 1m wide. Right panel: Spanwise-averaged along-wave velocity profiles at different streamwise locations as compared to classical theoretical estimates, including the log-law.

Finally, when the volumetric forcing is turned off the near-bed turbulent wake does not self-sustain. Instead, it advects out of the rear of the domain into the sponge layer (Figure 4, left panel). This highly puzzling lack of self-sustainance may be attributed to two factors: Either our relatively low Reynolds number, with respect to the ocean, or our lack of full resolution in the streamwise/spanwise direction where certain fine-scale motion, critical to self-sustainance of the turbulence, is unresolved or filtered out.

The case with no-oncoming current generates a transitional near-bed 3-D structure in the lee of the wave which is indicative of a higher-order instability, though not fully developed turbulence (a further confirmed by the structure (Figure 4, right panel). Any 3-D motion immediately advects out of the domain upon turning off of the forcing. Curiously, recent unpublished experimental data (Prof. Leon Boegman, pers. Comm.) shows a persistent near-bed vortex wake under a NLIW in a similar configuration. We conjecture that this difference is in the inevitable non-negligible roughness of the laboratory flume bed (which provides persistent excitation) and the non-symmetric wave that is generated in the flume which differs significantly from the theoretical fully nonlinear waves examined in our study.

Finally, Figure 6 shows representative findings from our application of LCS analysis to results from 2-D simulations of NLIW-induced boundary layers. Backward and forward-time finite Lyapunov exponents (FTLE ; Haller 2001) are indicators of transport attractors and barriers, respectively, in the flow induced by the vortices shed by the separating NLIW-driven BBL. Transport barriers are identified as local maxima in the FTLE field and define the boundaries within which fluid is entrained. Particles cannot move through such barriers. At the time depicted, the primary vortices shed of the BBL have completely engulfed intermediate vortices that originated in-between the primary vortices. Fluid above and leading the primary vortices is entrained, contributing to the growth of the vortices. Attractors in the flow are identified by local maxima in the FTLE field determined backward in time. Attractors responsible for the upwelling and re-suspension of particles follow each primary vortex. A superposition of particles on the forward-time FTLE field shows the exact trajectory of resuspended near-bed particles and enables key insight into the physical mechanism underlying resuspension.

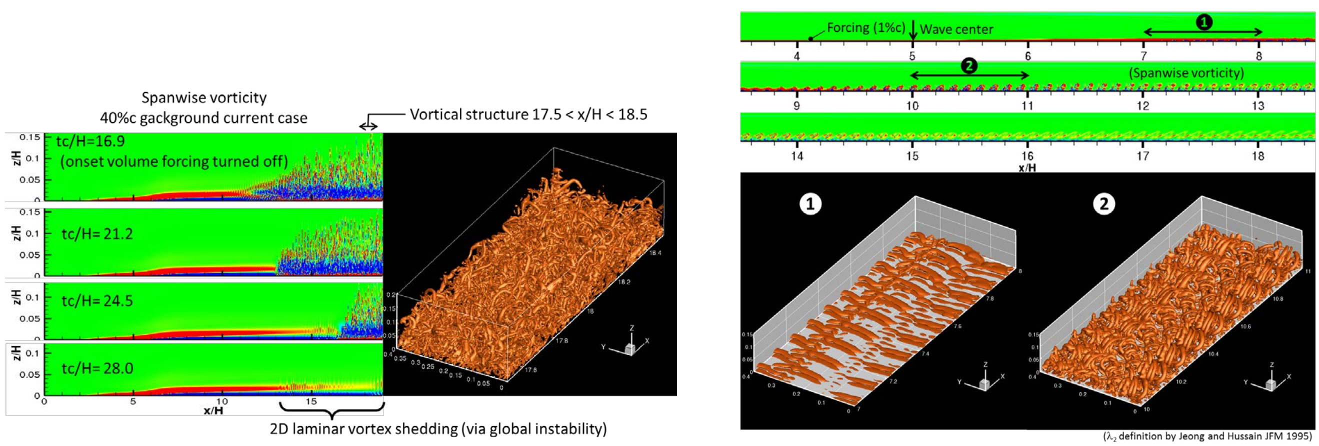

Figure 4: Left panel: 3-D coherent structures in the near-bed turbulent wake in the NLIW-induced BBL in the case with an oncoming barotropic current after the forcing has turned off. The contour plots on the left show stream-depth contours of spanwise vorticity at different times. The turbulent wake progressively exits the domain leaving behind only a 2-D global instability. Right panel: Similar visualization at two different regions along the bed for the no-current case. Note that, in this case, despite non-negligible three-dimensionalization, these complex structures never transition to fully-developed turbulence along the bed.

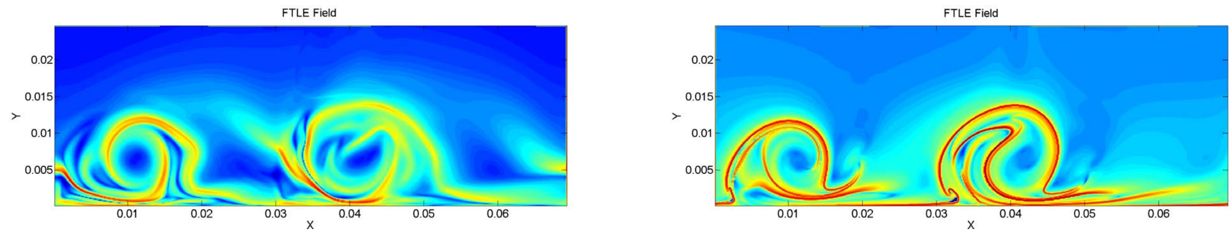

Figure 5: Finite-time Lyapunov exponents (FTLEs) computed via Lagrangian Coherent Structure (LCS) analysis for two shed vortices in the separated NLIW-induced BBL, as generated through 2-D simulations. Left and right panels show forward and backward-time FTLEs which show transport barriers and attractors, respectively, linked to the two particular vortices. Any particles originating from the bed in the right panel will faithfully follow the red contour lines. Ongoing studies are examining the role of this Langragian transport in benthic nepheloid layer formation.

IMPACT/APPLICATIONS

The accurate representation of the structure and magnitude of shear stress field field in the NLIW footprint and accurate estimation of the NLIW energy losses due to bottom interactions will allow the formulation of improved subgrid-scale parameterizations of energy dissipation and bottom boundary conditions for larger-scale operational forecasting models used to simulate environments with high NLIW activity. An enhanced understanding of the underlying physics of the NLIW-driven BBL also provides critical insight on how the bottom shear stress and pressure fields conspire to generate high-amplitude sandwaves, such as those observed in the South China Sea, which can pose significant challenges in efforts of acoustic bathymetry mapping. Finally, the generated resuspended particle distributions under NLIWs, a reliable proxy of BNLs, can be used to quantify the transmission or backscatter of optical/acoustic signals of importance to remote sensing efforts and near-bed SONAR operation.

RELATED PROJECTS

Funded by an NSF-CAREER award in Physical Oceanography and a NDSEG fellowship, a Ph.D. student in the P.I.'s group has completed the design of a high-performance hybrid MPI/open-MPI quadrilateral SMPM code that accounts for variable bathymetry (see Escobar-Vargas et al. 2014 for the non-deformed subdomain version of this code). This new code will be used to study the shoaling of NLIWs in domains with bathymetry replicating the South China Sea (SCS). In collaboration with Dr. Scott Wunsch, the P.I. recently published an article on the nonlinear generation of harmonics during the impact of an internal wave beam (IWB) on a model sharp oceanic pycnocline and the associated interfacial wave generation (Diamessis et al. 2014). Supported by internal funds, a Ph.D. student in the P.I.'s group is studying the energetics of IWB-pycnocline interaction. Parallel efforts, funded by O.N.R. code 33, have investigated Lagrangian mean flows associated with the reflection of an IWB off a free-slip surface (Zhou and Diamessis 2014). In collaboration with Prof. Luis Parras at the U. of Malaga, Spain, the P.I. and a Ph.D. student are investigating numerically and theoretically the 2-D and 3-D instability analysis of the BBL under long surface solitary waves (Sadek et al. 2014).

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PUBLICATIONS

Published:

Escobar-Vargas, J.A., Diamessis, P.J and Sakai, T. 2014: A quadrilateral spectral multidomain penalty method model for highly nonlinear and non-hydrostatic stratified flows. ***International Journal of Numerical Methods in Fluids***, 75, pg. 403-425.

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Submitted:

Escobar-Vargas, J.A., Joshi, S.M., Diamessis, P.J. and Van Loan, C.F. “The numerical solution of the pressure Poisson equation for the incompressible Navier-Stokes equations using a quadrilateral spectral multidomain penalty method” , (Submitted SIAM Journal of Scientific Computing).

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